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Hydrodynamic Forcing Along the Open Sea Boundaries of Small-Scale Coastal Models

By ROBERTO MAYERLE, JORT WILKENS, CARLOS ESCOBAR and WIWIN WINDUPRANATA

Summary

This paper deals with hydrodynamic forcing along the open sea boundaries of process-based models for simulating flow and waves in the central Dithmarschen Bight, a tidally-dominated area on the German North Sea coast. The effectiveness of various approaches for determining water levels and waves as open sea boundary input to coastal area models was verified. Comparisons of measured and computed water levels and waves at several locations for a wide range of conditions typical of the study area were carried out in order to verify the performance of the approaches adopted. The results obtained were found to be in good agreement with observations and confirmed the suitability of the different approaches for describing the hydrodynamics in the study area. In the case of the flow model better agreement was obtained using the approach based on water levels measured directly along the open sea boundaries. The mean absolute error in amplitudes and phases at high and low water levels was found to be less than 3 % of the mean tidal range and about 5 % of the tidal period, respectively. Corrections to the results obtained from the north-west European Continental Shelf Model based on measured water levels proved to be quite effective for improving the water levels prescribed along the open sea boundaries of larger models. The open sea boundary conditions for the wave model, which represent incoming swell energy, were defined by directly imposing (parametric) values deduced from measurements at a location along the open boundary and by the application of a model nesting sequence. A comparison between the results of the latter approach and direct measurements showed good agreement. On the basis of the quality standards adopted, the results obtained by applying model nesting were rated as 'good' for significant wave heights and 'reasonable to fair' for peak periods.

Zusammenfassung

Der Beitrag beschäftigt sich mit dem hydrodynamischen Antrieb prozessgebundener Modelle zur Simulation von Strömung und Seegang in der Zentralen Dithmarscher Bucht, einem tidedominierten Seegebiet vor der Deutschen Nordseeküste. Verifiziert wurde die Effektivität verschiedener Näherungen zur Bestimmung von Wasserständen und Wellen als Eingabeparameter für Küstenmodelle an den Offene-Seegrenzen. Um die Leistungsfähigkeit der verwendeten Näherungen zu verifizieren, wurden Vergleiche gemessener und modellierter Wasserstände und Wellen an mehreren Stellen für weites Feld von Bedingungen durchgeführt, die für das Untersuchungsgebiet typisch waren. Die erzielten Ergebnisse wiesen eine gute Übereinstimmung mit den Beobachtungen auf und unterstrichen die Eignung der verschiedenen Näherungen zur Beschreibung der Hydrodynamik im Arbeitsgebiet. Beim Strömungsmodell wurde eine bessere Übereinstimmung erzielt, wenn für die Näherung die unmittelbar an den Offene-Seegrenzen gemessenen Wasserstände verwendet wurden. Der mittlere absolute Fehler bei Amplitude und Phase bei Hochwasser und Niedrigwasser lag unter 3 % des mittleren Tidehubs bzw. bei 5 % der Tideperiode. Die Korrekturen zu Ergebnissen, die aus dem Nordwesteuropäischen „Continental Shelf Model" gewonnen wurden, und auf gemessenen Wasserständen beruhten, erwiesen sich als recht effektiv, um die Wasserstände, die an den Offene-Seegrenzen größerer Modelle vorgegeben sind, zu verbessern. Die Offene-Seegrenze-Bedingungen für das Wellenmodell, die die einlaufende Seegangsenergie repräsentieren, wurden durch ein direktes Einsetzen parametrischer Werte definiert, die aus örtlichen Messungen entlang der Offene-Seegrenze und aus der Anwendung einer Modell-Nesting-Sequenz hergeleitet wurden. Ein Vergleich zwischen den Ergebnissen letzterer Näherung und direkten Messungen zeigte eine gute Übereinstimmung. Gemäß der verwendeten Qualitätsmaßstäbe wurden die Ergebnisse aus dem Modell-Nesting für signifikante Wellenhöhen als „gut" und für die Peakperioden als „befriedigend bis mäßig" eingestuft.

Keywords

Open Sea Boundary, Boundary Conditions, Hydrodynamics, Waves, Modelling, Dithmarschen Bight, Tidal Flats, Tidal Channels, DELFT3D, SWAN, PROMORPH

Contents

1. Introduction

Numerical models of flow and waves are finding increasing application in the management of coastal areas. As these models usually cover only part of the coastal area under investigation, open sea boundaries with the enclosed sea are introduced to limit the size of the modelled domain and hence reduce computational effort. Open sea boundaries are virtual "water-water" boundaries representing the influence of the sea area surrounding the modelled domain. The predictive capability of process-based models of coastal areas depends very much on an adequate description of environmental forcing along the open sea boundaries. In order to avoid a predominant influence of environmental forcing on model results the open sea boundaries are usually specified at a sufficiently large distance away from the area of interest. The type of open sea environmental forcing applied in practice often depends on the available data. Measured values or the results of simulations performed with larger-scale models covering the adjacent sea area are usually used for this purpose.

This paper summarizes the results of investigations carried out to verify the effectiveness of the approaches usually adopted for determining water levels and waves as open sea boundary input to process-based flow and wave models is verified. Several approaches were tested for a coastal area on the German North Sea coast. Comparisons between measured and computed water levels and waves at several locations along the open boundaries and within the modelled domain were made for a wide range of conditions typical of the study area in order to verify the quality of the various approaches.

2. Study Area and Process-Based Models

The study area considered in the present investigation is the central Dithmarschen Bight on the German North Sea coast, located between the Elbe and Eider estuaries (Fig. 1).

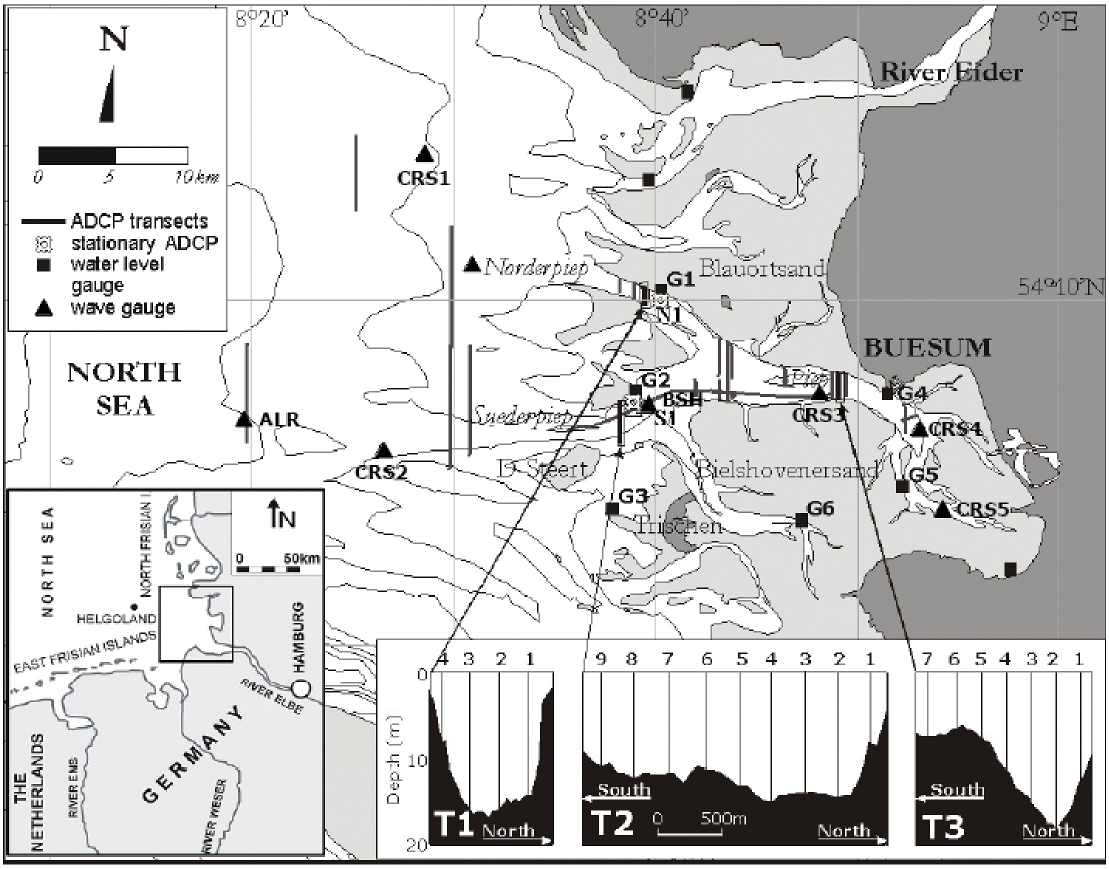

Fig. 1: Investigation area (Dithmarschen Bight) and location of gauge stations

The hydrodynamics of the central Dithmarschen Bight are not directly influenced by the discharges of these rivers, as extensive tidal flats separate these systems from the study area. Two major tidal channels, namely the Norderpiep and Suederpiep, connect the bight with the open sea. These channels intersect within the domain to form the Piep tidal channel. These channels attain a width of up to 4 km, with maximum depths of about 20 m. Approximately 50 % of the study area is inter-tidal and the entire area is submerged during high tide.

The hydrodynamics and sediment dynamics in the study area are driven by the combined effects of tides, waves and winds. The mean tidal range in the region is about 3.2 m. The propagation direction of the tidal wave is normal to the western boundary of the Dithmarschen Bight, with an easterly and westerly tidal flow during the flood and ebb phases, respectively. Wave heights of up to 4 m are observed in the outer region of the investigation area. Under normal conditions, however, the influence of waves on the flow field is moderate on the tidal flats and negligible in the tidal channels. Wave breaking generally occurs along the edge of the tidal flats. Wind effects may include the afore-mentioned wind-induced wave generation as well as the forcing of wind-driven currents. The enhanced wave action and currents may initiate additional sediment transport and alter the patterns of sediment dynamics.

Within the framework of the research project PROMORPH, process-based models for simulating flow, waves, sediment transport and bed level changes have been developed and subsequently calibrated and validated using field data. The aim of the project was to develop a modelling system for predicting medium-scale morphological changes in the central Dithmarschen Bight. Several curvilinear grids adjusted to the bathymetry of the study area were developed. Two-dimensional depth-averaged (2DH) flow and sediment transport models based on the DELFT3D modelling system developed by Delft Hydraulics in the Netherlands (ROELVINK and VAN BANNING, 1994) as well as the phase-averaged spectral wave model SWAN (BOOIJ et al., 1999; RIS et al., 1999) were implemented in the project. Confirmation of the good quality of the model results for flows is given in PALACIO et al. (in this volume); for waves in WILKENS (2004) and WILKENS et al. (in this volume); for sediment transport in WINTER et al. (in this volume) and for morphodynamics, in WILKENS (2004), WILKENS and MAYERLE (2004) and JUNGE et al. (in this volume).

Fig. 2 shows the computational grid and local bathymetry of the Dithmarschen Bight Model (DBM) indicating the limits of the two nested models, namely the Central Dithmarschen Bight Model (CDBM) and the Extended Central Dithmarschen Bight Model (ECDBM). Flow simulations were carried out for all three domains whereas wave simulations were only performed for the larger domain. The size of the CDBM is approximately 20 km by 17 km and covers an area of about 300 km^2. The offshore boundary of the CDBM lies about 14 km west of Buesum. The computational grid of the CDBM consists of about 30,000 cells with a grid spacing ranging from 60 m to 180 m. In view of the intense morphological changes that occur along the western open sea boundary of the CDBM, particularly on the sand banks and outer tidal flats (see WILKENS et al., 2001), the model was extended a further 14 km westwards. The resulting ECDBM measures 35 km by 17 km and covers an area of approximately 520 km^2. The computational grid of the ECDBM consists of almost 36,000 cells with a grid spacing ranging between 90 m and 180 m. The good performance of the flow models is documented in PALACIO et al. (2001) and PALACIO et al. (in this volume).

In order to simulate waves and medium-scale morphodynamics in the study area an even larger model domain was found to be necessary (WILKENS et al., 2001). By extending the ECDBM in the northward and southward directions it was possible to reduce the influences

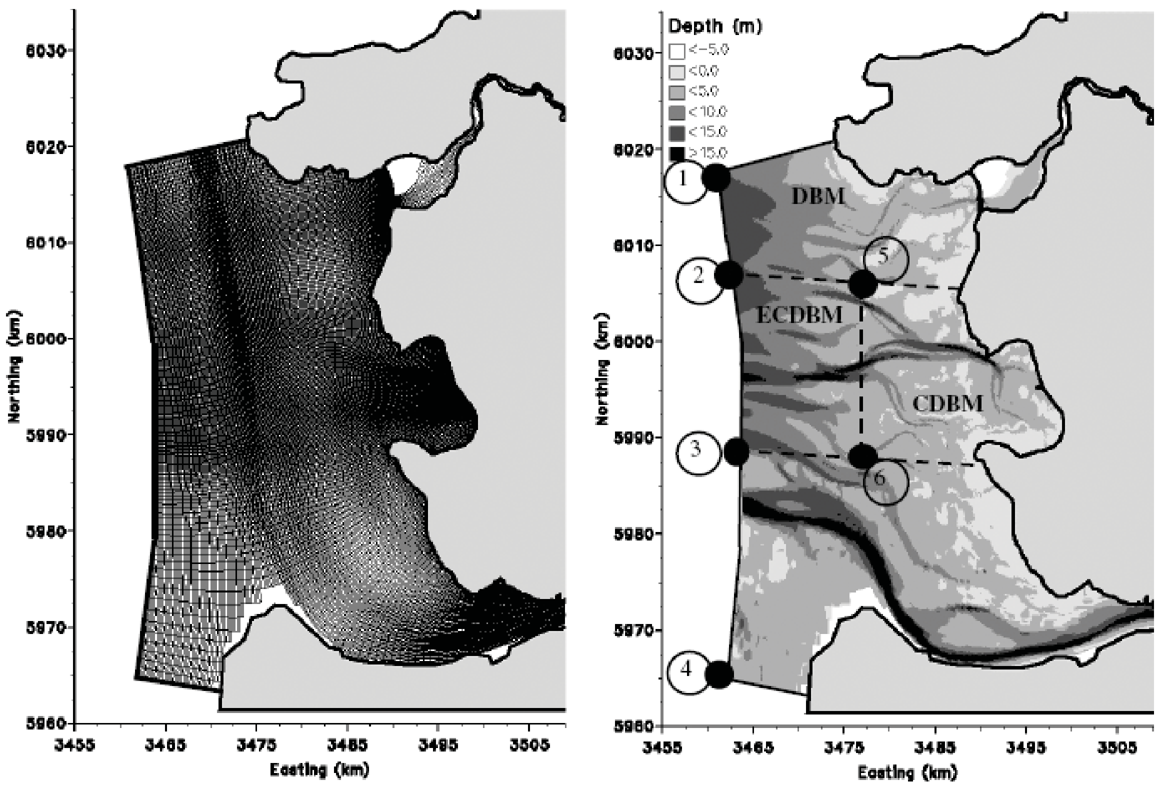

Fig. 2: Computational grid, bathymetry and model limits

of the respective open sea boundaries on the computed wave characteristics and medium-scale morphodynamics in the central Dithmarschen Bight. For the purpose of wave modelling it was also possible to dispense with boundary conditions on the northern and southern open sea boundaries, as these boundaries are located in very shallow tidal flat areas. The resulting Dithmarschen Bight Model (DBM) measures approximately 37 km by 54 km and covers an area of about 1,640 km^2. The model grid consists of approximately 43,250 cells with a grid spacing ranging from 80 m to 200 m. The offshore boundary is located about 29 km west of Buesum. The performance of the DBM for predicting water levels and current velocities was found to be similar to that of the CDBM and ECDBM (PALACIO et al., in this volume).

3. Flow Models

Flow models solve the non-steady flow field resulting from tidal and meteorological forcing. Along the open sea boundaries of models it is necessary to prescribe water levels, current velocities or a combination of both in order to ensure a well-posed mathematical initial boundary-value problem.

Water levels obtained from astronomical constituents are usually prescribed along the open sea boundaries of larger models. As the open sea boundaries are located far away from the coast in the present study, the effects of wind set-up may be accounted for by proper wind forcing. Typical examples of this set-up for the north-west European Continental Shelf area are implemented in the Continental Shelf Model (VERBOOM et al., 1992), the Promise Model (BRUMMELHUIS et al., 1997), and the BSHcmod Model (DICK et al., 2001). The latter model combines the tidal forcing of 14 harmonic constituents with water levels from an even larger model.

Small-scale coastal area models, on the other hand, are either driven by measured water levels from gauge stations or by computed water levels or current velocities. Water levels and current velocities may also be obtained from simulations using larger models covering the adjacent sea area, such as those mentioned above. Under calm weather conditions, where meteorological forcing is negligible, water levels obtained from astronomical constituents may also be applied directly along the open sea boundaries of coastal models. Examples of models driven by water levels specified along open sea boundaries have been reported among others by ELIAS et al. (2000) and ASPELIEN and WEISSE (2005). Models driven by velocities or a combination of water levels and velocities have also proved their effectiveness in several coastal regions (see, for example, MEWIS et al., 1998; ANNAN, 2001; SIEGLE et al., 2002; MILBRADT and PLÜSS, 2003).

The use of water levels based on measurements at gauge stations located in the proximity of the open sea boundaries is probably the most suitable and straightforward approach for specifying the hydrodynamic forcing of coastal flow models. In this approach, measured water levels that account for astronomical and meteorological effects are imposed directly along the open sea boundaries. For cases in which meteorological effects are negligible, water levels hindcasted from astronomical tidal constituents may also be used. If the open sea boundaries are long, interpolation between measurements from a limited number of gauge stations may be carried out to provide water level approximations at intermediate boundary grid points. Water levels along the open sea boundaries may also be obtained with the aid of models covering the adjacent sea area. This approach is recommended for larger models with long open sea boundaries, where interpolation between gauge measurements could introduce errors. In some cases a combination of the latter approach with measured water levels may be applied to correct water levels along the open sea boundaries.

3.1 Model Limits and Modelling Approaches

The effectiveness of the various approaches for prescribing water levels along the open sea boundaries was assessed for several flow models of the central Dithmarschen Bight, i.e. the CDBM, ECDBM and DBM. The limits of the models shown in Fig. 2 were selected on the basis of the results of preliminary model runs covering the German Bight (see Fig. 4). The flow models considered have open sea boundaries along their western, southern and northern extremities. It was found that the hydrodynamics of the study area are mainly determined by conditions along the western boundaries, through which the tidal wave and swell propagate into the coastal region. The northern and southern open sea boundaries of the models are either located on the tidal flats and fall dry during low water (CDBM and ECDBM in Fig. 2) or are fairly distant from the region of interest (DBM). Sensitivity tests were carried out to check the effects of the conditions specified along these boundaries on flow patterns. Generally speaking, it was found that the effects of hydrodynamic forcing specified along these boundaries are negligible.

Fig. 3 shows comparisons of the main tidal components at the northern and southern corners of the open sea boundaries of the three model domains. It is seen that the amplitudes and phases of the water levels at the corners of the CDBM (points 5 and 6 in Fig. 2) and ECDBM (points 2 and 3) are fairly similar. This is due to the fact that the crest of the tidal wave entering the domain of interest is almost aligned with the western open sea boundaries of the models as well as the edges of the tidal flat areas (TORO et al., in this volume). Hydrodynamic forcing along the western boundary of the flow models may thus be realised by specifying the water levels measured at one of the gauge stations located in the proximity of this boundary (G1, G2 or G3 in Fig. 1). The measured water levels (MWL) at the gauge stations G1 (Blauort) and G3 (Trischen) as well as the results of simulations using the larger-scale model covering the north-west European Continental Shelf were used in the present study (see Fig. 4). For periods during which meteorological effects are negligible, water levels along the western open sea boundary were hindcasted with the aid of tide tables (TT). Tide tables of the harmonic constituents obtained for the six tide gauges are summarized in TORO et al. (in this volume). Spatial and temporal linear interpolation was carried out between the measured water levels at one of the gauge stations in the vicinity of the boundary (G1, G2 or G3) and G5 (Steertloch) along the northern and southern boundaries (Fig. 1). In view of the fact that the gauge stations G1 and G3 are located at a fair distance from the western boundary of the ECDBM, the measured water levels at these stations were appropriately adjusted.

Comparisons of the main tidal constituents at several locations along the western boundaries of the Dithmarschen Bight Model (DBM) showed significant differences in amplitudes and phases between the central Dithmarschen Bight and the Elbe estuary (see points 3 and 4 in Fig. 3). As there are no gauge stations along the western boundary of the DBM, it was only possible to adopt the approach based on simulations using a larger model covering the adjacent sea area.

In this study the north-west European Continental Shelf Model (CSM) was used for this purpose (VERBOOM et al., 1992). This model has a grid spacing of about 9 km and implements two-dimensional depth-integrated flow approximations based on the DELFT3D modelling system developed by Delft Hydraulics in the Netherlands (ROELVINK and VAN BANNING, 1994). The 10 main harmonic tidal constituents (M2, S2, N2, K2, O1, K1, Q1, P1, NU2, and L2) were prescribed along the open sea boundaries of the CSM. In order to improve the descriptions of water levels along the coast a Large-Scale Model Nesting (LSMN) procedure was adopted (Fig. 4). The CSM was nested with the German Bight Model (GBM), which

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has a grid spacing ranging from 0.5 km to 1.9 km (HARTSUIKER, 1997). The water levels and current velocities along the open sea boundaries of the coastal models were obtained in successive steps. Simulations were first performed for the entire investigation period using the CSM. The information obtained along the open sea boundaries of the GBM were then used to drive this model, which in turn yielded the required boundary conditions along the open sea boundaries of the coastal models (CDBM, ECDBM and DBM).

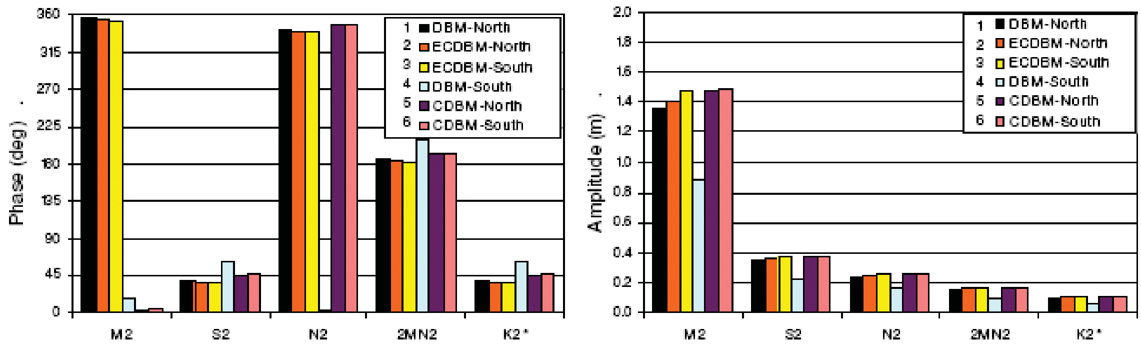


Fig. 3: Comparison of the main tidal components at the northern and southern corners of the open sea boundaries of the coastal models

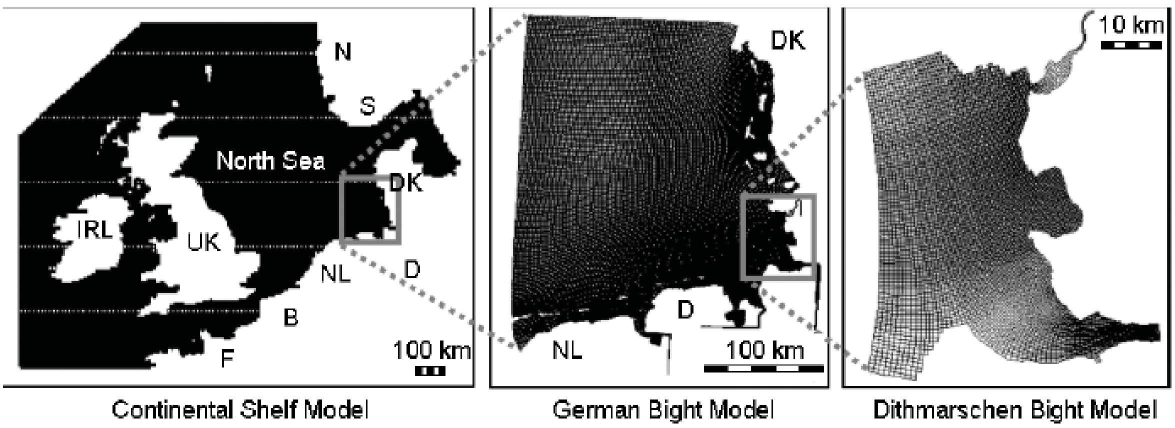


Fig. 4: Nesting sequence for the generation of open sea boundary conditions

In order to improve the descriptions of water levels along the open sea boundaries of the coastal models the results of simulations using the LSMN were subsequently adjusted. This was achieved by comparing measured and computed water levels at one of the gauge stations located at the entrance to the central Dithmarschen Bight. The discrepancies in amplitudes and phases at the Tertius gauge station (G2) were used to correct water levels along the open sea boundaries of the DBM. Owing to a lack of data at the Tertius station during storm periods, the Blauort gauge station (G1) was used instead to cover such periods.

Wind data was obtained using the PRISMA interpolation model developed by the Max Planck Institute of Meteorology in Hamburg (LUTHARDT, 1987). This model generates synoptic wind fields from a large set of measurements at locations along the coastline as well as from offshore data covering the entire North Sea. The PRISMA wind data is generated every three hours with an area resolution of 42 km. A comparison of computed wind data with wind measurements made by the Research and Technology Centre Westcoast (FTZ) of the University of Kiel over a period of 8 years confirms the high quality of the PRISMA model results (WILKENS, 2004).

3.2 Assessment of Modelling Approaches

The various approaches for determining environmental forcing in terms of prescribed water levels along the open sea boundaries were assessed by comparing measured and computed water levels at several locations (G1 to G5 in Fig. 1) over a wide range of conditions. Attention was focused on the effectiveness of the approaches for computing flows in the central parts of the Dithmarschen Bight.

Table 1 summarizes the periods considered in the assessment. These include periods lasting up to 65 days with relatively calm weather conditions (Periods P_{N1} to P_{N6}) as well as stormy periods (Periods P_{S1} to P_{S3}) with water level set-ups of up to about 4.6 m and wind velocities of up to about 30 m/s. Discrepancies between the computed and measured phases and amplitudes at high and low water were evaluated. For periods during which meteorological effects were not significant, comparisons were also made between the tidal constituents of measured and computed water levels.

3.2.1 Approach Based on Measured Water Levels (MWL)

An assessment of the approach based on measured water levels was tested for the CDBM and the ECDBM. In the case of the CDBM, measured water levels at either the Blauort gauge station (G1) or the Trischen gauge station (G3) were specified directly along the western boundary of the model. Along the northern and southern boundaries linear interpolation was applied between the water levels measured at the gauge stations G1 or G3 and G5. For periods during which meteorological effects were negligible (Periods P_{N1} to P_{N6} in Table 1) hindcasted water levels from tide tables were also used (TORO et al., 2005). As the western open sea boundary of the ECDBM is some distance from the Blauort and Trischen gauge stations, it was first necessary to apply corrections to the gauge data in order obtain representative water levels along this boundary. Optimum values were obtained by adjusting the measured phases and amplitudes by about 15 min and 5 %, respectively. Water levels along the northern and southern boundaries were obtained by applying linear interpolation between the corrected water levels on the western boundary and measurements at the Steertloch gauge station (G5) located nearer to the coast.

Simulations were carried out for the conditions listed in Table 1. Comparisons between the measured and computed water levels at gauge stations G2 and G5 are shown in Figs. 5 and 6, respectively. For the sake of compactness, only the results obtained for the period July 7 to July 22, 1990 (first two weeks of Period P_{N4} in Table 1) are shown. It should be noted that the high overlapping obtained between computed and measured water levels at gauge station G2 is due to the fact that the measured water levels at one of the gauge stations in the proximity of the open sea boundary were used to drive the CDBM. The predictive capability of the approach for simulating water levels under more adverse conditions is shown for gauge stations G1 and G4 in Figs. 7 and 8, respectively. Comparisons of the amplitudes and phases of the six main tidal constituents at gauge stations G1, G3, G4 and G5 are shown in Fig. 9 for

Table 1: Periods selected for testing the effectiveness of the various environmental forcing approaches

Period			Duration (days)	Characteristics
Relatively calm weather conditions	P_{N1}	May 31 to June 26, 1989	27	Wind velocities throughout the entire period lower than 8 m/s
	P_{N2}	May 31 to July 12, 1989	43	Incorporates 2 small storms with wind velocities of about 9 m/s and 11 m/s.
	P_{N3}	April 27 to June 30, 1990	65	Incorporates 4 small storms of short duration with wind velocities ≤ 10 m/s
	P_{N4}	July 7 to August 18, 1990	43	Incorporates 4 storms lasting longer than 1 day with wind velocities ≤ 10 m/s
	P_{N5}	August 15 to Sept. 15, 2000	32	Incorporates 5 storms lasting longer than 1 day with wind velocities ≤ 13 m/s.
	P_{N6}	Sept. 22 to Oct. 22, 2000	31	Incorporates 6 small storms of short duration with wind velocities ≤ 11 m/s, also a storm lasting longer than 1 day with wind velocities ≤ 18 m/s.
Storms	P_{S1}	Jan 25 to Jan 31, 1990	6	Wind velocity up to 30 m/s Water level set-up up to 4 m
	P_{S2}	Feb 25 to March 1, 1990	8	Wind velocity up to 25 m/s Water level set-up up to 4.5 m
	P_{S3}	Nov 26 to Dec 5, 1999	9	Wind velocity up to 33 m/s Water level set-up up to 4.4 m

periods during which meteorological effects were negligible. Details of the tidal analysis are summarised in TORO et al. (in this volume). Since the methods based on MWL and TT rely on water levels measured close to the western boundaries, the effectiveness of these methods was only assessed at locations nearer to the coast. It is seen that the results given by all approaches for the amplitudes and phases of the main tidal constituents are in good agreement with observations. Considering the six main constituents, and taking into account MWL and TT, the ratios between the computed and measured tidal constituents were less than 20 % and 25 % for the Buesum (G4) and Steertloch (G5) gauge stations, respectively. The approaches based on MWL and TT yielded phase lags of up to 11 min and 14 min, respectively.

Comparisons of the Mean Absolute Errors (MAE) and Mean Errors (ME) and their Standard Deviations (StDev) are shown in Figs. 10 and 11. Values are given for the gauge stations G1, G2, G4 and G5. The results obtained using MWL along the open sea boundaries of the CDBM and ECDBM are comparable. Better agreement between amplitude values was obtained at high water levels. The average MAE values are generally less than 5 cm and 10 cm (about 1.5 % and 3 % of the mean tidal range) at high and low water level, respectively. The MAE values of the phase lags at high water levels and low water levels were on average less than about 3 % (about 25 min) and 5 % (about 35 min) of the tidal period, respectively. Based on average ME values there is a tendency towards an underestimation of tidal elevations, particularly at low water levels. Moreover, the high and low water levels are attained in advance of the observed values at the stations nearer to the coast. The highest MAE is obtained for the approach in which water levels hindcasted from tidal constituents

(TT) are specified on the open sea boundaries. At high and low water levels the approach based on TT resulted in average MAE values at the station nearer to the coast of less than about 20 cm and 35 cm, respectively. The corresponding MAE values for the phase lags were about 30 min and 33 min. The discrepancies in amplitudes and phases are comparable to those obtained by comparing the hindcasts using TT and measured water levels (see TORO et al., in this volume).

3.2.2 Approach Based on Simulations using Large-Scale Model Nesting (LSMN)

The water levels along the open sea boundaries of the coastal models may also be obtained from simulations using a model covering the adjacent sea area. In this study the north-west European Continental Shelf Model (CSM) was used for this purpose. A nesting sequence was developed to improve the predictive capability of the models in shallow water areas. Details of these models are summarised in the foregoing. In order to improve predictions along the open sea boundaries water level corrections were applied by comparing measured and computed water levels at a gauge station located at the entrance to the tidal channels. The Tertius gauge station (G2) was used for this purpose in the present study. The amplitudes and phases of the values obtained along the open sea boundaries were adjusted on the basis of the discrepancies between measured and computed values. The effectiveness of this approach was verified for the ECDBM and DBM. Simulations were performed for the conditions listed in Table 1.

Comparisons between measured and computed water levels from July 7 to August 18, 1990 (Period P_{N4} in Table 1) at gauge stations G2 and G5 are shown in Figs. 5 and 6, respectively. It is seen that modelled water levels are slightly better at station G2 than at G5, which may be explained by the closer proximity of station G2 to the western boundary. It is also found that larger discrepancies between modelled and measured water levels occur when astronomical constituents are used for hydrodynamic forcing. The predictive capability of this approach for simulating water levels under more adverse weather conditions is shown for gauges G1 and G4 in Figs. 7 and 8, respectively. Fig. 9 shows comparisons of the main tidal constituents at gauge stations G1, G3, G4 and G5 (see Fig. 1). Comparisons of the MAE, ME and StDev are shown in Figs. 10 and 11 for gauge stations G1, G2, G4 and G5 during Period PN4 listed in Table 1.

The MAE values obtained using the ECDBM and DBM are comparable and less than about 10 cm and 20 cm on average (about 3 % and 6 % of the mean tidal range) at high and low water levels, respectively. The corresponding MAE values of the phase lags are about 25 min and 20 min (about 3 % of the tidal period) at high and low water levels, respectively. Similar to the approach based on MWL there is a tendency towards underestimation of low water levels and the occurrence of high and low water levels in advance of those observed.

Investigations to verify the effect of the quantity specified (water levels or current velocities) along the open sea boundaries of the DBM on the momentum balance were also carried out. The DBM was driven along the open sea boundaries using water levels and current velocities obtained from simulations performed using the model nesting sequence shown in Fig. 4. Comparisons of the resulting water levels and current velocities at several locations within the model domain showed only minor discrepancies.

3.3 Discussion

It was found that the simulated conditions along the open sea boundaries given by the approaches based on MWL and LSMN all are in good agreement with observations. Slightly better agreement between observed and computed water levels was obtained for the smaller model, which was driven directly by measured water levels on the open sea boundary. The highest MAE values result from the approach in which astronomical constituents are imposed on the open sea boundaries. The discrepancies are comparable to those obtained from the hindcasted values using astronomical constituents. This approach thus offers an alternative method for prescribing water levels along the open sea boundaries for conditions in which meteorological effects are negligible and measured water levels or larger models are not available. The approach based on simulations using the larger model also proved to be quite effective in all model domains. A correction of the conditions along the open sea boundaries obtained from simulations using measured water levels is essential for ensuring high predictive capability. As measurements covering long periods are seldom available, this approach may be used for generating long-term time series of open sea boundary conditions provided wind fields are available over the surrounding sea area.

The effectiveness of the approaches adopted for prescribing water levels as open sea boundary forcing conditions proved to be quite satisfactory (see PALACIO et al., in this volume). The mean absolute errors between computed and observed depth-averaged velocities at several cross-sections in the tidal channels were generally found to lie below 0.2 m/s, which represents less than 20 % of the tidally-averaged value. In terms of the quality standards usually adopted (VAN RIJN et al., 2002), the performance of the model with regard to current velocity predictions was found to lie between good and excellent.

Comparisons were also made between the results obtained using 2DH and 3D flow model approximations. The suitability of the approaches for prescribing water levels along the open sea boundaries was investigated. The reference grid of the 2DH model was extended to include 10 layers in the vertical direction. The vertical grid spacing of the 3D model was chosen to follow a logarithmic distribution in order to reproduce the vertical flow profile more accurately. Comparisons between the flow model computations were made for water levels at several locations and current velocities at a number of cross-sections. In general, it was found that the results given by the two flow models are fairly similar during most of the tidal cycle, except during slack water periods when current reversal occurs (see PALACIO et al., in this volume).

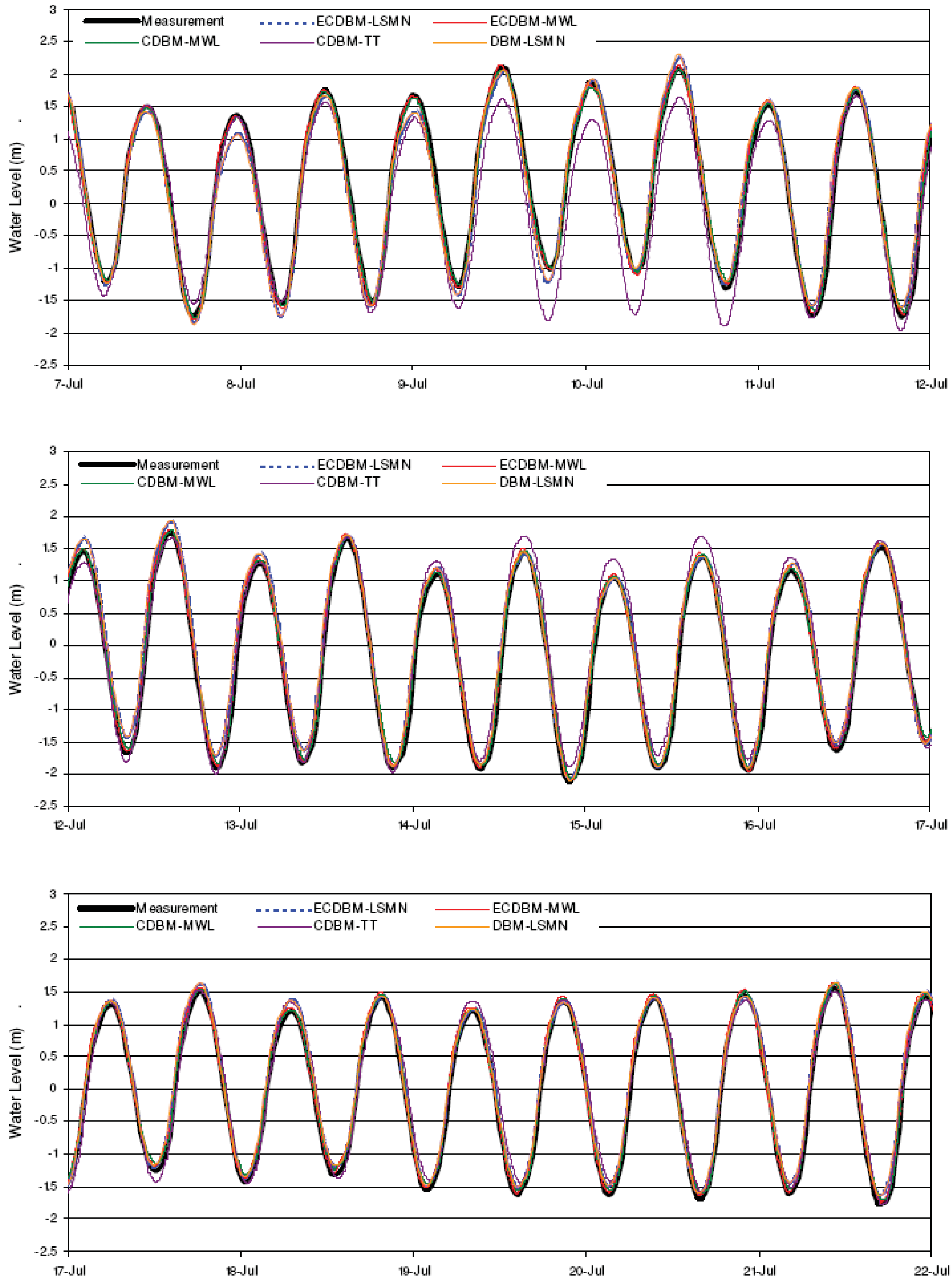


Fig. 5: Measured versus computed water levels at the Tertius gauge station (G2) during Period P_{N4}

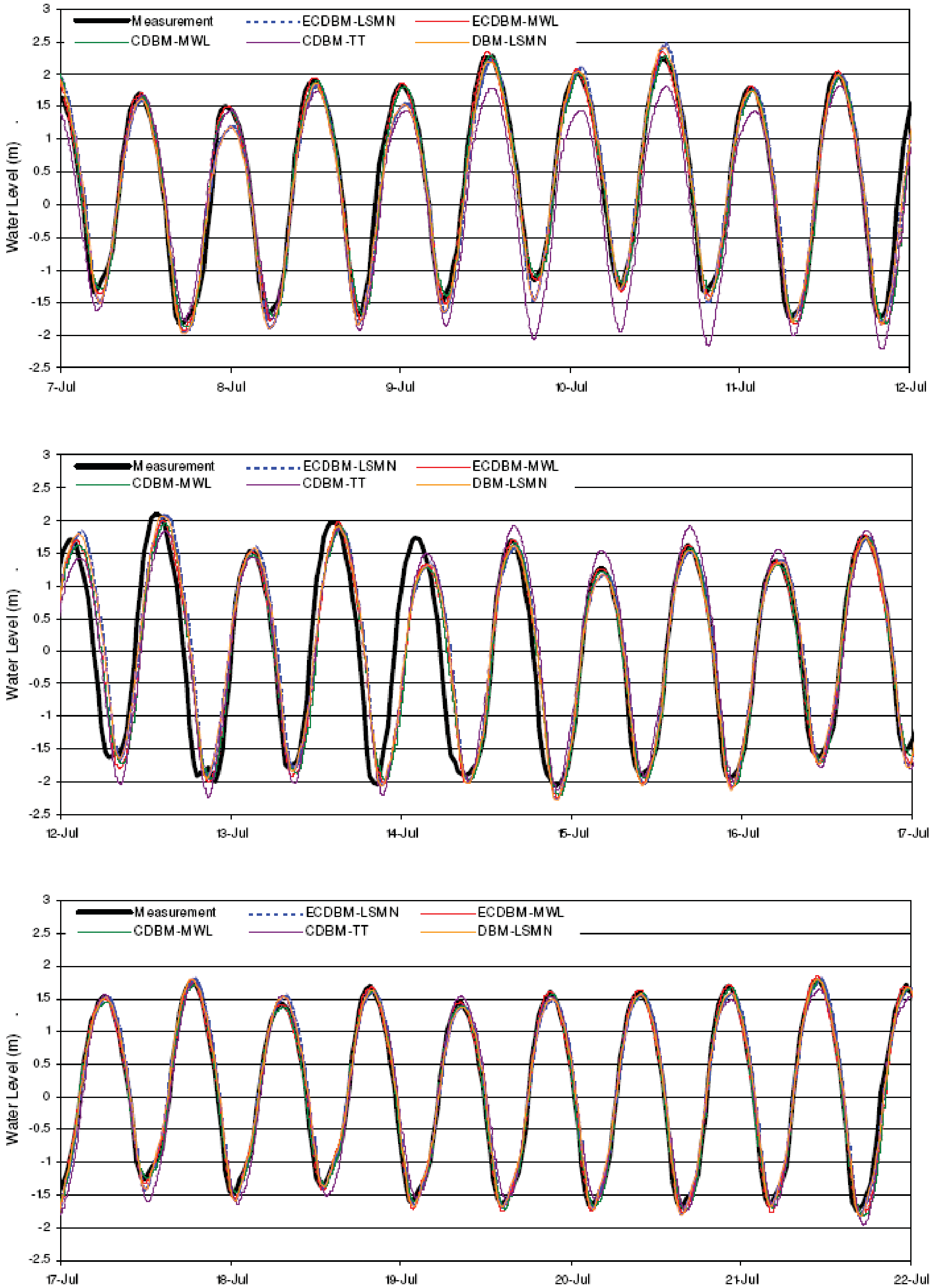
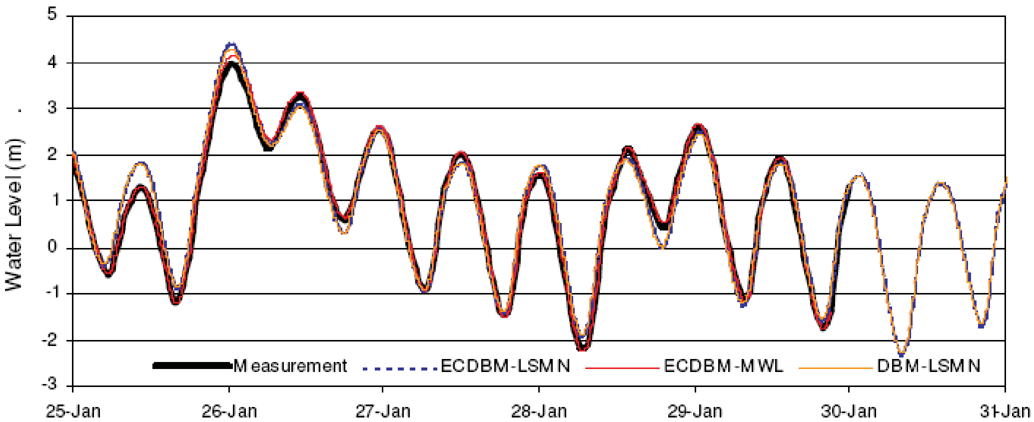
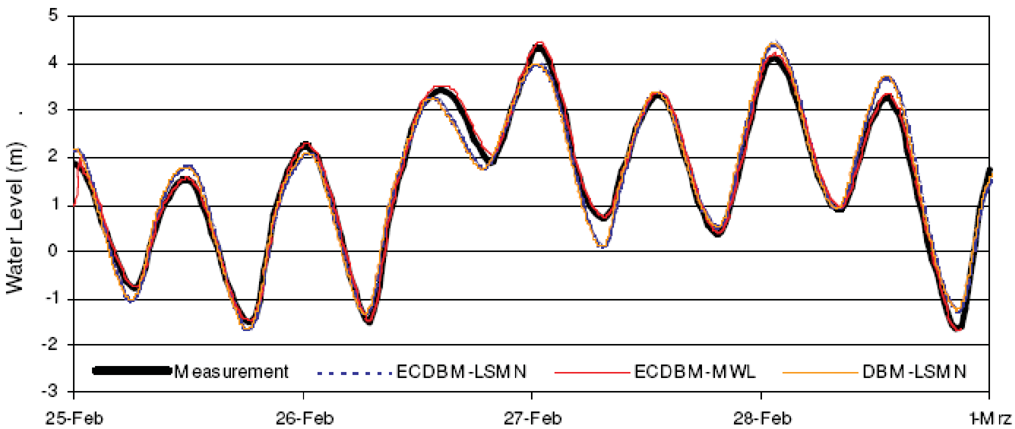


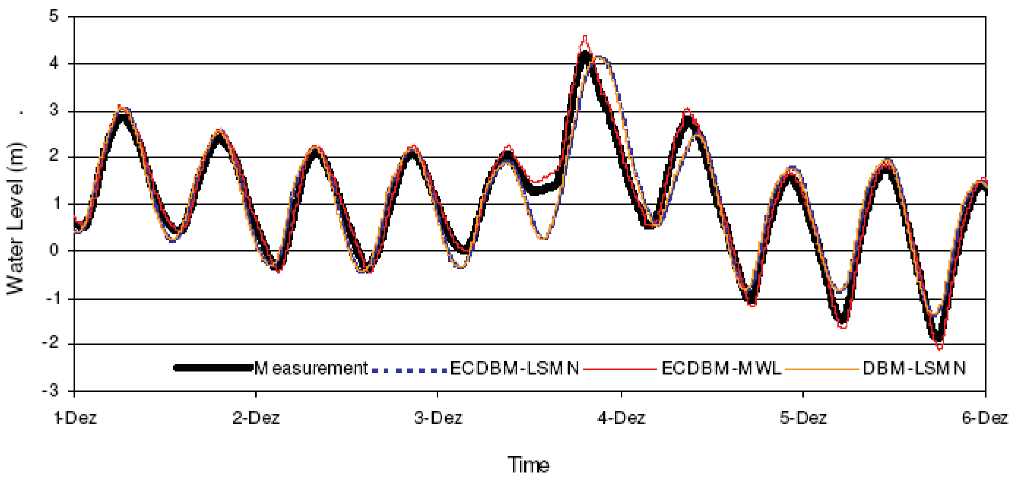
Fig. 6: Measured versus computed water levels at the Steertloch gauge station (G5) during Period P_{N4}



a) Period S1: Jan 25 to 31 of 1990

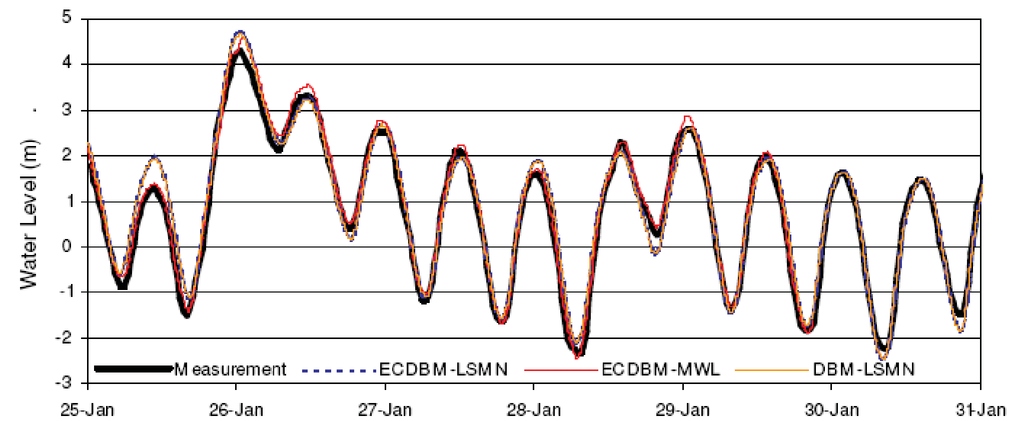


b) Period S2: Feb 25 to March 1 of 1990

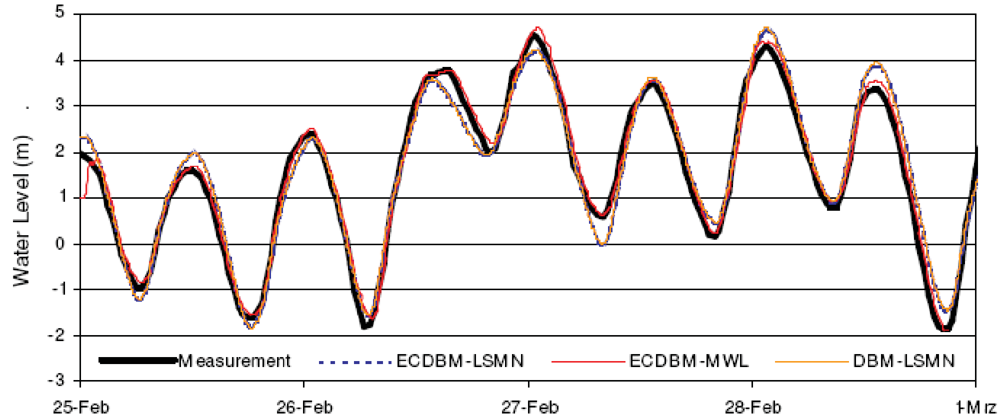


c) Period S3: Nov 26 to Dec 05 of 1999

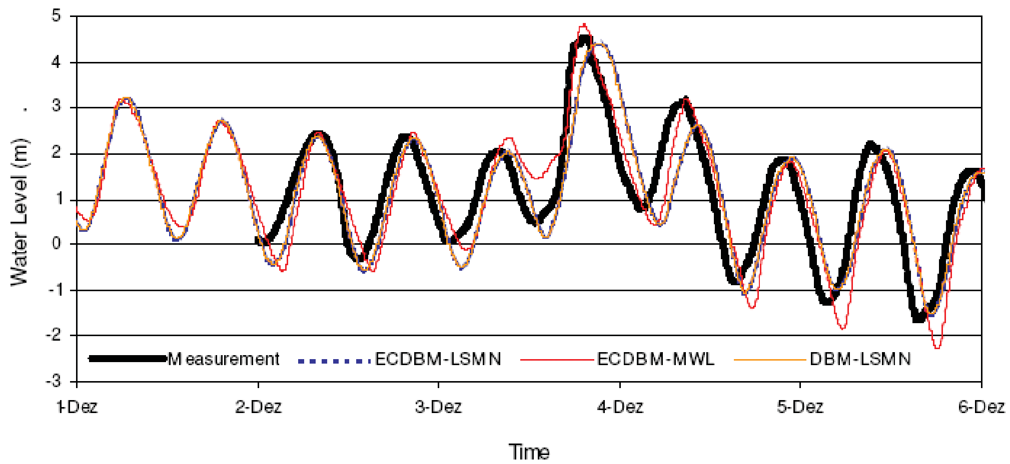
Fig. 7: Measured versus computed water levels at the Blauort gauge station (G1) during stormy periods



a) Period P_{S1}: Jan 25 to 31 of 1990

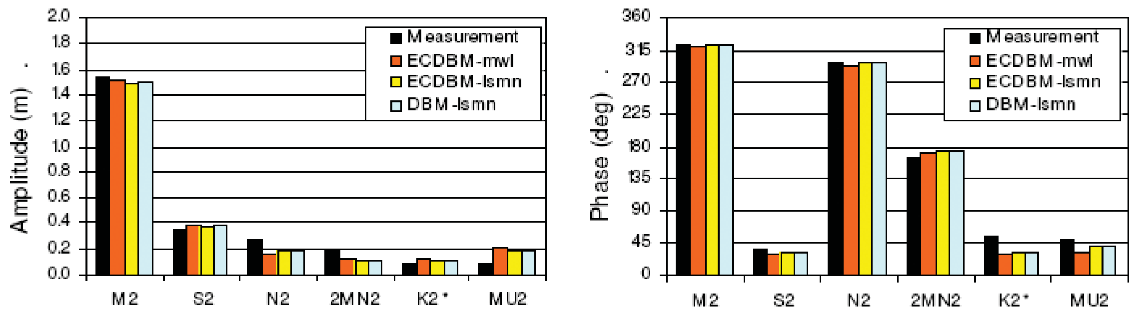


b) Period P_{S2}: Feb 25 to March 1 of 1990

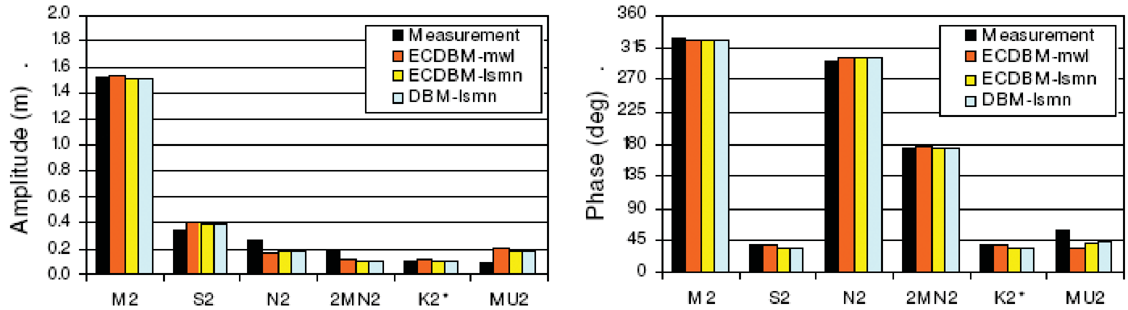


c) Period P_{S3}: Nov 26 to Dec 05 of 1999

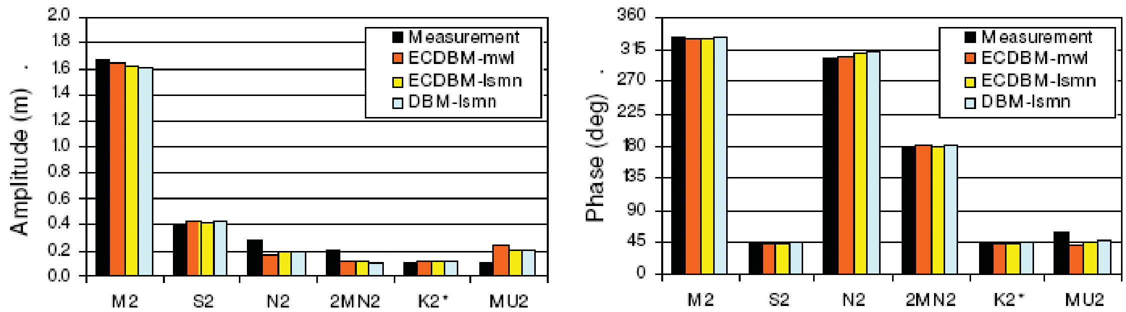
Fig. 8: Measured versus computed water levels at the Buesum gauge station (G4) during stormy periods



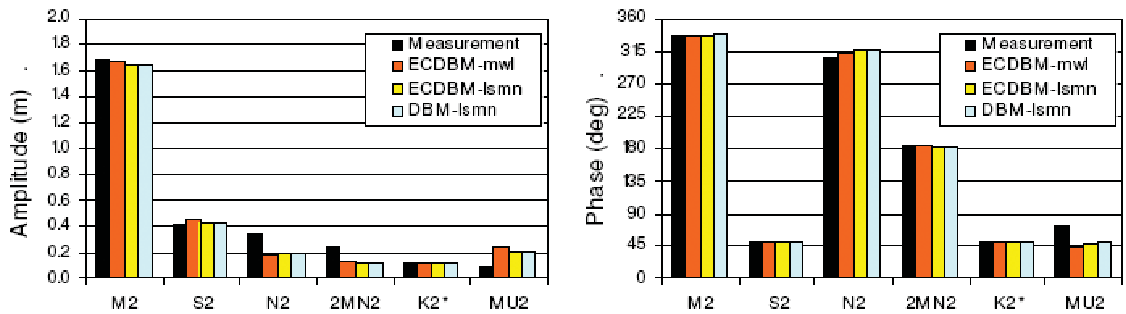
a) Tidal constituents at Trischen (G3)



b) Tidal constituents at Blauort (G1)

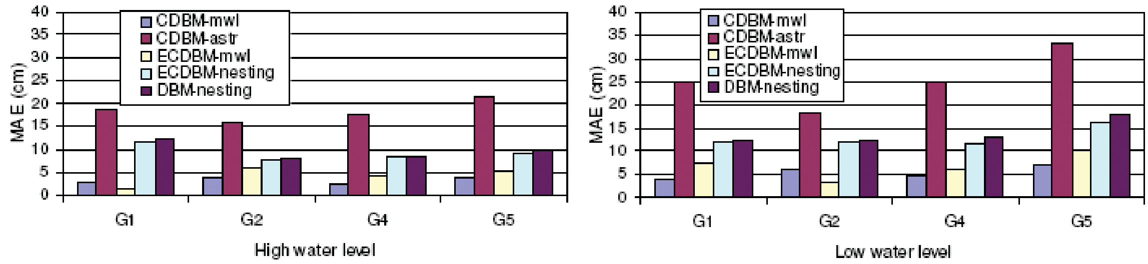


c) Tidal constituents at Buesum (G4)

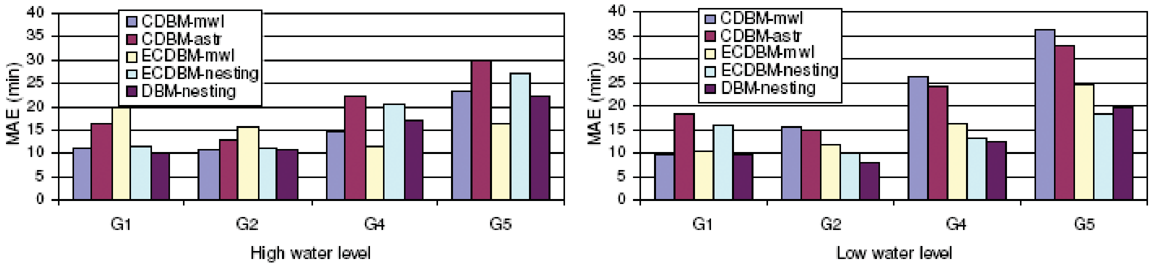


d) Tidal constituents at Steertloch (G5)

Fig. 9: Comparisons of measured and computed tidal constituents at gauge stations G1, G3, G4 and G5 during Period PN4

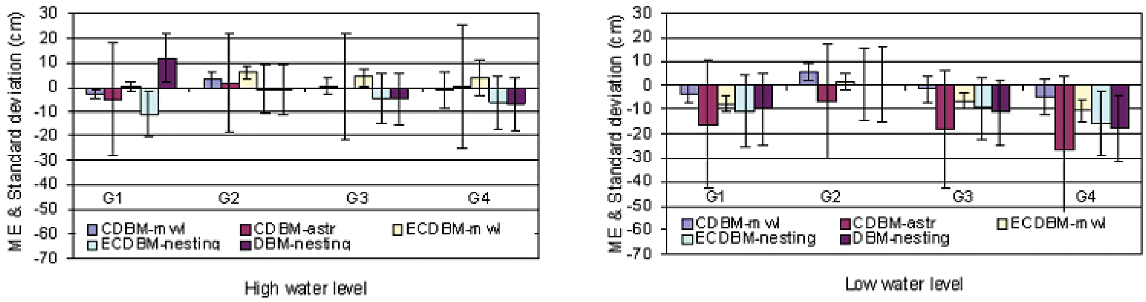


a) Amplitude

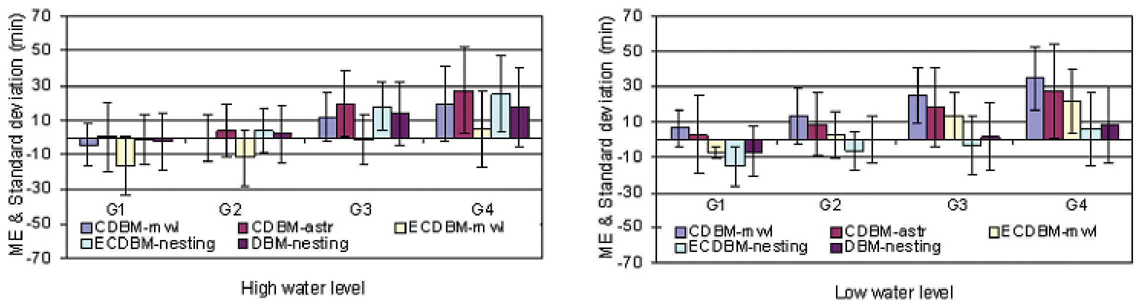


b) Phase

Fig. 10: MAE of computed water levels at several gauges during Period P_{N4}



a) Amplitude



b) Phase

Fig. 11: ME and StDev of computed water levels at several gauges during Period P_{N4}

4. Wave Models

Several approaches are available for modelling waves in coastal areas. Wave models may either be stationary or instationary, and phase-averaged or phase-resolving. Instationary models are applied in situations where the time taken for wave energy to travel through the model domain is significantly longer than the period during which wind and wave boundary conditions are constant. In such models, previous states of wave energy distribution are taken into account when computing the wave energy distribution at a certain point in time. In stationary models, on the other hand, a final state based on the imposed wind and wave boundary conditions is assumed. Phase-resolving models are used when the hydrodynamic variations during a wave period are of significance. This is the case, e.g. in studies of wave impact on coastal structures or for investigating the wave transformation in harbours. Due to the fact that the computational costs of instationary models and phase-resolving models are much higher than for stationary and phase-averaged approaches, the latter approaches are preferably used if permitted by the objectives of the study. As the model considered here was set-up to determine the general wave conditions for morphodynamic modelling in a coastal area of limited size, the latter approach was adopted in this study.

Conditions along the open sea boundary of a wave model may be specified parametrically by means of a pre-defined spectral shape, e.g. a JONSWAP-spectrum, or by imposing a user-defined spectrum. The conditions specified along the open sea boundaries may either be spatially varying or constant. Data records of boundary conditions may either stem from wave measurements at locations near the open sea boundaries, from the results of a larger wave model (model nesting), or may be estimated using relationships between wind conditions and fetch lengths. The latter approach is generally limited to water bodies subject to small spatial variations in meteorological conditions. Unless this is the case, this method would become too complex and too inaccurate for practical application.

4.1 Model Domain and Modelling Approaches

The wave model developed for the Dithmarschen Bight is based on the SWAN wave model (BOOIJ et al., 1999; RIS et al., 1999). This model was coupled to a flow model in order to include the effects of ambient currents and water levels on the computed wave characteristics. Calibration and validation of the wave model yielded good results regarding a visual comparison of the computed and observed time series as well as a statistical evaluation based on the Relative Mean Absolute Error (RMAE), as proposed by VAN RIJN et al. (2002). The set-up, evaluation and application of this model is described in detail by WILKENS et al. (in this volume). The computational grid and bathymetry of the wave model are shown in Fig. 2. Based on the results of a sensitivity analysis, only the western boundary was defined as an open sea boundary through which wave energy can enter the domain. The shallow tidal flats in the proximity of the southern and northern boundaries prevent the intrusion of a significant amount of wave energy at these locations. The main purpose of the wave model was to compute the general wave characteristics throughout the study area for medium-scale morphodynamic simulations. For this reason the wave model focuses on characteristic wave parameters rather than actual wave energy spectra. Wave conditions along the open sea boundary are thus imposed parametrically, i.e. by defining the significant wave height, peak period and mean wave direction. The following two approaches were adopted for defining the open sea boundary conditions.

In the first approach, records of wave parameters deduced from wave measurements at a buoy located close to the middle of the open sea boundary (Position 2 in Fig. 12) were subsequently specified as boundary conditions. Owing to the relatively small variations between the observed wave characteristics at Positions 1 and 2 and the inaccuracies introduced by interpolating between the values at these locations, it was decided to impose uniform conditions along the open sea boundary. The wave data recorded during September and October 1996 were kindly provided by the Coastal Research Station of the Lower Saxony Board of Ecology on Norderney, who carried out measurements within the framework of the KFKI project 'Bemessung auf Seegang' (Grant No. KFKI 45) funded by the German Ministry of Education and Research (BMBF) under Grant No. MTK 0561 (NIEMEYER, 1997).

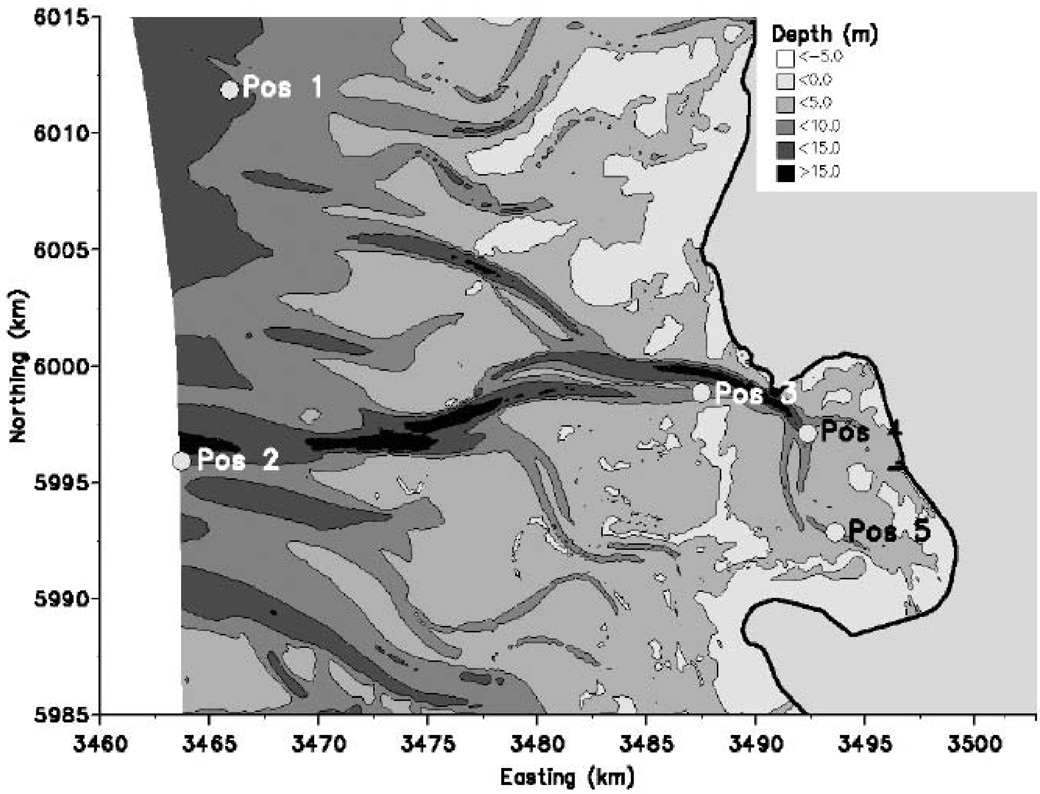


Fig. 12: Wave measurement locations during September and October 1996

In the second approach, the Dithmarschen Bight Model (DBM) was nested in the larger German Bight Model (GBM) (see Fig. 4). This nesting sequence was applied for flow simulations, commencing with the even larger Continental Shelf Model (CSM). The GBM was forced by wind only, neglecting any incoming wave energy through the open sea boundaries. From a sensitivity study it was concluded that the extra computational costs of nesting the GBM in the CSM were not justified due to only slight differences in wave parameters along the boundary of the DBM. The stationary version of the GBM was thus implemented for wave computations. Although the data generated in this way are subject to inaccuracies inherent to model results, this approach permits the definition of acceptable boundary conditions outside the observation periods.

4.2 Assessment of Modelling Approaches

The results of the validated wave model have shown that incoming swell energy does not penetrate the entire tidal flat area during moderate weather conditions (WILKENS et al., in this volume). Although the limit of swell energy is generally close to the 10 m isobath, swell may penetrate slightly further into the domain via the tidal channels. Although wave penetration through the tidal channels is possible due to their greater depths, it may be hindered by channel geometry.

Eastwards of the 10 m isobath, waves are mainly generated by local winds. Under average conditions an improvement of the open sea boundary conditions is thus only relevant over the outer tidal flats. It thus only possible to assess the quality of the imposed boundary conditions on the basis of measurements carried out near the open sea boundary. Furthermore, the quality of the model results at locations within the model domain depends partly on the imposed boundary conditions and partly on the performance of the model itself. A proper assessment of the quality of the boundary conditions should thus be made at locations in the vicinity of the open sea boundary. The method of imposing values measured in the direct proximity of the open sea boundaries clearly yields the most accurate results. Considering the wave characteristics at Position 2, the results of the second approach were therefore compared with the results of the first approach for the observation period September/October 1996. Comparisons between observed and computed significant wave heights, peak periods and mean directions at Position 2 during the period September/October 1996 are shown in Figs. 13, 14 and 15, respectively. Although only minor tuning of the model parameters was carried out in this study, fair agreement is obtained between observations and computed results. A possible reason for the differences between the GBM results and observations could be the inaccurate representation of bathymetry due to a fairly coarse grid resolution. Another reason might be the stationary nature of the applied model, whereby changes in meteorological conditions are directly transferred to the resulting wave fields without consideration of previously generated waves. Apart from minor differences between observed and computed wave heights in some instances, the model results reflect the major trends fairly well.

Besides a visual and somewhat subjective comparison of the time series of the aforementioned parameters, they are also compared in scatter plots in Figs. 16 and 17. In order to obtain a more objective evaluation of the quality of the model results the data pairs of the scatter plots were used to compute the following relative mean absolute error (RMAE, see Eq. 1), as defined by VAN RIJN et al. (2002).

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

in which:

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

P_c = computed parameter; and

ΔP_m = inaccuracy of the measured parameter (values of 0.1 m and 0.3 s were assumed for wave height and period, respectively).

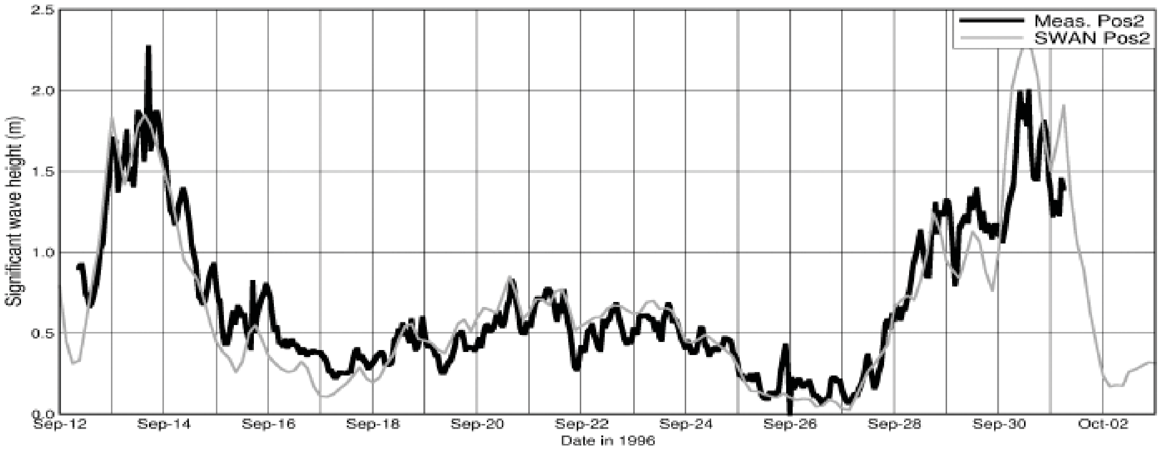


Fig. 13: Comparison between observed and computed significant wave heights at Position 2

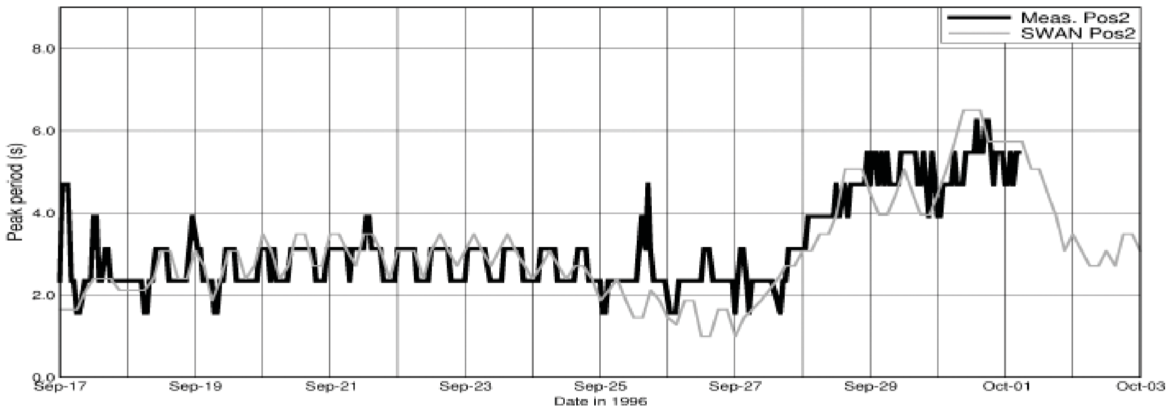


Fig. 14: Comparison between observed and computed peak periods at Position 2

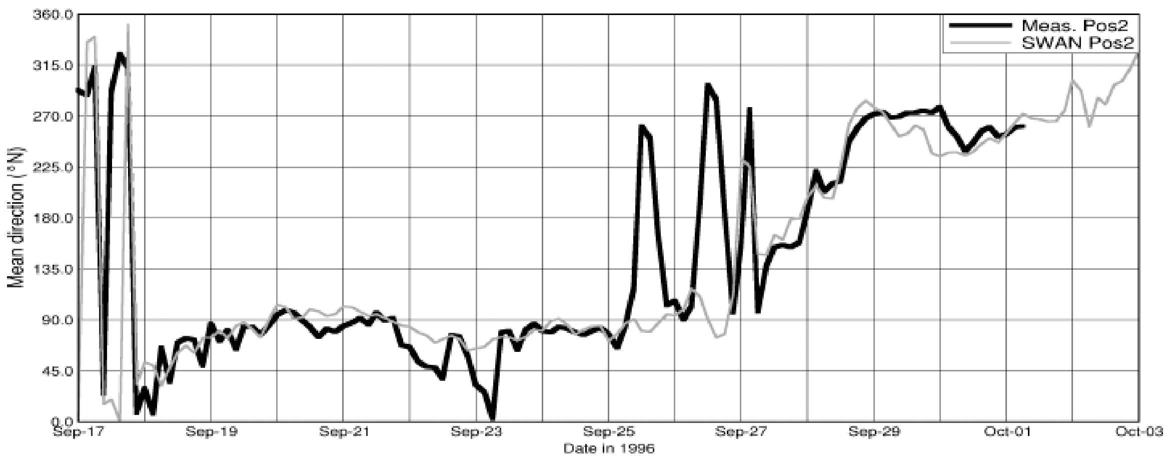


Fig. 15: Comparison between observed and computed mean wave directions at Position 2

The numerator and denominator of Eq. 1 are averaged over the evaluation period. The quality of a model in terms of simulated significant wave heights is rated on the basis of the RMAE value according to the classification of VAN RIJN et al. (2002) shown in Table 2. No such rating scheme is available at present for wave periods. In view of the definition of the RMAE, it is not possible to apply this rating scheme to wave directions.

Table 2: Quality of simulated wave heights based on RMAE values (VAN RIJN et al., 2002)

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

As is evident from the scatter plots of Figs. 16 and 17, fairly good correlations are obtained between observed and simulated values for the three parameters considered. Considering the RMAE value of 0.08 obtained for significant wave heights, the model results may be rated as 'good' according to the classification of VAN RIJN et al. (2002). Applying the same classification scheme to peak periods with an RMAE value of 0.17, a rating of 'reasonable/fair' is obtained.

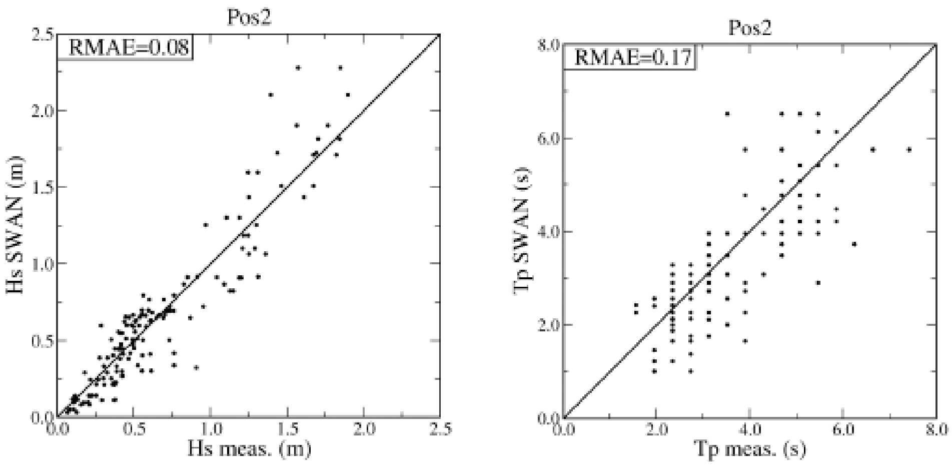


Fig. 16: Scatter plots and RMAE values for significant wave heights and peak periods at Position 2

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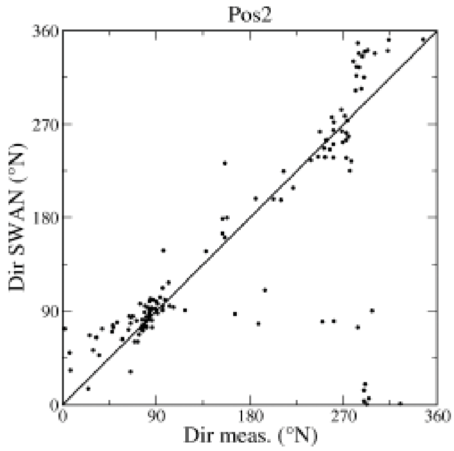

Fig. 17: Scatter plot of mean wave direction at Position 2

4.3 Discussion

On the basis of the foregoing it is seen that the results obtained from the stationary version of the GBM are in fair agreement with observations. Imposing these model results along the open sea boundary of the DBM, the slight deviations from observed values are likely to have some effect on the results of the DBM. If direct observations close to the open sea boundary of the DBM are available for the modelling period in question, however, it is clearly preferable to use such data rather than the results of GBM simulations. Observations are generally not available over large time spans, however. In view of this, the model nesting approach offers a valuable alternative for defining open sea boundary conditions. Although the application of the instationary version of the GBM might lead to further improvements, these should however be weighed against additional computational costs.

Imposing measured wave characteristics directly on the open sea boundary is obviously the most accurate approach, provided measurements are made in the proximity of the open sea boundary concerned. In the case of wave measurements further away, however, additional errors may be introduced due to changes in prevailing conditions, e.g. changes in water depths and current velocities. Moreover, this method is only applicable for periods during which measurements are available. It was shown in the foregoing that the application of model nesting yields fairly good results even when a stationary wave model is used. If wind data are available for the model domains in the nesting sequence, this approach serves as a valuable alternative to direct measurements.

5. Conclusions

In this paper the relevance of hydrodynamic forcing on the predictive capability of process-based flow and wave models has been demonstrated for a coastal area model on the German North Sea coast. Two-dimensional depth-averaged (2DH) flow models based on the DELFT3D modelling system developed by Delft Hydraulics in the Netherlands (ROELVINK and VAN BANNING, 1994) as well as the phase-averaged spectral wave model SWAN (BOOIJ et al., 1999; RIS et al., 1999) were implemented in the study.

The selection of the model limits for the coastal area using the results of preliminary model runs covering a larger area proved to be quite effective. The orientation of the western open sea boundary was chosen be orthogonal to the direction of propagation of the tidal wave and swell entering the coastal area. It was found that the flow conditions in the study area are mainly determined by the conditions specified along this boundary.

Several approaches usually adopted for determining open sea boundary conditions for driving flow and wave models were compared for a coastal area on the German North Sea coast. Approaches based on water level measurements and the results of simulations using a model covering the entire North Sea were investigated. It was shown that both approaches are capable of providing water levels along the open sea boundaries for driving the 2DH flow models. In the majority of the tests carried out in this study better agreement with observations was obtained at locations in deeper water and closer to the open sea boundaries where the effects of bathymetry and bottom roughness are less pronounced.

In the case of the flow model it was found that the best agreement with observations was obtained using direct measurements along the open sea boundaries. This approach, however, is usually restricted to smaller domains in which gauge stations are located in the proximity of the open sea boundaries. Under normal conditions the mean absolute errors (MAEs) in amplitudes were found to be less than 5 cm (1.5 % of the mean tidal range) and about 10 cm (3 % of the mean tidal range) at high and low water levels, respectively. The MAE of phase lags was found to be less than about 35 min (about 5 % of the tidal period), whereas during storm conditions, the MAE for water levels was found to be less than 35 cm. The use of simulation results from a larger model covering the adjacent sea area also proved to be quite effective. The robustness of the method for correcting water levels along the open sea boundaries based on comparisons between measured and computed water levels has been demonstrated. The application of the approach to three model domains yielded comparable results. The mean absolute errors in amplitudes and phases during periods with calm winds were found to be less than 3 % (about 10 cm) and 6 % (about 18 cm) of the tidal range and 4 % (about 27 min) and 3 % (about 20 min) of the tidal period at high and low water levels, respectively, whereas the MAE of water levels during storm conditions was found to be less than about 26 cm. Compared with the approaches based on measured water levels or large-scale model nesting (LSMN), the approach based on astronomical constituents gave the poorest agreement with observations. The resulting discrepancies were found to be of the same order as those obtained by comparing hindcasts using tide tables and measured values. This approach offers an alternative means of determining water levels along the open sea boundaries in cases where measured water levels or larger models covering the adjacent sea area are not available. It should be pointed out, however, that the latter approach is limited to periods with moderate winds.

The effectiveness of specifying water levels along the open sea boundaries in relation to the preservation of momentum balance was also verified. Comparisons between the model results obtained at several locations in the study area from simulations with a)water levels and b)current velocities specified on the western open sea boundary showed fair agreement. Moreover, the various approaches adopted in this study were found to reproduce current velocities over several cross-sections in close agreement with observations. The results of model validation using measured current velocities are summarised in PALACIO et al. (in this volume).

In order to confirm the suitability of the approaches adopted for prescribing water levels along the open sea boundaries for a 3D model approximation, a comparison was made between the results obtained from 2DH and 3D flow model simulations. In general, it was found that the results given by the two flow models are fairly similar during most of the tidal cycle, except during slack water periods when current reversal occurs (see PALACIO et al., in this volume).

An evaluation of the generation of open sea boundary conditions for the wave model by model nesting showed that this approach yields acceptable results. The general trends in wave characteristics are reproduced fairly well, with good correlation between computed and measured values. A statistical evaluation based on the RMAE yielded the rating 'good' for wave heights and 'reasonable / fair' for wave periods. As is generally known, the latter parameter is difficult to model accurately. As indicated by the scatter plot of Fig. 17, good results were also obtained for mean wave directions. Generally speaking, it may be concluded that the model nesting approach is a reliable alternative for estimating wave conditions along the open sea boundary of wave models. An advantage of this approach, of course, is that it may be applied during periods when direct measurements are not available.

6. Acknowledgements

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