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Long-term and post-storm dynamic patterns of the subtidal rhythmic morphology along the East Frisian island coast, Germany

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Abstract

This report evaluates the dynamic pattern of the subtidal, longshore-rhythmic morphology along the East Frisian barrier island coast. Analysis of high-resolution sounding charts from the shoreface of Spiekeroog Island, which span a period of 37 years, leads to the following: (a) the alongshore spacing as well as the eastward increasing shore-normal orientation of the channels of the morphology were markedly constant over time; (b) the main pattern of migration of the channels was rotational about well-defined nodal points, rather than translational; (c) four rotational patterns are distinguished, two of which are symmetric, i.e. the seaward and shoreward segments (relative to a nodal point) of the channel are characterized by a similar sense (clockwise or anti-clockwise) in rotation, whereas the two asymmetric patterns display opposite rotation at both segments; (d) the sense and degree of channel rotation showed no time-dependent progression; (e) the frequency of the clockwise angular displacement > 20° was higher than that of the anti-clockwise counterpart, and (f) the Mode 1 rotational pattern, in which both the seaward and shoreward segments of the channel depict a clockwise rotation, was found to be typical of, but not exclusively associated with, storm conditions in which the storm surge height exceeded 3 m. These observations are inconsistent with the dynamic behaviour of a flow-transverse (sand wave or dune) morphology. The channels of the morphology are considered to represent channels of storm rip-currents. The regularity in the alongshore spacing of the channels suggests an edge-wave control. However, the quality and type of hydrodynamic data required to verify the above assertion are presently unavailable. In the rock record, the channels would be best recognized in laterally-extensive, paleocoast-parallel vertical sections as regularly-spaced channel-fill sequences, in which epsilon crossbeds are lacking; seaward-dipping crossbeds may be widespread or rare depending on environmental conditions prior to preservation.

Introduction

Coastal geologists and engineers are aware of a variety of rhythmic forms that exist along sandy shorelines and their adjacent surf zones. Of particular interest are those forms displaying a longshore spacing of the order of 10^2 to 10^3 m. These rhythmic forms can be viewed as flow-transverse bedforms (sand waves) or rip-current-formed morphology. The former have been described in the North Sea area, for example, by Bruun (1954) and Verhagen (1989). Allen (1980, 1982a, b), amongst others, provides an elaborate discussion on the flow, form and facies characteristics of sand waves.

Rip currents are channellized seaward flows. Their significance is evident in their role in nearshore sediment transport and in the danger posed to unexperienced swimmers (Cook 1970, Reimintz et al. 1976, Short 1985, Hammack et al. 1991, Huntley & Short 1992). However, as shown by Tang & Dalrymple (1989), the mechanism of rip-current generation can vary.

Detailed reports dwelling on the temporal and spatial dynamic pattern of storm rip-currents or their channels are rare. This is primarily because of the short duration of field observations. However consensus exists in the literature on the description of Cook (1970) that ‘rip currents are by no means constant fea-

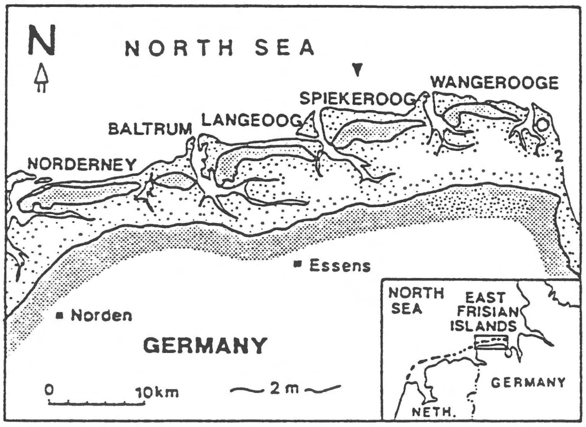

Fig. 1. Location of Spiekeroog Island (after Davis 1992).

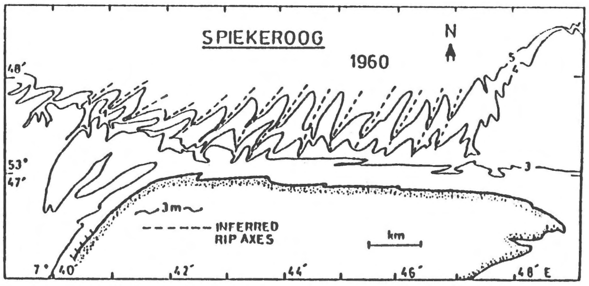

Fig. 2. Nearshore bathymetry of Spiekeroog Island showing the inferred storm rip-channel axes seaward of the 3 m (relative to NN) isobath. Also note the well-developed ebb-tidal deltas at both ends of the island. (See also Fig. 1.)

tures; they flow intermittently, the head swings back and forth, and the channels migrate'.

The rhythmic morphology described in this report has been previously studied by Reineck (1963) and Wunderlich (1983), among others. The latter-named author asserted, based on the absence of coast-parallel cross-stratified units in cores retrieved from the morphology offshore of Spiekeroog Island, that the morphology is very unlikely to be sand waves (dunes). This viewpoint is also shared by Flemming & Antia (1990) and Antia (1992). However, A.P. Oost (pers. comm.) observes that similar rhythmic features along the West Frisian barrier island coast of Schiermonnikoog (the Netherlands) display both translational and rotational dynamic patterns.

The objective of this report is to describe in detail the dynamic patterns of these rhythmic subtidal features along the island of Spiekeroog. This information is central to assessing the nature of the morphology on the one hand, as well as to broadening our insight on storm-related sediment transport processes along the East Frisian barrier island coast, on the other. Spiekeroog Island is used as a case study, because of its good data base.

Study area

Spiekeroog is one of the East Frisian barrier islands (Fig. 1). It is located in the southeast corner of the German Bight. Tides are semi-diurnal with neap and spring ranges of 2.1 and 2.9 m respectively. Exclusively fair-weather, spring and neap tidal current measurements made on the shoreface at 1 m above the sea bed, in water depths of 3 to 22 m, revealed a variation in peak velocity of 30 to 60 cm/s (Antia 1992).

Based on the data of Dette (1977), the significant height and range of period of the incident wind waves in the study region are respectively 1.5 m and 4 to 8 s in 80% of the time. From the data given by the Coastal Engineering Research Station in Norderney over the last two to three decades, it is estimated that coast-parallel storm currents occur at least 10 to 30 days annually in the study region (Antia 1992).

The bathymetry of Spiekeroog shows that the rhythmic ridge and channel morphology is situated in water depths of 4 to 6 m, relative to the Normal Null (NN) datum. Based on the wave data above, the fair-weather surf zone will extend, in at least 80% of the time, landward of the 3 m isobath (Fig. 2). The above implies, therefore, that the development and dynamics of the morphology are related to either or both of non-surf zone processes and storm activities.

Methods

High-resolution sounding charts (1:10 000) of the German Hydrographic Institute in Hamburg constitute the main data base. These charts cover the time interval 1950 to 1987. The density of depth soundings on these charts generally ranged between 28 to 33 per km^2. Thus, while the density of the soundings was relatively constant, the alongshore coverage was not in all cases comparable. This is mostly evident in pre-1960 charts.

In view of the averaging process adopted in chart analyses, the latter observation as well possible technical errors arising from the soundings itself, especially since they are to a great extent systematic, are not likely to adversely affect or influence the interpretation of the results obtained. Moreover, surveys with a large areal coverage show that the geometric characteristics of the morphology of interest revealed an alongshore pattern comparable to that of the time-averaged counterpart.

The charts were hand-contoured at half-metre contour intervals. The channel axes of the morphology were subsequently delineated, as exemplified by Fig. 2. The general spatial trend of the channel axes over the 37-year interval, based on overlay of successive charts processed as mentioned above, is shown in Fig. 3.

By considering the sounding dates, the channel axes shown in Fig. 3 can be grouped into a total of twelve axis clusters (Fig. 4). In order to define better the boundaries between the channel axis clusters at the western sector of the island (panels 1 to 4 of Fig. 4), the 1973 axis of the next successive cluster is indicated in each panel. Thus, the westerly of the two 1973 axes in a given panel belongs to the cluster group.

Figure 4 constitutes the basis for evaluating the dynamic characteristics of the morphology. The points of intersection of the axes are considered hinge or nodal points. Only a channel axis which passes through the nodal point (dark circle in definition sketch of Fig. 5a) and extends at least 500 m seaward (northward) and shoreward (southward) from this point was evaluated.

The dynamic patterns of the channels were assessed by overlaying successive charts and then measuring differences in their orientation over time and space. On the whole, a total of 111 pairs of historical channels were evaluated.

The angular displacement ($\delta\O$) of each of the channel segments relative to a reference (arbitrary) shore-normal axis passing through a nodal point was determined. As shown in Fig. 5a, the angular displacement of the two channel segments is denoted with subscripts 1 and 2. The above data enabled the assessment of the following channel characteristics in the alongshore direction: (a) the mean variation in orientation relative to the W-E shoreline trend (Fig. 5b), (b) the mean rotational asymmetry, defined as the ratio of $\O_1$ to $\O_2$ (Fig. 5c), and (c) the mean rotational direction (Fig. 5d).

Besides the average characteristics of the channels summarized in Figs 5 a–d, data from Fig. 4 also enabled the assessment of the consistency or otherwise of the dynamic behaviour of channel pairs over different time intervals, irrespective of their actual sounding dates (Fig. 6). The intention here is to determine if changes (not average) in the displacement and direction of both segments of two channels, for example, over a 3-year interval (such as between 1969 and 1972, 1979 and 1982, 1982 and 1985, etc.) are comparable to those of other time intervals, given the relative consistency in the storm flow direction in the study region.

Results

Channel spacing and orientation

Figure 3 shows that the channel axes are segregated into a number of clusters rather than being random or continuous alongshore. The axes reveal a historical longshore mean spacing of 460 ± 200 m. With the exception of the 1967 channel orientation (panels 3–5 of Fig. 4), all others are northerly or northeasterly oriented. It is further evident that, within each channel axis cluster, the majority of the axes appear to rotate about one or more nodal points.

An obvious exception to the aforementioned general trend is demonstrated by the 1973 channel axes. This deviation from the nodal point in itself does not necessarily imply a time-varying alongshore translation of a pre-existing channel. For the 1973 case, the deviation from the long-term nodal position is most distinct at the westerly sector of panels 1 to 3, east of which equilibrium position is re-established. As such, in subsequent sections of this report the primary focus will be on the rotational dynamic pattern of the channels.

Data on the mean shore-acute angle of the axes within each cluster given in Fig. 5b, suggest that for both axis segments this angle tends to increase eastward, i.e. to become more perpendicular alongshore from cluster 1 to 12. The mean ratio of the angular displacement of the seaward and shoreward segments from the shore-normal for the twelve channel axis clusters, here defined as the rotational asymmetry, is shown in Fig. 5c. With the exception of axis cluster 1, all others depict values < 1.

The deviation of the angular displacement ratio from unity implies that the channels are curvilinear, rather than straight. Furthermore, the angular displacement of the shoreward segment of the channel from shore-normal is generally larger than for the sea-

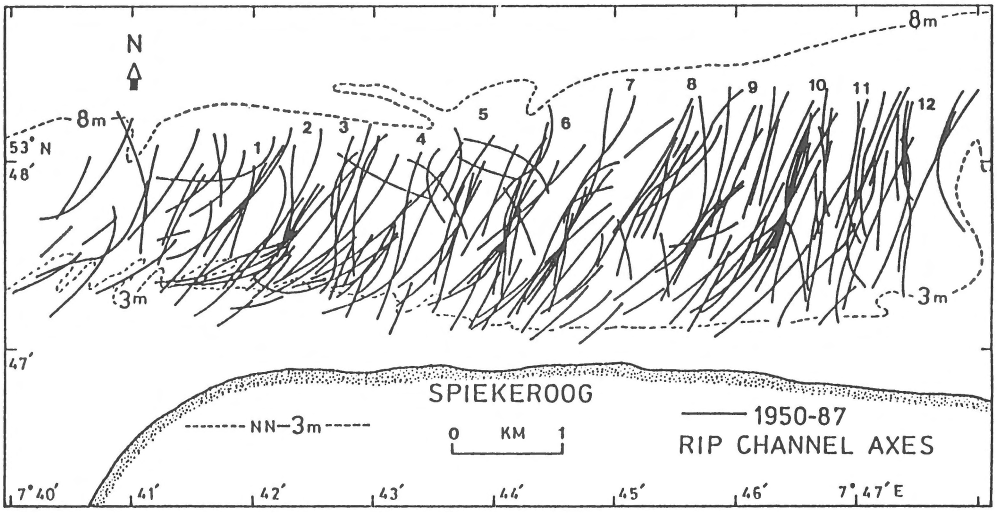

Fig. 3. Inferred storm rip-current channel axes based on overlay of survey charts within the period 1950 to 1987. The axes were delineated as illustrated in Fig. 2. Note the tendency for the axes to occur in clusters. Twelve, nearly equidistant, axis clusters are delineated.

ward segment. An upward-convex alongshore pattern of rotational asymmetry is depicted in Fig. 5c.

Direction and degree of channel rotation

Figure 5d shows that channel segments of a given time, when compared with successive counterparts, rotated in either a clockwise or in an anti-clockwise direction. Further illuminating from this figure is the observation that the sense of rotation of the seaward (open circle) and shoreward (dark circle) channel segments was not always similar. The clockwise rotation of both channel segments showed a mean frequency of occurrence of 50% or more in all but axis clusters 5, 6 and 10. By contrast, the frequency of anti-clockwise rotation was generally less than 40% in axis clusters 7 to 12.

The degree or magnitude as well as sense of angular displacement of pairs of historical channels in relation to the time interval between their survey dates is given in Fig. 6, from which three observations emerge. Firstly, none of the channel segments indicates a statistically significant relationship between angular displacement and time-interval, i.e. the angular displacement ($\delta Ø$) between a pair of channels separated by a longer time interval of survey was not necessarily larger than that separated by a shorter time interval. Secondly, for both channel segments, the extent of clockwise rotation or re-orientation is more pronounced than the anti-clockwise counterpart. The frequency of clockwise angular displacement values exceeding 20° for both the seaward and shoreward channel segments (29% and 46%, respectively) is higher than for their anti-clockwise counterparts (14% and 20%). Thirdly, the clockwise rotation for the shoreward channel segment is more intense than for the seaward counterpart.

A classification of channel rotation patterns

Based on the observed spatial and temporal patterns of angular displacement in channel orientation of Figs 5d and 6 respectively, a four-fold classification of their rotational patterns is proposed (Fig. 7). Two of the rotational modes are symmetric, whereas the other two are asymmetric. The symmetric modes are characterized by both the seaward and shoreward channel segments depicting either a clockwise (Mode 1) or an anti-clockwise (Mode 2) angular displacement relative to a pre-existing channel orientation. The asymmetric modes, on the other hand, are typified, respectively, by a clockwise (Mode 3) and an anti-clockwise (Mode 4) angular displacement of the seaward channel segment, with an opposite rotation at their shoreward channel segments.

Over the 37-year study period, the symmetric Mode 1 occurred most frequently (38% of the time). It was indicated in > 50% of the time at seven out of the eleven axis clusters examined (cluster 1 did not yield adequate data and was therefore excluded). The symmetric Mode 2, with a long-term frequency of occurrence of 23%, was the principal pattern of two of the

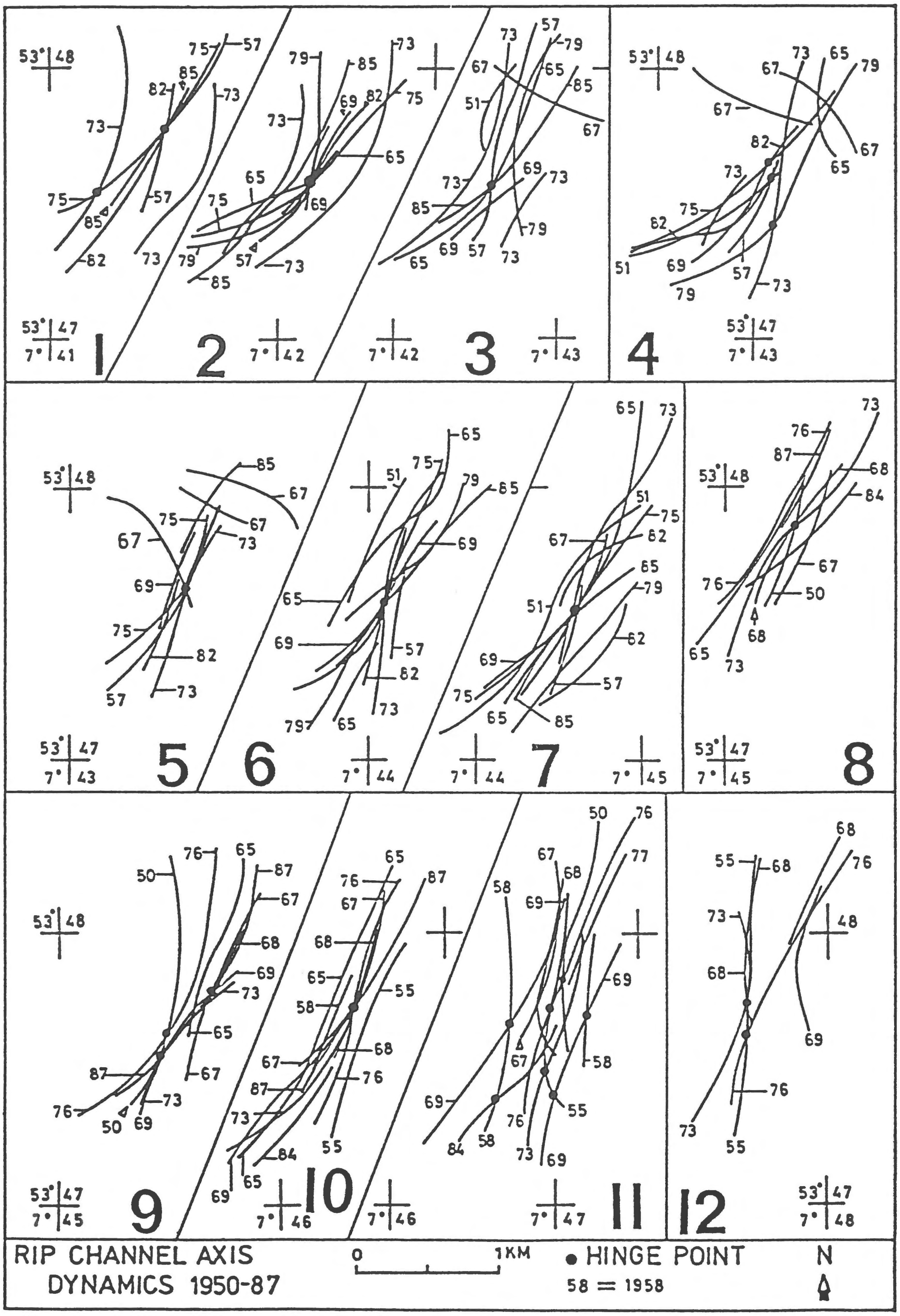

Fig. 4. Temporal variation in orientation of inferred storm rip-current channel axes for each of the twelve axis clusters shown in Fig. 3. Most of the axis clusters depict one principal hinge or nodal point about which the channels appear to rotate.

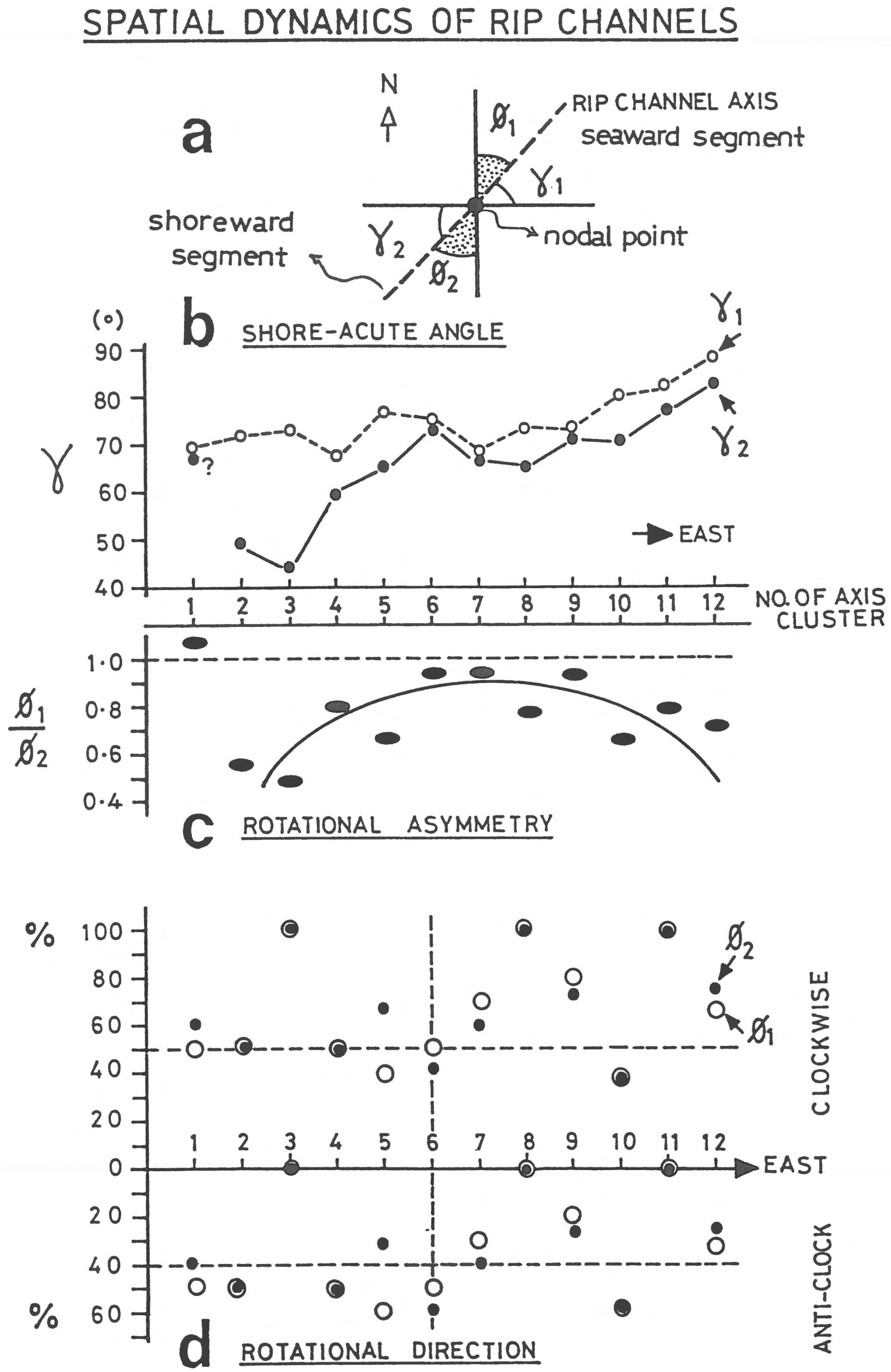

Fig. 5. (a). Definition sketch of parameters of rip channels relative to the W-E shoreline trend of Spiekeroog and shore-normal. γ_1 and γ_2 respectively designate the shore-acute angle of the seaward and shoreward channel segments, while $\emptyset_1$ and $\emptyset_2$ designate their angular displacement from shore-normal. (b). Variation in the mean shore-acute angle of the seaward (γ_1) and shoreward (γ_2) segments of the inferred rip-channel axes of each cluster. Note the alongshore trend whereby the easterly located channels approach a shore-normal orientation. (c). Variation in the mean rotational asymmetry of the axis clusters. Note the upward-convex alongshore pattern of the values. (d). Variation in the mean frequency of clockwise and anti-clockwise rotation of the seaward ($\emptyset_1$) and shoreward ($\emptyset_2$) channel segment for each of the twelve axis clusters. For both channel segments, the principal rotation is clockwise.

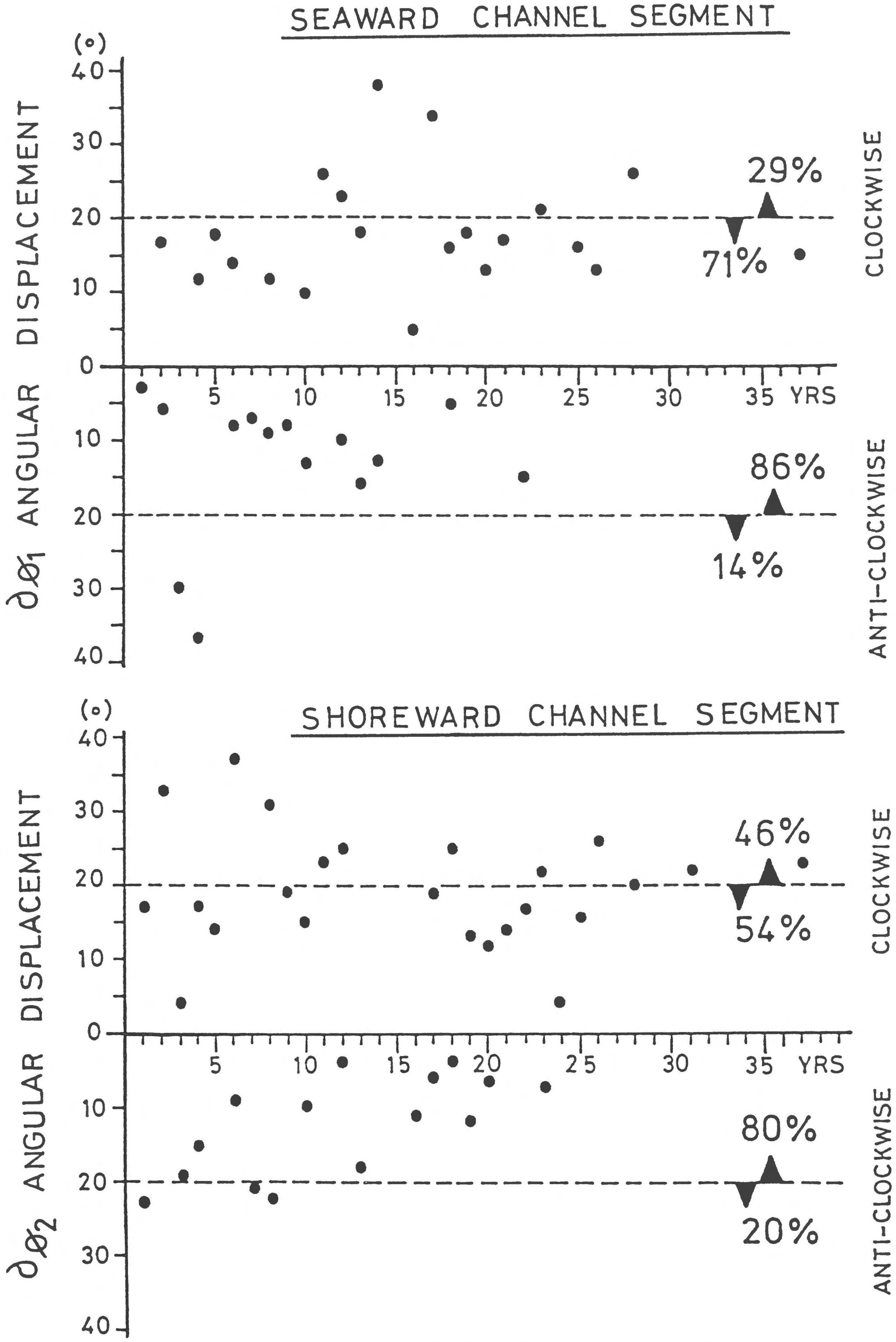

Fig. 6. Relationship between magnitude and sense of angular displacement between pairs of channels (seaward and shoreward segments) and the time interval between their survey dates. No well-defined pattern in the magnitude of angular displacement with increasing time interval is evident.

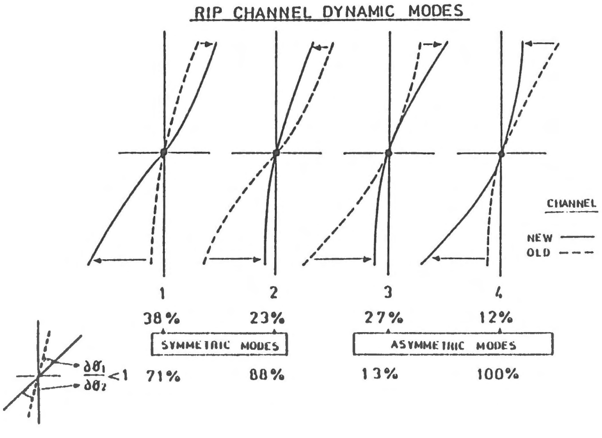

Fig. 7. A schematic representation of the four modes of rip channel rotation observed and their frequencies of occurrence. The symmetric Modes 1 and 2 occur in 38% and 23% of the time respectively. Mode 1 is characterized by a clockwise angular displacement seaward and shoreward of the nodal point, whereas Mode 2 shows an anti-clockwise angular displacement in both channel segments. The asymmetric Modes 3 and 4, with frequency of occurrence of 27% and 12% respectively, display opposing angular displacement patterns in both channel segments. Note also that, with the exception of Mode 3 (13%), the other modes display in > 70% of the cases a larger angular displacement of the shoreward segment of the rip channel than the seaward counterpart.

axis clusters. The asymmetric Modes 3 and 4, on the other hand, occurred in 27% and 12% of the time respectively.

Discussion

Edge waves and channel spacing

The segregated pattern of the channel axes noted in Fig. 3 for the 37-year period is not consistent with an expected continuous pattern of trough or crest axes of longshore-migrating sand waves (dunes). Furthermore, the eastward increasing mean shore-acute angle of the channels documented in Fig. 5b is also inconsistent with a flow-transverse bedform nature of the rhythmic feature (Antia 1992), unless one supposes that the current generating the bedform systematically veers seaward by about 20° within a distance of 10 km, this corresponding to the island's length.

Considering that longshore currents are inconsequential to the development of the observed subtidal morphology, edge waves in the infragravity domain (period > 30 s) provide an alternative explanation for the longshore rhythmic pattern (Flemming & Antia 1990) as well as the longshore mean spacing of 460 m of the channels (Antia 1992). Edge waves are essentially waves propagating along the coast, i.e. their crestlines are shore-normal, in contrast to the commonly observed wind-generated waves whose crestlines are parallel or oblique to the shoreline.

Detailed discussions on the role of infragravity edge waves in the development of large-scale (> 100 m) geomorphic features in the nearshore are contained in the reports of, and references cited by, Komar & Holman (1986) and Aagaard (1991). Theoretically, as formulated by Bowen & Inman (1971), a rhythmic feature of any given longshore spacing can be related to the edge-wave oscillation, based on the equation:

$$\lambda = (g/2\pi)T^2 sin([2n + 1]\beta)$$

where λ is the edge-wave length (this corresponds to twice the value of the longshore spacing of the morphology), T and n are respectively the period and mode number (an integer defining the number of zero-crossings in the offshore direction) of the edge wave, for which several combinations are possible, and β is the nearshore gradient.

The subtidal longshore-rhythmic rip-current channels of Spiekeroog can, among other edge-wave oscillations, be attributed to one having a period of 232 s and mode number 3 (based on $\beta = 0.09°$). However, one of the obvious requirements for the initiation of a rhythmic pattern is that the oscillation must be standing alongshore. In the study area, reflection of the edge waves at the margins of the ebb-tidal deltas fringing each island can readily lead to such a longshore standing oscillation.

Flow conditions and channel dynamics

The fair-weather flow observations documented by Antia (1992) from the study area are not at all instructive with regard to the dynamics of the channels. Unfortunately, due to the inherent difficulties, simultaneous observations of the storm currents and the corresponding sea-bed response were not conducted in the course of this investigation. Therefore, any flow-morphodynamic relationship at this time can only be deductive.

While not directly providing an insight on the velocity structure of the nearshore storm flow, the annually published data on wind condition and storm-surge height in the study region by the Coastal Engineering Research Station in Norderney enable a qualitative

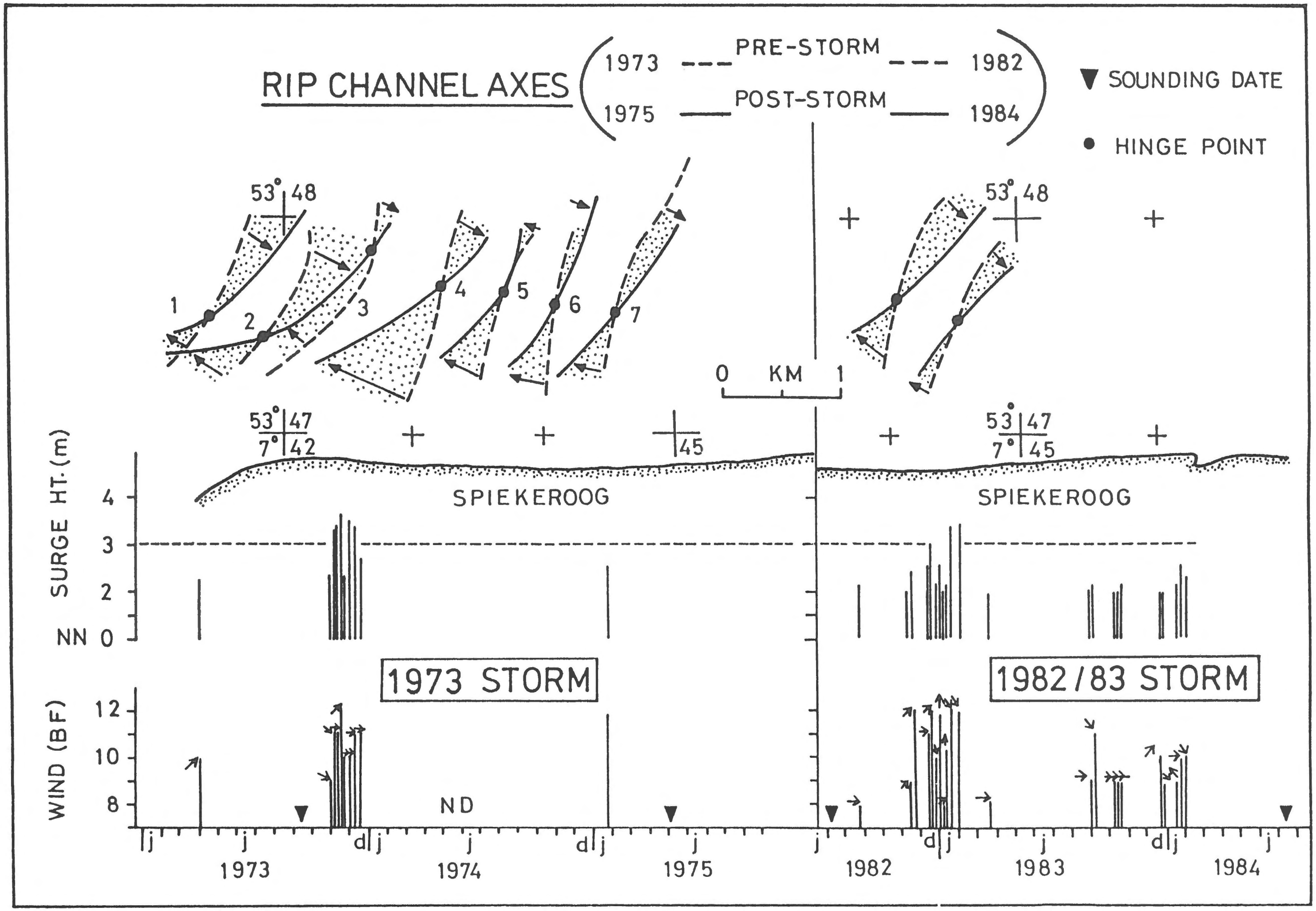

Fig. 8. Response pattern of the inferred rip channels to 1973 and 1982/83 storm events. The post-storm channel orientation is more shoreline-oblique than the pre-storm counterpart. Wind intensity is given in Beaufort force and wind direction indicated by the orientation of the arrows. Wind data are based on measurements made in the vicinity of the island of Norderney by the Coastal Engineering Research Station in Norderney.

assessment of the relationship between the pre- and post-storm state of the channels. Two such attempts are depicted in Fig. 8 for a 1973 and a 1982/83 storm condition. The pre- and post-storm survey dates and the corresponding orientation of the channel axes are also illustrated.

In both of the above storm conditions, in which the peak surge height exceeded 3 m, the Mode 1 rotational pattern is displayed. Moreover, the post-storm channel axis generally tends to be more shore-oblique, i.e. the eastward-opening shore-acute angle is about 20° smaller than the pre-storm counterpart.

Due to limited data, it is impossible to reliably correlate, at this time, the magnitude of angular displacement with an appropriate storm-flow parameter. The observation that the above pattern is also encountered during periods of lower storm-surge (height) conditions suggests that it is not a reliable predictor of the dynamic pattern of the morphology. Based on an edge-wave-related development of the channels earlier mentioned, a conceptual model for the rotational dynamic patterns observed is illustrated in Fig. 9.

A symmetric Mode 1 rotational pattern of the rip-current channel results if a standing edge-wave oscillation at time T_2 is caused to skew eastward relative to the antecedent shore-normal symmetric counterpart (at time T_1) by a superimposed longshore storm current (Fig. 9A). A reversal of the above sequence, whereby channels developed by an easterly skewed edge-wave oscillation are succeeded by those of a symmetric counterpart, will result in a re-orientation defined by a symmetric Mode 2 rotational pattern.

In the two symmetric rotational modes above, it is assumed that the alongshore structure of the standing edge-wave oscillation is more or less similar and that the superimposed longshore storm current shows no cross-shore variation in intensity, at least in the water-depth region where the morphology is located.

As commonly observed for wind-waves, it is logical to expect, intermittently, a large deviation in the period and wave length of edge waves from their long-term time-averaged values. The same applies to the cross-shore velocity structure of the superimposed longshore currents. In Fig. 9B, the initial condition at time T_1 (continuous lines) is such that there is only a slight cross-shore (seaward increasing) velocity gradient in the superimposed longshore current.

A seaward increasing velocity gradient in the eastward longshore flow may be a consequence of a stronger dampening effect closer to the shoreline, compared to the offshore region, due to the reflected, westward propagating, edge-wave oscillation whose amplitude, and hence energy, generally rapidly decay seaward. This being the case, the rip-current channels at time T_1 will skew more eastward from the shore-normal at their seaward than at their shoreward segments.

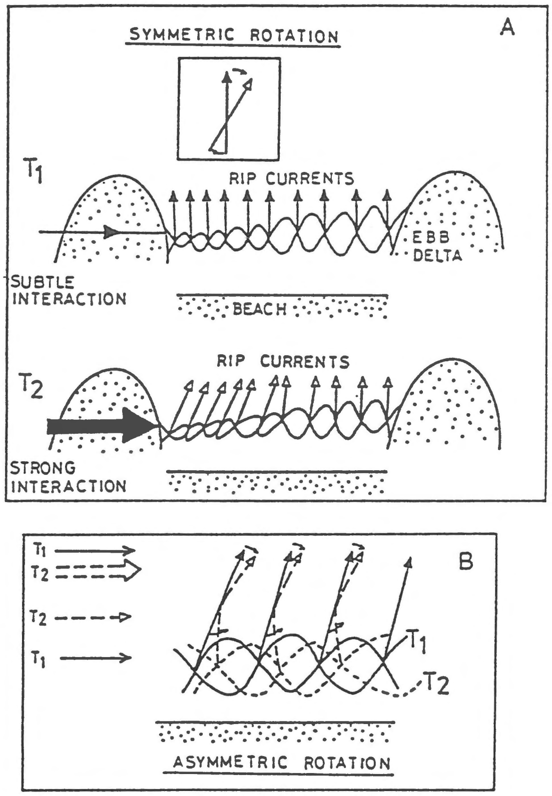

Fig. 9. A conceptual model of the development of (A) symmetric and (B) asymmetric rotational patterns of the inferred storm rip-channels based on the interaction between a longshore standing edge-wave oscillation and a longshore storm current (see text).

The conditions at time T_2 (dashed lines) of Fig. 9B are such that the wave length of the edge wave is somewhat different from that of time T_1 (hence a slight displacement in the nodal positions); furthermore, the cross-shore velocity gradient of the superimposed longshore current is stronger. Consequently, an overlay of survey charts at both times will result in a clockwise angular displacement of the seaward channel segment at time T_2 relative to time T_1. The shoreward channel segment will display, on the other hand, an anti-clockwise angular displacement between time T_1 and T_2.

The above pattern of channel re-orientation is designated as asymmetric Mode 3 rotation in Fig. 7. A reversal of the above sequence of conditions, whereby T_2 now becomes T_1, will give rise to an asymmetric Mode 4 rotation.

Channel translation versus channel initiation

There is at present no strong evidence to support the notion that the subtidal morphology migrates appreciably alongshore (Wunderlich 1983; Antia 1992). In this respect, the channel axes whose positions deviate from the long-term nodal points in Fig. 4 must be viewed as newly initiated channels due to edge wave oscillations whose wave lengths differ from the normal or modal value. The storm rip-current channels are probably incised when the ebb-storm surges interact with the longshore standing edge-wave oscillation, as shown in Fig. 9. The edge waves are envisaged to be generated based on a mechanism postulated by Evans (1988), which involves an interaction between longshore storm-currents and the updrift (western) ebb-tidal delta.

Conclusions

This study was primarily aimed at understanding the dynamic behaviour of the subtidal rhythmic morphology along the coast of the East Frisian barrier island of Spiekeroog. The lack of storm flow data on which the dynamic behaviour of this feature depends, limits the present report to a qualitative description of same. It is believed that much of the documented results can be beneficially applied to the West Frisian barrier islands off the Dutch coast.

An important observation emerging from this study is that the above morphology is very unlikely to represent flow-transverse bedforms. At the same time, the inferred storm rip-current origin needs to be verified from flow data.

It is not obvious to what extent the results presented here will be applicable to normal rip currents whose origin and occurrence are related to surf-zone processes. In general, some identical characteristics are observed to enable one to contemplate such application, namely, the quasi-periodic longshore spacing and a markedly constant long-term spatial distribution pattern of the channels, both of which are consistent with a standing edge-wave-generating mechanism. Furthermore, the observation that the magnitude of angular displacement between pairs of channels was independent on the time interval between their survey dates is consistent with the viewpoint of Cook (1969) that (normal) rip currents (and their channels) must be highly dynamic features.

The here-described variability in the channel axis orientation over time seems compatible with the implied morphologic response to the interaction between the surf-zone-generated edge-wave oscillation and a superimposed longshore current (e.g. Howd et al. 1992). Thus, the dynamic modes observed for the studied channels probably depend on the scale of interaction between a longshore storm flow and a longshore standing infragravity edge wave.

The fact that subtidal features are commonly observed in the rock record leads one to believe that the preservation potential of the here-described rhythmic feature must be good. Additional work is, however, required in order to fully establish criteria that unequivocably distinguish these inferred storm rip-current channels from their fair-weather (surf-zone) counterparts of generally diverse origin.

In vertical sections which are laterally extensive and parallel to the palaeocoast, the rip channel-fill sequences, but particularly their erosional, bounding lower surface would be distinguishable from other shallow-marine channel-fill sequences on the basis of their periodicity and regular longshore spacing. Given the relatively stationary nature of the rip channels, epsilon crossbeds, which are typical of laterally migrating channels, should be rare in the sequence, in comparison to seaward-dipping strata. It is envisaged that the rip channel-fill sequence in the study area would show a strong bias toward sedimentary structures formed by fair-weather flow regimes.

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