CHAPTER 14

Wave Climate Study in Wadden Sea Areas

Ralf Kaiser[1], Günther Brandt[1], Joachim Gärtner[2], Detlef Glaser[1], Joachim Grüne[3], Frerk Jensen[4], Hanz D. Niemeyer[1]

Abstract

Significant features on Wadden Sea wave climate are evaluated in respect of the state of the art. Main emphasis was laid on an analysis of the governing boundary conditions of local wave climate in island sheltered Wadden Sea areas with extensions being sufficient for local wind wave growth. Explanatory for significant wave heights a reliable parametrization of local wave climate has been evaluated by using generally available data of water level and wind measurements.

Introduction

In the German Bight comprehensive wave climate investigations in six distinct Wadden Sea areas have been carried out in recent years (fig. 1). Each of them represents a significant type of Wadden Sea coastal areas: Mesotidal barrier island coasts where the protective islands are seaborne or remnants of former mainland and macrotidal estuarine coasts [NIE-

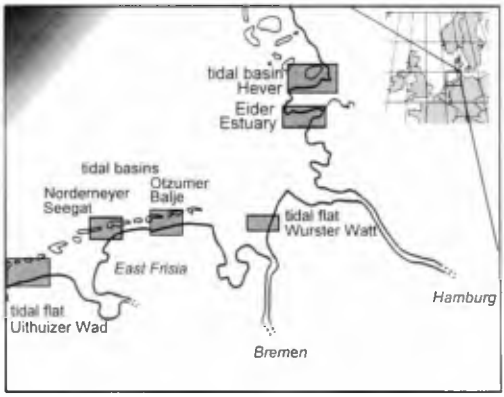


Fig. 1: Investigation areas on Wadden Sea Wave climate in the German Bight

[1]Coastal Research Station of the Lower Saxonian Central State Board for Ecology, Norderney/East Frisia, Germany

[2]Regional Board for Water Management (ALW), Heide, Germany

[3]Joint Research Facility Large Wave Channel, Hannover, Germany

[4]Regional Board for Water Management (ALW), Husum, Germany

MEYER 1990]. The measuring locations within each of these typical areas have been chosen in such a way, that each location itself represents the conditions of a significant part of the total area in respect of the typical morphological boundary conditions. Main aim of these investigations was to establish a parametrization for local wave climate in dependence of the distinct types of morphological boundary conditions of each area as a basis for a more general approach.

Wave climate in Wadden Seas is characterized by strong hydrodynamical-morphological interactions due to restriction of water depths and an often very complex three-dimensional underwater topography. Waves propagating from the offshore shelf via ebb deltas towards the flats break partly or completely experience significant energy dissipation. The generation of strong waves by local windfields on the intertidal flats depends remarkably on tidal elevation and on the wind-induced surge set-up. Therefore this effect is restricted to those limited time intervals for which these necessary boundary conditions occur. On the one hand a reliable forecasting of wave parameters is mostly not achievable by using generally known forecasting procedures, which have been evaluated in areas for less differentiated boundary conditions. On the other hand as useful field data are still very poor the need for such data is tremendous.

Wave climate in island sheltered Wadden Sea areas is characterized by three different types of origin [NIEMEYER 1984, 1991]:

1. Local wind waves,
2. offshore swell entering via the tidal inlets,
3. offshore generated wave systems being generated by onshore directed strong winds and storms and propagating via the tidal inlets.

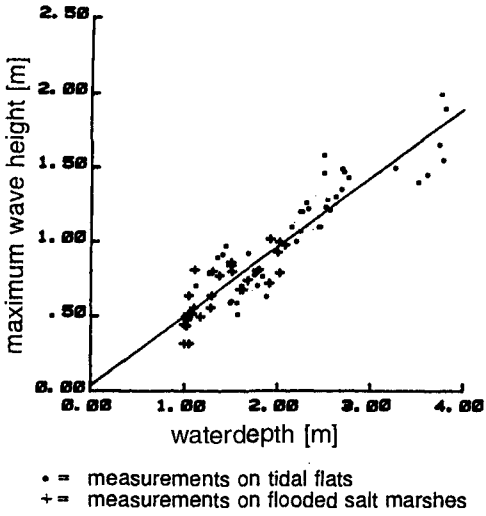


Fig. 2: Wave height/water depth relation for island sheltered tidal flat areas and salt marshes at the East Frisian coast [NIEMEYER 1991]

Due to previous investigations it was established knowledge that the latter type is the most important one as well for design of coastal structures as for impacts on tidal flat and salt marsh morphology [NIEMEYER 1983]: The dynamical equilibrium

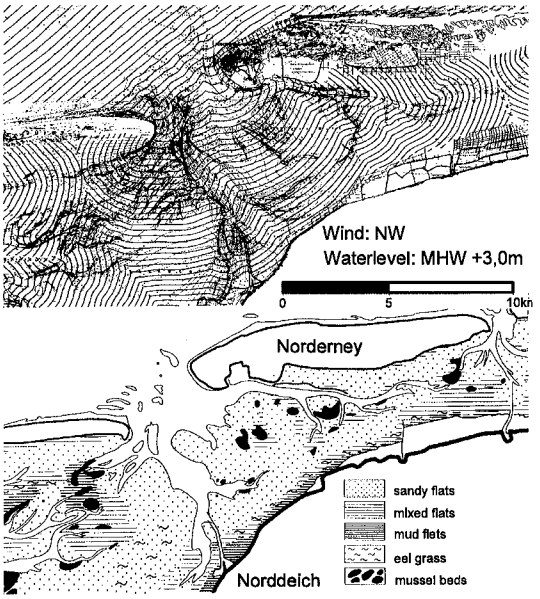
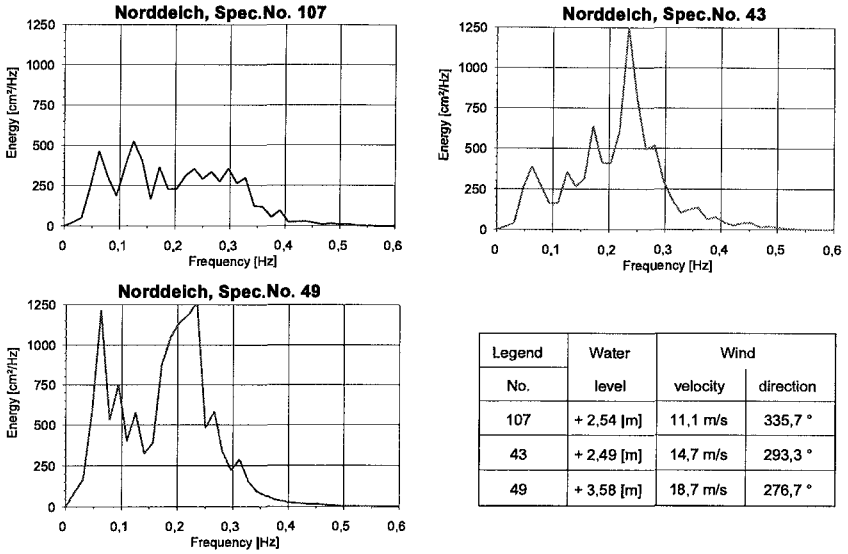


Fig. 3: Combination of refraction diagram and map of surface sediments for the Norderneyer Seegat [NIEMEYER 1987b]; map of surface sediments by RAGUTZKI [1982]

between morphologically stable tidal flats above mean sea-level and waves of type 3 is characterized by a strong linear relationship of local wave heights and water depths which is also valid for adjacent supratidal salt marshes (Fig. 3). The relationship is strictly fitting for onshore directed strong winds and storm but is only valid for areas above MSL.

A combination of refraction diagram and a map of surface sediments has been used by NIEMEYER [1987b] in order to demonstrate the interaction of waves and morphology and the resulting surface sediment distribution for the tidal basin of the tidal inlet Norderneyer Seegat (Fig. 3). The landward succession of sandy, mixed and muddy flats follows the wave propagation from the inlet to the main land. The sector of wave propagation with only modest refraction coincides with the smallest band of mixed and muddy flats in front of the mainland. Due to the dominant changes the wave climate experiences on the tidal inlet bar [NIEMEYER 1987a], wave propagation landward of the inlet is mainly independent from offshore wind direction and setup above mean high water level [NIEMEYER 1986]. There are also small muddy and sandy flats landwards in wave direction of the mussel beds.

Although the data of Wadden Sea waves for the areas above MSL fits generally to the linear relationship H_s/h one has to be aware that different boundary conditions generate distinct spectral energy distributions which is evident by examples of wave spectra (fig. 4) taken from NIEMEYER et al. [1992]. For spectrum No. 107 the still water level is about 1m above MHW and there are wind velocities of 11 m/s from NNW. Energy is distributed over the range from 15-3 seconds, with even higher energy for lower frequencies. For the same water level occurring in coincidence with higher wind velocities from more westerly directions spectrum no. 43 shows a more pronounced peak energy concentration, but its total energy is only about 20% higher than that



Legend	Water	Wind	
No.	level	velocity	direction
107	+ 2,54 [m]	11,1 m/s	335,7 °
43	+ 2,49 [m]	14,7 m/s	293,3 °
49	+ 3,58 [m]	18,7 m/s	276,7 °

Fig. 4: Wave spectra for station Norddeich (see fig. 3) for different boundary conditions [NIEMEYER et al. 1992]

one of no. 107. Waterdepth and fetch for the spectrum No. 107 were more convenient in respect of generating higher waves. The high peak in spectrum No. 43 is due to waves entering from the North-Sea experiencing an energy shift to higher frequencies. An increase in water level of about 1m and higher wind velocities from west produced perform the boundary conditions for spectrum No. 49 with a significant low frequent high peak. For water levels with this height even longer waves with periods of about 15 s can penetrate into the Wadden Sea.

Regional characteristics of Wadden Sea wave climate

An detailed study on wave climate in distinct German Wadden Sea areas [NIEMEYER et al. 1992] reflects their remarkable morphodynamical features in the different regions causing specific characteristic interactions everywhere. Regional wave climate in a particular Wadden Sea area is therefore often very remarkably distinct from that one occurring in another one. Explanatory a comparison of the wave climate in the Hever tidal basin (fig. 1 + 5) and the East Frisian Wadden Sea coast is carried out in order to make differences evident as explained before. The East Frisian Wadden Sea is protected by sea built barrier islands and with relative small tidal basins. The Hever tidal basin has comparatively larger extensions (e. g. width up to 25 km), a wider spreaded tidal inlet and a lower ebb delta with shoals laying 3m below MSL.

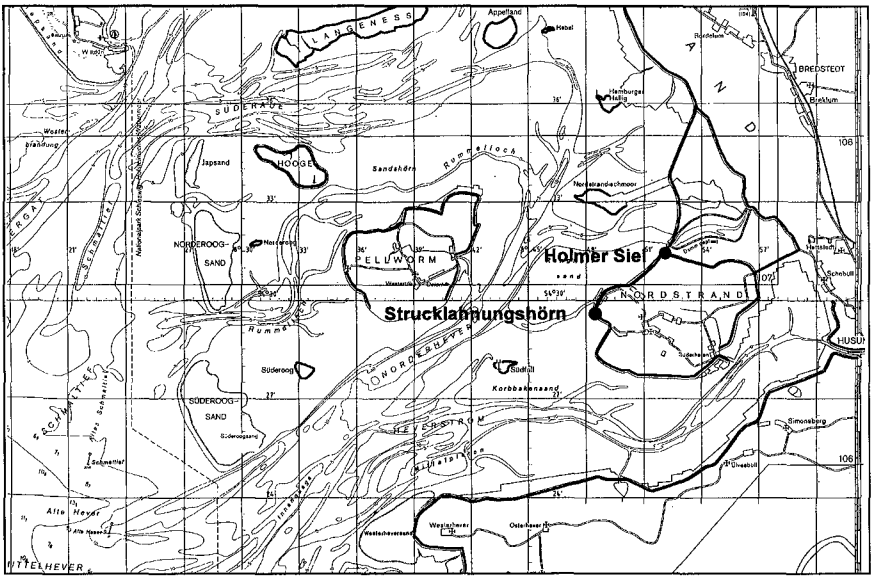


Fig. 5: Hever tidal basin with measuring locations Strucklahnungshörn and Holmer Siel

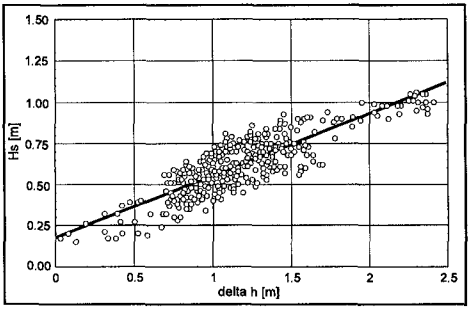


Fig. 6: Norddeich [Hs=0.177+0.378*Δh]

The islands in this system are remnants of the former mainland. According to the hydrodynamical classification of tidal inlets [HAYES 1979] both areas are mesotidal and characterized by mixed energy, tide dominated [NIEMEYER 1990, NIEMEYER et al. 1992].

In the figures 6 to 8 significant wave heights versus wind-induced set-up is plotted for the stations Norddeich (fig. 3) at the mainland coast of the tidal basin of the Norderneyer Seegat and the stations Strucklahnungshörn in the tidal basin of the Hever (fig. 5). At the station Norddeich data represent strictly fitting linear relationship for the whole range of positive Δh-values with relative small scattering. The data of the station Strucklahnungshörn (fig. 7) reflect a more differentiated correlation of both parameters: There is no pronounced relationship between significant wave height and smaller values of Δh. With increasing Δh two distinct values of both parameters can be distinguished which identify

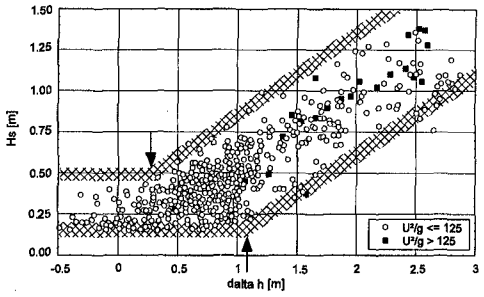


Fig. 7: Significant wave height as function of wind-set-up; Strucklahnungshörn

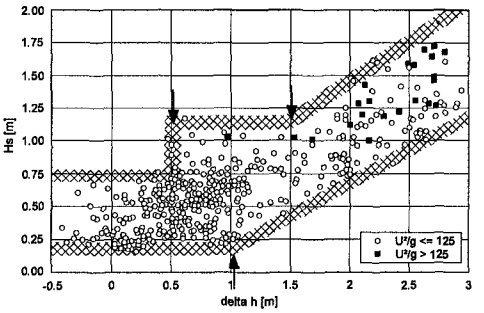


Fig. 8: Significant wave height as function of wind-set-up; Holmer Siel

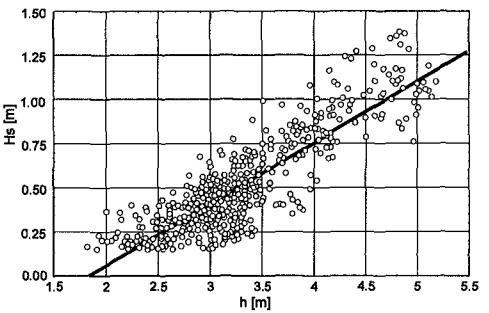


Fig. 9: Strucklahnungshörn [Model: Hs = -0.633 + 0.347 h]

the transition to a relationship for an upper and a lower value. Higher waves increase already for a lower Δh. Smaller waves need a larger critical value of Δh in order to fulfill the same linear relationship. The scattering of the data is significantly higher than for that one of the station Norddeich, which is also valid if only higher wind velocities are taken into consideration.

The station Holmer Siel (fig. 8) is situated landward of Strucklahnungshörn. Regarding the correlation of the same parameters three distinct values of Δh mark significant changes. Similar to the data from Strucklahnungshörn the significant wave heights cover a certain range of values for set-ups in the same order of magnitude. For a wind-set-up of about 0.5 m a rapid increase of the upper value of significant wave height variation is obvious but it remains constant for increasing Δh until the value of 1.5 m. Beyond that figure as well the upper limit as the lower limit of significant wave height variation increase with the set-up whereas the lower one starts already to increase from a set-up of about 1.0 m.

It is of great importance to find a reliable parametrization of local wave climate in order to make the results of field data analysis for a broader range of applications suitable and easily adaptable for coastal managers. Therefore relations are

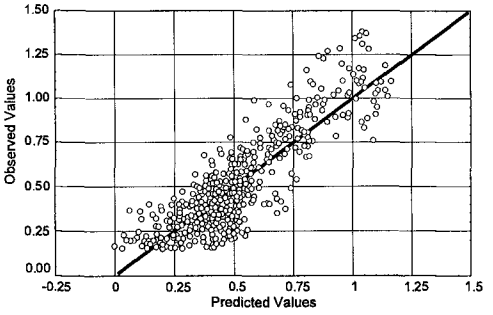


Fig. 10: Strucklahnungshörn [Model: Hs = -0.633 + 0.347 h]; r = 0.859

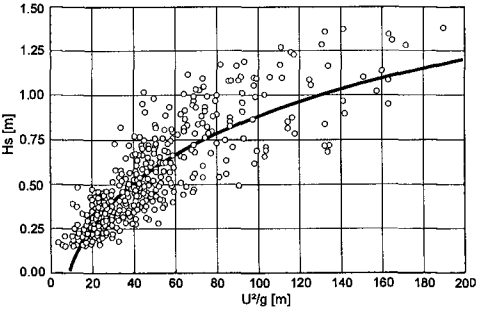


Fig. 11: Strucklahnungshörn [Model: $Hs=1.757 + 1.231\ (U^2/g)^{0.166}$]

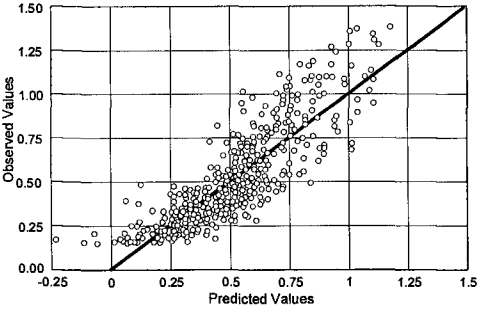


Fig. 12: Strucklahnungshörn [Model : $Hs = -1.76 + 1.23\ (U^2/g)^{0.166}$]; r = 0.84994

required which on the one hand vary only to a small extent and can on the other derived from a small number of parametrizated boundary conditions. Comparing the correlation of the significant wave-height and local water depth for the station Strucklahnungshörn (Fig. 9) with the same one island sheltered tidal flat areas and salt marshes at the East Frisian coast, it becomes evident that the first one in respect of its statistical quality must be regarded as insufficient for a reliable parametrization of local wave climate in the basin of the Hever inlet. Correlating significant wave heights with local water-depths and plotting observed against predicted values (Fig. 10), there are deviations of more than ± 35%. The strength of the relationship given by the coefficient of determination is $r^2 = 0.74$. Doing the same for significant wave heights and local wind velocities (Fig. 11) for the station Strucklahnungshörn the relationship is in agreement with the physical process nonlinear. The results of the nonlinear regression model scatter as well as that one for the linear wave height / water-depth regression (fig. 9) in relation to measured data. Evaluating the fit of the model by the correlation of predicted versus observed values there are also large deviations and the coefficient of determination has a similar value: $r^2 = 0.72$ (Fig. 12).

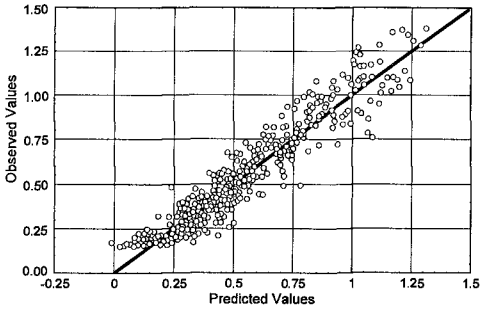


Fig. 13: Strucklahnungshörn [Model: Hs = -0.81 + 0.21 h + 0.16 $(U^2/g)^{0.372}$]; r = 0.950

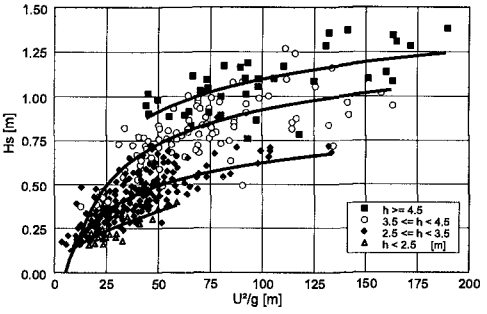


Fig. 14: Strucklahnungshörn, Models: Hs = f(U^2/g) differentiated for four ranges of water depth

The boundary conditions waterdepth and local windfields effect the local wave climate interactively by superimposing each other. These combined effects are described by the following equation: H_s = f (h, U). According to the physical background the model for the estimation of the relationship has a linear term for waterdepth and a nonlinear one for the wind velocity (fig. 13). The scatterplot of values predicted by this model versus observed wave heights show much smaller deviations of about 25% in comparison with those ones which estimate significant wave heights by considering only one boundary condition. The coefficient of determination is r^2 = 0.903 which can directly be compared with those ones gained previously, because they are calculated for the same data set. But for a reliable parametrization of local wave climate this result is still insufficient. In order to improve the empirical relationship by a more differentiated consideration of boundary conditions we have to break down the data of water levels and wind into different groups. The creation of four data subsets for different ranges of water depths allow a deeper insight into the processes governing local Wadden Sea wave climate (fig. 14): The significant wave heights are plotted versus the local wind velocities for four distinct water level subsets. Incorporated are additionally the nonlinear regression models for the different groups, but the scattering is significantly large. Due to the limiting condition of the water depth even higher wind velocities result in lower wave heights for lower water depth. The limitation of local wave heights due to water depth are stronger than could be expected in respect of the shallow water breaking criteria. This effect has already been detected for East and West Frisian Wadden Sea areas [NIEMEYER 1983] and is obviously a typical feature of wave climate in island sheltered Wadden Sea areas.

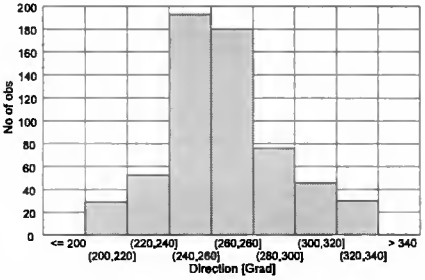


Fig. 15: Wind Strucklahnungshörn; numbers of observations for wind directions from 200° to 340°

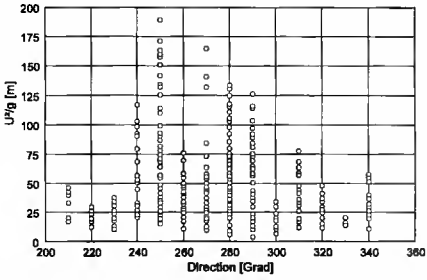


Fig. 16: Wind Strucklahnungshörn; distribution of velocities in respect of directions

For coastal areas and particularly regions like the Wadden Sea with their complex morphology the orientation to the open sea and the wind direction are of great importance because they determine both wave growth and energy dissipation. Therefore a differentiation in respect of wind directions seems to be an appropriated approach. The distribution of both the numbers of observations and the wind velocities in respect of the relevant sectors for the Hever inlet are documented in the figures 15 and 16. Due to measurement procedures the distribution of wind observations in these graphs is dependent of wave measurements, because these measurements were triggered by distinct wave height or water depth exceedence levels and reflect therefore situations with higher water levels and higher waves. Highest waves could be expected in the Hever tidal basin for wind from the sector South-West to North-West. Grouping the data sets for the wind directions from 240° to 290° for sectors of 10° is used to produced differentiated data sets for the nonlinear model $H_s = f(h, U)$. The fit of the nonlinear model $H_s = f(h,U)$ after grouping for different wind directions has generally improved (fig. 17-22). Particularly for the sectors 240°, 250° and 270° the relationship has a very high significance.

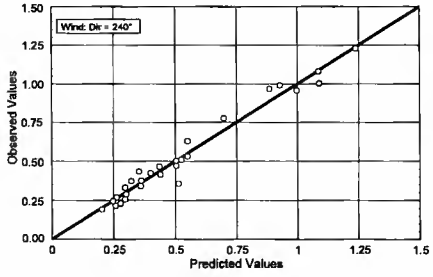


Fig. 17: Strucklahnungshörn [Model: $Hs= -1.32+0.27\ h+0.27\ (U^2/g)^{0.34}$] $r = 0.98453$

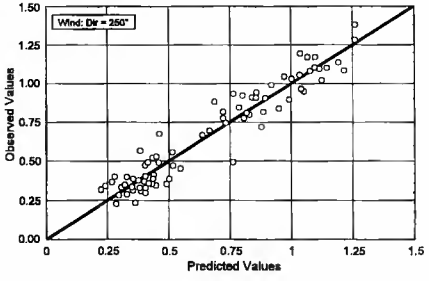


Fig. 18: Strucklahnungshörn[Model: $Hs= -1.84+0.27\ h+0.93\ (U^2/g)^{0.13}$] $r = 0.96238$

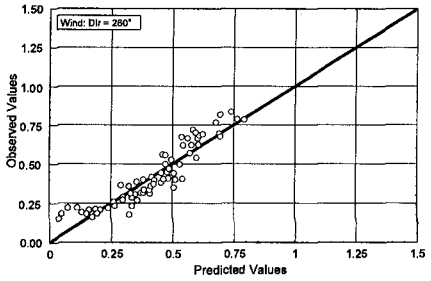


Fig. 19: Strucklahnungshörn [Model: Hs=1.25+0.22 h+(-2.58) $(U^2/g)^{-0.16}$] r = 0.92363

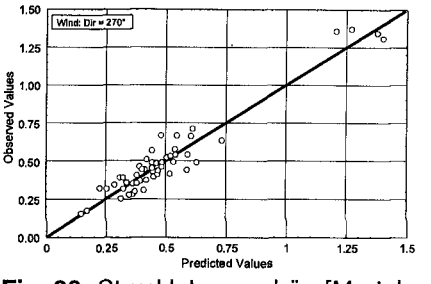


Fig. 20: Strucklahnungshörn[Model: Hs= -0.24+0.16 h+0.003 $(U^2/g)^{1.09}$] r = 0.95980

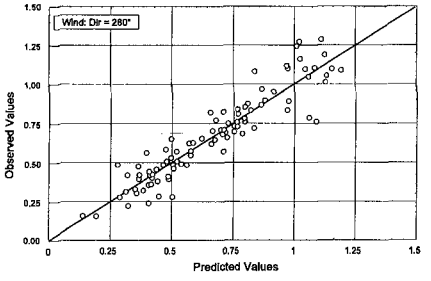


Fig. 21: Strucklahnungshörn [Model: Hs= -0.63+0.23 h+0.06 $(U^2/g)^{0.50}$] r = 0.93208

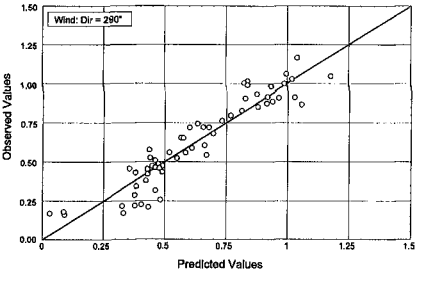


Fig. 22: Strucklahnungshörn[Model: Hs= -0.76+0.24 h+0.11 $(U^2/g)^{0.40}$] r = 0.93705

Conclusions:

- In island sheltered Wadden Sea areas with large onshore-offshore extensions local wind effects on wave climate cannot be neglected. The simple wave height / waterdepth relation is therefore no longer sufficient for a parametrization of Wadden Sea wave climate.

- The maximum wave heights in Wadden Sea areas are limited by water depths by a critical value below the shallow water breaking limit. They are independent from wind velocities beyond a certain level but depend on wind direction in respect of both wave growth and energy dissipation.

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