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Patterns of Hydrodynamics in a Tide-Dominated Coastal Area in the South-Eastern German Bight

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Summary

The results of an analysis of field measurements leading to an identification of the basic patterns of hydrodynamics in a tidally-dominated area on the German North Sea coast are presented in this paper. The analysis was carried out within the framework of the research project "Predictions of medium-scale morphodynamics-PROMORPH" funded by the German Ministry of Education and Research from 2000 to 2002. The investigation area is the central Dithmarschen Bight between the Elbe and Eider estuaries. Recommendations for the set-up of the process-based models for flow and waves taking into account the available data and the dynamics of the study area were proposed. Continuous monitoring of water levels and waves by the relevant authorities was supplemented by field measurements at key locations. The planning and execution of field surveys specially intended to obtain a dense spatial and temporal coverage of current velocities is described. The tidal analysis, based on records from a number of tide gauge stations, yielded the 39 harmonic constituents that best represent the measured water level time series at several locations. An analysis of the seasonal variation of tidal asymmetries on the basis of water level measurements at several locations enabled flood or ebb dominance to be identified in the cross-sections of the tidal system. The current velocity measurements provided a good description of the spatial and temporal variation of current velocities. The measured wave data provided a better understanding of wave characteristics and wave transformation throughout the study area. The field measurements not only form a basis for identifying the most dominant physical processes governing the hydrodynamics of the study area but also provide a valuable data set for clarifying several aspects for developing and evaluating process-based models for the simulation of flow and waves.

Zusammenfassung

In diesem Artikel werden die Analysenergebnisse von Naturuntersuchungen vorgestellt, welche die grundlegende Verteilung der Hydrodynamik in einem tidedominierten Seegebiet der Deutschen Nordseeküste identifizieren. Diese Analyse wurde durchgeführt im Rahmen des Forschungsprojekts „Vorhersage mittelskaliger Morphodynamik – PROMORPH", das vom Bundesministerium für Bildung und Forschung von 2000 bis 2002 finanziert wurde. Auf der Grundlage von mehreren Tidepegelstationen lieferte die Tideanalyse etwa 39 harmonische Komponenten, welche die gemessenen Wasserstand-Zeitreihen am besten repräsentieren. Um die räumlichen und zeitlichen Variationen der Strömung in den Hauptgezeitenrinnen besser zu verstehen, wurden über mehrere Querschnitte und Lokalitäten selektive Messungen der Strömungsgeschwindigkeit durchgeführt. Die maximalen Punktgeschwindigkeiten und tiefengemittelten Geschwindigkeiten lagen in den Gezeitenrinnen bei 2,8 m/s bzw. 1,7 m/s. Aufgrund der geringen Rauigkeit der Bodenformen ist die Geschwindigkeitsverteilung über die Vertikale nahezu gleichförmig. Es war möglich, in den Querschnitten nahe der seewärtigen Grenzen des Untersuchungsgebiets unter normalen Bedingungen eine Flutdominanz zu erkennen und einen signifikanten Anstieg der Strömungsgeschwindigkeit mit steigendem Tidehub. Etwa 10 km weiter seewärts der äußeren Wattflächen wurden Wellenhöhen bis 3,5 m aufgezeichnet. Landwärts wurde ein grader Abfall der Wellenhöhe gemessen, der mit dem immer stärker werdenden Effekt abnehmender Wassertiefe (führt zur Wellenenergie-Dissipation durch Wellenbrechen und Bodenreibung) wie auch mit der Hubwirkung der Wattflächen in Zusammenhang steht. Die maximalen Wellenhöhen entlang der äußeren Wattenkanten und in der zentralen Gezeitenrinne lagen bei jeweils 2,0 m und 1,5 m. Näher zur Küste weiter östlich lagen die Wellenhöhen generell unter 0,7 m. Aus der Analyse der Wellenperioden war zu schließen, dass die Dünung bis zum zentralen Bereich der äußeren Wattflächen reichte, während weiter östlich lokal erzeugte Wellen die Hauptenergiequelle bilden.

Keywords

Gauge Stations, Waverider Buoy, Tides, Tidal Analysis, Swell, Wind Waves, Tidal Channels, Tidal Flats, Measurements, Dithmarschen Bight, North Sea, PROMORPH

Contents

1. Introduction

Hydrodynamic phenomena constitute the underlying mechanisms governing sediment transport and reaction processes such as morphodynamics in coastal areas. Process-based numerical models for simulating morphological changes over time scales of several years have been developed, evaluated and applied within the framework of the research project "Predictions of Medium-Scale Coastal Morphodynamics – PROMORPH" funded by the German Ministry of Education and Research (PALACIO et al., in this volume; WILKENS et al., in this volume; WINTER et al., in this volume; JUNGE et al., in this volume; WILKENS and MAYERLE, in this volume). The investigation area considered in this project is the central Dithmarschen Bight located between the Elbe and the Eider estuaries.

This paper gives an overview of the data used to assist in identifying the basic features of hydrodynamics and to provide sets of data for the development of process-based models for simulating flow and waves in the investigation area. Gaps in information were identified, focusing on the requirements for the proper development of the coastal model. The planning and execution of field surveys specially designed to obtain a dense spatial and temporal coverage of current velocities is also described. Results of an analysis of field measurements of tidal flows, storm surge levels, current velocities and waves are presented. The main tidal constituents and asymmetries based on water level records at several locations as well as the results of an analysis of the spatial and temporal distribution of current velocities in the tidal channels are presented. Wave data provided by several authorities from waverider buoy recordings were analysed to investigate the distribution of wave characteristics and wave transformation throughout the study area. Vertical profiles of salinity and temperature were additionally measured at various locations along the current velocity measurement transects.

Although extensive measurements covering a wide area and a wide range of conditions were made during the investigations, only typical results are presented here for the sake of compactness.

2. Investigation Area

The investigation area consists of a tidal region on the German North Sea coast (Fig. 1). It is part of the Wadden Sea extending along the North Sea shore from the Netherlands to Denmark and covers an area of about 600 km² between the Elbe and Eider estuaries. The morphology of the area is dominated by tidal flats, intertidal channels and sandbanks in the outer parts of the domain. Water depths in the channels attain about 23 m, and approximately 50 % of the domain is intertidal. Water depths in the tidal flat region at high water are typically of the order of 0.5–2 m. Bed levels over the tidal flats range from about 0 to 1 m above NN (German Reference Datum, roughly equivalent to MSL). The system consists of three tidal channels; the Norderpiep in the northwest and the Suederpiep in the southwest, which intersect within the study area to form the Piep tidal channel. The surficial seabed sediment is mainly comprised of very fine to fine sand with varying proportions of silt and clay, whereas the sediment transported in suspension is mainly silt. Due to the high tidal range and small particle sizes the distribution of sediment concentration over the vertical is quite uniform and most of the sediment is transported in suspension. Similarly, the distribution of salinity over the vertical is fairly uniform and only very small spatial gradients are observed (POERBANDONO and MAYERLE, in this volume; RICKLEFS and ASP, in this volume).

The hydrodynamics of the investigation area are mainly driven by the combined effects of tides, waves, winds and storm surges. Under normal conditions, tidal action constitutes the main driving force. The area is characterised by a semi-diurnal tide with a mean tidal range of 3.2 m. Westerly winds prevail (SW–W). Although wave heights of up to 3–4 m are observed in the outer region, the influence of wave action on the resulting flow field is moderate over the tidal flats and negligible in the tidal channels. Wave-breaking usually occurs along the edge of the tidal flats.

The patterns of hydrodynamics in the outer and inner regions of the study area are quite distinctive. In the outer regions, with water depths of about 20 m, the hydrodynamics are mainly driven by tides and swell. The effect of waves on the sandbanks can be quite significant. In the inner regions of the domain there is a clear distinction between the physical processes over the tidal flats and in the channels. The hydrodynamics in the tidal channels are mainly driven by tides. Due to the large water depths in the channels (up to 20 m) the effect of waves on currents is relatively small. Under normal conditions wave heights are generally below about 0.5 m. On the tidal flats the flow is driven by the combined effect of tides, waves and winds. Due to the small water depths over the tidal flats the effects of waves and winds on currents and sediment transport can be significant. Storm surges may produce water level set-ups of up to 3.6 m, thus favouring wave propagation in shallow areas. Even under such conditions, however, wave effects are more pronounced on the outer sandbanks.

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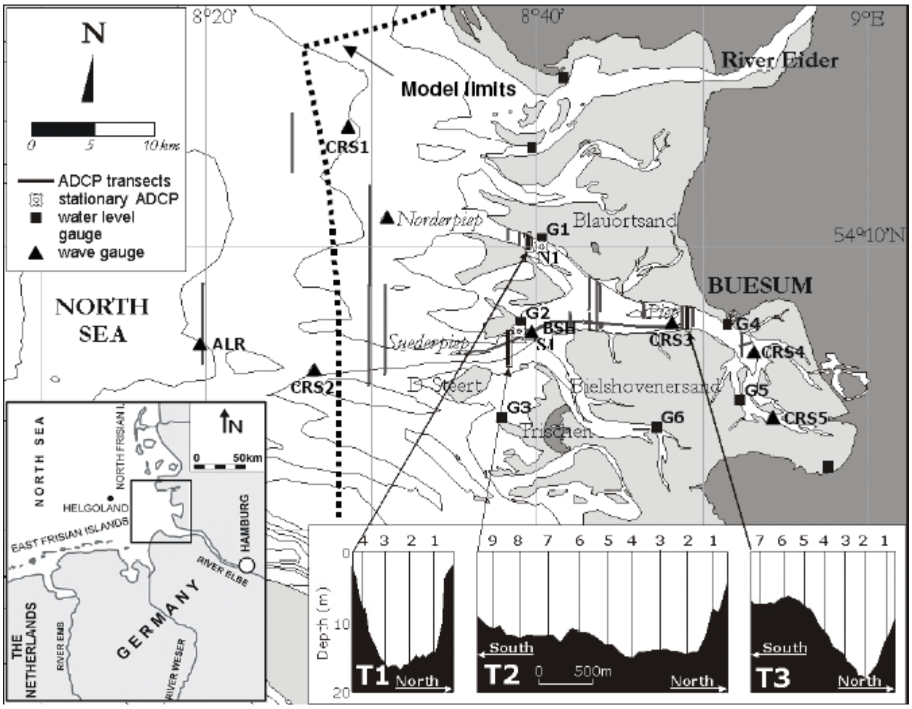

Fig. 1: Investigation area and measurement locations

3. Data Requirements

The data required to identify the most relevant physical processes governing hydrodynamics as well as the data necessary for developing and evaluating the process-based models for simulating flow and waves in the study area were made available during the early stages of the research project through close cooperation between experimentalists and numerical modellers. Initial simulations with ad-hoc models, i.e. non-calibrated models, were performed to analyse the general hydrodynamic behaviour in the study area. Field data requirements were subsequently determined on the basis of these model results and the data available from previous measurements.

3.1 General Knowledge from Ad-hoc Modelling

The results of initial simulations using a flow model of the German Bight developed by Delft Hydraulics (see HARTSUIKER, 1997), and made available by the CRS (Norderney), as shown in Fig. 2, clearly illustrate the propagation of a tidal wave in the German Bight during a tidal cycle. It is interesting to note that although the tidal wave propagates in the anti-clockwise direction in the German Bight, it approaches the Dithmarschen Bight almost parallel to the coastline. The tidal currents are directed onshore and offshore during the flood and ebb phases, respectively. From sensitivity tests with an initial ad-hoc flow model

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of the Dithmarschen Bight it could be shown that the flow exchange in the area takes place mainly through the Norderpiep, Suederpiep and Piep tidal channels. Furthermore, it was shown that the dynamics of the study area are not influenced by the discharges of the Elbe and Eider rivers, as extensive tidal flats separate these systems from the study area. Similarly, the application of an ad-hoc wave model showed that these shallow tidal flats also prevent the intrusion of a significant amount of wave energy at these locations. Even under storm conditions, there is no evidence that interaction takes place over the shallow areas. Pronounced wave attenuation was also found to occur on moving from east to west through the Dithmarschen Bight.

3.2 Data Needs for Model Development

Although numerical models now find increasing application in the management of coastal areas, these models are rarely validated with adequate measurements. The reason for this is that the purpose of most of the field data collected in the past was to clarify physical processes rather than for developing numerical models. The evaluation of numerical models, particularly for coastal areas, places special requirements on the data such as detailed measurements along the open-sea boundaries and a dense spatial and temporal coverage within the modelled domain for calibration and validation purposes. Complete and simultaneous data sets are thus essential for driving and checking the performance of numerical models.

3.3 Available Data and Information Gaps

Table 1 gives an overview of the existing data on water levels, waves and winds available in the study area. The locations of existing gauge stations for water level measurements as well as the positions of waverider buoys are shown in Fig. 1. Water levels are monitored by the Regional State Office for Rural Areas in Husum (ALR). In this study, water level data recorded at the following gauge stations were used: G1: Blauort in the Norderpiep tidal channel; G2: Tertius in the Suederpiep tidal channel; G3: Trischen; G4: Buesum; G5: Steertloch West and G6: Flackstrom. Gauge stations G1 to G3 are situated along the western boundary of the investigation area whereas stations G4 to G6 are located in the inner part of the domain. The high spatial and temporal coverage of these gauge stations provides an ideal basis for calibration and validation of the flow model with respect to water levels.

Information on waves in the study area was gathered from several sources. An essential set of data was made available by the Coastal Research Station of the Lower Saxony Board of Ecology (CRS) on Norderney, who conducted a one-month measuring campaign with five waverider buoys within the framework of the German Coastal Engineering Research Council (GCERC-KFKI) Project "Bemessung auf Seegang" (grant number KFKI 45) funded by the German Ministry of Education and Research (grant number MTK 0561 – NIEMEYER, 1997). The positions of the waverider buoys in the study area were carefully defined in order to provide the data necessary for developing the wave model. Two directional waverider buoys (CRS1 and CRS2) were positioned some distance offshore of the study area at water depths of about 10 m to provide information for driving the model. The remaining waverider buoys were positioned in the inner parts of the study area to provide the data required for calibrating and validating the model (CRS3 to CRS5). Further wave data were collected with

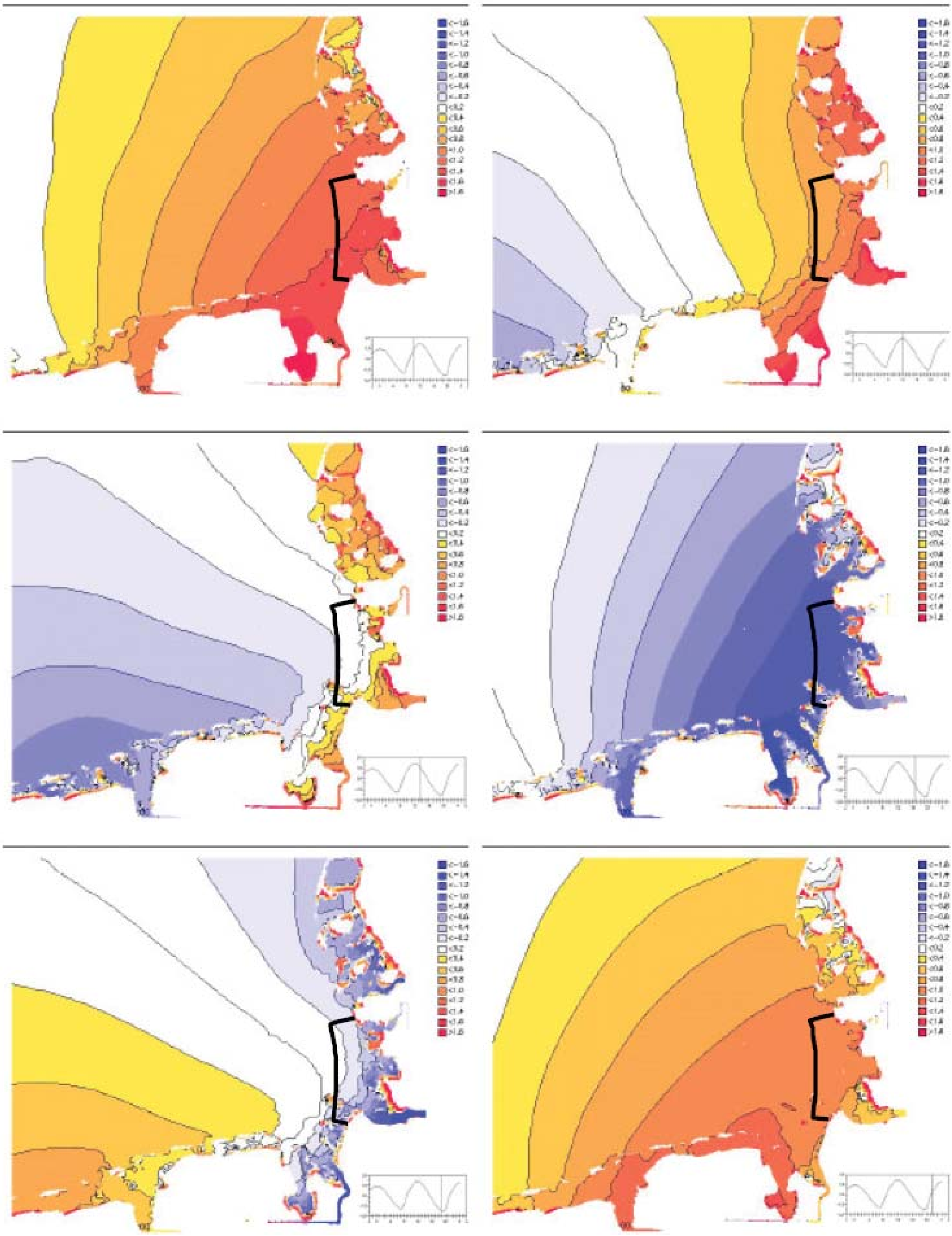

Fig. 2: Tidal wave propagation in the central part of the German Bight

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Table 1: Overview of Available Data Recordings

Data	Device & Location (Fig. 1)	Period	Source
Water level	Gauge stations: G1 to G6	January 1989 till December 1990	Regional State Office for Rural Areas in Husum (ALR)
Waves	Waverider buoys: Directional: CRS1 & CRS2 Non-directional: CRS3 to CRS5	September–October 1996	Coastal Research Station of Lower Saxony Board of Ecology at Norderney
	Waverider buoy: Directional: ALR	June 2000–May 2001	Regional State Office for Rural Areas in Husum (ALR)
	Waverider buoy Directional: BSH	November 2000–April 2001	German Federal Maritime and Hydrographic Agency in Hamburg (BSH)
Wind	PRISMA interpolation model	1989–2000	Max Planck Institute of Meteorology in Hamburg (LUTHARDT, 1987).

aid of waverider buoys by the Regional State Office for Rural Areas in Husum (ALR) and the German Federal Maritime and Hydrographic Agency in Hamburg (BSH). The measuring locations at the approach to the Dithmarschen Bight and at the entrance to the Suederpiep tidal channel are shown Fig. 1.

The wind data used in the project were obtained with the aid of 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 stations covering the entire North Sea. The PRISMA model generates wind data every three hours at the nodes of a grid with a mesh spacing of 42 km.

Based on the available data and taking into consideration the hydrodynamics of the study area and the additional data required for developing the flow and wave models, gaps in information were identified and several aspects concerning the development and evaluation of process-based models for simulating flow and waves were clarified. As the hydrodynamics of the study area are very much governed by conditions along the western open-sea boundary, it was necessary to obtain simultaneous sets of data for driving the flow and wave models as well as data within the model domain for the purpose of model calibration and validation. Moreover, as the main exchange of flow in the study is through the tidal channels, for which little information on current velocities is available, it was planned to undertake several measuring campaigns to obtain essential information on the temporal and spatial variations of current velocities and directions at a number of key locations. The planning and execution of the field surveys as well as an analysis of the results are presented in the following sections.

3.4 Clarification of Various Aspects of Model Settings

With regard to the definition of the model limits it was decided to position the western open-sea boundary at right angles to the direction of propagation of the tidal wave and swell into the coastal area. In view of the intensive morphological changes that occur on the sand banks and outer tidal flats it was proposed to shift the model limits further westwards to a location where the bathymetry is reasonably stable. By setting up the western open-sea boundary in the near vicinity of the waverider buoys CRS1 and CRS2 it was possible to directly use the data from these buoys to drive the wave model and subsequently employ the simultaneous data from the waveriders CRS3 to CRS5 for calibration and validation purposes. Fig. 1 shows the proposed limit of the model covering the entire Dithmarschen Bight. With regard to the development of the flow model it was proposed to follow a two-step approach. In the first step a smaller model covering only the central parts of the study area was set-up. The western open-sea boundary of this model was positioned in the vicinity of the gauge stations G1 to G3, whereas the northern and southern boundaries were located on tidal flats. The eastern boundary of the model consists of the shoreline together with the open boundaries formed by the mouths of the Eider and Elbe estuaries. Hydrodynamic forcing along the western open-sea boundary of the flow model could thus be realised by specifying the water levels measured at one or more gauge stations in the proximity of this boundary (G1, G2 or G3 in Fig. 1), provided that the momentum balance could be maintained. The water level measurements at the remaining gauge stations (G4 to G6) could then be used for the purpose of model calibration and validation. In a second step it was proposed to extend the flow model to cover the same domain and utilise the same grid as the wave model. In order to permit flow and wave simulations for a wider range of conditions than those of the measuring periods it was additionally proposed to set-up nested and coupled flow and wave models covering the adjoining area of the North Sea (see MAYERLE et al., in this volume). Detailed descriptions of model set-up, sensitivity studies, and calibration and validation of the flow and wave models are given in PALACIO et al. (in this volume) and WILKENS et al. (in this volume), respectively.

4. Measurements of Current Velocity

4.1 Measuring Devices and Experimental Set-up

Measurements of current velocity and direction were performed over several cross-sections and at various locations in the tidal channels, as indicated in Fig. 1. The data were gathered with the aim of obtaining detailed information on the temporal and spatial variations of current velocity and direction at key locations in the study area. The field surveys were planned and executed in such a way as to provide the data necessary to gain a better understanding of the underlying physical processes, define the strategy for model development, and check the performance of the flow models. The temporal resolution of the measurements was dictated by the physical conditions prevailing in the investigation area. As the hydrodynamics of the study area are driven by tides, winds and waves, it was planned to perform the measurements over at least one tidal period in each case for the main range of tidal conditions.

Current velocity data were obtained using 1200 kHz Acoustic Doppler Current Profilers (ADCPs) manufactured by RD Instruments. These instruments were set to record a 0.5 m bin size over a 12 seconds averaging ensemble. An investigation of the accuracy of the ADCPs for measurements in the tidal channels of the central Dithmarschen Bight showed that the standard deviations for point measurements are approximately constant, with values of about 0.06 m/s and 0.14 m/s for distances above and below 1m from the seabed, respectively. The accuracy of the devices for measuring depth-averaged velocities was found to be about 0.015 m/s (JIMÉNEZ-GONZÁLEZ et al., in this volume).

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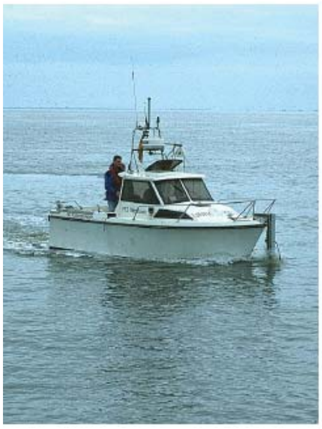
The measurements from moving vessels were intended to provide detailed spatial coverage of the velocity distribution over a tidal period. These measurements covered several cross-sections of the main tidal channels, as indicated in Fig. 1. A number of vessels equipped with similar acoustic profilers were deployed simultaneously to cover a larger area. Fig. 3 shows the vessels used within the framework of the research project PROMORPH. The research vessel Suedfall and the research boat Seston are operated by the Research and Technology Centre "Westcoast" of the University of Kiel. The RV Suedfall, which is 19 m long, 5 m wide and has a draught of 1.6 m, is equipped for operations in coastal waters of the North and Baltic Sea. The research boat Seston, which is 6.3 m long, 2.5 m wide and has a draught of 0.6 m, is mainly deployed for measurements in the German Wadden Sea, particularly in shallow areas. In order to permit measurements in deeper areas and perform simultaneous measurements over several cross-sections the RV Ludwig Prandtl operated by the GKSS

(a) RV Suedfall operated by the FTZ Westcoast, Kiel University



(b) RB Seston operated by the FTZ Westcoast, Kiel University

(c) RV Ludwig Prandtl operated by the GKSS Institute for Coastal Research

Fig. 3: Research vessels deployed for measuring current velocities

Institute for Coastal Research was also deployed in a number of measuring campaigns. The RV Ludwig Prandtl is 32.5 m long, 7.5 m wide and has a draught of about 1 m. During measurements from moving vessels the acoustic profiler was directed downwards from the bow of the vessel and deployed for the continuous measurement of current velocity profiles along cross-sectional transects.

Fig. 4 illustrates the approach adopted for profiling from moving vessels. In addition to current velocity measurements, profiling of suspended sediment concentration, salinity and temperature was also carried out at defined stations within the cross-sectional transects. Details of these measurements are given in Poerbandono and Mayerle (in this volume). During a full measuring campaign, which usually covers a complete tidal period, the survey vessel moves back and forth along a cross-sectional transect. Measurements of current velocity profiles covering the entire cross-section were carried out along each transect following approximately the same track. The number of cross-sectional transects surveyed during a tidal period depends primarily on the cross-sectional width and measuring conditions.

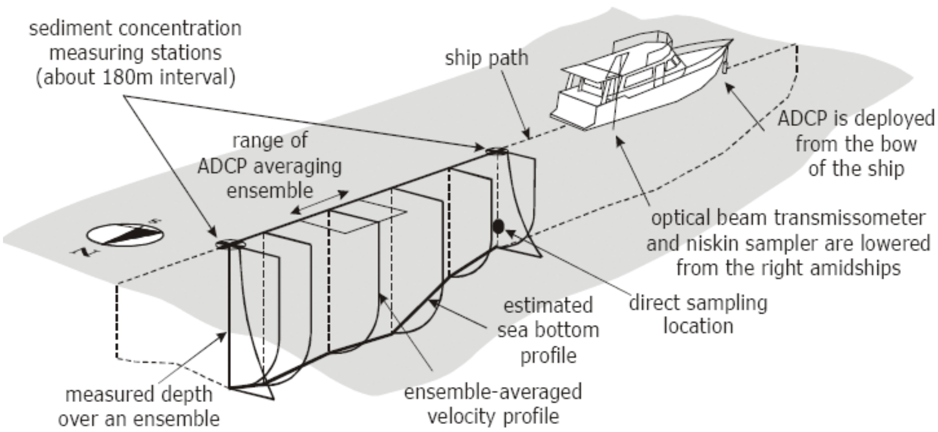


Fig. 4: Measurement procedure for profiling current velocities from moving vessels

Measurements over the water column were made from about 1.5 to 2.0 m below the free surface (to avoid the effects of transducer draught and blanking distance) down to about 6 % of the depth above the seabed (to avoid side lobe effects). As the measurements did not cover the entire water column, extrapolations were necessary in the surface and near-bed layers to obtain a complete velocity profile over the full depth. For this purpose a constant velocity value from the uppermost point measurement to the free surface and a linear variation from the lowest measured value towards zero at the seabed were adopted in this study.

Bearing in mind that measurements from a moving vessel are limited to calm weather conditions, moored devices were also deployed in order to gather information during more adverse weather conditions. The aim of this was to obtain information on the velocity distribution over the depth covering longer periods and more adverse weather conditions. Two locations along the main tidal channels at the entrance to the central Dithmarschen Bight (see N1 and S1 in Fig. 1) were chosen for the moored devices, which were anchored on the bed and directed towards the free surface. Profiles of current velocities were obtained during the entire period of measurements. A definition sketch illustrating the installation of the moored devices is shown in Fig. 5. Measurements from the moored devices covered the water column from the free surface to about 2 m above the seabed. The depth-averaged velocity was determined by assuming a linear variation from the lowest cell measurement towards zero at the seabed. It is noted that this approximation may lead to discrepancies compared with observed values, especially at low water levels.

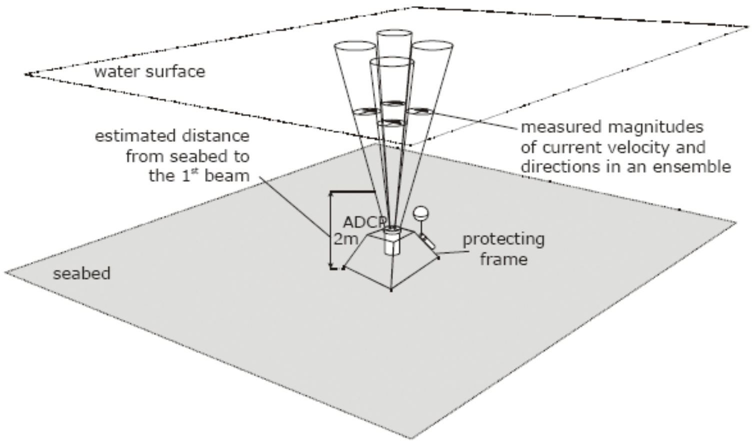


Fig. 5: Measurement procedure for profiling current velocities using acoustic devices moored on the seabed

4.2 Environmental Conditions

The measurements from moving vessels were performed over several cross-sections covering a wide area extending from the deeper regions of the central Dithmarschen Bight to the inner parts of the main tidal channels. Fig. 1 shows the locations of the surveyed cross-sections. The measurements were carried out at regular time intervals from March 2000 to September 2001 in order to account for seasonal variations. Each measuring campaign was conducted twice within about seven days to cover neap and spring tidal variations. Measurements were also carried out for a wide range of tidal conditions in order to investigate spatial (vertical and horizontal) and temporal (tidal phase, lunar cycles, seasonal) variations.

The sets of field data based on measurements from moving vessels are listed in Table 2. In this paper attention is focused on measurements carried out over two cross-sections T1 and T2 in the main tidal inlets, and an additional cross-section T3 near the coast (see Fig. 1). T1 in the Norderpiep tidal channel is about 770 m wide with water depths varying from 2.8 m to 16.1 m; T2 in the Suederpiep tidal channel is about 2040 m wide with water depths varying from 7.3 m to 15.6 m, and T3 in the Piep tidal channel is about 1200 m wide with water depths varying from 6.2 m to 17.9 m. The bed profiles of cross-sections T1, T2 and T3 are also shown in Fig. 1. In order to obtain full coverage over a complete tidal period, measurements were made over several cross-sectional transects per measuring campaign. The astronomical tidal range during the field surveys varied between 2.3 m and 4.2 m for neap and spring tides, respectively. The measuring campaigns were undertaken under relatively calm wind conditions not exceeding Beaufort 4-5. The maximum point, depth-averaged, and cross-sectionally averaged velocities derived from these measurements are listed in Table 2.

Table 2: Current velocity data sets based on measurements from moving vessels

Cross-section [width]	Date	Tidal range (m)	Number of transects – Measuring duration (h)	Max. point velocity (m/s)		Max. depth-avg. velocity (m/s)		Max. cross-sect.-avg. vel. (m/s)	
				Flood	Ebb	Flood	Ebb	Flood	Ebb
T 1 [775 m]	Mar. 16, 2000	3.2	31 – 11.7	1.4	–2.0	1.3	–1.2	1.0	–1.0
	Mar. 22, 2000	4.0	31 – 11.6	1.5	–1.6	1.5	–1.4	1.1	–1.2
	Jun. 5, 2000	3.7	10 – 6.1	1.8	–1.6	1.7	–1.4	1.5	–1.2
	Sep. 5, 2000	3.0	26 – 10.4	1.4	–1.4	1.2	–1.3	1.0	–1.0
	Sep. 12, 2000	3.4	33 – 11.6	1.3	–1.2	1.3	–1.2	1.1	–1.0
	Dec. 5, 2000	2.3	11 – 5.5	0.7	–1.0	0.6	–0.9	0.5	–0.7
	Mar. 21, 2000	4.1	15 – 11.9	2.1	–1.7	1.6	–1.4	1.2	–1.0
T2 [2040 m]	Jun. 5, 2000	3.7	10 – 8.4	NA	–1.5	NA	–1.5	NA	–1.1
	Sep. 5, 2000	3.1	8 – 9.8	1.8	–1.4	1.3	–1.1	1.0	–0.9
	Sep. 12, 2000	3.3	10 – 10.8	1.6	–1.4	1.6	–1.2	1.1	–0.9
	Dec. 5, 2000	2.3	9 – 10.8	1.0	–1.1	0.8	–1.1	0.7	–0.7
	Mar. 14, 2000	3.6	14 – 8.8	1.5	–1.7	1.2	–1.3	1.0	–1.0
	Mar. 23, 2000	4.2	24 – 13.0	1.6	–1.7	1.2	–1.4	1.1	–1.0
	Jun. 6, 2000	3.9	15 – 8.2	1.4	NA	1.4	NA	1.1	NA
	Jun. 14, 2000	3.6	19 – 11.8	1.4	–1.4	1.3	–1.4	0.9	–1.1
T3 [1200 m]	Sep. 6, 2000	2.9	14 – 10.7	1.1	–1.1	0.9	–1.1	0.8	–0.8
	Sep. 13, 2000	3.5	8 – 4.6	1.6	NA	1.3	NA	1.1	NA
	Dec. 6, 2000	2.5	22 – 12.0	1.2	–1.1	0.9	–0.9	0.7	–0.8
	Jun. 22, 2001	3.9	9 – 5.9	1.5	NA	1.4	NA	1.1	NA
	Jun. 28, 2001	3.6	13 – 11.4	1.4	–1.3	1.2	–1.1	1.0	–0.8
	Sep. 11, 2001	3.1	14 – 11.1	1.2	–1.4	1.1	–1.3	0.9	–0.9

Notes: 1) negative current velocities are directed offshore
2) NA means not available

The sets of field data based on measurements over longer periods from the moored devices are listed in Table 3. These devices were deployed along the two main tidal inlets at the entrance to the Dithmarschen Bight, i.e. in the Norderpiep and Suederpiep tidal channels at locations N1 and S1 shown in Fig. 1. The devices were moored close to the gauge stations G1 and G2 located in the vicinity of cross-sections T1 and T2 (see Fig. 1). The mean water depths at the measuring stations N1 and S1 are about 9 m and 13 m, respectively. The measurements were carried out during the year 2000 over two periods lasting about 15 days and one period lasting about 3 months. The astronomical tidal range during measurements varied between 1.6 m and 3.9 m. Wind velocities of up to 15 m/s were observed during the measuring periods.

Based on the cross-sectional measurements carried out from moving vessels, the maximum point current velocities in cross-sections T1, T2 and T3 were found to be 2.0 m/s, 2.1 m/s and 1.7 m/s, respectively. A similar order of magnitude was obtained for the maximum depth-averaged and cross-sectionally averaged values of current velocity observed in the two cross-sections at the entrance to the study area. Smaller values were observed in the cross-section nearer to the coast (cross-section T3). An analysis of longer-term measurements from moored acoustic profilers showed that maximum current velocities (depth-averaged values) in the Norderpiep and Suederpiep tidal channels (Stations N1 and S1) are about 2.8 m/s (1.3 m/s) and 2.1 m/s (1.5 m/s), respectively.

Table 3: Current velocity data sets based on measurements from moored devices

Location	Measurement period	Water depth (m) Range and (mean)	Tidal range (m)	Max. & (mean) wind speed (m/s)	Max. velocity values (m/s)					
					Point				Depth-averaged	
					top layer		bottom layer			
					Flood	Ebb	Flood	Ebb	Flood	Ebb
N1 Norderpiep tidal inlet	Aug. 10 to Sep. 27, 2000	6.5–11.0 (9.0)	1.8 to 3.9	15.0 (4.5)	1.86	1.55	1.00	0.93	1.27	1.07
	Nov. 15 to Dec. 7, 2000	6.9–10.8 (9.1)	1.6 to 3.6	15.2 (6.0)	2.79	2.18	0.99	0.85	1.19	0.93
S1 Suederpiep tidal inlet	May 31 to June 15, 2000	10.3–14.8 (12.8)	2.6 to 3.9	12.2 (4.6)	2.10	1.80	1.00	1.00	1.54	1.47

5. Data Analysis

5.1 Tides

Tidal oscillations in the North Sea are determined by its dimensions and the progressive semi-diurnal tides entering from the Atlantic Ocean. The tidal flow is deflected by the Coriolis force, resulting in three amphidromic systems. Tidal conditions in the central Dithmarschen Bight depend primarily on the rotation of the semi-diurnal tidal wave around the amphidromic point in the south eastern part of the North Sea. As previously mentioned, the tidal wave propagates counter-clockwise along the German Wadden Sea coast (see Fig. 2). According to ASP (2004), the area is characterised by a semi-diurnal tide with a tidal period of about 12 hrs and 24 min. The mean tidal range varies from about 3.1 m to 3.4 m between the mouth of the Elbe estuary in the south and the Eiderstedt peninsula in the north. Referred to NN, the mean high and low water levels at the gauge station Buesum (G4 in Fig. 1) are +1.6 m and –1.6 m, respectively. An analysis of a long time series of water level measurements reveals that the mean tidal range in the study area is about 3.2 m, with neap and spring tidal ranges of about 2.8 m and 3.5 m, respectively.

A tidal analysis was carried out for gauge stations G1 to G6 over a 65-day period characterised by relatively calm weather conditions from April 27 to June 30, 1990. The water level data was available at 30 min. intervals. During this period only a few storms of short duration were observed with wind velocities not exceeding 10 m/s. Fig. 6 shows the variations in water level and wind velocity during part of the period in question at the stations Tertius (G2) at the entrance to the domain, and Steertloch (G5) near the coastline. It is seen from the figure that the amplitudes of water levels nearer the coast are slightly higher than at the entrance to the domain. Although a time lag exists between the measured tidal curves at the two stations, this is hardly discernable in the plots.

The main astronomical constituents were identified on the basis of previous studies carried out in the area (HARTSUIKER, 1997). Based on sensitivity studies using different groups of constituents, 36 independent and 3 coupled harmonic constituents that best represent the measured water level time series were selected. The computed amplitudes and phases of the constituents considered in the tidal analysis are shown in Tables 5 and 6, respectively. Fig. 7 shows a comparison of the ten main constituents obtained at the five locations. It is interesting to note that the tidal constituents at the gauge stations located on the western boundary of the study area (G1 to G3) exhibit similar phases and amplitudes. This is due to the fact that the crest of the tidal wave approaches the study area almost aligned with the edges of the tidal flat areas (see Fig. 1 and 2). An examination of the maximum amplitudes of the main tidal constituents observed at all stations reveals the pronounced semi-diurnal nature of the tides in the region. The main tidal constituent is M2. The next constituent of importance is S2 followed by N2. The maximum amplitude is found at the station Steertloch (G6). ASP (2004) analysed the variation of water level measurements at the gauge stations Blauort and Tertius (G1 and G2 in Fig. 1) at the entrance to the domain and at Buesum (G4) near the coast. As a result of this analysis it was found that high water occurs at station G4 about 10 to 12 min. later than at stations G1 and G2 whereas low water occurs at about the same time at the gauge stations Buesum (G4) and Tertius (G2), and 4 min. later at Blauort (G1).

In order to verify the quality of the constituents, comparisons were made between hindcasted and observed water levels. Hindcasts for the three periods listed in Table 4 were computed using the derived constituents. A comparison between measured and predicted tidal elevations for the three periods is shown in Fig. 8 for the gauge station Tertius. Fig. 9 shows the standard deviations of the discrepancies between measurements and hindcasts in cm and as a percentage of the tidal range. The discrepancies presented in Fig. 9 are given in terms of the mean error (ME) and the corresponding standard deviation (STD) and the mean absolute error (MAE). The results indicate fair agreement between measurements and hindcasts, with a mean absolute error at all locations and for all periods of generally less than 20 cm, i.e. less than about 6 % of the mean tidal range.

Table 4: Periods selected for checking the accuracy of hindcasted water levels

Period	Beginning & end dates	Duration (days)	Wind characteristics and storms
1	May 31 to June 26, 1989	27	Wind velocities less than 8 m/s
2	May 31 to July 12, 1989	43	Incorporates 2 small storms with wind velocities of 9 m/s and 11 m/s, respectively
3	July 07 to August 18, 1990	43	Incorporates 4 storms with durations longer than 1 day but with wind velocities ≤ 10 m/s

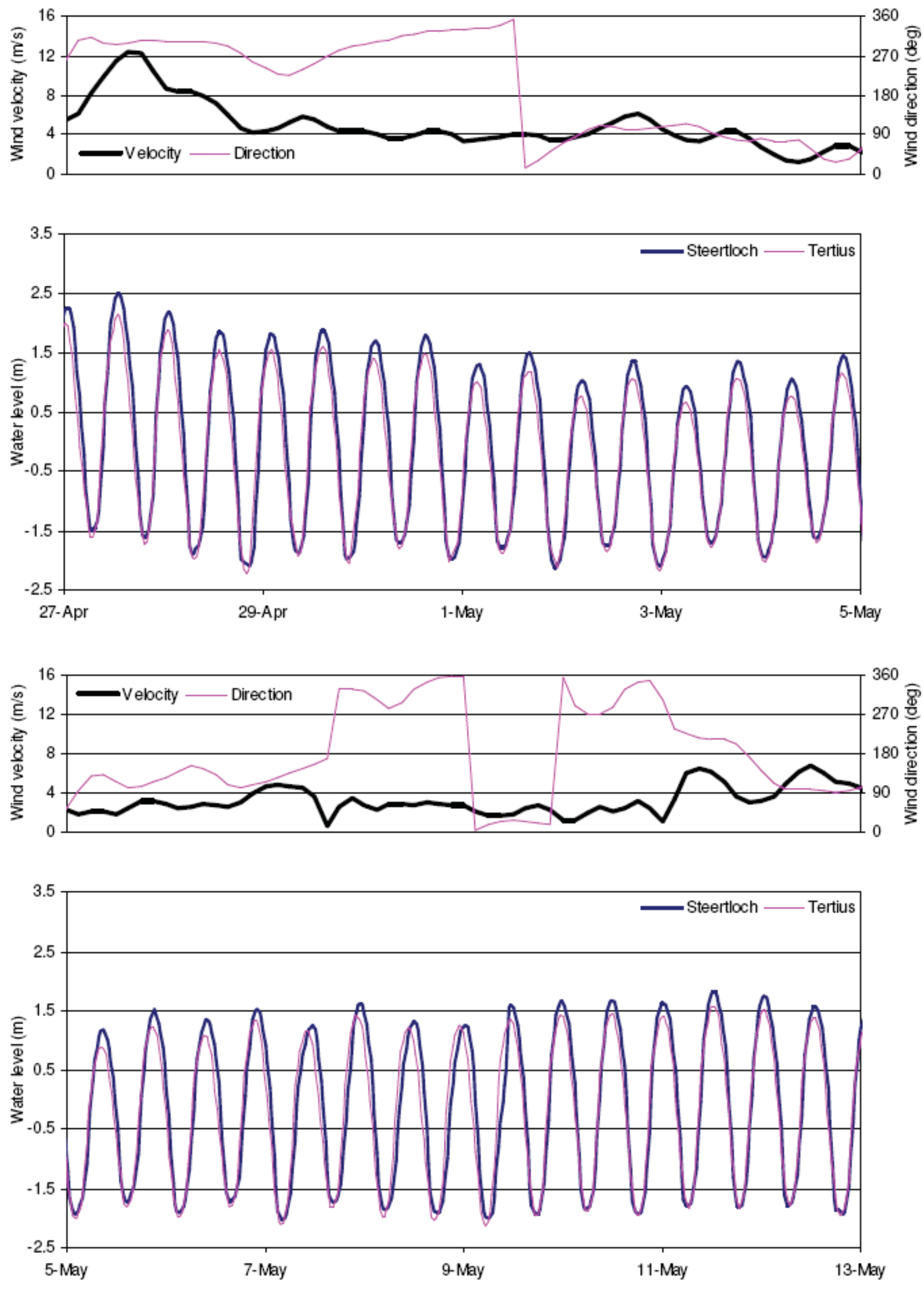
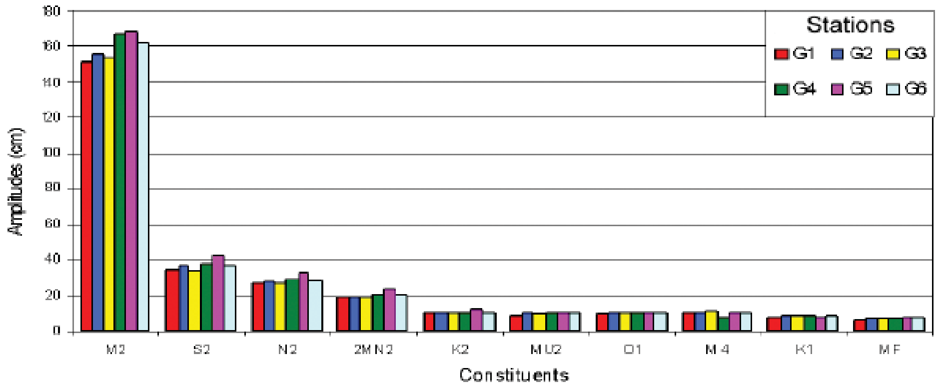
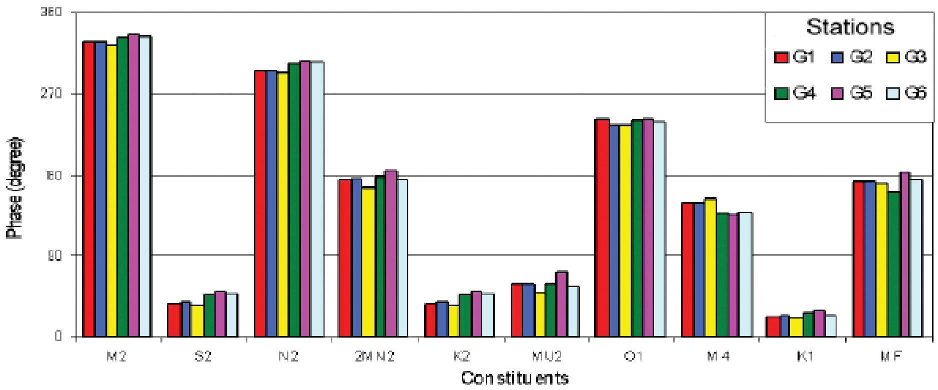


Fig. 6: Tidal records at the gauge stations Tertius (G2) and Steertloch (G5) for the period considered in the tidal analysis



(a) Amplitude



(b) Phase

Fig. 7: Comparison of the main tidal constituents at gauge stations G1 to G6 in the Dithmarschen Bight

The seasonal variation of tidal asymmetry was investigated at several locations in the tidal channels by Asp (2004). This investigation was carried out owing to the relevance of tidal asymmetry regarding sediment transport and accumulation. The water levels measured at several locations in the tidal channels were used to determine flood or ebb dominance, i.e. dominant phases corresponding to phases of shorter duration and hence with higher velocities, as defined by Friedrichs and Aubrey (1988). The water levels used in the investigation were measured at three gauge stations; stations Blauort (G1) and Tertius (G2) at the entrance to the study area and station Buesum (G4) in the Piep tidal channel near the coast, representing the cross-sections T1, T2 and T3, respectively (see Fig. 1). The analysis covered the months of June, September and December 2000, corresponding to summer, autumn and winter periods, respectively. Fig. 10 shows the duration of ebb and flood phases separately for neap and spring tides. Differences of up to about 45 min. between ebb and flood phases were identified. According to the results, the cross-sections located at the entrance to the central

Dithmarschen Bight (T1 and T2) are flood-dominated during most of the year, particularly during the winter months and for spring tides. The cross-section nearer the coast (T3), on the other hand, is generally ebb-dominated during the summer. During the autumn and winter months, however, the ebb and flood phases are more or less balanced, i.e. almost no tidal asymmetry exists during these periods.

Fig. 11 shows the variation of monthly mean ebb and flood durations, water level set-ups and wind velocities from July 1999 to August 2002 at the gauge station Buesum (G4). It is seen that under relatively calm and moderate wind conditions, corresponding to almost undisturbed water levels, there is a clear tendency towards shorter ebb phases and hence ebb dominance. During the winter months, on the other hand, there is a tendency towards similar durations of ebb and flood phases due to more frequent and stronger westerly winds and hence higher water level set-ups. A sharp reduction in tidal asymmetry at this gauge station was observed for a threshold value of water level set-up of about 0.2 to 0.3 m.

Table 5: Amplitudes of the harmonic constituents (in cm) at gauge stations G1 to G6 in the Dithmarschen Bight

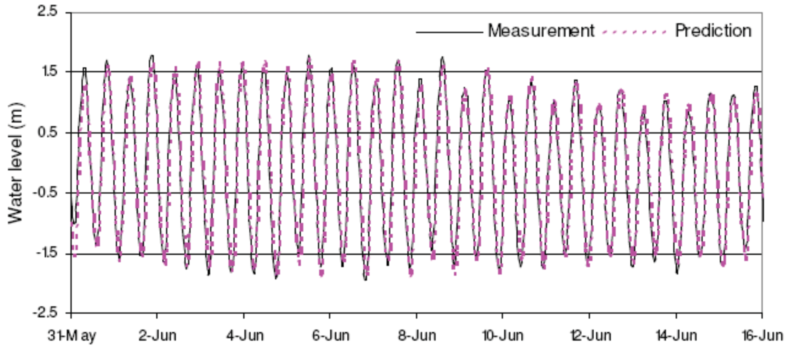
Harmonic Constituents	G1 Blauort	G2 Tertius	G3 Trischen	G4 Buesum	G5 Steertloch	G6 Flackstrom
M2	151.619	156.018	153.496	167.277	168.296	162.592
S2	34.998	36.928	34.282	38.129	42.518	36.736
N2	26.147	26.949	26.691	28.957	33.600	28.021
2MN2	18.559	18.612	19.048	20.385	23.363	20.264
K2	9.940	10.488	9.736	10.829	12.075	10.433
MU2	8.550	10.121	8.858	10.034	9.675	10.030
O1	9.415	9.898	10.190	10.447	10.668	9.872
M4	10.834	10.741	11.113	7.783	9.528	9.624
K1	7.722	8.259	8.363	8.648	7.480	8.692
MF	6.407	6.585	6.728	6.576	7.797	7.374
NU2*	5.073	5.228	5.178	5.618	6.518	5.436
MS4	4.773	4.779	4.684	4.271	5.299	5.085
MSN2	2.953	2.550	3.321	3.521	5.300	4.130
MN4	4.351	4.161	4.296	2.855	3.578	3.910
MNS2	3.984	4.401	4.113	4.337	7.795	3.812
2SM2	2.843	2.530	3.041	3.124	2.372	3.480
3MN4	3.458	2.986	3.071	3.053	3.843	3.457
M6	3.337	4.160	5.680	5.571	6.816	3.336
P1	2.533	2.709	2.743	2.836	2.453	2.851
2MN6	2.120	2.806	3.820	3.961	5.487	2.437
MM	3.288	3.048	1.653	0.98	2.916	2.402
3MS2	2.303	1.237	1.818	1.425	3.167	2.344
3MS4	1.320	1.607	1.474	1.625	2.268	2.153
M8	2.065	1.993	1.747	3.012	3.532	1.910
2MSN4	1.775	1.727	2.092	1.436	1.349	1.826
Q1	2.111	1.783	1.994	2.221	1.914	1.658
2MS6	2.161	2.311	3.612	3.035	4.260	1.452
3MS8	1.723	1.531	1.156	2.834	3.561	1.452
3MNS6	0.362	0.724	0.513	1.59	2.480	1.253
MK3	1.625	0.512	1.154	1.153	1.335	1.058
MSN6	0.202	0.307	0.828	1.183	1.678	1.034
2MNS4	1.013	0.895	0.881	1.024	1.417	0.989
M3	0.922	0.593	0.734	0.821	0.818	0.805
2MSN8	0.312	0.194	0.377	0.729	1.224	0.565
4MS6	0.438	0.152	0.388	0.564	0.687	0.548
S4	0.392	0.227	0.399	0.115	0.528	0.413
2SM6	0.098	0.296	0.251	0.172	0.266	0.396
4MS10	0.996	1.044	0.702	0.931	0.979	0.324
2(MS)8	0.310	0.181	0.198	0.446	0.628	0.028

* coupled constituent

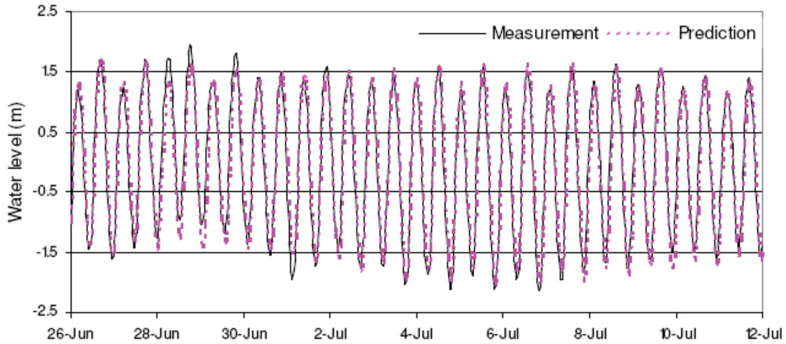
Table 6: Phases of the harmonic constituents (in degrees) at gauge stations G1 to G6 in the Dithmarschen Bight

Harmonic Constituents	G1 Blauort	G2 Tertius	G3 Trischen	G4 Buesum	G5 Steertloch	G6 Flackstrom
M2	326.9	327.6	323.1	332.9	335.7	333.5
S2	37.1	38.2	35.0	46.3	50.7	47.7
N2	295.7	295.2	294.7	303.7	306.2	304.6
2MN2	173.9	176.7	165.3	177.5	185.1	175.3
K2	37.1	38.2	35.0	46.3	50.7	47.7
MU2	59.7	57.7	49.3	60.2	72.4	54.7
O1	241.3	234.3	234.3	240.5	241.7	238.6
M4	149.1	149.1	153.7	138.3	136.6	139.7
K1	22.5	24.6	21.9	27.3	30.2	24.9
MF	171.8	171.0	170.6	160.5	182.2	174.6
NU2*	295.7	295.2	294.7	303.7	306.2	304.6
MS4	211.2	205.3	209.0	198	203.3	201.1
MSN2	234.4	230.4	203.9	210.3	220.1	221.0
MN4	107.3	108.9	120.7	100.4	105.2	106.2
MNS2	47.4	41.4	25.8	31	24.1	30.0
2SM2	248.1	218.2	226.3	232	258.2	243.4
3MN4	335.0	333.8	335.2	320.1	311.3	323.6
M6	22.5	43.9	19.4	120	134.1	127.0
P1	22.5	24.6	21.9	27.3	30.2	24.9
2MN6	344.4	7.2	343.9	86.2	103.8	94.1
MM	265.3	277.1	264.6	221.4	304.3	282.0
3MS2	177.7	227.2	207.6	222.4	204.0	213.8
3MS4	216.9	217.1	205.6	185.1	166.8	182.5
M8	280.3	283.1	265.7	293.3	299.4	298.8
2MSN4	38.8	34.7	28.6	32.7	21.6	15.8
Q1	169.0	171.6	178.0	172.4	165.4	186.6
2MS6	60.6	85.1	65.0	188.9	208.1	211.7
3MS8	342.7	344.5	314.0	350.7	355.8	355.0
3MNS6	185.8	172.5	111.1	218.6	225.8	236.5
MK3	136.9	183.5	152.5	163.2	114.4	139.8
MSN6	154.9	238.5	165.6	315.6	318.4	344.2
2MNS4	213.1	201.8	203.2	147.6	141.1	165.1
M3	147.7	106.7	125.7	174	169.4	172.6
2MSN8	64.1	60.9	18.9	52.5	44.7	60.2
4MS6	283.2	284.7	358.5	270.9	337.6	300.4
S4	52.6	10.5	61.5	34.2	348.6	352.1
2SM6	143.5	64.3	96.8	43.5	307.6	80.9
4MS10	162.2	203.2	185.3	150.5	127.5	269.2
2(MS)8	336.4	326.5	340.7	51.3	57.7	270.3

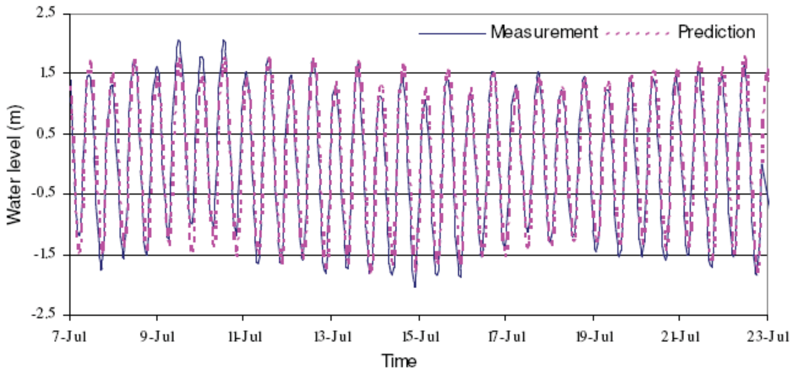
* coupled constituent.



a) Period 1

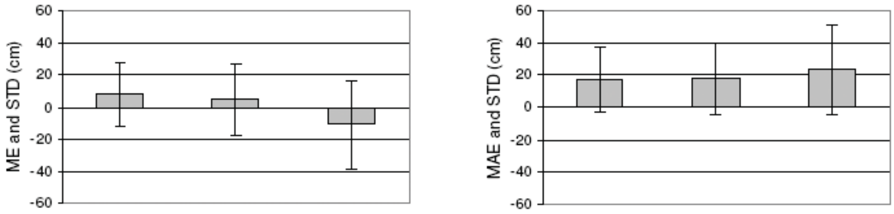


b) Period 2

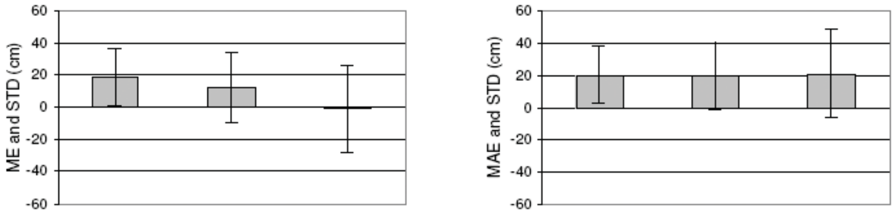


c) Period 3

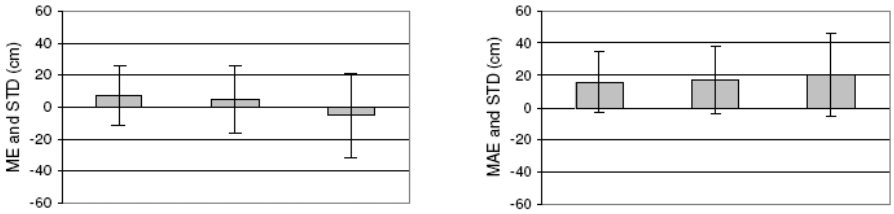
Fig. 8: Comparison of tidal records and astronomical predictions at the gauge station Tertius (G2)



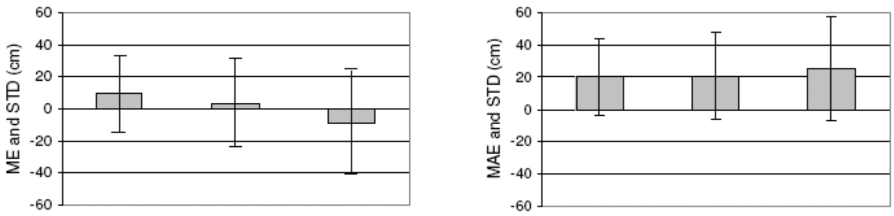
(a) Station G1 – Blauort



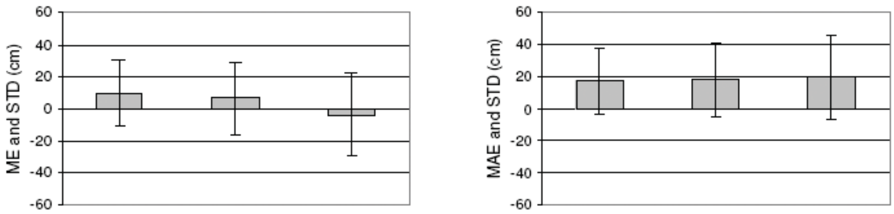
(b) Station G2 – Tertius



(c) Station G3 – Trischen



(d) Station G5 – Steertloch



(e) Station G6 – Flackstrom

Fig. 9: Mean Error (ME), Mean Absolute Error (MAE), and corresponding standard deviations of water level at gauge stations G1, G2, G3, G5 and G6 in the Dithmarschen Bight

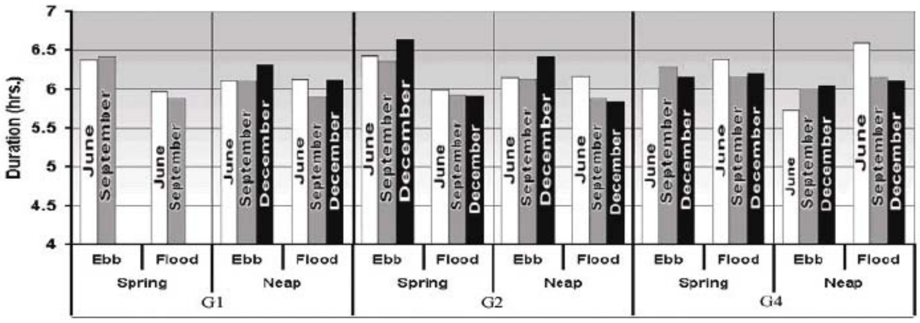
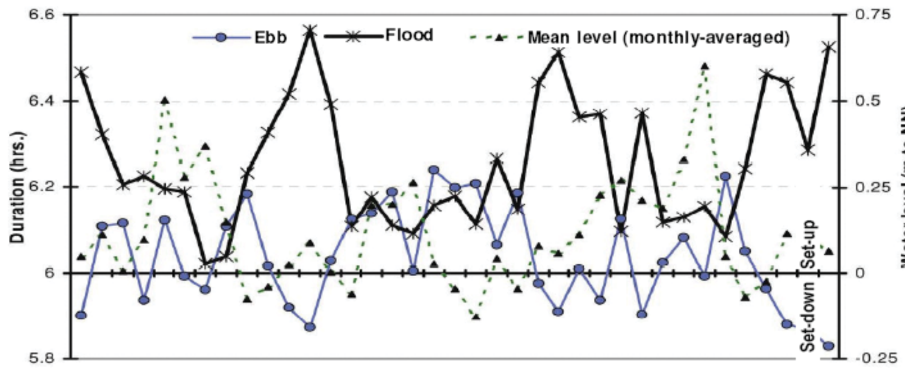
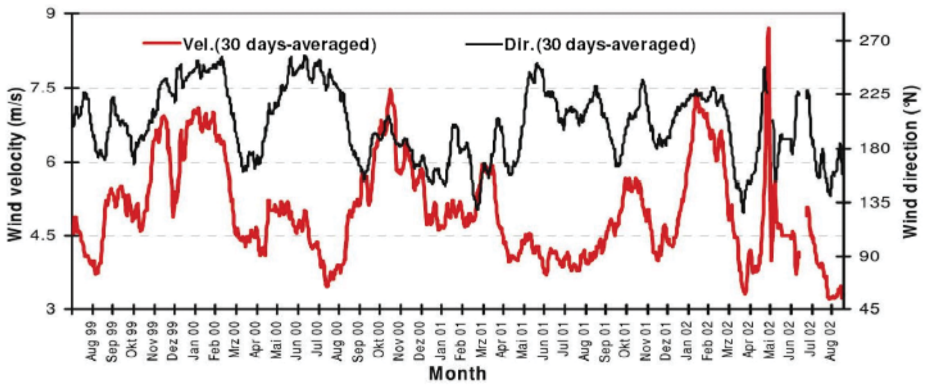


Fig. 10: Mean duration of ebb and flood phases at gauge stations G1, G2 and G4 (ASP, 2004)



a) Duration of flood and ebb phases



b) Wind velocity

Fig. 11: Variation of the duration of ebb and flood phases at gauge station G4 (ASP, 2004)

5.2 Storm Surges

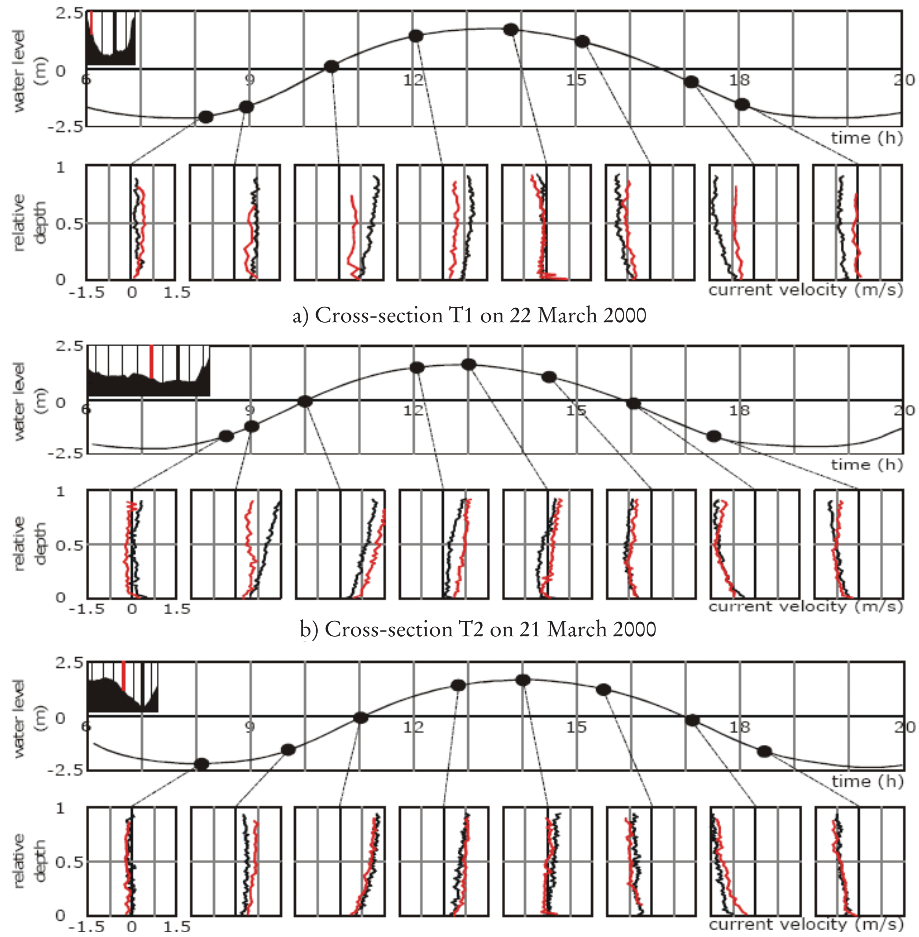
Storm surges, which result from extreme meteorological events, lead to a temporary increase in water levels in the near-coast region. The magnitude of a surge depends primarily on the size, intensity and movement of the storm responsible, and may be further influenced by the shape of the coastline, local bathymetry and state of the astronomical tide. The actual height of a storm surge is determined by subtracting the instantaneous astronomical tidal water level from the observed water level. A surge is mainly generated by the shear stresses exerted by the wind on the water surface and may be enhanced by the reduced atmospheric pressure associated with a storm depression. Since the wind-induced water level set-up is inversely proportional to the local water depth, the tidal flat areas of the Dithmarschen Bight are strongly affected by storm surges.

ROHDE (1992) found that the probability of storm surges exceeding 1.5 m at the mouth of the Elbe (Cuxhaven) annually is centred around December, with over 60 % occurring from November to January and over 80 % from October to February. MERTSCH (2004) presented a list of severe storm surges at Sankt Peter-Ording between 1990 and 2002 based on water level measurements supplied by the Regional State Office for Rural Areas (ALR) in Husum. This list contains 15 records of high water levels exceeding 3.5 m. Subtracting a mean high water level of an estimated 1.5 m above NN from the recorded high water levels results in storm surges of 2.0 m and above. It should be noted that these results are based on the mean high water level, as the instantaneous astronomical tidal water levels were not available for the periods in question. Similarly, the height of the maximum storm surge based on this list was found to be 2.85 m. The largest well-documented storm surge at Buesum occurred in 1967, when a maximum water level of 5.16 m above NN was observed (EAK, 2002). Subtracting a mean high water level of approximately 1.6 m above NN from the latter results in a storm surge of approximately 3.6 m. Again, the mean high water level was assumed due to lack of information on instantaneous astronomical tidal water levels during the storm surge.

5.3 Currents

The spatial and temporal variations of current velocity were investigated by analysing measured current velocities in the main tidal channels. This analysis focused on the sets of field data obtained from moving vessels and moored devices, as summarised in Table 2 and 3. Plots showing the variation of current velocity over the vertical and across the surveyed cross-sections as well as the variations of depth-averaged current velocity during a spring tide (21 to 23 March 2000) are shown in Fig. 13. Profiles of current velocity obtained from moored devices at two locations in the main tidal channels (stations N1 and S1 in the Norderpiep and Suederpiep tidal channels, respectively) are presented for selected conditions in Fig. 14. The variations of current velocity in the bottom and surface layers as well as depth-averaged values are also shown for neap and spring tides under relatively calm wind conditions as well as for periods with stronger winds.

Typical current velocity profiles during a spring tide are shown in Fig. 12. The results are shown for two measuring stations (marked in red and solid black) in cross-sections T1, T2 and T3. The variation of current velocities over the vertical is typical for tidal areas, with almost zero current velocity during low and high water slack and maximum values during the ebb and flood phases. In cross-section T2, through which most of the flow is conveyed into and out of the central Dithmarschen Bight, however, a different behaviour is observed in this respect during neap and spring tides. Whereas the maximum current velocity is along the south bank during the flood phase and the north bank during the ebb phase during spring tides, the opposite behaviour is observed during neap tides.



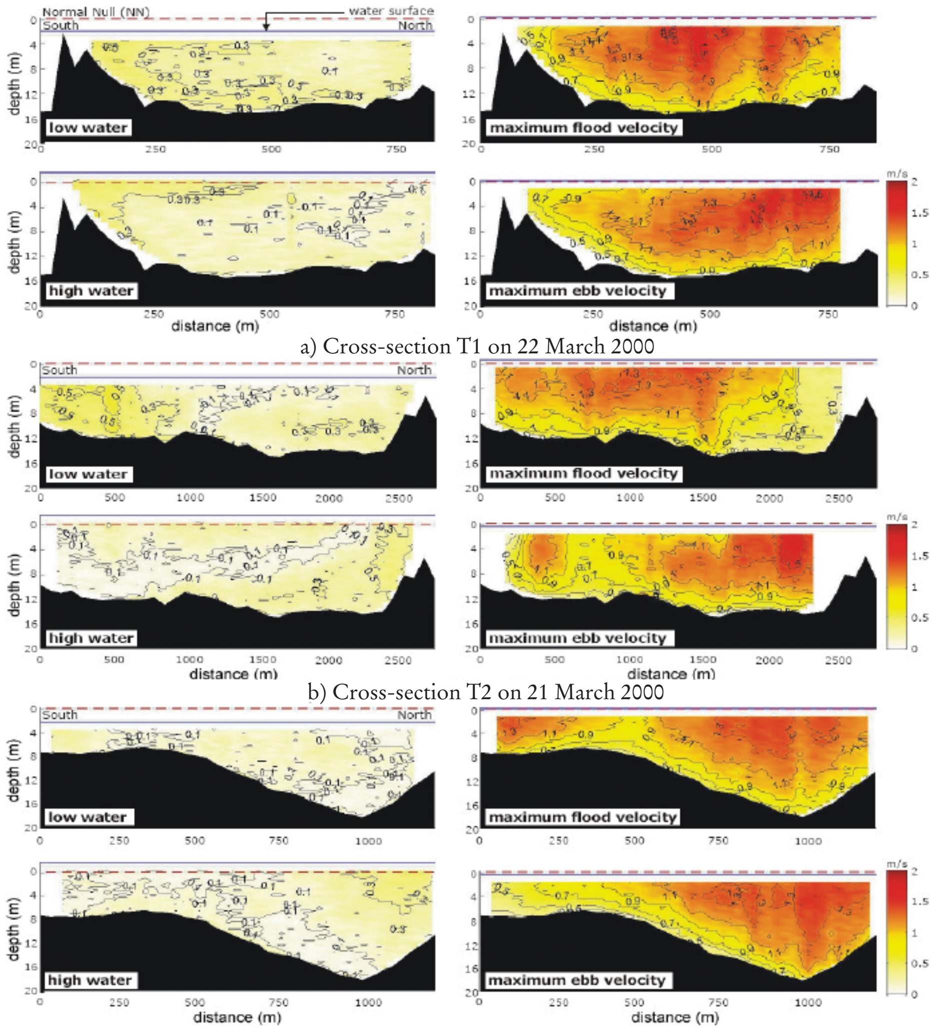
a) Cross-section T1 on 22 March 2000

b) Cross-section T2 on 21 March 2000

c) Cross-section T3 on 23 March 2000

Fig. 12: Variation of current velocity profiles for a spring tide during relatively calm weather conditions

The cross-sectional variation of current velocity in the tidal channels was investigated by analysing the distributions of measured velocities over the surveyed cross-sections. Typical distributions of current velocity in cross-sections T1, T2 and T3 for a spring tide are shown in Fig. 13. The results shown are for high and low water slack conditions and at times of maximum ebb and flood currents. These results reveal that in cross-sections T1 and T3 the cross-sectional variations during the flood and ebb phases attain a maximum at approximately the same location and that the gradient over the width is less pronounced than in cross-section



a) Cross-section T1 on 22 March 2000

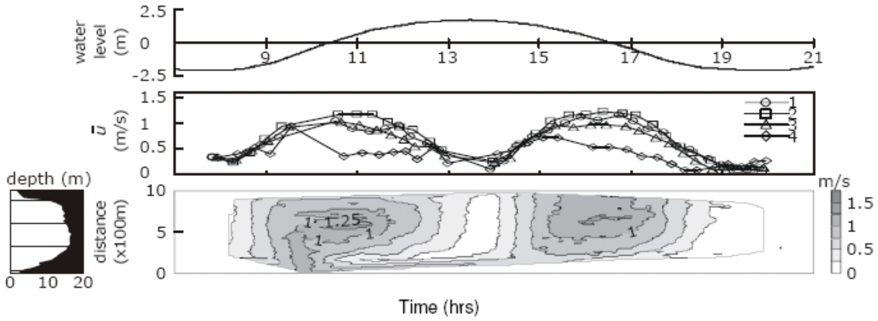
b) Cross-section T2 on 21 March 2000

c) Cross-section T3 on 23 March 2000

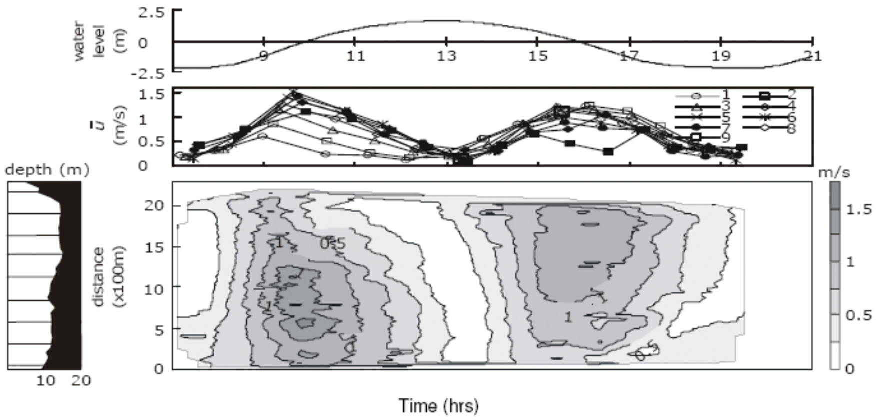
Fig. 13: Current velocity variations over the surveyed cross-sections during a spring tide

T2. In cross-section T2 it is also evident that the flood flow enters the study area predominantly through the northern part of the cross-section, whereas the ebb flow leaves the study area essentially through the southern part.

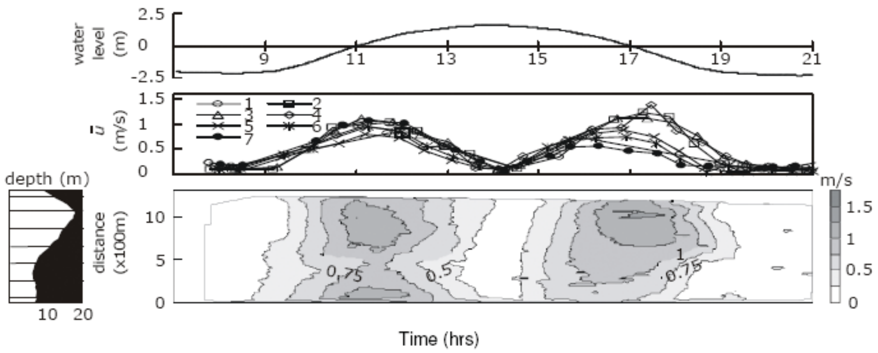
The cross-sectional variations of depth-averaged current velocity in cross-sections T1, T2 and T3 during a full spring tidal period are shown in Fig. 14. The spatial plots were obtained by interpolating the current velocities measured along the cross-sectional transects with respect to time. It is interesting to note that the maximum current velocities during the flood and ebb phases of neap and spring tides are at approximately the same location in cross-sections T1 (Norderpiep channel) and T3 (Piep channel), namely in the deepest parts of the channels. In cross-section T2, through which most of the flow is conveyed into and out



a) Cross-section T1 on 22 March 2000



b) Cross-section T2 on 21 March 2000



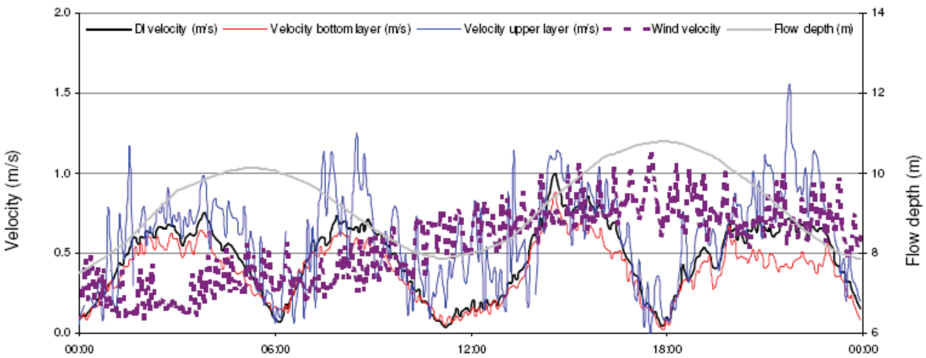
c) Cross-section T3 on 23 March 2000

Fig. 14: Variations of depth-averaged current velocity over the cross-sections during a spring tide

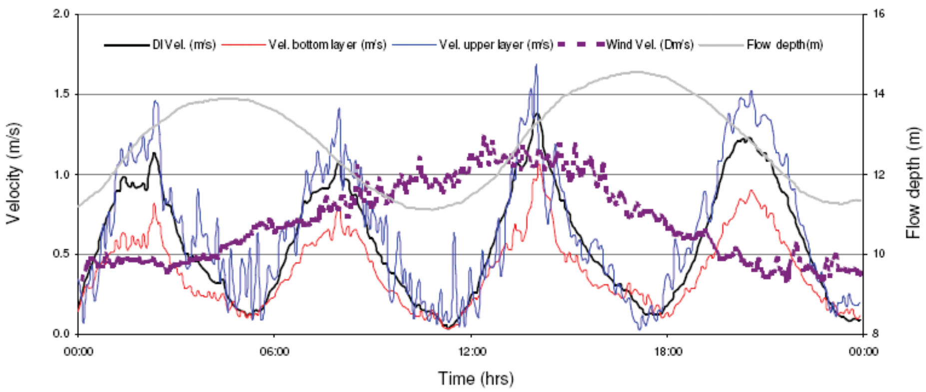
of the central Dithmarschen Bight, however, a different behaviour is observed in this respect during neap and spring tides.

In order to investigate the variations of current velocity during spring and neap tides under different weather conditions the measurements obtained from the moored devices were analysed. Typical results are shown for periods with stronger winds. Current velocities measured near the free surface and the seabed as well as depth-averaged values are shown together with water level variations and observed wind speed and direction in Fig. 15. Maximum values of current velocity of about 1.8 m/s were observed in the Suederpiep tidal channel during the flood phase of a spring tide. Flood dominance is clearly evident in the Norderpiep channel, and to a lesser extent also in the Suederpiep. The current velocities in the upper layers are seen to be influenced by wind velocity, particularly at the measuring station N1 in the Norderpiep tidal channel. This measuring station is more exposed than station S1 and is not protected by sand banks.

The temporal variations of flow discharge through cross-sections T1, T2 and T3 for a spring (March 21 to 23, 2000) and neap (December 5 to 6, 2000) tide are shown in Figs. 16 and 17, respectively. These estimates were obtained by assuming constant cross-sectional widths. The discharges through cross-section T2 were found to be significantly higher than through the other two cross-sections (T1 and T3). On the basis of calculations it was found



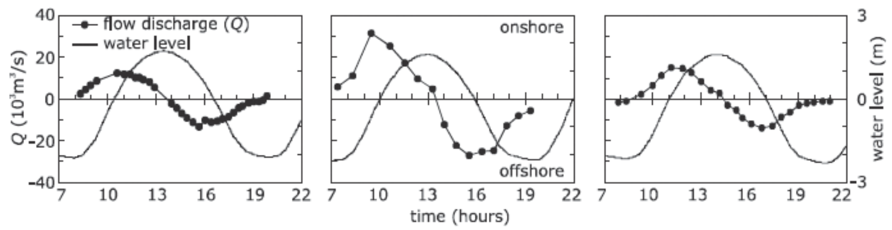
Station N1 in the Norderpiep tidal channel on 24 August 2000 – tidal range of 3.25 m and wind velocities of up to 10 m/s



Station S1 in the Suederpiep tidal channel on 9 June 2000 – tidal range of 3.5 m and wind velocities of up to 13 m/s

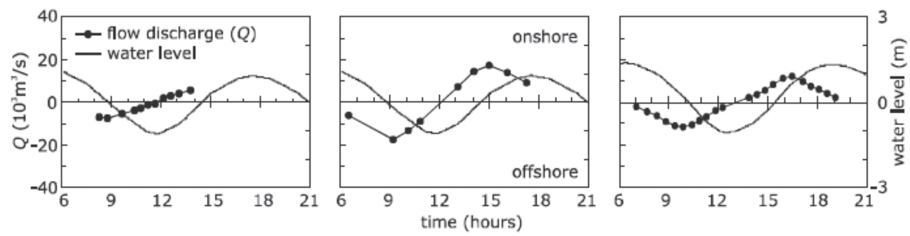
Fig. 15: Variation of current velocities in the Norderpiep and Suederpiep tidal channels recorded by moored devices during periods with strong winds

that the flow discharge through cross-section T2 almost doubles from about 15,000 m^3/s during neap tides to about 30,000 m^3/s during springs. In the case of cross-sections T1 and T3 the increase in flow discharge with tidal range was found to be less pronounced. An investigation of current velocity variations over lunar cycles was carried out by analysing measured values of current velocity for different tidal ranges. This analysis was performed on the basis of the measurements listed in Table 2. The variations of maximum depth-averaged and cross-sectionally averaged current velocities with tidal range are shown in Fig 18. As would be expected, the results clearly indicate an increase in measured current velocities with tidal range, with maximum values during spring tides. The maximum depth-averaged and cross-sectionally averaged current velocities for a given tidal range were found to be similar in each of the surveyed cross-sections.



a) Cross-section T1 b) Cross-section T2 c) Cross-section T3

Fig. 16: Total flow discharges through cross-sections T1–T3 during a spring tide on March 21–23, 2000



a) Cross-section T1 b) Cross-section T2 c) Cross-section T3

Fig. 17: Total flow discharges through cross-sections T1–T3 during a neap tide on December 5–6, 2000

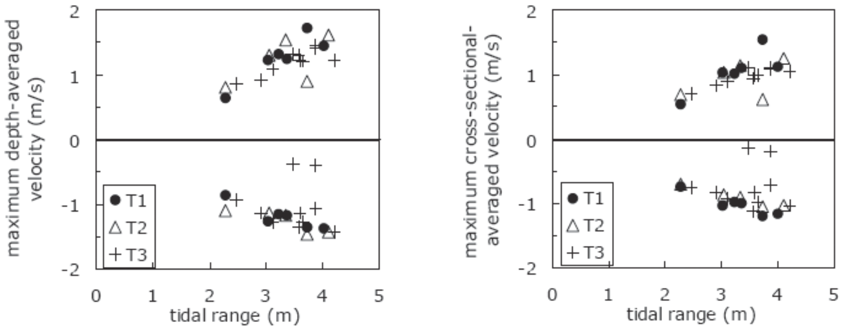


Fig. 18: Variation of depth-averaged and cross-sectionally averaged current velocities with tidal range in cross-sections T1–T3

5.4 Waves

Data from several waverider buoys provided by the Coastal Research Station of the Lower Saxony Board of Ecology (CRS) on Norderney, the Regional State Office for Rural Areas in Husum (ALR) and the German Federal Maritime and Hydrographic Agency in Hamburg (BSH) were analysed to investigate wave characteristics in the study area. The available data were analysed to gain a better understanding of wave characteristics and wave transformation throughout the study area and also to identify the data required for developing the wave model. The locations of the waverider buoys listed in Table 1 are shown in Fig. 1. Typical results of this analysis as well as an interpretation of the results are presented in the following sections.

5.4.1 Data from the CRS

During the one-month measuring campaign undertaken in September and October 1996 by the CRS, Norderney (NIEMEYER, 1997), wave measurements were obtained from five waverider buoys developed by Datawell in the Netherlands. Waverider buoys are equipped with an installed accelerometer that measures the vertical movements (heave) of the buoy. The buoys were strategically located in the Dithmarschen Bight in order to provide the data necessary for developing the wave model. The two buoys located further offshore were directional waveriders equipped with two additional accelerometers to measure north-south and east-west displacements.

The waverider buoys record hourly displacements based on wave sampling at 20-minute intervals. 20-minute intervals are considered long enough to measure a sufficient number of waves for analysis and at the same time short enough to avoid significant changes in wave conditions during a single interval. Recording takes place at a frequency of 2.56 Hz and 1.28 Hz for non-directional and directional waveriders, respectively. The significant wave height, peak period and wave direction are determined from the relative fluctuations over the 20-minute sampling intervals.

The time series of significant wave heights recorded by the five waverider buoys during September and October 1996 are shown in Fig. 19. The occurrence of at least two storms during the measurement period with significant wave heights of up to 2 m makes this data set ideal for calibration and validation of the wave model. Generally speaking, it was found that waves are much higher at positions CRS1 and CRS2 than at the other measurement locations. Most of the wave energy apparently dissipates between the two exposed buoys to the west and the three landward buoys to the east. This energy dissipation is due to depth-induced wave-breaking and bottom friction once the waves enter shallower water. Owing to refraction and diffraction wave energy is partly re-directed into shallower water, thus enhancing the afore-mentioned dissipation.

Relatively high significant wave heights were observed around 13 September and at the end of September 1996, with values attaining up to 2 m at positions CRS1 and CRS2. Wave heights during the remainder of the recording period are significantly lower. Although these trends are reflected in the wave heights recorded by the buoys at positions CRS3, CRS4 and CRS5, wave heights at these locations were found to remain below 0.7 m during the entire measurement period. This is due to the sheltering effect of the tidal flats combined with refraction and diffraction of the wave energy that penetrates beyond them.

Fig. 20 shows the mean wave direction recorded by the waverider buoy at location CRS1. After an initial period of fluctuations during stormy conditions the wave direction remains relatively constant in the onshore direction at about 280° N. About 6 days later the wave direction reverses over north to the offshore direction at about 90° N. The wave heights during this period are in the range of only 0.3 to 0.7 m, which may be explained by the short fetch between the coastline and the CRS1 buoy. Following this calm period with very low wave heights the wave direction turns over south back towards west-northwest after about 25 September. At the same time the waves again increase in height, attaining up to 2.0 m at the CRS1 buoy. This increase in wave height is explained by the fact that westerly (onshore) winds have much larger fetches. From an analysis of the wave spectra (not shown here for the sake of compactness) it was found that double-peaked spectra may occur during periods of westerly winds, indicating a mixture of swell and locally-generated wave energy. During the identified periods of easterly winds, on the other hand, only single-peaked spectra were observed. This is explained by the fact that no swell enters the investigation area during these periods. Fig. 21 shows the wind speed and direction in the study area during the measurement period. These data were generated by the synoptic PRISMA interpolation model (LUTHARDT, 1987), which processes meteorological observations from various coastline and offshore stations. Although the wind and wave directions are fairly dissimilar up to 18 September, a clear correlation between the two is observed subsequently. During the second stormy period, i.e. around 30 September, a dissimilar trend is again apparent. As waves from the west consist to a large extent of swell energy, their direction does not necessarily correspond to the instantaneous local wind direction. In the case of easterly winds, however, the wave energy is almost entirely associated with locally wind-generated waves and thus a much higher correlation is obtained between wind and wave directions.

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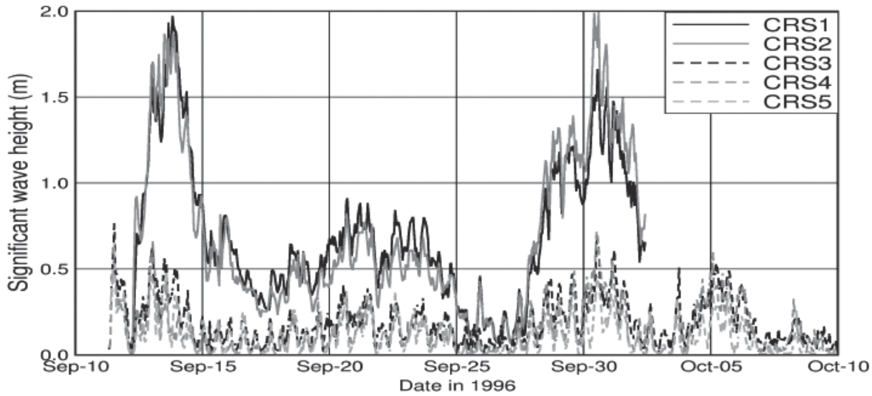


Fig. 19: Observed significant wave heights at the five CRS waverider buoy locations

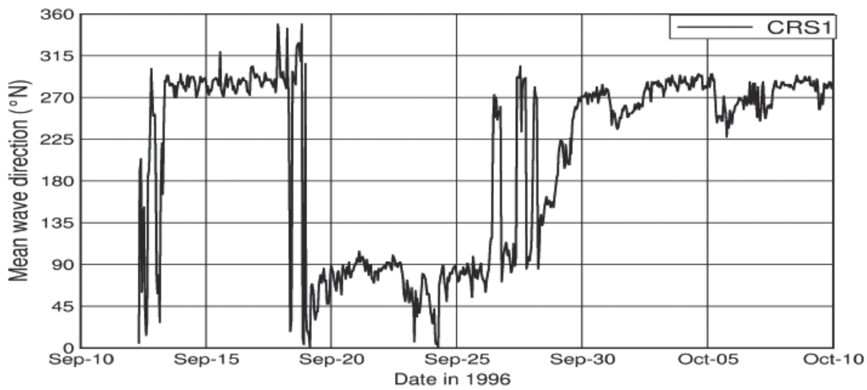


Fig. 20: Observed wave direction at waverider buoy location CRS1

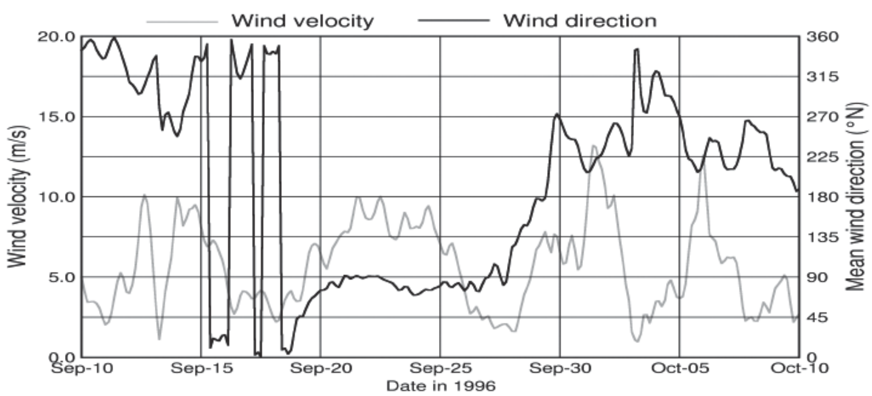


Fig. 21: Wind speed and direction in the Meldorf Bight. Data generated by the PRISMA model (LUTHARDT, 1987)

5.4.2 Data from the ALR and BSH

Simultaneous measurements of significant wave heights and mean wave direction were made available from November 2000 to May 2001 by the ALR in Husum and BSH in Hamburg. Fig. 22 shows significant wave attenuation between the ALR buoy at the entrance to the Suederpiep tidal channel and the BSH buoy in the near vicinity of Tertius. It is evident that the wave heights recorded by the BSH buoy are as much as 50 % lower than those recorded by the ALR buoy. Wave measurements from the ALR waverider buoy show significant wave heights of up to 3.4 m. Average wave heights were generally found to lie within the range of 0.5 to 1.5 m. These wave heights reflect the relatively exposed location of this buoy at the entrance to the Suederpiep tidal channel. The measured wave heights recorded by the BSH waverider buoy generally lie within the range of 0.0 to 1.0 m. During a number of brief periods, however, wave heights of up to 1.5 m were attained. Considering the fact that the predominant wave direction is from southwest to northwest, wave heights tend to reduce towards the east. This reduction may be due to several processes, e.g. wave-breaking, energy dissipation due to bottom friction, diffraction behind shallow or dried-up flats and shoals, and refraction towards channel banks and shoals. Although not deducible from the presented measurements, wave-breaking and shoaling are suspected to play an important role along the western edge of the outer tidal flats. Waves approaching from the east are locally-generated wind waves with a limited fetch, which is longer at the ALR buoy than at the BSH buoy. The increase in depth, and fewer morphological obstacles such as shoals and tidal flats, also account for a reduction in the magnitude of wave energy dissipation on moving eastwards.

As may be seen in Fig. 23, the mean wave directions recorded by the two buoys are nonetheless very similar. These are either governed by the local wind direction in the case of locally-generated waves, or by the mean swell direction. Differences in the mean wave direction are thus only expected for waves from the southwest to northwest. With regard to waves entering the investigation area from this sector, they may be swell-dominated at the ALR buoy and wind-dominated at the BSH buoy. This may well account for differences in the mean wave direction at the two measurement locations. A second possibility is that residual swell energy arriving at the BSH buoy from the western sector has already been diffracted or refracted, thus altering the mean wave direction at this location.

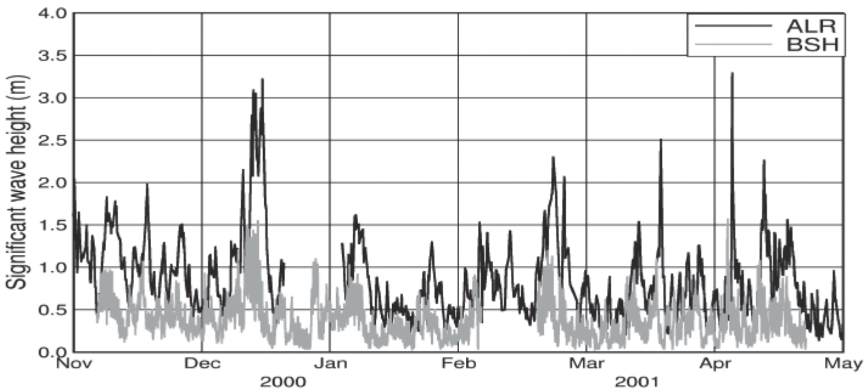


Fig. 22: Wave heights measured simultaneously by the ALR and BSH waverider buoys

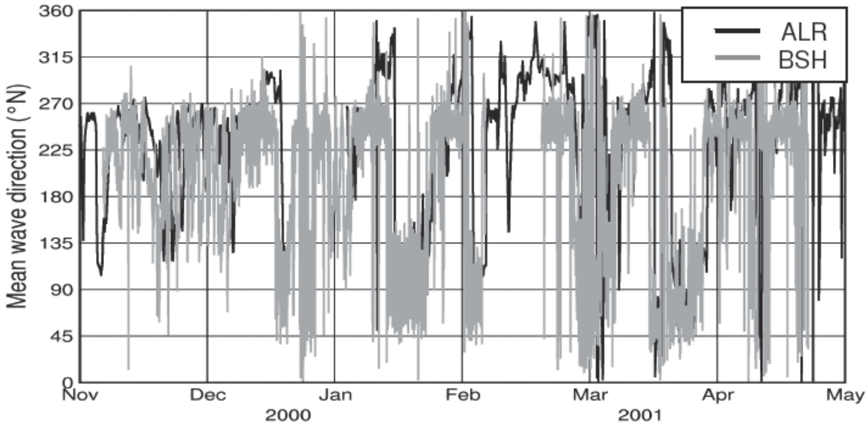
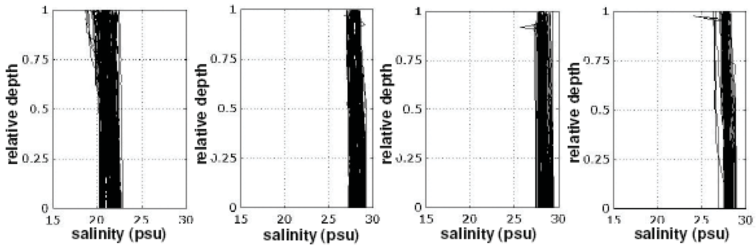


Fig. 23: Wave directions measured simultaneously by the ALR and BSH waverider buoys

5.5 Salinity and Temperature

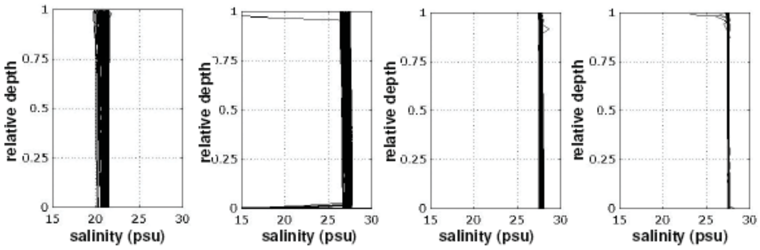
The seasonal variations of salinity and temperature in the study area were also analysed within the framework of the present investigation. Vertical profiles of salinity and temperature were measured at 3-monthly intervals during the year 2000 from vessels at cross-section T2 at the entrance to the investigation area and at cross-section T3 closer to the coast (see Fig. 1). Fig 24 shows measured vertical salinity profiles over complete tidal periods at cross-sections T2 and T3 on 21–23 March 2000 (tidal range of about 3.9 to 4.1 m), 5–6 June 2000 (tidal range of about 3.7 m), 5–6 September 2000 (tidal range of about 2.9 to 3.1 m) and 5–6 December 2000 (2.3 to 2.5 m). It is seen that the vertical salinity distributions in both cross-sections are fairly uniform throughout the year. This is not surprising, considering the fact that the water column in this fairly shallow area is always well-mixed due to strong tidal currents. The salinity values range from about 20 to 28 psu, indicating the influence of coastal freshwater run-off derived mainly from the discharge of the Elbe estuary in the south. It is interesting to note that not only salinity values but also their tidal variations are slightly higher further away from the coast. A certain seasonal variation in salinity is also evident, with lower values prevailing during the month of March. The maximum variation in salinity throughout the year is found to be about 7–8 psu. This is most probably due to seasonal variations in the freshwater discharges of the Elbe and Eider estuaries in combination with prevailing meteorological conditions. Extensive measurements carried out in the area within the framework of the research project TRANSWATT (SÜNDERMANN et al., 1999) have clearly shown that the salinity distribution in the Dithmarschen Bight is highly dependent on the magnitude of riverine discharges and local wind conditions.

Variations in the vertical temperature profile were analysed in a similar manner to salinity. Fig. 25 shows vertical profiles of temperature at cross-sections T2 and T3 measured in conjunction with the above-mentioned salinity measurements. Similar to salinity, the variation in temperature over the water column was found to be fairly uniform. The seasonal variation in water temperature was found to range from about 6–7 °C in March to about 16–17 °C in September. Spatial variations, on the other hand, were found to be negligible. The uniform vertical profiles of salinity and temperature in the study area is indicative of well-mixed conditions without flow stratification due to density effects.



March 21, 2000 June 5, 2000 September 5, 2000 December 5, 2000

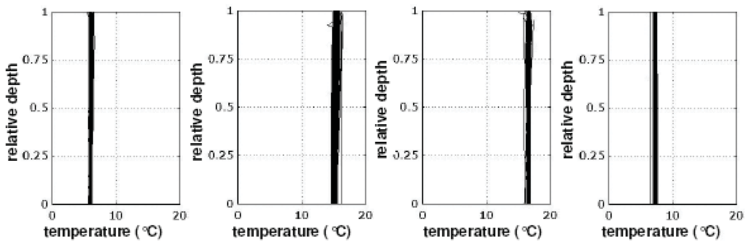
a) Cross-section T2



March 23, 2000 June 6, 2000 September 6, 2000 December 6, 2000

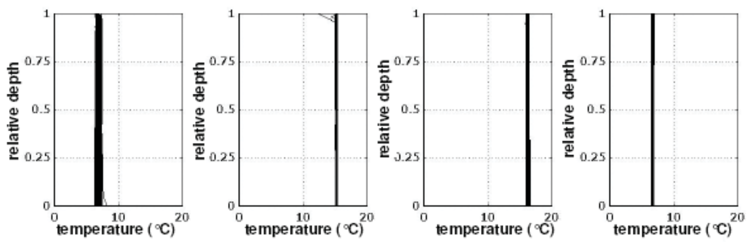
b) Cross-section T3

Fig. 24: Seasonal variation of vertical salinity profiles in cross-sections T2 and T3



March 21, 2000 June 5, 2000 September 5, 2000 December 5, 2000

a) Cross-section T2



March 23, 2000 June 6, 2000 September 6, 2000 December 6, 2000

b) Cross-section T3

Fig. 25: Seasonal variation of vertical temperature profiles in cross-sections T2 and T3

6. Conclusions

This paper presents the results of an analysis of field measurements of water levels, current velocities, waves, salinity, and temperature for a wide range of conditions in a tidally-dominated area of the German North Sea. The area investigated is the central Dithmarschen Bight located between the Elbe and Eider estuaries. Continuous monitoring of wind speed, water levels and waves by the relevant authorities was supplemented by field measurements specially intended to provide a dense spatial and temporal coverage of current velocities. The field measurements not only serve as a means of identifying the most dominant physical processes governing the hydrodynamics of the study area but also provide a valuable data set for defining the modelling strategy as well as for developing and evaluating process-based models for the simulation of flow and waves.

Water levels at six locations were implemented for the purpose of tidal analysis and calibration of the flow model. The mean tidal range in the study area was found to vary from about 3.1 m to 3.4 m between the mouth of the Elbe estuary in the south and the Eider peninsula in the north. The neap and spring tidal ranges in the study area are 2.8 m and 3.5 m, respectively. As a result of the tidal analysis it was possible to identify the 39 tidal constituents that best represent the observed water levels at the six monitoring stations. The quality of the tidal constituents was verified for three periods of up to 43 days under relatively calm wind conditions. On the basis of this analysis, satisfactory agreement was obtained between observed and predicted tidal elevations. A mean absolute error of less than 20 cm was obtained at all locations, representing about 6 % of the mean tidal range.

The seasonal variation of tidal asymmetries was analysed on the basis of water level measurements at the entrance to the main tidal channels, i.e. the Norderpiep channel to the northwest, the Suederpiep channel to the southwest, and the Piep channel nearer the coast. This analysis revealed differences of up to 45 min in the duration of the tide at the latter three locations. The results of this analysis indicate that cross-sections located at the entrance to the study area are flood-dominated during most of the year, whereas the cross-section nearer the coast is generally ebb-dominated during the summer and exhibits virtually no asymmetries during the autumn and winter months. Flood dominance in the cross-sections at the entrance to the main tidal channels, in particular the Norderpiep tidal channel, was also confirmed by current velocity measurements.

The highest storm surge in the study area, measuring approximately 3.6 m (EAK, 2002), was recorded in 1967. About 60 % of all storm surges occur between November and January; a further 20 % between October and February. At the nearby gauge station of Sankt Peter-Ording, storm surges exceeding approximately 2.0 m occurred on average once a year during the period 1990 to 2002 (MERSCH, 2004).

Selective measurements of current velocities over several cross-sections were performed using acoustic profilers from moving vessels. Additional current velocity measurements over the water column were provided by moored devices. These measurements covered a wide range of conditions typical of the study area. The measurements from ship-based devices provided a good description of the spatial variation of current velocities. Measurements were carried out for a variety of tidal conditions, with tidal ranges varying from about 2.3 m to 4.1 m under relatively calm weather conditions. The resulting data sets provided a good description of spatial and temporal variations of current velocities in the study area.

The maximum values of point and depth-averaged current velocity in the main tidal channels were found to be about 2.8 m/s and 1.7 m/s, respectively. The vertical distribution of current velocity was also found to be fairly uniform at all surveyed locations due to low bed roughness. Owing to high tidal dominance in the study area, vertical profiles of temperature and salinity were found to be fairly uniform. This is concomitant with the observed absence of vertical velocity stratification. An increase in current velocity with increasing tidal range was clearly evident. The maximum depth-averaged current velocity approximately doubles from neap to spring tide.

Wave data obtained from simultaneous measurements at five locations during a one-month period (NIEMEYER, 1997) provided a valuable insight into wave transformation throughout the study area. Measurements covering two longer periods of about 12 and 6 months at locations about 10 km seawards of the outer tidal flats as well as in the Suederpiep tidal channel yielded essential information regarding the range and probability of wave characteristics. On the basis of these wave data it was found that the major part of swell energy is dissipated along the edge of the outer tidal flats. The limited depths to the east of this location are responsible for energy dissipation due to wave-breaking, bottom friction, refraction, and diffraction. Together with the sheltering effect of the tidal flats and shoals, the wave energy in the eastern part of the study area is essentially locally-generated. Maximum wave heights some 10 km westward of the outer tidal flats were found to be about 3.5 m. Wave heights of less than 2.0 m were measured along the edge of these tidal flats during the observation period, with maximum values of approximately 1.5 m in the Suederpiep tidal channel. Further eastwards, no waves exceeding 0.7 m were recorded.

Besides providing the basis for a better understanding of the governing physical processes in the study area, the data acquired in the present investigation were also of considerable value for the further development of the flow and wave models. From an analysis of the data it was possible to clarify various aspects of model development. Suggestions regarding the dimensions and limits of the model have also been proposed. As the hydrodynamics of the study area are very much dependent on conditions along the western boundary, it was proposed to locate the open-sea boundary of the model eastwards of the approach to the main tidal channels in regions where morphological activity is less intense. In view of the available wave data it was recommended to develop a model covering the entire Dithmarschen Bight. Owing to the fairly uniform vertical distributions of velocity, salinity, and temperature, the application of a 2DH model approximation should be considered initially in preference to a 3D approach.

The derived data have been used among others for the assessment of open-sea boundary condition approaches (MAYERLE et al., in this volume), the development of set-up flow and wave models (PALACIO et al., in this volume; WILKENS et al., in this volume), and the definition of representative conditions for the simulation of medium-scale morphodynamics (JUNGE et al., in this volume; WILKENS and MAYERLE, in this volume).

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Agency (BSH Hamburg), the Regional State Office for Rural Areas (ALR Husum) and the German National Meteorological Service (DWD). The CRS Norderney is also gratefully acknowledged for making available the German Bight Model, which was developed by Delft Hydraulics (the Netherlands) within the German-Dutch project WADE (Wadden Sea Morphodynamic Development) and funded by the German Ministry of Education and Research. We are also indebted to Dr. Ian Westwood for his meticulous corrections and final proofreading of the English manuscript. Finally, we wish to thank the anonymous reviewers for their constructive remarks.

8. References

ASCE TASK COMMITEE: Sediment Transportations Mechanics: Suspension of Sediment. Proc. Am. Soc. Civil Engrs., Vol. 89, No. HY5 (September 1963) p. 45, 1963.

ASP NETO, N. E.: Long- to Short-term Morphodynamic Evolution of the Tidal Channels and Flats of the Dithmarschen Bight, German North Sea, Ph.D. thesis, University of Kiel, Germany, 2004.

EAK: Empfehlungen für Küstenschutzwerke, Die Küste, Heft 65, in German, 2002.

HARTSUIKER, G.: Deutsche Bucht and Dithmarschen Bucht, Set-up and calibration of tidal flow models. Delft, Delft Hydraulics, Report H1821, 1997.

JIMÉNEZ GONZALEZ, S.; MAYERLE, R. and EGOZCUE, J. J.: On the accuracy of Acoustic Doppler Current Profilers for in-situ measurements. A proposed approach and estimations for measurements in tidal channels. 7th IEEE Conference on Current Measurement Technology, March 13–15, San Diego, USA, 2003.

JIMÉNEZ GONZALEZ, S.; MAYERLE, R. and EGOZCUE, J. J.: A Proposed Approach for the Determination of the Accuracy of Acoustic Profilers for Field conditions, Die Küste, Heft 69, 2005.

JUNGE, I.; WILKENS, J.; HOYME, H. and MAYERLE, R.: Modelling of Medium-Scale Morphodynamics in a Tidal Flat Area in the South-Eastern German Bight, Die Küste, Heft 69, 2005.

LUTHARDT, H.: Analyse der Wassernahen Druck- und Windfelder über der Nordsee aus Routinebeobachtungen, Hamburger Geophysikalische Einzelzeitschriften, A 83, in German, 1987.

MAYERLE, R. and PALACIO, C.: Assessment of Open Sea Boundary Condition Approaches for Coastal Models, in 13th Congress of the Asia and Pacific Division of the International Association for Hydraulic Engineering and Research, Asia and Pacific Division of IAHR, Singapore, August, 2002.

MAYERLE, R.; RAZAKAFONIAINA, T.; PALACIO, C. and PRAMONO, G.: Bed forms and equivalent roughness sizes in tidal channels. Proceedings of the International Conference on Fluvial Hydraulics (River Flow 2002), IAHR, Louvain-la-Neuve. Belgium, 2002.

MAYERLE, R.; WILKENS, J.; ESCOBAR, C. and WINDUPRANATA, W.: Hydrodynamic Forcing along the Open Sea Boundaries of Small-Scale Coastal Models, Die Küste, Heft 69, 2005.

NIEMEYER, H. D.: Bemessung auf Seegang. Entwicklung abgesicherter Verfahren zur Ermittlung der Bemessung des Wellenauflaufs. KFKI-project No. 45, in German, 1997.

PALACIO, C.; MAYERLE, R. and TORO, F.: Tidal Analysis in the Meldorf Bight, North Sea Coast, Germany (in Spanish), XV National Seminar of Hydraulic and Hydrology, Colombia, 2002.

PALACIO, C.; MAYERLE, R.; TORO, M. and JIMÉNEZ, N.: Modelling of Flow in a Tidal Flat Area in the South-Eastern German Bight, Die Küste, Heft 69, 2005.

POERBANDONO and MAYERLE, R.: Composition and Dynamics of Sediments in Tidal Channels of the German North Sea Coast, Die Küste, Heft 69, 2005.

RICKLEFS, K. and ASP NETO, N. E.: Geology and Morphodynamics of a Tidal Flat Area along the German North Sea Coast, Die Küste, Heft 69, 2005.

ROHDE, H.: Entwicklung der hydrologischen Verhältnisse im deutschen Küstengebiet. In: Kramer, J. and H. Rohde: Historischer Küstenschutz, Verlag K. Wittwer, Stuttgart, in German, 1992.

SÜNDERMANN, J.; HESSE, K.-J.; BEDDIG, S. and WILKENS, J.: Coastal mass and energy fluxes in the southeastern North Sea. German Journal of Hydrography Vol. 51, No. 2/3, 113–132, 1999.

VAN RIJN, L. C.: Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas. Aqua Publications, Amsterdam, The Netherlands, 1993.

WILKENS, J.: Medium Scale Morphodynamics of the Central Dithmarschen Bight, Ph.D. thesis, University of Kiel, Germany (available under http://e-diss.uni-kiel.de/diss_1369/d1369.pdf), 2004.

WILKENS, J.; ASP NETO, N. E.; RICKLEFS, K. and MAYERLE, R.: Medium-scale Morphodynamic Modelling in the Meldorf Bight. Proceedings of the EWRI/ASCE World Water and Environmental Resources Congress 2001, Orlando, USA, 2001.

WILKENS, J.; JUNGE, I. and HOYME, H.: Modelling of Waves in a Tidal Flat Area in the South-Eastern German Bight, Die Küste, Heft 69, 2005 (a).

WILKENS, J. and MAYERLE, R.: Calibration of Coupled Flow-Wave Models and Generation of Boundary Conditions for the Central Dithmarschen Bight, Germany. Poster at the 11th International Biennial Conference on Physics of Estuaries and Open Seas (PECS) 2002, Hamburg, Germany, 2002.

WILKENS, J. and MAYERLE, R.: Modelling of Medium Scale Morphodynamics of a Tidal Flat Area in the German Wadden Sea, Proceedings of the 29th ASCE International Conference on Coastal Engineering (ICCE), Lisbon, Portugal, 2004.

WILKENS, J. and MAYERLE, R.: Morphodynamic Response to Natural and Anthropogenic Influences in the Dithmarschen Bight, Die Küste, Heft 69, 2005 (b).

WINTER, C.; POERBANDONO, HOYME, H. and MAYERLE, R.: Modelling of Suspended Sediment Dynamics in Tidal Channels of the German Bight, Die Küste, Heft 69, 2005.

ZIELKE, W.; GROSS, G.; HOYME, H.; MAYERLE, R.; RICKLEFS, K.; WINTER, C.; EPPEL, D. and WITTE, G.: Predictions of medium-scale morphodynamics (PROMORPH). Proceedings of the 27th ASCE International Conference on Coastal Engineering (ICCE) 2000, Sydney, Australia, 2000.