APPENDIX C: The SWAN Model

C1. Introduction

SWAN is a sophisticated 3rd-generation spectral wave model, designed for the nearshore zone (outside the surf zone). SWAN has (almost) state-of-the-art physics, is relatively quick to set up and user-friendly in operation. However, some terms need to be improved and not all wave-current interactions are included (e.g. bottom friction). It is expensive in terms of computer time so that running long time series of wave predictions on a PC is prohibitive.

A limited area wave model requires, as input, the boundary wave spectrum, wind speed and direction and water level. Minimum requirements are wave height, period and direction, from which a standard spectrum (e.g. JONSWAP) can be constructed. Also wind speed and direction and water level are required. 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 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 need input from a directional wave buoy or larger-area wave model.

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, but it is not clear how the return period of the resulting wave should be determined. SWAN is too computationally-intensive to run a long time series of wave predictions in order to obtain the extreme statistics directly. Waves at the coast are more depth-limited than those offshore. The true return period is obtained from the joint probability of waves and water level.

In this appendix we describe the SWAN model and the validation exercise that was carried out at Holderness. Some of the test cases at Lyme Bay and Carmarthen Bay are also described.

C2. SHALLOW WATER WAVE MODELLING

C.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 intercomparison studies (e.g. SWAMP) the WAM 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, 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. Spectral models with various levels of parameterisation are also still in use. A review of wave transformation models is given by Smallman (1994). 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.

The advantage of a relatively simple model such as Halcrow s STORM model (Muir-Wood and Fleming, 1980), which models refraction by means of ray-tracing and the shoaling by self-similarity scaling, is that it 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 3rd-generation spectral wave model. Spectral wave modelling may be applicable to a minimum water depth of about 5m (although this has not been absolutely defined and the water depth is not the only controlling variable - wavelength and wave amplitude are also critical). By this depth nonlinear wave effects are important and depth-limited wave breaking becomes important. Certainly the SWAN model is not applicable inside the surf zone. It has been suggested that the Rayleigh distribution is not applicable in shallow water or that a new definition of significant wave height, *Hs,* is needed. Phase-resolving (e.g. Boussinesq) models are required at the shallow water limit and to deal with the physics of diffraction and reflection around obstacles and breakwaters, for example.

C.2.2 The SWAN model

SWAN (Simulating WAves Nearshore) is a 3rd generation phase-averaged spectral wave model, specifically designed for modelling shallow water coastal regions (Booij et al., 1999; Ris et al., 1999). The categorisation of the model as 3rd-generation means that it includes some explicit redistribution of the wave energy within the wave spectrum, by nonlinear wave-wave interactions, although this is not an exact solution but uses the so-called discrete interaction approximation (DIA) developed for the WAM model (Komen et al. 1994). The model includes wave generation by wind, using two different formulations which can be selected by the user. Wave dissipation is due to white-capping (deep-water breaking), depth-induced breaking and bottom friction. Nonlinear wave-wave transfer of energy is included as quadruplet and triad interactions. Depth-induced breaking and triad interactions can be de-activated in the model and various options for bottom friction are available: termed the JONSWAP, Collins and Madsen formulations respectively. The corresponding friction coefficients can be chosen by the user.

One of the benefits of SWAN is that it produces a 2-dimensional 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 CCMS-POL. For example, SWAN does not include wave-current interaction in the bottom friction term which is probably important. A very detailed view of the physics of SWAN has been carried out by Dingemans (1998), which 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.

C3. MODEL SETUP

C.3.1 Selection of sites for modelling studies

The variability of wave conditions around the UK coast is typified by the selection of three different sites, see figure C.1.

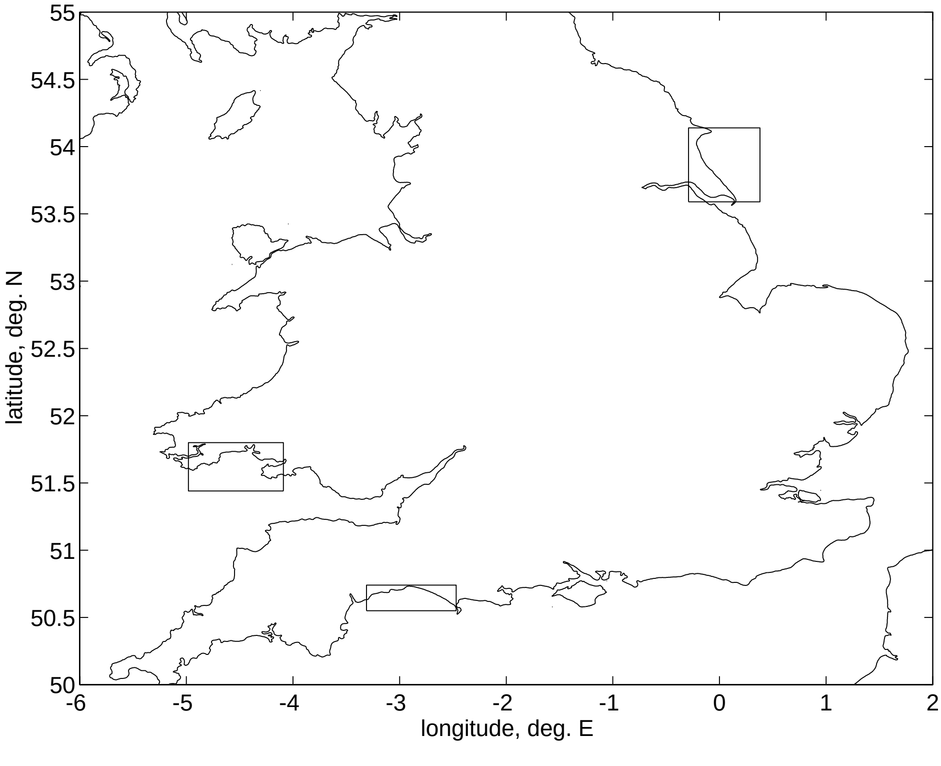

Figure C.1 Location of the 3 shallow water models

The SWAN shallow water wave model was applied to 3 coastal sites at Holderness, Lyme Bay and Carmarthen Bay. The depths, on a 200m grid, were provided by Halcrow from digitisation of Admiralty charts. A substantial dataset on waves at Holderness, in the NE of England, facing the North Sea, was available from other projects (Prandle et al., 1996), 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, in the North Sea, is much less exposed to wave energy, especially swell, than the west coast locations. Prevailing SW winds cause fetch-limited conditions and combined wind-sea and swell. There is a moderate tidal range. Lyme Bay on the south coast, facing the English Channel, is an open exposed 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). The tidal range is less than Holderness, being near to the M_2 amphidrome. Carmarthen Bay is more enclosed, with complex bathymetry, but 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. In this area there is most need for an accompanying tide-surge model to provide the spatial gradients of currents which may affect wave refraction substantially.
SWAN was run in time-independent mode on a Unix Workstation and on a Pentium PC. The model was validated against observed data at Holderness and the settings for various parameters were optimised. The output was compared where possible with Halcrow s STORM model. 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.

C.3.2 Holderness

The Holderness experimental layout is shown in Figure C.2

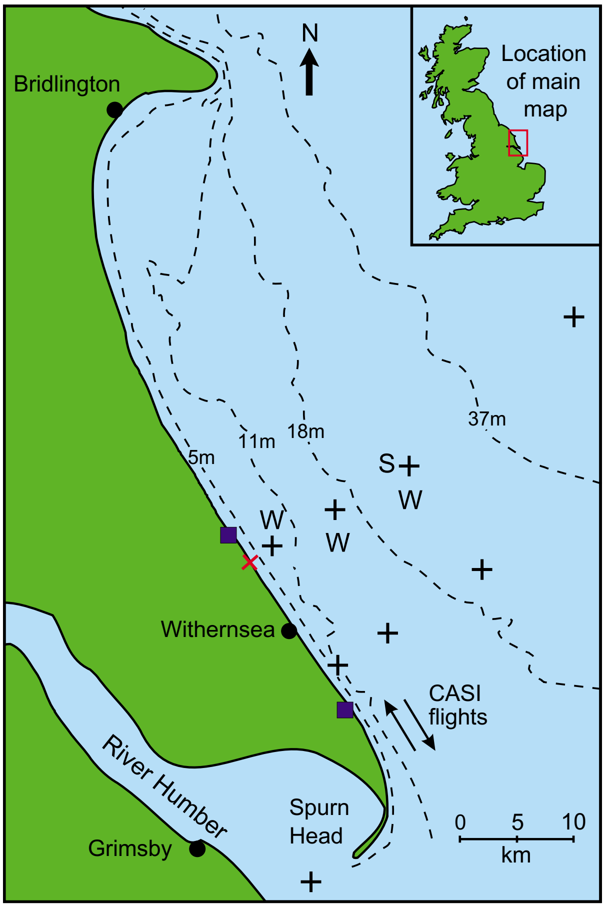

Figure C.2: Wave measurements at Holderness (1994/95 and 1995/96)
+ indicates PMP(POL Measuring Platform, on which were deployed bottom pressure recorders, including InterOcean S4DW s, which measure directional waves, at nearshore stations)W is Waverider location, blue squares are OSCR HF radar shore stations (master and slave) and the red cross is the X-band radar shore station

The bathymetry is quite uniform in the longshore direction. The model (Cartesian) grid was oriented parallel to the coast. Figure C.3 shows the original model layout and bathymetry (with depth contours at 10m intervals). The locations of N1, N2 and N3 are shown as crosses. The model was later modified to make N3 lie on the outer open boundary.

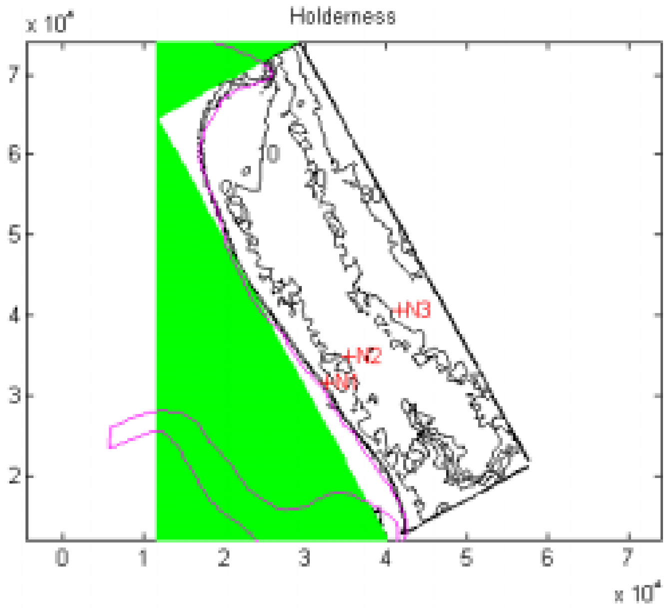

Figure C.3: Holderness, contours at 10m intervals, crosses are locations of Waverider measurements, 1994-95 (N1, N2, N3)

C.3.3 Lyme Bay

Lyme Bay is a wide bay with quite steeply sloping bathymetry nearshore, especially at eastern end of bay. Figure C.4 shows the model layout and bathymetry.

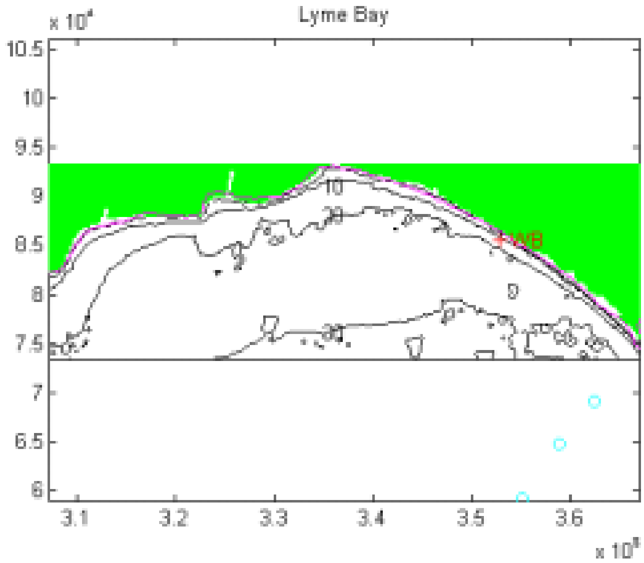

Figure C.4: Lyme Bay, contours at 10m intervals, circles are TOPEX tracks, cross is location of inshore data (West Bexington)

Nearshore waves were recorded by a pressure recorder at West Bexington (WB), in about 10m water, from December 1987 to May 1995 (with gaps) (Carter, 1999b). Maximum waves recorded during this time were at 09:56 8th December 1994, with significant wave height, Hs=5.13m and mean period, Tz=7.99s. Offshore data were taken from TOPEX tracks 061 and 146.

C.3.4 Carmarthen Bay

Carmarthen Bay has quite complex 2-D bathymetry. Figure C.5 shows the model layout and bathymetry (with contours at 10m intervals).

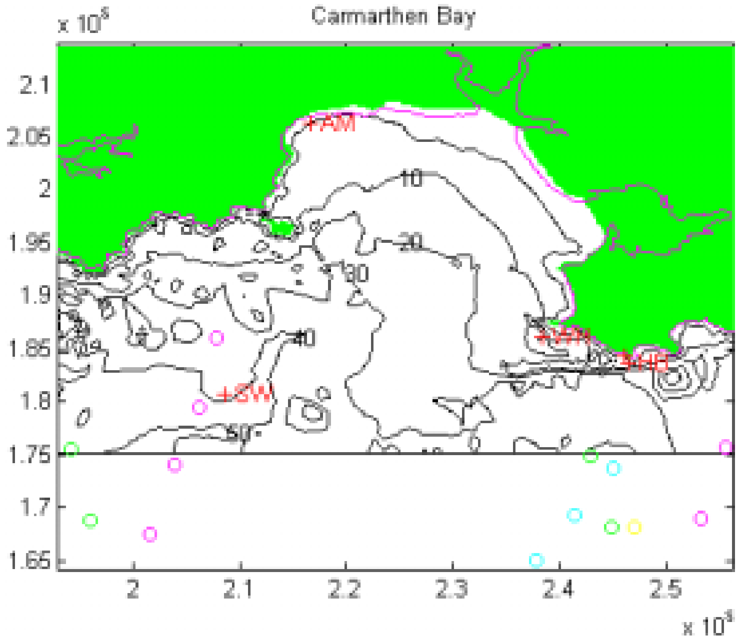

Figure C.5: Carmarthen Bay, contours at 10m intervals, circles are TOPEX and ERS-2 tracks, crosses are locations of output points (SW = SWALES buoy, AM = Amroth, WH = Worm s Head, HB = Helwick Bank)

Offshore wave data were measured for several years at the St Gowan buoy. No inshore data were available except a small amount at Helwick Bank. The largest (offshore) waves observed were during the SWALES experiment in on 8th December 1993. The SWALES buoy location is shown in figure C.5.

C4. MODEL VALIDATION

The only location at which both inshore and offshore data were available was Holderness. The model boundary conditions were taken as the observed wave spectra at N3 and output at N2 and N1 compared with the observations at the latter locations, concentrating on December 1994 - January 1995 and in particular the largest event on 1-2 January 1995.

The Holderness bathymetry obtained from Halcrow was used for running SWAN with the offshore boundary coincident with the N3 buoy (Figure C.3). Before it could be used in the model, the bathymetry required some correction from 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.

Some idealised model tests were carried out to examine the effect of various cross-shore boundary conditions (Wolf, 1998a).

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 required since the up-wave direction was north of offshore for this test period. Wind forcing to the model was provided by the 10-metre wind speed and direction at the UKMO coastal station at Donna Nook. The value was taken to be constant over the whole grid.

The spatial grid used was 78 by 296 points with 200m resolution. In the frequency domain there were 31 frequencies (0.04-0.5Hz) and 24 directions. The model took 120MB of RAM and 25 minutes per run on a Silicon Graphics R10000/195MHz (1996) workstation. It was run in stationary mode at three hourly intervals between 00:00 on 1st January and 00:00 on 3rd January. This event was a combination of wind-sea and swell and so is a good test of the validity of the model. The offshore boundary was taken as station N3 and output compared at N1. The time-varying water level and current were available from observations and 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. Based on the results of this study it was decided to switch off triad interactions and use the Madsen default bottom friction The results were in reasonable agreement with the observations at N2 and N1.

C5. SENSITIVITY TESTS

The effects of the following on the SWAN model were tested: local wind, water level, boundary conditions (i.e. spectral shape, offshore wave height and period), spatially homogeneous currents, triads, bottom friction and depth-limited breaking. The results from these studies are summarised from those reported in Wolf (1998b) and Hargreaves (1998, 1999a, 1999b, 1999c).

Water depths were obtained from POL's hydrodynamic (tide plus surge) model at station N1 and also from 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. The changes to the model output were significant and of the same order as the undulations obvious in the buoy output. These were absent from the model results with no depth variation. A wavelet analysis of the wave data from N1 and N3 during December 1994 and January 1995 showed 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.

One item of concern was bathymetry. The position of N1 is approximately 1 km offshore from observation during the Holderness experiment. In the model, however, it appears to be about 400 m offshore and there is a difference between the model (chart) depth and the observed depth of several metres.

In SWAN there are three possible formulations for the bottom friction term, and parameters may be set by the user for each. These parameters may be influenced by the sediment grain size and the presence of ripples in the sea bed so may quite reasonably be expected to be different for in different locations. The default formulation is the empirical model of JONSWAP. The SWAN model was run with the JONSWAP and Madsen bottom friction formulations using the default parameters. Through the European project EUROWAVES 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). We find that the decrease in wave height onshore is indeed better modelled by the Madsen formulation of bottom friction.

The results below show some statistics for the two cases. RMS, STDDEV and BIAS are the root mean square, standard deviation and mean of the (Hs_{model} - Hs_{buoy}) statistic. Note the large decrease in the bias at N2 and N1 in the Madsen bottom friction case.

Table 1: Bottom friction = JONSWAP

	RMS (m)	STDDEV (m)	BIAS (m)	MEAN(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

	RMS (m)	STDDEV (m)	BIAS (m)	MEAN(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

The wind input term has very little effect on the results obtained from SWAN in this example. The winds are North to North Westerly during this particular storm event.

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. There is little evidence for such spectral shapes in the Waverider spectra. 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 and the triad were deactivated for the rest of the work.

Spatially homogeneous currents were not found to have much effect on the results, particularly Hs. The wave period is affected more, due to the Doppler shift. Some tests were carried out with a cross-shore variation in current but long-shore uniformity. These also produced negligible effects at Holderness although it may be that current refraction is more important in an area of complex bathymetry like Carmarthen Bay.

The question of how to use TOPEX data to specify the offshore boundary condition was examined. The wave heights at N3 was found to be in good agreement with the nearest TOPEX data (Carter, 1999). The altimeter-derived wave period had to be converted into an equivalent peak period for input to SWAN.

C6. APPLICATIONS AT LYME BAY AND CARMARTHEN BAY

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. Details of model runs are given in Wolf (1999a).

The SWAN model at Carmarthen Bay was more problematic in that no nearshore data were available, although offshore boundary conditions were available from wave data recorded at St. Gowan. Enquiries were made regarding interesting events with the Welsh Office of the Environment Agency and some data was acquired at Helwick Bank from Associated British Ports (Wolf, 1999b). Part of the SWALES data set (October - December 1993) (Taylor et al., 1994) was chosen for detailed modelling. The model was set up based on the validation at the other 2 sites. Output was generated at 2 contrasting locations: Amroth in very shallow water and Worms Head in quite deep water.

C7. COMPARISON OF SWAN AND STORM

Output from both SWAN and STORM for some selected events at Holderness and Carmarthen Bay were compared (Hargreaves and Flather, 1999). There are some significant differences in wave height. Discrepancies in the models can often be partly explained by different depths at the comparison point, probably due to different model resolution, but this does not explain the whole difference. The STORM model at Holderness did not seem to model the tidal modulation of wave height as well as SWAN although the r.m.s. error was better. This was even more noticeable in the very shallow station at Amroth. Unfortunately, in the latter case, no ground truth data were available to confirm which model was more accurate.

C8. CONCLUSIONS

The SWAN model was found to be suitable for use in the above application for investigation of wave transformation in the nearshore zone. It is useful to be able to examine the details of the physical processes. However it is not economical to run long time series with this model so the use of SWAN for extreme value analysis is restricted to modelling the transformed extreme event.

Acknowledgements

The Holderness data were collected for the Ministry of Agriculture, Fisheries and Food under its Flood Protection Commission. The analysis was carried out as part of the European Community SCAWVEX Project. Data at Helwick Bank was provided by Bill Cooper (Associated British Ports).

References

Booij, N., R.C. Ris and L.H. Holthuijsen 1999. A third-generation wave model for coastal regions, Part I, Model description and Validation. J.Geophys. Res. 104, C4, 7649-7666.

Carter, D.J.T., 1999 TOPEX and N3 wave heights. JTR-16

Carter, D.J.T., 1999 Waves and winds in Lyme Bay. JTR-25

Dingemans, M.W. 1998 A review of the physical formulations in SWAN, report no. H3306, 69pp.

Hargreaves, J.C. 1998 Application of SWAN in the Holderness region. JTR-7

Hargreaves, J.C. 1999 Application of SWAN in the Holderness region. JTR-13

Hargreaves, J.C. 1999 Modelling at Holderness. JTR-17

Hargreaves, J.C. 1999 Application of SWAN in the Holderness region. No. 3. JTR-24

Hargreaves, J.C. and Flather, R.A. 1999 Comparison of SWAN and STORM. JTR-29

Hurdle, D.P. and Stive, R.J.H. (1989) Revision of SPM 1984 Wave Hindcast Model to avoid inconsistencies in engineering applications. Coastal Engineering, 12, 339-351.

Komen, G.J., Cavaleri, L., Donelan, M. , Hasselmann, K., Hasselmann, S. & Janssen, P.A.E.M. 1994 Dynamics and modelling of ocean waves. Cambridge University Press. 532pp.

Prandle, D., Ballard, G., Banaszek, A., Bell, P., Flatt, D., Hardcastle, P. Harrison, A., Humphrey, J., Holdaway, G., Lane, A., Player, R., Williams, J.J. and Wolf, J. 1996 The Holderness Coastal Experiment 93- 96 POL Report no. 44, 48pp.

Ris, R.C., N. Booij and Holthuijsen, L.H. 1999 A third-generation wave model for coastal regions, Part II, Verification. J.Geophys. Res. 104, C4, 7667-7681.

Smallman, J.V., Lawson, J. and Coultrup, J. Comparison of wave transformation models. Proceedings of 1994 MAFF Conference of River and Coastal Engineers, Loughborough University of Technology, 4-6 July 1994.

Shore Protection Manual 1984 Vol 1. 4th edition. Washington D.C. US Army Corps of Engineers Coastal Engineering Research Centre, 1984.

Taylor, P.K., Yelland, M., Birch, K., Clayson, C. and Pascal, R. 1994. Field measurements of wind and wind stress: the sonic buoy. Proceedings of 1994 MAFF Conference of River and Coastal Engineers, Loughborough University of Technology, 4-6 July 1994.

Wolf, J. 1998 JERICHO Project Report - POL September 1998. JTR-3

Wolf, J. 1998 JERICHO Progress Report - CCMS POL November 1998. JTR-8

Wolf, J. 1999 Lyme Bay Near Shore Wave Modelling. Specification of Boundary Conditions. JTR-29