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Near Shore Wave Modelling

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Abstract

Within the German BMBF project (Federal Ministry of Education and Research) MOSES (Modelling of mid-term wave climate within the German North Sea coastal area) two small-scale shallow-water wave models, k-Model and SWAN, are applied around the Norderney Inlet, a coastal area with inhomogeneous topography and strong tidal influence.

The models are driven by hindcast results from the European project HIPOCAS (Hindcast of Dynamic Process of the Ocean and Coastal Areas of Europe). This project provides 40 years wind, water level, current, and wave spectral data. Buoy data from four different locations are used for validation of k-Model and SWAN results. The used data span a complete 3-months period, September until November 2002.

It is demonstrated that HIPOCAS gives a valuable data basis for driving near-shore spectral wave models. K-Model and SWAN results as well as in-situ data are inter-compared.

The overall results show that there is not a simple relationship between the offshore wave climate and the in-shore climate in particular regions. The topography, tidal changes, near-shore currents, and the incident wave-propagation direction are important factors. They lead to high spatial and temporal variation in the amount of energy dissipated in the coastal area.

1 Introduction

Mid-term time series and high-resolution area covering data of waves, currents and water levels in coastal areas are important information for coastal engineering.

These data allow a better assessment of:

1. The probabilities and return values of representative wave parameters,
2. The continues loads on constructions in the coastal areas,
3. The impact of sea state on the morphodynamics,
4. The reconstructions of extreme events, e.g. storm surges

The required data, in particular the wave information, is normally not available from the few existing measuring sites. In recent years the reconstructions of atmospheric and ocean parameters by numerical models have proven to be a powerful tool to generate the necessary data for the global scale and with appropriate downscaling methods for the regional scale.

A multi-decadal (1948-2006) medium-resolution reconstruction of winds, waves, water levels and currents has partly been generated for the North Sea within the EU project HIPOCAS (Hindcast of Dynamic Process of the Ocean and Coastal Areas of Europe) The wind fields were determined by the regional atmospheric model REMO (Jacob, 1997) using a nudging technique (Feser, 2001), which was driven by data from the global reanalysis of the National Center for Environmental Prediction (NCEP) (Kalnay et al., 1996, ; Kistler et al. 2001). The generated homogeneous and high-resolution wind and pressure fields are hourly stored with a resolution of about 50 km x 50 km.

The fields from these simulations have been used to run regional storm surge and wind wave models. The water level and current data have been processed by the barotropic, two-dimensional finite-element model TELEMAC-2D (Kopmann and Markofsky, 2000). The resolution is varying between 5 km and 100 m and the data were stored hourly (Weisse and Plüß 2006). The wave information was generated by the WAM wave model (cycle 4), set-up in a nested mode. For the Southern North Sea the resolution was about 5 km. Integrated wave parameters have been stored hourly and two-dimensional wave spectra every three hours. The spectra are represented by 24 directions and 25 logarithmically spaced frequencies. (Weisse et al, 2006 and Weisse und Günther, 2006)

Within the German BMBF (Federal Ministry of Education and Research) project MOSES (Modelling of mid-term wave climate within the German North Sea coastal area) the HIPOCAS time series are used as forcing data basis for high resolution shallow-water wave modelling in the area around Norderney Inlet.

Two different wave models are applied to the Norderney Inlet area. The k-Model is a spectral wave model, which uses a source function describing nonlinear dissipation by wave turbulence interaction. Thereby nonlinear interactions are neglected. The action density is handled in the wave-number direction domain as prognostic field. This enables a convenient treatment of in-stationary systems under strong tidal and current influence like the Norderney Inlet.

SWAN is applied to this area using identical input data and topography. SWAN is a third-generation spectral wave model. It calculates the development and propagation of the energy density spectrum in the frequency-direction domain. The model is based on WAM, but has been extended in various ways for use in coastal regions. It includes non-linear wave-wave interactions and energy dissipation by wave breaking.

The Norderney Inlet is a coastal area with inhomogeneous topography and strong tidal influence. Both, the k-Model and SWAN results are validated with in-situ data from different buoys located off-shore of the island, within the inlet and between the island and the main land. Additionally, a direct comparison of k-Model and SWAN results is performed. The results show that there is not a simple relationship between the offshore wave climate and the in-shore climate in particular regions. The topography, tidal changes, near-shore currents, and the incident wave-propagation direction are important factors. They lead to high spatial and temporal variation in the amount of energy dissipated in the coastal area.

The present paper is organized as follows: A brief overview of the HIPOCAS project and database is given in section 2. The study area, the Norderney Inlet and the in-situ data are described in section 3, and the model configuration in section 4. The results and inter-comparisons are presented and discussed in section 5. The conclusions are summarized in section 6.

2 The HIPOCAS Data Basis

The long-term data that have been determined within the European project HIPOCAS (Guedes Soares et al., 2002) are the data basis for the investigations in this paper. In this project a 40-years (1962-2001) hindcast has been performed amongst other areas in the Southern North Sea. Wind- and wave fields as well as water level and current fields have been calculated for this period. Fig.: 1 gives an overview of this part of HIPOCAS.

The wind fields were determined by the regional atmospheric model REMO (Jacob and R. Podzun, 1997) using a nudging technique (Feser et al., 2001), which was driven by 40-years of data from the global re-analysis of the National Center for Environmental Prediction (NCEP) (Kalnay et al. 1996; Kistler et al. 2001). The generated homogeneous and high-resolution wind fields are hourly with a resolution of about 50 km x 50 km for the area as shown in Fig. 1.

Using the available wind fields wave fields for the hindcast period were reconstructed using the WAM wave model (cycle 4), set-up in a nested mode for the Southern North Sea (see upper left of Fig. 1). The resolution is 0.1o in longitude and 0.05o in latitude (about 5 km x 5 km) in space and one hour in time. Frequency-direction spectra are additional stored for each grid point every three hours. The spectra are represented by 24 directions and 25 logarithmically spaced frequencies.

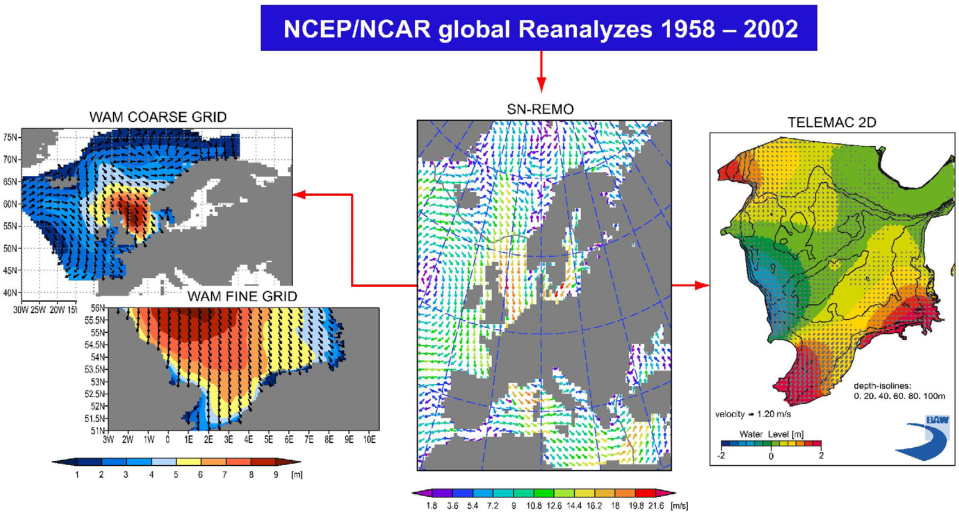

Fig. 1 Layout of the consistent met-ocean hindcast 1948-2006 for the Southern North Sea. From the regional atmosphere hindcast (middle) hourly wind fields were used to force a tide-surge (right) and a wave model hindcast (left). The figure shows an example of consistent met-ocean conditions obtained from the hindcast for 12 UTC on 21 February 1993. Middle: near-surface (10 m height) marine wind fields in ms^{-1} and corresponding wind direction obtained from the regional atmospheric reconstruction. Left: corresponding significant wave height fields in m and mean wave direction from the coarse and the fine grid wave model hindcast. Right: Tide-surge levels in m from the corresponding tide-surge hindcast (after Weisse and Günther 2006).

The needed water level and current data are processed by the barotropic, two-dimensional finite-element model TELEMAC-2D (Kopmann and Markofsky (2000)). The model was operated by Federal Waterways Engineering and Research Institute (BAW). The topographic information was provided by the German Federal Office of Sea Navigation and Hydrography (BSH). The resolution is varying between 5 km and 100 m and the data were stored in hourly time steps.

More details and an assessment of the HIPOCAS results are given in Weisse et al., 2006.

3 Area of Investigation

The aim was to investigate the feasibility of using k-Model and SWAN forced by HIPOCAS data to reconstruct the near shore wave climate for coastal engineering applications. The area around Norderney Island was chosen, because it is exposed to the North Sea waves and includes a variety of different bathymetric and coastal features. Fig. 2 shows the location of the model area around the Norderney Inlet within the German Bight. The topography was recorded during 2002. It is given in geographical coordinates with an extension of 0.75° in longitude, 0.55° in latitude, and a resolution of 400 m.

The Norderney Inlet area is characterized by a high spatial temporal variability of water levels, currents and sea state. The superposed effect of tides, weather conditions and complex topography cause complicated experimental and numerical investigations of such a system. The water depth is rapidly decreasing from more than 20 m north of the island to less than 10 m in the tidal flat between the island and the main land. The mean tidal range is 2.36 m. During low tide a large part of the tidal flat is falling dry. During high and low tide the current within the inlet is typically exceeding 1 m/s. There is little discharge due to rivers in this area.

For comparisons of the k-Model and SWAN results timeseries of sea state data including frequency-direction spectra and integral sea state parameter from four buoys were available, arranged north of the Norderney Island and within the tidal flat between Norderney and the main land (see Fig. 2). Sea state data were used from September 1st until November 30th, 2002. Spectra were measured up to a frequency of 0.6 Hz with an increment 0.01 Hz. The mean water depths at the measurement sites are ≈ 10 m.

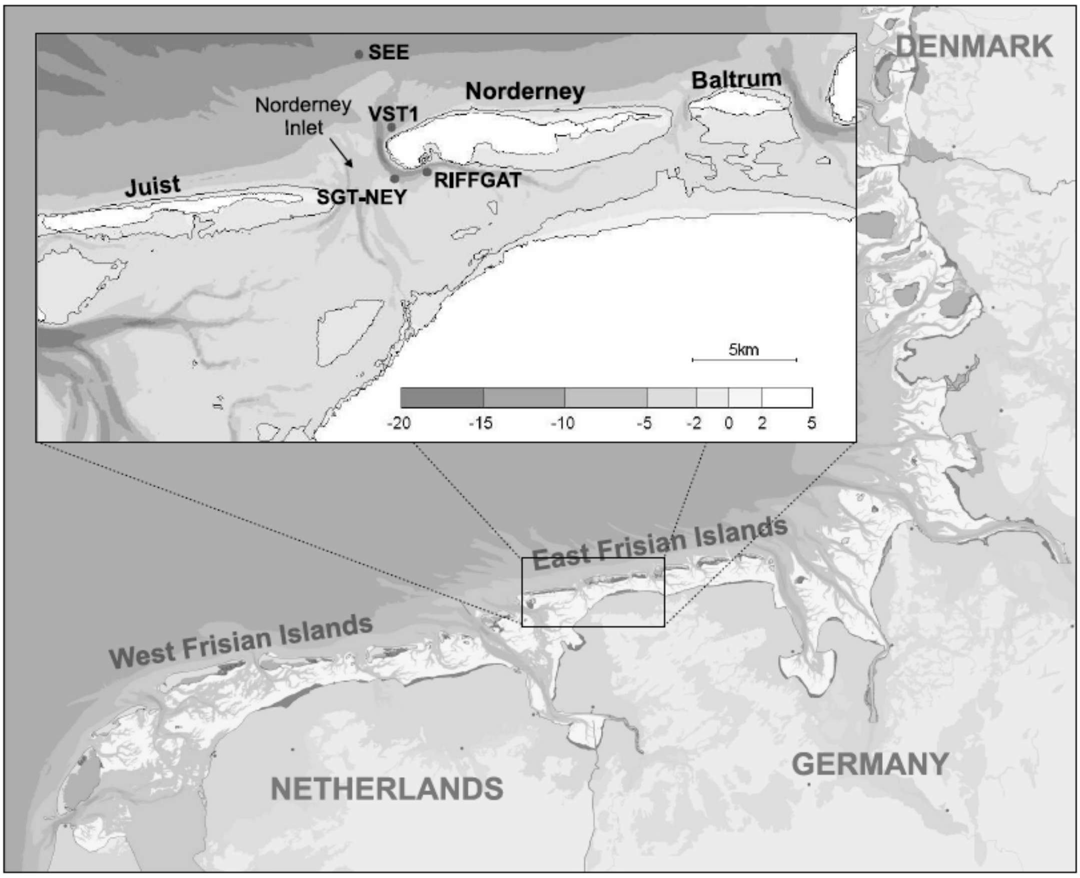

Fig. 2 Topography of the Norderney Inlet area from 2002. The resolution is 400 m. The locations of the buoys are marked by dots.

4 Models

4-1 SWAN

SWAN is a public domain third-generation spectral wave model (Booij et al., 1999; Ris et al., 1999) based on the wave action conservation equation formulated in terms of a two-dimensional frequency-direction spectrum. The fundamental model physics are: propagation of wave energy, its generation by wind, quadruplet wave-wave interactions, energy dissipation due to white capping, and bottom friction is based on JONSWAP (Hasselmann et al., 1973). In addition processes for wave modelling in shallow coastal regions can be accounted for in SWAN, e.g. the depth-induced wave breaking, and triad wave-wave interactions. All these processes have been used in the calculations described in this paper.

The governing energy balance equation is solved numerically by means of an implicit iterative scheme. In the non-stationary mode used in this work a proper choice of the time step and the number of iterations per time step must be made. A number of calibration model runs showed that a time step of 10 min with 2 iterations per time step is an optimal combination of these parameters for the present model configuration.

The area of the Norderney Inlet is modelled in curvilinear coordinates. The grid cells have a resolution varying between 200 m at the northwest border of the grid and 30 m within the inlet. As input for SWAN, the HIPOCAS frequency-direction spectra are used as boundary conditions. The required water levels and current fields are obtained with a two-dimensional version of the Delft3D model (WL / Delft Hydraulics, 2003), forced at the open boundary by interpolated timeseries of free surface elevation and wind fields from the HIPOCAS data base.

4-2 k-Model

The k-Model (Schneggenburger, 1997 and Schneggenburger et al., 2000) solves the wave action conservation equation given in wave-number direction. The model describes wave propagation and wave development in a balance of linear wind input, non-linear dissipation, and bottom friction. An explicit treatment of quadruplet nonlinear interactions and wave breaking is abandoned.

The balance equation is solved by the some numerical schemes (first order explicit for propagation and a semi for the source function) as in the WAM model (Hasselmann et al., 1988).

The model area of the Norderney Inlet is given in regular, geographical coordinates with a resolution of 400 m. Boundary spectra, water level, current and wind fields are provided from HIPOCAS. The input data basis is therefore equivalent for both, k-Model and SWAN.

The resolution of the k-Model spectra is 24 directions and 28 wave numbers. The frequencies of the output spectra are between 0.04 Hz and 1 Hz. The source-term integration step is 60 s. Propagation, current-refraction, and depth-refraction time step are 10 s, 10 s, and 2.5 s.

5 Results

For a 3-months period from September 1st, 2002 until November 30th, 2002, the Norderney Inlet area has been modelled. Thereby the same input data (boundary spectra, water levels, currents, and wind fields) are used, so that the calculations of both models are performed under consistent conditions. Both model determined hourly spectra and integral sea state parameters. These results are first validated using measured data from buoys at four different locations (Fig. 2). All directions are given in the nautical convention, counting counter clockwise from North, indicating where the system is coming from.

5-1 Parameter Fields

Fig. 3 exemplarily shows the water depth and current conditions (a), the distribution of significant wave heights H_S (b), and the mean periods T_{m2} (c) for the Norderney Inlet at September 1st, 2002, obtained by the k-Model. The left side describes the conditions shortly before high tide during flood phase, and on the right side short time before low tide during ebb phase.

During the flood phase water is flowing through the inlet into the Wadden Sea area between the island and the mainland. During ebb phase the water is mainly discharged through the inlet into the open North Sea, and large areas of the Wadden Sea area fall dry. The lower water depths in the whole area during the low tide cause a stronger depth effect onto the waves - the wave heights are noticeable reduced.

The wave height decreases with increasing distance from the open boundaries, the mean periods slightly decrease, too. A small increase is only visible very close to the North beaches of the islands, caused by the dynamic balance of shallow-water dissipation and shoaling. The shoaling effect increases T_{m2}, whereas the low frequency energy is decreased by enhanced dissipation in shallow water. The rising T_{m2} periods coincide with the steep depth gradients north of Norderney Island and the tidal flats between the mainland and the island.

The refraction of propagating waves north of the island is visible by varying mean wave-travel directions. Comparing high- and low-tide situations, it can be inferred that refraction is mainly caused by depth gradients and not by the current shear.

5-2 Time Series

For comparison and validation data from the four buoys around the island, called SEE, VST1, SGT-NEY, and RIFFGAT, as indicated in Fig. 2 are used. Because the buoys measure the spectra up to a frequency of 0.6 Hz all sea state parameters from the model data are determined by integrating up to this cut-off frequency. The higher frequencies up to 1 Hz are not considered here. In addition only wave heights above 10 cm have been considered due to the measuring limitations of the buoy.

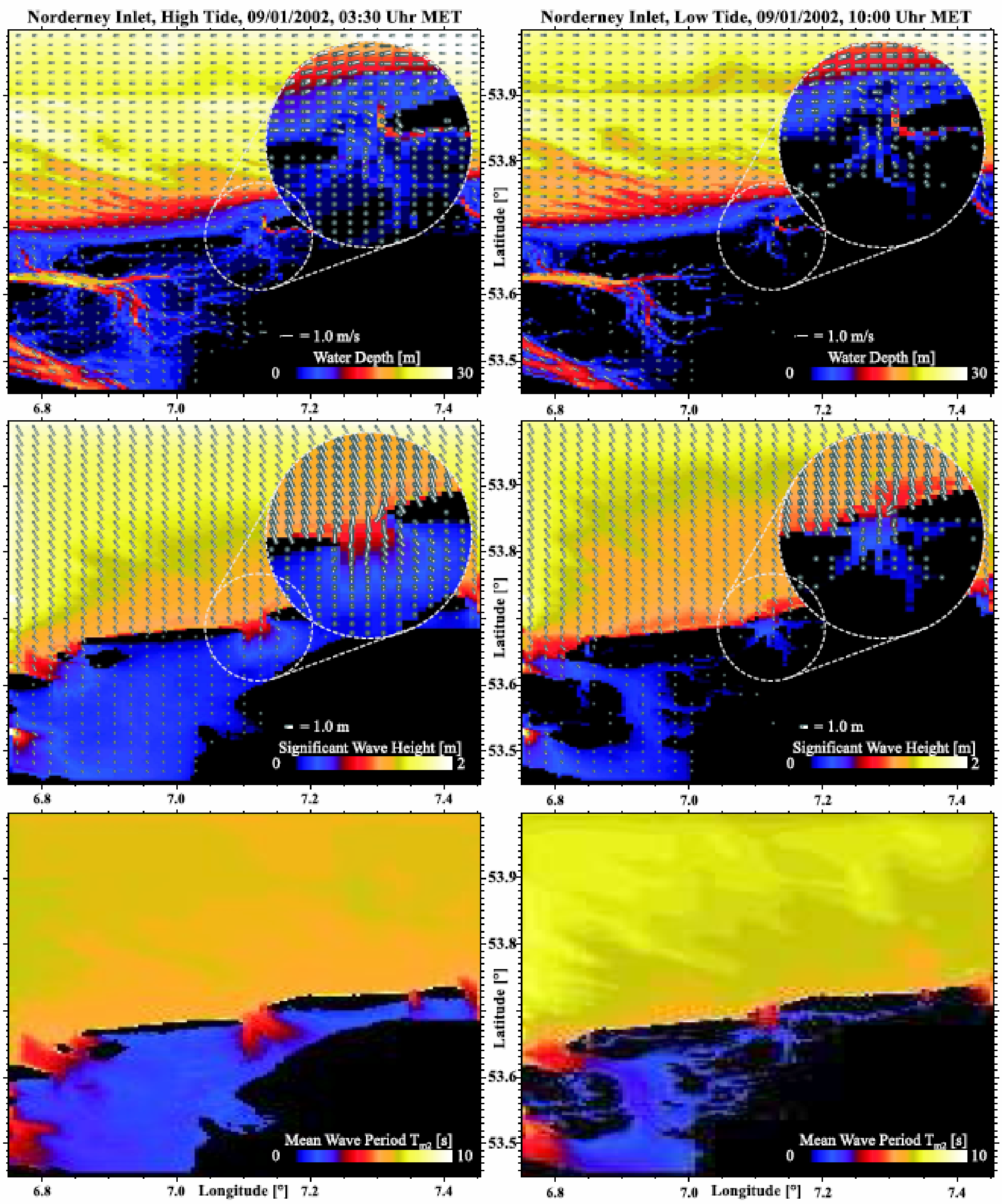

Fig. 3 Current and water depth maps (above), HS and wave propagation direction (centre), *Tm*2 (below) in the Norderney Inlet area at high tide (left) and low tide (right).

Fig. 4 shows the wind and wave propagation direction at station SEE for October 2002. The mean wave travel directions from k-Model (blue) and buoy measurements (red) show good agreement. The wind speed is given in green colour. Strong wind events, e.g. on October 28th with > 20 m/s, are expectedly usually blowing in east-south-easterly directions. Driven by local winds the waves turn always southwards due to refraction regarding the local topographic conditions.

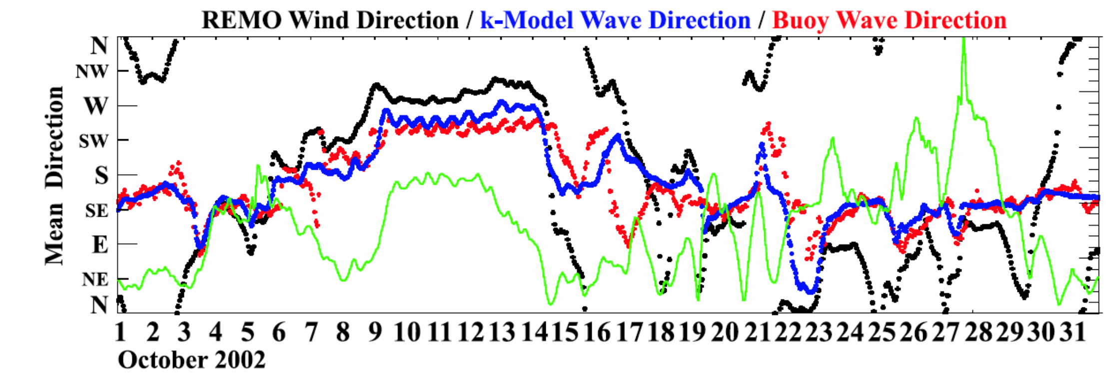

Fig. 4 Time series from October 2002. Model (REMO) wind speed (green), wind direction (black), mean wave propagation direction (K-Model: blue, buoy: red).

Fig. 5 exemplarily shows the complete time series for stations SEE and SGT-NEY in October 2002. The upper part presents the significant wave height H_S, the lower one the mean period T_{m2}. The buoy SEE is located at the 12 m depth contour. Waves coming from the open sea are passing through the Norderney Inlet into the tidal flat between the mainland and the island before arriving at the station SGT-NEY.

The k-Model results are shown by the blue, short-dashed curves and SWAN results by the green, long-dashed. The in-situ data are given as red-coloured crosses. Additionally, the forcing boundary values taken from the HIPOCAS data set at the boundary grid point directly north of the site SEE are plotted for comparison. The depth of this boundary point is 30 m.

The comparison of the boundary values with the modelled values at both stations SEE and SGT-NEY gives a good impression of the strong dissipation processes active in both models.

The tidal modulation of the sea state parameter is visible at station SEE mainly in the wave period and at station SGT-NEY, more pronounced in wave height and wave period. With the wave propagation towards the island and through the Norderney Inlet into the inner area (from stations SEE to SGT-NEY) the wave heights are considerable reduced by dissipation. The mean periods are also decreasing, because the low-frequency parts of the energy spectrum are dissipated. Overall there is a qualitatively good agreement between in-situ measurements and both wave model results.

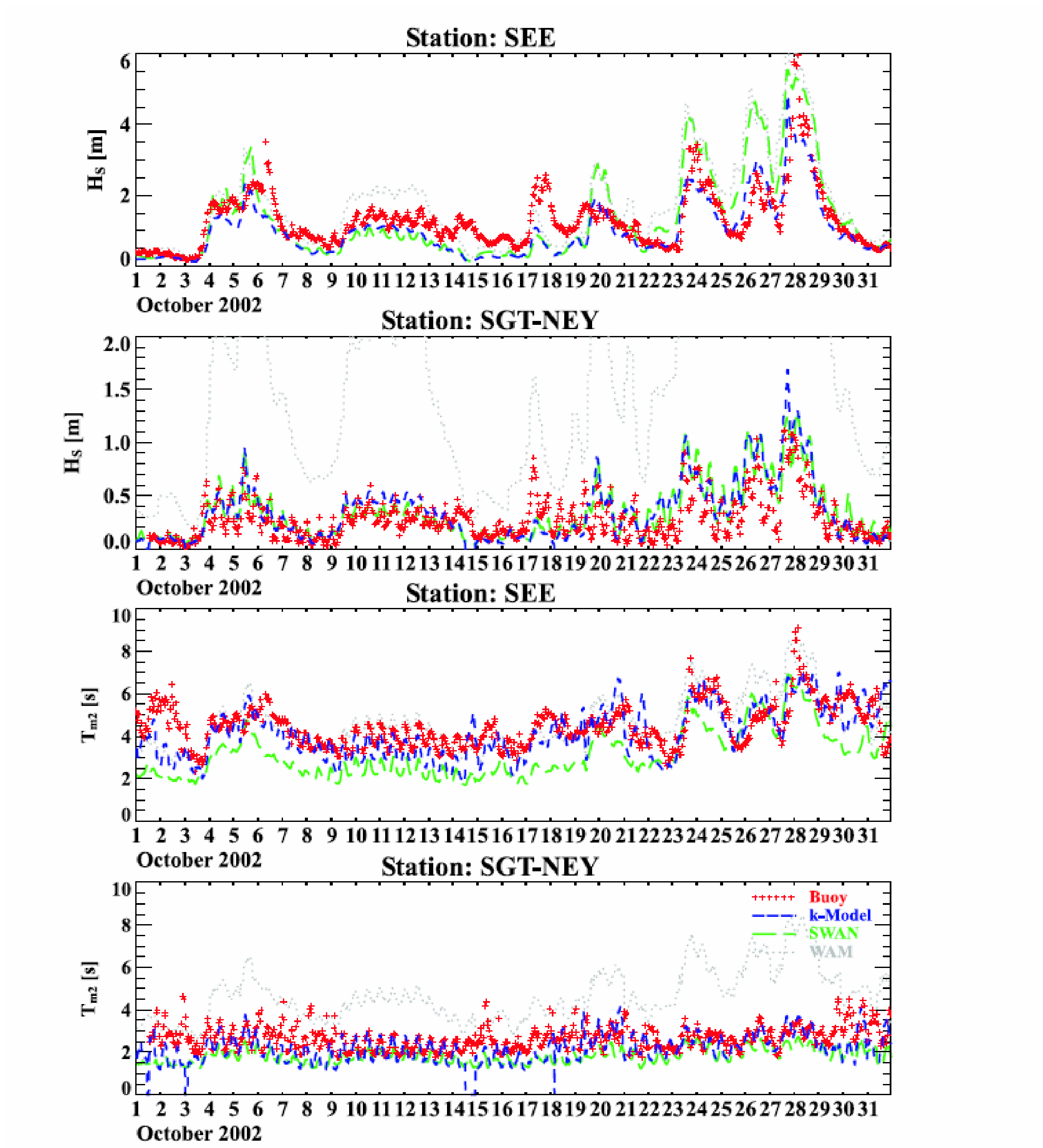

Fig. 5 Comparison of significant wave height HS and mean period Tm2 from k-Model (blue short dashes), SWAN (green long dashes), and buoy (red crosses) at station SEE and SGT-NEY (see Fig. 2). For comparison the boundary data from HIPOCAS (WAM) are shown (grey crosses).

It is interesting to notice, that SWAN overestimates the high wave heights, not reducing the spectral energy from the boundary-energy level to the real value for long period waves, whereas the k-Model results show a better agreement for these waves. This is reflected in the corresponding statistics (cf. Table 1 and 2.), which summarize the inter-comparison between k-Model, SWAN, and measurements at all four sites over the full three-month period. Whereas the bias (-0.07 m for SWAN and -0.21 m for k-Model) at station SEE is in favour of SWAN,

Table 1 Statistical parameter resulting from comparison of buoy observations and k-Model hindcast at stations SEE, VST1, SGT-NEY and RIFFGAT for period September until November 2002.

		H_S [m]			T_{m2} [s]		
stat	no.	corr	bias	σ	corr	bias	σ
SEE	2124	0.821	-0.21	0.38	0.617	-0.45	0.78
VST	787	0.679	-0.08	0.29	0.535	-0.64	0.69
SGT	736	0.726	0.08	0.20	0.241	-0.16	0.92
RIFF	563	0.571	0.19	0.19	0.396	-0.38	0.33

Table 2 Statistical parameter resulting from comparison of buoy observations and SWAN hindcast at stations SEE, VST1, SGT-NEY and RIFFGAT for period September until November, 2002.

		H_S [m]			T_{m2} [s]		
stat	no.	corr	bias	σ	corr	bias	σ
SEE	2146	0.745	-0.07	0.56	0.563	-0.88	0.81
VST	809	0.672	-0.13	0.30	0.383	-1.15	0.76
SGT	754	0.790	0.02	0.15	0.638	-0.37	0.43
RIFF	617	0.652	0.01	0.12	0.624	-0.09	0.23

the standard deviations (0.56 m for SWAN 0.38 m for k-Model) are considerable smaller for the k-Model. At the other stations the wave height statistics are comparable, slightly better for SWAN.

Both models underestimate the mean periods. The underestimation is about two times stronger in the SWAN results than in the k-Model at the stations SEE, VST1, and SGT-NEY. Only at the very shallow station RIFFGAT SWAN has a much smaller bias.

5.3 Spectra

Fig. 6 shows double-peak frequency direction spectra for station SEE shortly after high tide from k-Model (left) and SWAN (right). Crosses for each frequency mark the measured mean wave-propagation directions. The wind is blowing with 7-8 m/s from easterly directions. The current direction is with 278± pointing westwards. The wind and currents are therefore nearly parallel to the coast.

Both spectra are bimodal, whereby the narrow-banded, southeast travelling wave field is ascribed to swell. The peak frequency is ≈0.1 Hz. This swell system has been generated in the North Sea, outside of the local wind field influence. The second, broad-banded wave field is equivalent to the local-generated wind see. It has a higher peak frequency of ≈2.5 Hz. Thereby the wind-wave travel direction is turning from the local wind direction of 274^{o} towards the shore, following the local topography gradient southwards due to refraction.

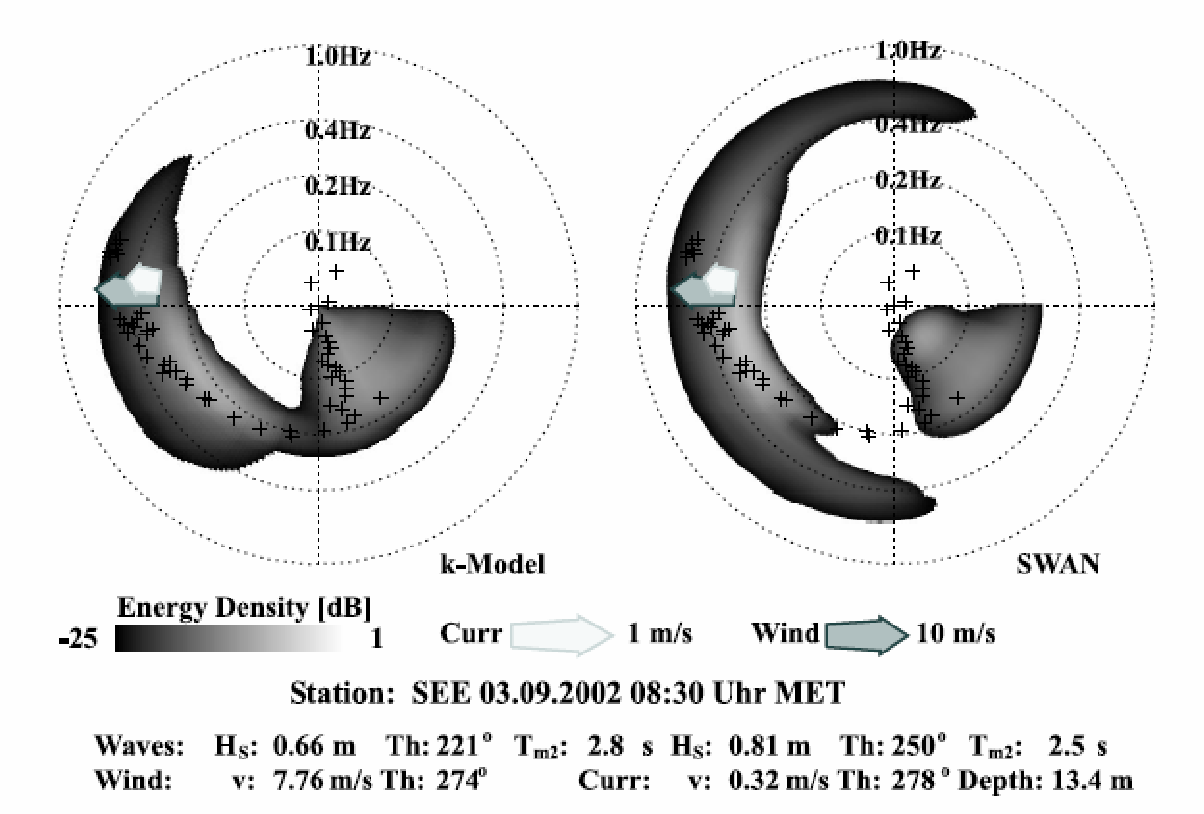

Fig. 6 Frequency-direction spectra from k-Model (left) and SWAN (right) of station SEE at high tide, September 3rd, 2002, 8:30 MET. The energy density is in decibel. The crosses mark the mean-wave propagation direction at each frequency bin, measured by the buoy.

Comparing k-Model and SWAN spectra shows, that SWAN compared to k-Model is clearly more broad-banded in the directions for the wind-wave part of the spectrum and slightly shifted to higher frequencies. On the other hand, the swell-wave field is dominating in the k-Model spectrum. This has significant influence on the calculated mean wave-propagation direction, which is, e.g., for the k-Model 195^{o} and 247^{o} for SWAN, underlining the importance of the two-dimensional frequency-direction spectra comparisons to avoid misinterpretations of the model performance.

The crosses within both spectra mark the buoy measurements for each frequency within the buoy-measurement range. The spectra show that the buoy recognizes both, swell and wind wave system. Comparing measured and modelled mean wave-travel directions per frequency bin there is a good agreement between buoy and k-Model for both wave systems. SWAN turns the swell wave field propagation into a more easterly direction.

Fig. 7 gives the frequency-direction spectra at station SGT-NEY, within the Norderney Inlet (compare Fig. 2), for the same time as in Fig. 6. Different from the offshore situation the current is following the shape of the tidal channel with higher current velocity. The mean wave propagation direction is close to the wind direction. Compared to the spectra at station SEE, the swell system has almost completely vanished. With the propagation of waves into the geometric shadow area behind the island of Norderney the wave energy is further distributed and dissipated.

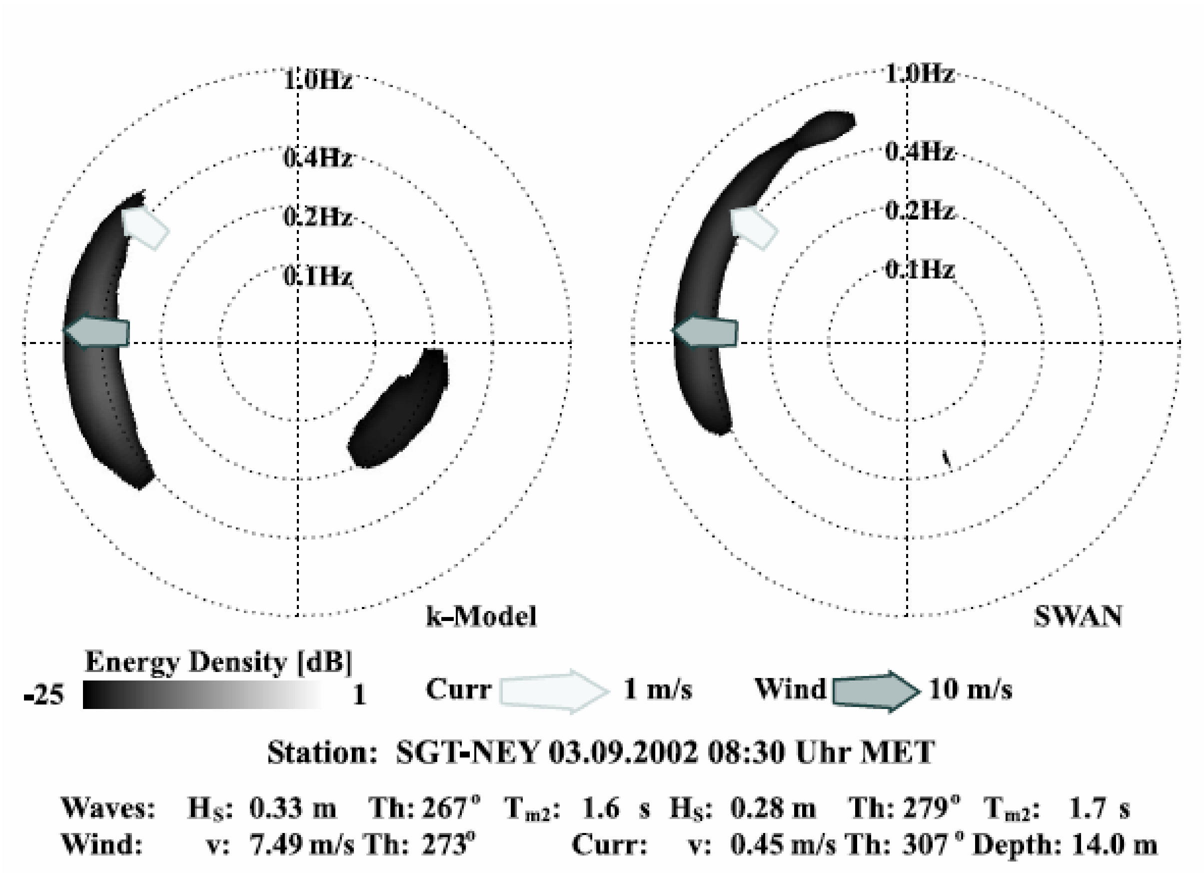

Fig. 7 Frequency direction spectra from k-Model (left) and SWAN (right) of station SGT-NEY at high tide, September 3rd, 2002, 8:30 MET. The energy density is in decibel.

Thereby especially lower frequency components are reduced. Further the waves turn regarding the topographical conditions.

The local-generated wind-wave field is still propagating aligned with the wind direction. It is also driven into the inlet area, between the mainland and the island, but cannot develop due to the very small fetch.

Fig. 8 gives the complete time series of all energy-density frequency spectra. Thereby, from top to bottom, the SWAN, k-Model, and buoy spectra are plotted. It is important to notice the frequency range, which is 0.04 Hz - 1 Hz for both, k-Model and SWAM, and 0 Hz - 0.6 Hz for the buoy. The frequency axis of the k-Model and SWAN spectra are logarithmically scaled, whereas the frequency axis of the buoy spectra is on a linear scale.

The tidal signal is clearly visible within these time series by the periodically changing spectra. The components of the SWAN spectra are always shifted to higher frequencies than in k-Model spectra. Thereby k-Model spectra are more broad-banded. The measured buoy spectra clearly show an energy distribution over a broader frequency range than the modelled spectra. In the model spectra the energy is mostly concentrated at the spectral peak. Comparing buoy and model spectra gives no clear advantages for SWAN or k-Model.

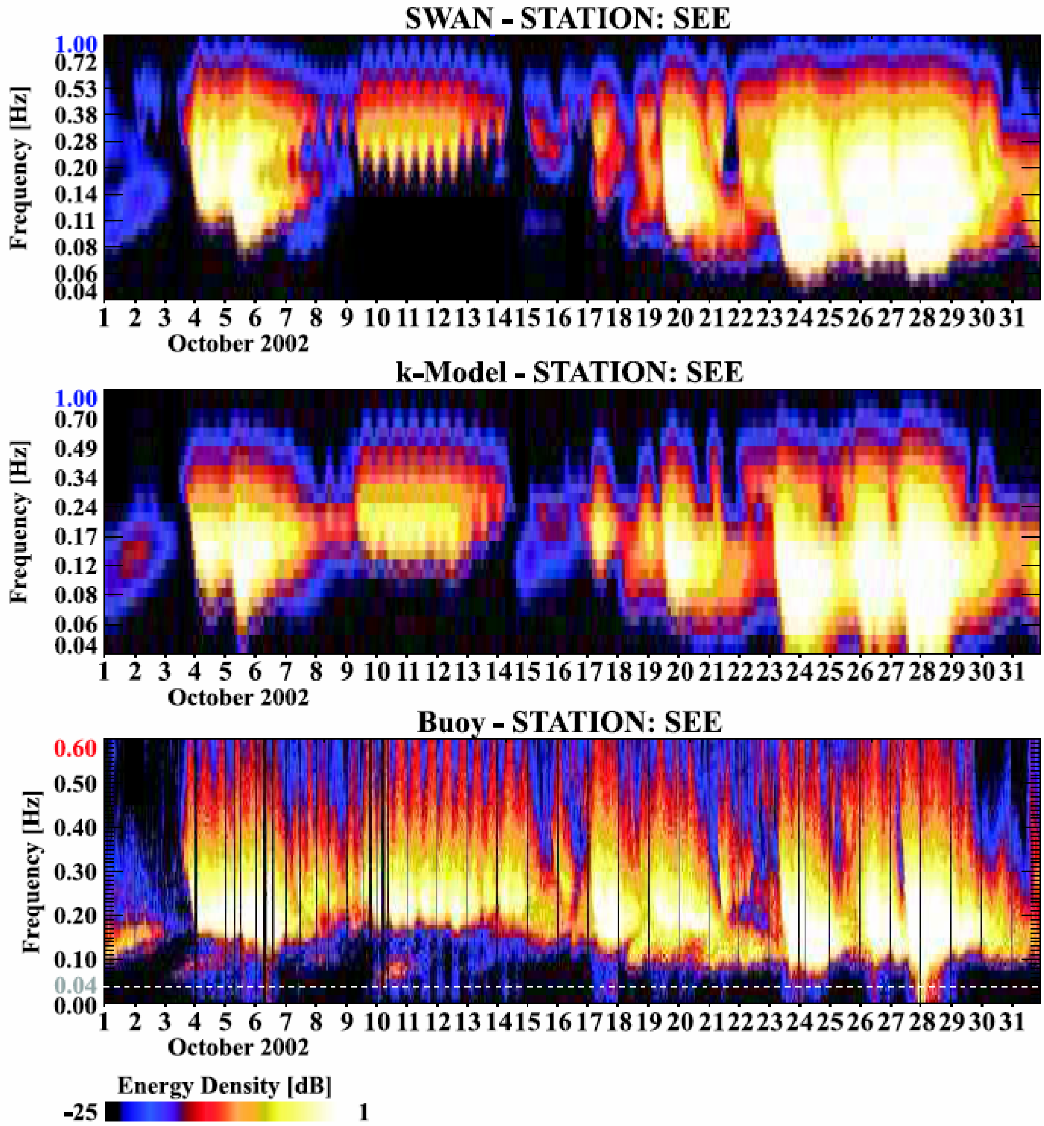

Fig. 8 Time series of all energy-density frequency spectra. From above to below: SWAN, k-Model, and buoy spectra. The frequency axis of the model spectra are logarithmically scaled, buoy spectra are on a linear scale.

6 Conclusions

The present results show that both, k-Model and SWAN, are applicable to small-scale, shallow-water coastal areas with tidal influence.

The HIPOCAS data were used in this work providing wind, water level, and current fields as well as boundary spectra. It could be proved, that these data from the reconstruction on regional scale could be used successfully to force wave models to produce realistic statistics of near shore wave conditions.

The modulation of sea state parameter by tidal change and the connected varying water depths and currents are reproduced by SWAN and k-Model.

Comparison of sea state parameters at different tidal phases shows that wave heights and wave periods are strongly influenced, whereas the mean wave direction is almost not changed by the tides.

A comparison of k-Model and SWAN results, performed under equal conditions for topography, input-data fields, and boundary conditions, shows that wind wave spectra in SWAN are usually more narrow-banded in direction and have a shift to higher frequencies than in the k-Model. This results in an underestimation of wave periods by SWAN compared to k-Model results and buoy measurements. For the significant wave heights the k-Model is underestimating the measured values. However, k-Model results give a smaller standard deviation compared to SWAN. This is caused by the different wave energy dissipation processes characteristics in different water depths. Whereas the k-Model is reducing the energy of longer waves stronger than the SWAN model in intermediate depth of about 20 m the effect is reversed in depth less than 10 m.

7 Acknowledgement

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