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FIELD STUDY ON WAVE CLIMATE

IN WADDEN SEAS AND IN ESTUARIES

BY

JOACHIM GRÜNE

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Abstract

This paper deals with a field study on wave climate in wadden seas and in estuaries at the German Bight. In the paper some first results are presented with special respect to the influence of local windspeed and winddirection on the waveheight - waterdepth correlation.

Introduction

Wave climate in wadden sea areas are strongly influenced by the complex three-dimensional underwater topography of extented tidal flats with gullies and parts of estuaries. Fully developed wind waves at the landside borders only occur under storm surge conditions with a considerable rising of the water level up to some meters above Mean High Tide. Similar boundary conditions occur in estuaries, where additionally tidal currents and restricted fetches for local winds have to be considered. Forecasting of realistic wave climate parameters is mostly unaccurate and unsatisfactory by using common formulae, due to the complex boundary conditions. Useful field data are poor, consequently there is still a great need for such data.

Field measuring program and equipment

The field study is a part of a comprehensive research program on the savety analysis of coastal protection works against storm surges at the German Bight with special respect to the increasing of storm surges and the supposed long-term rising of water levels at the coastline of the North Sea. Wave climate and wave run-up have been measured for recent years at four different locations at the landside borders of the wadden sea and the Elbe river estuary (Fig. 1) in

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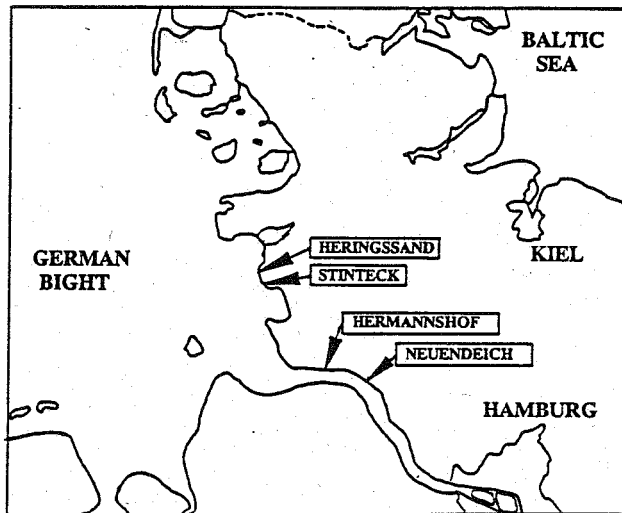
Fig. 1 Measuring locations at the German Bight

cooperation with the Regional State Board for Water Management (ALW Heide, supervision Dipl.-Ing. J. Gärtner) of the State of Schleswig-Holstein.

About the field equipment with respect to the wave run-up measurements has already been reported by Grüne, 1996. Thus in the following only some further informations about the wave measurement equipment will be given.

The cross-sections of the normal profiles in front of the dykes at each location (different distortions) are shown in Fig. 2. The incoming wave climate at the most remote seewards position in front of the dykefoot (W 1) of each location has been recording with two sensors: with a pressure cell for evaluation of surface elevation and with a two component velocity meter for evaluation of wave approach direction. At two locations the surface elevation between position W 1 and the dykefoot has been recording with pressure cells in one (W 2) or two (W 3) additional positions. The dotted lines in Fig. 2 indicate the geodetic reference level Normal Null (*NN*). The highest stillwaterlevel (*max SWL*) of the time periods, for which data have been measured within this field program, is plotted between Mean High Tide (*MThw*) and ever recorded highest one (*HHThw*).

The wave climate at location Heringsand may be characterized as a distinct wadden sea orientated one due to extended tidal flats seawards up to the deeper part of the shelf. In front of the dyke at Heringsand extend a high green foreland (salt marsh) with a width of approximately 500 m and a ground level, which is roughly 0.5 m above Mean High Tide (*MThw*). The distance to the 10 m deepwater line is roughly 7 km. Results presented in the following are restricted to the most remote seawards position W 1 (just as for the three other locations). First results on wave climate changes due to the foreland (W 2 and W 3) are reported by Wang & Grüne, 1997. At Stinteck location the wave
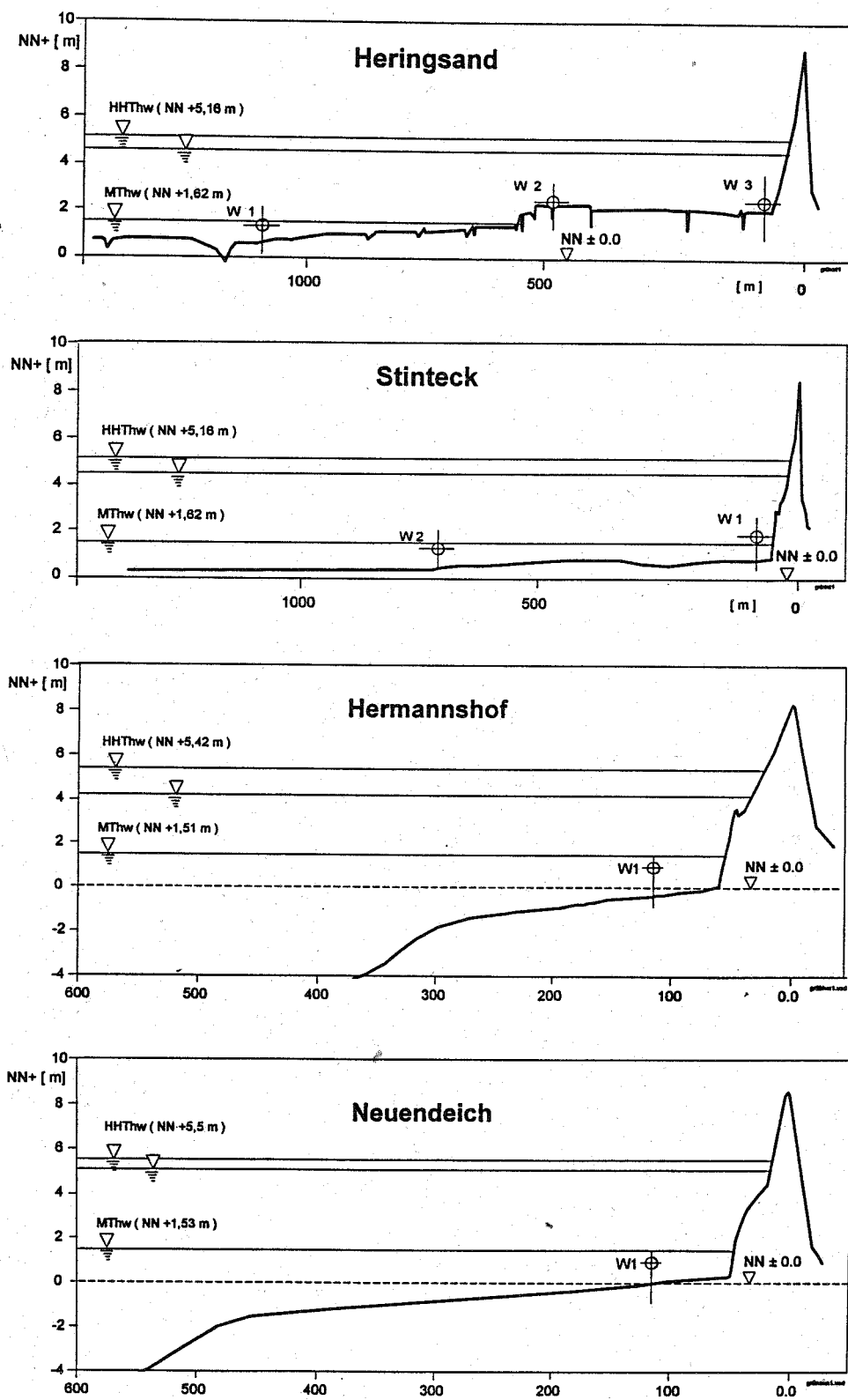
Fig. 2 Cross-sections of the normal foreshore profiles at the measuring locations

climate may be similar to that at Heringsand, though the distance to deepwater (10 m) is only roughly 2 km. The tidal flat sandy bottom extent up to the dyke foot directly.

A strong influence by the tidal regime of the Elbe river estuary on wave climate may be expected at the locations Hermanshof and Neuendeich, where the flats in front of the dykefoots at Hermannshof extend only roughly 200 m up to the deeper part of the river and roughly 400 m at Neuendeich, respectively. Due to this small width wave climate only have been measuring at position W 1.
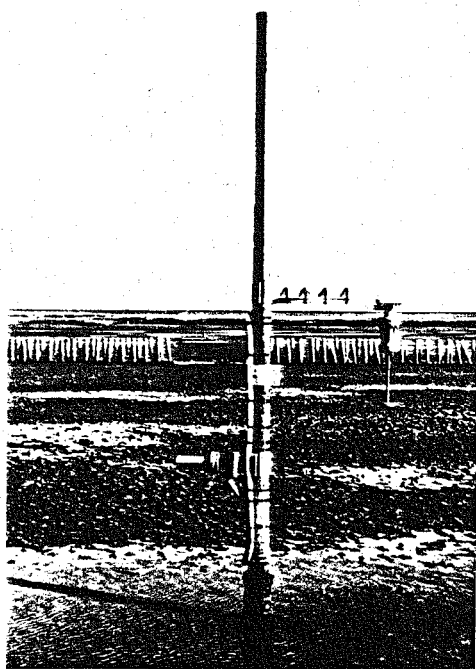
The wave measuring equipment at all locations is identic. Fig. 3 shows a photo of the most remote seewards position W 1 at Heringsand location. The pressure cell is on the left side of the pile support and the two-component velocity meter is on the right side. The surface elevations were evaluated from the pressure cell records by means of 1st order theory transfer function, extended by empirical factors, depending of relative sensor depth and verified in small scale model tests and in field measurements.

Fig. 3   Pile support with sensors

Results

It is well known, that the waterdepht has a distinct influence on wave decay and propagation. Results from previous investigations on wave climate in nearshore areas have already demonstrated, that the waterdepht is the most accurate indicator for occuring wave heights in wadden seas (see e.g. Grüne, 1991; Kaiser et.al., 1994). This can be confirmed in general by the results of this field study. For example the strong waveheight-waterdepht correlation at location Stinteck comes out very clearly in Fig. 4. Totally 956 time periods (each 15 minutes long) have been measured during 3 winter seasons with High Tide levels up to 3 m above Mean High Tide *Thw*. In Fig. 4 the waterdepht is defined as stillwaterlevel *SWL*, which is refered to the national geodetic zerolevel Normal Null (*NN*). Comparing this correlation with such for for waveheight-windspeed relation as shown in Fig. 5 for same data as used in Fig. 4, in general one find a much less accurate correlation with windspeeds.
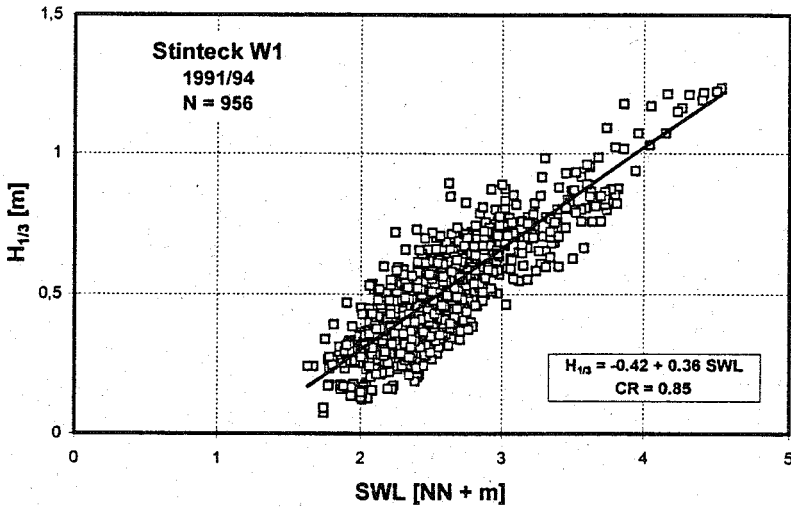
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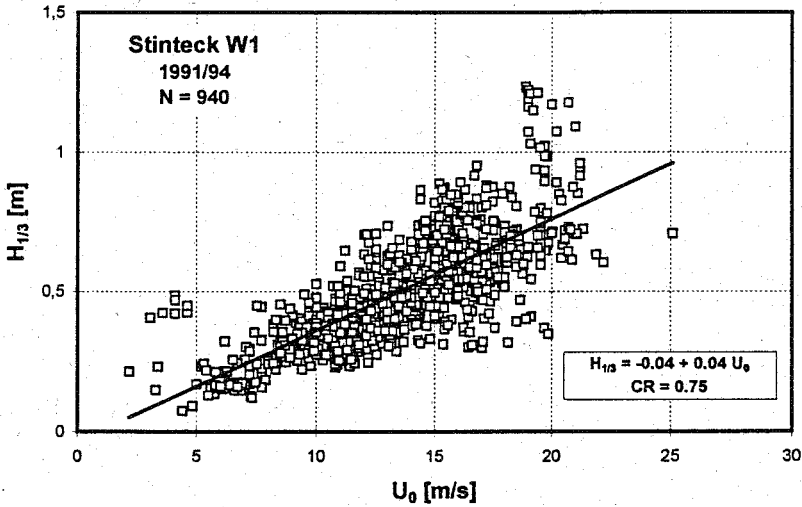Fig. 4 $H_{1/3}$ versus SWL (waveheight-waterdepth correlation)

Fig. 5 $H_{1/3}$ versus U_0 (waveheight-windspeed correlation)

The accurate waveheight-waterdepht correlation may be explained by the sheme of generalized wave decay and generation process on wadden seas, as shown in Fig. 6. The waves coming in from the deeper parts of the shelf are generated by far and near windfields. At reefs or at the front of the wadden sea these waves break partly or totally. On the wadden sea the wave climate is strongly influenced by local bathymetry and local windfield. As well as the wave climate also the surge set-up is a result of the far, near and local windfields and of the bathymetrie of offshore and onshore areas. Thus both the local surge set-up and the local wave climate are connected undetachable. This means, that the local surge set-up contains in terms of a black box all informations about the two-dimensional windfields as well as the wave generation process on the shelf including the wave transfer process to nearshore and therefore the local wave climate is a function of local surge set-up or waterdepth, respectively.
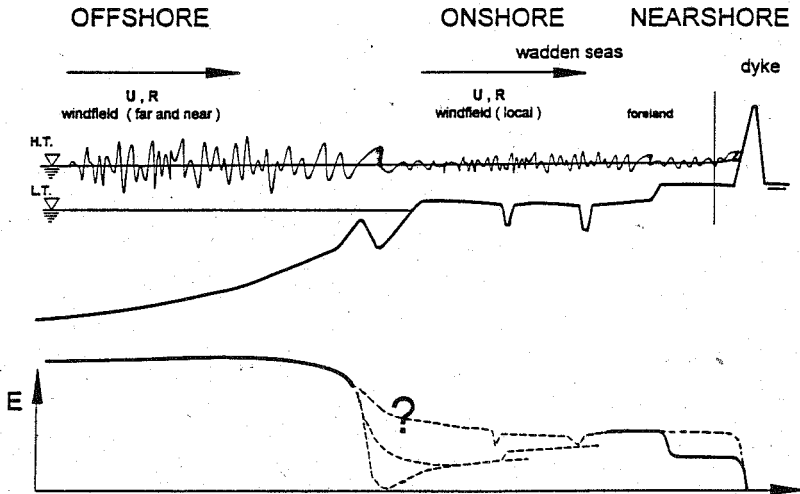
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Fig. 6 Scheme of generalized wave decay and generation on wadden seas

The waveheight-waterdepth correlations from all measuring locations are compared in Fig. 7, where the significant waveheights $H_{1/3}$ are refered to the local waterdephts D. The data of the estuary locations show a less accurate correlation compared to the wadden sea locations, which has to be investigated in more detail within the ongoing work, whereas the relations between the
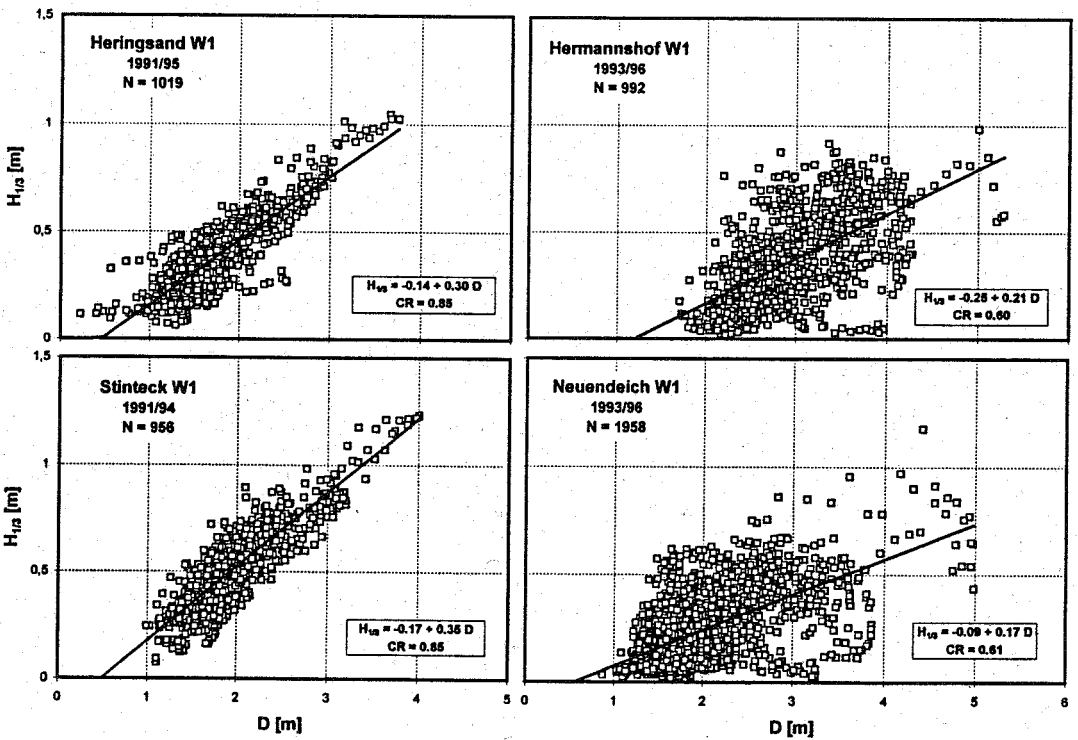

Fig. 7 $H_{1/3}$ versus D at all locations (waveheight-waterdepth correlations)

waveheight and waveperiod parameter in Table 1 agree quite well. The regression lines in Fig. 7 do not fit the zeropoint of the local waterdepht D. That confirms previous statements, that the local waterdepht D can be devided in a waveinactive and a waveactive part (Grüne, 1991) with respect to using the regression line for data representation.

	Heringsand	Stinteck	Hermannshof	Neuendeich
$H_m / H_{1/3}$	0,69	0,70	0,67	0,68
$H_{max} / H_{1/3}$	1,63	1,56	1,67	1,64
$H_{1/10} / H_{1/3}$	1,23	1,21	1,25	1,24
$H_{1/100} / H_{1/3}$	1,54	1,49	1,58	1,55
$H_{rms} / H_{1/3}$	0,74	0,75	0,73	0,73
$T_{H_{1/3}} / T_m$	1,04	1,10	1,01	1,08
T_{m01} / T_m	1,10	1,10	1,07	0,96
T_{m02} / T_m	0,93	0,85	0,79	0,77

Table 1 Comparison of waveheight and waveperiod parameter at all locations

Due to restricted space in this paper the following results will be focussed on the topic: influence of the local windfield (windspeed and winddirection) on the waveheight - waterdepht relation.

The significant wave height data $H_{1/3}$ in Fig. 5 are refered to the present wind velocities U_0 during each measured time period. Such correlations were done further with those wind velocities, which occured 0.5 , 1.0 , 1.5 and 3 hours before the wave measurements (*delta T(U)*), respectively. Fig. 8 shows the accuracies of the correlations in terms of correlation factors *CR* for all data, measured at the locations Heringsand and Stinteck. It is obvious, that the local wind speeds U_0 , measured in phase (*delta T(U)* = 0) give the best correlation and that the correlation factor decrease with increasing time difference *delta T(U)* between wind and wave measurement. This may indicate a strong influence of present local wind, but may also be influenced by the tide stillwaterlevel time history, which can have a gradient of roughly up to 1 m waterlevel rising per hour.
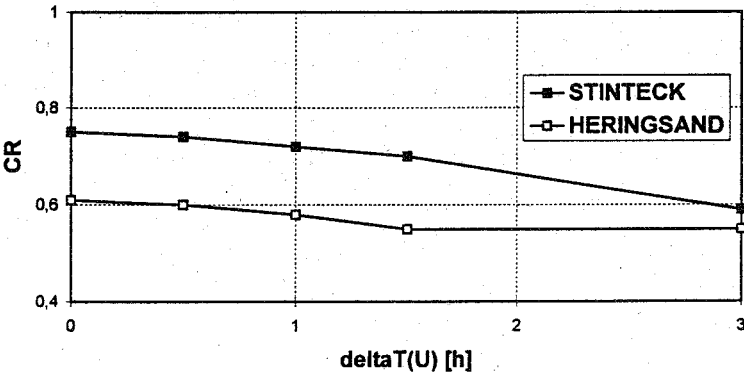

Fig. 8 Waveheight-windspeed correlation factors *CR* versus time lag *delta T(U)*

The influence of the wind velocities was further investigated on the accuracy of the waveheight - waterdepht relation. As an example the significant wave data $H_{1/3}$ in Fig. 9, measured at Stinteck location are related to classified windspeeds U_0 with respect to minimum values of windspeeds. In the upper part all data (windspeeds $U_0 \geq 0$ m/s) are plotted, in the middle part the data with U_0 equal or more than 12.5 m/s and in the lower part the data with U_0 equal or more than 17.5 m/s. The regression lines indicate slightly higher correlation factors CR with increasing windspeeds, the differences of the gradients are small. In Fig. 10 the correlation factors CR and the number of measured time periods N are plotted versus the classified windspeeds $U_0 \geq$, both for Stinteck and for Heringsand location. The results confirm the strong and stabile relation between wave heights and water levels (waterdepths). Further the regression lines in Fig. 9 indicate slightly higher waveheights with increasing windspeeds, but only for lower SWL. This is due to the simple fact, that the higher waveheights only occur with higher windspeeds and higher waterlevels.
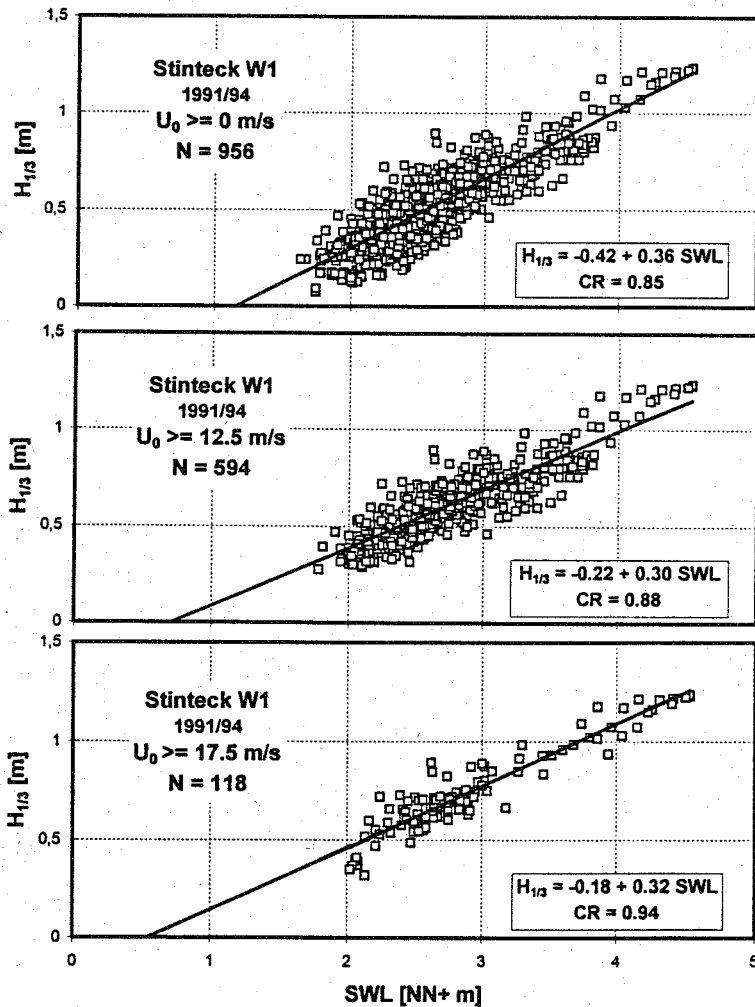

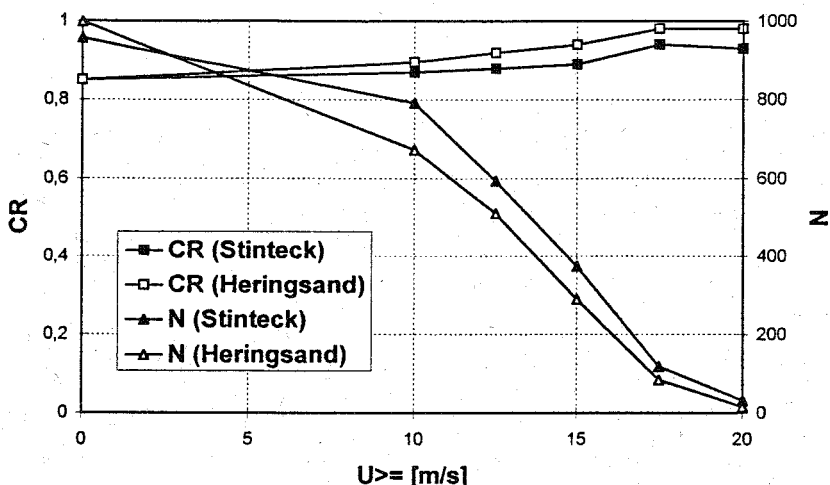Fig. 9 $H_{1/3}$ versus SWL in dependence on minimum windspeeds U_0

Fig. 10 Regression line parameters in dependence on minimum windspeeds U_0

Thus the upper part of the regression line is more or less unsensitive with respect to variations of the boundary conditions for analysis. This is an important fact, when the regression lines are used for forecasting waveheights by interpolation for higher waterlevels.

The data in Fig. 11 are refered to the present winddirections R_0 during the measurements. In the upper part the significant waveheights $H_{1/3}$ of all time periods, measured at Stinteck location are plotted versus the winddirection R_0. These data indicate firstly, that waves up to roughly 80 cm occur with winddirections from Southwest (225°) to North (360°), which is a sector of 135° and secoundly, that the highest waves occur within a sector from West (270°) to Northwest (315°). Both facts agree in general with the wind directions, which occur (turning from southwest to north) when Zyklons are passing the North Sea from west to east.

The distribution of $H_{1/3}$ versus the winddirection agree quite well with the one of the surge set-ups (defined as: SWL - $MThw$, which is a waterdepth), whereas the agreement with the dimensionless faktor $g * H_{1/3} / U_0^2$, which may be used in forecasting formulae, is only fair.

As well as the influence of windspeed on waveheight-waterdepth relations the influence of the winddirection was investigated. The waveheight-waterdepth relations were analyzed with different variations of mean value R_0 and seize *delta R* of winddirection sectors. The results for some of these variations with the Stinteck data in terms of the regression line parameters for gradient *GR*, correlation factor *CR* and the number of measured time periods *N* are plotted versus the mean value of winddirection R_0 in Fig. 12. In both plots the mean winddirection values are varied in steps of 10 degrees, each windsector *delta R* in the upper plot has a seize of 30° and in the lower plot 10°. The regression line parameters *GR* and *CR* don't differ much in dependence of mean
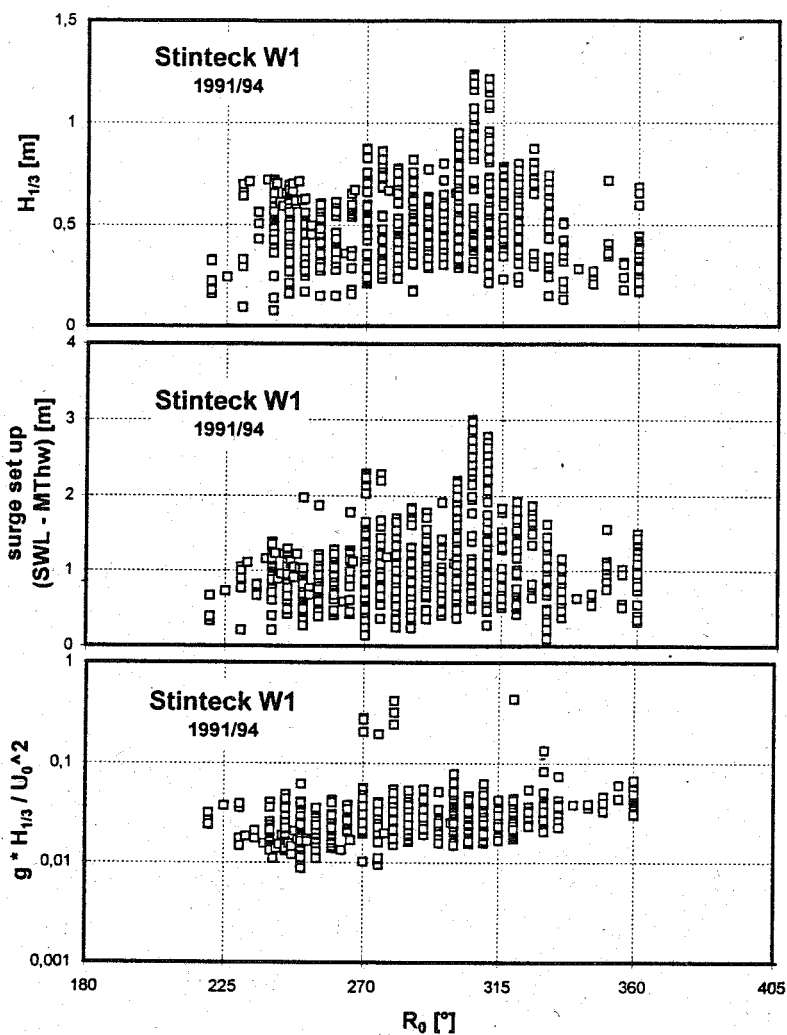
Fig. 11 $H_{1/3}$, surge set-up (SWL - $MThw$) and $g * H_{1/3} / U_0{}^2$ versus R_0
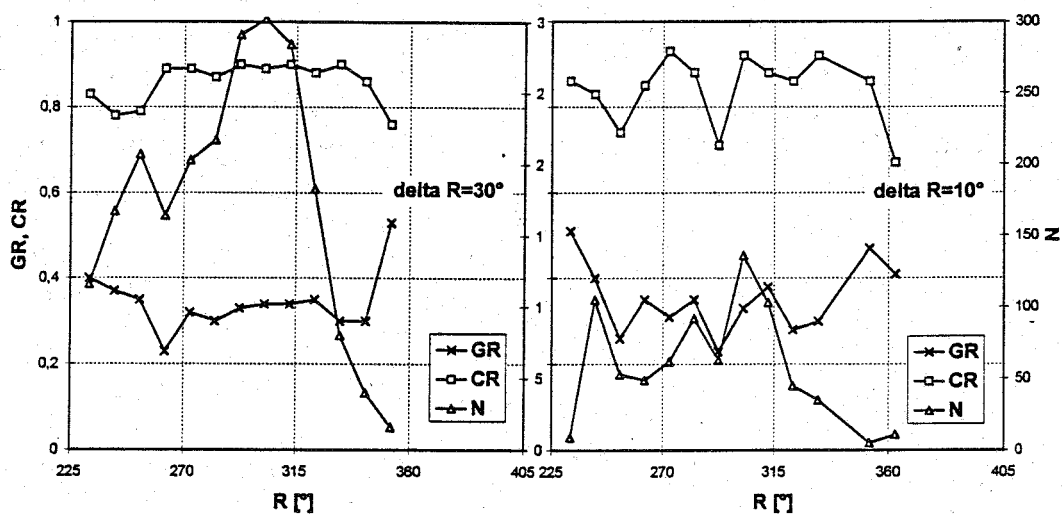

Fig. 12 Regression line parameters in dependence on winddirections R_0

winddirection from Southwest to North and agree quite well for both sector seizes. Due to the number of time periods a smaller windsector consequently leads to more scatter, whereas the overlapping effect in the upper graph smoothes the distribution of the parameter values.

Similar results also occur for the windsectors with the highest measured waveheights $H_{1/3}$ at Stinteck location. The waveheight-waterdepth relations with all data ($U_0 \geq 0$ m/s) for the mean value $R_0 = 307.5°$ and three different sector seizes *delta R* $= 30°$, $20°$ and $10°$ shows Fig. 13. For these three sectors the differences of the regression line parameters *GR* and *CR* are negligible small. This also is confirmed by the results in Fig. 14, where the parameters *GR*, *CR* and *N* for two sectors with minimum windspeeds from $U_0 \geq 0$ m/s up to $U_0 \geq 15$ m/s are compared with those of all data. The parameter *CR* increase slightly with increasing minimum windspeed U_0 as well as in Fig. 10 and the gradients *GR* decrease slightly with increasing minimum windspeed U_0 due to the same effect, already discussed with respect to the results in Fig. 9.
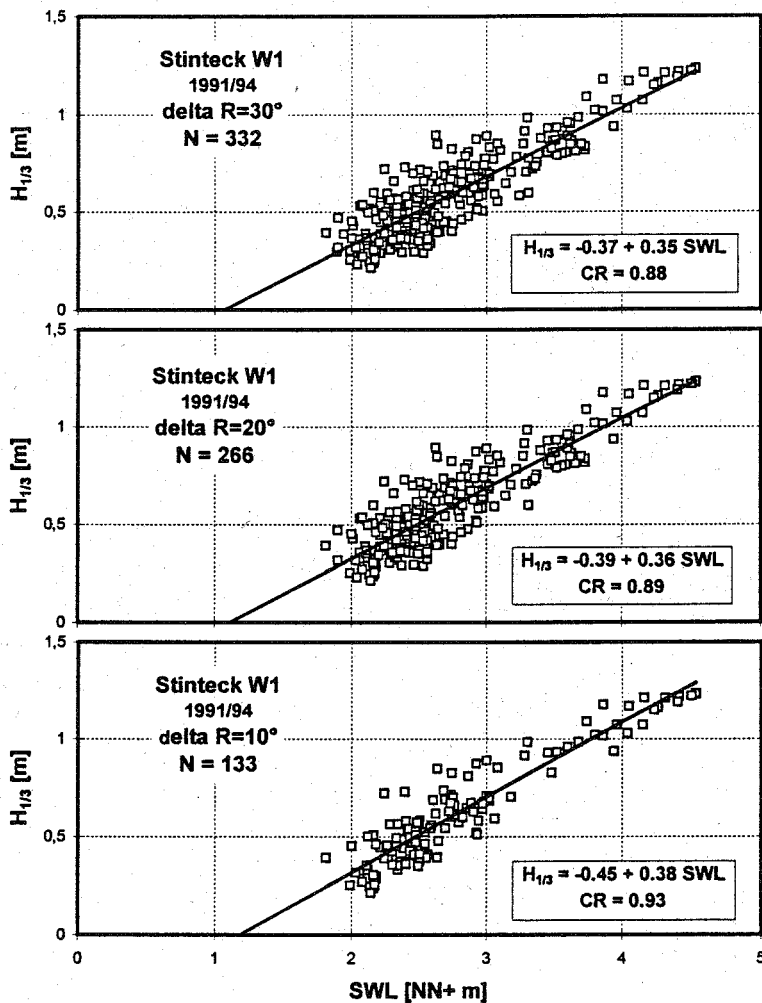

Fig. 13 $H_{1/3}$ versus *SWL* in dependence on windsector seize *delta R*

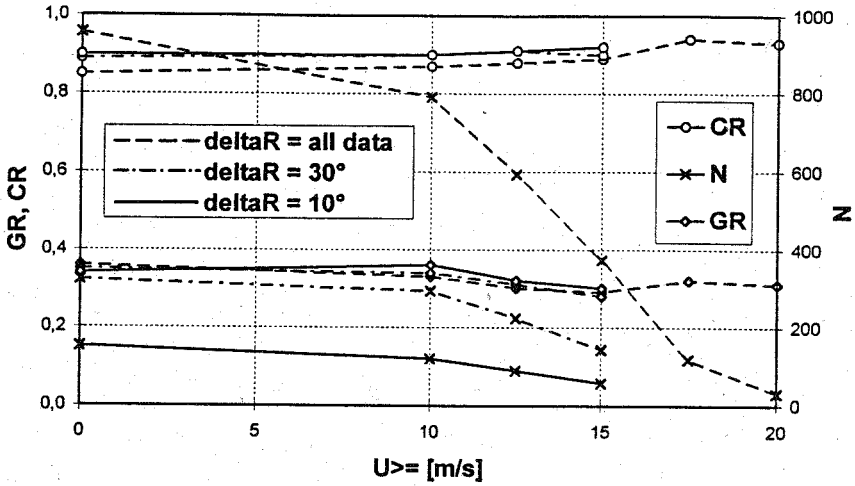Fig. 14 Regression line parameters *GR*, *CR* and *N*
in dependence on windspeed U_0 and windsector *delta R*

All presented results leads to the conclusion, that the influence of windspeed is only small on waveheight-waterdepht relation and the influence of winddirection (mean direction and sector seize) is negligible small for wadden sea locations. Nevertheless there are still two questions left:
- firstly: Is the conclusion also true for each single storm surge event?
- secondly: How much do the results differ between the wadden sea and the estuary locations?

A first example of waveheight-waterdepth relations measured during a single storm surge event at both wadden sea locations Heringsand and Stinteck is shown in Fig. 15, where the waveheights $H_{1/3}$ and the present windspeeds U_0 are plotted as courses during the event versus the stillwaterlevel *SWL*. The data
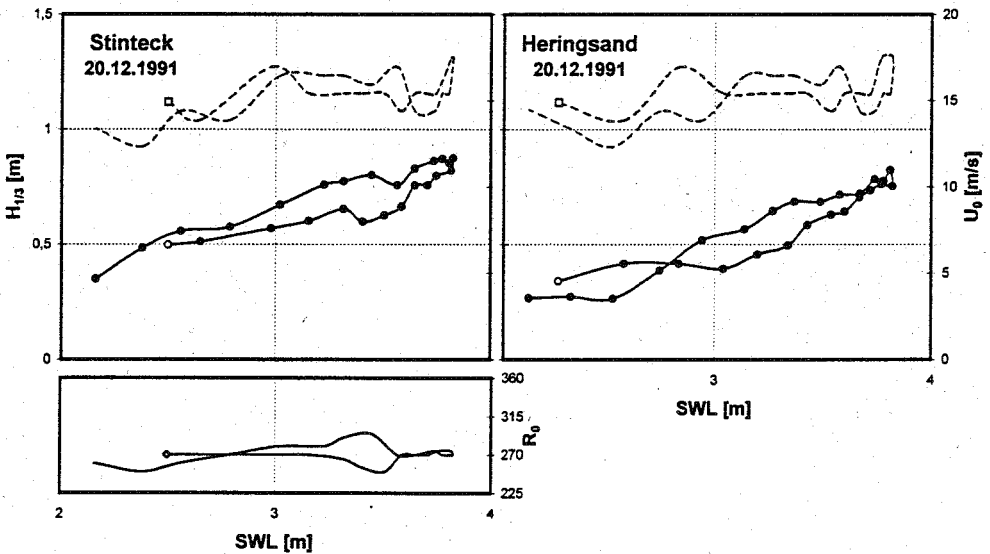

Fig. 15 $H_{1/3}$, U_0 and R_0 versus *SWL* during a single storm surge event

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measured continuously for constant time periods are connected by smoothed lines
(full line for $H_{1/3}$, dotted line for U_0). The beginning of the measurements are
indicated by an open data symbol. Comparing the data both of $H_{1/3}$ and U_0 in
Fig. 15 it is found that the course of waveheight data follow more or less exactly
the one of the windspeeds.

This comes out more distinctly in Fig. 16 with another example of a
storm surge. Shortly after the beginning of the measurement the windspeed
course decrease distinctly, so do the course of the waveheights (in spite of
increasing waterlevels). Thereupon the windspeed increase abruptly roughly by
5 m/s and without remarkable phaseshift the waveheights increase by roughly
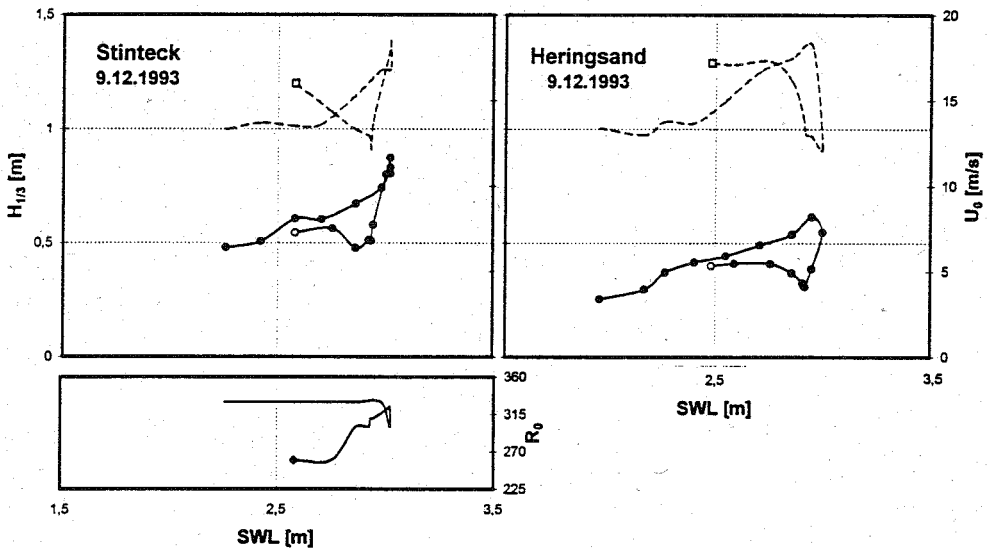80%. Subsequently the windspeed decrease slightly and so do the course of the
waveheights.

Fig. 16 $H_{1/3}$, U_0 and R_0 versus SWL during a single storm surge event

The data in Fig. 17 are recorded during a storm surge with absolut
constant winddirections and relative constant windspeeds. The course of the
waveheights $H_{1/3}$ for the increasing parts of the storm surge agree quite well with
the ones for the decreasing parts at both wadden sea locations Heringsand and
Stinteck. The waveheight course at the estuary orientated location Neuendeich
differ distinctly from the ones of the wadden sea locations, firstly there is a
waveheight difference between increasing and decreasing part of the storm surge
and secondly there is a considerable waveheight reduction before reaching the
highest stillwaterlevel SWL. Both effects may be caused by currents in the
estuary and have to be investigated in detail within the ongoing research work.

The windspeeds plotted in Fig. 18 for another storm surge event vary
considerable contrary those in Fig. 17. From the beginning of the storm surge

event the windspeed U_0 decrease only slightly from about 20 m/s down to roughly 15 m/s. The windspeed decrease further during the highest stillwaterlevel and continue decreasing till the end of the measurements. The same trend have courses of the waveheights at all four locations, but with different order of magnitude.
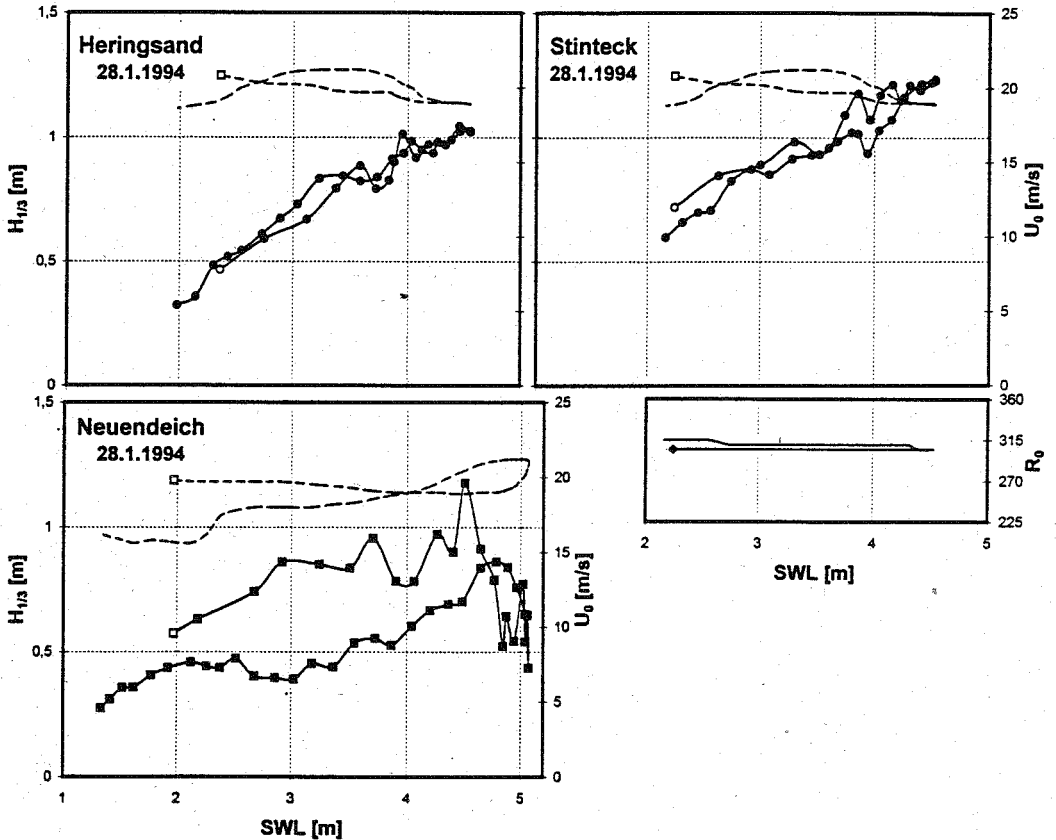

Fig. 17 $H_{1/3}$, U_0 and R_0 versus *SWL* during a single storm surge event

Conclusion

From the first results of a field study on wave climate at the coastline of wadden seas and in estuaries the following may be stated:
- The waveheight-waterdepth correlation is a distinct indicator of wave climate especially on wadden seas. The correlation is less accurate for estuary orientated locations, thus the influence of tide and ebb streams have to be investigated in detail within the ongoing research work.
- The influence of windspeed on such regression lines from data of plenty of storm surge events is found only small and the influence of winddirection (mean direction and sector seize) is found negligible small for wadden sea locations.
- Nevertheless from single storm surge events the strong influence of local wind on waveheight fluctuation can be pointed out, which also has to be investigated in detail within the ongoing research work.
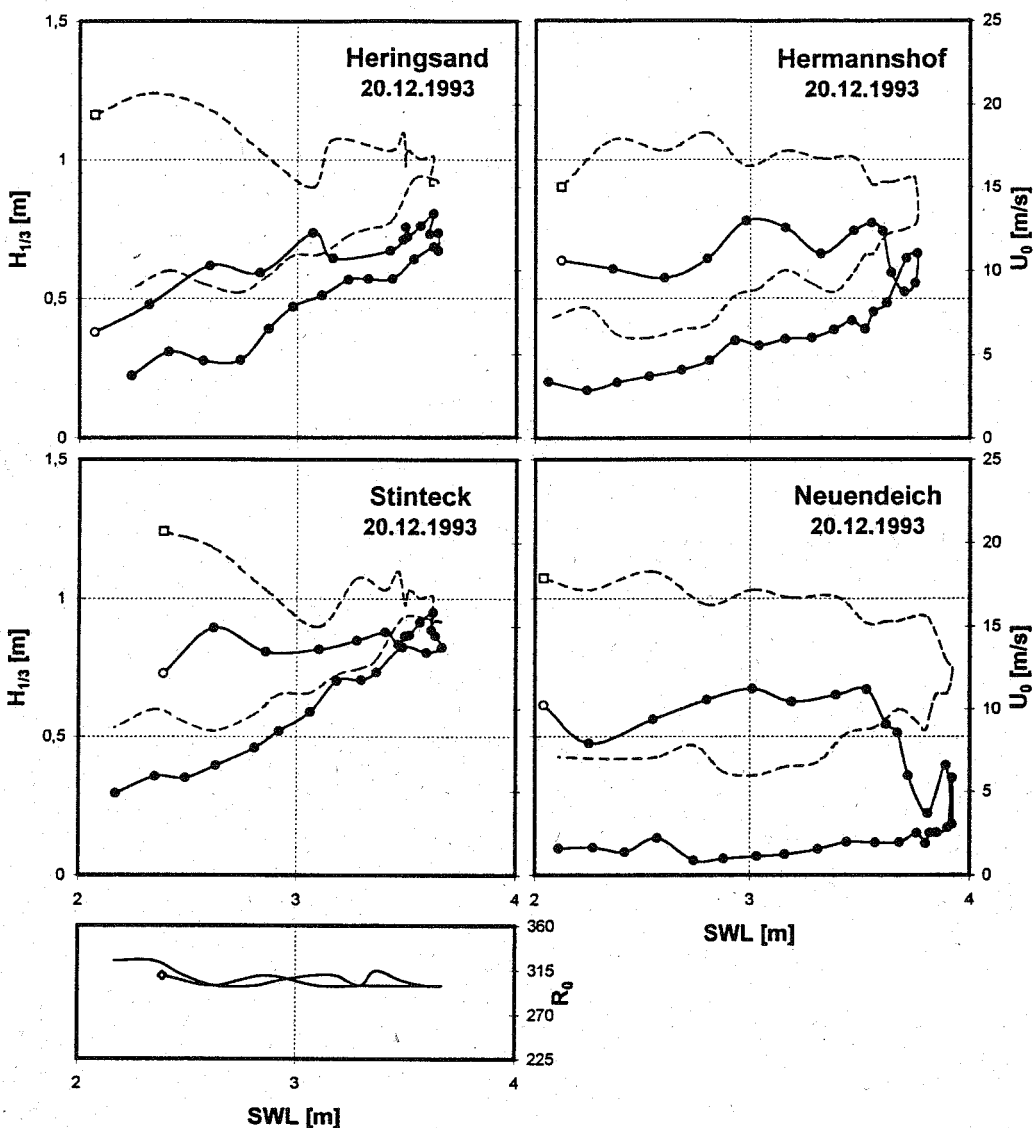
Fig. 18 $H_{1/3}$, U_0 and R_0 versus *SWL* during a single storm surge event

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