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By JORT WILKENS, INGO JUNGE and HELGE HOYME

Summary

As part of the project PROMORPH funded by the German Federal Ministry of Education and Research the calibration, validation and application of four wave models for the central Dithmarschen Bight are presented in this paper. The models have been coupled to flow models, which is necessary for correctly modelling the wave characteristics in this tidal environment. In the calibration and validation measurements taken by five wave buoys over a period of one month were considered. Using the root mean average error (RMAE) evaluation, the model results are qualified as reasonable to good. Considering the complex hydrodynamic patterns and bathymetry of the area this is satisfactory. The validated models have been applied to analyse the wave height distribution over the area during moderate and storm scenarios. It is shown that during moderate conditions in the sheltered eastern part of the domain only locally generated waves with limited heights occur. During storm conditions wave heights may reach 2 m in the eastern part and 5 m near the outer edge of the tidal flats. Furthermore, the significance of wave-induced currents was investigated. It could be shown that the waves have a limited effect on the tidal currents in shallow areas. In the tidal channels the wave-induced currents are negligible. Coupled to the flow models, the wave models form a good basis for the morphodynamic model simulations that have been carried out within the project PROMORPH.

Zusammenfassung

Die vorliegende Arbeit zeigt die Kalibrierung, Validierung und Anwendung von vier Wellenmodellen im Untersuchungsraum der Dithmarscher Bucht. Die Modelle wurden mit Strömungsmodellen gekoppelt, um die Wellencharakteristik in dem tidegeprägten Wattgebiet mit guter Genauigkeit wiederzugeben. Der Kalibrierungs- und Validierungsprozess erfolgte mittels einer einmonatigen Seegangsmessung, die Aufzeichnungen von fünf Messbojen umfasst. Die erzielten Ergebnisse können unter Berücksichtigung der komplexen Strömungscharakteristik und der anspruchsvollen Bathymetrie als gut bezeichnet werden, was durch Ermittlung des „root mean average error“ (RMAE) belegt wird. Die validierten Modelle wurden anschließend eingesetzt, um die Wellenverteilung im Untersuchungsgebiet bei mäßigen Wetterbedingungen und unter Berücksichtigung eines Sturmereignisses zu ermitteln. Die Analyse der Wellenhöhen zeigt, dass bei moderaten Wetterbedingungen das Wellenfeld im östlichen, geschützten Teil des Untersuchungsgebietes allein lokal generierte Wellen enthält. Bei Sturmverhältnissen können die Wellenhöhen in diesem Abschnitt bis zu zwei Meter anwachsen. Am westlichen Rand des Wattgebietes erreichen die Wellen Maximalwerte um fünf Meter. Im Weiteren wurde der Einfluss der welleninduzierten Strömungen näher untersucht. Im westlichen Modellgebiet bei geringen Wassertiefen ist der Einfluss begrenzt, in den tieferen Tiderinnen sogar vernachlässigbar gering. Es lässt sich festhalten, dass die im Folgenden vorgestellten Modelle in der Lage sind, die beobachtete Wellencharakteristik in angemessener Weise zu reproduzieren. Gekoppelt mit entsprechenden Strömungsmodellen bilden sie die Grundlage für die weiterführenden morphodynamischen Simulationen im Rahmen des Forschungsprojektes PROMORPH.

Keywords

Wave Modelling, Wadden Sea, Dithmarschen Bight, Promorph, Calibration, Validation, RMAE, COWADIS, HISWA, SWAN, TOMAWAC, DELFT3D, TELEMAC, PROMORPH

Contents

1. Introduction

The objective of this investigation was to set up and optimise several wave models to be used as modules of morphodynamic models for the central Dithmarschen Bight in the southeastern North Sea (for details refer to HOYME, 2002 and WILKENS, 2004). Therefore, a focus was placed on the distribution of wave energy between the exposed western edge of the domain and the sheltered eastern part. Due to the fact that the wave models were to be applied in medium scale morphodynamic simulations, the computational requirements formed a restricting factor for their spatial and spectral resolution. The models were optimised through calibration on the basis of the results of several one-day periods during a one-month field campaign using five Wave Rider buoys. The analysis of the field data is described in Section 2. Consequently, their performance was evaluated in the validation process considering the entire measurement period. Several scenarios were simulated after a successful validation in order to investigate the significance and characteristics of waves in the study area.

A total of four wave models were set up. These models and their characteristics are the topic of Section 3. In Section 4 the set-up of the coupled flow-wave models is presented. This is followed by a description of the calibration and validation in Section 5. The validated wave models were applied to investigate the wave characteristics during moderate and storm conditions. Furthermore, the effect of wave induced currents on the main current regime was examined. These investigations are discussed in Section 6. In Section 7 the conclusions are given.

2. Field Data

For evaluation of the coupled flow-wave models, field data of bathymetry, water levels, waves and wind were considered.

Bathymetric data from 1995 to 1997 with varying coverage of the study area that were made available by the Federal Maritime and Hydrographic Agency (BSH) in Hamburg were used to generate the model bathymetries. Gaps were filled with bathymetric data from 1986 through 1993, provided by the Office of Rural Development (ALR) in Husum.

The ALR also provided the water level data for various stations that were used for the evaluation of the flow model results.

Field measurements of waves considered in this study were made available by the Coastal Research Station at Norderney and the Office of Rural Development in Husum, Germany. These measurements had been obtained using 5 waverider buoys deployed in September and October 1996 (KFKI project 'Bemessung auf Seegang' (grant number KFKI 45), funded by the German Ministry of Education and Research (BMBF) under grant number MTK 0561, NIEMEYER, 1997). 20-Minute records have been taken at hourly intervals. The locations of the buoys are shown in Fig. 1.

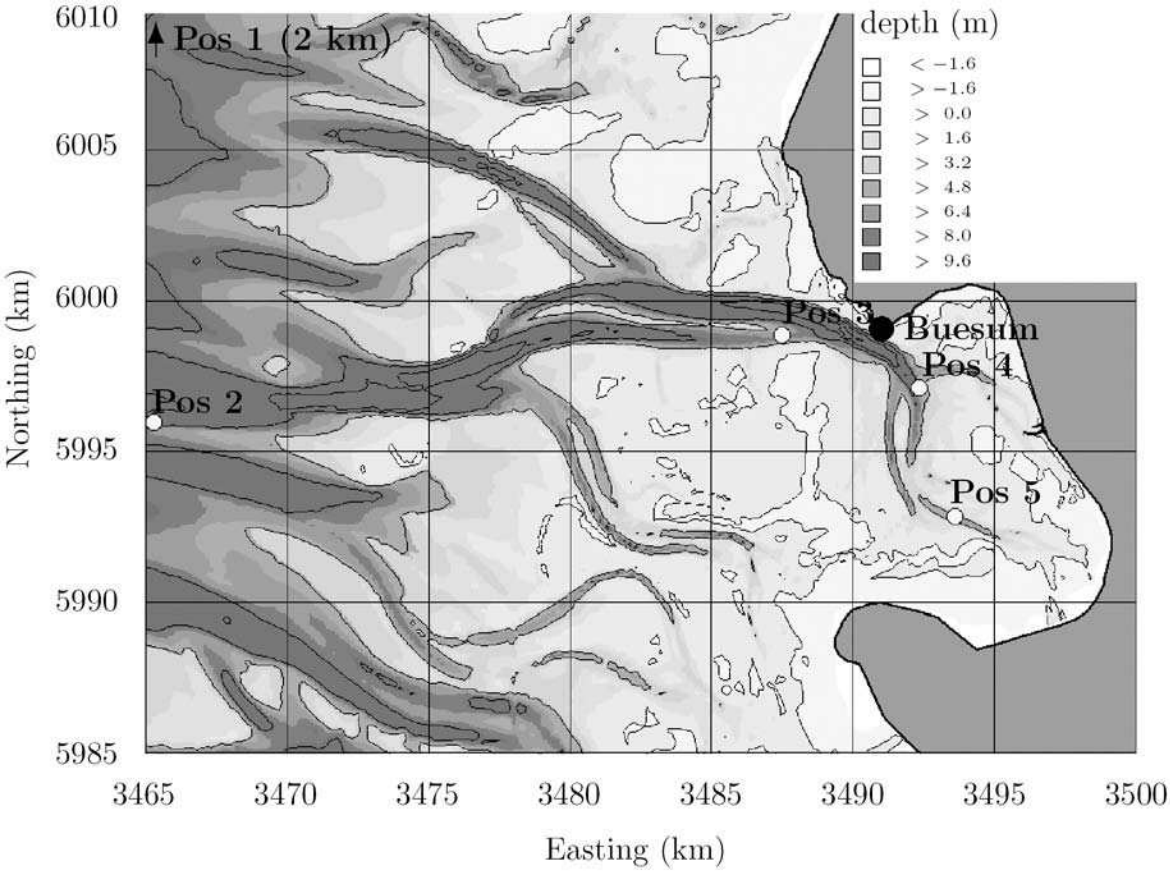

Fig. 1: Location of the wave measurements, taken during September and October 1996

The analysis of the wave data resulted in time series of significant wave height as shown in Fig. 2. Maximum values can be seen at the beginning and end of the observation period. They reach 2 m at Pos 1 and Pos 2, and up to 0.7 m at Pos 3, Pos 4 and Pos 5. During the intermediate period the waves are much lower. The wave heights at the western buoys are much higher than those of the three eastern buoys, due to the sheltering effect of the tidal flats.

Further wave data from two buoys near the study area taken during the storm event Anatol (see Section 6.3) were made available by the BSH.

Synoptic wind data sets were generated by using the PRISMA interpolation model developed by the Max Planck Institute of Meteorology (MPI-M) in Hamburg (LUTHARDT, 1987). This model creates temporally (every three hours) and spatially (approx. 42 km-spacing) varying wind fields from a large set of measurement locations along the coastline and offshore. Comparison of the synoptic model results to wind measurements at the Research and Technology Centre Westcoast (FTZ Büsum) for a period of 8 years confirmed the good quality of the PRISMA model, as shown in Fig. 3 (WILKENS, 2004). Due to the grid spacing of the PRISMA model, the selected output location was some 20 km westward (offshore) from Buesum. Together with the fact that the measurement station in Buesum is somewhat sheltered from westerly and northerly winds (pers. comm. Mr. Vanselow, FTZ Buesum) simulated values are slightly higher than measured ones (< 10 %).

Wind speed and direction in the study area as produced by the PRISMA model are shown in Fig. 4 for the wave observation period. It is apparent that calculated wind velocities are higher (up to 15 m/s) at the beginning and end of the period, corresponding to the peaks in the time series of significant wave heights of Fig. 2. The wind came from northwest during the beginning and from west during the end of the investigation period, causing sufficient fetch for waves to build up. The relatively strong wind in between, coming from the east, did not result in waves, as high as those by wind coming from the West. This is confirmed by the fact that the two western buoys do show some increase in wave height, related to the presence of a (limited) fetch, whereas the eastern buoys show no significant wave action.

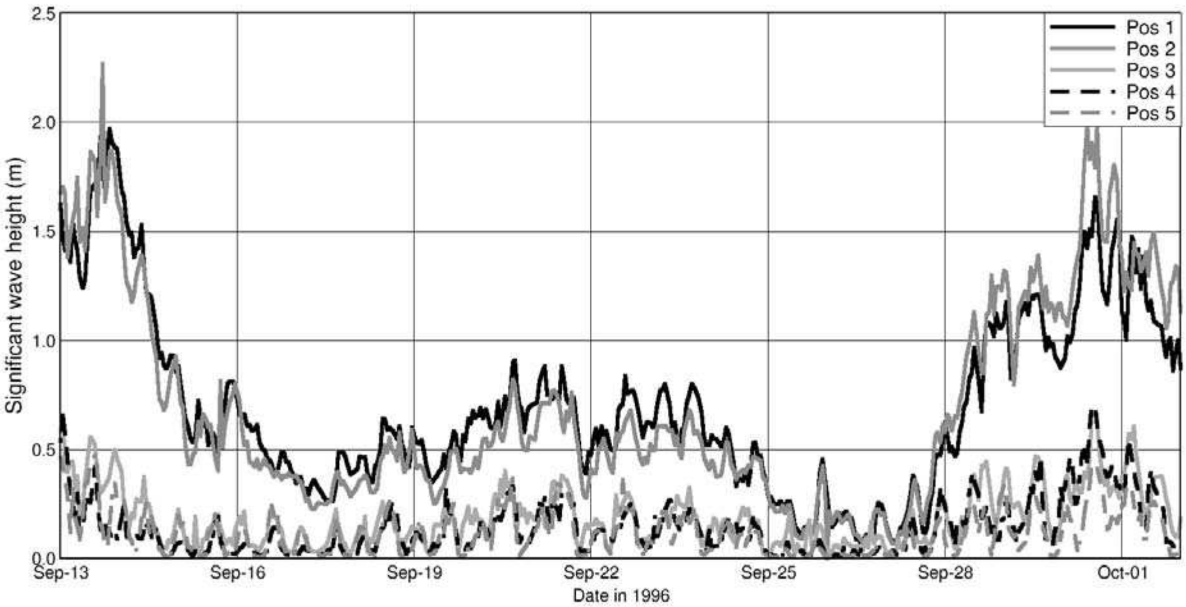

Fig. 2: Significant wave heights at the five wave buoys (data from NIEMEYER, 1997)

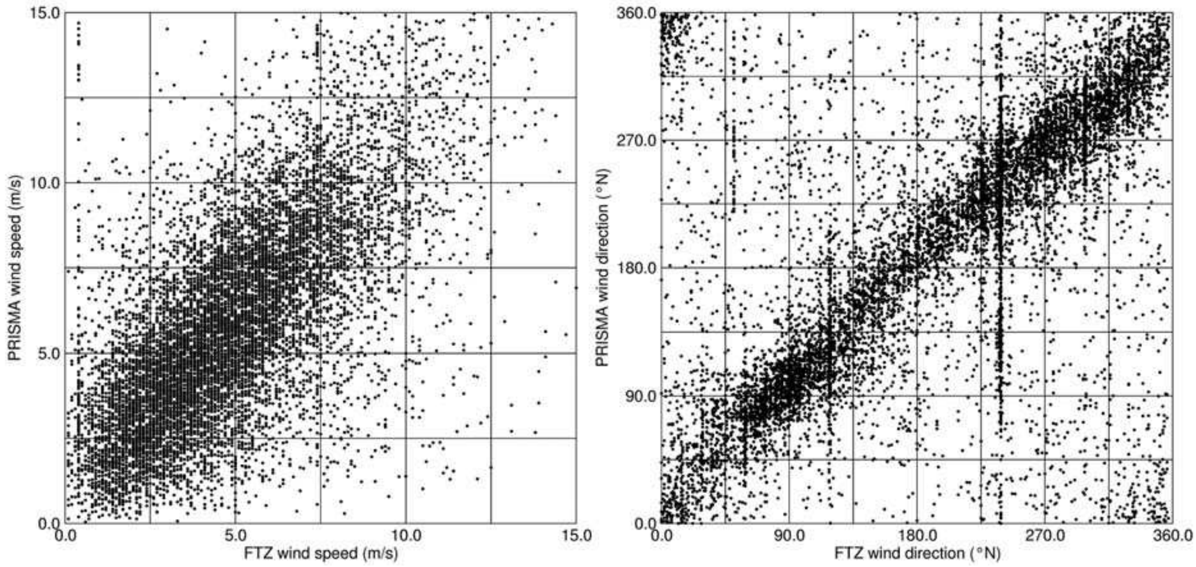

Fig. 3: Comparison between measured and PRISMA wind speed and direction at Büsum between March 1991 and December 1998 (WILKENS, 2004)

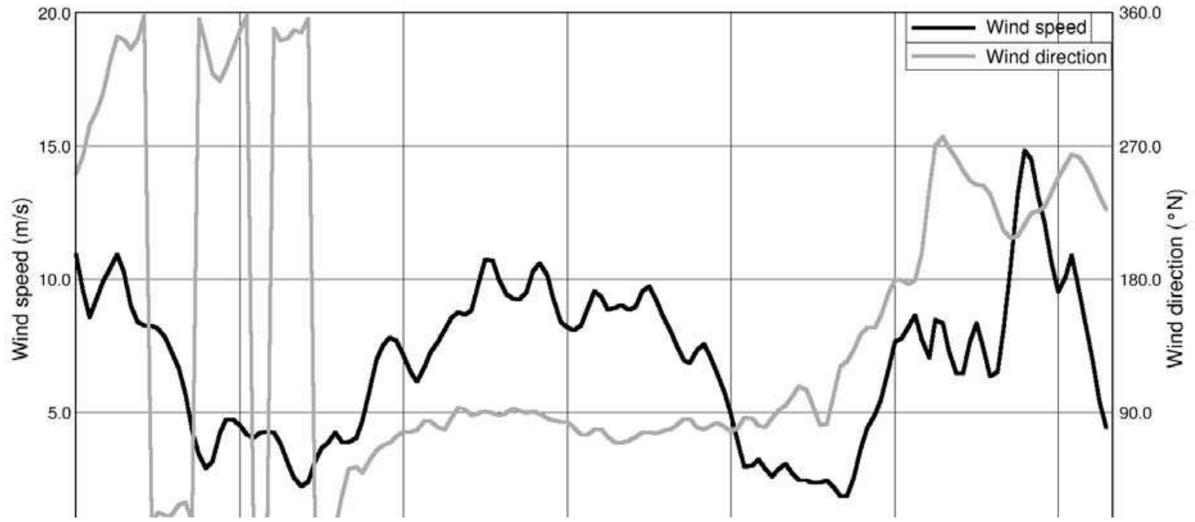

Fig. 4: Wind speed and direction during the wave measurement campaign. Based on the PRISMA interpolation model by LUTHARDT (1987)

3. Description of The Applied Wave Models

For a correct representation of the wave characteristics in the Meldorf Bight several phase-averaged wave models have been applied. Because of the influence of strong tidal currents in the channels as well as of varying water depths – particularly on and near tidal flats and shoals – all wave models were coupled to a flow model. Thus the ambient flow conditions are taken into account in the wave models.

The first two models used in the course of the investigation were set up within the DELFT3D modelling system, developed by Delft Hydraulics in the Netherlands (ROELVINK and VAN BANNING, 1994). The first was the wave model HISWA (HOLTHUIJSEN et al., 1998), the other one on the SWAN wave model (BOOIJ et al., 1999; RIS et al., 1999). These models have been developed at Delft Technical University in the Netherlands. The third and fourth wave model, COWADIS and TOMAWAC (BENOIT et al., 1996), are modules of the TELEMAC modelling system, developed by the Laboratoire National d'Hydraulique of the Electricité de France (refer to HERVOUET, 2000; GALAND et al., 1991). TELEMAC-2D provides the basis for currents and water levels and takes into account flow-wave interaction.

The HISWA wave model is a second generation stationary wave model that includes shoaling, refraction, wind-induced wave generation and energy dissipation due to wave breaking and bottom friction. The model is based on a parameterised formulation of the wave spectrum in the frequency domain and can only be applied on rectilinear grids.

The wave model SWAN is a third generation wave model, capable of simulating wave propagation, refraction, shoaling, wind-induced generation and dissipation due to white-capping, depth-induced wave breaking, bottom friction and wave-wave interactions. The model is fully spectral, meaning that it solves the spectral action balance for a specified number of directional sectors and frequency intervals. The model can be applied on both rectilinear and curvilinear grids.

The COWADIS wave model reproduces refraction due to the seabed and ambient currents, wave generation by wind, energy dissipation due to bottom friction, depth-induced wave breaking, white-capping and non-linear interactions, on a finite element grid.

The wave model TOMAWAC is a third generation wave model solving the balance equation of the action density directional spectrum, similar to the SWAN model. The main physical processes taken into account are wind shear stress, wave propagation, depth-induced refraction, shoaling, interaction with unsteady currents, non-linear wave-wave interactions and energy dissipation due to whitecapping, bottom friction, depth-induced wave breaking and wave blocking. Processes which are not included by the model are diffraction, reflection and wave blocking due to wind. It is noteworthy that in the present TOMAWAC release the COWADIS model is completely integrated. The user can activate the stationary model by choosing the steady parameterized mode. Otherwise the wave simulation is processed in the instationary third generation mode. In both cases the model runs on an unstructured triangular mesh.

The main characteristics of the four applied wave models are summarised in Table 1.

Table 1: Summary of the characteristics of the applied wave models

Model	SWAN	HISWA	COWADIS	TOMAWAC
Structure	Finite difference	Finite difference	Finite elements	Finite elements
Time dependency	Stat./instat.	Stationary	Stationary	Instationary
Frequency domain	Differentiated	Parametrical	Parametrical	Differentiated
Spectral shape	–	JONSWAP	JONSWAP	–
Direction domain	Differentiated	Differentiated	Differentiated	Differentiated
Refraction	Yes	Yes	Yes	Yes
Diffraction	No	No	No	No
Wind generation	Yes	Yes	Yes	Yes
Bottom friction	Yes	Yes	Yes	Yes
Depth-ind. breaking	Yes	Yes	Yes	Yes
Wave blocking	Yes	No	No	Yes
White-capping	Yes	No	Yes	Yes
Non-lin. interaction	Yes	No	Yes	Yes

4. Set-Up and Sensitivity Analysis

Only the HISWA model requires a grid orientation approximately parallel to the incident wave direction. Therefore, several grids have to be generated to cover the entire directional sector needed to represent these wave directions. The number of grids was varied in a sensitivity analysis. The sensitivity analysis for all applied models led to a basic configuration and a shortlist of calibration parameters.

For moderate conditions within the range of the field data (up to 2.5 m significant wave heights at the western edge of the domain, near Pos 1 and 2) the effect of waves on water levels and currents is limited, especially when considering that in a significant part of the investigation area strong tidal currents occur (see also Section 6.2). Therefore, a single forward coupling of the flow model to the wave model (solid lines in Fig. 5) was considered sufficient. For extreme conditions a second loop (dotted lines in Fig. 5) may be necessary when the wave-induced effects on the flow cannot be ignored. The coupling is schematically shown in Fig. 5.

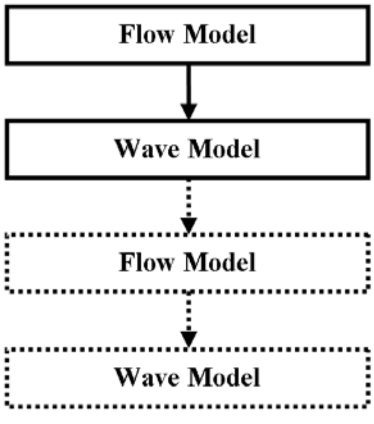

Fig. 5: Schematics of interaction between the coupled flow and wave models

Because of the different grid structures (see Table 1) and requirements, the horizontal extent and resolution vary. In Fig. 6 and Fig. 7 the grids for the COWADIS, TOMAWAC and the SWAN model are shown. The COWADIS and TOMAWAC grid is identical to the TELEMAC flow model grid whereas the SWAN model grid operates on the same grid as the DELFT3D flow model. Thus, interpolations during the information transfer between the flow and wave models are avoided. The rectilinear grid used for HISWA (not shown) consists of a large and a small grid for each direction. While the large grid covers the entire curvilinear flow grid, and provides the boundary conditions for a smaller high-resolution grid, the latter only covers the domain of interest. Due to geometrical differences between the HISWA wave grids and the flow grid, interpolations take place for the information transfer, constituting a source of inaccuracy. The grid resolutions of the four models are listed in Table 2. The COWADIS and TOMAWAC grids have the highest resolution concentrated on the eastern-most part of the domain (in Fig. 6). The SWAN and HISWA models cover a larger area, with the resolution increasing towards the area of interest with its tidal channels and flats (Fig. 7).

Within the DELFT3D modelling system, wave modelling can be carried out in stationary mode only, even though SWAN also contains an instationary. In combination with the TELEMAC system COWADIS can only be applied in stationary mode, too. A stationary model can produce satisfactory results when the time of wave propagation through the model domain is short in comparison with the time scale of the variation of the driving forces wind and swell. For the West-East domain length of approximately 30 km and typical wave speeds of 5 to 10 m/s, the wave conditions should remain relatively stable for a minimum period of 1 to 1.5 hours. This assumption holds for the available field data, considering the temporal resolution of the wind data and associated level of detail of the model evaluation, i.e. changes of wave characteristics on a time scale smaller than the temporal variability of the imposed wind data should not be evaluated. The variations in the tidal conditions, that are significant on a shorter time scale, are taken into account through the computational interval of one hour for the stationary models.

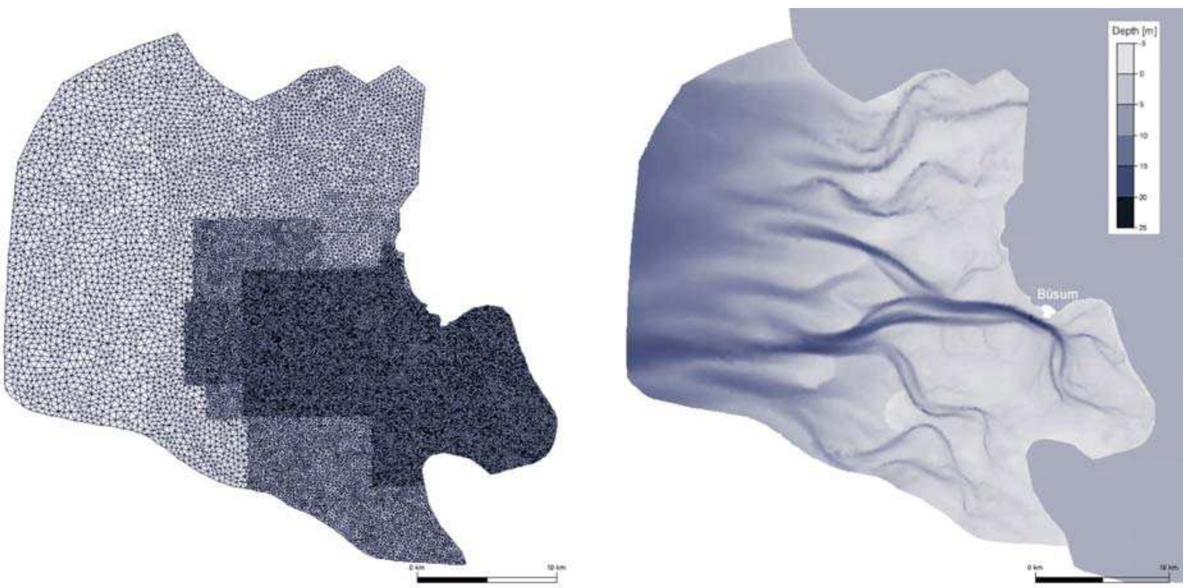

Fig. 6: Grid and bathymetry of the COWADIS, TOMAWAC and coupled TELEMAC flow model

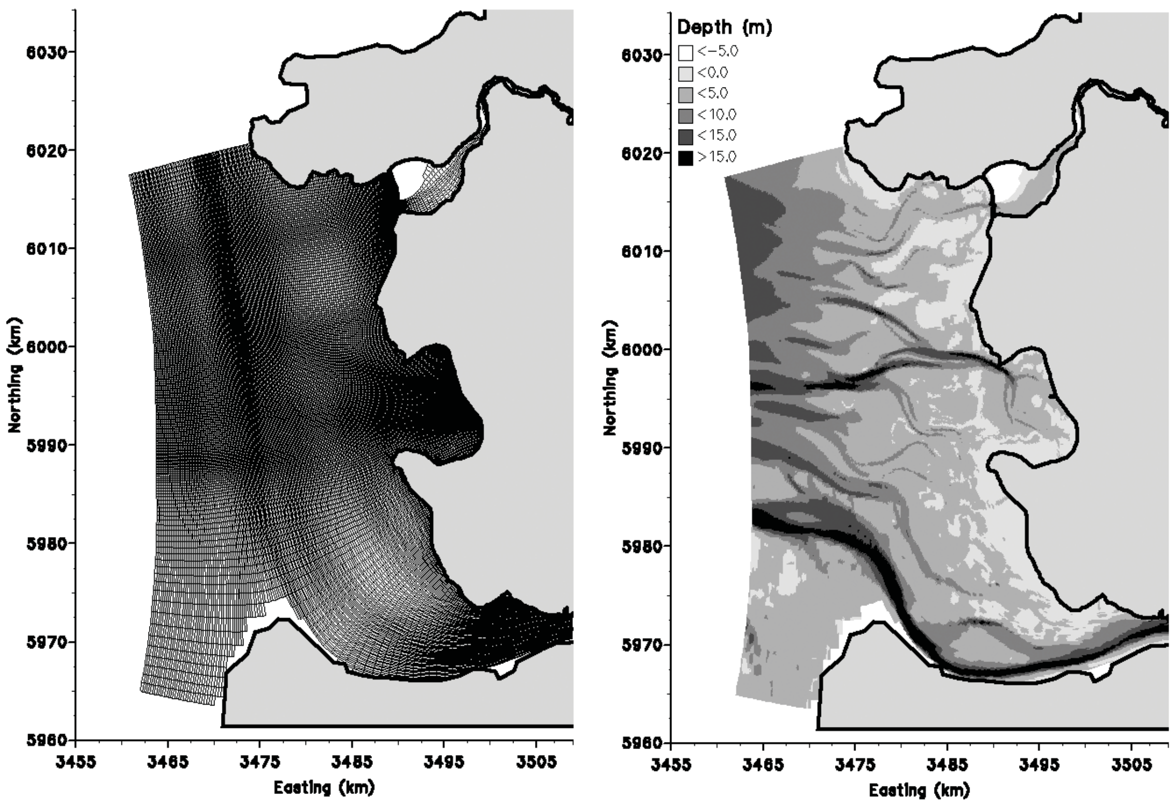

Fig. 7: Grid and bathymetry of the SWAN and coupled DELFT3D flow model

The spatial as well as the spectral resolution varies between the applied models. COWADIS and HISWA are parameterised in the frequency domain, i.e. a frequency-integrated energy and a mean frequency are computed rather than resolving the wave energy variation in the frequency domain, as the SWAN model does. All three models, however, solve the energy distribution over the directional space. The spectral resolution of the models was also defined on the basis of sensitivity analyses and is listed in Table 2.

Table 2: General settings of the applied wave models

Model	SWAN	COWADIS	HISWA	TOMAWAC
Cell size (m)	80–600	Triangles, 30–80	100–500	Triangles, 30–80
Time dependency	Stationary	Stationary	Stationary	Instationary
Frequency interval	~ 0.1 Hz (log.dist.)	–	–	~ .01 Hz (log.distr.)
Direction interval	15 degrees	30 degrees	10 degrees	30 degrees
Calculation interval	1 hour	1 hour	1 hour	–

5. Calibration and Validation of the Wave Models

5.1 HISWA and SWAN

In the calibration of the HISWA model only wave heights and directions were considered, for the SWAN model the peak periods have been analysed as well. Wave data from the outer buoys (Pos 1 and 2) were used as boundary values for the HISWA model, whereas the

SWAN model has been nested in a SWAN model for the German Bight. These German Bight model results were verified with the field data from the outer buoys. Fig. 8 and Fig. 9 show the measured and computed wave heights and periods at Pos 2. The main advantage of model nesting rather than imposing the field data directly is that periods outside the measurement period can be simulated as well. For the evaluation of the model performance the buoys in the inner part of the investigation area (Pos 3, 4 and 5 in Fig. 1) were considered.

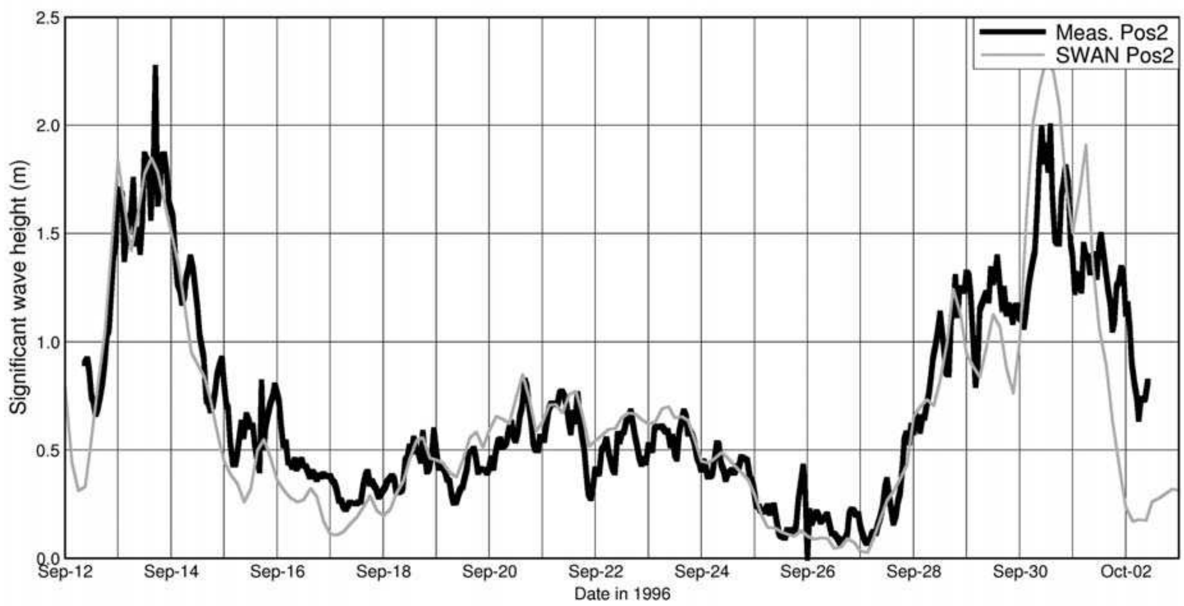

Fig. 8: Measured and computed significant wave heights at Pos 2, using model nesting

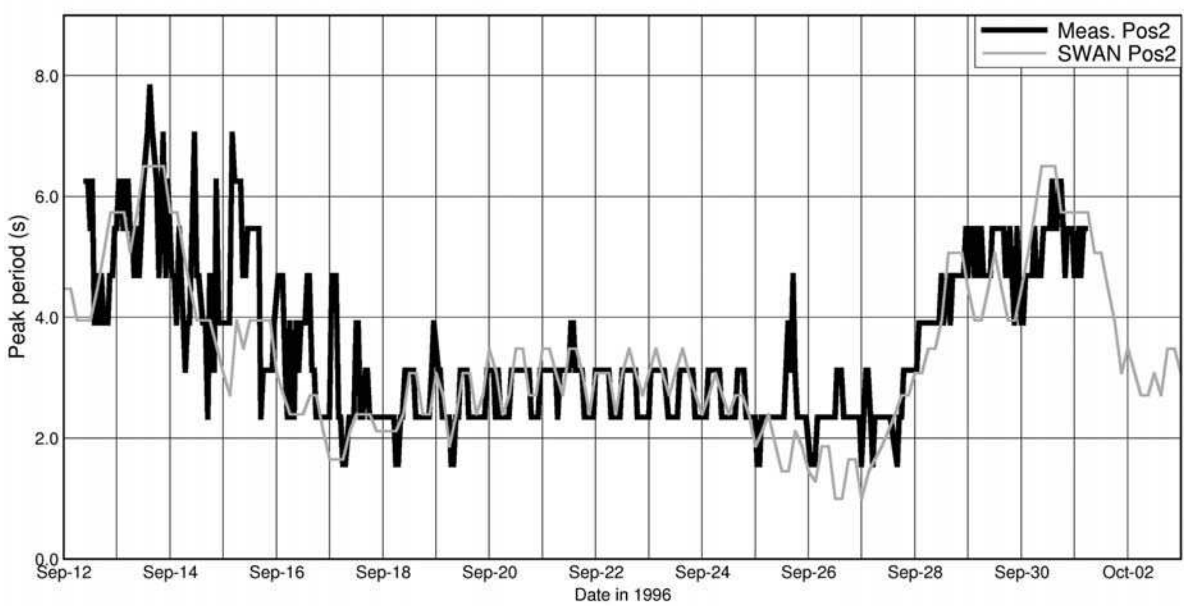

Fig. 9: Measured and computed peak periods at Pos 2, using model nesting

For calibration, five one-day periods with varying conditions were selected. Since the main objective of this study was to create a reliable wave model for deployment within a morphodynamic model, the computational efforts had to be kept within limits. Therefore, an increase of the horizontal and spectral resolution was not considered, although this might have improved the results through a more detailed representation of the bathymetry and local current patterns near the wave buoy locations. Main improvements could be made by tuning the bottom friction. Varying other parameters such as wave breaking and directional diffusion led only to insignificant improvements. The calibration study also led to the conclusion that an interval of one hour between the wave calculations was acceptable for the considered period. The variations in the ambient currents and water levels as well as the encountered wind conditions did not permit a larger interval.

On the basis of optimised model settings, the models were validated for the entire length of the field campaign. In a strict sense, the one-day calibration periods should have been excluded for validation of the models. However, they were included in the one-month simulation in order to obtain an uninterrupted overview of model quality during the entire period. The results of the validation are discussed in Section 5.3.

5.2 COWADIS and TOMAWAC

The calibration process of COWADIS was similar to that of HISWA. The procedure for the instationary TOMAWAC model, however, is different. During the simulation, the boundary conditions have been generated by the model in form of a JONSWAP-spectrum under considering of wind input (PRISMA data) and a presetting of a 250 km fetch length. For this reason, the calibration of TOMAWAC is based predominantly on data collected at wave buoys Pos 1, 2 and 3 (refer to Fig. 1).

5.3 Validation Results

The comparison between observed and computed wave heights of all four models, divided into three sections for more clarity, is shown in Fig. 10 to Fig. 12 for Pos 3 to 5. Fig. 13 to Fig. 15 show the comparison of the measured and computed peak periods (SWAN only).

All models reproduce the trend in wave height development quite well. HISWA reproduces the lower wave heights rather well, whereas SWAN shows good results for the higher wave heights (with some overpredictions). COWADIS shows good results for moderate wave conditions but under-predicts relatively high waves. The peak periods are somewhat underestimated by the SWAN model, however, they generally follow the observed trends in a good manner. The underestimation of the peak periods is a well-known problem of the SWAN model (ROGERS et al., 2003). Although TOMAWAC tends to under-predict low wave heights it does reproduce the observed trends and peak values. This is particularly true under easterly winds. It has to be mentioned again that the wave boundary conditions for this model were obtained by using wind input generated by the PRISMA model with a spatial resolution of approximately 42 km.

Although some discrepancies between the modelled and observed wave heights were found, generally speaking all models produce acceptable results for the entire period. Considering the relatively low waves, the complex bathymetry together with the strong ambient currents, the results are rather good.

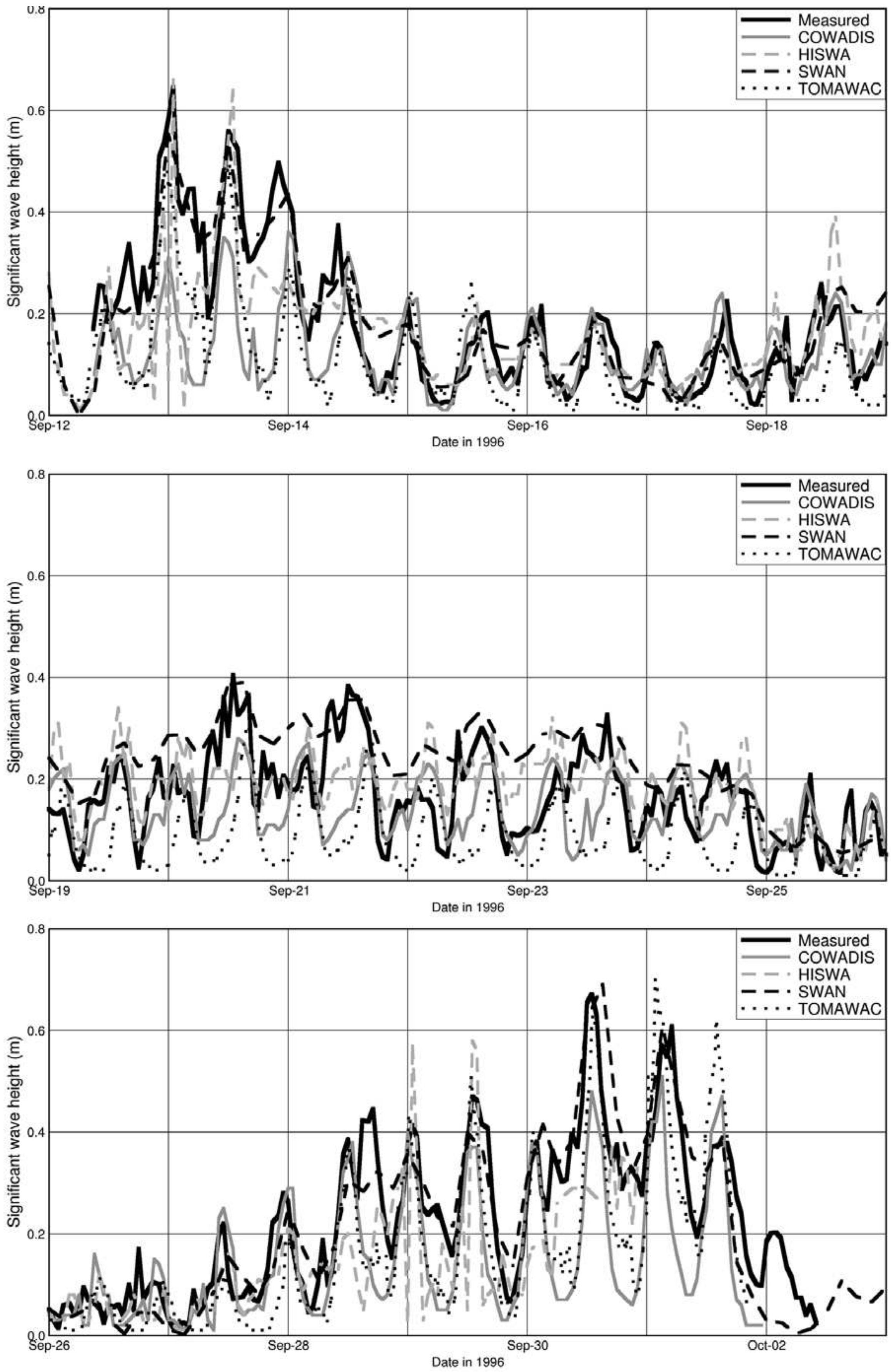

Fig. 10: Measured and computed significant wave heights at Pos 3 after model calibration

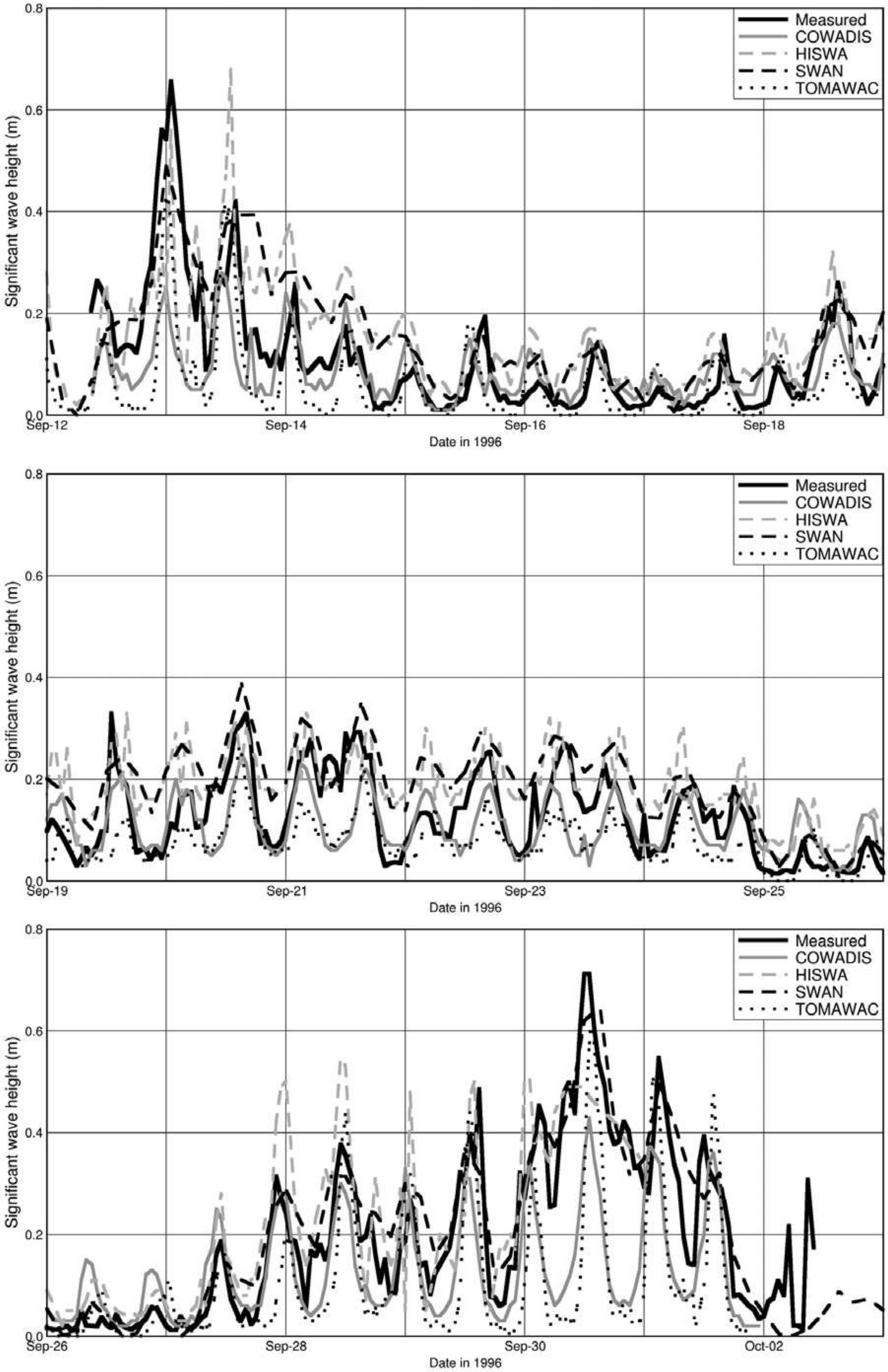

Fig. 11: Measured and computed significant wave heights at Pos 4 after model calibration

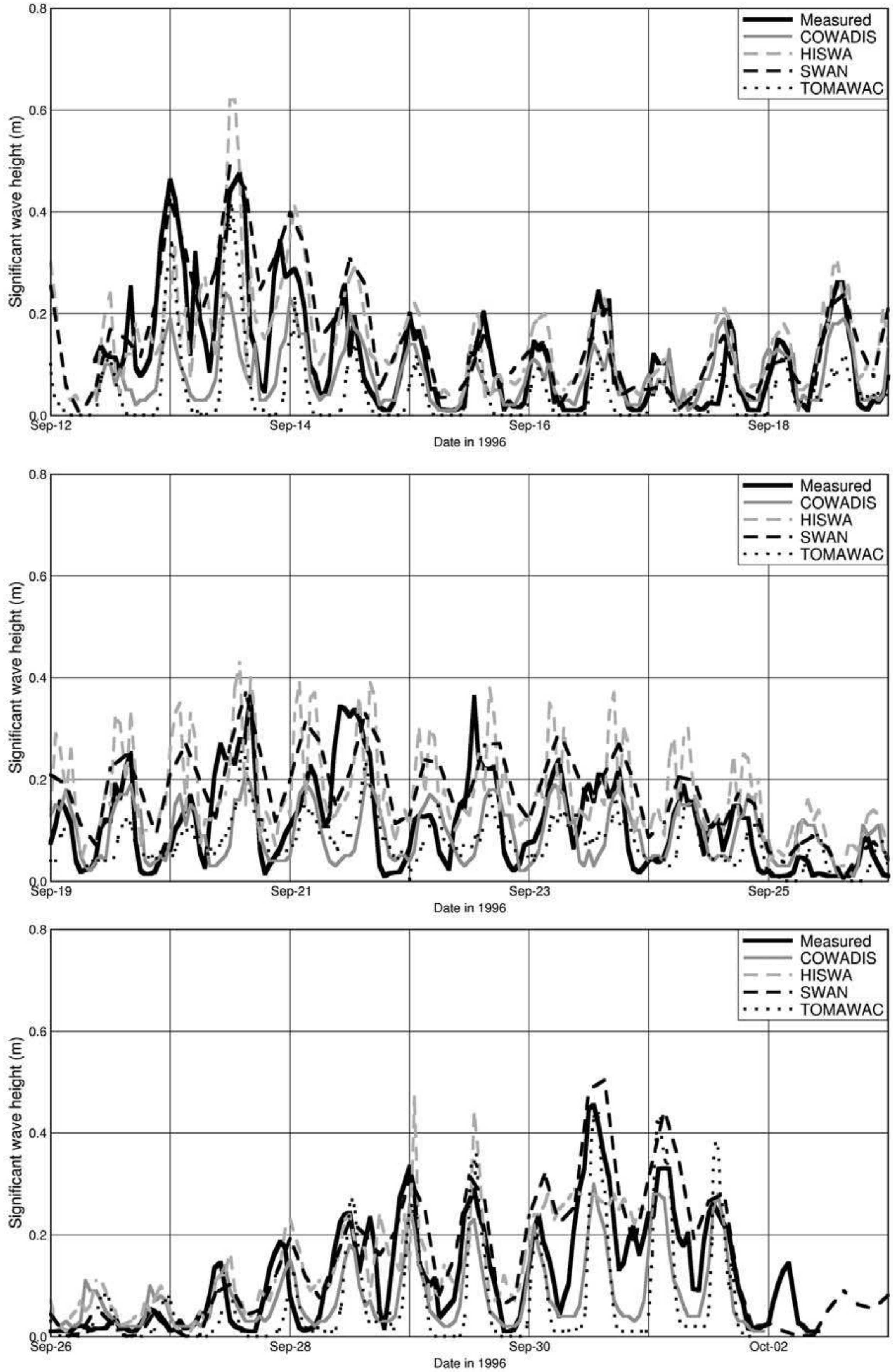

Fig. 12: Measured and computed significant wave heights at Pos 5 after model calibration

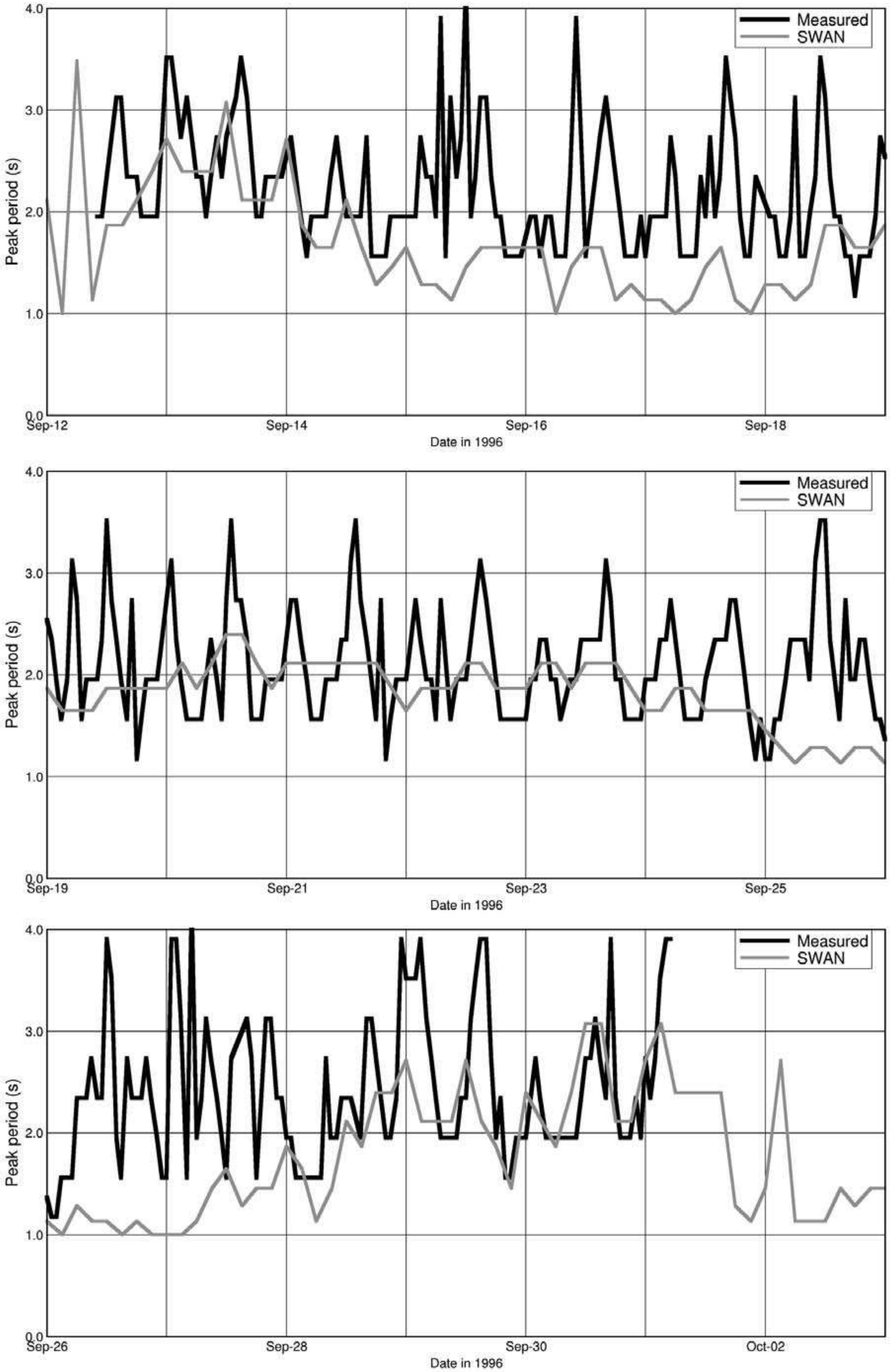

Fig. 13: Measured and computed peak periods at Pos 3 after model calibration

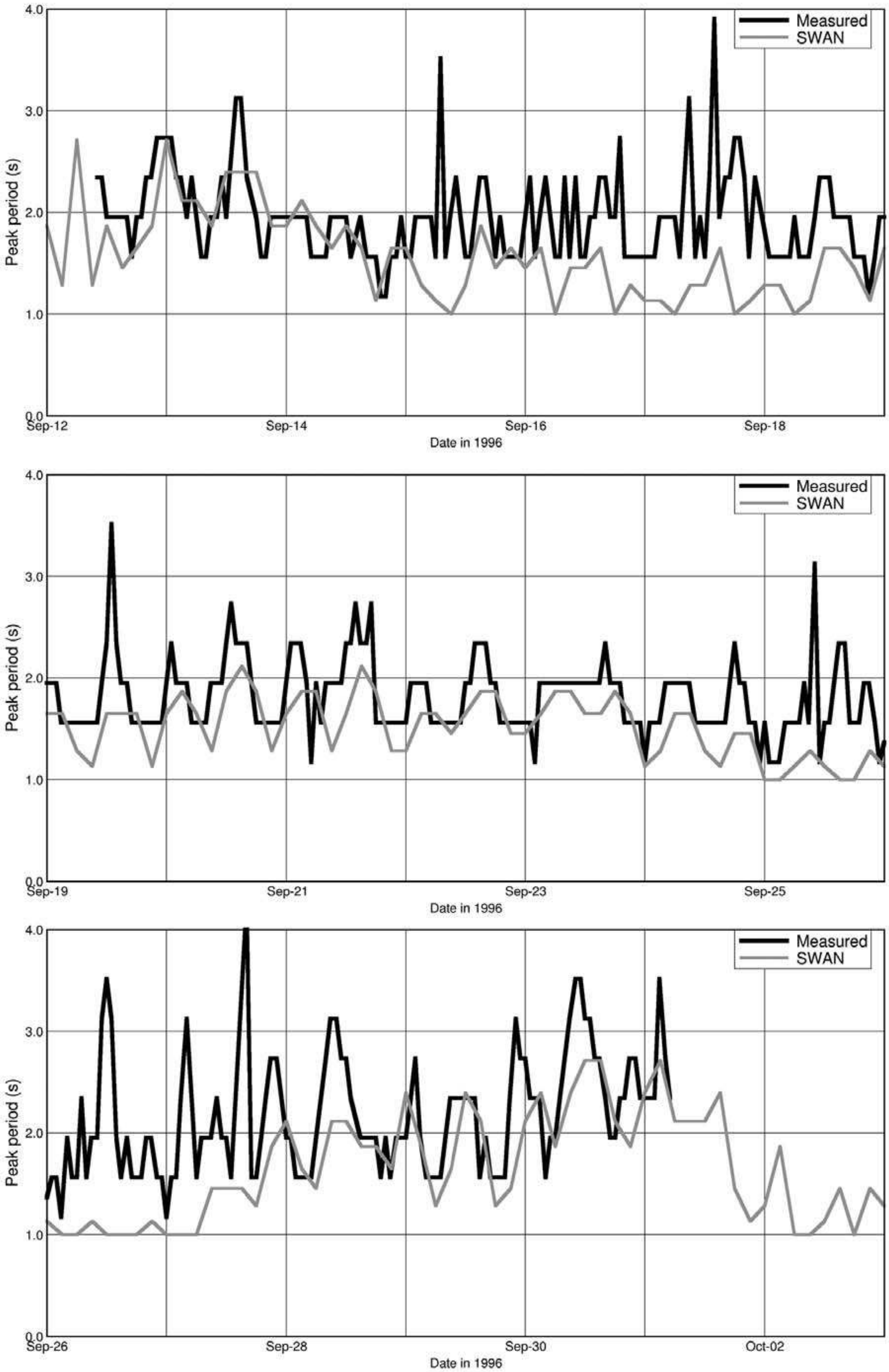

Fig. 14: Measured and computed peak periods at Pos 4 after model calibration

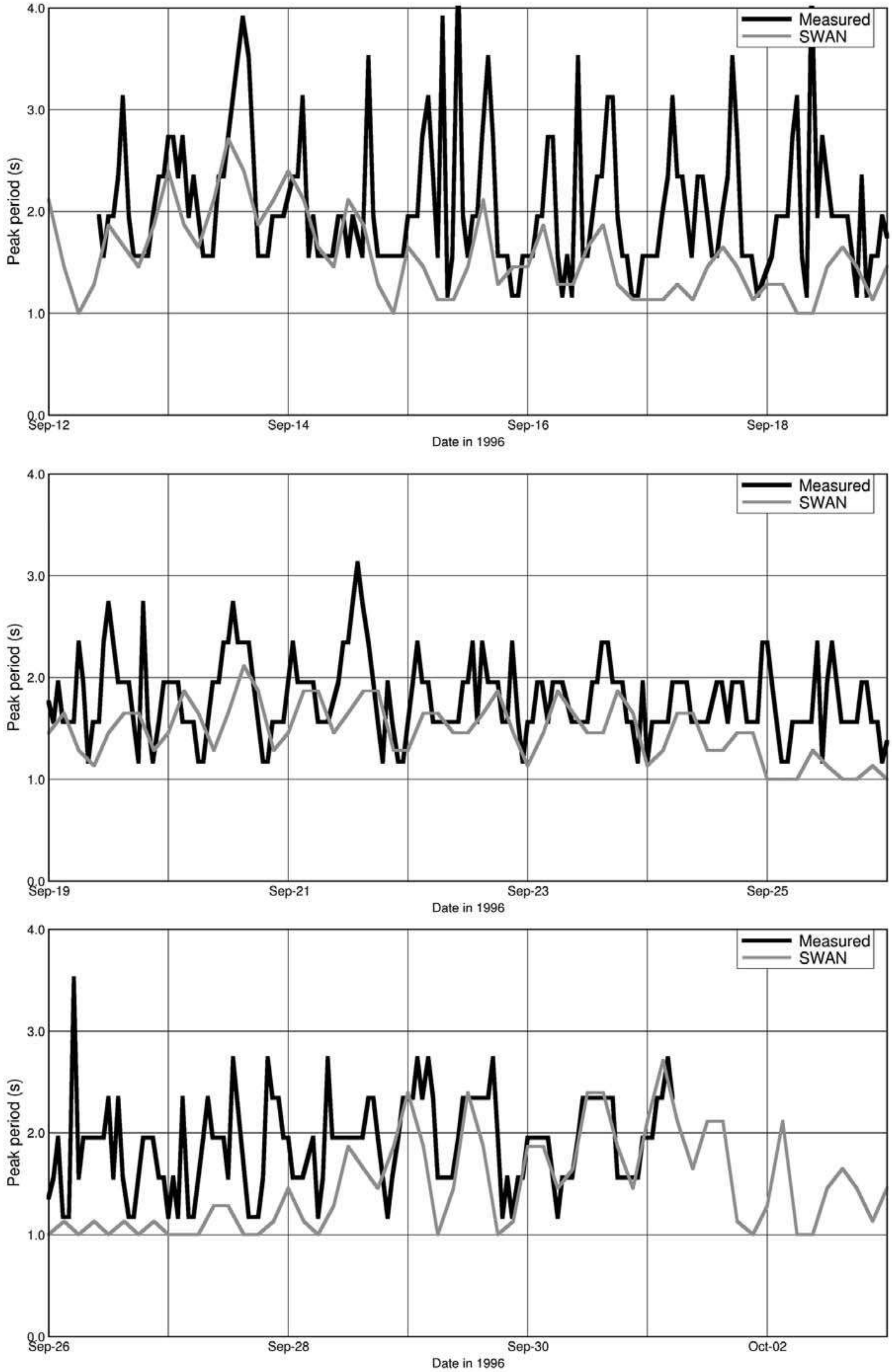

Fig. 15: Measured and computed peak periods at Pos 5 after model calibration

To evaluate the results more objectively than through visual comparison, the approach by VAN RIJN et al. (2002) was adopted in which the discrepancy between the computed and measured parameters is quantified through the relative mean absolute error (RMAE). The RMAE is defined as:

$$RMAE = \frac{\max\{|P_c - P_m| - \Delta P_m, 0\}}{\overline{P}_m}$$

with:

P_m = measured parameter (either wave height or period);

P_c = computed parameter; and

ΔP_m = inaccuracy of the measured parameter (value of 0.1 m respectively 0.3 s have been assumed).

The operator and denominator are averaged over the evaluation period. VAN RIJN et al. (2002) define the model quality based on the RMAE value for the significant wave heights as shown in Table 3. No such qualification is presently available for wave periods.

Table 3: Quality of simulated wave heights based on RMAE values (VAN RIJN et al., 2002)

Qualification	**RMAE value**
Excellent	< 0.05
Good	0.05 – 0.10
Reasonable / fair	0.10 – 0.20
Poor	0.20 – 0.30
Bad	> 0.30

Fig. 16 shows scatter plots of the modelled and measured significant wave heights at the three eastern wave buoys for the models COWADIS, HISWA and SWAN. The corresponding RMAE values are indicated in the top-left corner. In Fig. 17 the scatter plots of the peak periods are shown for the SWAN model, together with the RMAE values. Since the TOMAWAC model evaluation was carried out using data for Pos 1, Pos 2 and Pos 3, the corresponding scatter plots are shown in Fig. 18.

As can be seen, the quality index of the four wave models varies between "reasonable" and "good". The obtained RMAE values and the scatter plots confirm the findings based on the time series comparison. The SWAN model results show an over-prediction of the higher wave heights, especially for Pos 4 and Pos 5. The COWADIS and HISWA model show good results for the lower wave heights. The scatter plots of the peak periods show that the SWAN model underpredicts the wave periods, a general problem of SWAN for low-frequency energy (see for example ROGERS et al., 2003).

The TOMAWAC model shows good results for Pos 1 and Pos 2 and is less accurate for Pos 3. Once more considering the complex bathymetry and current patterns, the results are satisfactory.

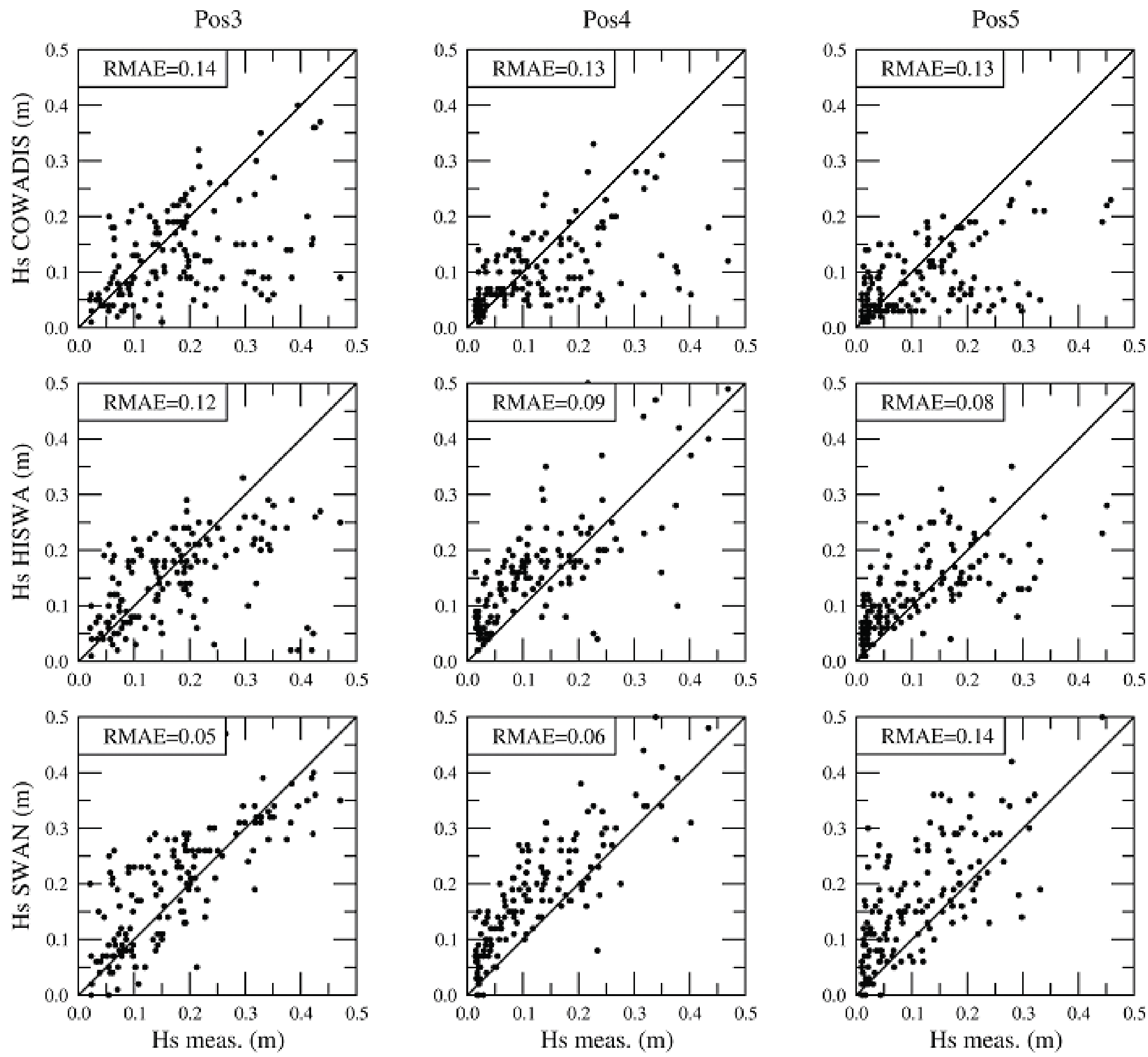

Fig. 16: Modelled vs. measured wave heights at Pos 3, 4 and 5 for COWADIS, HISWA and SWAN

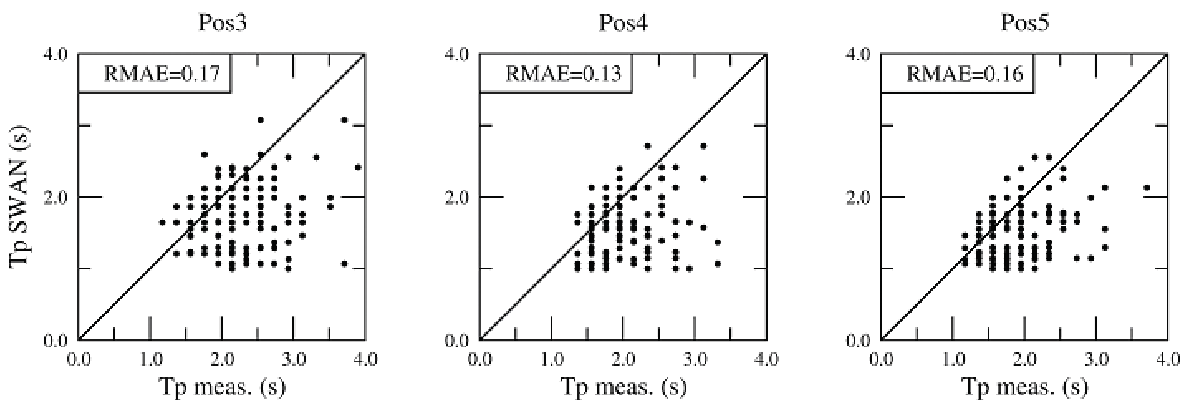

Fig. 17: Modelled vs. measured peak periods at Pos 3, 4 and 5 for SWAN

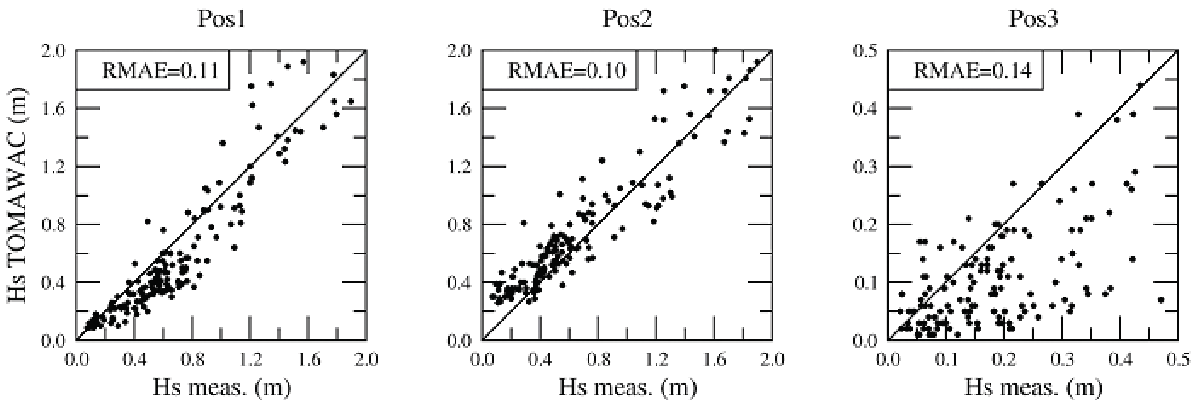

Fig. 18: Modelled vs. measured significant wave heights at Pos 1, 2 and 3 for TOMAWAC

6. Application of the Wave Models

The two third generation models SWAN and TOMAWAC were applied to analyse the behaviour of waves in the investigation area. Analysis results are discussed hereafter. Firstly, the wave fields at representative instants in the tidal cycle are presented and show the general distribution of the sea state over the area. The DELFT3D-SWAN model was applied for this purpose. Secondly, the impact of wave action on the current velocities was investigated. Results from the coupled TELEMAC-TOMAWAC model with and without waves were compared. Finally, a wave hindcast for the storm event "Anatol" in December 1999 was carried out with the DELFT3D-SWAN model. The wind conditions of this event were fed into the entire nesting sequence from the North Sea model, over the German Bight model to the Dithmarschen Bight model (see Fig. 22). This approach ensured an accurate simulation of the actual storm conditions for the boundary conditions of the Dithmarschen Bight model. The results display a realistic image of wave conditions during a major storm event.

6.1 General Wave Distribution in the Central Dithmarschen Bight

To find out whether the observed sheltering effect of the tidal flats with respect to the location of the eastern buoys is reproduced by the models, the computed spatial distribution of wave heights over the investigation area was analysed. The analysis was carried out for typical points in the tidal cycle, i.e. high water, low water, maximum ebb currents and maximum flood currents. In the following, the wave conditions computed with the SWAN model and covering the first day of the field campaign (September 13th) are discussed. The imposed conditions are listed in Table 4.

Table 4: Conditions considered at the western open boundary

Parameter	Value
H_s	1.5 m
Swell direction	285 °N
Wind speed	10 m/s
Wind direction	315 °N

With these boundary conditions, which have been kept constant during the simulation, and the ambient tidal conditions derived from the flow model the results shown as wave height distributions in Fig. 19 are as follows:

The main wave action is found in the western half of the area domain for all four instants of the tidal cycle. The sheltering effect of the western tidal flats is rather significant, limiting the wave energy in the eastern part of the domain. Wave action in the sheltered part is largely due to locally generated waves, whereas in the western part it is a combination of incoming swell and locally generated waves. These model results are consistent with the observed wave heights. From spectral analysis of the field data of the western buoys double-peaked spectra confirm the different sources of waves at these locations. For the inner buoys, single-peaked spectra indicate only local wave generation as energy source.

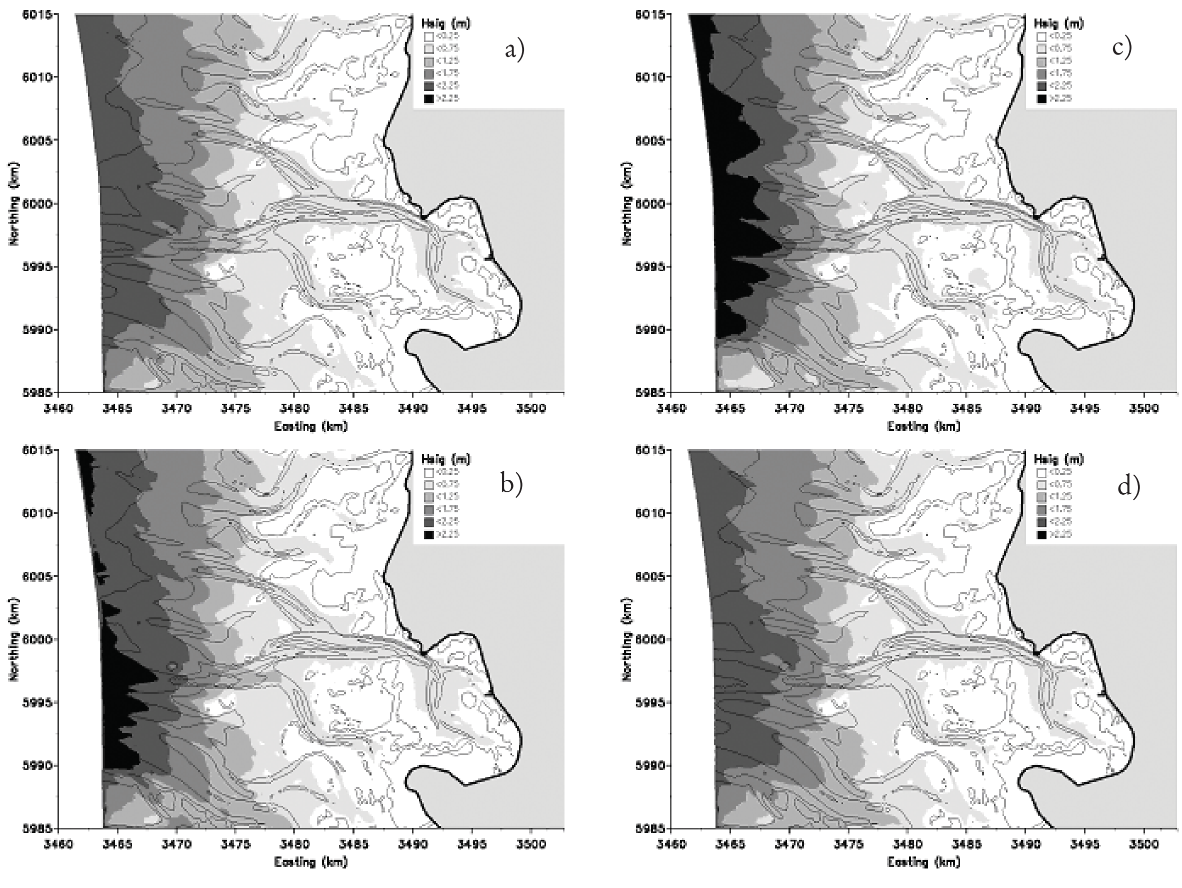

Fig. 19: Modelled significant wave heights during a) high water, b) ebb, c) low water and d) flood

6.2 Investigation of the Significance of Wave-Induced Currents

Waves in the coastal zone are generally an important driving force for sediment transport and, consequently, morphodynamic evolution. While orbital movement stirs up the sediment other wave-induced together with tidal currents will transport sediment over larger distances. To evaluate the importance of waves in this process the calibrated wave models SWAN and TOMAWAC were applied to calculate the wave driven forces for several monitoring points in the area of investigation, shown in Fig. 20. The imposed waves at the open boundary vary between 1 and 3 m.

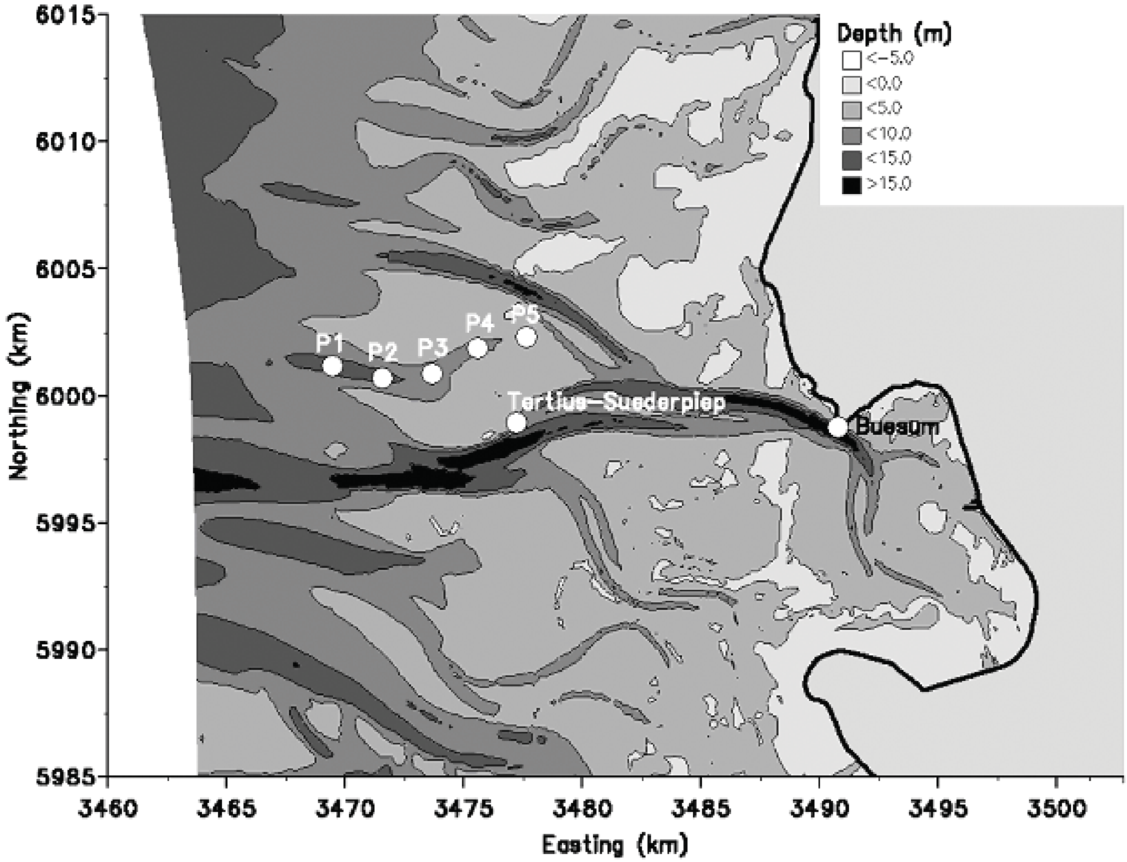

Fig. 20: Location of the monitoring points

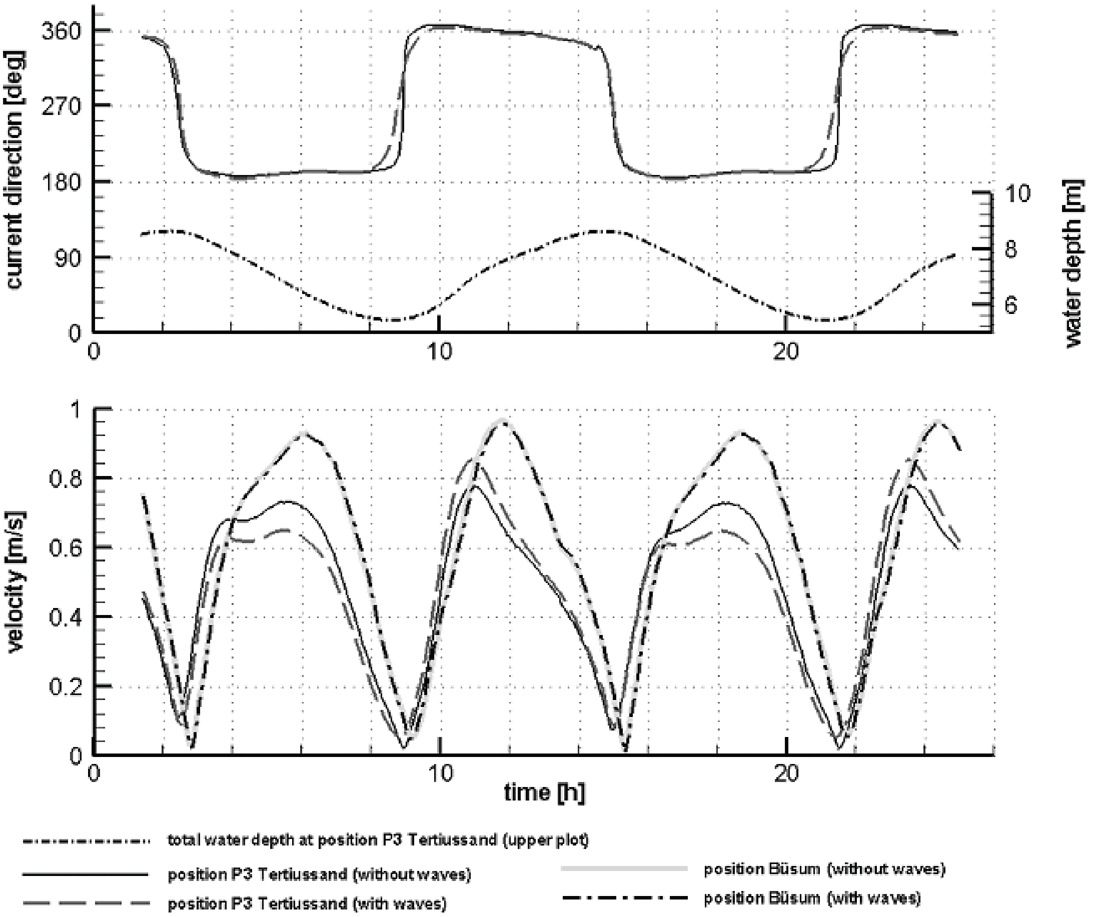

Fig. 21: Wave impact on currents at Tertiussand P 1 and near Büsum

Fig. 21 exemplarily illustrates the computed current velocities with and without wave influence for position P 3 located in a shallow channel on Tertiussand and for a location near Buesum. The results were generated by the wave model TOMAWAC with an imposed wind speed of 15 m/s from the Southwest and a fetch of 200 km. Under these conditions the computed wave heights at the western boundary measure up to 3 m and cause a deviation of the depth-integrated flow velocities up to 0.10 m/s (approximately 15 %) at location P 3. At the monitoring point near Buesum the deviations are negligible due to the large local depth and smaller wave heights. In Fig. 21 the effect on flow directions is also displayed (for point P 3 only). A significant deviation is only observable during slack water.

A similar consideration of the changes at all monitoring points led to the conclusion that the impact of waves on the depth-integrated currents is negligible in the tidal channels for the considered wave conditions. A distinct influence can be seen in both the SWAN and TOMAWAC model results for the considered observation points in shallow water. Simulation results for more moderate wave conditions, with wave heights of 1 and 2 m at the open boundary, have also been analysed (not shown). Wave heights of 1 m have a limited effect even on the tidal flat, whereas those of 2 m show effects similar to but smaller than those presented in Fig. 21, as computed with the TOMAWAC model.

6.3 Hindcast of the Storm Event "Anatol"

The storm "Anatol" occurred in December 1999. An extreme low pressure area moved from West to East over the central North Sea, inducing strong onshore winds. In order to correctly hindcast the hydrodynamic conditions during the storm with the coupled DELFT3D-SWAN model, wind conditions were initially imposed in all three models of the nesting sequence of Fig. 22. This approach resulted in a reasonable hindcast of the storm surge. By hourly updating the wind conditions a satisfactory representation of the storm was ensured. For the TOMAWAC model the flow boundary conditions were also generated by a nesting sequence similar to Fig. 22. During the instationary computation the boundary conditions are updated in a time interval of 15 minutes. The wave boundary conditions are determined with a fetch-based approach under consideration of PRISMA wind data.

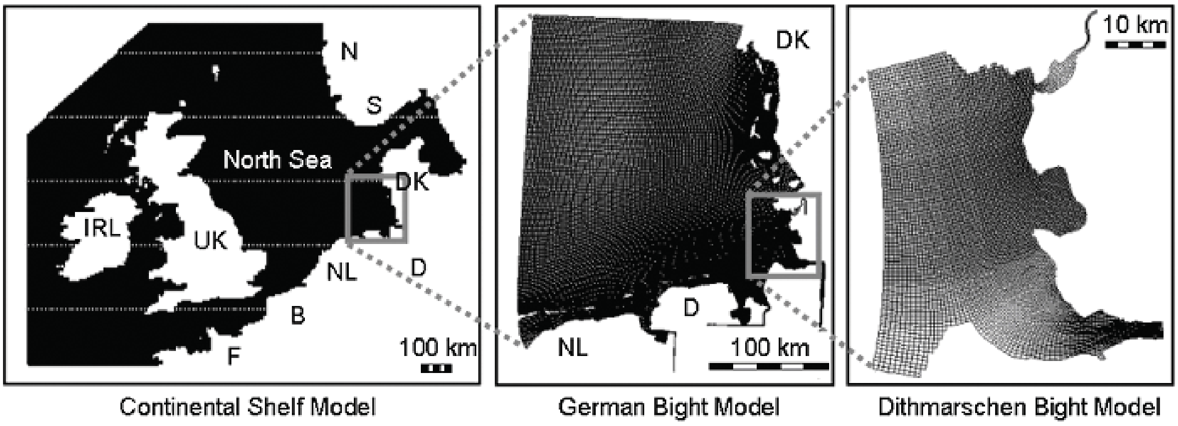

Fig. 22: Nesting sequence for the generation of open boundary conditions

Since the SWAN model within Delft3D can only be run in stationary mode resulting wave heights are based on the actual wind field, and previously generated waves are not considered. A sensitivity analysis on all three grids showed that the inclusion of the Continental Shelf Model, i.e. imposing wave boundary conditions in the German Bight model would not significantly influence the wave fields in the vicinity of the Dithmarschen Bight. Therefore wave modelling was carried out only with the German Bight model and the Dithmarschen Bight model. Currents and water levels have been computed throughout the entire nesting sequence, however.

For the German Bight field data for two locations, one near Heligoland, the other between Heligoland and the mouth of the Elbe were made available by the BSH. Observed and computed wave heights (German Bight model) are shown in Fig. 23. The comparison indicates an under-prediction of wave heights before the storm and too fast a decrease after peak values have been reached. The latter may well be related to the stationary approach. The maximum values as well as the main trends are simulated satisfactorily. Therefore, it can be expected that the German Bight model produces acceptable boundary conditions for the Dithmarschen Bight model.

Wave heights computed with SWAN and TOMAWAC for the locations of the wave buoys Pos 2 and Pos 3 (cf. Fig. 1) are illustrated in Fig. 24. One can see that both models yield similar results. The graph shows that at the western boundary (Pos 2) maximum wave heights reached 5 m whereas at the eastern buoy almost 2 m were computed. Because of the storm surge with elevated water levels the tidal flats did not provide the same sheltering as is typical during moderate conditions.

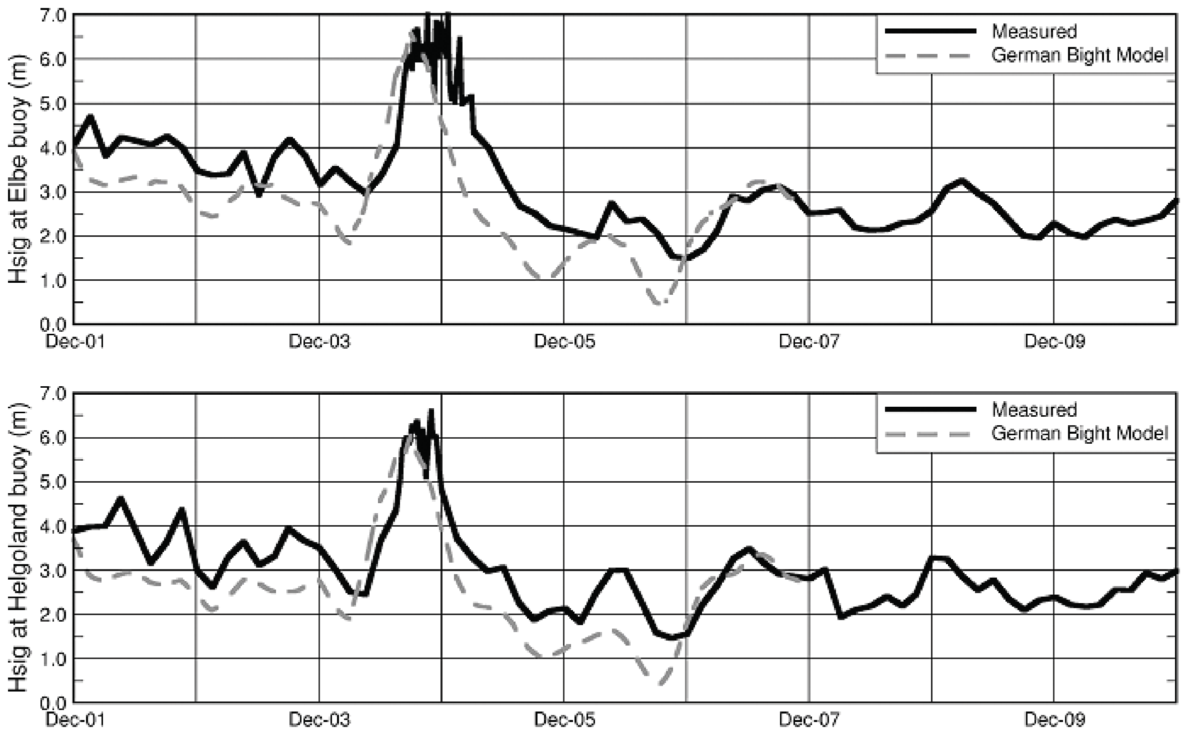

Fig. 23: Observed and computed (German Bight model) wave heights during the storm "Anatol"

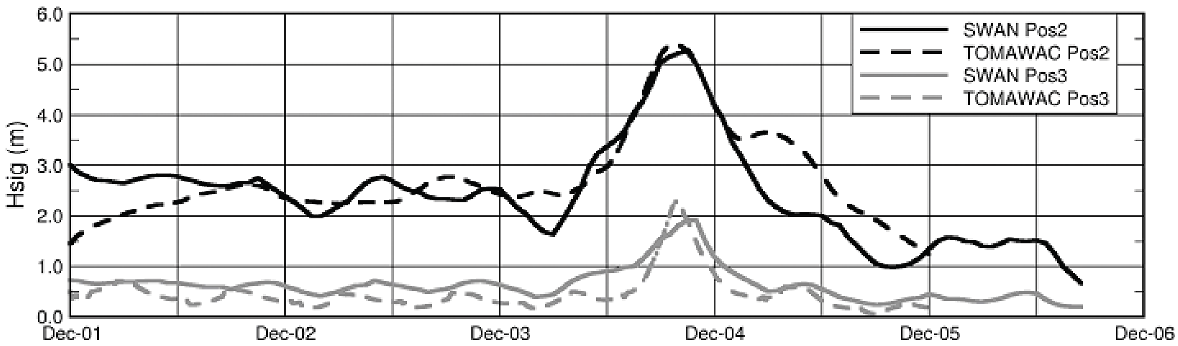

Fig. 24: Hindcast wave heights (storm "Anatol") computed with SWAN and TOMAWAC

7. Discussion and Conclusions

It was shown that the four wave models used in the investigation were able to reproduce the observed wave heights during the one-month measurement period satisfactorily. The quantitative evaluation based on the RMAE parameter showed that the results could be qualified as "reasonable" and "good" for all five locations of the field campaign. Differences between computed and observed data are partly due to the limited spatial and spectral resolution. This limitation was necessary to maintain reasonable computational costs when including the wave modules in medium scale morphodynamic models.

The first application, simulating wave height distribution during a tidal cycle at moderate wind conditions provided a good insight into the wave climate in the area of interest with higher waves near the exposed outer tidal flats and relatively low wind waves in the sheltered eastern part. Hardly any swell enters the sheltered part during moderate conditions.

In the second application, investigations of wave-induced currents showed that even higher waves have only a moderate impact on the depth-averaged currents in shallow-water areas.

Finally, the hindcast of the storm Anatol showed that wave heights up to 2 m may occur even in the sheltered parts of the area. The increase in water level diminishes the natural protection by the tidal flats. Both applied models show similar results.

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