Investigations of Wave Climate in the Harbour of Rostock-Warnemünde with a Spectral Wave Model

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Abstract

The wave model *WARM* is used to predict the wave climate in the inner part of the Warnow subsequent to an extension of the harbour of Rostock-Warnemünde. *WARM* is a numerical spectral wave model with a nonlinear dissipation function. The internal nonlinear interactions of waves are neglected. The analytic solution of the source functions correctly reproduces the total energy and peak frequency of the Pierson-Moskowitz fully developed sea state. Since the wave climate in the Warnow estuary is influenced by currents and changes in the water levels, the wave model *WARM* has been coupled with the hydrodynamic model *TRIM-2D*. In order to verify the wave model, computed wave heights are compared with measurements in the inner part of the Warnow estuary. The agreement is excellent. The verified model predicts changes in wave climate during south-westerly winds. The applicability of the wave model (coupled with a hydrodynamic model) for determining the wave climate is clearly demonstrated for a small-scale coastal environment under tidal influence.

1 Introduction

The harbour of Rostock-Warnemünde is located off the Baltic in the Warnow estuary (Fig. 1). It is enclosed by the state of Mecklenburg-Vorpommern. The Seekanal navigation channel (Fig. 4) provides the only connection between the Baltic and the Breitling, a wide enclosed body of water with flats in the Warnow estuary (Fig. 3). A navy base is situated at the northern part of the Breitling.

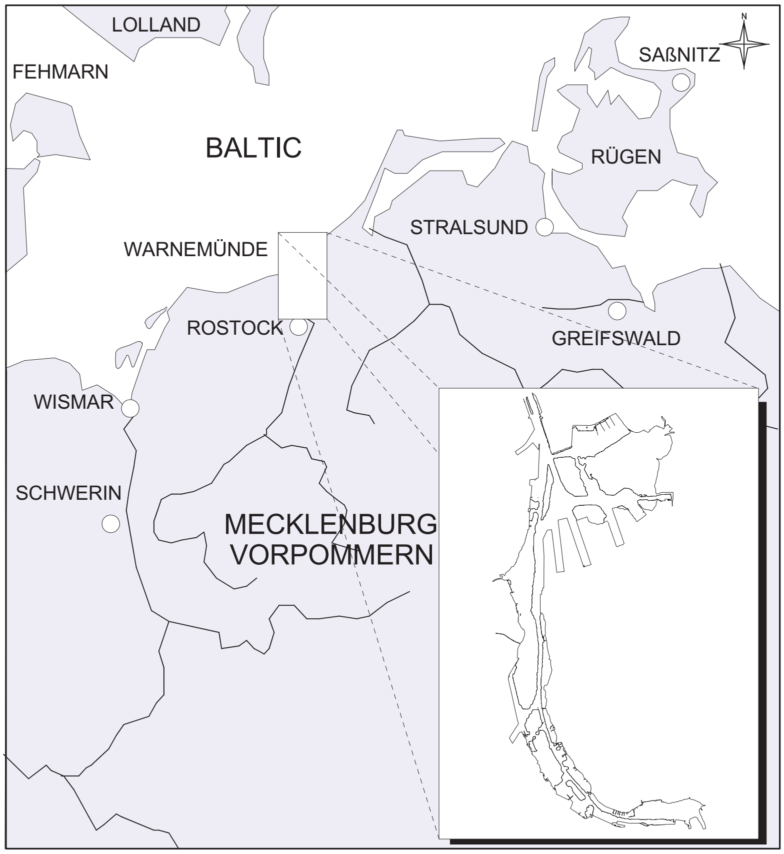

Figure 1: *Coastal area with the harbour of Rostock-Warnemünde*

South-westerly winds over the Breitling can generate high waves in the harbour basin of the navy base. It was necessary to predict wave climate changes in this basin resulting from the extension of the Rostock-Warnemünde harbour.

2 The wave model

The spectral wave model *WARM* is used to investigate wave climate. *WARM* is an acronym for *WA*ve *R*ay *M*odel. It is a numerical spectral wave model used to obtain wave parameters in coastal areas and estuaries for given stationary and instationary wind-, water level- and current conditions.

The wave model computes the 2-dimensional spectrum taking into account:

- refraction by bottom- and current variations,
- wave-current interaction (wave-blocking),
- generation of wave energy by the wind,
- non-linear dissipation of wave energy and
- dissipation of wave energy by bottom friction.

The model is based on the spectral transport equation for the action density $F(\vec{k},\vec{x},t)$

$$\frac{d}{dt}F(\vec{k},\vec{x},t) = \left(\underbrace{\frac{\partial}{\partial t}}_{A} + \underbrace{\frac{d\vec{x}}{dt}\cdot\frac{\partial}{\partial \vec{x}}}_{B} + \underbrace{\frac{d\vec{k}}{dt}\cdot\frac{\partial}{\partial \vec{k}}}_{C} \right) F(\vec{k},\vec{x},t) = S \quad (1)$$

where S is the sum of different source functions, $\vec{k} = (k_1,k_2)$ is the wave number vector, $\vec{x} = (x_1,x_2)$ is the location vector and t is the time. In deep water only term A and B are used ($C = 0$). In shallow water all terms are used. The term C determines the direction of the wave propagation.

The model solves the spectral transport equation in two steps:

1. it computes the propagation term;
2. it solves the source function on the basis of the first calculation.

The physical processes of growth and decay of ocean surface waves are discribed by the source function (Günther, H. and W. Rosenthal, 1995)

$$S = S_{in} + S_{dis} + S_{bot} \quad (2)$$

which is the sum of dissipation S_{dis}, atmospheric input S_{in} and dissipation by bottom effects S_{bot}.

For dissipation, a non-linear function is used which has been introduced by Rosenthal (1989). The process of vertical momentum exchange by turbulent eddy viscosity results in

$$S_{dis} = -\gamma\, \omega^2 k^4 \cdot F^2(\vec{k}) \quad (3)$$

where $\gamma = 0.14$ and ω is the angular frequency.
The standard source function of the input from the atmosphere and bottom dissipation is linear in the action density. The transfer of wind energy to waves is described with

$$S_{in} = \beta \cdot \omega \,\max\left\{ 1.7\frac{\vec{u}_{10}\cdot\vec{k}}{\omega} - 1; 0 \right\} \cdot F(\vec{k}), \quad (4)$$

where $\beta = 0.0003$ and $\vec{u}_{10}$ is the velocity vector 10 meters above the sea surface. This equation is due to Snyder et al. (1981), rescaled in terms of friction velocity.

$$S_{bot} = -\alpha\, \omega^{-2} k^2 (1 - \tanh^2 kd) \cdot F^2(\vec{k}), \quad (5)$$

is a bottom dissipation function where $\alpha = 0.04$ m^2 s^{-3} and d is the water depth. The function was originally developed in JONSWAP (Hasselmann et al., 1973) and is widely used in numerical wave modelling.

Under consideration of a homogeneous ocean of constant water depth without currents and a stationary homogeneous wind field, transport (1) together with source functions (3 to 5) has been tuned to reproduce correctly total energy and peak frequency of the Pierson-Moskowitz fully developed sea state.

3 The coupled model system

Investigations in the German Bight have shown that wave climate is influenced by spatial and temporal variations of the water level (Winkel, 1994). This phenomenon can be observed along the entire German coast, at the North Sea as well as at the Baltic. The currents in the estuaries and in the tidal gullies also play an important role for the propagation of waves.

This coupled hydrodynamic and wave system has been studied in a flume with a trapezoidal cross-section and a length of 10 kilometres. For the investigations presented here, the hydrodynamical numerical model *TRIM-2D* (Casulli, V., 1990 and Cheng, R.T., V. Casulli and J.W. Gartner, 1993) and the wave model *WARM* are used.

TRIM-2D is a 2-dimensional finite difference model. It solves the shallow water equations, i.e. the continuity equation and the equation of motion. As input the model needs the topography of the estuary, fresh water discharge, water level at the seaward open boundary and also the wind over the estuary during the period of interest. *TRIM-2D* can provide time series of e.g. water level at points of interest and two-dimensional fields of water levels and currents at selected times. The wave model *WARM* simulates the wave propagation on the basis of these results.

One result of these simulations is shown in Figure 2. The flow is from right to left. For one point in the middle of the flume *WARM* calculates the wave rays on which energy parts of the spectra can be transported (back tracing). The waves have a period of 1.8 seconds and the directional resolution is 5 degrees. When they are entering from the left end of the flume, they are trapped by the opposing current. Therefore, it is possible that the waves travel upstream to the point of interest. For waves entering from the right end the refraction of the currents causes only small changes in the propagation direction of the waves.

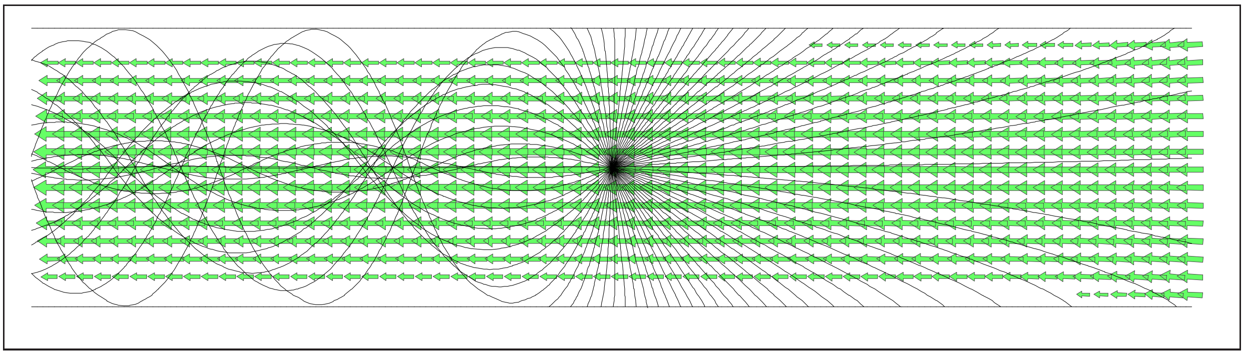

Figure 2: *Computed current velocities and wave rays in a flume. The waves have a period of 1.8 seconds and the directional resolution is 5 degrees.*

4 Investigations of wave climate in the harbour of Rostock-Warnemünde

The purpose of these investigations is to predict the wave climate at the naval basin (nothern part of the harbour, see Figure 3) after the extension of the navigation channel (Seekanal) and the harbour. In 1995, the navigation channel was 80 m wide and approximately 13 m deep at the narrowest point. After the extension the channel will have a width of 120 m and a depth of 14.5 m. The water depth of the naval basin will increase from 6 m to 8 m. In addition to these changes, a new small island Pagenwerder 2 (Fig. 4) will be hydraulic filled in the Warnow estuary.

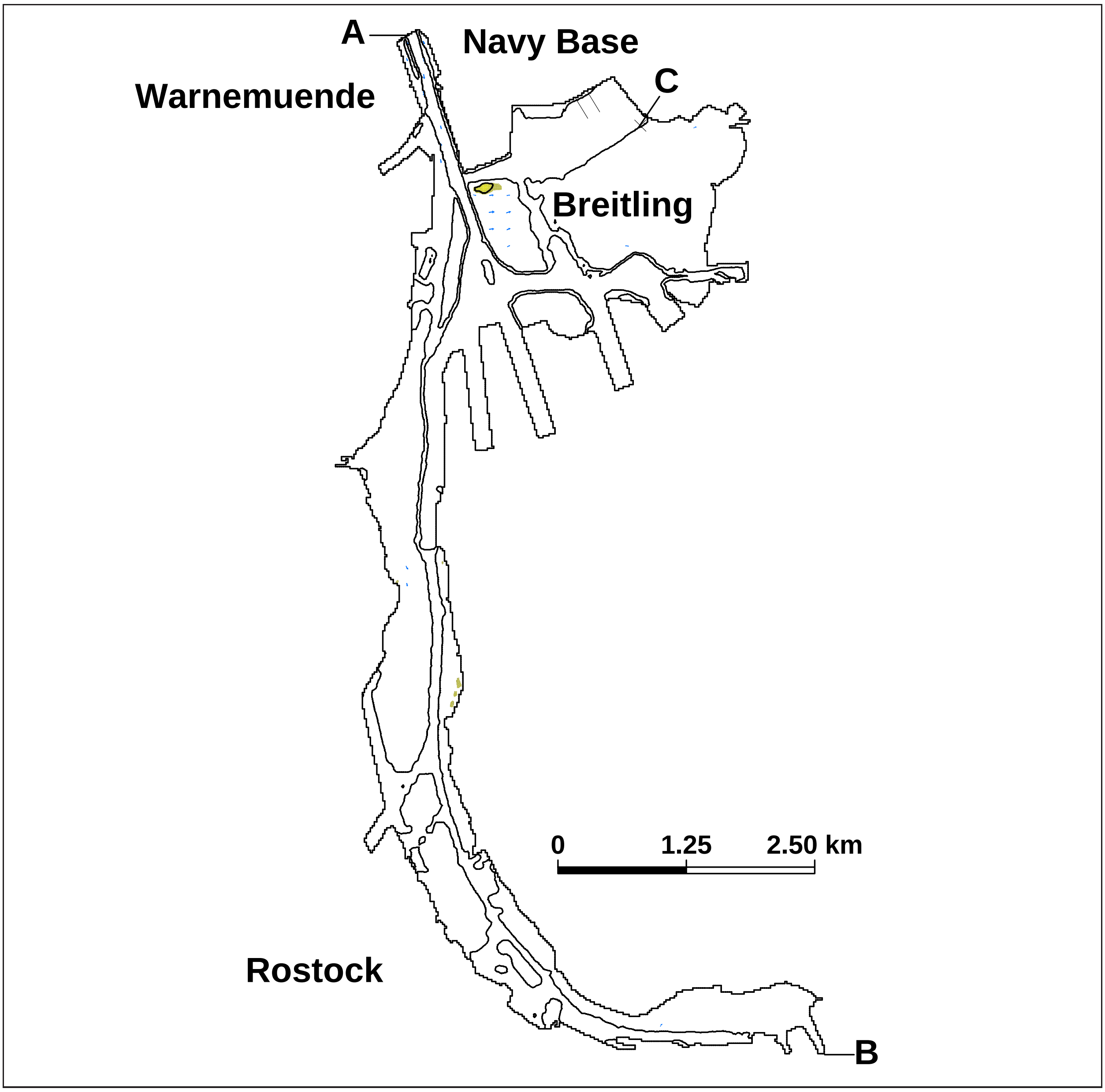

Figure 3: *Bathymetry of the Warnow estuary in 1995 with the locations of measurements:* **A** *water level,* **B** *fresh water discharge,* **C** *wind and waves.*

The investigation is carried out in 3 steps:

1. verification of the model with respect to the model system,
2. determination of wave climate before the extension and
3. determination of wave climate after the extension.

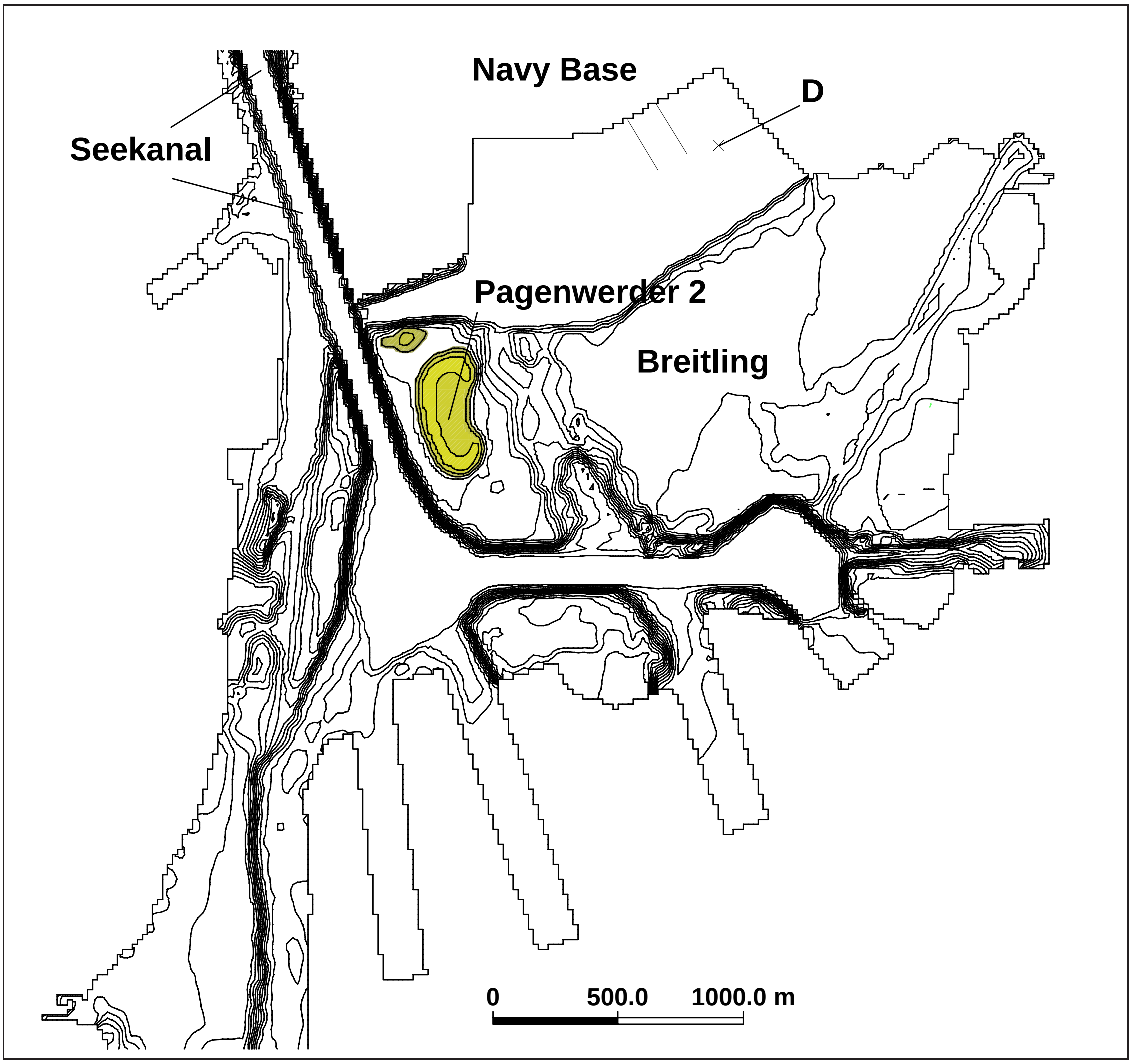

Figure 4: *Bathymetry of the northern part of the Warnow estuary after the extension.* **D** *denotes the location, where computed wave heights are compared.*

For the investigations of the wave climate of the north-eastern part of the harbour of Rostock-Warnemünde the described model system is used. The influence of the currents and water level has to be taken into account because changes of the water level induce the drying and wetting of sandbanks and tidal flats. Under stormy conditions, wind induced circulation influences the propagation of waves.

The model domain of the Warnow estuary reaches from Warnemünde the entrance of the harbour, to Rostock in the south. (see Figure 3). The grid spacing is $\Delta x = \Delta y = 20$ m.

The topography represents the conditions in 1995. The water level at the boundary to the Baltic was measured at the Seekanal gauge. This measurement is used to control the open boundary to the Baltic. The measured fresh water discharge is added to the model at Rostock. In addition to these data sets, BAW (Federal Waterways Engineering and Research Institute) has measured wind and waves during November 1996, in the Warnow estuary. The measured wind is representative for the entire model area. Figure 3 indicates the location of various measurements.

Under consideration of wind, fresh water discharge (station **B**) and water level at the open boundary (station **A**) *TRIM-2D* calculated water level and currents. The wave simulations are carried out on the basis of these calculations.

For the period of the 1st to the 11th of November 1996 significant wave heights, which have been computed from the 2-dimensional spectrum, are compared with measurements in the inner part of the Warnow estuary. Figure 5 shows the comparison of measured and computed waves at station **C** (see Figure 3). The abscissa denotes the date and the ordinate the wave height up to 60 cm. The agreement is excellent.

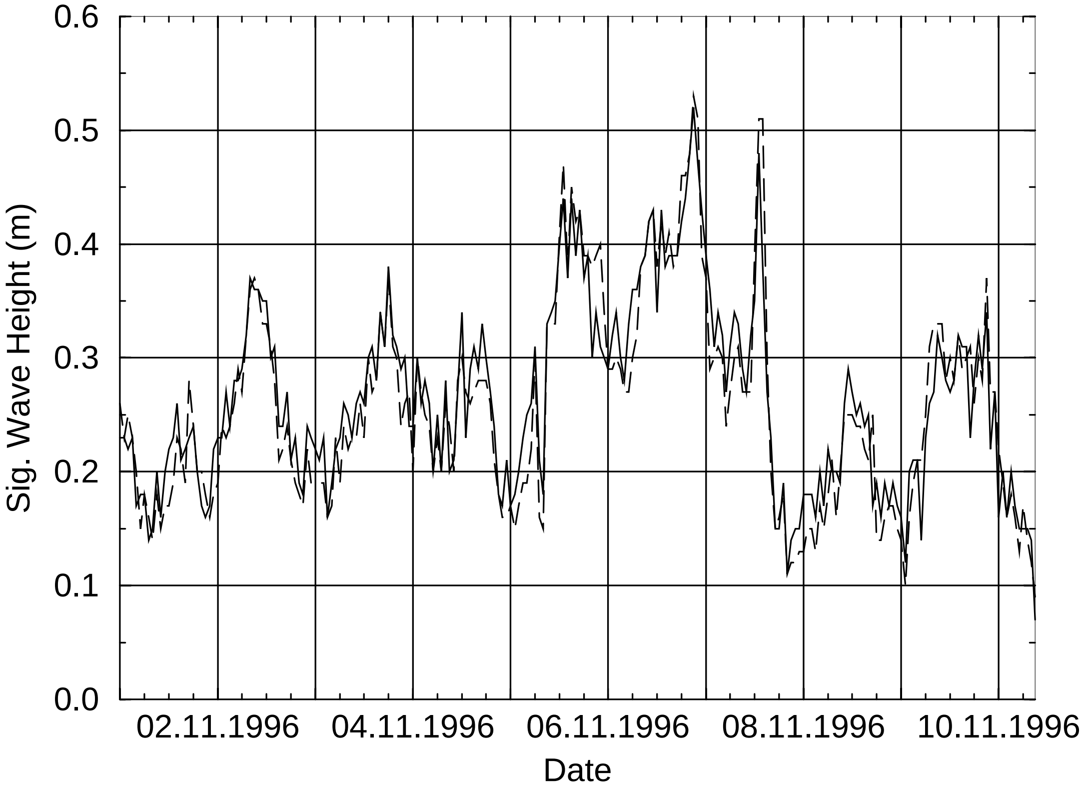

Figure 5: *Comparison of computed (solid line) and measured wave heights (dashed line) at station* **C.**

In order to predict changes in wave climate due to the extension of the harbour a storm scenario was created. The highest waves in the naval basin are generated by strong winds coming from south-west. Therefore, especially south-westerly wind generated waves were investigated. Figure 6 shows the wind velocity, which is used as atmospheric input for the simulations. Wind velocity was gradually increased from 5 m/s up to 35 m/s during a period of 46 hours.

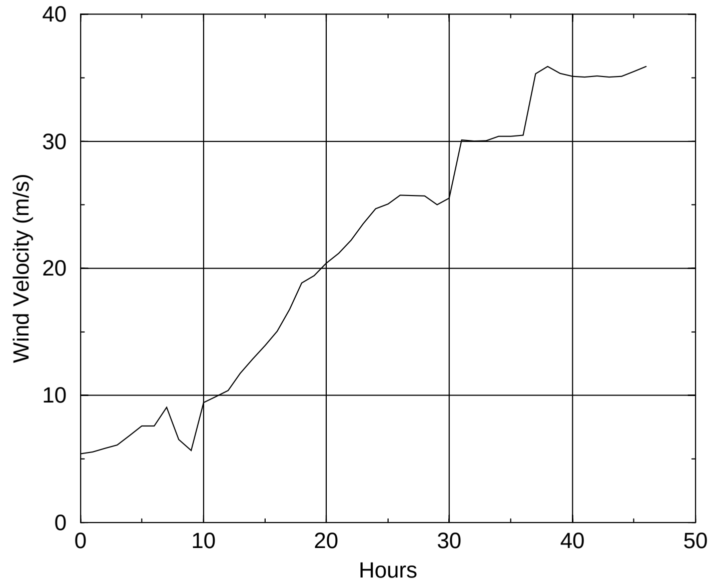

Figure 6: *Wind velocity used as atmospheric input for the storm scenario.*

A result of the computations is shown in Figure 7. It shows the significant wave height at station **D** in the middle of the naval basin. The solid line denotes the wave height for the 1995 situation and the dashed line the wave height after the extension. Due to the shadowing effect of the new island Pagenwerder 2, the predicted wave heights are lower (up to 0.1 m) after the extension. Finally the extension will reduce wave agitation in the naval basin under these conditions.

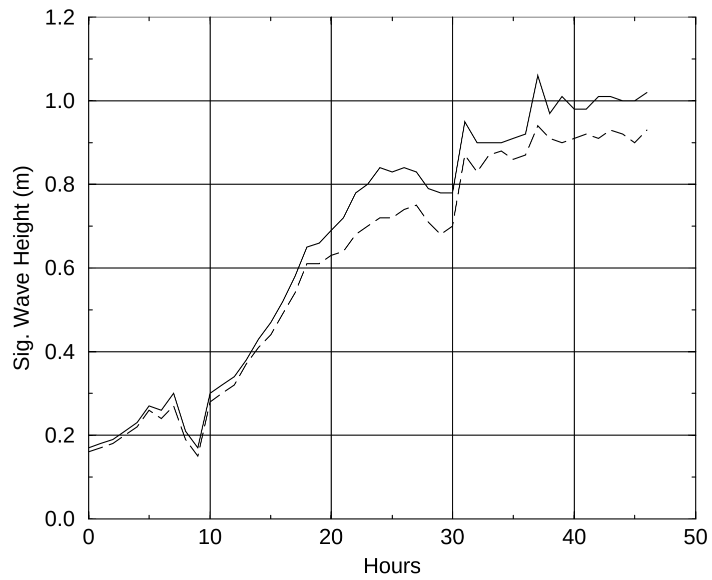

Figure 7: *The solid line significant wave height for the storm scenario at station* **D** *for the situation 1995 and the dashed line wave height after the extension of the harbour.*

5 Conclusion

The wave model *WARM* has been used for predicting the wave climate in the inner part of the Warnow estuary after the extension of the harbour of Rostock-Warnemünde. Since the wave climate in the Warnow estuary is influenced by currents and changing water levels the wave model *WARM* has been coupled with the hydrodynamic model *TRIM-2D*. Under consideration of calculated data sets, the wave model reproduces time series of measured wave heights in an excellent manner. A storm scenario with strong winds coming from south-west was also simulated. Predicted wave heights after the extension are lower, because of the shadowing effect due to the new island Pagenwerder 2. This implies that the extension of the harbour of Rostock-Warnemünde will reduce wave agitation in the naval basin for wind generated waves coming from the south-west. This investigation shows that the wave model coupled with a hydrodynamic model can be successfully applied to a small-scale coastal environment under tidal influence.

6 References

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