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Meteorological Data and Wind Field Modelling in the Dithmarschen Bight

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Summary

The topic of this study was to identify meteorological data suitable for forcing numerical simulations of morphodynamic processes in the Dithmarschen Bight.

A comparison between Numerical Weather Prediction (NWP) output data from the Local Model (LM) of the German Weather Service (Deutscher Wetterdienst – DWD) and PRISMA (PRozesse Im Schadstoffkreislauf Meer-Atmosphäre) data demonstrates the applicability of both data sets for forcing hydrodynamic models. PRISMA data are available on a regular grid and are based on field measurements. Compared with station data from Heligoland (German Bight of the North Sea), PRISMA data tend to underestimate long-term mean wind speeds while overestimating the frequency and number of high wind speed events.

Furthermore, time series of wind measurements were statistically analyzed and checked for quality. By evaluating the statistics of the wind field over the German Bight it was possible to classify meteorological conditions for the purpose of morphodynamic modelling. The results of simulations with a high-resolution version of the LM were used to identify areas where the station data may be confidently used to represent the wind field.

Zusammenfassung

Ziel der Studie war es, geeignete meteorologische Antriebsdaten für die numerische Simulation morphodynamischer Prozesse in der Dithmarscher Bucht zu identifizieren und bereit zu stellen.

Ein Vergleich zwischen den Ausgabedaten numerischer Wettervorhersagemodelle (hier dem Lokalmodell (LM) vom Deutschen Wetterdienst) und den PRISMA-Daten (PRozesse Im Schadstoffkreislauf Meer-Atmosphäre) zeigt die Eignung beider Datensätze zum Antrieb hydrodynamischer Modelle mit meteorologischen Randbedingungen. PRISMA-Daten stehen auf einem äquidistanten Gitter zur Verfügung und werden auf der Basis von Stationsbeobachtungen berechnet. Im Vergleich zu Stationsmesswerten von Helgoland zeigen die PRISMA-Daten im langjährigen Mittel eine zu geringe mittlere Windgeschwindigkeit, während sie gleichzeitig die Häufigkeit des Auftretens von Starkwindereignissen sowie die dabei auftretenden Windgeschwindigkeiten überschätzen.

Weiterhin werden lange Zeitreihen von Windmessungen statistisch analysiert und auf Fehler geprüft. Durch die Auswertung der Windstatistik in der Deutschen Bucht kann die meteorologische Situation für den Zeitraum der morphodynamischen Modellierung klassifiziert und eingeordnet werden. Dazu wurden Simulationsrechnungen mit einer hochaufgelösten Version der LM durchgeführt, um Flächen über dem Meer zu bestimmen, für die die Stationsmessungen als repräsentativ angesehen werden können.

Keywords

Dithmarschen Bight, LM, PRISMA, Wind Measurements

Contents

1. Introduction

The aim of the investigation described in this paper was to supply hydrodynamic models in the project PROMORPH (PROgnose mittelfristiger küstenMORPHologieaänderungen: PROgnosis of medium-term coastal MORPHology) (cf. ZIELKE et al., 2003) with the most realistic atmospheric data possible for simulating forcing effects on the sea surface. The morphodynamic models implemented in PROMORPH to study bathymetry changes in the Dithmarschen Bight are nested within the hydrodynamic model CSM (Continental Shelf Model). The CSM, which covers the entire area of the North Sea, uses shear stress data based on wind measurements at a height of 10 m above the sea surface according to the scheme of SMITH and BANKE (1975) (ZIELKE et al., 1996). The discussion about useful meteorological data hence focuses on these 10 m-wind data distributed over all water grid points of the hydrodynamic model. One method of obtaining these data is to make use of station measurements of wind speed and barometric pressure. These data are interpolated to obtain values at the grid points of a mesh covering a certain area as described by e.g. LUTHARDT (1987). An alternative method is to use the output data of Numerical Weather Prediction (NWP) models. Both NWP model output data and station data were examined in the present study to check their suitability for forcing hydrodynamic models.

During the period chosen for the PROMORPH simulations a variety of weather conditions were experienced over the North Sea as well as the coastal region of the German Bight. Periods of calm winds alternate with periods of storm surge conditions. These different weather conditions have a significant influence on the evaluation of bathymetric changes. Moreover, it is necessary to compare the statistical behaviour of the wind situation during the simulation period with long-term wind behaviour in order to assess the impact of single events on long-term bathymetric changes.

In order to generate wind-forcing data for medium-term and long-term hydrodynamic computations it is necessary to extrapolate point measurements so as to cover the entire investigation area. This was carried out using both the time series of wind speed and direction at 6 stations in the German Bight and the results of numerical simulations performed with the high-resolution version of the LM. The LM is an operational NWP model run by the German Weather Service (Deutscher Wetterdienst – DWD). The simulation results of the NWP model, which covers an entire area in a physically consistent manner, may be used for comparisons with point measurements and PRISMA data.

In order to simulate morphological changes in the Dithmarschen Bight wave modelling is also necessary. In wave modelling, both local and regional wind fields play an important role. For storm conditions, however, a wind field on the continental shelf scale is more relevant than local wind behaviour. Whether the wind characteristics of the German Bight (e.g. characterised by Heligoland measurements) may be applied to smaller bights within the German Bight area such as the Dithmarschen Bight is examined in the present study with the aid of the high-resolution version of the LM.

2. Meteorological Data for Forcing Hydrodynamic Models

2.1 PRISMA Data

Meteorological forcing of the hydrodynamic models implemented in PROMORPH may be realised using the surficial distributions of wind and surface pressure from the PRISMA dataset. PRISMA data consist of observed wind fields, sophistically modulated and interpolated over a grid with a regular mesh spacing of 42 km and a time resolution of 3 hours. In addition to measured winds, the observed surface pressure data are used to generate a synoptic scale wind field by means of the geostrophic wind equation. A detailed account of the generation of PRISMA datasets from measurements is given by LUTHARDT (1987). Although the use of PRISMA datasets offers some advantages – e.g. the fact that they are generated from measurements means that they are free of forecast errors and that they also have a relatively sharply defined land-sea mask in the speed of the wind (NIELINGER, 1998) – the use of these datasets also has a number of serious shortcomings. Because there are no regular meteorological stations in the open sea the only means of generating these datasets is from measurements made from ships, platforms and coastal synoptic stations. The fact that wind measurements from platforms are performed at a height exceeding the standard height of 10 m and not reduced to the standard height means that wind speeds over the sea are likely to be overestimated. Moreover, the quantity of in situ wind and barometric pressure measurements over sea within the entire North Sea area is small. At e.g. 21 UTC (Universal Time Coordinates) the number of wind and barometric sea level pressure reports is below an average of 30. Additionally, the locations of reporting platforms and ships are irregularly distributed, leaving large areas of the North Sea domain without reported wind and pressure measurements. Therefore, for these large areas it is highly unlikely to detect regional deviations from the synoptic scale wind and sea level pressure field that are for example created by frontal systems, thunderstorms or squall lines. As a result, in general the processed PRISMA data cannot show that small-scale deviations in the wind field over sea. For further information on the latter refer to ZIELKE et al. (1997) or LUTHARDT (1987). It is a serious shortcoming for the practical use of PRISMA data in current studies that these data only become available in March of the calendar year following the year of measurements.

2.2 NWP Data

Due to a lack of near-surface wind measurements over the open sea it is only possible to obtain a realistic representation of the offshore wind field with sufficient temporal and spatial resolution by means of numerical simulations. In order to generate a physically consistent wind field in this study the Local Model (LM) of the German Weather Service was used.

The LM is an operational NWP model with a grid resolution of 0.0625 degrees (approx. 7 km). The LM is a state-of-the-art non-hydrostatic NWP model based on the compressible Navier-Stokes equations and is suitable for application with high-resolution grids. The application as an operational NWP model guarantees maintenance of the model. The version used in PROMORPH is LM version 2.17., which is described by DOMS et al. (2001).

The LM is operationally forced by GME (MAJEWSKI et al., 2002) forecasts. The DWD uses the global general circulation model GME operationally to run numerical weather forecasts. The GME has a grid size of approx. 60 km. These forecasts were also used in PROMORPH to initialise the LM. Access to the GME data as well as the operationally produced LM output data at the DWD is provided via the oracle database of the DWD. This permits numerical simulations of specific synoptic weather situations for the present as well as the past.

Numerical simulations have been performed on a Cray T3E massive parallel supercomputer at the NIC (John von Neumann Institute for Computing), Jülich.

In order to resolve the pronounced land-sea contrast of the wind field close to the ground a small grid size is necessary. Such high-resolution data will become available once the grid size of the LM has been reduced to 0.025 degree (approx. 2.8 km). The 2.8 km grid version of the LM requires initial and boundary values, which are obtained by operational running of the LM and interpolation over the 0.025 degree grid.

The output data, with a time resolution of 2 hours and a spatial resolution of 7 km and approx. 60 km in the LM and GME model, respectively, have been checked for quality and processed specifically for use in the PROMORPH hydrodynamic models. These data were interpolated barycentrically from the original NWP model grid to the grid implemented in the hydrodynamic models. The inclusion of GME data is necessary because the operational LM does not completely cover the entire domain of the hydrodynamic model. It was only found necessary, however, to force 3 of the 3743 CMS model grid points by GME model output wind data.

The results of the numerical simulations performed using the high-resolution version of the LM show a very detailed and structured wind field in areas characterised by pronounced changes in orography or roughness length such as, e.g. along the transition region between the shoreline and the sea or over the ascent from the German lowlands to the highlands. The simulations also demonstrate that the observed wind speed at Heligoland may be assumed to be representative of wind conditions throughout the German Bight at a distance of approx. 10–15 km from the shoreline. With the 7 km version of the LM this result would not have been so pronounced because the land-sea mask is much coarser (approx. 3 times). With 3 grid points necessary to resolve the land-sea contrast the 7 km LM would have smeared the wind-field transition zone between the land and sea over a length of 21 km due to numerical effects, thus yielding an incorrect representation of the natural characteristics of the wind field.

3. February 2000 – A Case Study

The output data from the NWP models LM and GME were compared to synoptic station data measurements and PRISMA data with regard to wind speed and direction. The simulated water levels generated from different input data (LM, GME or PRISMA) were also compared to each other as well as to measured water levels in order to analyse the effects of uncertainties in meteorological forcing on the results of the hydrodynamic simulation.

The period chosen for the case study was from 01 December 1999 to 31 December 2000. During this period a situation with strong north westerly winds lasting several days only occurred in February 2000. As this wind situation has the potential to cause high water levels along the coastline of the German Bight, the month of February 2000 was chosen for the comparison study.

For the whole of February 2000 the wind speed and direction given by the numerical weather prediction models as well as the PRISMA data were interpolated barycentrically relative to the synoptic station on Heligoland. Heligoland was chosen because it is located far enough away from the coastline to represent the wind field over the open sea. A distortion of the wind field nevertheless exists due to a change in the surface roughness between the island and the sea surface as well as the air flow around the island. As Heligoland is neither resolved in the NWP model nor in PRISMA, NWP data may be compared with PRISMA data at this location.

In Table 1 the wind data measurements at the Heligoland station are compared with the data generated by PRISMA and the NWP models LM and GME. The model data are interpolated to obtain a value at the grid point representing the Heligoland station. The wind speeds are compared as monthly mean values for February 2000. It is seen that the LM yields the smallest vector difference between the measured and simulated wind speed.

Table 1: Monthly mean wind speed at the Heligoland station/grid point

	Observed (synoptic)	PRISMA	GME	LM
wind speed in m/s	10.15	9.73	9.94	10.03
vector difference between observed and modelled wind speed in m/s	–	2.81	2.68	2.62

The time series of predicted and observed wind speed is shown in Fig. 1. The differences between simulated and measured wind speeds are found to be smaller for LM results than for PRISMA results, especially during periods of maximum wind speed. With regard to wind direction, all datasets (PRISMA, GME and LM) show a deviation to the right compared to the synoptic station report. This is in good agreement with the fact that the direction of

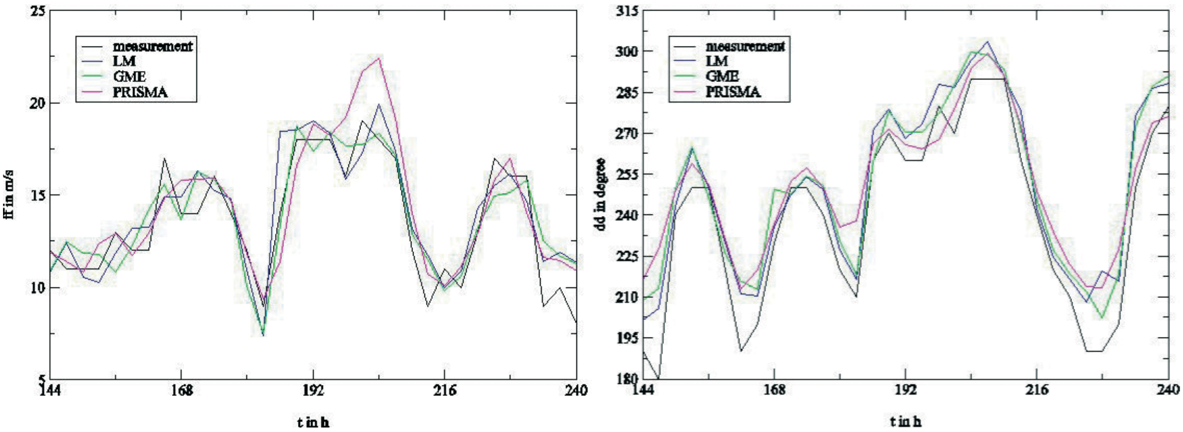

Fig. 1: Wind speed in m/s (left) and direction in degrees (right) at the Heligoland station/grid point. A time series of observed data, PRISMA, GME and LM data from 07 February 2000, 00 UTC to 11 February 2000, 00 UTC

onshore winds tends to deviate 15 degrees to the left (northern hemisphere) at near-coastal land stations (VESELOV, 1988).

Operational NWP output data from the LM and the GME model may be used for the meteorological forcing of hydrodynamic models for simulating sea level changes. The results of such a coupled model system are shown in Fig. 2. This 4-day time segment of the February 2000 simulation includes periods of high wind speeds with a significant increase in shear stress acting on the sea surface whereas in periods of low wind speed the astronomical tide dominates. Although forcing of the hydrodynamic models with PRISMA, GME or LM data yields different results, these differences are small compared to the differences between modelled and observed water levels. It should be noted that the hydrodynamic model CSM used here is appropriately adapted to make use of PRISMA data (ZIELKE et al., 1997). The simulated maximum water levels (PRISMA: 2.19 m, GME: 2.23, LM: 2.26) are also found to be in close agreement with observations (observed: 2.27 m).

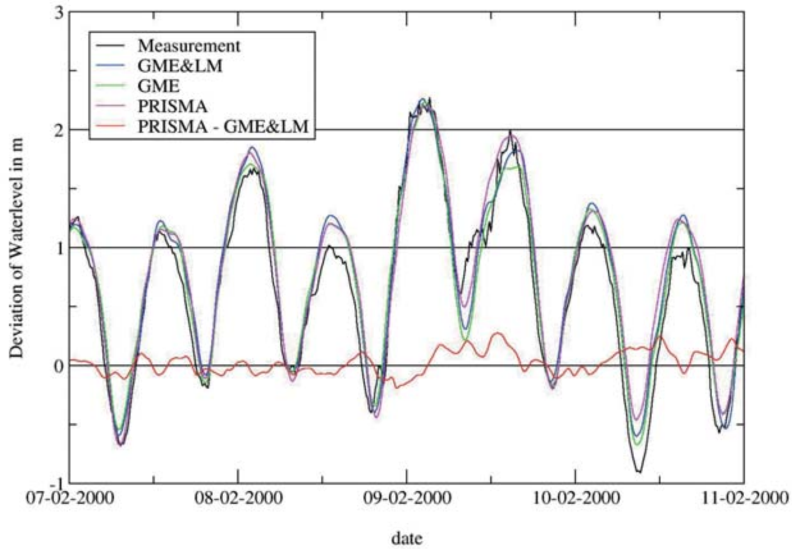

Fig. 2: Modelled and observed water level changes during the strong wind period from 07 February 2000, 00 UTC to 11 February 2000, 00 UTC at Westerland (HOYME, pers. comm., 2001)

4. Wind Statistics

4.1 Station Data

Hydrodynamic models are able to simulate morphodynamic changes in the area of the Dithmarschen Bight for specific meteorological conditions. In order to classify such conditions on a long-term basis a statistical analysis of meteorological observations is necessary. For this analysis the surface wind observations at different weather stations around the Ditmarschen Bight were selected which fulfil the following conditions:

- The time series must be as complete and as long as possible.
- Station measurements should represent the statistical behaviour of the wind in the study area as far as possible. The stations should be located either on an island, at an inland site removed from the coastline but sufficiently close to detect the influence of sea breezes, or directly on the shoreline of the German Bight.

Considering these requirements, the following stations were chosen:

- Heligoland (an island in the open sea),
- Norderney (an island approx. 10 km north of the shoreline),
- Cuxhaven (shoreline),
- Büsum (shoreline),
- Jever (land station),
- Hamburg-Fuhlsbüttel (land station).

The observed data at these synoptic stations ("SYNOPTIC data") are available in the form of time series consisting of mean values over one-hour intervals at a resolution of 0.1 m/s and 10 degrees. The SYNOPTIC data records date back to 01-01-1959 at the Heligoland station, and back to 01-01-1969 at the other stations. Only the data recorded between 01-01-1969 and 31-12-2001 were used in the comparative study.

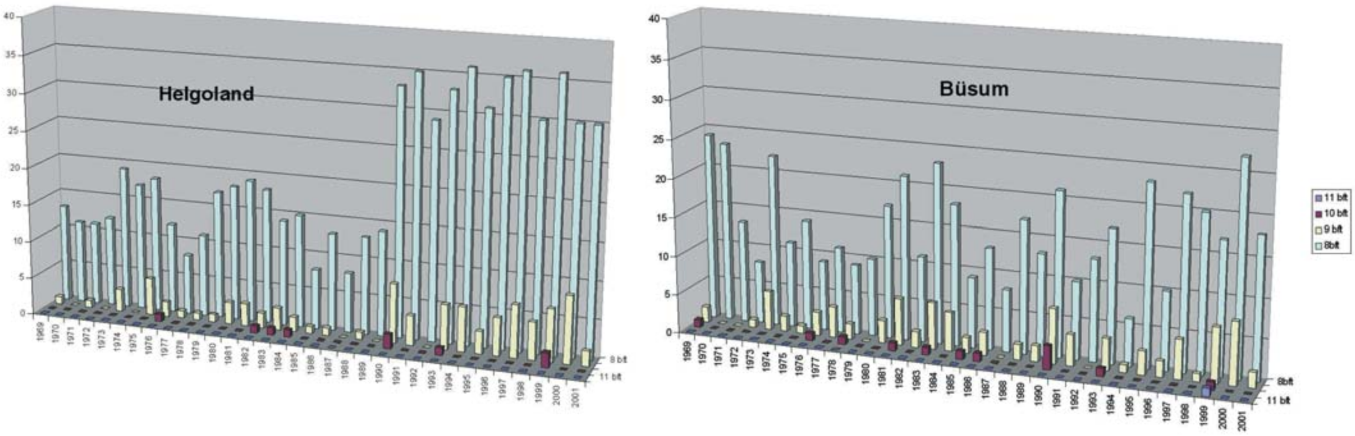

Fig. 3: Yearly number of days during which the wind force exceeds defined thresholds

Unfortunately the station anemometers were relocated several times during the observation period, thus making the time series inconsistent. On Heligoland the anemometer was removed from its original position close to the rocky headland and relocated on the harbour mole in 1989. At the new location it was found that the recorded wind speed was reduced for wind directions between 340 and 10 degrees due to various orographic disturbances. In 1993 the anemometer was again shifted a further 550 m in the seaward direction to the end of the mole. The apparent increase in storm activity at Heligoland during the period from 1989 to 1993 (Fig. 3) is unrealistic as it is directly related to the relocation of the anemometer. Also in Büsum the anemometer was relocated twice during the observation period. In Büsum, however, wind measurements were not so much affected by relocation of the instrument (Fig. 3). The changes in wind behaviour due to anemometer relocation make it difficult to draw a comparison with published results (e.g. SCHMITT, 1988; CHRISTOFFER and ULBRICHT-EISSING, 1989; TROEN and PETERSEN, 1989).

The most frequent wind direction at all six stations is south to west (Fig. 4 shows this for Heligoland and Büsum), whereby the most frequent combination of wind speed and direction at the Heligoland station occurs in the interval 170 to 210 degrees and 8 m/s to 10 m/s. The mean wind speeds at the 6 selected stations during the entire observation period are shown in Table 2.

Table 2: Mean wind speed during the period 01-01-1969 to 31-12-2001, calculated from one-hour means

Norderney	Heligoland	Büsum	Cuxhaven	Jever	Fuhlsbüttel
6.47 m/s	7.62 m/s	7.04 m/s	5.59 m/s	4.30 m/s	3.97 m/s

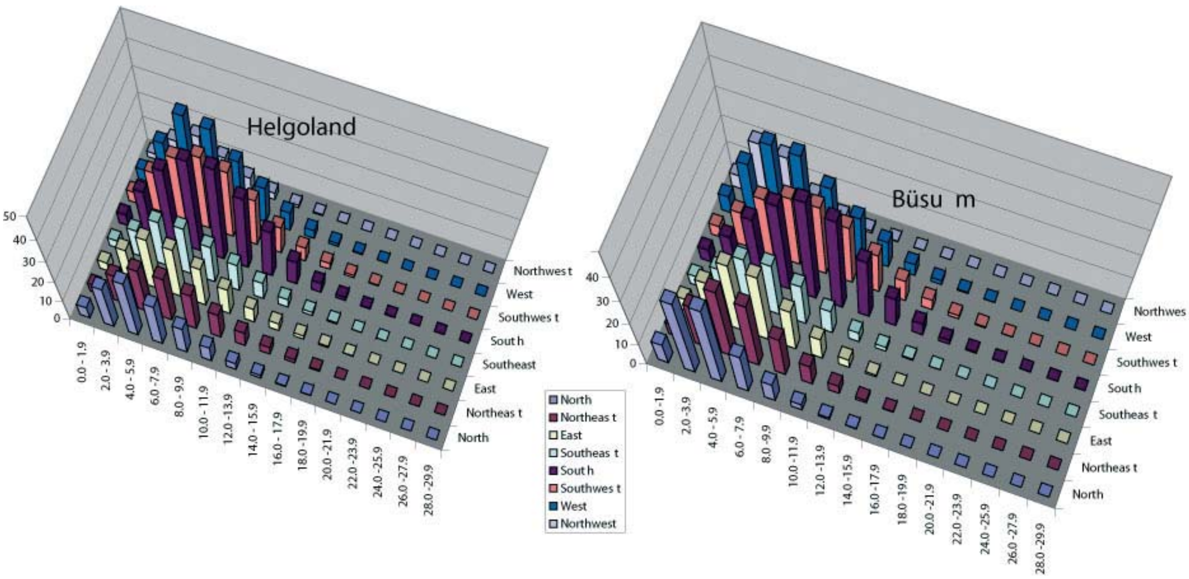

Fig. 4: Frequency distribution of wind speed (in m/s) and wind direction

4.2 PRISMA Data: A Comparison with Station Measurements

Although the applicability of both PRISMA and LM/GME data for forcing hydrodynamic models has been confirmed (ZIELKE et al., 2002), deviations naturally exist between NWP/PRISMA data and "real" (measured) data. Especially for long-term simulations and reference measurements it is necessary to obtain a realistic estimation of systematic differences between simulated data and observations.

In this investigation the PRISMA data time series was analysed at the Heligoland grid point because the Heligoland station is located further away from the coastline than Büsum or Norderney. The PRISMA data were interpolated barycentrically from the 42 km x 42 km grid to the Heligoland grid point. PRISMA grid points around Heligoland are located over the sea whereas those around Norderney or Büsum are just partially located over the sea. Therefore an interpolation of PRISMA grid points to Büsum or Norderney would also include wind information from grid points over land leading to large errors in the interpolated wind speed and direction for Büsum or Norderney.

A comparison was carried out between the time series of the PRISMA data and station measurements over the period 01-01-1989 to 31-12-2000. Mention should be made, however, of a discrepancy in this comparison: the PRISMA data, based on ten-minute means, are stored at 3-hour intervals whereas the station data are available at 1-hour intervals as hourly means. Due to the gustiness of the wind the mean of the shorter time-averaging period is greater than that of the longer time-averaging period. According to SCHROERS and LÖSSLEIN (1983) the 90%-value of the 10-minute mean serves as a good approximation of the hourly mean.

Although the synoptic station data (Table 3) yield the highest mean wind speed during the period 01-01-1989 to 31-12-2000 (with wind speeds above 8 m/s occurring more frequently in the station time serie and wind speeds below 8 m/s occurring more frequently in the PRISMA time series) (Fig. 5), wind speeds above 20 m/s are found to occur more frequently in the PRISMA data record (not shown).

Table 3: Overall mean wind speed (in m/s) from 01-01-1989 to 31-12-2000 at Heligoland

Station data (hourly mean)	PRISMA (10-minute mean)	PRISMA (hourly mean)
8.31	7.37	6.64

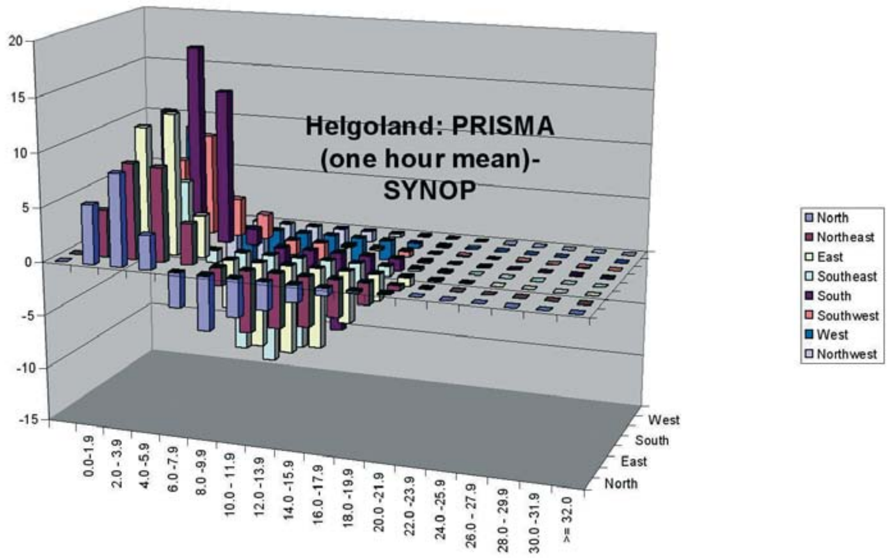

Fig. 5: Frequency distribution of wind speed difference (observations Heligoland – PRISMA) for different wind directions

4.3 Characteristic Forcing for a One-Year Period

The morphodynamic changes in the Dithmarschen Bight were studied for the period 01-05-1998 to 30-04-1999. These 12 months are characterized by a period of high wind speeds in the autumn, as it is typical for this season. Particularly extreme high wind speeds did not occur, however.

In order to simulate a first guess result for a longer period the hydrodynamic models were driven by a characteristic wind speed and direction representative of conditions throughout the German Bight. In accordance with the foregoing, the time series at Heligoland was chosen to generate these representative values.

As the PRISMA data show some deviations from the observed station data during a period when the measurements of wind speed and direction at Heligoland were as accurate as possible, the observed data at Heligoland were used as input forcing for hydrodynamic modelling during this period (May 1998 to April 1999). Measurements at the Heligoland station were considered to be representative for the German Bight area, as demonstrated by the results of numerical (NWP) simulations for this specific area.

By subdividing a distribution into classes the maximum number of classes may be expressed a function of the sample size, e.g.:

$K = 5 \log(n)$,

with K: number of classes,
log: logarithm to base 10,
n: sample size (PANOFSKY and BRIER, 1958).

By definition, the modal centre of the wind distribution is assumed to describe the characteristic wind for the whole period. With 0.5 m/s wind speed classes and 20 degree wind direction classes the location of the modal centre is calculated to be 8.75 m/s and 225 degrees. This wind was assumed to be representative for the 12-month period considered in the present study and was thus used as input to the hydrodynamic models. However, this classification is too fine to fulfil the condition formulated by PANOFSKY and BRIER (1958). In fact, 1080 classes are obtained if all wind speed measurements up to 30 m/s are considered. As the sample size is 8760, the condition formulated by PANOFSKY and BRIER (1958) would permit a maximum of 20 classes. If, however, only the classes from 180 to 260 degree and from 7.5 to 9.4 m/s are considered, a sample size of 564 falls into these 16 classes as these classes occur much more frequently than other classes (see also Fig. 4, which shows a similar distribution for a longer time scale). Instead of selecting a subset of the sample it would also have been possible to increase the class width. Although a class width of e.g. 90 degrees and 7.5 m/s would have fulfilled the classifying condition mentioned above, it would have been worthless due to its coarse and inadequate resolution as well as a misleading location of the modal centre. With 0.5 m/s wind speed classes and 20 degree wind direction classes the modal centre of both the full sample and the subset may be clearly identified. The dependence of the location of the modal centre on the chosen classification is shown in Table 4.

Table 4: Dependence of modal centre location on chosen classification

Class width	0.5 m/s and 10 degrees	0.5 m/s and 20 degrees	2.0 m/s and 45 degrees
Location of modal centre	8.75 m/s, 230 deg. 7.75 m/s, 200 deg.	8.75 m/s, 225 deg.	9.00 m/s, 180 deg.
Percentage of modal centre occurrence	0.32	0.64	4.6

The wind considered here to be representative (8.75 m/s and 225 degrees) is also in agreement with other statistical results: the median of the wind speed is found to be 8.7 m/s while the mean wind speed is computed to be 8.82 m/s for a mean wind direction of 210 degrees.

5. Conclusions

Hydrodynamic simulations using PRISMA and NWP data for external forcing were carried out in the present study for conditions of high winds over the German Bight in order to demonstrate the influence of meteorological data on simulated water levels. Even for the case of maximum water levels during storm surge conditions in February 2000 the differences between the simulated results using different forcing data (LM, GME, PRISMA) were less than the differences between each of the simulated results and measured water levels. Moreover, the differences between measurements and the results of the LM-forced simulation were found to be less than the corresponding differences with PRISMA forcing. In general, the results demonstrate that both the PRISMA and NWP data (in particular, the LM data) are suitable for forcing hydrodynamic models in a realistic way.

A comparison between PRISMA data and SYNOPTIC measurements at the Heligoland station from 01-01-1989 to 31-12-2000 indicates that the PRISMA results tend to underestimate the mean wind speed, even though PRISMA data usually overestimate wind speed. On the other hand, the frequency of occurrence of particularly high wind speeds based on PRISMA data is higher than that given by SYNOPTIC station measurements.

The results of numerical simulations using a cascade of NWP models (GME, LM) demonstrate the applicability of these models for meteorological forcing in morphodynamic computations. The finer the horizontal grid resolution of the meteorological models, the better are the results. Especially near the coast with a well-defined change in surface characteristics, it is found that the high-resolution LM with a 2.8 km grid is necessary to resolve the distinct modification of the wind field. Over the open sea, however, even the results of the coarse-resolution version of the GME are usually in closer agreement with observations than PRISMA data.

On the basis of numerical simulations it has been shown that observations at the Heligoland station may be adopted as representative wind information for the whole of the German Bight (with the exception of near-coastal areas).

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