

**APPLICATION OF THE SWAN SHALLOW WATER WAVE MODEL TO
SOME U.K. COASTAL SITES**

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ABSTRACT <p>As part of the JERICHO (Joint Evaluation of Remote sensing Information for Coastal defence and Harbour Organisations) project the following questions needed to be answered:</p> <ul style="list-style-type: none">(a) What is the best type of wave model to use for near-shore wave transformations?(b) What are the strengths and weaknesses of the SWAN model?(c) How can satellite altimeter and in-situ wave data be combined with wave models in an optimum way?(d) How do extreme wave statistics offshore transform to the coast?(e) If waves offshore (at a distance of about 20km, in water of depth about 30m) increase in height in some future climate change scenario, what will be the effect on waves at the coast (say in depths of about 5m)?(f) What differences are likely between different coastal locations? <p>This report attempts to answer these questions by means of the application of the SWAN wave model to three contrasting coastal locations around the UK: at Holderness on the North Sea, Lyme Bay in the English Channel and Carmarthen Bay in South Wales on the Bristol Channel.</p> <p>SWAN is a sophisticated third-generation spectral wave model, designed for the near-shore zone (outside the surf zone). Other wave models, using ray tracing for refraction and a self-similarity scaling for shoaling, can run much faster and may capture sufficient of the physical processes for most purposes, but do not allow an in-depth understanding of the physics to be obtained. SWAN has (almost) state-of-the-art physics and fewer parametric assumptions than previous models. It is relatively quick to set up and user-friendly in operation, but some terms should be improved and not all interactions are included (e.g. bottom friction). It is expensive in terms of computer time. Running long time series on a PC is prohibitive.</p> <p>The prediction of extreme wave statistics is quite problematic. SWAN can transform a number of individual wave events from a few kilometres offshore to the coast. However it is not clear how the return period of the resulting wave should be determined. Waves at the coast are much more controlled by water depth than those offshore. If the wind-speed is increased this can support larger waves, but an unrealistically high wind would be needed to substantially increase the wave</p>	

height in very shallow water. The wave field adjusts continuously to the local depth so that imposing a very large wave height at the offshore boundary causes the model to increase energy dissipation dramatically until a more appropriate wave height is achieved.

The variability around the UK coast is typified by the selection of three different sites. The main controlling factors for coastal wave climate are exposure to offshore waves, tidal range and coastal steepness. Highest waves at the coast occur at high water. Holderness, in the North Sea, is much less exposed to wave energy, especially swell, than the West Coast locations. There is a moderate tidal range. This site is the least steep in the region 5-16km offshore. Wave energy is dissipated mainly very near to the coast. The Lyme Bay location in the English Channel is a wide shallow bay with rapidly shoaling bathymetry, deep offshore then steepening rapidly in the last 2km, with fetch varying greatly with direction. Waves from the SW have longest fetch and large swell events have caused damage at Chesil Beach in the past. The tidal range is less than Holderness, being near to the M_2 tidal amphidrome. The wave energy is quite high close to shore, then dissipates rapidly as the waves experience the steeply shoaling water. Carmarthen Bay on the South Wales coast is a deep bay with complex bathymetry, in an area of very large tidal range and strong currents. The area is the most exposed with the largest wave heights from the SW. Carmarthen Bay depths reduce at a steady rate with a marked shoal at about 4km offshore, which dissipates wave energy. The coastal wave climate depends on which output location is selected: much higher waves are predicted at a rocky headland than at a beach location.

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1. INTRODUCTION

1.1 The JERICHO project – background and objectives

The JERICHO project (Joint Evaluation of Remote sensing Information for Coastal defence and Harbour Organisations) was a BNSC Earth Observation LINK programme, funded by the British National Space Centre and the Environment Agency. The participants were Satellite Observing Systems (SOS), Southampton Oceanography Centre (SOC), the Proudman Oceanographic Laboratory (POL) and Sir William Halcrow & Partner (Halcrow).

The principal objective of the JERICHO project 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. The economic goals were 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. The challenge was to combine expertise from satellite remote sensing, statistical analysis and wave modelling to provide a useful tool for those involved in coastal management. This goal was very ambitious within the limited scope of the project. During its 2-year existence the project sought to identify the means to be used to make progress towards this goal, assessing the inter-annual trends in wave statistics from satellite and buoy data and their likely impact at the coast of the UK by means of shallow water wave models.

The satellite record of wave heights, measured almost continuously since 1985, shows a clear signal of an increase in winter of about 10% over the last decade. Satellites cannot measure right up to the shoreline because the offshore signal to the sensor becomes contaminated by land within the footprint. That presents a problem since coastal defences are based on a prediction of the highest waves reaching the shore. The UK is, however, reasonably well served by a network of wave measuring buoys. The best procedures for comparing the buoy recordings with the satellite observations, and the methods for modelling wave behaviour at the coast from the wave field derived or observed in deeper water were tested. David Cotton at SOC (later at SOS) compiled a database of satellite and buoy data. The work on the analysis of waves from satellite and in-situ data and the North Atlantic wave climate was carried out by other partners in the JERICHO project (Cotton et al., 1999). Here we focus on the SWAN wave modelling studies done at POL.

1.2 Review of wave climate modelling studies relevant to JERICHO

This is not an exhaustive list but includes some interesting modelling and observational studies.

- (a) Early studies include JONSWAP (Joint North Sea Wave Project) – focussing on the measurement of waves in the North Sea (Hasselmann et al., 1973). This was the basis for development of much of wave modelling physics and a standard wave spectrum, which is widely used. Other early experiments were MARSEN (Maritime Remote Sensing in the North Sea) – based in the southern North Sea (Shemdin and Hasselmann, 1983) and ARSLOE (Atlantic Remote Sensing Land

Ocean Experiment, Baer and Vincent, 1983), leading to derivation of the shallow water TMA (Texel-MARSEN-ARSLOE) spectrum (Bouws et al, 1985). The LEWEX (Labrador Sea Extreme Waves EXperiment) project did not observe very high waves, but demonstrated the need for accurate winds, and that an inter-comparison of buoy versus model spectra can show differences not seen in H_s only. SWADE (Surface Wave Dynamics Experiment) in the NW Atlantic / east coast USA used a hierarchy of nested wave models (using WAM), driven by various model wind fields: ECMWF Atlantic winds and regional winds from ECMWF, FNOC, NMC, NASA, OW/AES, UKMO. It demonstrated the need for the best possible wind fields. Standard meteorological models alone produced disappointing results, analysed model winds (by Oceanweather/AES) were better.

- (b) The performance of wave models in extreme conditions has been studied by various authors e.g. Eid et al. (1992) for the Beaufort Sea and Cardone et al. (1996). Khandekar et al. (1994) examined the performance of the Canadian spectral ocean wave model (CSOWM) during the Grand Banks ERS-1 SAR wave spectra validation experiment. Hubertz et al (1994), Hubertz (1995) made comparisons of models and observations for the NW Atlantic, USA coast. The latter used WISWAVE 2.0 model (Wave Information Studies wave model), and winds from the NOGAPS data set (1976-1990, 2.5°, 6-hourly), to compare model output with climate atlas data (i.e. ship observations), buoys and GEOSAT (4 years). Using a trend test he saw an overall pattern of decreasing waves in the northern North Atlantic.
- (c) Wave statistics have been produced for the North Sea based on observations e.g. Hogben (1990), Korevaar (1990). There is a European wave atlas developed in an EC MAST project: OCEANOR World Wave Atlas (<http://www.oceanor.no/wwa>). Operational models for the North Atlantic and North Sea include UKMO - winds and waves archives, based on a 2-G wave model, ECMWF – a global WAM model now on 0.5° grid and DNMI - wind and waves data base, running the WINCH wave model. Various data inventories have been produced, for the UK, one of the most recent being that of Harford (1998).
- (d) The WASA Project (Guenther et al., 1998) produced hindcast waves for the North Atlantic and North Sea on a grid 0.5°x1.5° from 38°-77°N, 30°-45°W, with the following results:
 - (i) 40 years of hindcasts were produced, based on 100 years of observations, for the Northeast Atlantic
 - (ii) the WAM 3-G wave model was run on 2 nested grids: 1.5°x1.5° for the North Atlantic and 0.5°x0.75° for the Northeast Atlantic.
 - (iii) FNOC and DNMI winds were used to drive the models.
 - (iv) Results do not support large increases in wave height. The mean significant wave height, H_s , is increasing by about 0.2% annually. The large variability spatially and temporally may be the cause of an apparent increase in 'storminess'. Part of the variability is attributed to the North Atlantic Oscillation, which has increased over the past 30 years.
 - (v) In the WASA results there is only very small change in mean significant wave height but significant increases in the 90 and 99th percentiles. Whilst the authors claim that this result is real, it is just the effect that would be expected for a long dataset where resolution of events had considerably improved over the period in question.

- (e) NEPTUNE - an EC MAST II project with partners: BMT, Delft Hydraulics, Universities of Lancaster, East Anglia, Erasmus, Rijkswaterstaat and GKSS. This studied the coastal impact and statistics of extreme storms over a period of 38 years (1955-1983), including 40 storms. The models used were POL CSX (continental shelf model) for tide and surge, GKSS HYPA for offshore waves, DUT HISWA and SWAN (deep to shallow wave transformations) with 6-hourly met. data from DNMI model. A 14-day run was carried out for each storm event to study cause and effect. Various aspects were studied – the validation of meteorological model data, classification of storm events, validation of offshore wave, tide and surge model results, transfer of offshore waves to coastal cells, parameterisation of transform processes for selected coastal zones and development of joint statistics of extremes. There were 2 study regions: Irish Sea and Dutch coast.
- (f) California Swell Model – this gives online swell predictions (see web-site http://cdip.ucsd.edu/models/about_swell.html). The swell model is based on wave refraction-diffraction simulations. The model only simulates waves arriving from outside the islands (wave periods of 8 seconds and longer). It doesn't consider any local generation of seas (O'Reilly and Guza, 1993). The model includes various sub-regions: San Francisco Bay Area (initialized with data from CDIP's Pt. Reyes Buoy), Monterey Bay Area (initialized with data from NOAA Buoy 46042), Central California (initialized with data from Chevron's Harvest Platform), Southern California Bight (initialized with data from Chevron's Harvest Platform). For the Southern California Swell Model, deep water directional data are collected from an array of pressure sensors attached to Chevron's Harvest Platform located in 200 meters of water, about 10 kilometers west of Pt. Conception. These data are transferred to the Coastal Data Information Program at Scripps at roughly 1-hour intervals. The sensor data are processed to produce an estimate of the deep-water directional spectrum. The coastal swell height plots are generated by selecting the shallowest model results (~5-8m water depth) along the coastline.
- (g) Recent developments include the PROMISE project, in which some shallow water improvements to WAM were made, now included in PRO-WAM (Monbaliu et al., 1999). Wave transformations from the WASA wave hindcasts to the PROMISE grid were investigated by van Vledder (1997), using transformations based on shallow water growth curves for near-shore shallow grid points using nearest upwind WASA point. Where land intervenes, effective fetch length and fetch-limited growth are computed.
- (h) Wave measurement methodologies were compared in SCAWVEX, with remote sensing (including satellite altimetry and SAR) as well as conventional in-situ measurements.
- (i) Ongoing development of shallow water wave models is fostered by the WISE group (Wave modelling in Shallow Environments), which followed on from the work of the WAM group.
- (j) Another EC-MAST project was ECAWOM, developing a coupled atmosphere-ocean-wave model which includes the WAM model as the wave model

2. SHALLOW WATER WAVE MODELLING

2.1 Brief review of shallow water wave models

By the early 1980's it was recognised that to model wave spectra properly it was necessary to include the wave-wave interactions. Previous generations of spectral wave models used a self-similarity scaling to model the shape of the wave spectrum, but it was realised that in many cases the spectrum would not follow such simple parametric shapes. Therefore after some model inter-comparison studies (e.g. SWAMP, 1985) the WAM (Wave Modelling) group was formed to develop a so-called 3rd-generation wave model which included explicitly wave generation by wind, white-capping and nonlinear quadruplet interactions as well as propagation. The results of a 10-year programme of model development were published in Komen et al. (1994). The model was originally developed for deep water but then extended to shallow water with depth and current refraction. The SWAN model was developed using the same physics as WAM with the addition of depth-induced wave breaking and triad interactions, plus an implicit integration scheme for more efficient computation on fine grids. Many other types of model are still used. These range from simple parametric wave models, e.g. Shore Protection Manual (1984) updated by Hurdle and Stive (1989), and ray tracing models to phase-resolving models including wave diffraction e.g. Boussinesq models, which are more applicable in very shallow water at the beach, within the surf zone. Spectral models with various levels of parameterisation are also still in use. Smallman et al (1994) gives a review of wave transformation models. This covers the range of shallow water models in use by the coastal engineering community to transfer wave conditions from an offshore to an inshore site, including ray-tracing and finite difference (or finite element) models.

Various levels of sophistication of wave model can be applied, as seen above, and there is much to be said for a simple ray-tracing model, which can be run economically over a long period, to generate wave statistics. At the other extreme is a state-of-the-art model, which includes all relevant physical processes explicitly, such as the SWAN 3-G spectral wave model. Note that spectral wave modelling may be applicable to a minimum water depth of about 5-10m. By this depth nonlinear wave effects are important and depth-limited wave breaking becomes important. These models are not applicable inside the surf zone. 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.

A limited area wave model requires, as input, the boundary wave spectrum, wind speed and direction and water level. Minimum boundary data requirements are wave height, period and direction, from which a standard spectrum (e.g. JONSWAP) can be constructed. Satellite altimeters can provide wave height, an estimate of period (although not in a form ideal for SWAN) and wind speed. Water level can be obtained from tide and surge model predictions or a local tide gauge. Wind direction can be obtained from coastal stations or offshore buoys. Specification of offshore wave direction or the full frequency-direction spectrum needs input from a directional wave buoy or larger-area wave model.

2.2 The SWAN model

SWAN (Simulating Waves Nearshore) is a 3-G phase-averaged spectral wave model, specifically designed for modelling shallow water coastal regions (Booij et al., 1999; Ris et al., 1999). The model is termed 3-G because it includes explicit redistribution of the wave energy within the wave spectrum, by nonlinear wave-wave interactions. This is not an exact solution but uses the so-called discrete interaction approximation (DIA) developed for the WAM model (Komen et al. 1994).

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. It can be applied on grids ranging from kilometres down to a few metres and on rectangular or curvilinear grids.

The SWAN model is still under development by the Delft University of Technology, funded by the US Office of Naval Research, and the international user community, including POL. For example, 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. He identifies some terms as not being correctly derived, including the depth-limited breaking. This model will be likely to provide the basis for the next generation of shallow water wave models.

The SWAN model proved able to reproduce wave events given good boundary input spectra at Holderness. Note that the version of SWAN used for this project was version 30.75. More recent versions are now available with some modifications.

3. MODEL SETUP

3.1 Selection of sites for modelling studies

POL's contribution to JERICHO was to work closely with Halcrow on the shallow water modelling which transforms the offshore waves to waves which impact at the coast. It was decided that the SWAN shallow water wave model would be applied to three coastal sites at Holderness, Lyme Bay and Carmarthen Bay (see Figure 1). Holderness is in NE England, Lyme Bay is on the south coast of England and Carmarthen Bay is on the Welsh side of the Bristol Channel.

A substantial dataset on waves at Holderness, in the North Sea, was available from other projects e.g. LOIS, SCAWVEX and PROMISE, and this was therefore chosen as a validation site for the model methodology. Lyme Bay and Carmarthen Bay were chosen to represent different coastal configurations for comparison of the impact of waves at the coast. Holderness is much less exposed to wave energy, especially swell, than the west coast locations. Prevailing SW winds cause fetch-limited conditions and a typical bimodal combined wind-sea and swell spectrum (Wolf, 1998). The open coastal location at Holderness leads to less variability in the long-shore direction and the need for specification of a cross-shore boundary condition. There is a moderate tidal range. Lyme Bay is a wide bay with steeply shoaling bathymetry, with fetch varying greatly with direction. Waves from the SW have longest fetch and large swell events at Chesil Beach to the east have caused damage in the past (e.g. February 1979 - Draper and Bownass, 1983). The tidal range is less than Holderness, being near to the M_2 tidal amphidrome. Carmarthen Bay is more enclosed, with complex bathymetry, in an area of very large tidal range and strong current. It is also exposed to some of the largest waves experienced on the UK coast, from the SW Approaches and the North Atlantic. The Bristol Channel also has the largest tidal range in the UK and correspondingly large tidal currents.

The number of SWAN runs that were carried out was constrained by the limited time available for this project. The approach taken was a combination of modelling events and using offshore wave statistics to drive the models.

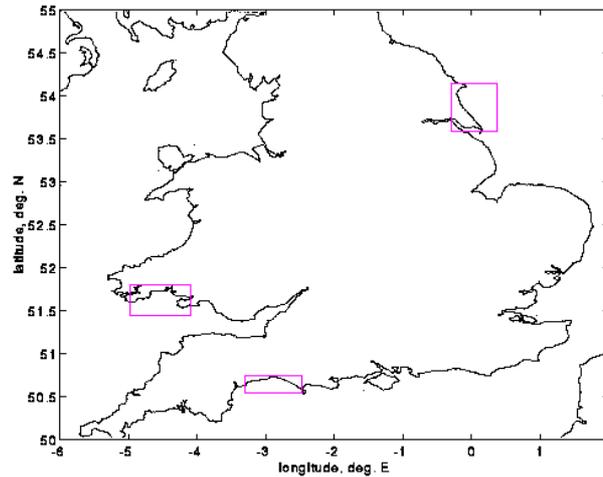


Figure 1: Location of three coastal sites for JERICHO wave modelling

The first phase consisted of setting up the fine-scale coastal wave models on three grids, with bathymetric data supplied by Halcrow on a 200m grid for the three coastal sites. Each model was set up with an extent of about 20km in the offshore direction and about 60km in the long-shore direction. This aspect ratio was chosen to minimise the effect of errors at the cross-shore boundaries in the model interior. Some idealised test cases were run on a grid similar to the Holderness grid, but uniform in the long-shore direction in order to test the optimum method for specification of the cross-shore boundary condition. The models were run on a Unix Workstation and on a Pentium PC. The following tasks were then carried out:

- (a) A study was made of the processes affecting shallow water wave transformation at Holderness, based on observed data from that area. The largest event observed (1-2 January 1995) was modelled at 3-hour intervals. This event was a combination of wind-sea and swell and so is a good test of the validity of the model. The time-varying water level and current were available from observations and from the POL tide and surge model. The effects of local wind, water level, boundary conditions (including spectral shape), offshore wave height and period, currents, triad interactions, bottom friction and depth-limited breaking were investigated. Also the question of how to use TOPEX altimeter data to specify the offshore boundary condition was examined.

- (b) For Lyme Bay the SWAN model was set up with the same parameters as chosen for Holderness. There was a shortage of offshore data for Lyme Bay, so effort was put into specification of the offshore boundary condition from satellite data. The model output was compared with waves measured by pressure sensor at West Bexington in 10m mean water depth.
- (c) The SWAN model at Carmarthen Bay was more problematic in that no near-shore data were available, although offshore boundary conditions were available from wave data recorded at St. Gowan. Part of the SWALES data set (Oct-Dec 1993) was chosen for detailed modelling. The model was set up based on the validation of the other two sites. Output was generated at two contrasting locations: one in very shallow water and one in quite deep water at an exposed headland.

SWAN was run in time-independent mode, setting switches for various processes e.g. wind input, triad interactions, depth-induced breaking. The output was compared where possible with Halcrow's STORM model (Muir-Wood and Fleming, 1980). Finally the model was used to run extreme events using offshore statistics together with assumptions about the appropriate water level to be used for e.g. 1-year, 100-year and 1000-year return periods. More details of the model setup in each case are given in the following sections.

3.2 Holderness

The Holderness coast was chosen as a useful validation site because near-shore and offshore wave data were available from the Holderness Experiment in the winters of 1994-95 and 1995-96 (Wolf, 1996; 1998). The bathymetry is gently sloping offshore from a boulder clay cliff and is fairly uniform in the long-shore direction. In order to obtain the best alignment with the coastline the grid was rotated by 30° anti-clockwise. Figure 2 shows the original model layout and bathymetry (contours at 10m intervals). The locations of N1, N2 and N3 are shown as crosses, with N1 nearest the coast and N3 the furthest offshore. The model was later modified so that the outer open boundary ran through N3 and the northern boundary met the coast at Flamborough Head.

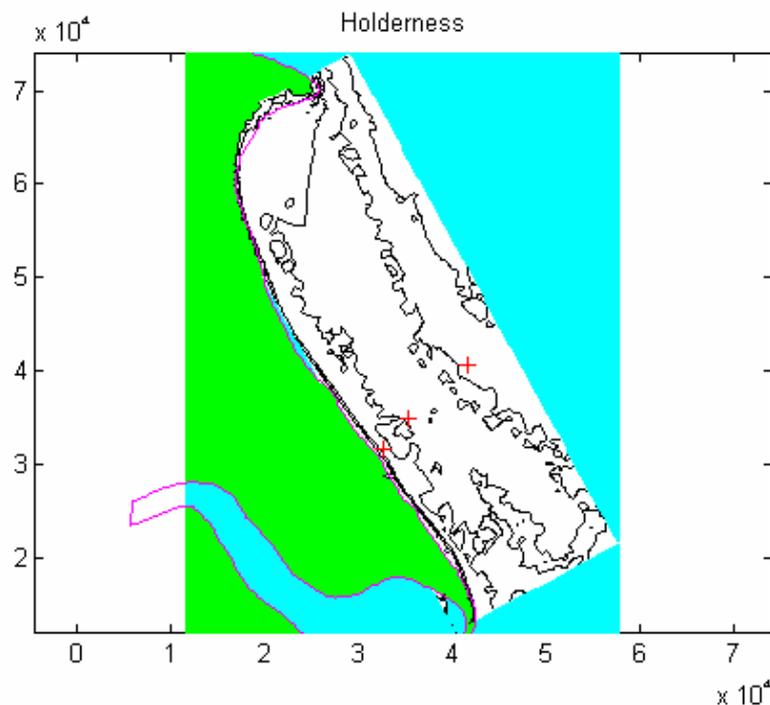


Figure 2: Holderness

Before it could be used in the model, the bathymetry required some correction from chart datum (Lowest Astronomical Tide) to Mean Sea Level. The array of corrections was derived from the POL hydrodynamic model and although there was variation of 0.8m across the model grid, for simple implementation within SWAN a correction of 3.6m was chosen for the whole grid.

The final spatial grid was 78 by 296 points with approximately 200-metre resolution. In the frequency domain there were 31 frequencies (0.04-0.5Hz) and 24 directions. It took 120MB of RAM and 25 minutes per run on a Silicon Graphics R10000/195MHz (1996) workstation. SWAN was run in stationary mode.

One item of concern is the bathymetry. Figure 3 shows the line offshore close to N1, N2 and N3, and the difference between the model grid bathymetry (blue) corrected to mean sea level and the mean depth measured by the bottom pressure recorder (green).

There appears to be a systematic offset between the two. An error of this nature in the bathymetry would cause a systematic underestimate of the wave height in the model due to the bottom dissipation term being too large. The position of N1 is approximately 1km offshore. In the model, however, it appears to be about 400m offshore.

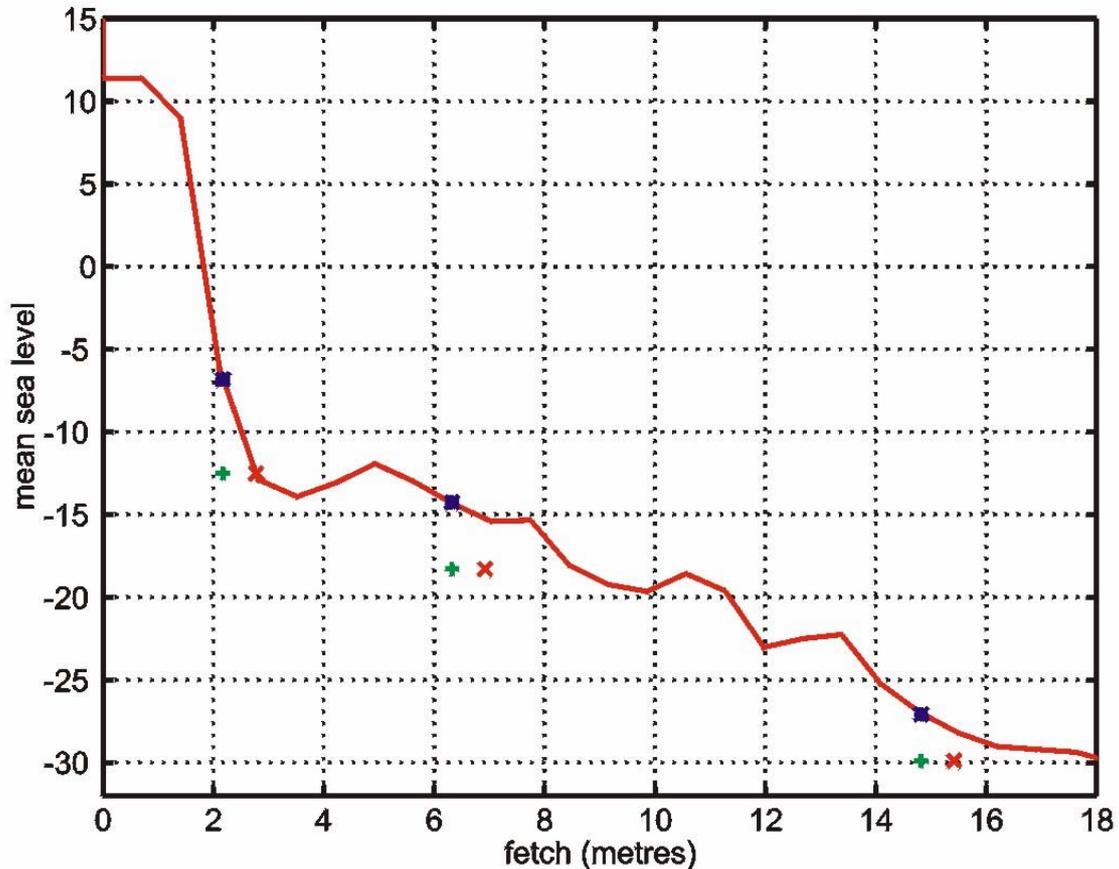


Figure 3: Cross-shore depth profile at Holderness showing effect of position error

The red crosses show the effect of shifting the coastline so that all the points are 600m further offshore. The results reported in the rest of this document use the original grid positions.

3.3 Lyme Bay

Lyme Bay was chosen because there was a useful near-shore data set from the West Bexington pressure sensor and to provide a contrasting south coast site. Some potential offshore in-situ buoy measurements turned out to be poor quality. The offshore boundary therefore relied on the TOPEX data, and some statistics produced by Ewing et al (1993). The cross-shore depth profile has quite a steep slope especially at the eastern end of bay. Figure 4 shows the model layout and bathymetry. The model grid had 300 by 100 grid-points with 200-m resolution. The mean sea level correction was +2.0m.

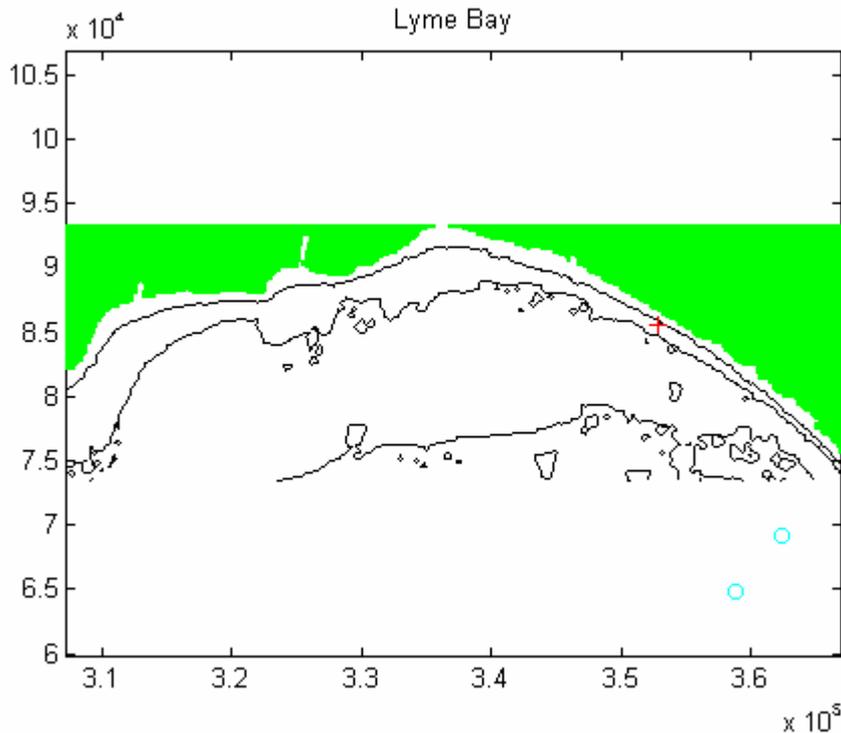


Figure 4: Lyme Bay, contours at 10m intervals, circles are TOPEX tracks, cross is location of inshore data (West Bexington)

3.4 Carmarthen Bay

Carmarthen Bay provides a contrast to the other sites in having a very large tidal range, quite strong tidal currents offshore and exposure to large waves from the Atlantic. A good data set existed offshore at the St Gowan buoy. The bathymetry is quite complex and 2-dimensional in contrast to the other sites which were more uniform in the long-shore direction (Holderness more so than Lyme Bay). Figure 5 shows the model layout and bathymetry (contours at 10m intervals). The model grid was the largest with 319 by 192 grid point at 200-m resolution. The mean sea level correction was +4.5m.

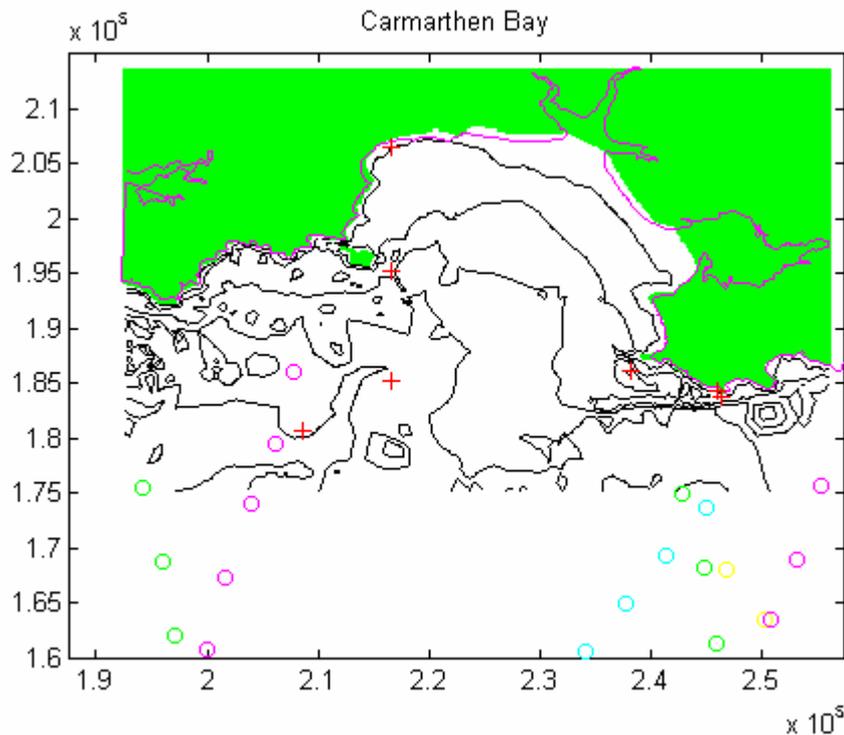


Figure 5: Carmarthen Bay - contours at 10m intervals, circles are TOPEX tracks, and crosses are locations of output points

3.5 Boundary conditions

3.5.1 Long-shore boundary conditions

The long-shore boundary can be fully specified only if sufficient information is available e.g. from observations or a coarser model within which the fine grid model is nested. Observations are rarely likely to be available at more than 2 points along the boundary. Nesting is a useful tool and the local area models could be nested in a shelf-scale WAM model (Monbaliu et al., 1999). One aim of JERICHO was to use the TOPEX data to specify offshore boundary conditions and this is examined in more detail for each model in section 4. In general, a uniform offshore boundary condition is applied here. The TOPEX measurements can supply H_s and an estimate of wave period, T_{alt} (not identical to the more commonly used zero-up-crossing wave period, T_z) (Davies et al, in press).

3.5.2 Cross-shore boundary conditions

The incorrect specification of a cross-shore boundary condition at the upwind boundary can lead to spurious results near that boundary. A simple method has been examined to scale the wave height from the offshore boundary to the coast using the cross-shore depth profile, based on Tucker (1994). This is described more fully in Wolf (in preparation). Four boundary conditions have been compared: (a) zero waves, (b) constant waves equal to the offshore wave height (c) the new method and (d) a 'periodic' boundary condition in which the waves at the downwind boundary are fed back in at the upwind boundary. Contours of wave height from an idealised rectangular model, with dimensions similar to Holderness but no long-shore variation,

are shown in Figure 6. The model was forced by 3.5m waves at the offshore boundary ($x=20\text{km}$). The periodic condition (d) gives the most accurate results but is only appropriate when there is no variation of depth profile in the long-shore direction, which is not usual in real applications. Method (c) gives an improvement over the first two methods, assuming the correct solution to be wave height contours parallel to the shore.

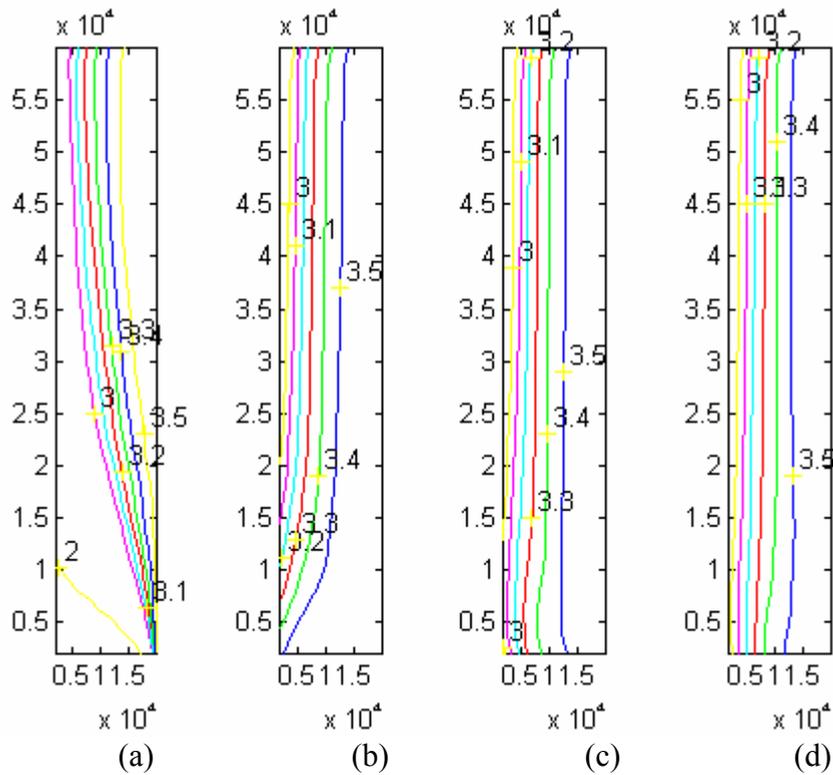


Figure 6: Idealised rectangular SWAN model with various cross-shelf boundary conditions at upwind boundary ($y=0$)
(a) $H_s=0$ (b) $H_s=3.5\text{m}$ (c) H_s scaled according to Tucker (1994) (d) ‘periodic’ boundary condition

4. RESULTS

The effects of the following parameters were tested in the SWAN model: wind, water level, currents, boundary conditions - spectral shape, offshore wave height and period. Various options in SWAN for triad interactions, bottom friction and depth-limited breaking were used. An important issue was how best to use TOPEX altimeter data to specify the offshore boundary conditions.

4.1 Holderness

A constant wave field was input at the offshore boundary taken from the directional spectra from the N3 buoy. Cross-shore boundary conditions were not critical since the up-wave direction was north of offshore for this test period (see Figure 2). The 10-metre wind speed and direction at Donna Nook (a coastal station to the south of the model area) provided wind forcing to the model. This was taken to be constant over the whole grid.

Optimisation of the Holderness SWAN model was carried out, by comparison of model results at N1 with observations, concentrating on December 1994 - January 1995, which was the period of greatest wave height observed by the buoys over their deployment through the winters of 1994/1995 and 1995/1996.

Model sensitivity to various parameters, especially depth-limited breaking, bottom friction and wind stress was examined.

4.1.1 Bottom Friction

In SWAN there are three possible formulations for the bottom friction term. The user may choose some parameters or the default values can be used. These parameters are, in theory, influenced by the sediment grain size and the presence of ripples on the seabed and so may reasonably be expected to be different for different implementations of the model.

The default formulation is the empirical model of JONSWAP (Hasselmann et al., 1973). Other options are the drag law model of Collins (1972) and the eddy-viscosity model of Madsen et al. (1988). All three formulations may be expressed in the following form:

$$S(\sigma, \theta) = -C_{bottom} \frac{\sigma^2}{g^2 \sinh^2(kd)} E(\sigma, \theta)$$

where $S(\sigma, \theta)$ is the bottom friction source term and $E(\sigma, \theta)$ is the wave energy spectrum. C_{bottom} is the bottom friction coefficient, which depends in some functional way on the bottom orbital motion. It is the formulation of this coefficient which varies between the different models, and for which the user can change the inherent empirical constants.

The SWAN model was run with the JONSWAP and Madsen bottom friction formulations using the default parameters. Through the European project EUROWAVES (Cavaleri et al, 1999) the default SWAN parameters for the Madsen

bottom friction were found to be closer to the theoretical value for the estimated grain size at Holderness (Sclavo, private communication, 1998).

Figure 7 shows the wave height results for the period of the run for buoys N3 to N1 and the JONSWAP and Madsen formulations respectively. We find that the decrease in wave height onshore is indeed better modelled by the Madsen formulation of bottom friction.

The results below (Tables 1 and 2) show some statistics for the two cases. *Rms*, *St.Dev.* and *Bias* are the root mean square, standard deviation and mean value of the $(Hs_{model} - Hs_{buoy})$ statistic, respectively. Note the large decrease in the bias at N2 and N1 in the Madsen bottom friction case.

Table 1: Bottom friction = JONSWAP

	<i>Rms</i> (m)	<i>St.Dev.</i> (m)	<i>Bias</i> (m)	<i>Hs</i> (buoy) (m)
N3	0.06	0.06	-0.004	4.22
N2	0.55	0.48	0.30	3.38
N1	0.57	0.30	0.51	2.48

Table 2: Bottom friction = MADSEN

	<i>Rms</i> (m)	<i>St.Dev.</i> (m)	<i>Bias</i> (m)	<i>Hs</i> (buoy) (m)
N3	0.06	0.06	-0.01	4.22
N2	0.46	0.47	0.005	3.38
N1	0.36	0.29	0.22	2.48

There is some variability in the results at N1 and N2, which is not reproduced in the model. This variability has been studied in the full buoy data (as opposed to just the hourly measurements) and found to be a signal of 12.5 hours consistent with tidal effects. The signal is weak at N3 but much stronger at N2 and N1. Since no varying water depths and currents were included at this stage it is not surprising that this variability is not modelled at N2 and N1.

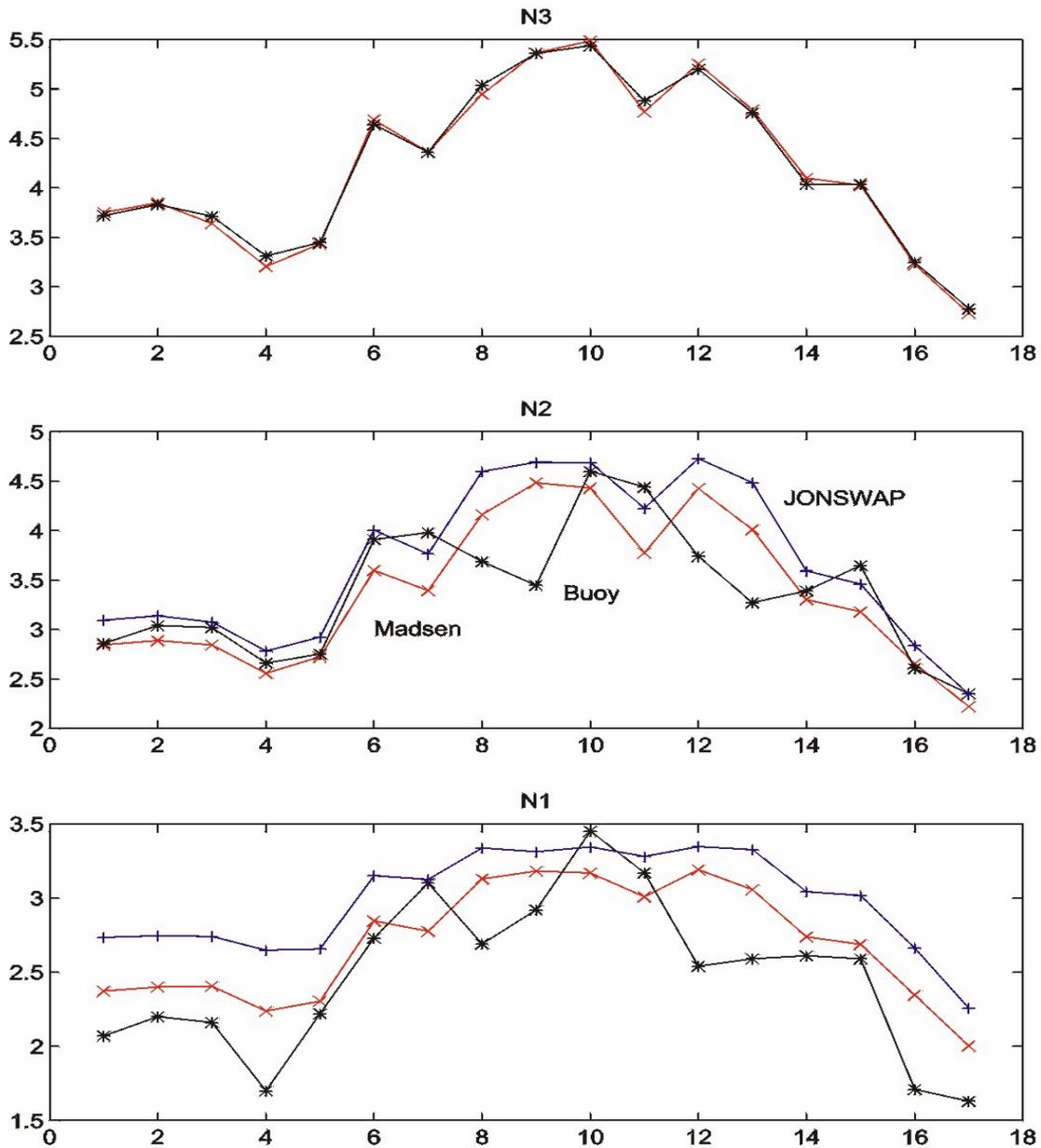


Figure 7: Holderness results with different bottom friction formulations

4.1.2 Effect of varying depth

Time-varying depths were used as input to the model. The model was run for the storm of 1-2 January 1995 using depths from POL's hydrodynamic model at N1 (Flather, 2000) and also the depths measured at N1 by the bottom pressure wave recorder. The water depth variation for this single point was used over the entire grid. (N.B. discrepancies between model and observed depths for N1 are quite significant, since N1 is very close to the coast, approximately 2km offshore, and locating it correctly in the grid could be very important).

The changes to the model output are significant and of the same order as the tidal-period oscillations obvious in the buoy output that were absent from the model results with no depth variation.

A wavelet analysis of the data at N1 and N3 over December 1994 and January 1995 has shown that energy at the 12.5 hour period consistent with the tidal cycle is intermittent but clearly present in the significant wave height measurements and N1. At N3 the only clear signature of the tidal cycle during the two months is around the storm of 1-2 Jan 1995.

The inclusion of varying water depths has a marked effect on the results, see Figure 8, particularly at N1. The model results show a variation much more in line with that shown by the buoy results. The effect may be over-exaggerated due to the inaccuracy in the bathymetry referred to in the previous section. The spectral results show an effect over the whole frequency range; the changing depth causes strengthening or weakening of the bottom dissipation.

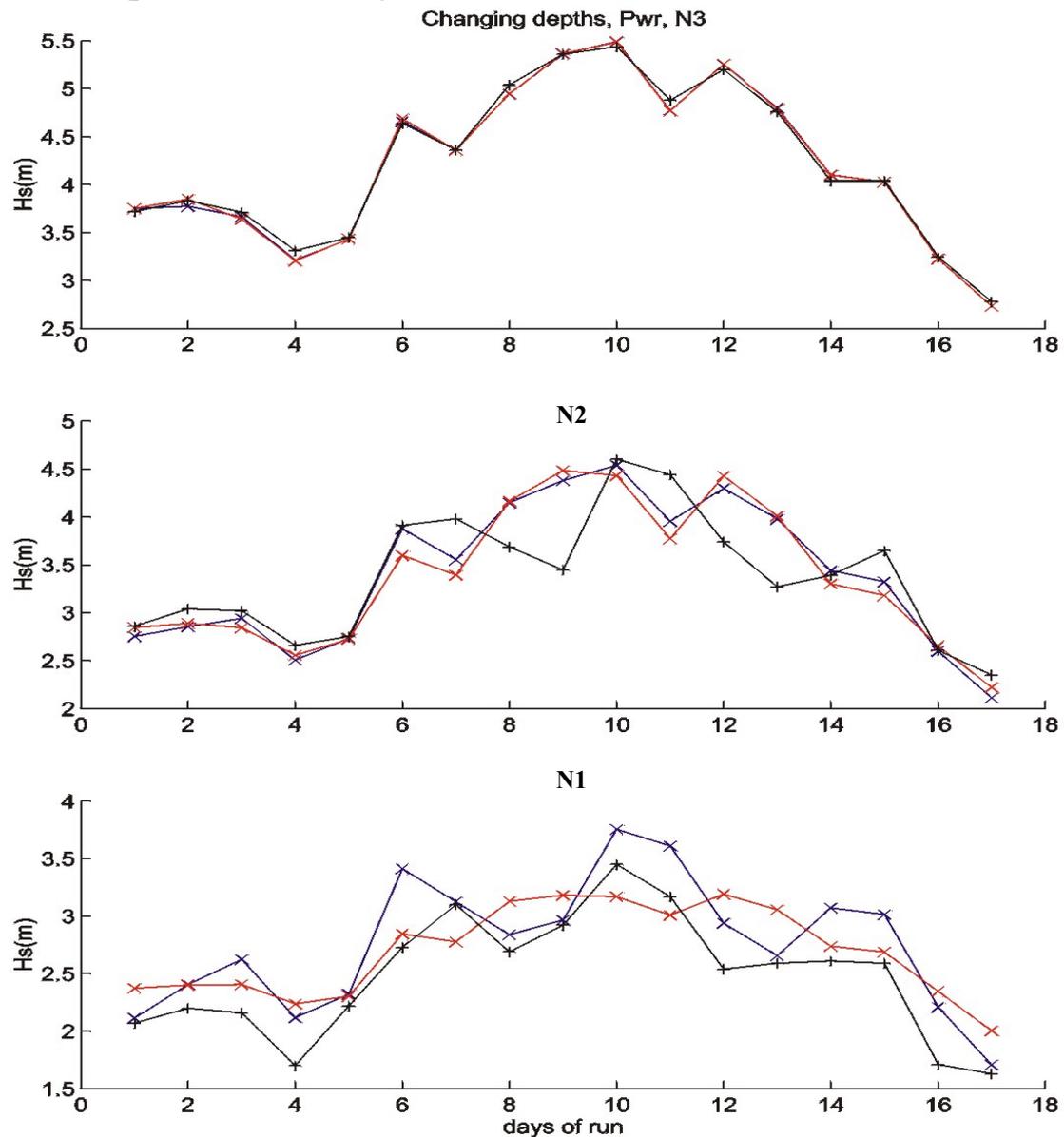


Figure 8: Holderness results with and without time-varying depth (blue line is model with depth-variation, red line is constant depth, black line is observed)

4.1.3 Wind input

The wind-input term has very little effect on the results obtained from SWAN in this example (although this may be partly due to the combined wind-se and swell nature of this event). The winds are N-NW during this event. Some wind must be included to force the model into 3-G mode.

4.1.4 Triad interactions

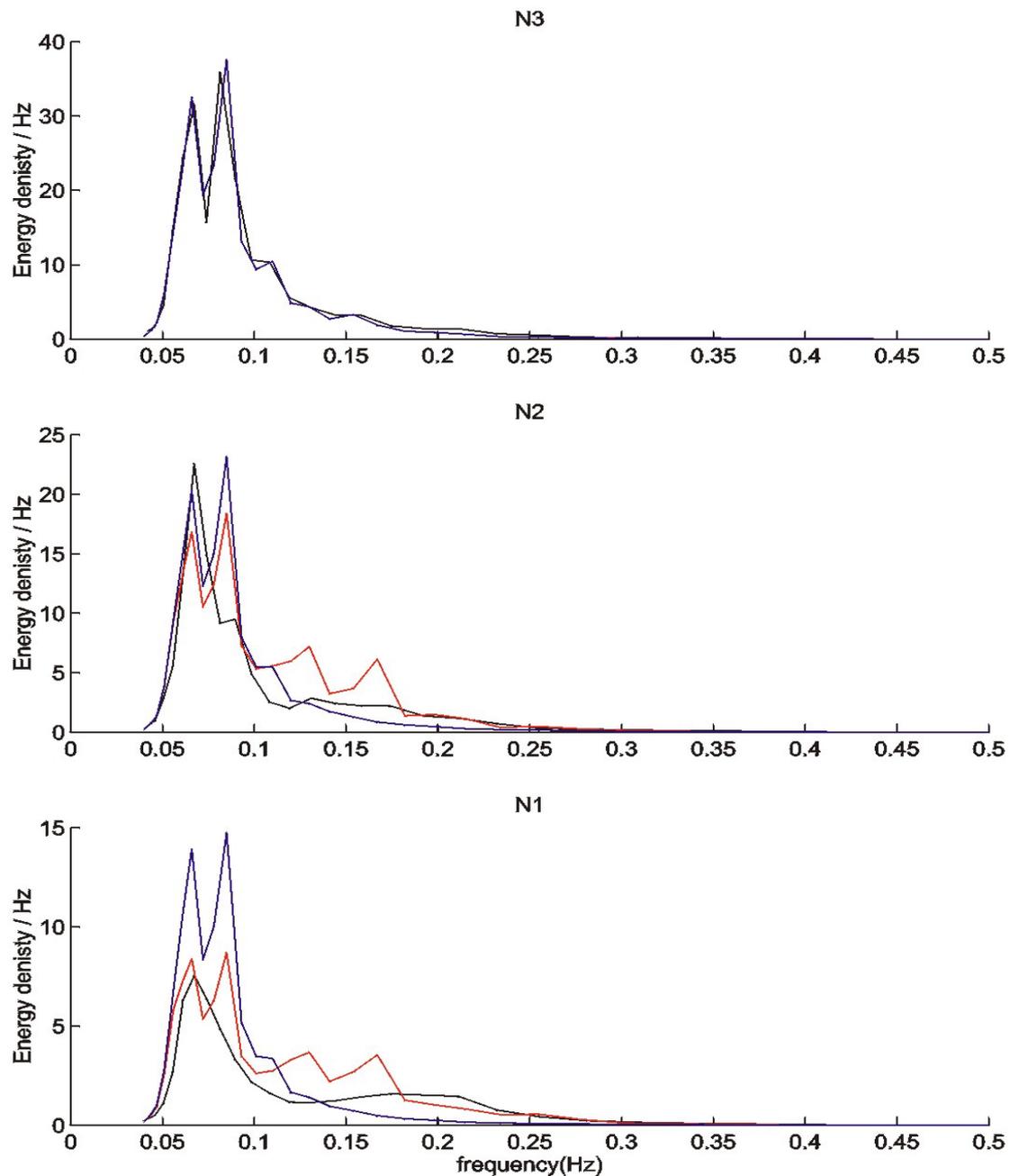


Figure 9: Example of Holderness spectra with and without triad interactions (blue line is model without triads, red line is with triads, black line is observed)

The triad interaction term has more effect than the wind input term. It increases the overall wave height and causes small peaks in the frequency spectrum at double the frequency of the main peaks (see Figure 9). There is little evidence for such spectral shapes in the Waverider data, although it can be argued that the Waverider is not good at observing such bound harmonics, tending to smooth out wave crests (Tucker, 1991, pp.64-67). The difference in the results with and without triads is most marked at N2. It would seem that the triad calculation in the model is poor. Theory and other measurements indicate that normally one requires high waves in shallow water (a large Ursell number, often over a bar in the bathymetry) to produce triad interactions. These are not expected to be important in water deeper than 8m, which make such effects unlikely at N2 (in a water depth of 18m).

4.1.5 Effect of currents.

The effect of currents on the bottom dissipation term is not included in SWAN. Tests including a spatially homogeneous currents were carried out at Holderness, using an estimated spring flood and ebb tidal current. These confirmed that the main effect is to produce a Doppler shift in wave period, especially at high frequencies. The effect on significant wave height is negligible.

4.1.6 Boundary conditions

One aim of the modelling 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.

The wave parameters available from the satellite data consist of estimates of significant wave height and zero up-crossing period (T_z). The wave model SWAN requires a full spectrum, so it is necessary to make some assumptions about the actual shape of the wave spectrum.

Several experiments were performed which illustrate how the model results are affected when the input spectrum is assumed to be a JONSWAP spectrum with a specified significant wave height (H_s), peak period (T_p), direction, and directional spread. This was done by using the parameters of H_s , T_p , T_z , direction and spread output by the buoy at N3 as input to the model and comparing the results obtained from the model using the full two directional spectrum on the boundary.

(a) Wave height at the boundary

In all previous runs of SWAN it has been found that the spectra input to the model and output by the model on the boundary at N3 were very close to identical. When using JONSWAP spectrum as input it was found that, when the wind direction was not aligned with the wave direction, a small additional amount of wave energy was apparent in the model output at N3. It is likely that the reason for this is that because the input spectrum contained no wind sea in the wind direction the model had to add some in order for the iterative solution to converge.

While the size of this error when viewed in terms of significant wave height is not great, the error does propagate through to N1, where the model already had a tendency to over-predict the wave height, so it was thought wise to remove this additional bias.

This was achieved by subtracting from the input significant wave height at the boundary an amount equal to the difference between the input and output boundary wave heights of the run. The model was then re-run using these new values of wave height. The new results showed no bias at the boundary. The results described in the next section used this procedure to derive the correct boundary wave height.

(b) Peak period

The JONSWAP spectrum uses the peak wave period as one of its principal parameters. While this is a standard parameter output by the wave buoy, 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.

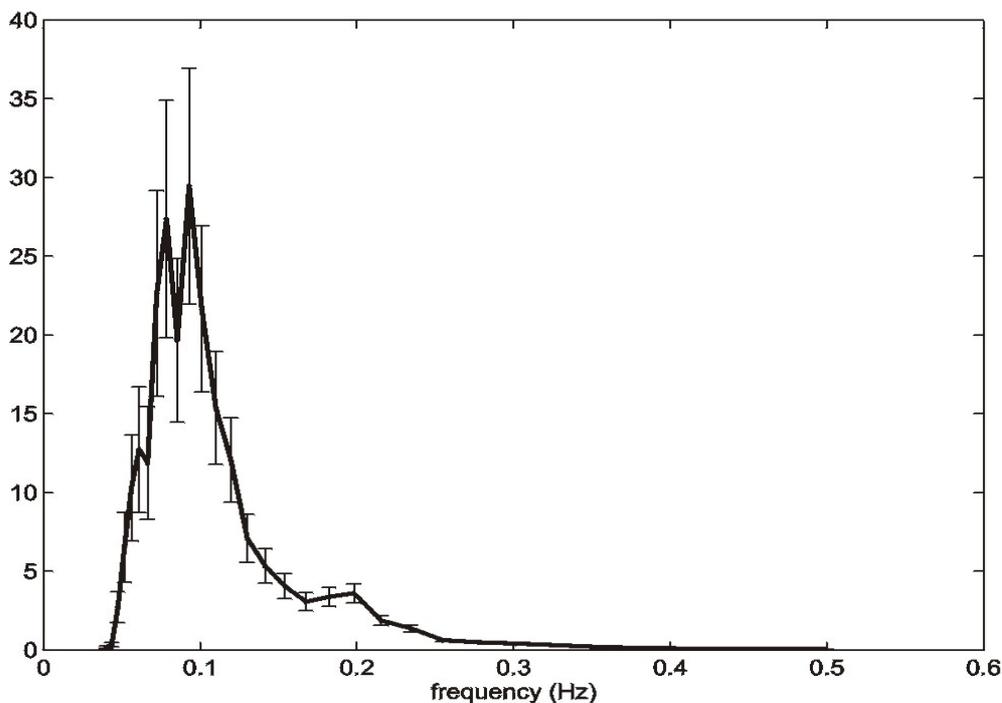


Figure 10: Spectrum at N3 with sampling error

Figure 10 shows one of the double peaked spectra from N3 with the confidence limits due to the sampling error. It is clear that the confidence limits are large compared to the apparent double peaked nature of this spectrum.

The zero up-crossing period (T_z) is also output by the Waverider buoy, and this parameter is more stable, but still may not be representative if the spectrum is bimodal with swell and wind sea components.

It is not completely straightforward to derive a good JONSWAP spectrum from the zero up-crossing period, since it requires numerical integration and iteration and

SWAN will only accept a peak period. Since the satellite is producing T_z not T_p we need to be able to convert between the two.

Figure 11(a) shows some numerical results for T_z/T_p for a JONSWAP spectrum in deep water (blue line) and that in 30 metres water depth (green line). Also plotted on this diagram are the values for T_z/T_p actually observed at N3 during the storm of 1-3 January, 1995. Figure 11(b) shows the same thing but includes all the results for the winter of 1994-1995.

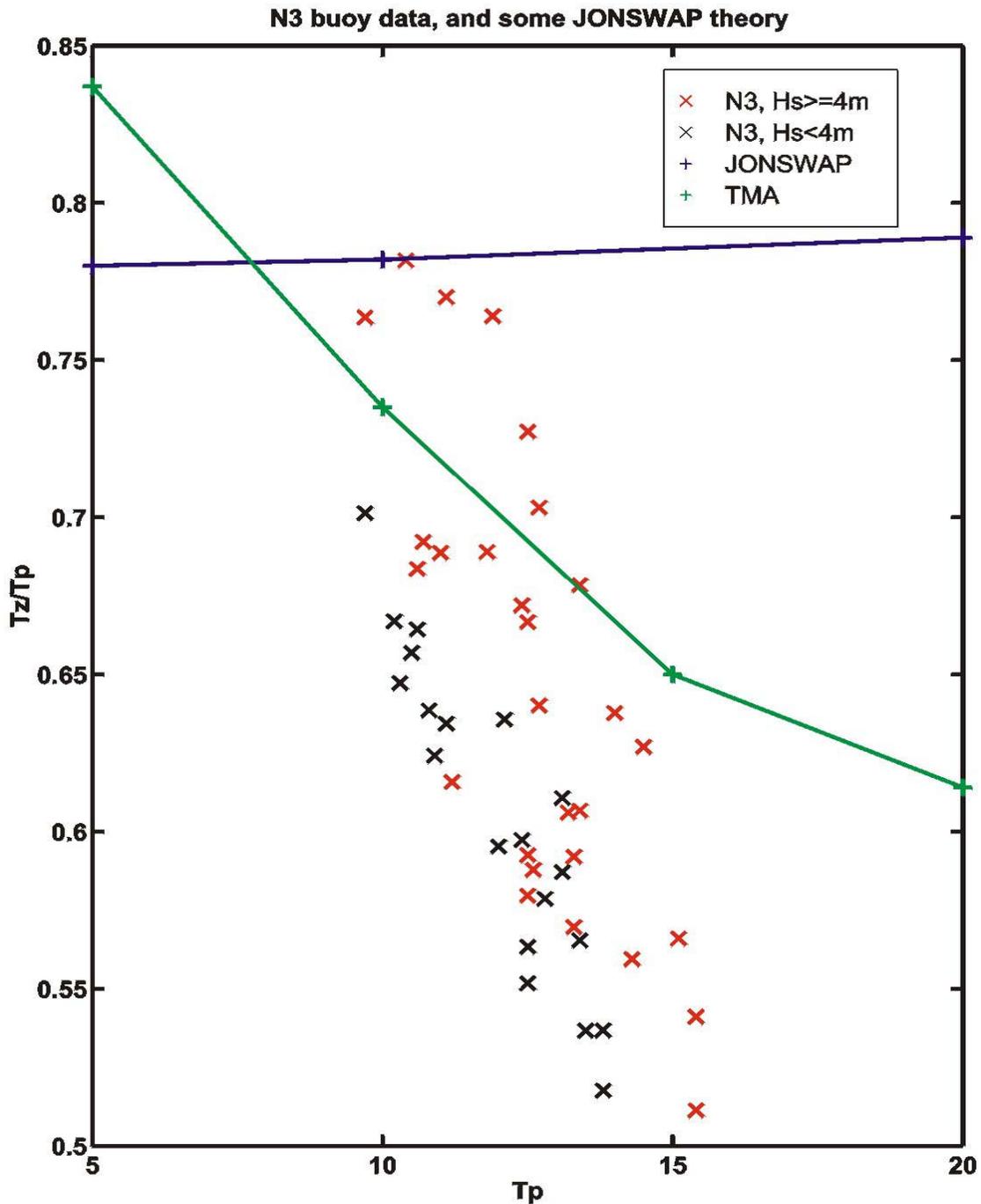
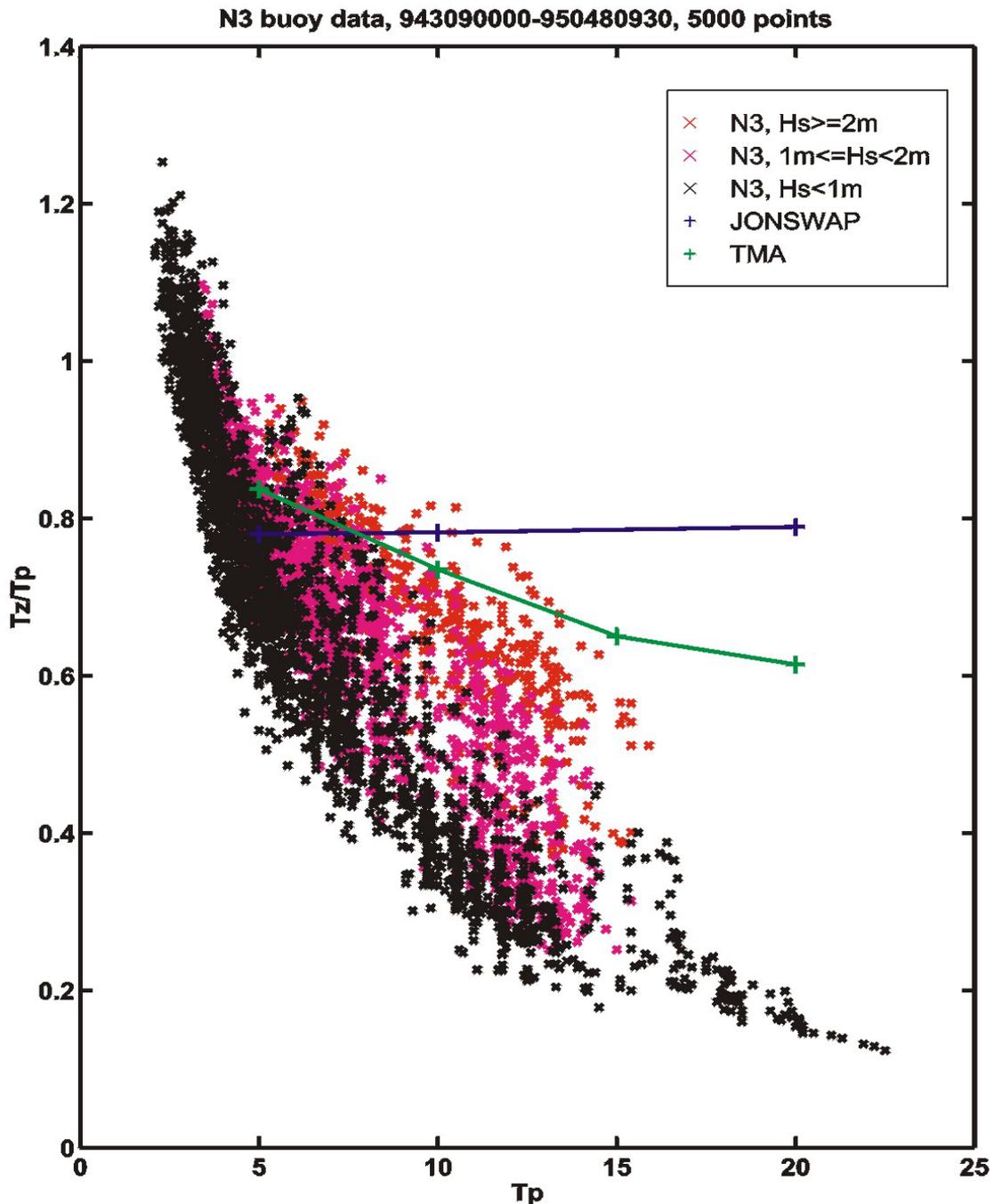


Figure 11(a): T_z/T_p versus T_p for the 1-3 January 1995 storm



To assess the sensitivity of the model to the different ways of defining the boundary spectra three model runs of the 1-3 January 1995 storm were compared. The first was the run using the full buoy spectrum at N3 at the boundary. The second run uses the buoy-derived value of T_p and a JONSWAP spectrum and the third run used the T_z measured by the buoy assuming $T_p = T_z/0.78$, which is the approximate relation for the JONSWAP spectrum in deep water. All runs were made with Madsen bottom friction, including water depth variation (due to tide and surge), but not including currents.

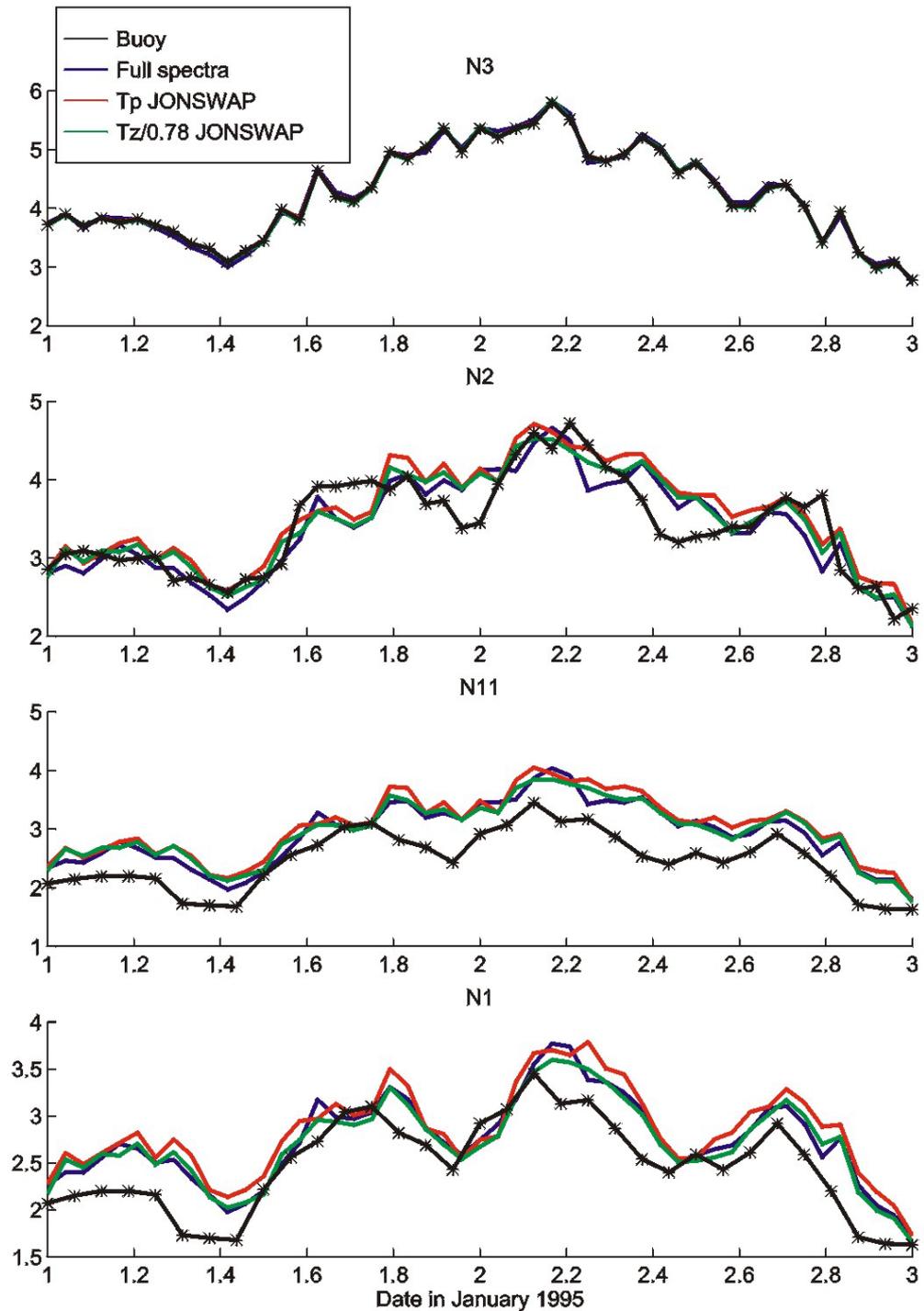


Figure 12: Results using different wave periods to generate the boundary input spectrum. The y-axes show significant wave height in metres. The x-axis shows time interval in days (January 1995).

Figure 12 shows the comparison of wave heights throughout the storm at the buoy stations. There is only a small difference between the results from the three runs; the overall mean and bias of the differences between the N2 results of the model and the buoy are shown in Table 3. Note that an extra output point has been introduced further offshore in a water depth of 12m (N11). Spectra were therefore output at N2, N1 and N11.

Table 3: Differences between model and buoy $H_s(m)$ at N2

Run	Mean	standard deviation
Full spectra	0.029	0.33
T_p from buoy	-0.14	0.31
T_z from buoy	-0.040	0.31

The significant wave height is not very sensitive to changes in wave period, as shown here, but at specific times during the storm event the spectra can be quite different. Figure 13 shows two examples of times when quite different spectra are obtained depending on the choice of wave period. Figure 13(a) shows the spectra where both T_p and T_z appear to give poor results and in 13(b) T_z appears to be a poor choice. In the first case the two JONSWAP spectra agree well but neither compares well with the buoy, and the second example is the more typical case where the T_p run fits the true spectral form more accurately than does the T_z run. Further work could be done on this in using different spectral shapes.

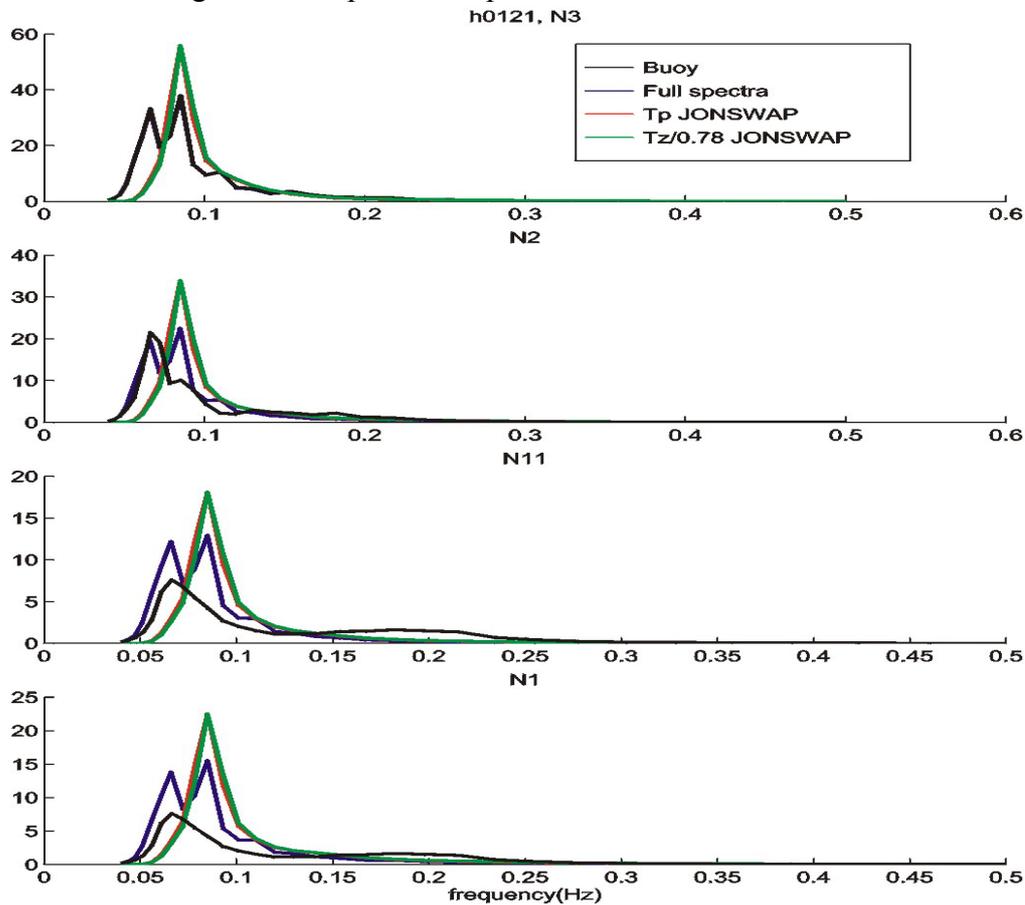


Figure 13(a): Example spectra

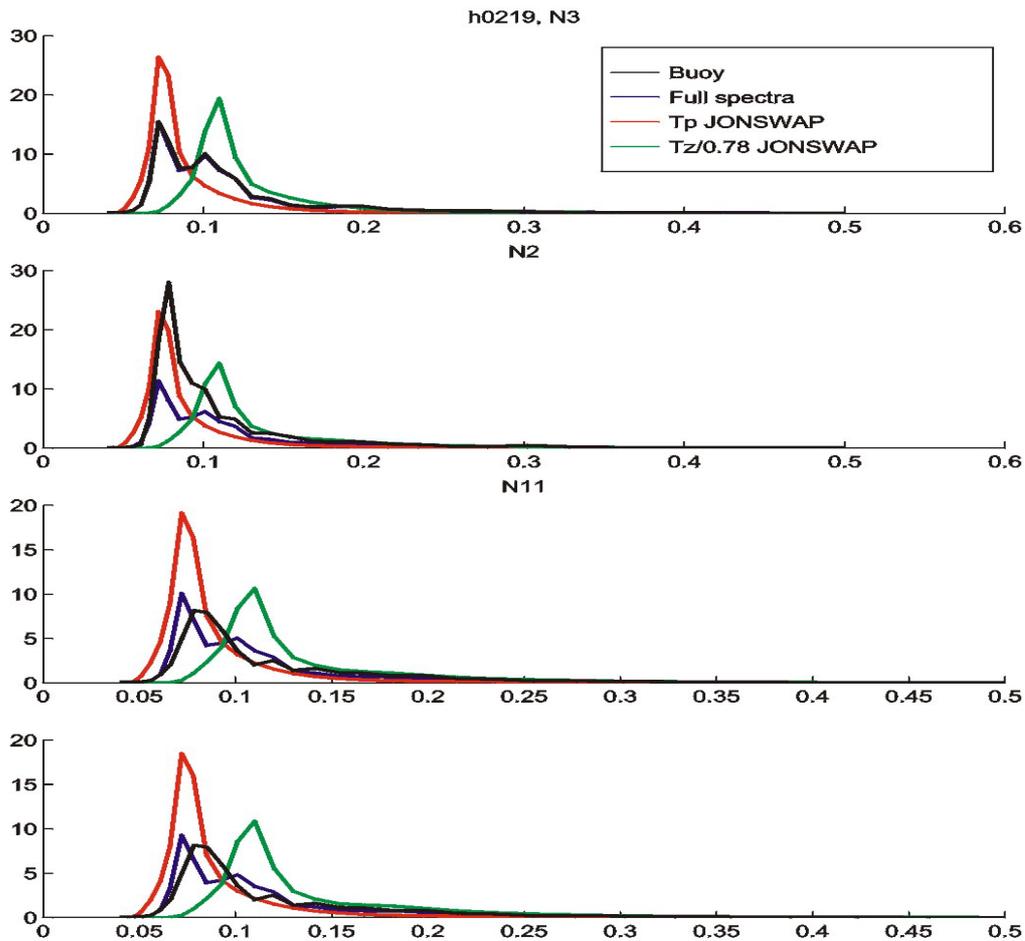


Figure 13(b): Example spectra

4.1.7 Model error versus observational error

From the model results an error at N1 could be calculated for the storm of 1-3 January 1995, however this does not give a very good estimate of the error of the model at N1 because the boundary conditions at N3 are imperfect.

A simple sampling error estimate can be derived from knowledge of the characteristics of the Waverider. Figure 10 shows an N3 spectrum plus error. The error in the N3 spectrum is propagated through the model to N1 so that the error at N1 is that due to model errors plus the boundary error. One should also take into account the error of the N1 buoy. This may well be greater than the standard given in the Datawell manual due to mooring interference effects.

Further experimentation is underway, aimed at deriving a better spectrum for the boundary using a least squares fit between the model results and the buoy data at N3 and N2 to re-derive a more representative boundary spectrum. This should reduce the error at the boundary, making the actual model error more apparent. Subsequently it may be possible to further tune the free parameter in the bottom friction to produce better results at N1. An alternative approach aimed at pinning down error caused by the boundary conditions rather than further improvement of the modelling results, would be to run an ensemble of runs over the domain of the errors shown in Figure

10. The results would produce an estimate of the error at N1 caused by the boundary conditions, which could then be subtracted in quadrature from the total error, yielding the error of the model itself.

4.1.8 Model implementation problems

The main problems that occurred were due to the bathymetry. At Holderness it was known that the N1 wave buoy was in an average of 12.5m of water and about 1km offshore, but the point on the model bathymetry specified from the lat./lon. of this point was in only 7m water and about 500m offshore. It is possible that the bathymetry was taken from the last survey of the area, which is 50 years old. An alternative explanation is that the N1 buoy was situated in a small hole that would not be resolved by the model bathymetry, although this does not explain the offshore distance problem. To explore this issue, we defined another output point further offshore in a water depth of 12m (N11).

Table 4: Results from SWAN, significant wave height

Station N2, d* =14.3m, 49 data points			
SWAN	<i>Bias</i> (m)	<i>St.Dev.</i> (m)	<i>H_S</i> (model)
	-0.03	0.33	3.39

Station N1, d* =7.0m, 17 data points			
SWAN	<i>Bias</i> (m)	<i>St.Dev.</i> (m)	<i>H_S</i> (model)
	0.22	0.21	2.70

Station N11, d* =12.7m, 17 data points			
SWAN	<i>Bias</i> (m)	<i>St.Dev.</i> (m)	<i>H_S</i> (model)
	0.39	0.23	2.87

* Depth at mean sea level.

$$Bias = \sum_{i=0}^N [Hs_{model}(i) - Hs_{buoy}(i)] / N$$

$$St.Dev = \sqrt{\frac{\sum_{i=0}^N [(Hs_{model}(i) - Hs_{buoy}(i) - Bias)]^2}{N - 1}}$$

The results for the Holderness storm are shown in Table 4. The buoy data was half-hourly at N2 and 1.5 hourly at N1. Since SWAN made only hourly runs, the statistics are calculated using hourly comparisons at N2 and three-hourly comparisons at N1. Studying first the mean error (*Bias* in Table 4) the results show that SWAN produces quite accurate results at N2. At N1 SWAN is over-predicting compared to the buoy. At N11, SWAN is over-predicting even more, which leads to the conclusion that the bottom friction coefficient may need increasing for SWAN at Holderness. It is apparent (see Figure 14) that the SWAN results follow the periodic variations in the buoy data. Also shown in this figure is the variation of the water level. It appears that the periodic variations in both the buoy data and the SWAN model results are consistent with the common cause of water level modulation due to the tide.

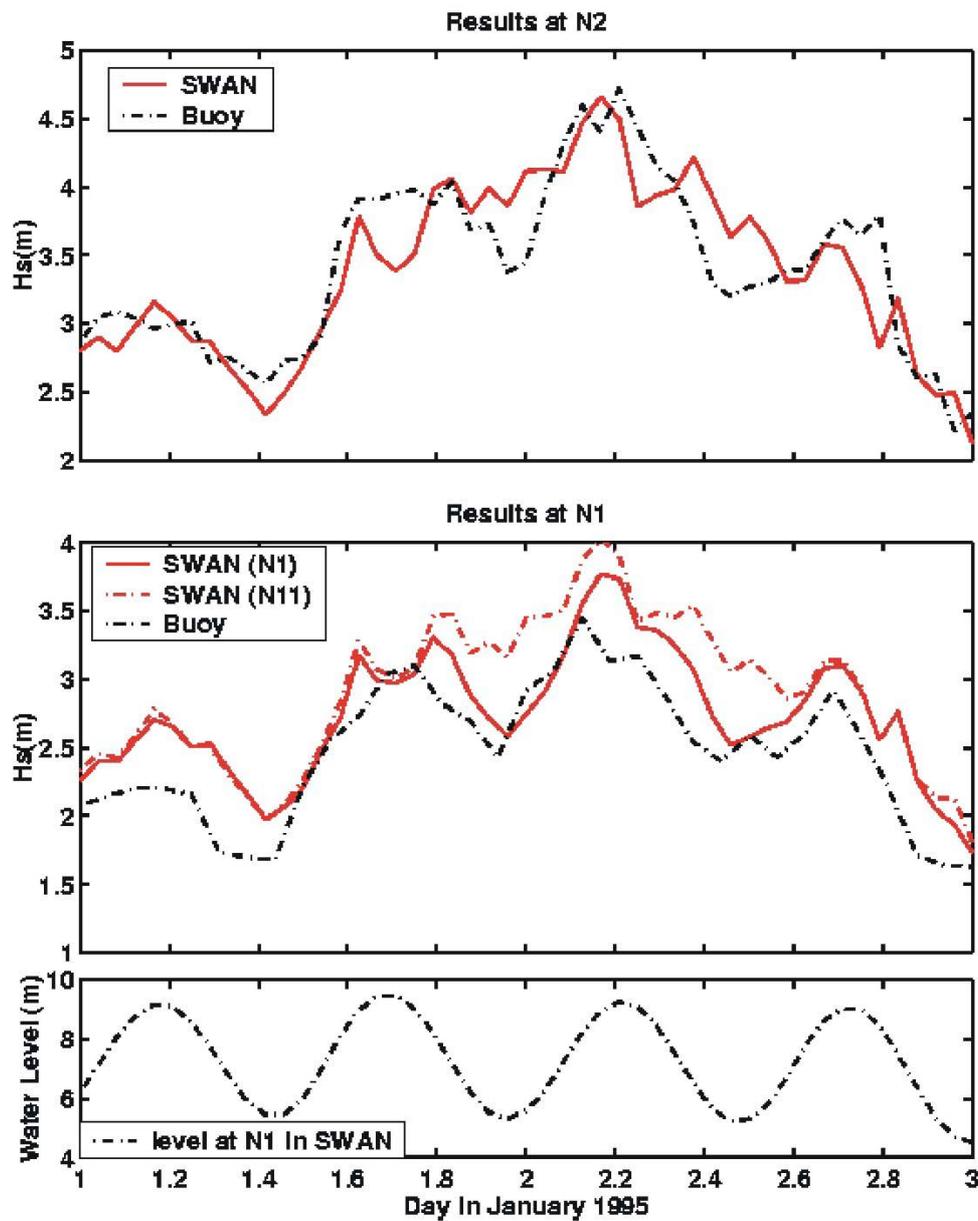


Figure 14: Holderness results at N2, N1 and N11

4.1.9 Model settings

Based on the results of the above study it was decided to switch off triad interactions and use the Madsen default bottom friction for the other case study sites

4.2 Lyme Bay

Here we examine the boundary condition requirements for running a near-shore wave transformation model for Lyme Bay, with specific application to the SWAN model. The data sets available for model validation were examined and seven events identified for which offshore (TOPEX altimeter) and inshore (bottom pressure) wave observations are available, where the wave heights exceeded 3m at least at the offshore locations.

Some wave and wind data are available simultaneously from the Channel Light Vessel, although in general the latter is rather far away to provide boundary conditions. For this we need to use the TOPEX data. An alternative would be to use another coarser grid wave model such as WAM on the continental shelf model grid, the WASA data set or the UK Met Office wave model.

A bottom pressure recorder at West Bexington (WB, 50° 40.0'N, 2° 40.0'W) recorded waves, in about 10m water, from December 1987 to May 1995 (with gaps). Maximum waves recorded during this time were at 09:56 8th December 1994, with significant wave height, $H_S=5.13\text{m}$ and mean period, $T_Z=7.99\text{s}$. A comparison of the WB data with TOPEX tracks 061 and 146 (September 1992 - August 1998) and Channel Light Vessel (UKMO data, referred to hereafter as CLV, January 1992 - May 1997) for the whole of December 1994 is shown in Figure 15. Wind speed and direction at CLV at 0900 8th December was 43 knots (22m/s) from 210°. $H_S = 6.5\text{m}$. West Bexington periods (T_Z) appear in quite good agreement with TOPEX values.

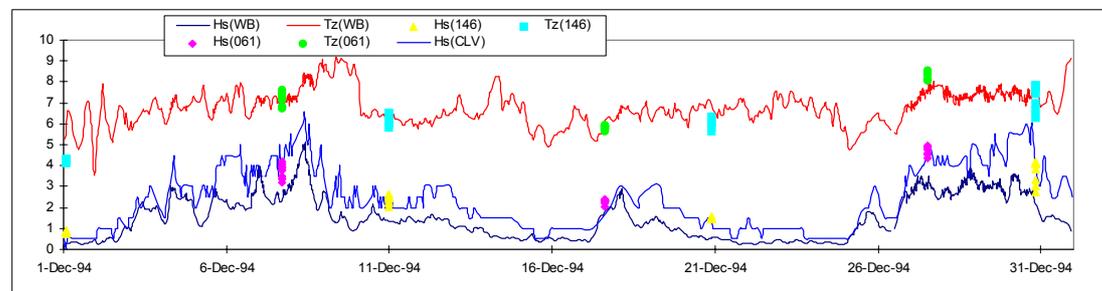


Figure 15: TOPEX (tracks 061 and 146), Channel Light Vessel and West Bexington data for December 1994

4.2.1 Reduction of wave height along TOPEX track

For TOPEX track 061 there is a reduction of wave height along-track, as the satellite approaches the coast as noted by Carter (personal communication). This track makes landfall at the eastern-most end of the SWAN model grid and the section shown begins just offshore of the southern boundary of the model. The nine highest wave cases are plotted in Figure 16(a), where the along-track point number increases towards the shore.

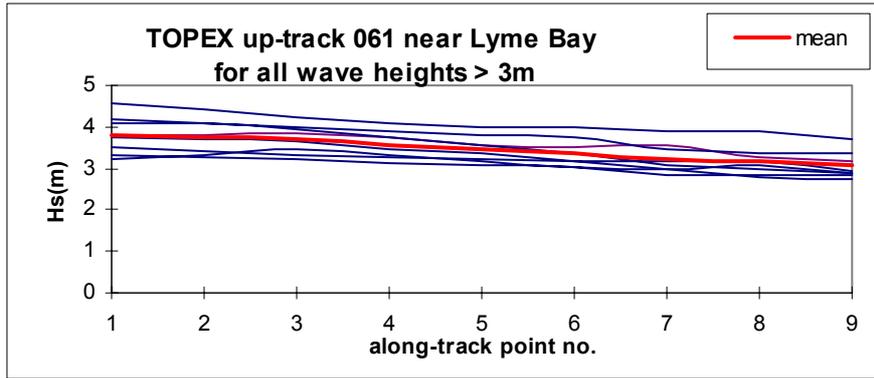


Figure 16(a): TOPEX wave data

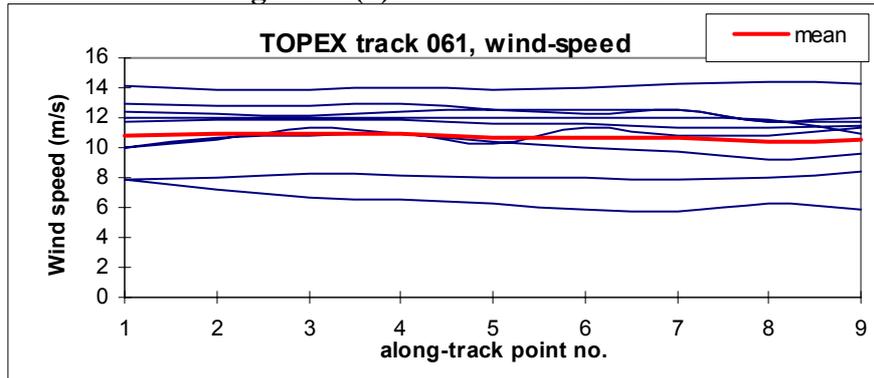


Figure 16(b): TOPEX wind data

These significant wave heights are reduced by a ratio of 0.81 on average. The associated wind speeds do not show such a consistent trend. Possible explanations include shoaling, fetch-limited growth and sheltering or a combination.

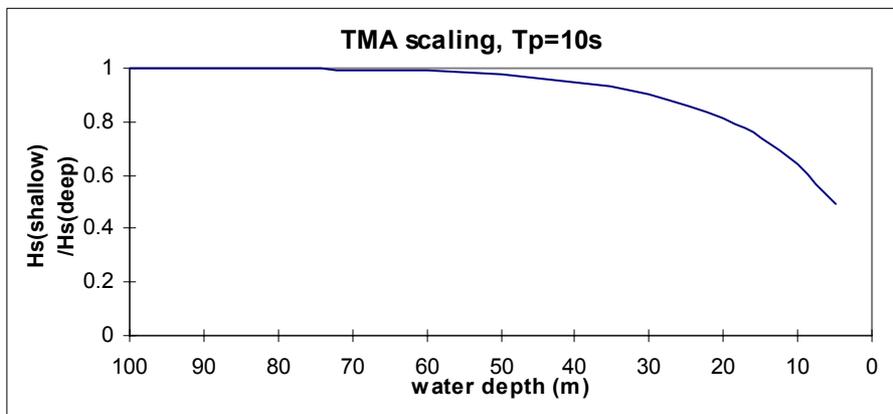


Figure 17: TMA scaling of wave height in 'shallow' water

- (a) TMA scaling (see figure 17): Water depths are too deep along the TOPEX track for TMA scaling to make much difference, although Tucker (1994a) finds that the TMA spectrum is a good fit to the growth phase of waves in this vicinity. The depths are estimated to shoal from 70m to about 40m along the track plotted in figure 15. The predicted reduction in wave height would be 0.95 for these water depths - much less than observed.
- (b) Fetch-limited growth in shallow water is a possible explanation (e.g. Hurdle and Stive, 1989, see Table 5). To test also whether a wind-sea or combined sea/swell situation was likely, the parametric fetch-limited growth law was applied to the

wind-speed and estimated fetch at the outer end of the TOPEX track (estimated depth 70m). The wind speed estimated from the TOPEX altimeter gives a better prediction of the local H_s than the CLV wind. Hurdle and Stive (1989) performs better than Shore Protection Manual (1984). Using a fetch of 200km seems to optimise agreement. No direct observation of wind direction is possible from the TOPEX data. Again the ratio of 0.96 is obtained for the difference in depth from 70m to 40m, assuming the fetch remains the same, whereas the observed average reduction for all 15 cases was 0.83. The assumption of constant fetch is probably unjustified. Most wind directions have limited fetch in the English Channel. Note that fetch from directions $\sim 215\text{-}230^\circ\text{T}$ would be almost unlimited, from the North Atlantic, whereas other directions have quite short fetch. In Lyme Bay directions $090\text{-}300^\circ\text{T}$ are off the land. Possibly there is some sheltering if winds are from SE or E due to Portland Bill, so that the fetch may be reduced substantially nearer the coast.

Table 5: Fetch-limited growth laws applied to TOPEX 061 data, where $H_s > 3\text{m}$, assuming fetch = 200km

Date	W_s (TP10)	Hurdle & Stive (1989) $h=70\text{m}$		Observed data (TOPEX)		H_s % error	T_z % error
		H_s	T_z $=0.777T_p$	H_s (TP10)	T_z (TP10)		
25 Oct 92	14.19	4.75	7.61	4.57	7.66	3.96%	-0.69%
3 Dec 92	9.98	3.02	6.42	3.76	7.55	-19.55%	-14.96%
12 Jan 93	11.99	3.85	7.04	3.45	6.84	11.52%	2.91%
11 Apr 93	7.14	1.80	5.20	3.23	7.46	-44.13%	-30.30%
15 Dec 93	12.91	4.22	7.29	4.11	7.42	2.78%	-1.79%
4 Jan 94	7.83	2.11	5.56	3.52	7.7	-39.95%	-27.85%
3 Feb 94	9.94	3.01	6.41	3.22	6.9	-6.58%	-7.15%
23 Feb 94	6.41	1.47	4.76	3.28	7.71	-55.21%	-38.23%
7 Dec 94	12.34	3.99	7.14	4.17	7.59	-4.30%	-5.99%
27 Dec 94	12.02	3.86	7.05	4.86	8.42	-20.58%	-16.30%
16 Jan 95	11.17	3.51	6.80	2.94	6.38	19.47%	6.60%
26 Jan 95	7.83	2.11	5.56	3.32	7.42	-36.33%	-25.13%
8 Jan 96	11.76	3.75	6.97	3.78	7.26	-0.70%	-3.94%
31 Oct 96	9.98	3.02	6.42	3.16	6.83	-4.28%	-6.00%
17 Feb 97	12.59	4.09	7.20	4.11	7.48	-0.41%	-3.71%
Mean error						-12.95%	-11.50%

From Table 5, it may be seen that many events are quite well predicted by the fetch-limited growth model, whereas others substantially underestimate wave height and period. These may be due to underestimating the wind-speed or fetch or the presence of a large swell component. Examination of the wind direction at CLV does not show any correlation between goodness of fit and long or short fetch conditions. However the time history of the wind was not examined.

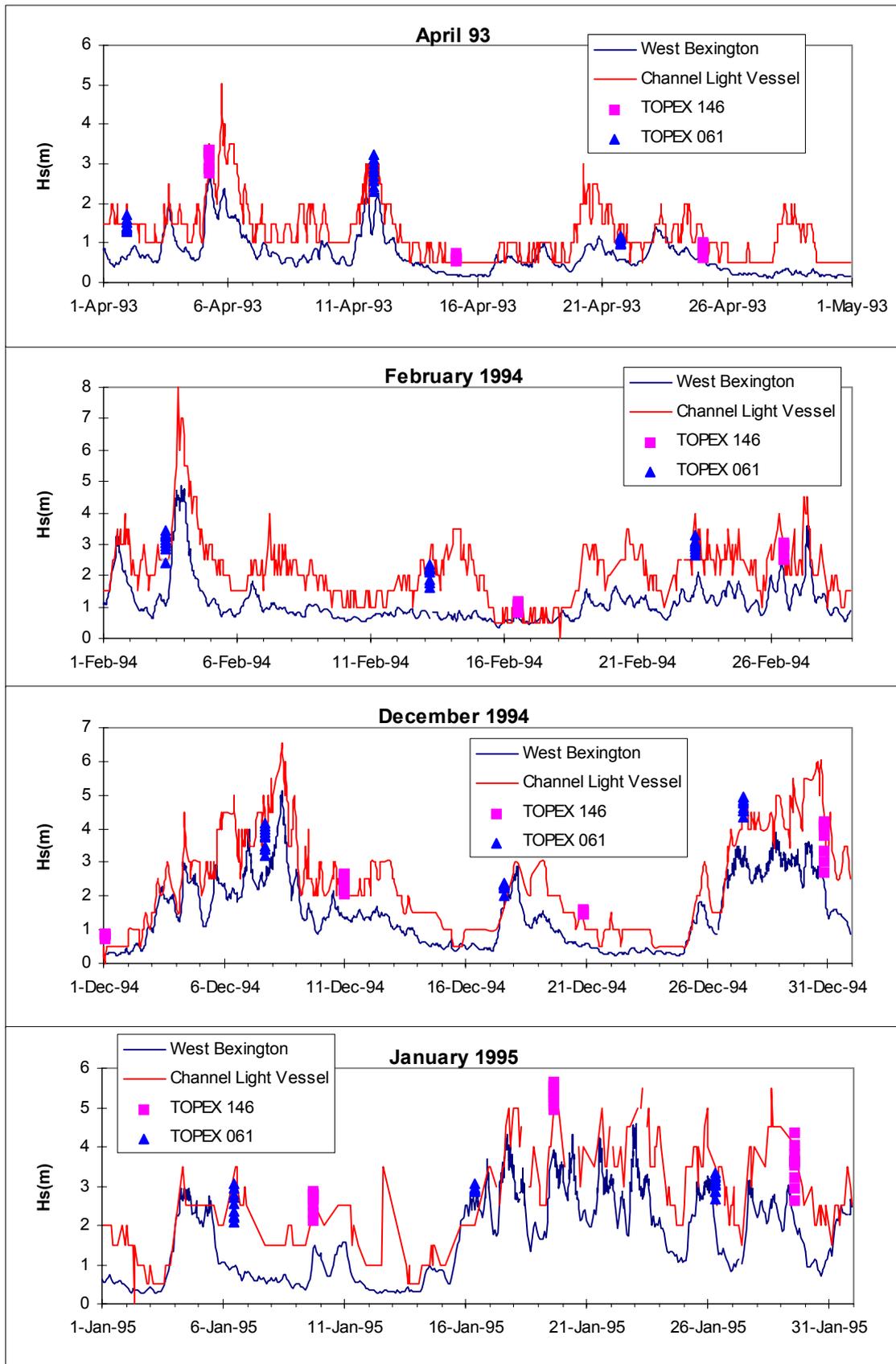


Figure 18: Comparison of significant wave height from TOPEX, CLV and West Bexington

To conclude, the observed reduction in wave height along the TOPEX track cannot be explained by the TMA (self-similarity) scaling alone, since the water is still quite deep (~40m) at nearest approach to coast. Therefore it seems more likely that the reduction is caused by a combination of shallow water fetch-limited wave growth and some sheltering, reducing the effective fetch as the coast is approached, i.e. by active wind effects rather than purely shoaling.

4.2.2 Comparison of observed data

We examined TOPEX, CLV and WB waves for all TOPEX 061 data with wave height greater than 3m (15 occurrences). At seven of these times there were also data at West Bexington. The dates are 11 April 1993, 3 and 23 February 1994, 7 and 27 December 1994 and 16 and 26 January 1995. The data for the months identified with these high wave events are plotted in Figure 18.

There is an overall agreement between the wave heights observed by TOPEX and CLV, with the track 061 data being lower than track 146 and generally less than the CLV data. The West Bexington wave heights are substantially lower than the TOPEX and CLV wave heights.

4.2.3 SWAN runs for high wave events

There were seven incidences of waves, with $H_s > 3m$, recorded on the TOPEX 061 line and with simultaneous data at West Bexington. These events were simulated with the Lyme Bay SWAN model, see Table 6.

Table 6: Results from SWAN runs

Date	Observed data (WB)		Topex	CLV	Model					
	H_s (m)	T_z (s)	W_s (m/s)	D_p (°)	T_p (s)	H_s (m)	T_z (s)	T_p (s)	H_s (m)	T_z (s)
11 April 1993	1.45	7.11	5	190	8	1.98	5.2	10	2.11	6.14
3 February 1994	1.05	6.4	10	180	8	2.09	4.8	10	2.30	5.13
23 February 1994	1.63	8.33	6	150	8	1.64	4.7	10	1.70	5.40
7 December 1994	2.35	6.97	11	230	8	2.7	5.2	10	2.87	5.74
27 December 1994	3.04	7.58	11	230	10	3.5	6.7	12	3.67	7.51
16 January 1995	2.4	6.56	10	170	8	2.32	4.9	10	2.38	5.39
26 January 1995	2.23	7.37	8	300	8	1.22	3.8	10	1.22	4.01

The model needs at least the following information: wind speed and direction, boundary wave height, peak period and direction. The TOPEX altimeter can supply

wave height, an estimate of mean period and wind speed. The wind and wave direction are the most difficult parameters, the nearest measurements are at Channel Light Vessel, some distance away. Tidal levels were estimated from Portsmouth so that this should not be a major factor in any errors in the model results. With only a wave height and period, the form of the input spectrum has to be estimated. Usually a JONSWAP spectrum is used, but this will not account for shoaling and combined sea/swell conditions. $T_p = T_z/0.777$ was chosen, (approximately constant for JONSWAP and OK for TMA in 30m water depth). The peak wave direction was set equal to the wind direction at CLV (this is not very likely).

Most of the runs overestimate H_s , the exception being the 26 January 1995, which substantially underestimates it. Generally there is not enough dissipation between the open boundary and WB. This is despite changing from the default SWAN bottom friction option to the Madsen option (as optimised for Holderness). SWAN usually predicts much smaller T_z values than observed at West Bexington. The West Bexington periods, derived from a pressure gauge, may tend to be substantially overestimated. In all but 2 of the 7 cases T_z (WB) > T_z at the open boundary, which is contrary to expectation for shoaling waves. Input wave direction is very important and difficult to determine. It is unlikely to be the same as wind direction at CLV. Specification of the input peak period is problematic. Increasing the peak period (see Table 6) does increase T_z at WB but also increases H_s , which is already too large.

Changing the input wave direction (which is an unknown quantity), for the 2 events with largest discrepancies in wave height, can improve the agreement (see Table 7). In the first instance this also reduces the wave period substantially, because effectively no waves are propagating into the model and the locally generated waves are very short, so this seems unrealistic. The last event is improved by allowing waves to enter the model whereas the wind direction is from the land.

Table 7: Runs with modified input wave direction

Date	Observed data (WB)		Topex	CLV	Model		
	H_s (m)	T_z (s)	W_s (m/s)	W_d (°)	D_p (s)	H_s (m)	T_z (s)
3 February 1994	1.05	6.4	10	180	90	0.95	2.5
26 January 1995	2.23	7.37	8	300	240	2.09	5.1

Note that the events of 11 April 1993, 23 February 1994, 27 December 1994 and 26 January 1995 were identified in section 2 as possibly being swell-dominated. This may explain the longer periods observed and the contribution of incoming waves in the last event.

4.2.4 Long-shore gradient of wave height

Several runs of the SWAN model were carried out to examine the long-shore variation of H_s . Output from a line parallel to the open boundary, 5km inside the boundary, have been plotted (figure 19). A range of wind-speeds, wind direction and corresponding input wave heights and directions were used.

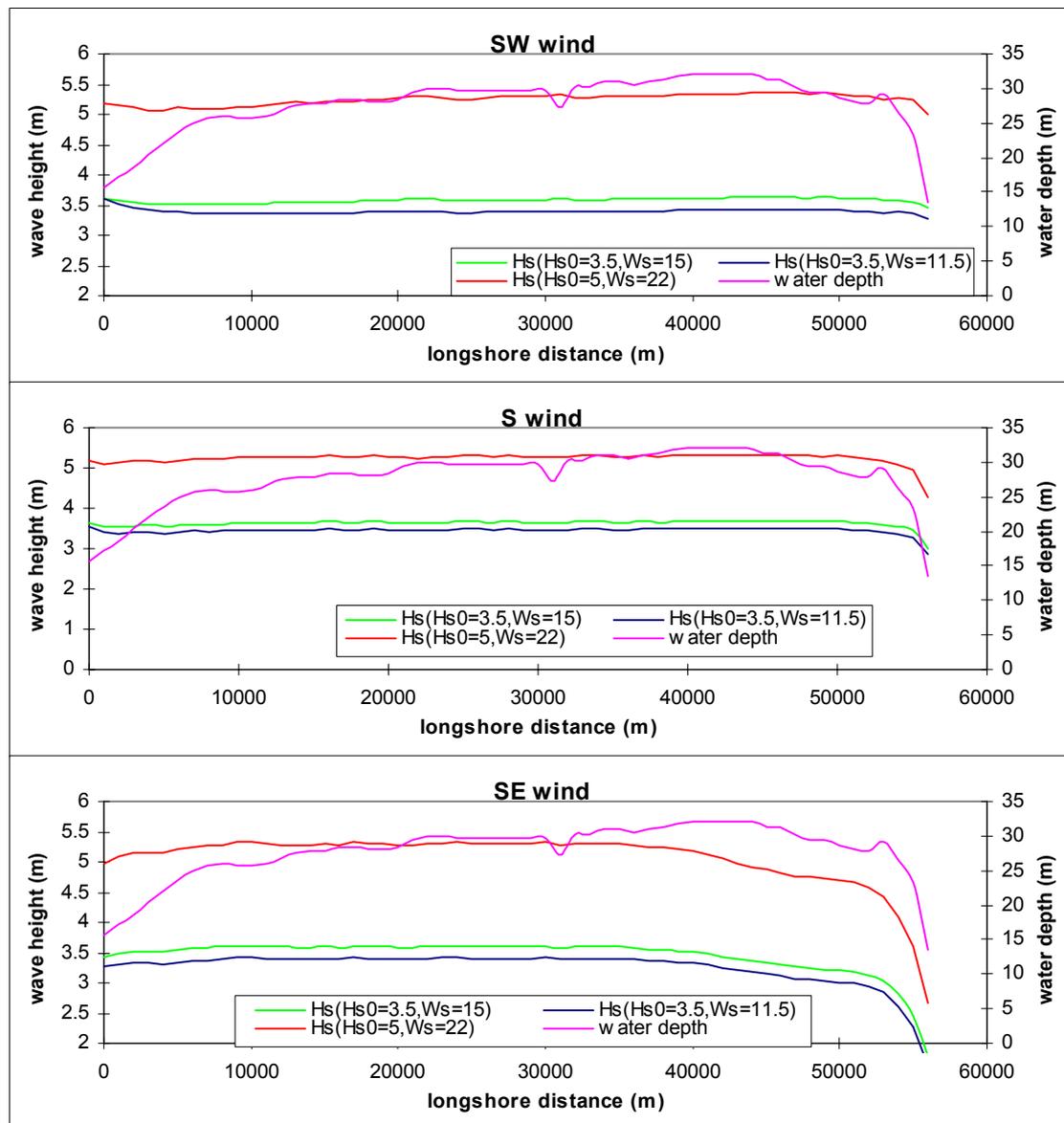


Figure 19: Long-shore variation of wave height for different approach directions in Lyme Bay SWAN model

These results confirm the sheltering effect for wave directions from south and southeast. The wave height can be substantially reduced at the eastern end of the open boundary if the wind has an easterly component. On the other hand it is probably not necessary to adjust the boundary values themselves since the model adjusts the wave heights rapidly within 5km of the boundary.

The only way to define the required input parameters more accurately is to nest the near-shore models in a coarser grid model of a much larger area e.g. the UK Met Office operational wave model. This would provide incoming wave direction and swell components, which are difficult to identify in the TOPEX data. The optimal

way to use the TOPEX data would then be in a data assimilation scheme, which corrected the boundary conditions in a physically consistent way. Lyme Bay is likely to be the most difficult type of area to model since there are many land masses surrounding it in the English Channel which make it prone to local effects of fetch-limited growth, mixed sea and swell and sheltering.

For the JERICHO project the final recommendation was to use the values from the inner end of TOPEX track 061 scaled by a factor 0.8 for the boundary significant wave height, with the associated T_z (converted to T_p for SWAN) and wind speed. The difference between H_s for TMA or JONSWAP spectrum at the outer boundary (30m water depth) is less than 5% so little would be gained by using a TMA spectrum. The ratio of $T_z/T_p=0.777$ is a reasonable approximation. Wind direction may possibly be equated with that at Channel Light Vessel but the most difficult parameter to specify is the incoming wave direction, particularly if there is a combined sea and swell. If the wave condition is wind-dominated, as is likely for extreme storm-generated waves, the wind direction may be reasonable. The largest waves are likely to come from the SW (215-240°T) since this is the direction of unlimited fetch. However we should remember the event of February 1979 when extreme swell waves devastated Chesil Beach in locally calm weather (Draper and Bownass, 1983).

4.3 Carmarthen Bay

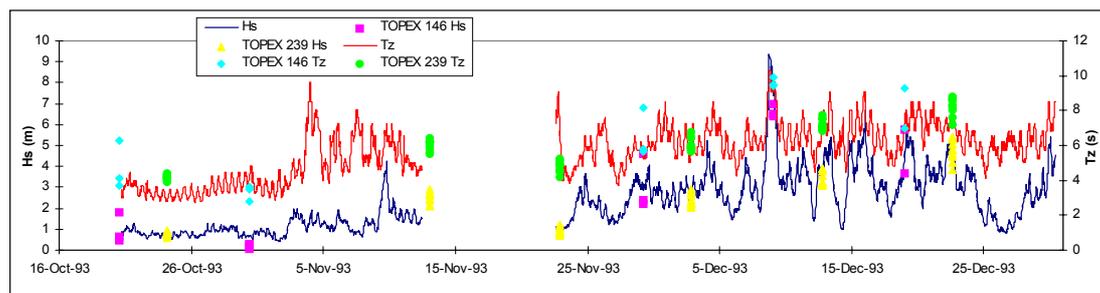
For the high-resolution SWAN run, unfortunately no near-shore validation data are available. The St Gowan data can provide the offshore boundary condition. Some TOPEX data are available. The output locations were agreed, after consultation with Environment Agency, Wales. The locations selected, to give a contrast of conditions, were a beach location at Amroth and in deeper water off an exposed headland at the end of the Gower Peninsula, at Worms Head. The beach at Amroth apparently gets some problems of flooding due to waves (Robin Copley, personal communication).

Locations:

Amroth	51° 43' 33.0''N	4° 39' 20.8''W	3.5m mean water depth.
Worms Head	51° 33' 0''N	4° 20' 0''W	32.4m mean water depth

4.3.1 St Gowan data

The St. Gowan data were examined to select an interesting period to examine in more detail. The SWALES period (Oct-Dec 1993) proved to be the largest waves observed. The model was run for selected events.



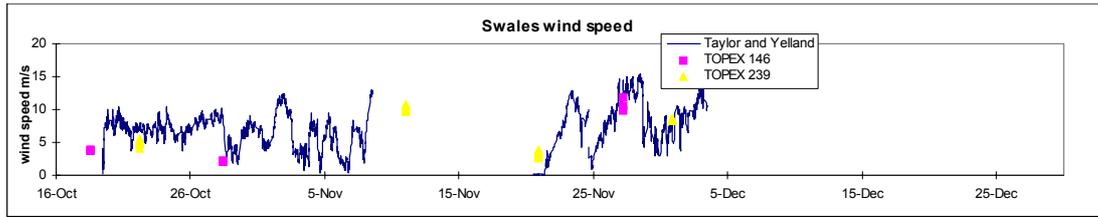


Figure 20: Wave height and period recorded during SWALES (Taylor et al, 1994)

The largest event observed was $H_s=9.4\text{m}$, $T_z=10.3\text{s}$ on 8/12/93. This period has already been modelled by Flather and Glorioso (1997) at POL using WAM on a 4km grid in the Bristol Channel, coupled to a 3D tide-surge model and nested within a 12km model extending to the shelf edge SW of the UK.

The St Gowan dataset is long enough to derive some useful statistics. The station was also suitably located to provide the offshore boundary conditions for the Carmarthen Bay model. However, there does not appear to be any near-shore point within the model for validation. As the model is proved at Holderness, it may be possible to assume its validity for other coastal situations such as Lyme Bay and Carmarthen Bay. The statistics derived from St Gowan were useful in determining the range of offshore conditions, which may be experienced, and possibly any trends. These results were applied in the study of extreme events, see section 5.

4.3.2 Helwick wave data

Some data were acquired from ABP (Bill Cooper, personal communication) which consisted of 3-hourly wave heights and periods taken from bottom pressure recorders at two locations over a one-month period (16th June - 16th July 1998). Currents, water levels and wave direction were also supplied. The data were recorded as 9-minute bursts every 3 hours.

The locations were described as:

- 1546 offshore wave meter – 19m CD
- 1545 inshore wave meter – 10m CD

The mean recorded depths were:

- 1546 13.7m
- 1545 10.9m

The wave height at 1546 was generally higher than at 1545 (see Figure 21), consistent with the relative depth, but the location appeared to be nearer to the coast, judging by the Halcrow-supplied bathymetry.

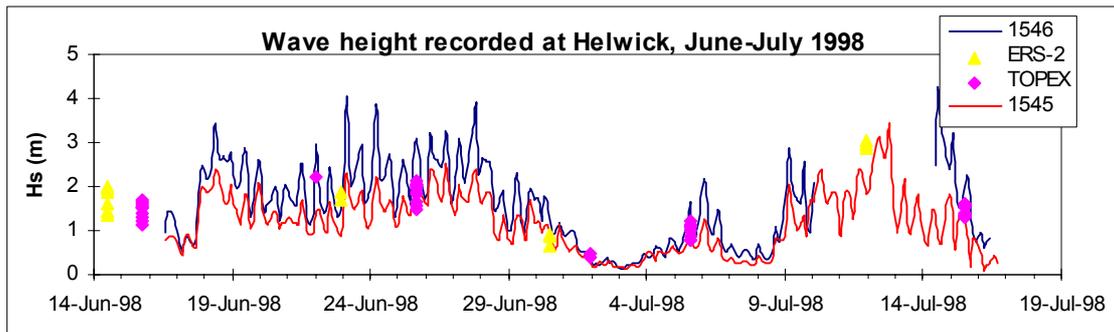


Figure 21: Observed wave heights

Figure 21 also shows the TOPEX and ERS-2 altimeter-derived wave height for the same time period. The whole of the adjacent track data is plotted, both ascending and descending, as supplied by David Cotton (personal communication). The agreement with the bottom pressure data is fair. The location of the altimeter tracks does not coincide with the Helwick measurements, being further offshore even at the nearest approach.

The SWAN model, implemented on a 200m grid, has a problem in that the so-called ‘inshore’ data point is apparently further offshore and in deeper water than the ‘offshore’ point. The model area, with locations of output points and TOPEX and ERS-2 tracks, is shown in Figure 5. The nearest approach of the altimeter tracks just reaches the model boundary at the eastern end of the grid, but data are not always available at these points. Using the positions given, point 1545 has a mean water level in the model of 9.5m, whereas 1546 is in only 2.7m, virtually onshore. The relative water depths mean that the model always gives much lower wave height for 1546 than 1545. For example, see Figure 22 for the maximum of the SWALES event (wave height at St. Gowan = 9.37m). The black dot-dash line represents the coast and 10m, 20m and 30m depth contours. The coloured lines are the wave height contours, starting at 1m (yellow line) and increasing at 1m intervals going offshore. Thus we have a wave height of 3.7m at 1545 but less than 1m at 1546.

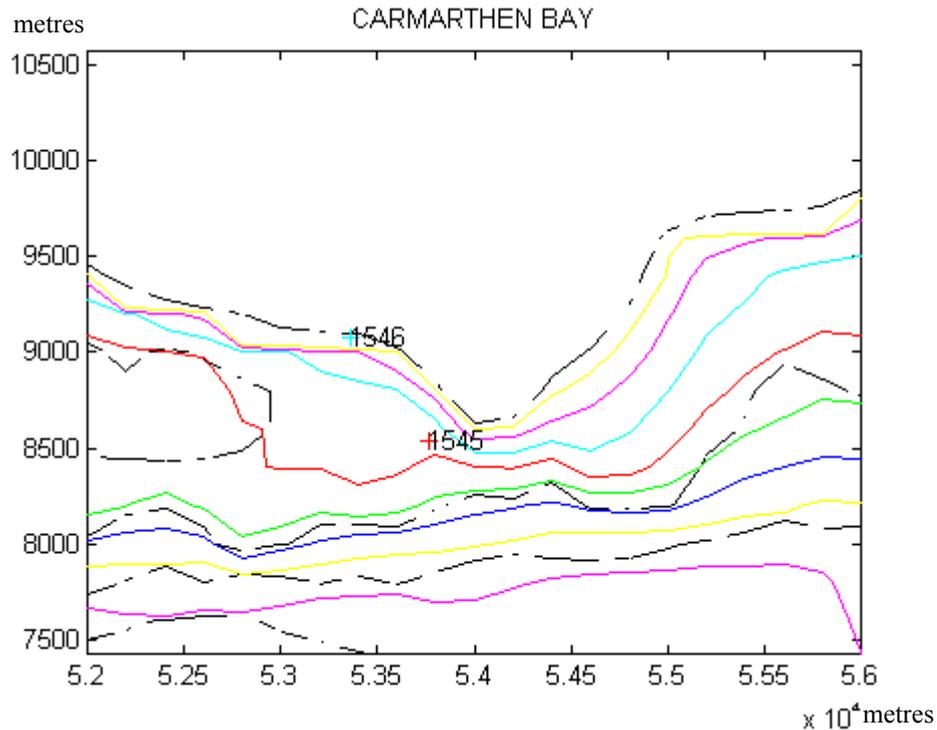


Figure 22: Wave height contours from SWAN run (maximum of SWALES 1993 event). Wave height contours are coloured lines at 1m intervals.

The Helwick recorded data have a mean wave height of 1.17m at 1545 and 1.57m at 1546. Unless there is an error in one or other of the locations, the recorded data must represent conditions due to very local bathymetric changes over their separation of 680m e.g. a near-shore bar, which is not resolved in the wave model. It is thus not possible to reproduce the details of the observations.

It may be possible to use the data at 1545 in conjunction with TOPEX or ERS-2 data for boundary conditions. However the uncertainty of boundary data extracted from TOPEX and ERS-2 and the low recorded wave heights mean that the results are not likely to be very conclusive. Also the Helwick stations are quite near the open boundary of the model grid. The following table shows the variation of H_s and T_z predicted by the model at station 1545 for specified H_s and T_p input at the model boundary. The waves have been assumed to come from SW, which is the prevailing wind and wave direction, with no local wind generation. A general reduction of 10% in wave height from the boundary to point 1545 may be seen. It is difficult to use such a small change to validate the model, however. There is perhaps a suggestion from figure 21 that the altimeter data have larger H_s than Helwick 1545, but there is also a reduction along-track as the altimeter approaches the shore and no certain way of extrapolating to the model boundary.

Table 8: Model results at station 1545

Input	<i>Hs</i>(m) (1545)	<i>Tz</i>(s) (1545)
<i>Hs</i> =1m, <i>Tp</i> =6s	0.9	4.2
<i>Hs</i> =2m, <i>Tp</i> =8s	1.8	4.4
<i>Hs</i> =3m, <i>Tp</i> =10s	2.7	5.8

4.3.3 SWALES event

The results from the SWAN runs at Amroth and Worms Head are shown in Table 9. The site chosen for Amroth was in very shallow water. To test the sensitivity to local water depth, one time (0h 9th Dec 1993) was rerun for SWAN with the water level over the whole grid increased by 2m.

Table 9: Significant wave heights (m) in Carmarthen Bay, 00h 9th Dec.1993

	Amroth	Worms Head
SWAN ¹	1.44	5.89
SWAN ²	1.56	6.33
SWAN ³	1.59	6.16
SWAN ⁴	1.93	6.86

¹ Standard run.

² Water level increased by 2m over whole grid

³ Directional spread increased; water level increased by 2m over whole grid

⁴ Nearest WASA model point input at boundary

The result, shown as SWAN² in Table 9, shows a significant difference in the results. Another variable concerns the propagation in SWAN, which is known to be highly diffusive. The big storm waves coming from a southwesterly direction have to undergo considerable refraction to arrive at Amroth. To test this, the directional spread was doubled in SWAN (while keeping the +2m water depth over the grid). As shown in Table 9 (SWAN³) this did not have a very large effect on the wave height although it did cause a slight decrease at Worms Head and a slight increase at Amroth. It is clear from the SWAN results at Amroth that the waves produced in SWAN are, like those at N1 in Holderness, subject to modulation by the tide. We do not have the data, unlike at Holderness, to verify this effect, but it seems likely that in water so shallow, and with the tidal range as large as 4m, this effect should be quite marked. We were, therefore, interested to know if the waves at Amroth were, indeed, being depth limited. As an experiment, a further run was performed (SWAN⁴ in Table 9), where the boundary input was taken from the nearest WASA model output point. The water levels were reset to their original values for this run. The result shows that the SWAN model is not depth limited at this time. This result is, however, at high tide, in a water depth of over 5 metres.

5. EXTREME EVENTS

The joint probability analysis for waves and still water levels commonly discusses the effect of surge e.g. HR (1998), Alcock and Carter (1986), but not tide. It is obvious that the largest possible waves will occur at high water (HW). This should be taken into account for the extreme analysis of waves in less than about 10m mean water depth. Surge effects may be important locally, but will be secondary to tidal effects. One can get positive or negative correlation of waves and surge (Owen et al, 1997).

It is difficult to estimate changes in return periods based on sea level and storminess scenarios. The estimates for extreme wave events at N3 were computed by David Carter (personal communication and Cotton et al, 1999). Some initial runs of SWAN were then performed using these runs as boundary forcing to the Holderness model.

SWAN was run for the 1-, 10-, 100- and 1000-year extreme events. To assess the range of variation due to uncertainties in the boundary parameters, seven runs were performed for each event. The first run used the average parameters supplied by SOS. For all the other runs only one parameter was varied from the average values. The wave height is varied according to the value for one standard deviation given by SOS. The period was varied to take account of the uncertainty in its derivation and also the uncertainties described in the previous section. The direction is varied through 50 degrees from close to northerly to east-north-easterly. The wind is at all times assumed to be 15 m/s along the same direction as the waves. In addition to these runs, the average conditions were re-run on an estimated high and low tide. The variation in the results in shallow water is more affected by the change in the water depth due to the tide than by anything else. This variation is also greater than the difference between the different events. This means that the distribution of extreme events is of a quite different form to that derived at N3. The joint probability of wave height and water depth is therefore of critical importance.

One question to be answered was to what extent it is possible to derive an extreme event distribution at N1 using SWAN. The problem is complicated by the fact that the tide (plus surge) is very important in the results. The extremes estimated are, supposedly, 3-hour events. This means that one in four times that each extreme occurs, it will occur on a high tide, which is when the waves at a certain distance offshore will be at their maximum.

Using four representative values of the tide, the variation of each extreme event can be approximated by running the model for each extreme event (24 runs in total). So, considering 4000 years, an approximation to the distribution function of events at N1 (C1) is given by 4000 1-year, 400 10-year, 80 50-year, 40 100-year and 4 1000-year events. The result is clearly inaccurate at both ends but the difference between this distribution function and that input at N3 should give an illustration of the effects of shallow water.

Small time-scale events [O(1-6 hours)] are smoothed out in wave models (caused by a mixture of smooth wind input and the propagation routine). The result of this smoothing is that peak events are, in general, underestimated (Hargreaves and Annan, 1999).

Offshore extreme wave statistics for all three sites were also computed by David Carter (personal communication and Cotton et al, 1999). Results are presented in Figure 23 for the three sites. It is shown clearly that the effect of the shoaling bottom makes the difference between the 100-year and 1000-year events quite small up to 8 km. offshore. From these results alone one would conclude that severe effects on the coast would not be caused by an increase of the 100-year wave height, since it is already effectively depth-limited. If, however, the 1-year extreme were to increase in size or if increased storminess caused the 1 year event to become more frequent than at present, then significant effects at the coast are to be expected.

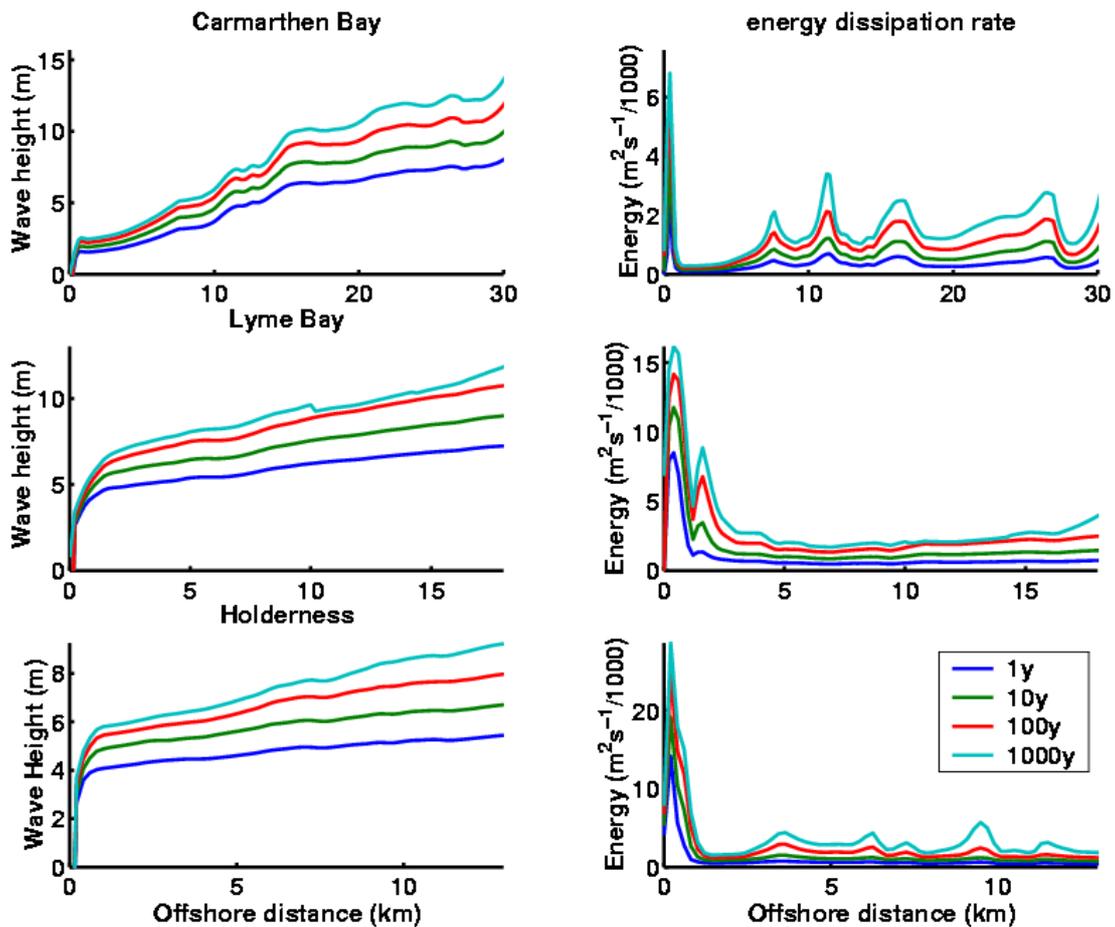


Figure 23: Extreme events – present-day climate

Figure 23 shows cross-shore profiles of model output in terms of significant wave height and total wave dissipation (the sum of white-capping, bottom friction and shallow-water wave breaking) for the different extreme events. The profiles were chosen to intersect the special interest sites chosen for study in the JERICHO project. At Holderness the profile is a line passing as close as possible to N3, N2 and N1. At Lyme Bay it is a south-north line intersecting West Bexington and at Carmarthen Bay it is a south-north line intersecting Amroth.

Figure 24 shows the potential change in extremes due to some future climate change scenario (approximately 2050) wave climate for the three sites. Future wave heights

were estimated to increase by +20% for the 1-year event and +10% for the others. These wave-height increases were not based on any observed or model data but merely used to give the ‘worst-case’ scenario. In fact there is still much uncertainty about whether wave height may increase or decrease over the next 50 years (Cotton et al, 1999). The estimated water level increase was taken from the IPCC sea level rise estimates. The results are summarised in Tables 10-12.

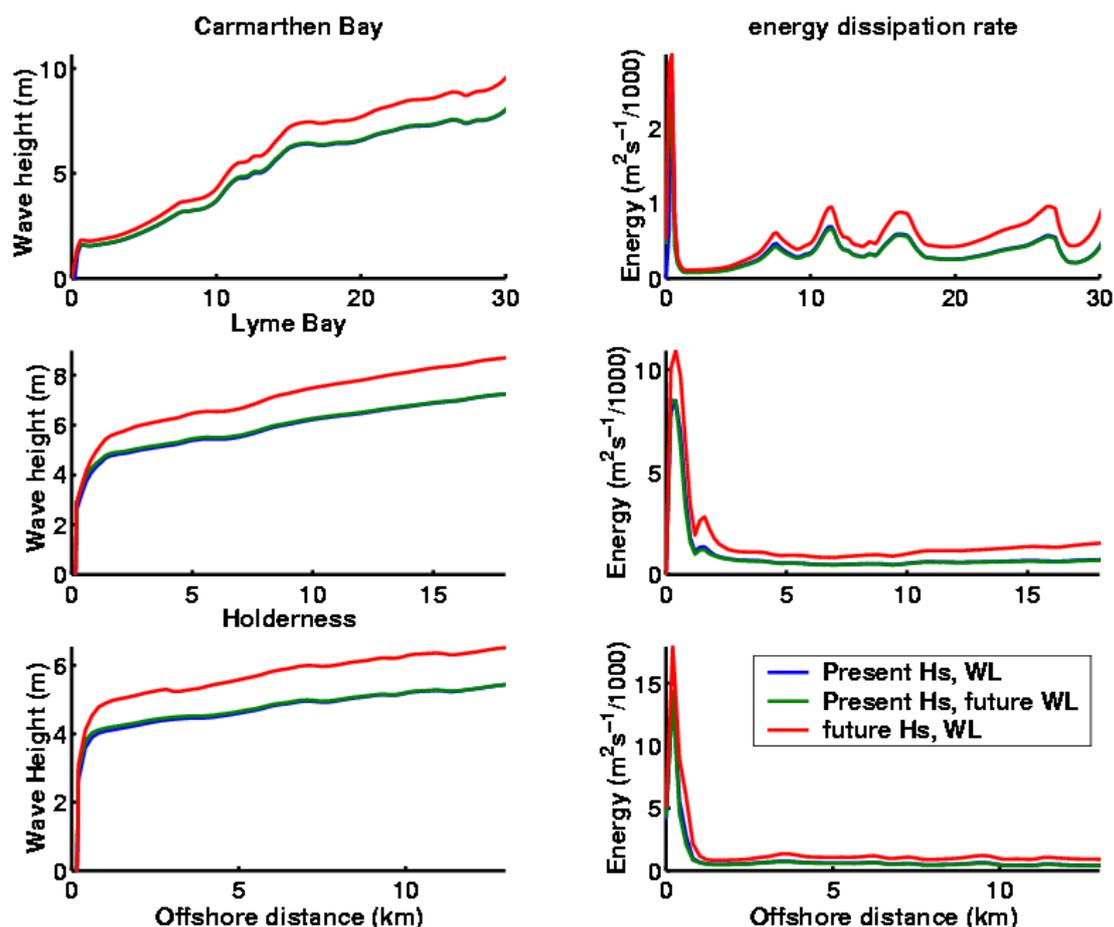


Figure 24: Extreme events – future climate

Water levels are as in tables 10 -12.

Table 10: Present-day extreme wave heights on present-day extreme water levels.

	1y extreme				100y extreme				1000y extreme			
	D(m)	Hs(m)	Tp(s)	Tz(s)	D(m)	Hs(m)	Tp(s)	Tz(s)	D(m)	Hs(m)	Tp(s)	Tz(s)
Worms Head	37.05	5.55	12.75	8.50	37.62	7.04	16.41	10.97	37.89	7.49	17.85	11.67
Amroth	8.15	1.56	12.75	4.67	8.72	2.27	16.41	6.40	8.99	2.51	17.85	7.06
N1	10.54	3.92	9.10	6.61	11.34	5.04	11.72	8.88	11.71	5.38	13.87	9.95
N11	16.33	4.12	9.10	6.47	17.13	5.50	11.72	8.50	17.50	5.85	13.87	10.00
N2	17.87	4.59	9.10	6.70	18.67	6.31	11.72	9.94	19.04	6.84	13.87	10.17
West Bexington	12.15	5.49	10.77	8.61	13.06	6.68	13.87	11.01	13.66	7.13	15.09	11.96

Table 11: Future extreme wave heights (+20% 1y, +10% 100y/1000y) on future extreme water levels

	1y extreme				100y extreme				1000y extreme			
	D(m)	Hs(m)	Tp(s)	Tz(s)	D(m)	Hs(m)	Tp(s)	Tz(s)	D(m)	Hs(m)	Tp(s)	Tz(s)
Worms Head	37.84	6.33	12.75	8.70	38.41	7.48	16.41	11.24	38.68	7.87	17.85	12.18
Amroth	8.94	1.80	12.75	4.89	9.51	2.45	16.41	6.14	9.78	2.68	17.85	6.47
N1	11.37	4.57	9.10	7.01	12.17	5.38	11.72	9.14	12.54	5.72	13.87	10.15
N11	17.16	4.98	9.10	6.85	17.96	5.83	11.72	8.94	18.33	6.19	13.87	10.15
N2	18.70	5.57	9.10	7.05	19.50	6.70	11.72	9.27	19.33	7.21	13.87	10.33
West Bexington	12.95	6.12	10.77	9.02	13.86	7.06	13.87	11.35	13.86	7.50	15.09	12.13

Table 12: Present day extreme wave heights on future extreme water levels

	1y extreme				100y extreme				1000y extreme			
	D(m)	Hs(m)	Tp(s)	Tz(s)	D(m)	Hs(m)	Tp(s)	Tz(s)	D(m)	Hs(m)	Tp(s)	Tz(s)
Worms Head	37.84	5.68	12.75	8.55	38.41	7.25	16.41	11.10	38.68	7.72	17.85	11.94
Amroth	8.94	1.57	12.75	4.59	9.51	2.33	16.41	5.88	9.78	2.58	17.85	6.50
N1	11.37	4.04	9.10	6.59	12.17	5.29	11.72	8.88	12.54	5.66	13.87	10.03
N11	17.16	4.20	9.10	6.51	17.96	5.72	11.72	8.44	18.33	6.09	13.87	10.05
N2	18.70	4.65	9.10	6.72	19.50	6.44	11.72	8.95	19.33	7.05	13.87	10.15
West Bexington	12.95	5.66	10.77	8.58	13.86	6.98	13.87	11.01	13.86	7.45	15.09	11.96

Further discussion of the extreme statistics is given in Hargreaves et al (submitted).

6. DISCUSSION

SWAN is a third generation spectral wave model, which explicitly includes the physics of wave generation by wind; dissipation by bottom stress, depth induced breaking and white-capping; energy transfer caused by nonlinear wave-wave interactions and the Doppler effects caused by currents. The user can make choices for different formulations for many of the source terms, and parameters such as the bottom friction parameter (which is highly dependent on the form and composition of the bed) can be freely chosen. In this way it is possible to 'tune' the model to produce reasonable results for a particular location. However, care should be taken not to over-tune the model resulting in the exacerbation of errors in the model inputs (bathymetry, wind field, currents, water levels and boundary forcing). The biggest obvious source of inaccuracy in SWAN is that in order to make computation times feasible a first order implicit integration scheme is used to calculate the wave propagation and refraction. This scheme is well known to be highly diffusive.

SWAN completes one run on one of the JERICHO grids (200m resolution) in about six minutes on a Silicon Graphics O2 R12000, 276 MHz workstation. It has a straightforward user interface when compared to, for example, WAMC4, although confusion can still arise in setting up the grid and orienting the forcing. Caution should be used since it would be all too easy for a non-expert user to be fooled by the apparent flexibility of the implementation into thinking the model can achieve what it cannot. A large number of integrated wave parameters can be optionally output over the whole area of the model grid. In addition, complete 2D spectra may be output at pre-selected model grid points.

Note that spectral wave modelling may be applicable down to a minimum water depth of about 5m. By this depth nonlinear wave effects are important and wave breaking becomes important. Certainly the model is not applicable inside the surf zone. The JONSWAP and Madsen formulations of bottom friction were compared, the latter was found to be preferable. The results are sensitive to the value of the bottom friction parameter. It may be possible to tune the bottom friction with reference to information on grain size and bed-forms if the information is available but this is likely to be difficult and very site-specific. Depth-limited breaking becomes important in very shallow water. The total dissipation (white-capping, depth-limited breaking and bottom friction) is critical in obtaining correct results and is an area of continuing development. To some extent the input and dissipation terms in spectral wave models have been developed empirically from historical data sets. There are various options that can be selected - in a model implementation with ground truth these can be tuned to some extent, but in an unknown area the optimum selection may vary. This needs to be addressed further. The details of the shallow water wave breaking term were not investigated. There are potential effects of the bottom slope on wave breaking which is an option included in SWAN - this was not investigated since the data available did not go into very shallow water.

SWAN is quite sensitive to changes in water level due to the tide. When we take into account that the water level at N1 was 5m too shallow in the model compared to the buoy measurements, it would appear that the model has a tendency to overestimate

the wave height in the shallow water. It is possible to adjust the bottom friction (which is still not well-understood physically) to produce more accurate results.

An important cause of the differences between the three model locations is the cross-shore depth profile and its steepness. This is illustrated in Figure 25, which shows a typical cross-shore variation of wave height and water depth across the models. The Holderness site is the least steep in the region 5-16km offshore, although there is evidence of some offshore banks, Lyme Bay is moderately steep in this region, then steepens rapidly in the last 2km. Carmarthen Bay depths reduce at a steady rate with a marked shoal at about 4km offshore.

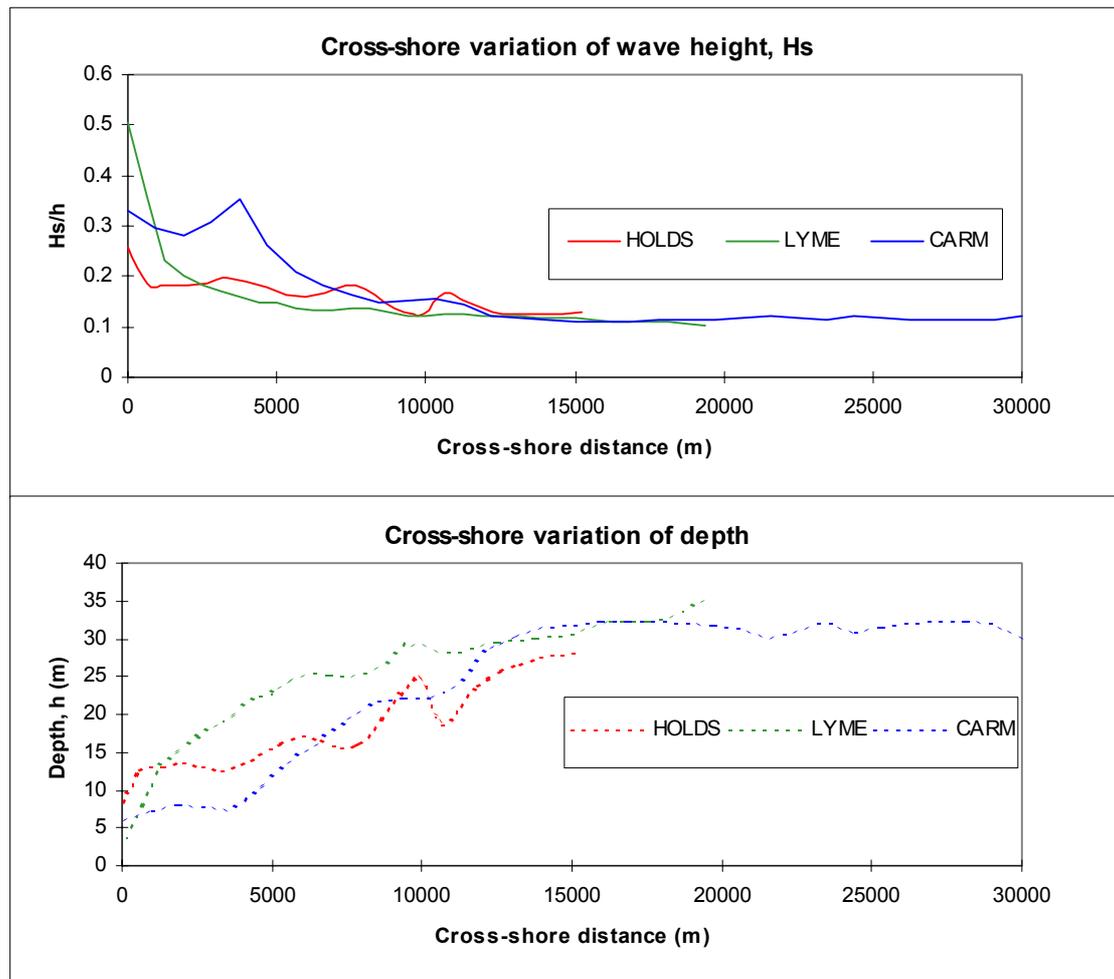


Figure 25: Cross-shore variation of wave height and water depth for the 3 different models

There is evidence of the importance of self-similarity scaling i.e. the TMA spectrum and its simplification by Tucker to scale wave height with peak wave-number. The applicability and limitations of this still need to be resolved. Triad interactions lead to the generation of higher harmonics. This mechanism needs high waves in shallow water - SWAN gives triad interactions with 4m waves in 15 metres of water, which seems unrealistic. There is some doubt about the correct implementation of the triad interactions in SWAN (in a spectral model of necessity this is an approximation). However the ground truth data are not totally reliable - Waverider buoys cannot

measure phase locked non-linearities since they smooth out peaks and sharpen troughs! This means the buoy is unlikely to see triads even if they are there.

There are further problems with ground-truth data e.g. there are sampling errors in Waverider data, there will be a propagation of boundary errors into the model and there is uncertainty in bathymetry (especially at a mobile eroding coast like Holderness, with possibly out of date survey data). The observed depth at N1 did not correspond to the model depth and the location had to be adjusted, since depth is an important controlling factor for wave height. The positional accuracy of observations at West Bexington is quoted as better than 200m but the location in the model grid had to be moved by more than 400m to obtain the correct water depth. This is critical for the accuracy of predictions.

The effect of currents on waves was only investigated partially. Homogeneous and spatially varying currents give very similar results, affecting the high frequency energy only, but this was only investigated at Holderness. They have little effect on wave height but more on mean period parameters - mainly due to Doppler shift in frequency. N.B. SWAN does not allow for the effect of currents in the bottom friction term, which may be very significant in shallow water. There is more evidence of interaction related to currents in the observations than in the model results. Carmarthen Bay is a complex area where the effect of currents is more likely to be important and the use of a hydrodynamic model on the same grid as the wave model would be advantageous.

The effect of increasing offshore wave height is a limited increase at the coast, since excess wave energy is dissipated further offshore. Interaction between waves and water levels is observed in that wave height is modulated in phase with water depth. Extreme wave heights at the coast will usually be depth-limited. Only waves on high water will be likely to be a risk to coastal defences. The study of extreme wave heights at the coast is very important but difficult. The method used in SWAN is to test the physical possibility of a hypothetical scenario. An advantage of this type of model is the possibility of using a very improbable event at the offshore boundary. An example of this is shown for Holderness in Figure 26, where the offshore wave height is increased to 10m (a very unlikely, if not impossible, event in the North Sea) with a correspondingly long peak period. The waves are rapidly dissipated in the model so that the coastal wave height is not much greater than that expected for a 7m wave.

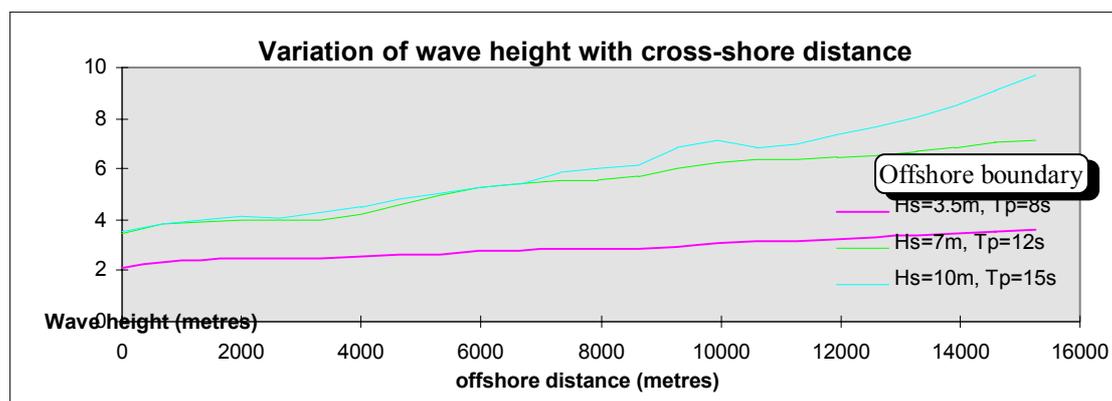


Figure 26: Effect of increasing offshore wave height

7. CONCLUSIONS

- a) The SWAN wave model is a 3-G spectral model, which has been designed for coastal wave predictions and is used extensively since it is in the public domain. It is computationally demanding. The physics now needs upgrading although it is less restrictive than less sophisticated models.
- b) Here, we describe how SWAN has been implemented on three grids around the coast of England and Wales: Holderness, Lyme Bay and Carmarthen Bay, which are sites with contrasting coastal dynamics.
- c) At Holderness there are sufficient data to validate the model, but the other sites must depend on less information. SWAN has been implemented for the Holderness region and run at three-hourly intervals over a two-day storm event in January 1995.
- d) The results show that varying the bottom friction formulation can have a significant effect on the results, with the Madsen formulation producing significantly better results than the JONSWAP formulation.
- e) Use of satellite altimeter data to drive the model is possible although giving poor time coverage. Various assumptions are required to extrapolate wave height to the model boundary, convert mean period to peak period and derive wave direction.
- f) To use SWAN for extreme value analysis it is possible to transform the statistical extreme events, but how to interpret the resulting transformed event is more problematic.
- g) To study future climate scenarios it was decided to choose the most likely plus worst case scenario. It is very difficult to assign errors in these cases. Coastal wave height is limited by water depth so it is not as likely to increase even if offshore waves increase.

The problems of predicting waves in the near-shore zone are contradictory. A simple parametric model can give good predictions most of the time but the need to forecast future extreme events means that the development and validation of physically-based models which include all relevant interactions is crucial. Empirical and statistical techniques can only tell us about what has already occurred.

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