The influence of local wind on wave approach direction in real shallow water sea state

by

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ABSTRACT

This paper deals with the influence of the local wind direction on wave approach direction in wadden sea areas under real sea state during storm surge conditions. It is well known, that the complex three-dimensional bathymetry has a strong influence on wave climate propagation in areas with restricted water depths like the wadden seas in the GERMAN BIGHT. Often wind direction doesn’t agree with wave propagation direction necessarily, which makes forecasting of wave approach difficult. Thus a more detailed knowledge about the wave approach directions is needed. In this paper firstly a simple method is presented to evaluate the approach direction from a triplet of signals including a horizontal 2D-current meter and a wave gauge in time domain. Secondly results from a comprehensive field study of local wave approach directions, which are discussed in comparison with local wind parameters and tidal regime influenced by the local bathymetry.

1. INTRODUCTION

Real sea state wave-induced water particle velocities keep their general three-dimensionally characteristics when wind waves are coming in from deeper parts of the shelf in areas with extremely restricted water depths. They even do so if the breaking wave crests seem to be more or less two-dimensional, however the particle velocities then often may show a distinct orientation towards the main wave approach axis.

The well-known fact, that the main wave approach direction doesn't agree necessarily with the local main wind direction in areas with restricted water depths like the wadden seas in the German Bight is due to the strong influence of the complex three-dimensional bathymetry both on wave climate propagation as well as on overlapping tidal flow regime. Detailed knowledge about this physical process in wadden seas is poor. Consequently this makes forecasting of wave approach directions in wadden seas complicate, sometimes even impossible. Thus improvement of the knowledge is needed for instance to considered the influence on wave run-up, which might lead to reduction in case of oblique wave approach.

2. FIELD MEASUREMENTS

For the study data were used from a comprehensive field research program on wave climate and wave run-up, which has been running in cooperation with the Regional State Board for Water Management of the State of Schleswig-Holstein for many years at different locations at the landside borders of the wadden sea in the German Bight. The field locations and the measuring equipments were described in previous papers (GRÜNE, 1996; GRÜNE, 1997; WANG & GRÜNE, 1997). The field data presented in this paper, are recorded at the wadden sea locations “HERINGSAND” and “STINTECK” at the coastline of the “DITHMARSCHER KÜSTE”, which is shown in Fig. 1. The cross-sections of the foreshore normal to the coastline are plotted in Fig. 2 for these locations.

At each of these locations in front of the dykeline in a line normal to the coastline several support piles (station W1, W2, W3 at HERINGSAND and station W1 and W2 at STINTECK) with measuring sensors are installed. All sensors are connected by cables with a computer controlled recording system, which is placed in shelters behind the dykes.

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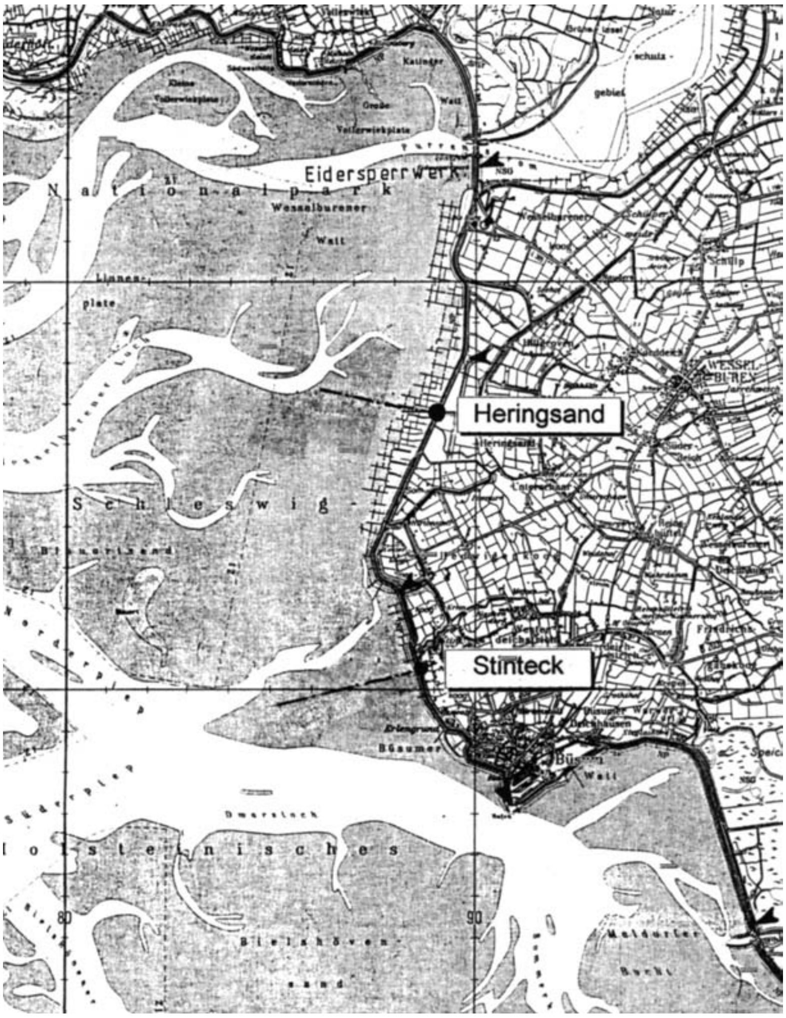


Fig. 1 Measuring locations at the DITHMARSCHER KÜSTE

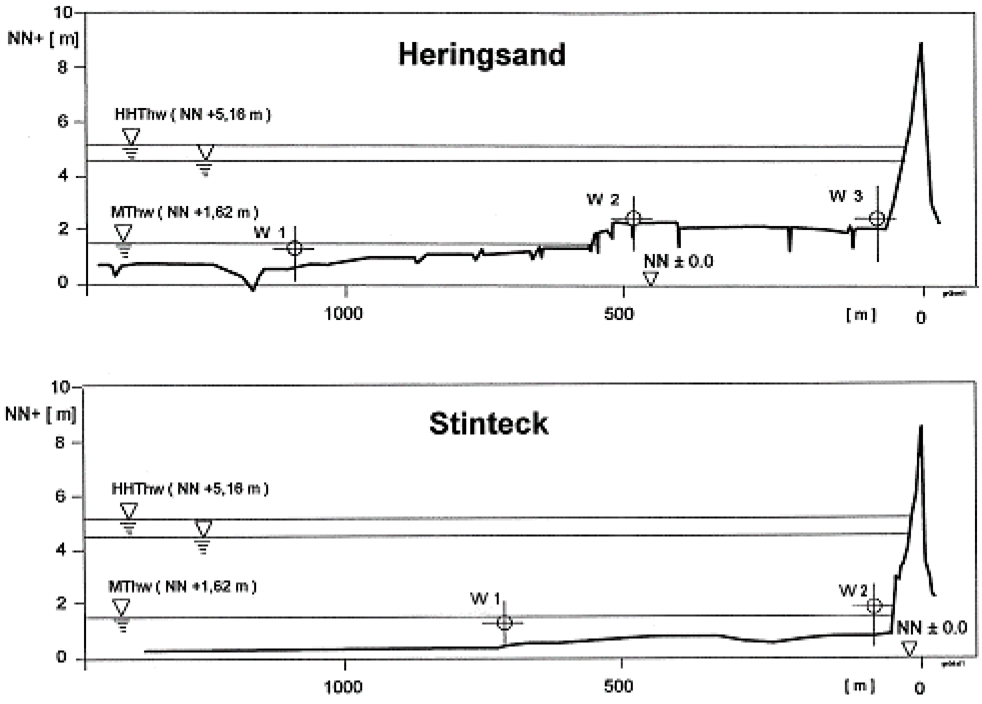


Fig. 2 Cross-sections of the foreshore normal to coast line at the measuring locations

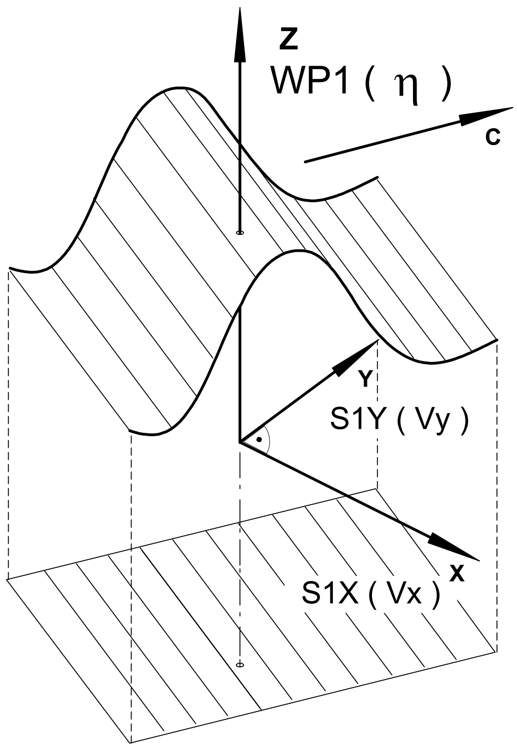
At both locations in each case the stations W1 were used to measure surface elevation and velocity components. The surface elevations are estimated from the records of a pressure cell, using the 1st order wave theory including empirical correction function for transferring the pressure data to surface elevation data. The velocity components are measured in horizontal plane with an electromagnetic two-component sensor.

3. EVALUATION OF WAVE APPROACH DIRECTIONS

There are different methods to evaluate wave approach directions, all methods depend on the type of sensors which are used for field measurements (GRÜNE, 1998). The most common method is to use a 2D-wave buoy including a computer analysing programme from the manufacturer of the buoy system. The analysing method for such systems mostly is based on data triplets (surface elevation and velocity components derived from acceleration sensors) and is done in frequency domain. Due to its complexness, it is hardly (seldom) being understood by a user.

In areas like the foreshore in wadden seas wave buoys cannot be used. Therefore the author has developed a simple method in time domain, which main advantage is its clear physical sense and its easy practicability. As the method already has been reported in detail in GRÜNE (1988); thus in the following only a short description is given.

This method is using a data triplet of surface elevation η and two rectangular velocity components V_y (normal to dyke line) and V_x (parallel to dyke line) in a horizontal plane as shown in Fig. 3 schematically. In Fig. 4 such a data triplet, recorded synchronously at location STINTECK; is shown exemplarily, including the time histories of the water surface elevation at WP1 and the horizontal velocity components S1Y and S1X.



Axis	**X**	**Y**	**Z**
Physical parameter	Horizontal velocity component ***Vx***	Horizontal velocity component ***Vy***	Surface elevation **η**
Sensor	**S1X**	**S1Y**	**WP1**

Fig. 3 Coordinate system of installed sensors at station W1 at both locations

For evaluation of the wave approach direction the time history of the water surface elevation η is subdivided in consecutive waves as demonstrated in Fig. 5, which shows a short cut-off with 4 wave events from the time history in Fig. 4. Wave crests and wave troughs of each separated wave event are marked and labelled with time. For this procedure the un-scaled pressure data may be used, a transfer to real surface elevations is not necessary.

The wave events are defined between the troughs. For this procedure the unscaled pressure data may be used, a transfer to real surface elevations is not necessary. For these 4 wave events the vector courses with the two horizontal velocity components V_x and V_y are plotted in Fig. 6. The vector positions at the dividing troughs between each of the consecutive waves are connected with a dotted line. These vector courses in combination with the water surface elevation give a kind of anatomy of a data triplet in time domain.

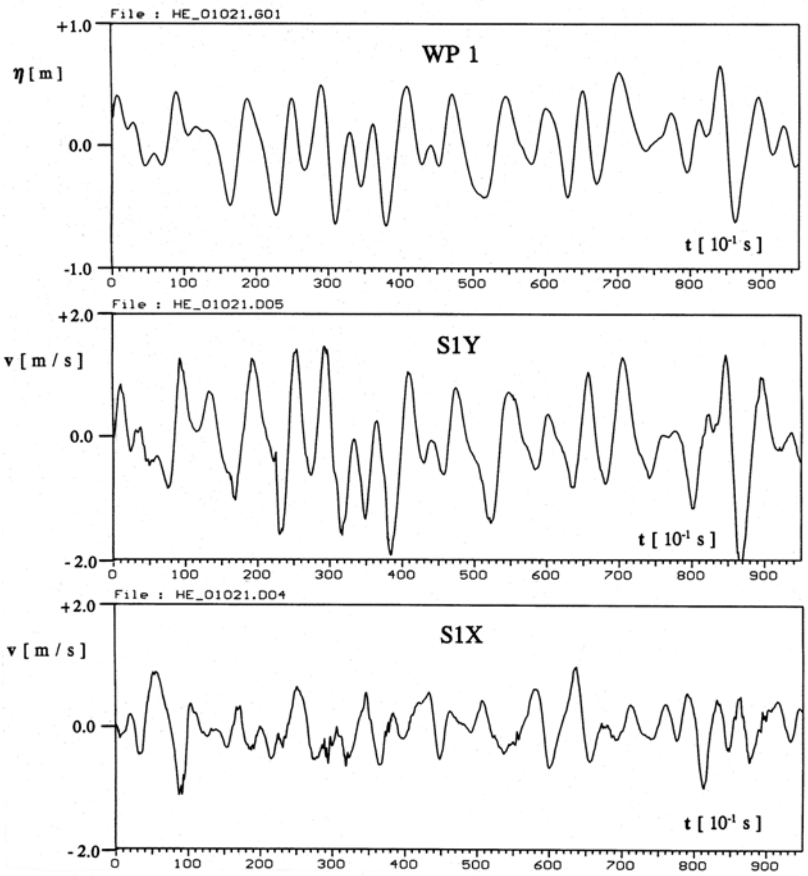


Fig. 4 Example of a synchronously recorded data triplet

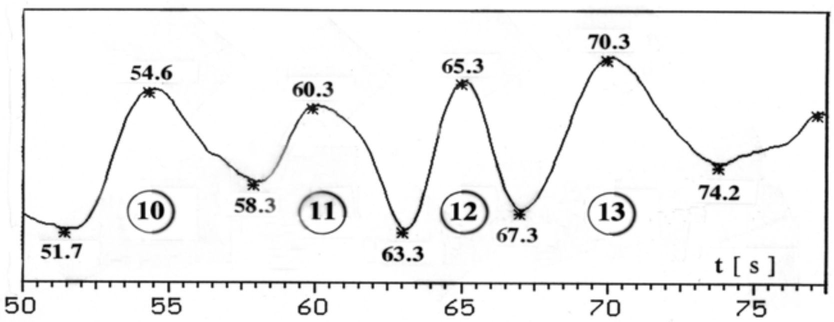


Fig. 5 Water surface elevation of consecutive wave events

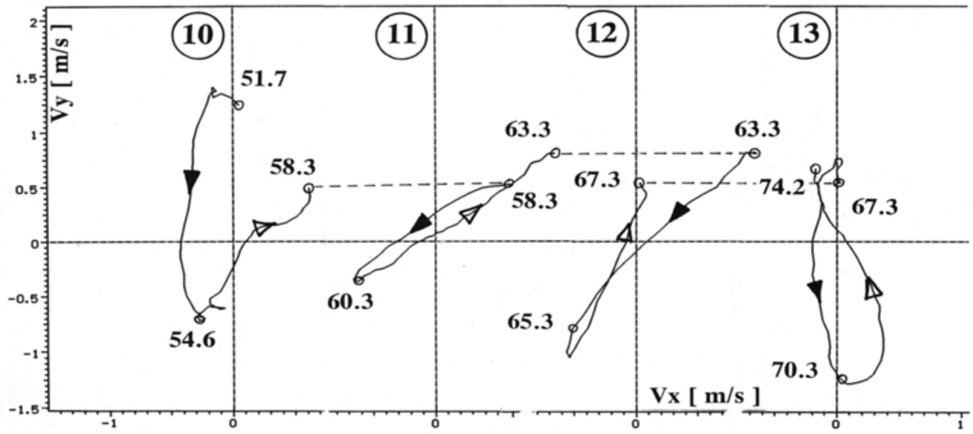
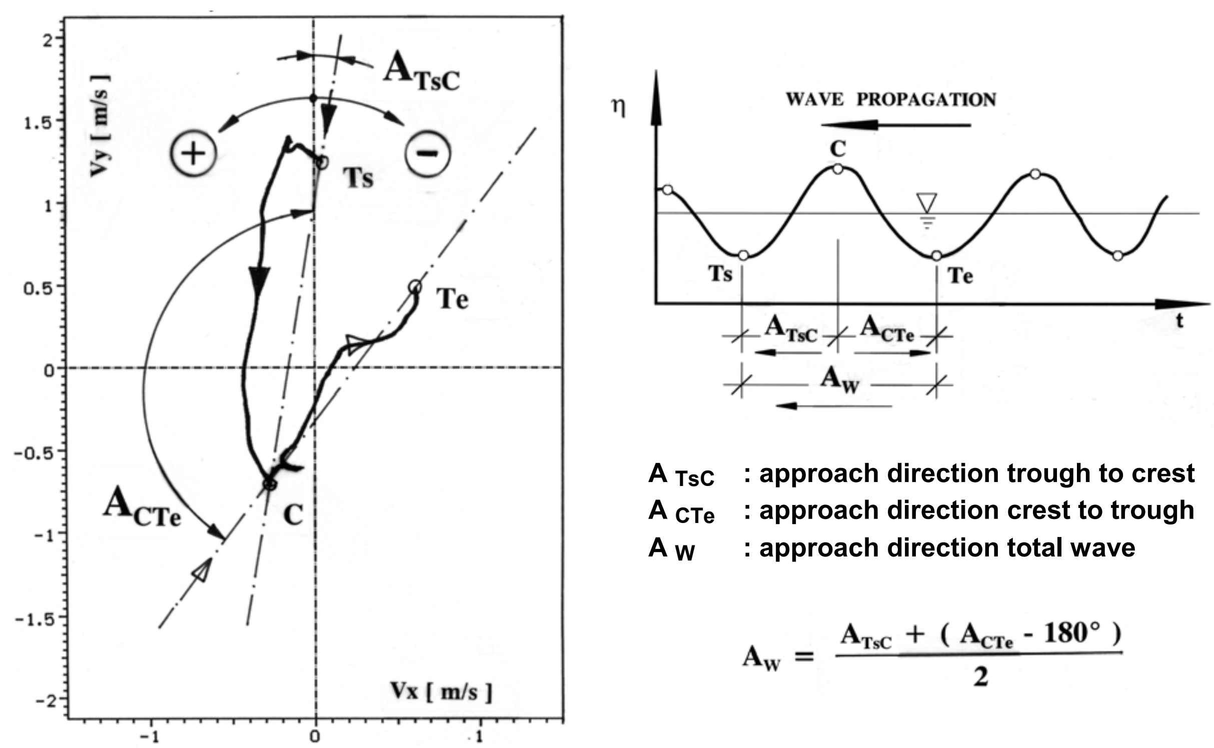


Fig. 6 velocity vector course of consecutive wave events

Comparing the vector plots for each wave event in Fig. 6, one finds a more or less distinct changing of the approach direction of the water particles at each wave crest and wave trough, which is self-evident for pure two-dimensional waves. This leads to the evaluation of wave approach directions for real sea state conditions from the vector course data between wave crests and troughs. The wave approach directions for this method are defined in Fig. 7 schematically.



A_{TsC} : approach direction trough to crest
A_{CTe} : approach direction crest to trough
A_W : approach direction total wave

$$A_W = \frac{A_{TsC} + (A_{CTe} - 180°)}{2}$$

Fig. 7 Definitions for wave approach directions

The definitions in Fig. 7 may be described as follows: The direction A_{TsC} is defined as mean direction between trough T_s and crest C. Ts is the trough at the start of the wave event according to the time and C is the crest, both are identified from the surface elevation in time history. Troughs and crests are related to time. According to physical sense A_{TsC} means the oncoming rising front of the wave. A_{TsC} is determined as angle between normal direction (Y - axis of horizontal plane) and linear connection between vector course positions at trough *Ts* and crest *C*, as defined in the left hand part of Fig. 7, where the rules of sign for the directions A_{TsC} and A_{CTe} are defined as well. The vector course of the oncoming rising front is marked with a black arrow in all figures.

The direction A_{CTe} is defined as mean direction between crest C and trough T_e, where T_e is the trough at the end of the wave event and this part of the vector course is marked with an open arrow in all figures.

A_W is defined as the total approach direction of each wave event. A_W is calculated as the mean value of A_{TsC} and A_{CTe}. It must be noticed, that A_{TsC} and A_W have approximately the same directions as the main direction of wave propagation has, whereas A_{CTe} has the opposite direction (see also the left hand part of Fig. 7, where the rule of sign is defined).

The vector courses in Fig. 6 indicate, that the evaluated approach directions of consecutive waves in a wave train have strong fluctuations. This comes out clearly in Fig. 8, where the evaluated values for A_{TsC} and A_{CTe} are plotted as time history exemplarily for a period of 15 minutes. But beyond a certain time period the mean values are relatively constant. In Fig. 8 for example the fat (pinc) line in the upper part stands for the A_{TsC} mean values of 9 consecutive time periods, each 100 seconds long. The differences compared with the mean value of the total period (A_{TsC} = 305,9°) are very small. It must be noticed, that in Fig. 8 and in all following figures the wave approach directions are transferred to the geodetic coordinate system with 0° = 360° = North.

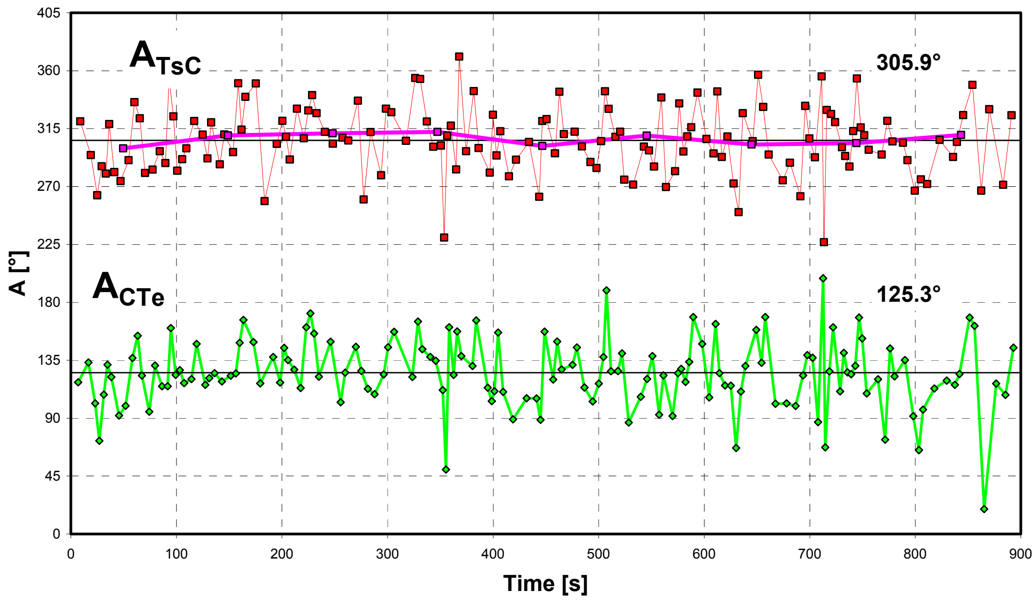


Fig. 8 Evaluated wave approach directions A_{TsC} and A_{CTe} from a record at location HERINGSAND

The values for A_{TsC} and A_{CTe} from the example in Fig. 9 are plotted as frequency distributions in Fig. 10. The mean values of A_{TsC} and (A_{CTe} + 180°) for the total period differ only 0.6 degrees from each other. The agreements with the calculated Normal - distributions are quite good.

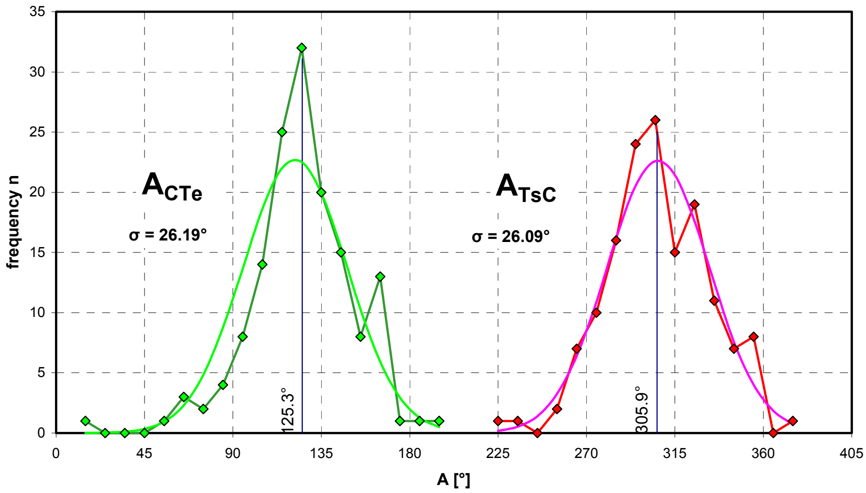
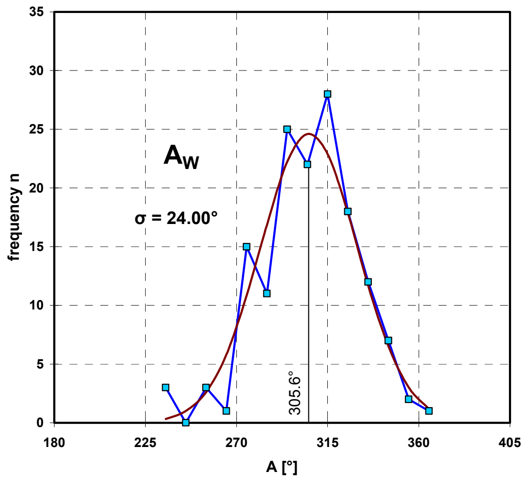


Fig. 9 Frequency distributions of the evaluated values A_{TsC} and A_{CTe} plotted in Fig. 8



The total range of fluctuation of the evaluated approach directions A_{TsC} and A_{CTe} is roughly around ± 70° and the standard deviation σ is approximately 26°. The frequency distribution of the total wave approach directions A_W is plotted in Fig. 10 and is consequently similar to those distributions in Fig. 9. Similar fluctuations of wave approach directions were found for all other measurements at both locations.

Fig. 10 Frequency distributions of the evaluated values A_W plotted in Fig. 8

4. RESULTS

Wave parameters including wave approach directions have been measured at the field measuring locations during several storm surges; during some storm surges the measurements have been done synchronously. Results are given in Fig. 11 exemplarily from such a measurement during one storm surge event at the location HERINGSAND, where some parameters are plotted as time history: the still water level *SWL*, the wave parameters $H_{1/3}$ and T_m, the local wind direction R_0, the local wind velocity U_0 , the wave approach direction A_W and the phase shift between A_W and R_0. Each plotted point is the result (mean value) of one analysed time periods, which each have a duration of 15 minutes and were recorded consecutively. The local wind direction R_0 and the local wind velocity U_0 were recorded during the measurements (phase shift zero between wind - and wave measurements).

The local wind velocities U_0 as well as the local wind directions R_0 were relatively constant during this storm surge event, whereas the wave approach directions A_W in Fig. 11 partly differ considerable from the wind directions R_0. From previous investigations on wave propagation direction in such wadden sea areas it was found that the local bathymetry has a dominant influence and that waves are even propagating against the wind, as far as they run along gullies. Thus a general influence may be expected by the local bathymetry on the differences between wind direction R_0 and wave approach direction A_W, which is defined as phase shift $A_W – R_0$ in the following.

The phase shift $A_W – R_0$ plotted in Fig. 11 indicates, that for this storm surge event there are three different ranges in dependence of time or still water level *SWL* respectively: firstly with increasing still water level (rising part of the storm surge) the phase shift decreases slightly, then secondly around High Tide level *Thw* the phase shift has its minimum values and thirdly with decreasing still water level (falling part of the storm surge) the phase shift increases distinctly. The phase shift of the falling part of the storm surge has roughly up to twice the value of that of the rising part, whereas in the High Tide range it tends towards zero.

The different phase shift values for rising and falling part of the storm surge may be explained by the general trend of tidal motion from South to North in this part of the GERMAN BIGHT. According to the bathymetry conditions around the location HERINGSAND in Fig. 1 it may be concluded, that the mean wave approach directions during the rising and falling part of the storm surge are adjusted to the end of the main gully. Thus the wave approach directions are strongly influenced both from the local bathymetry and the local tidal regime.

Similar results are found for other storm surge events at both locations, often in a more complex shape, especially for storm surges with lower High Tide levels *Thw*. From these results it can be stated that in general the phase shift A_W - R_0 between wind direction and wave approach direction mostly decreases with increasing water depth, but with different order of magnitude for rising and falling part of the storm surge still water level and also influenced by the local tidal regime.

In the following figures the wave approach directions evaluated from synchronous measurements at both measuring locations are compared for three different storm surge events. For each event the wind direction R_0 , the wind velocity U_0 and the wave approach direction A_W are plotted versus the still water level *SWL*. The beginning of the rising part of the storm surge is marked with an open quadrate in the R_0 – course. The directions normal to the coastline are plotted as green dotted lines, the normal direction at HERINGSAND is 281°, the normal direction at STINTECK is 257°.

The wind direction R_0 during the storm surge event shown in Fig. 12 is westerly and differ not very much from the directions normal to the coastlines at both directions, whereas the wind during the other storm surge events has southerly wind direction (in Fig. 13) and northerly wind direction (in Fig. 14). Comparing the results of the three different storm surge events, it can be stated that the results are different for each event, but also different between the both locations. Nevertheless the following general trends can be found:

- The general decrease of the phase shift A_W - R_0 with increasing still water level *SWL* as shown exemplarily in Fig. 11 may differ for wind directions R_0 with increasing difference to westerly directions.
- The phase shift A_W - R_0 changes its algebraic sign distinctly for wind directions R_0 with increasing difference to westerly directions, which means that for northerly wind directions the phase shift has a positive sign (greater values for R_0 compared to A_W in Fig. 14) and a negative sign for southerly wind directions (smaller values for R_0 compared to A_W in Fig. 13).

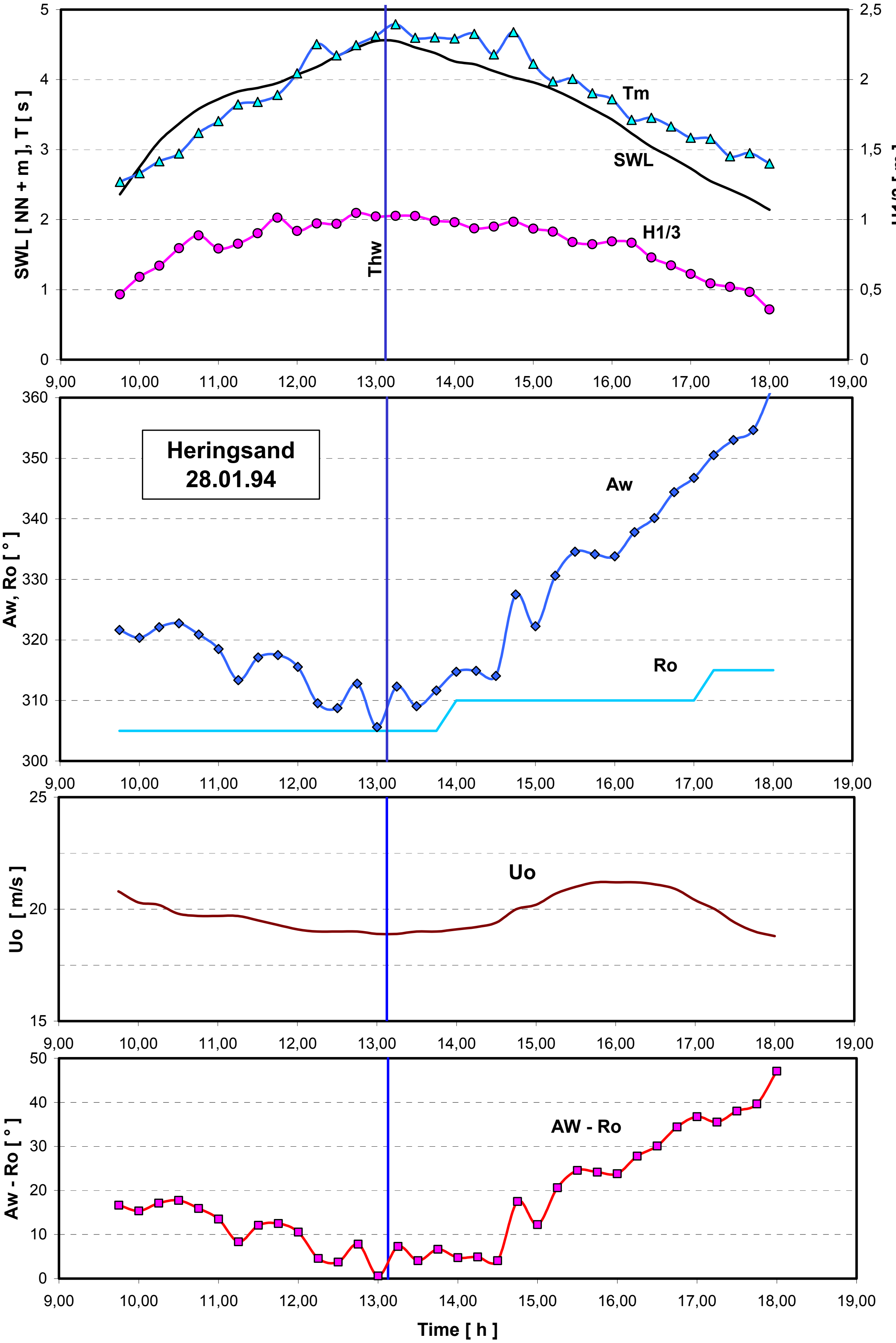


Fig. 11 Time histories of still water level *SWL*, wave parameters $H_{1/3}$ and T_m, wind direction R_0, wind velocity U_0, wave approach direction A_W and phase shift between $A_W - R_0$ measured during a storm surge at location HERINGSAND

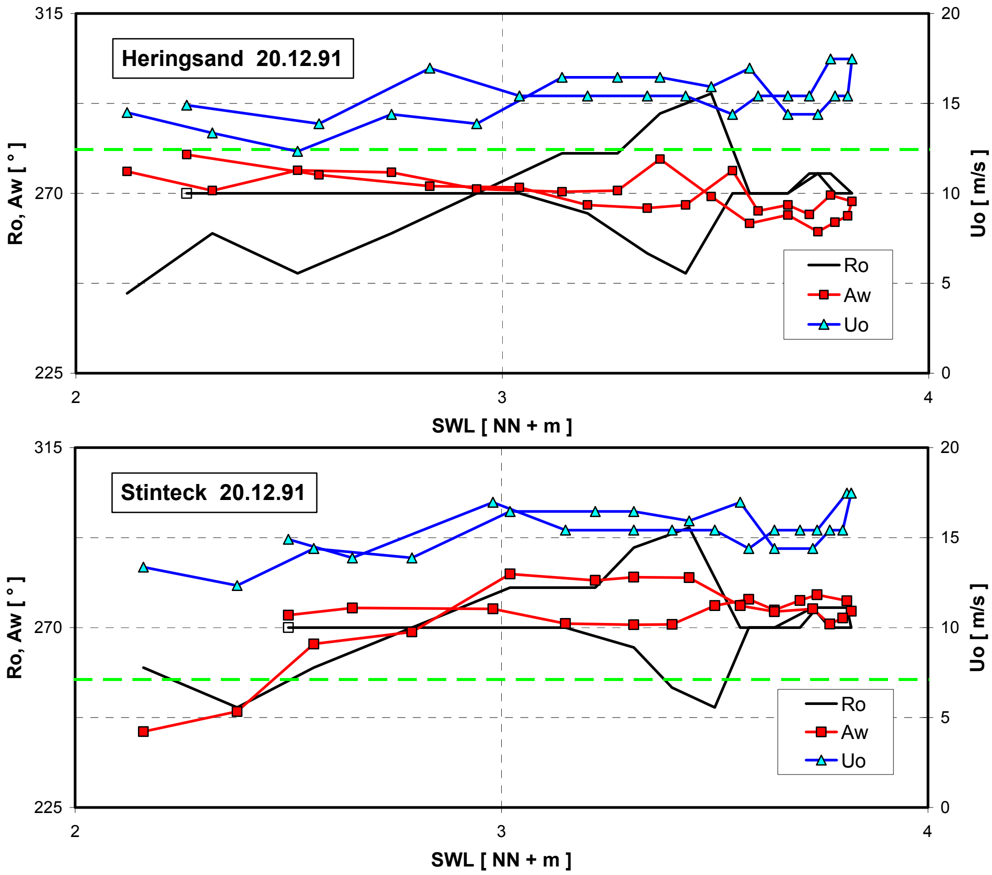


Fig. 12 Wind parameter R_0, U_0 and wave approach direction A_W versus still water level *SWL* measured during a storm surge event at both locations

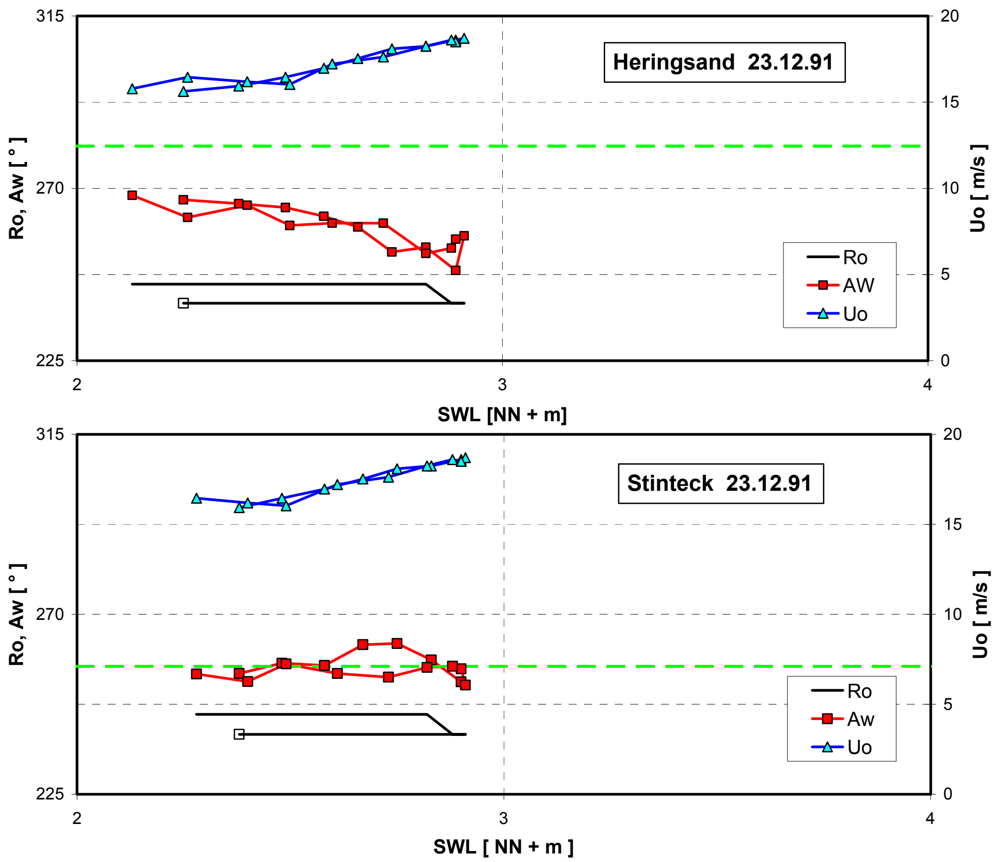


Fig. 13 Wind parameter R_0, U_0 and wave approach direction A_W versus still water level *SWL* measured during a storm surge event at both locations

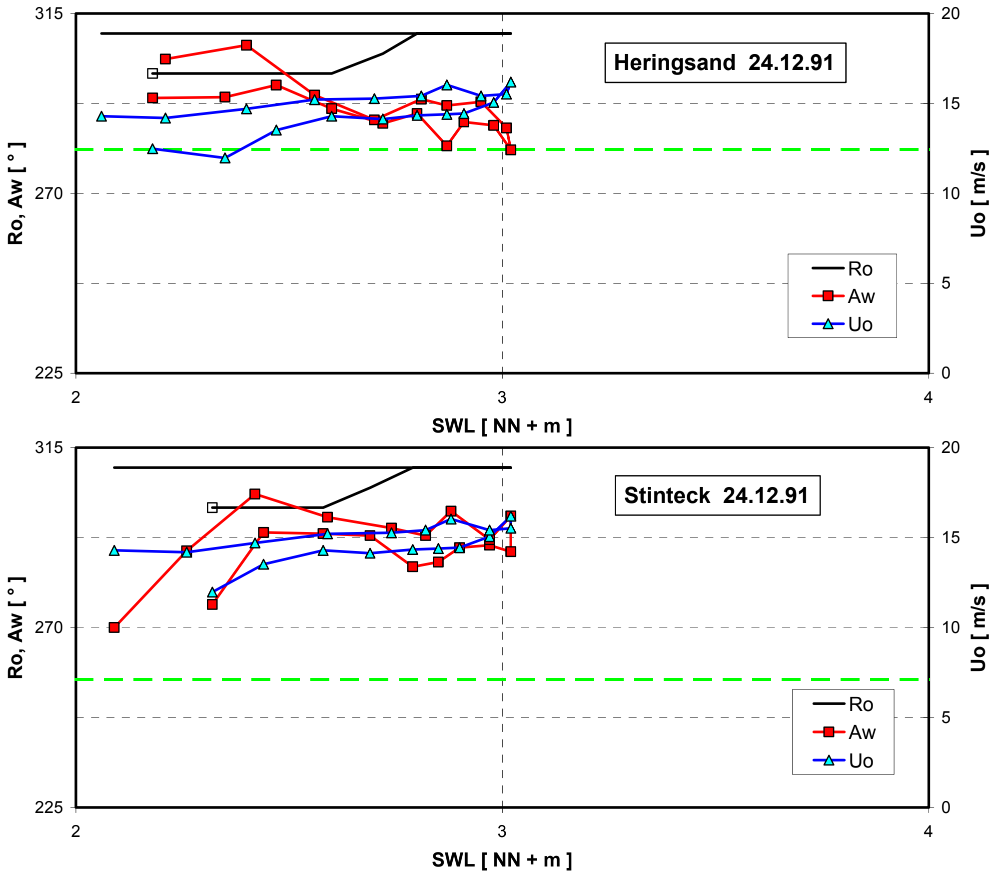


Fig. 14 Wind parameter R_0, U_0 and wave approach direction A_W versus still water level *SWL* measured during a storm surge event at both locations

- In physical sense the above stated second trend means that the wave approach directions don't differ as much from the direction normal to the coastline as the wind direction do, thus the wave approach direction is more "stable" due to the local influence of bathymetry and tidal regime (see also Fig. 19, where the sectors of occurrence of wave approach direction A_W and wind direction R_0 are marked for both locations).
- All courses of the wave approach directions A_W measured at the location HERINGSAND are more or less similar to the course, shown in Fig. 11, especially the northerly trend during the falling part and at the end of the storm surge event. The wave approach courses measured at the location STINTECK differ from those at location HERINGSAND, as these often tend to southerly directions at the end of the storm surge event. This seems to be caused by the interaction between local bathymetry and the tidal regime, as A_W at both locations are adjusted to the end of the determinedly main gullies.

The general trend to northerly wave approach directions at HERINGSAND and southerly directions at STINTECK at the end of the storm surge events is also demonstrated in Fig. 15, where the time histories of the phase shifts $A_W - R_0$, measured during the storm surge event shown in Fig. 12, are plotted for both locations.

The general trend of decreasing phase shift A_W - R_0 with increasing water depth, as already mentioned before, may be demonstrated by the results in Fig. 16. In this figure for all recorded storm surge events at both locations the phase shift A_W - R_0, measured at *Thw* (highest still water level *SWL* during a storm surge event), is plotted versus the highest water level *Thw* of each event. The infolding lines confirm the clear tendency, but nevertheless there seems to excist a certain northerly off-set for both locations, provided that the recorded storm surge events are representative ones. This may be caused by the local bathymetry, as the influence of the local tidal regime is expected to be mainly small around High Tide *Thw.*

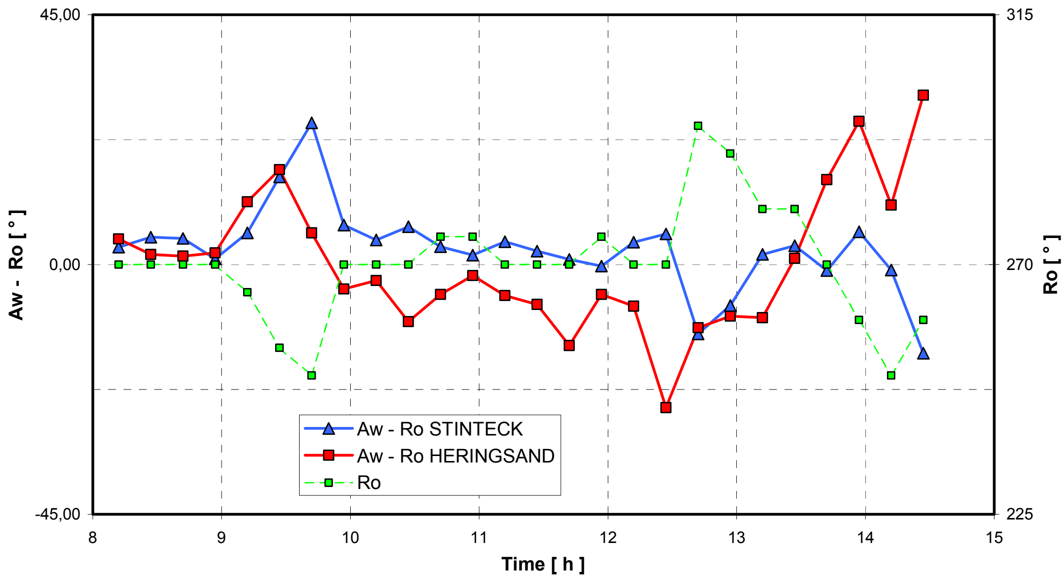


Fig. 15 Time histories of phase shift A_W - R_0 measured at both locations during the storm surge event from the 20.12.91 (shown in Fig. 12)

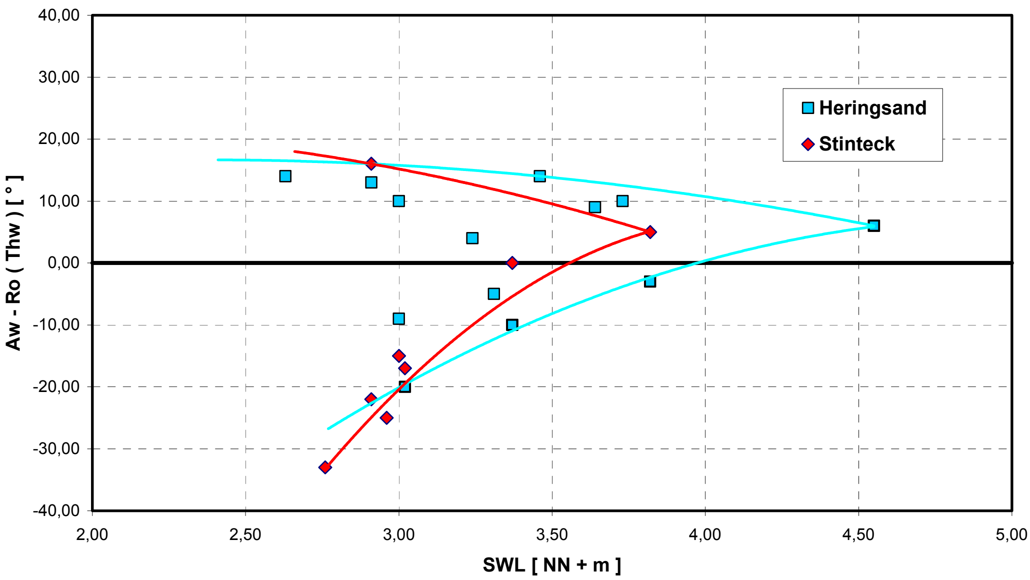


Fig. 16 Phase shift A_W - R_0 measured around *Thw* versus still water level *SWL* (*Thw*)

For each recorded storm surge event a main wave approach direction A_W and a main wind direction R_0 have been evaluated from the time histories for the time period around the highest water level *Thw* of each storm surge. These data are plotted in Fig. 17 and are summarised by a linear regression line. The results for both locations show a distinct scattering, nevertheless the linear correlations are quite good and indicate a clear tendency.

The linear regression line in the left hand plot of Fig. 17 for the data evaluated from the measurements at location HERINGSAND points out a tendency with relatively small differences between wave approach direction A_W and wind direction R_0 (which means small phase shift $A_W – R_0$), whereas the absolute phase shift $A_W – R_0$ ranges between +14° and –20° degrees (see also Fig. 16).

The regression line in the right hand plot of Fig. 17 for the STINTECK data indicates a tendency of stronger differences between A_W and R_0 compared to those at HERINGSAND. The absolute phase shifts A_W – R_0 ranges between +16° and –33° (see also Fig. 16) and have a bit greater values compared to those at HERINGSAND location.

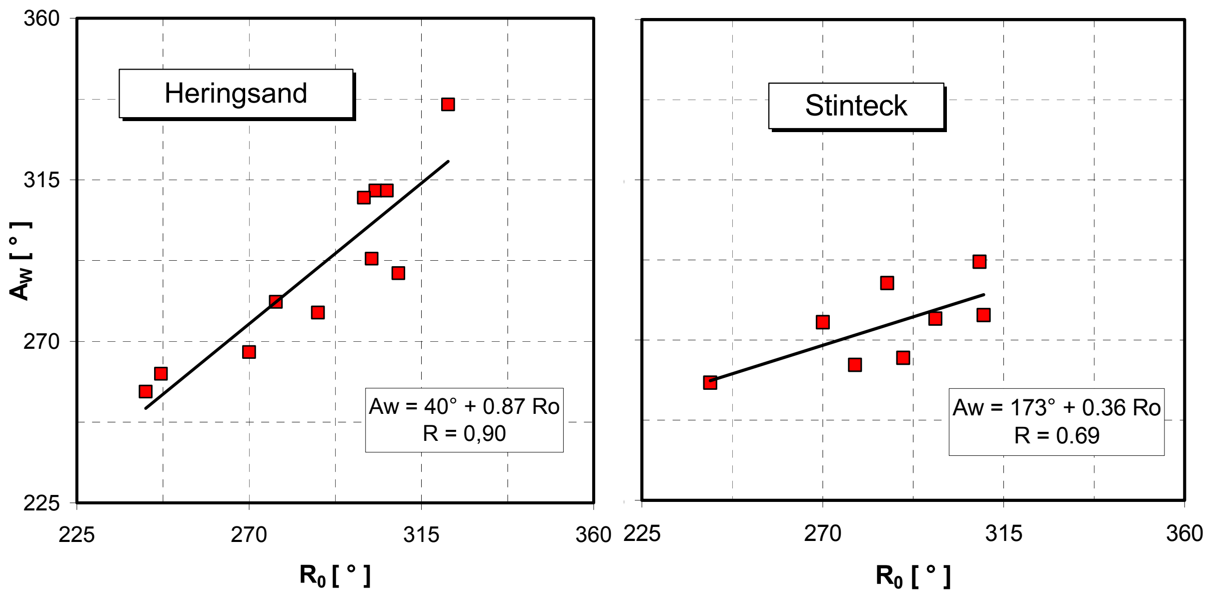


Fig. 17 Wave approach direction A_W versus wind direction R_0 measured around *Thw* for each storm surge event at two different locations

The range of occurrence is roughly the same both for wave approach directions A_W and wind directions R_0 at location HERINGSAND, whereas at location STINTECK the range of occurrence for A_W is much smaller compared to that for wind direction R_0. This comes out more clearly in Fig. 19, where the different sectors for A_W and R_0 are plotted for both locations.

The data from Fig. 17 are related to the direction *N* normal to the coastline at the two locations as follows: *delta* $A_W = A_W - N$ and *delta* $R_0 = R_0 - N$, where *delta* A_W is defined in degrees as difference between rectangular (normal) and oblique approach direction to the coastline. The direction *N* normal to the coastline is N = 281° at HERINGSAND and N = 257° at STINTECK. In Fig. 18 the normal related wave approach directions A_W are plotted versus the normal related wind directions R_0.

As the data in Fig. 18 are only displaced in mathematical sense to the normal directions of the coastlines at both locations, the same remarks mentioned before all guilty. Nevertheless the different sectors for A_W and R_0 come out more clearly in this figure.

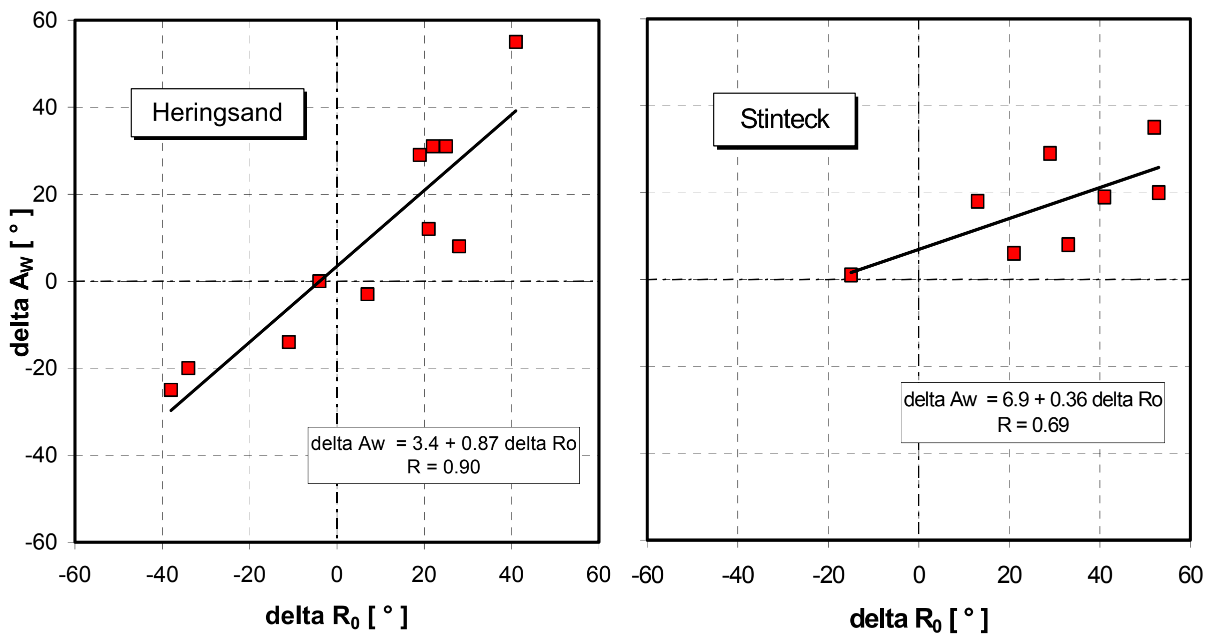


Fig. 18 Delta A_W versus delta R_0 (related to direction normal to coastline)

The sectors for A_W and R_0 at HERINGSAND location overlap more or less in the same range and the wave approach direction A_W occurs in a sector northerly and southerly from the normal direction of the coastline. At STINTECK location the sector for A_W is much more restricted compared to that for the wind direction R_0 and occur only northerly from the normal direction of the coastline. This points out a more stable behaviour of A_W at STINTECK location caused by the local bathymetry and local tidal regime.

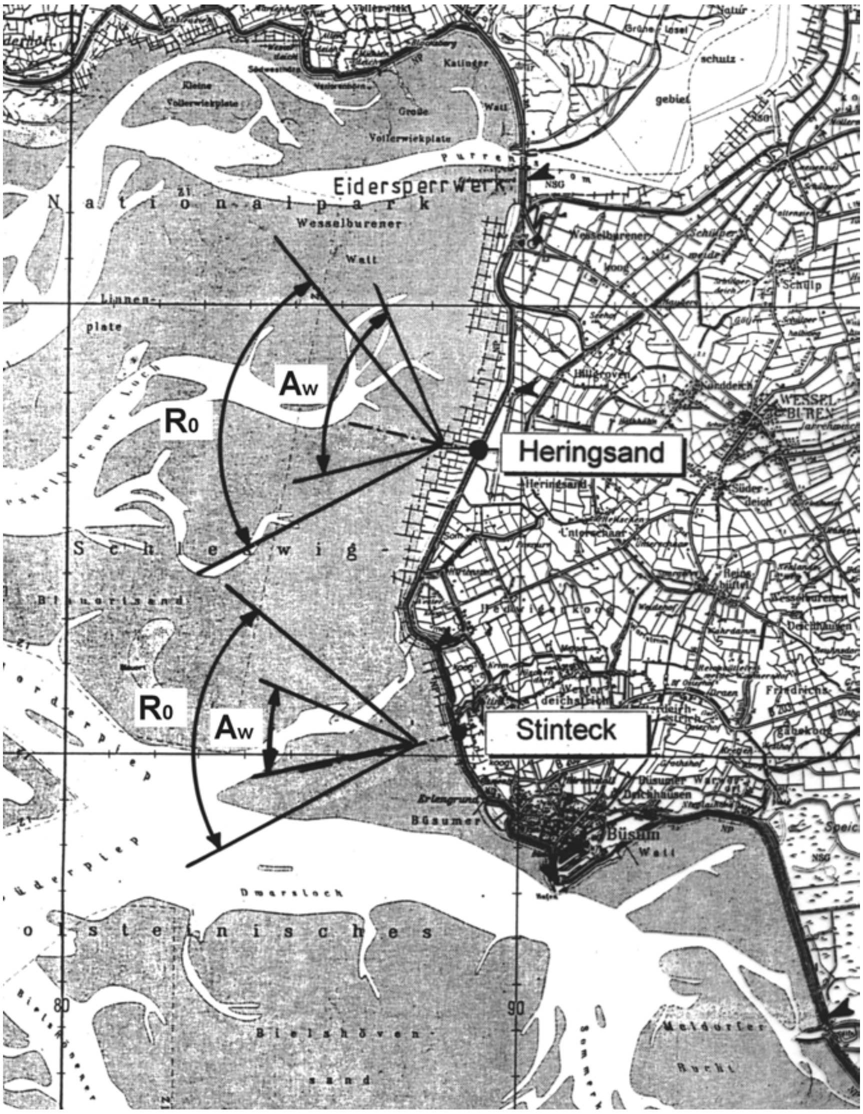


Fig. 19 Sectors of occurrence of wave approach direction A_W and wind direction R_0 measured around *Thw* for each storm surge event

5. CONCLUSION

In the paper the influence of local wind direction on wave approach direction in wadden sea areas have been discussed. Data from field measurements at two different locations were used to evaluate wave approach direction with a simple method in time domain. This method is explained exemplarily.

The presented results demonstrate the complex influence of the local bathymetry and the local tidal regime. The tendency may be stated that in general the phase shift A_W - R_0 between wind direction and wave approach direction mostly decreases with increasing water depth, but with different order of magnitude for rising and falling part of the storm surge still water level and also influenced strongly by the local interaction between bathymetry and tidal regime.

6. REFERENCES

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