Journal of Coastal Research	7	3	801–813	Fort Lauderdale, Florida	Summer 1991

Multiple-Bar Morphodynamics and Its Relation to Low-Frequency Edge Waves

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ABSTRACT

AAGAARD, T., 1991. Multiple-bar morphodynamics and its relations to low-frequency edge waves. *Journal of Coastal Research*, 7(3), 801–813. Fort Lauderdale (Florida). ISSN 0749-0208.

An analysis of aerial photos from multiple-bar localities in Denmark has revealed the presence of 8 different types of nearshore bar systems. This is the background for the proposal of a tentative beach state model for multiple-bar systems in protected environments. The inner bar displays an evolutionary tendency similar to the bar in the single-bar, oceanic beach state model of WRIGHT and SHORT (1983), while the morphology of outer bars varies according to state. Moreover, outer bars are morphologically and dynamically arrested for long periods of time.

Field studies have shown that bar morphology may be very much influenced by infragravity edge waves. During a very intense storm, progressive edge waves occurred, while a less intense storm produced standing edge waves. In both cases a single edge wave mode dominated the energy spectra. Offshore and longshore length scales of this wave corresponded reasonably well with the ensuing bar patterns. In moderate energy situations, standing edge waves also occurred. However, in those cases the waves had a higher frequency and a lower mode number, probably producing the smaller-scale rhythmicity of the inner bar. Outer bars thus only respond to the most highly energetic conditions, while the more mobile inner bar has a lower energy threshold.

ADDITIONAL INDEX WORDS: *Rhythmic topography, beach state model, infragravity waves, edge wave modes.*

INTRODUCTION

Nearshore bars are one of the most conspicuous features in the coastal environment. Even though bars possess a certain number of universal characteristics, their behaviour and appearance may vary depending upon the environmental setting. They may be very dynamic, migrating seawards during storms and shorewards during low-energy periods. This particularly seems to be the case on oceanic coasts where storm waves and/or high-energy swell alternate with periods of lower-energy swell (*e.g.* WRIGHT and SHORT, 1983; MASON *et al.*, 1984; HOWD and BIRKEMEIER, 1987). SALLENGER *et al.* (1985) reported a seaward bar migration rate of 2.2 m/h during a storm, subsequent to which the bar migrated landward at a rate of 1.2 m/h driven by long-period swell.

In other settings, the bars may be very stable features. This is particularly the case in multiple-bar systems in protected environments where swell is absent (*e.g.* GREENWOOD and SHERMAN, 1984; DOLAN and DEAN, 1985; DAVIDSON-ARNOTT and MCDONALD, 1989). Further, in multiple-bar systems spatial differences in bar dynamics may occur; outer bars are more stable than inner bars (*e.g.* BIRKEMEIER, 1984; SONNENFELD and NUMMEDAL, 1987; AAGAARD, 1988a) probably reflecting the fact that outer bars only migrate seaward during the most highly energetic conditions. On the other hand, for most of the time the energy level may be too low to cause shoreward migration of outer bars. Outer bars may thus be more or less arrested in place.

Morphologically, nearshore bars display a large variation as well, as they may be linear or rhythmic features (*e.g.* GREENWOOD and DAVIDSON-ARNOTT, 1979; SHORT, 1979; WRIGHT *et al.*, 1979). In the case of more than one bar being rhythmic, the largest rhythmic wavelength is seen on the outer bar (VINCENT, 1973; CARTER and KITCHER, 1979; SONNENFELD and

90143 submitted 26 November 1990; accepted in revision 27 February 1991.

NUMMEDAL, 1987). More commonly, outer bars are linear and inner bars are rhythmic (*e.g.* OWNES, 1977; GREENWOOD and SHERMAN, 1984; GREENWOOD, 1987).

It is clear that these very variable bar characteristics have hampered the determination of their origin, and indeed several hypotheses for bar formation exist. The bars must in some way reflect the hydrodynamic processes at work during their formation, or during the initiation of the bar migration cycle which is under storm conditions when the bars have migrated seaward.

Some hypotheses relate bar formation to the position of the breakpoint during storms, as an offshore directed bottom return current exists inside this point. Seaward of the breakpoint, sediment is transported shoreward by incident wave asymmetry. Thus sediment transport will converge at the breakpoint (DALLY, 1987; DAVIDSON-ARNOTT and MCDONALD, 1989; ROELVINK and STIVE, 1989). However, this model suffers from a number of shortcomings, *e.g.* the difficulty in explaining the presence of several bars within a saturated surf zone, as reported by SALLENGER *et al.* (1985) and AAGAARD (1988a), as well as in explaining rhythmic topography.

A particularly attractive theory of bar formation is associated with the presence of standing infragravity waves in the nearshore. These waves will induce spatial gradients in oscillatory as well as in mean currents. Bars should form under nodes or antinodes of the waves, depending upon the mode of sediment transport (SHORT, 1975; BOWEN, 1980). Infragravity waves may occur in the form of two-dimensional leaky mode standing waves or as edge waves, *i.e.* waves which are trapped in the nearshore due to refraction. Leaky mode waves and longshore progressive edge waves should form linear bars as there will be no spatial gradients in sediment transport potential parallel to the beach (averaged over time), while longshore standing edge waves are able to produce rhythmic bars (*e.g.* BOWEN and INMAN, 1971; BOWEN, 1980; HOLMAN and BOWEN, 1982). In both cases the number of bars will depend on the mode number of the infragravity waves.

The definitive verification of the validity of the infragravity wave model has not yet been accomplished, one of the main reasons being that sampling the three-dimensional velocity field during storms is a very complicated and expensive task. However, a precondition for accepting the model is that it must be able to account for the different morphological features in multiple-bar systems (*i.e.* small-scale inner-bar rhythmicity; large-scale rhythmic or linear outer bars).

The rhythmic wavelength of the morphology, λ, is theoretically related to the standing edge wave wavelength L_e through

$$\lambda = (g/4\pi)\, T_e^2 \sin(2n+1)\beta$$

(BOWEN and INMAN, 1971) with T_e being the edge wave period, β the nearshore gradient and n the mode number of the edge wave (the number of offshore zero crossings). Spatially varying morphology could thus be due to a spatial segregation of modes during storms, *i.e.* leaky modes and/or high-mode (low-frequency?) edge waves dominating over the outer bars, while low-mode (higher-frequency?) edge waves might dominate over the inner parts of the profile.

Alternatively, the reason could be a temporal segregation of modes or frequencies with high-mode (low-frequency) edge waves or leaky modes dominating during storms when outer bars are active, and low-mode (or higher-frequency) edge waves occurring during the waning phases of storms or in moderate-energy situations when outer bars are arrested and inner bars are active. However, this latter hypothesis would require that the edge waves had a particular mode/frequency combination at a given time, *i.e.* a single dominant edge wave. Positive identification of a single dominant edge wave under high-energy conditions has largely proved elusive, a notable exception being the work reported by BAUER and GREENWOOD (1990). Most studies seem to indicate that infragravity wave spectra are near-white during storms (*e.g.* HOLMAN, 1981; GUZA and THORNTON, 1985; OLTMAN-SHAY and GUZA, 1987), while in some moderate-energy situations, a single dominant edge wave has been found (*e.g.* WRIGHT *et al.*, 1986). However, on the latter occasions the frequency of the edge waves was obviously selected by the bar itself, or rather the distance between the bar and the shoreline. While this edge wave could remould the rhythmic topography it would be unable to form the bar itself.

In this paper, which is based on results obtained at a beach in Denmark, it will be

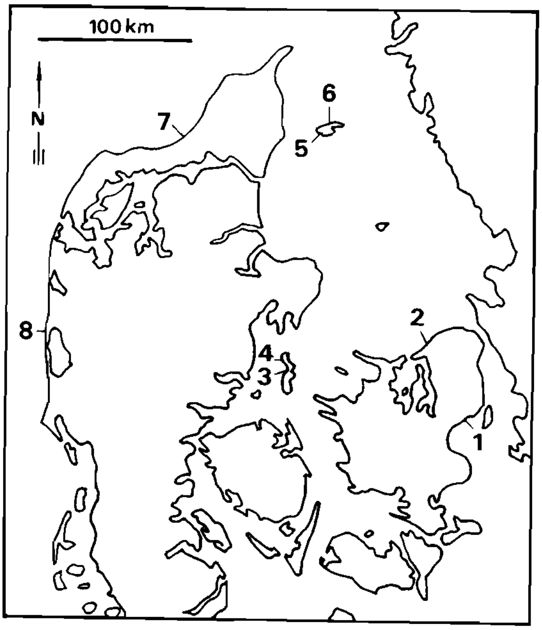

Figure 1. Map showing the 8 localities used in the air-photo analysis. See also Table 1.

shown that infragravity wave spectral characteristics during storms were relatable to outer-bar topography while waves occurring under moderate-energy conditions were able to account for inner-bar topography.

FIELD SITE AND METHODS

The field work took place at Staengehus on the northern coast of Zealand, Denmark (location 2, Figure 1). The beach is broad and backed by aeolian dunes; three bars are present in the nearshore which slopes ~0.016. The sediment is rather coarse with a mean sand grain size of 300–400 μ, but there is an admixture of pebbles and cobbles which may be exposed as lag pavements on the beach and in the troughs between bars.

This protected beach experiences comparatively short fetches (~40–200 km) between north and west which means that the wave climate is dominated by brief and intense storms, separated by long periods of low wave energy. Swell is virtually absent and the bar system is arrested for long periods of time when wave energy is too low to cause shoreward bar migration. During westerly and northwesterly storms, which are most frequent in autumn and winter, wave heights may reach 3 m with periods of about 6 seconds but the mean annual wave height is ~0.55 m with periods of 2.5–3.5 seconds. Tides are semidiurnal with a spring range of 0.3 m.

Field work consisted of video recordings of run-up oscillations during moderate- and high-energy conditions. Eight experiments took place during 1987 and 1988 with wave heights varying between 0.9 and 3.0 m and T = 4–7 seconds. Run-up was recorded in 2–3 transects for approximately 34 minutes and digitized at 2 Hz, using a computer-based scanning routine (AAGAARD and HOLM, 1989). Spectral characteristics of infragravity waves were quantified using a Fast Fourier Transform on the digitized time series. The resulting energy spectra all have 38 degrees of freedom.

Following storms, the area was surveyed using echo-sounder and standard surveying techniques. Eight transects were spaced 50 m apart and the recorded bar patterns were compared to theoretical length scales of edge waves with a period corresponding to the spectral peak during the storm.

MORPHOLOGICAL VARIATION OF BARS

Analysis of 51 sets of aerial photos from various multiple-bar locations in Denmark (Figure 1) has revealed the presence of 8 general types of bar system morphology. The types have been synthesized in a beach state model for multiple-bar systems in protected settings. This model contains 9 states progressing through successively lower energy levels (Figure 2); however, the most highly energetic state (state 1) has not been identified on aerial photos. As argued later, this state is inferred to occur during storms when aerial photos are not taken.

State 1 is characterized by linear morphology while states 2, 3, 4 and 5 possess different rhythmic forms at several scales, more seaward located bars having larger scales. The inner bar displays an evolutionary tendency similar to the bar in the model presented by WRIGHT and SHORT (1983) while outer bars are morphologically and dynamically arrested for long periods of time. The difference between sequences a and b lies in the configuration of the outer bar which is linear in sequence a and rhythmic in

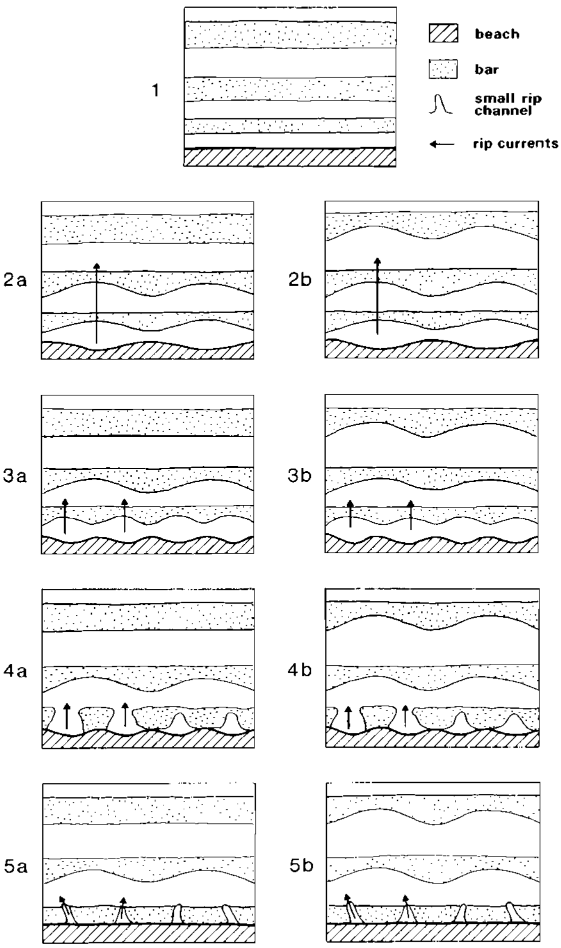

Figure 2. Schematic diagram of observed multiple-bar beach states in Denmark. Rips are seen only in states 2–5 when the bar system is active. In state 1, horizontal circulation is absent. See text for further explanation.

sequence b. The latter sequence generally occurs when more than three bars exist at a given site. Bar systems with more than three bars are favored by broad, shallow nearshore zones and low exposure, as *e.g.* locations 1 and 3/4 (Figure 1), while this zone is narrow at location 5 where only three bars exist.

The ranking of the states is based partly on field observations, as *e.g.* reported in AAGAARD (1988b) where the succession 2a–4a was observed over a 4-week period with gradually decreasing energy levels, and partly on the computation of an annual energy index (EI). As wave records are scanty, EI is computed from

Table 1. *Relationship between annual energy index (EI) and occurrence of beach states at the 8 locations shown in Figure 1.*

Location	EI 10^4 (m^2/s)	No. of Occurrences 1	2a&b	3a&b	4a&b	5a&b
8	72.2	—	3	1	1	1
7	35.1	—	3	3	1	—
2	9.0	—	1	1	2	1
6	4.0	—	—	2	2	3
1	2.8	—	—	—	4	3
3/4	1.8	—	—	—	6	6
5	1.7	—	—	—	1	6

wind data. The annual energy index at a given site is defined as

$$EI = \sum(F \cos\alpha (\sum_{5}^{12} fV))$$

where F is fetch in meters, α is angle of wind incidence to the beach, V is wind velocity in m/s and f is annual frequency of occurrence of a given velocity/direction combination. fV is summed over wind forces 5 to 12 on the Beaufort scale, and the total is summed over seven onshore wind components.

The relationship between EI and number of occurrences of given beach states is given in Table 1. The most highly energetic sites display a prevalence for the occurrence of states 2 and 3, while the low-energy sites are dominated by states 4 and 5.

Available field evidence (AAGAARD 1988b) and results reported elsewhere (*e.g.* WRIGHT and SHORT, 1983) indicate that the beach will proceed from the higher states (1,2,3) toward the lower states (4,5) with a gradually decreasing energy level. However, at any point in time, this progression may be halted if the energy level becomes too low to cause further morphological development. This lower-energy threshold probably depends on the beach state itself with higher thresholds occurring in higher states. The reason is that the capability of the incident waves to cause onshore sand transport depends on water depth and thus on bar distance from shore.

At Staengehus, only states 2a, 3a, 4a and 5a have been identified on photos. The difference between these states is expressed in the morphology of the inner bar which may be crescentic, transverse or in the low-tide terrace state (WRIGHT and SHORT, 1983). Rhythmic wavelengths of the inner bar are 100–150 m, although on one occasion it was about 300 m (state 2a). The second bar is sinuous or crescentic in all four states with a wavelength of 240–300 m while the outer bar is always linear.

These features suggest that if infragravity waves are responsible for the formation, or rather, the configuration of the bars, leaky mode waves or progressive edge waves should be dominant over the outer parts of the profile, or alternatively, dominate the velocity field during the most intense storms when the outer bar is active. Further, high-mode ($n \geq 2$), low-frequency standing edge waves should be dominant over the intermediate parts of the profile, or alternatively, dominate during less intense storms, changing the morphology of bars 1 and 2. Finally, low-mode and/or higher-frequency standing edge waves should be dominant in the inner nearshore or during moderate-energy conditions when only the inner bar is active.

The distances from the shoreline to bars 2 and 3 show that infragravity wave periods corresponding to these dimensions are on the order of 51–58 sec while the rhythmic wavelengths on bar 2 (and on a single occasion on bar 1 as well) suggest standing edge wave periods of 51–60 seconds, assuming mode number $n = 3$ (corresponding to the number of bars), and $\beta = 0.015–0.017$ which is the gradient of the entire nearshore zone. The smaller-scale inner bar rhythms suggest $T_e = 39–53$ sec, assuming $n = 1$ or $T_e = 26–36$ sec, assuming $n = 3$. In this case, however, the period ranges are difficult to determine precisely as the inner nearshore gradient, applicable in the $n = 1$ case is quite variable ($\beta = 0.023–0.028$) as is the appropriate $n = 3$ gradient ($\beta = 0.021–0.027$). It should be noted here that an interdependence between T and β exists, as longer periods (as well as larger mode numbers) will extend the edge wave structure further seawards, thus altering the gradient which should be applied in the calculations.

The outer bars are quite stable in position, their distance from the shoreline varying from 100–125 m (bar 2) and 235–255 m (bar 3). Indications are that the outer bars are in near-equilibrium with hydraulic conditions during storms and as such they are relict features for long periods of time.

FIELD RESULTS

A field experiment was conducted during high-energy storm conditions on November 29, 1988. The visually determined breaker height was ~3.0 m with a wave period of 6.9 sec. Waves broke through spilling over the third bar and the entire surf zone was saturated. Run-up spectra are shown in Figure 3. A statistically significant, highly coherent peak exists at 0.019 Hz (53 sec) with a phase of $\sim -\pi/5$ between the two transects which were spaced 50 m apart. The phase relation is consistent with the computed (progressive) edge wave wavelength which is 550 m. Thus the spectral signatures suggest that the dominant infragravity energy was in the form of a progressive edge wave. Secondary energy peaks occur at 0.036, 0.045 Hz (28 and 22 sec, respectively). Peak periods differ in the two transects, and they are situated on either side of the coherence peak at 0.04 Hz. Therefore, this energy may not represent free waves.

Due to various problems, only 5 of the 8 profile lines were surveyed after the storm, and the longshore morphology of the bars was therefore impossible to determine. However, if the assumption is correct that the infragravity waves recorded during the storm peak were in fact progressive edge waves, the bars should have been linear at that time (*e.g.* WRIGHT, 1982), corresponding to state 1 in the model (Figure 2). The survey showed that the correspondence between bar positions and theoretical antinode positions of 53-sec mode 3 edge waves was quite satisfactory (AAGAARD, 1990).

Another experiment took place on September 15, 1987 during a less severe storm. The breaker height reached 2.0 m with a period of 5.5 sec. Waves broke over the third bar and reformed in the succeeding trough while the inner surf zone was saturated. The run-up spectra shown in Figure 4 reveal a statistically significant highly coherent peak at 0.018 Hz (54.5 sec). An interesting feature is that the spectral density of the peak in the two transects is significantly different, in contrast to the experiment described above. Also, the phase between the transects is zero. These spectral characteristics suggest that the dominant infragravity

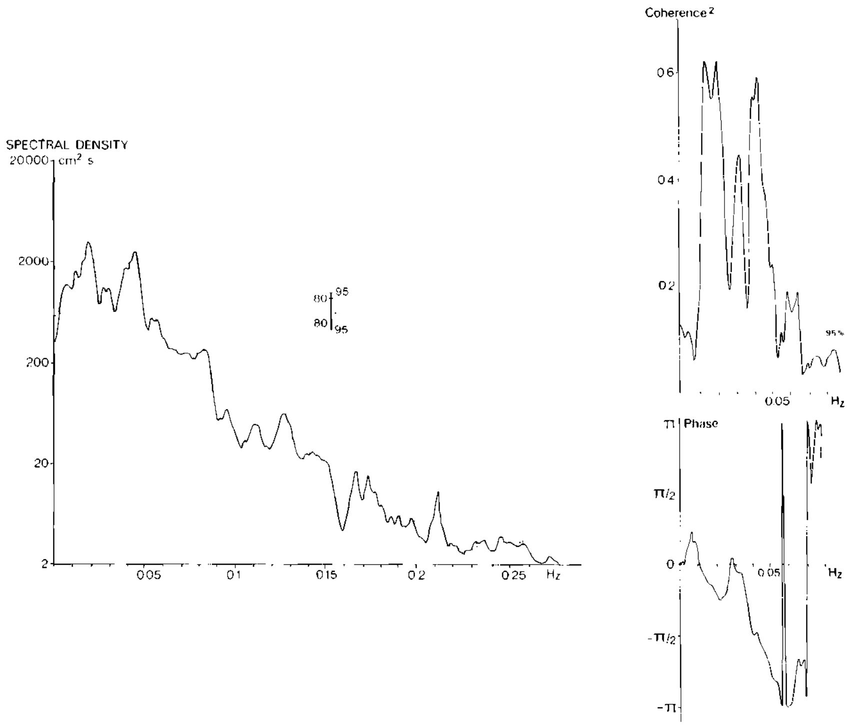

Figure 3. Energy, coherence and phase spectra from two transects (solid and dashed lines) during the storm 291188.

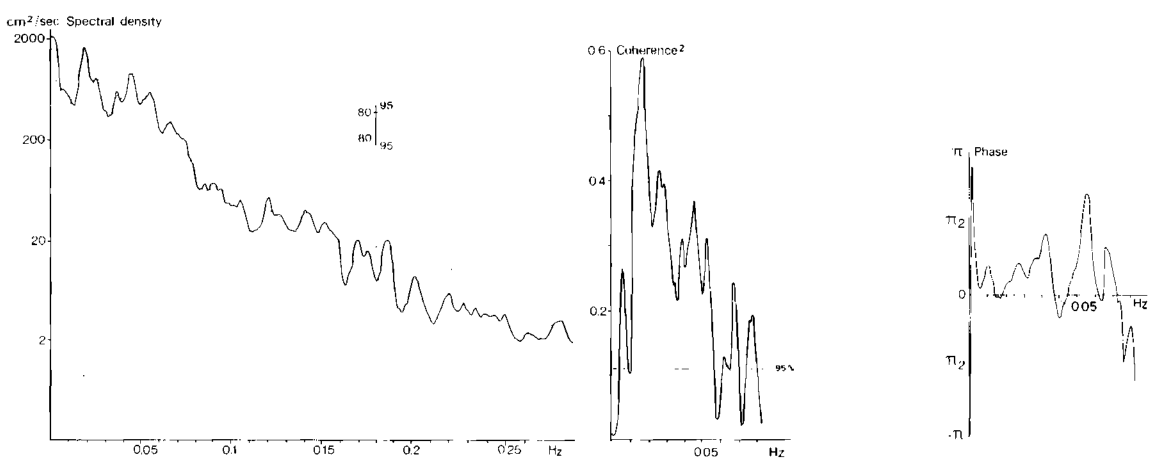

Figure 4. Energy, coherence and phase spectra from the 150987-storm.

energy represents leaky mode waves or, more likely (on account of the different spectral estimates) a standing edge wave.

Again, a low-coherency secondary peak occurs at 0.043 Hz (23 sec). Phases suggest a longshore progressive wave motion. The nature of these peaks is still somewhat of a moot point. They could be due to the retarding effects of the strong backwash on succeeding incident waves, the incident waves not being able to produce swash until the backwash has drained off the beach face (*e.g.* MASE, 1988). Alternatively, they might represent progressive edge waves or bounded long wave energy, incident from offshore. In fact, ongoing investigations seem to indicate that energy at 0.035–0.05 Hz may be present within the surf zone at Staengehus.

The ensuing survey (Figure 5) showed that bar positions were in good correspondence with theoretical positions of 54.5 sec mode 3 edge wave antinodes. Bar 2 was rhythmic with a longshore wavelength λ of 240 m (Figure 6), in the lower end of the range identified on air photos. Using the mean nearshore gradient in the survey area ($\beta = 0.0165$), predicted λ becomes 268 m. However, accounting for alongshore variations in the gradient ($\beta = 0.0154$–0.0168) and for the fact that FFT-resolution is ~1.5 sec at a frequency of 0.018 Hz, the possible λ-range becomes 236–288 m.

The outer bar was not rhythmic in form, even though its crestal position had a wavy outline, in phase with bar 2, thus suggesting the presence of standing edge waves of mode 3, or higher. However, the velocity field induced by these waves seems to have been insufficient in magnitude, or of too short duration to develop a rhythmicity of the outer bar.

The inner bar was rhythmic with $\lambda = 105$ m, which is also within the range commonly seen on air photos. This wavelength could not have been generated by the mode 3 edge waves. Two possible causes for this rhythmicity exist. One is that the inner-bar morphology was generated at a later stage of the storm, probably during its waning phases. The other is that it was generated by mode 1 edge waves during the height of the storm, this mode dominating the inner parts of the surf zone, while the mode 3 wave dominated the outer parts. This is theoretically possible as a mode 1 wave will decay quickly beyond the first antinode from shore, and a coexistence of a strong mode 1 wave and a weaker mode 3 wave could lead to a spatial segregation of modes. However, significant run-up spectral peaks only occurred at 54.5 and 23 secs. The spectral signatures certainly do not suggest that the higher-frequency peak should have been due to standing edge waves. Further, the rhythmic wavelength produced by mode 1 waves of either of these periods would be ~170 m and ~30 m, respectively, which is nowhere near what was in fact observed. It is therefore much more likely that a temporal segregation of modes occurred. The implications are that while the beach was in state 3a after the storm, the state could have been 2a at the storm peak.

The remaining field experiments all took place during more moderate energy conditions ($H_b = 0.9$–1.3 m) with incident wave periods of 3.9–4.5 secs. Infragravity wave frequencies were somewhat higher than on the occasions described above. However, in most cases spectral peaks were not statistically significant, and alongshore coherence was much lower than in the experiments conducted during storms.

An example of a spectrum sampled during moderate energy conditions on September 19, 1987 ($H_b = 1.3$ m, $T = 4.4$ sec) is shown in Figure 7. This experiment took place four days after the storm described above. Waves broke over the inner bar and the inner nearshore region was saturated. In this case, statistically significant low-frequency peaks did exist in the run-up spectra. Although overall coherence was disturbingly low, a spectral peak having a relatively high level of coherence and a zero-phase occurred at 0.021 Hz (48 sec); further, two peaks having low coherences and fluctuating phases are seen at 0.042 and 0.05 Hz. The 48-sec peak may represent a standing edge wave, while the latter two may be due to forced waves, progressive edge waves or swash/backwash interactions.

The ensuing survey on September 22 showed that the morphology of bars 2 and 3 remained generally unaltered through the September 19-event, apart from trough infillings and a smoothing of the irregular features on the third bar (Figure 8). The beach was still in state 3a. However, bar 1 had changed position, and the rhythms consisting of two prominent bar horns/megacusps at $x = 85$, 305 m, and the subdued horn/cusp at x ~200 m had been displaced since the September 17-survey. Rhythmic wavelength was thus $\lambda = 110$ m. As a morphological

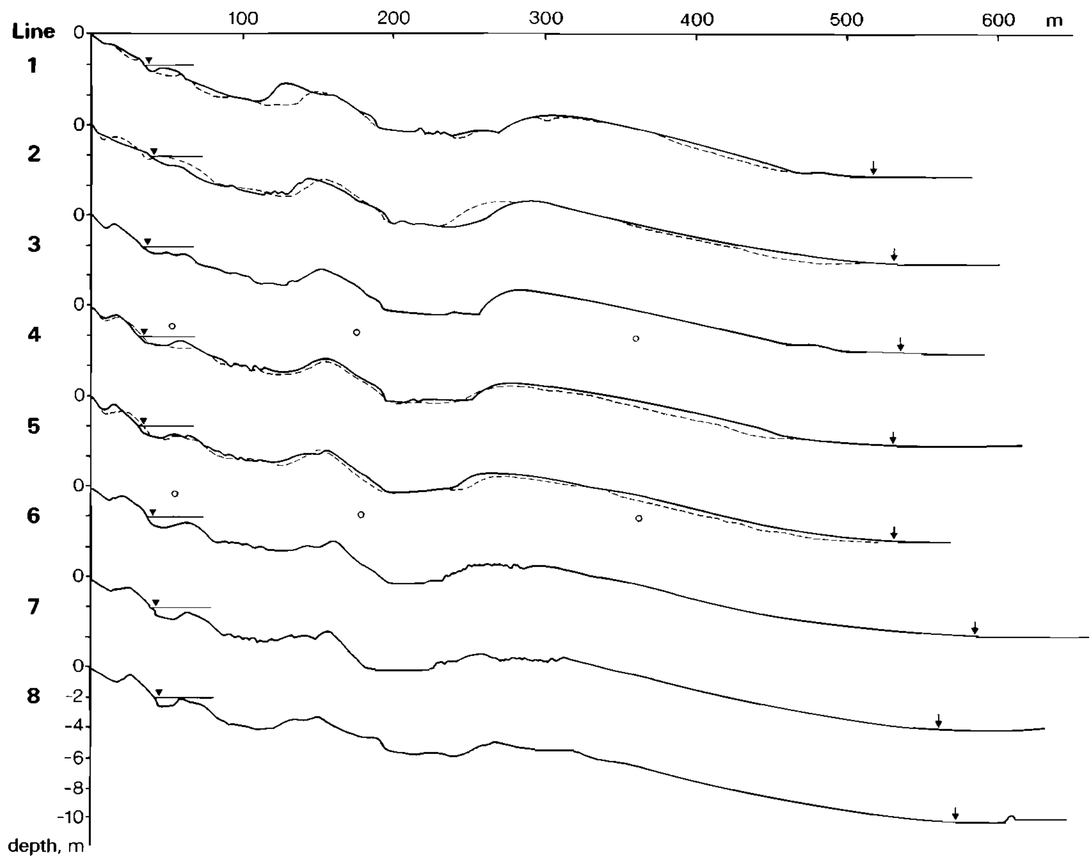

Figure 5. Profiles surveyed on 100987 (dashed lines) and 170987 (solid lines). Circles show theoretical positions of antinodes of the infragravity edge waves recorded on 150987. Arrows indicate the seaward limit of the nearshore profile. At this point, β tends to zero.

modification of the outer bars did not occur, it may be assumed that the standing edge waves, altering the morphology of the inner bars either was of mode 1 or that possible n> 1 waves were too weak to cause any morphological modifications of outer bars. A 48-sec mode 1 wave would generate a rhythm with $\lambda = 134$ m (using the mean inner nearshore gradient $\beta = 0.025$). Again, accounting for FFT-resolution (± 1.2 sec) and longshore variations in nearshore gradient ($\beta = 0.018$–0.030), the possible range becomes 92–170 m, while modes larger than $n = 1$ are impossible as they would produce significantly longer wavelengths. On the other hand, assuming that the 0.042–0.05 Hz peaks did in fact represent standing edge waves (which is at odds with spectral signatures), $n = 2,3$ combinations would yield wavelengths of 28–93 m. The only reasonable combination thus seems to be $n = 1$, $T_e \sim 48$ sec.

The correspondence between the observed and predicted (from $\bar{\beta}$) is, however, not very good. Reasons for this may be due to difficulties in determining the inner nearshore gradient, as this is very variable alongshore due to the rhythmic topography. Alternatively, bar adjustment during the September 19 event may have been incomplete due to the rather low energy conditions. Thus morphological lag may have occurred.

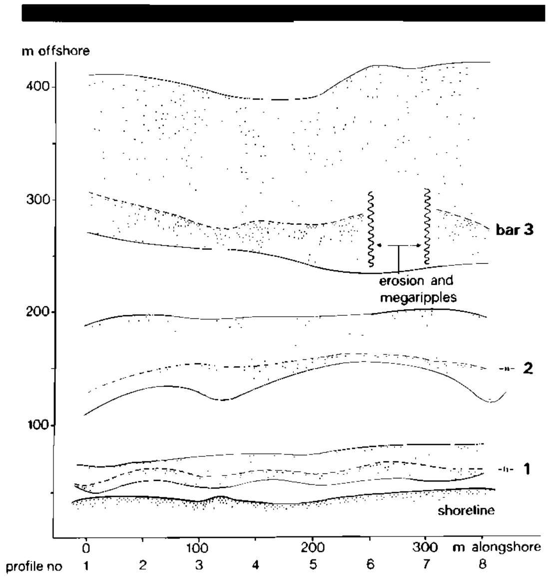

Figure 6. Configuration of bars on 170987. Dashed lines represent bar crests while the solid lines show the outline of the bars.

DISCUSSION

The results from the present study suggest that at this locality, the occurrence of edge wave modes is temporally, and not spatially segregated. As the maximum surface expression of edge waves is at the shoreline where the measurements were made, problems associated with sensor location relative to edge wave offshore structure are avoided. On occasions where instruments are located in the surf zone, particular modes might be invisible to a given instrument if this is situated close to a standing wave node.

During the events reported here, it appears that only one statistically significant and coherent edge wave mode dominated a given spectrum with mode 3 waves (T_e ~50–55 sec) occurring during high-energy conditions, and mode 1 waves (with a slightly higher frequency) during moderate-energy conditions. Significant energy also occurred at periods between 20–28 seconds. However, coherence was generally low and, as argued above, this energy could represent a variety of physical phenomena. The only wave type which could apparently be disregarded was a standing edge wave.

The dominance of mode 3 waves during storms, and mode 1 waves during lesser energetic conditions may be the reason why bars 2 and 3 are remarkably stable in position along this stretch of coast (AAGAARD, 1988). Adjustments of their position and morphology occur during storms when they are influenced by high-mode edge waves. Between storms, outer bars only migrate very slowly shorewards under the influence of incident wave asymmetry. Due to the absence of long-period swell, these bars are arrested in position for most of the time, as the energy level is too low to move them shoreward. Bar 3 in particular is extremely stable in position; this bar is probably in a state of long-term equilibrium with environmental conditions.

Aerial photographs and the limited field evidence indicate that bar 3 is usually linear in plan form, while bar 2 is commonly rhythmic. The reasons may be that during very intense storms, the edge waves seem to be progressive. Such edge waves would be expected to produce linear bar features (beach state 1). During more moderate storms (and during the decline of intense storms?), edge waves are probably standing producing beach states 2a or 3a, depending upon the edge wave mode number generated. Field evidence suggests that the drift velocity field associated with these standing edge waves may be insufficient to produce a rhythmicity of bar 3 (while the crest of this bar may still be slightly rhythmic). However, the magnitude of the velocity field is still adequate to form a rhythmic bar 2, this bar being situated at a lesser depth. The above sequence of events could thus account for the different morphology of bars 2 and 3.

An interesting problem is why edge waves are standing during moderate storms, while they appear to be progressive during intense storms—or rather, why they are phase-locked in the former case while not being so in the latter. Some research on phase-locking of edge wave modes has been carried out recently by *e.g.* HAINES and BOWEN (1988) and HUNTLEY (1988), but this particular problem has not yet been solved.

Bar 1 is situated at a much smaller depth than the outer bars and therefore it displays a much more dynamic behavior. Its position and morphology may become altered under the influence of mode 1 edge waves during moderate-energy conditions and during the decline of storms (the lower mode and the higher fre-

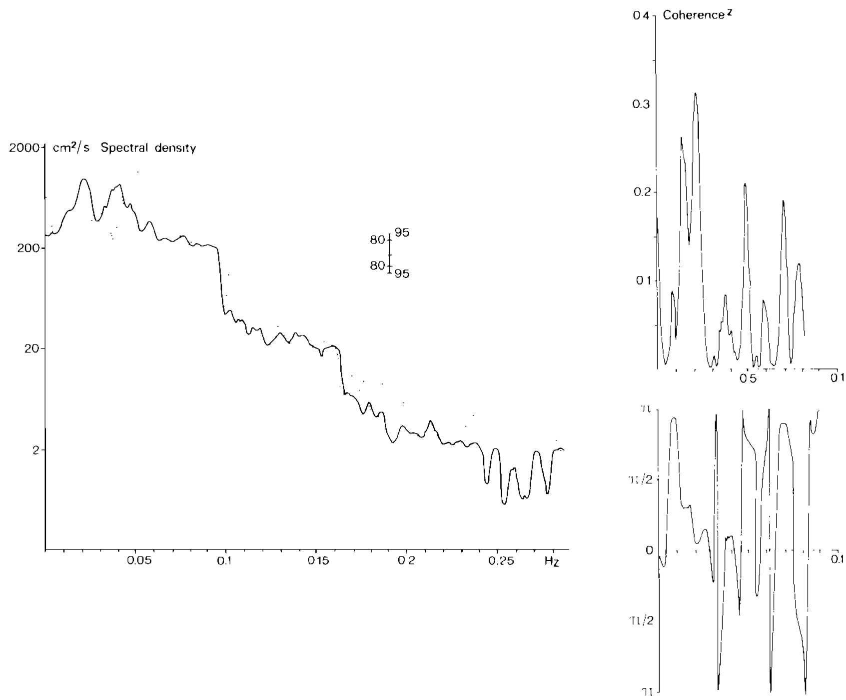

Figure 7. Energy, coherence and phase spectra from 190987.

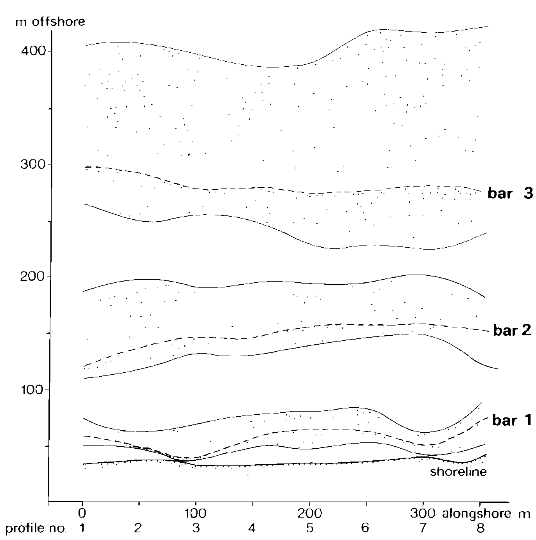

Figure 8. Configuration of bars on 220987.

quency of these waves accounting for the smaller rhythmic wavelength generally seen on this bar). The bar also migrates shoreward much more readily than outer bars (AAGAARD, 1988). While the morphology of the inner bar probably resembles bars 2 and 3 during storms (whether being linear or rhythmic, corresponding to beach states 1 or 2), this is not generally reflected by air photos or by field experiments. However, this is what would be expected, as photography and surveys are only conducted during low-energy conditions. As the energy threshold required to modify the morphology of bar 1 is much lower than that required at the outer bars, it is quite reasonable that the morphology of the inner bar generally differs from that of outer bars.

Beach states 4a and 5a only occur after prolonged periods of onshore inner-bar migration. Edge waves probably play no significant part in the development of these states. However, when a storm sets in, the beach will reverse to one of the higher states (1, 2 or 3), the state depending upon the edge wave mode generated, *i.e.* upon the intensity of the storm.

As argued above, it seems that only one statistically significant and coherent edge wave mode dominates at a given time at this locality. It was argued by AAGAARD (1990) that edge wave frequencies during storms could be selected by a cut-off mechanism (HUNTLEY, 1976), this being due to a slope break situated some 530 m offshore at this site. The cut-off edge wave period is given by

$$T_e = 2\pi(x_s/g \tan\beta \, \chi_{min})^{1/2}$$

with x_s being the distance from the shoreline to the slope break, β is the nearshore gradient and χ_{min} is given by

$$\chi_{min} = 3.5 \, n \, (n+1)$$

(HUNTLEY, 1976). Mode 3 cut-off waves would thus have periods of ~54–58 seconds at this site (β = 0.015–0.017; x_s = 520–540 m). Those periods are similar to what was actually recorded during the storms.

Under moderate energy conditions like those encountered on September 19, edge wave frequency could not have been selected by the slope break as this would yield a period of 135 sec (n = 1). It has been suggested by SYMONDS and BOWEN (1984) and WRIGHT *et al.* (1986) that preexisting bars might be able to preferentially select edge wave periods during moderate-energy conditions, the edge waves having antinodes at the bar crest. This mechanism could not have selected the period on September 19, as a mode 1 wave with antinodes at the shoreline and the bar crest would have a period of 30 sec which is obviously too short. An alternative explanation for the preferential selection on September 19 could be that the prominent second bar (Figure 5) might act as a barrier to offshore edge wave propagation, in combination with the $\beta = 0$ condition at the inner edge of bar 2. Thus a cut-off edge wave (n = 1) might become trapped shoreward of bar 2, much in the same way as an n = 3 cut-off wave would be trapped shoreward of the slope break at x ~530 m during storms. A cut- off period (n = 1) shoreward of bar 2 would have been T_e ~45 sec on September 19, in quite reasonable agreement with what was recorded.

Another interesting question is why n = 3 waves occur during storms, while the edge waves are of a lower mode with lower incident waves. In the former case, the surf zone is wide and the edge wave forcing region is situated far from shore. It would be logical to assume that the edge waves would have a higher mode number under such conditions, the exact number perhaps being influenced by the number of preexisting bars shoreward of the forcing region. An alternative possibility is that the edge wave generating mechanism, *i.e.* the wave groups are instrumental in the selection process. AAGAARD (1990) has argued that in theory, wave groups might be sufficiently narrow-banded in frequency, only being able to generate edge wave resonance within a reasonably narrow frequency band at this locality. An interaction between wave groups and the cut-off could narrow down the number of possible (cut-off) edge wave modes. However, this is still very speculative and the problem will be a topic of future research.

This paper has attempted to provide correlations between predicted and observed rhythmic wavelengths of bars. While these correlations have been reasonably satisfactory, they are certainly not perfect. Predictions based on peak spectral period and mean nearshore slope are somewhat larger than what was observed. Several reasons for the deviations may exist. One is due to the fact that bar adjustment is never instantaneous. When environmental conditions change there will always be a certain lag in the morphological response. Another reason is that spectral resolution is 0.00049 Hz, corresponding to roughly ± 1.5 seconds at the periods considered here. Thus some uncertainty exists as to the exact peak period. A further factor of potentially greater importance lies in the determination of the nearshore slope. For one thing, this slope varies somewhat alongshore. Besides, in a barred environment several methods could be employed to determine the slope. In the present paper, the mean slope between the shoreline and the slope break, denoted by arrows in Figure 5, has been employed in the mode 3 calculations. An alternative is to use the method suggested by HOLMAN and BOWEN (1979) which yields near- similar estimates (AAGAARD, 1990). However, until satisfactory procedures have been determined for the computation of mean beach slope in a barred environment, any exact correspondence between predicted and observed morphological length scales is probably fortuitous.

ACKNOWLEDGEMENTS

This study was supported by the Danish Natural Science Research Council through grant nos. 11-6853 and 11-8164. Figures were drawn by John Jønsson, while Morten Rasch and Kim Bøge assisted in the field. Thanks are due to an anonymous reviewer whose helpful comments significantly improved the contents of the paper.

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□ RÉSUMÉ □

Par l'analyse de photos aériennes d'un site à barres multiples du Danemark, on a pu distinguer 8 types différents de barres prélittorales. Cela a servi à établir un modèle d'états des plages pour les systèmes à barres multiples d'environements protégés. La barre interne montre une évolution semblable à celle d'une plage à une seule barre du modèle de plage de WRIGHT et SHORT (1983, alors que la morphologie des barres externes varie selon le cas. Du point de vue de la morphologie et de la dynamique, les barres externes ont des formes fixes sur de longues périodes. Les études de terrain on montré que la morphologie de la barre était fortement influencée par le bord de l'onde d'infragravité. Au moment de fortes tempêtes, des ondes progressives se produisent, par de plus faibles tempêtes, ce sont des ondes stationnaires. Dans les deux cas, un mode unique domine le spectre d'énergie de la houle. Les longueurs d'onde au large et à la côte de ces houles correspondent assez bien avec la répartition des barres. Pourtant, dans ce cas, la fréquence des houles était plus élevée et leur mode plus bas, ce qui a pu produire les rythmes à petite échelle de la barre interne. Les barres externes ne répondent qu'aux conditions d'énergie les plus fortes et la plus mobile des barres internes a un seuil d'énergie plus faible.—*Catherine Bousquet-Bressolier, Géomorphologie EPHE, Montrouge, France.*

□ ZUSAMMENFASSUNG □

Eine Analyse der Luftaufnahmen von Lokalitäten mit zahlreichen Sandbarren in Dänemark ergab die Existenz von acht verschiedenen Typen solcher Barrensysteme im strandnahen Bereich. Auf diesem Hintergrund wird ein Vorschlag erarbeitet für ein vorläufiges zustandsmodell für Strände mit Mehrfachbarren in geschützter Lage. Die innere Bank zeigt eine Entwicklungstendenz ähnlich dem ozeanischen Strandmodell mit Einzelbarren von WRIGHT & SHORT (1983), während die Morphologie der äußeren Barren sich stärker verändert. Darüber hinaus ist festzustellen, daß die äußeren Sandbänke morphologisch und dynamisch längere Zeit unverändert liegen können. Feldstudien haben gezeigt, daß die Sandbankmorphologie durch infragravitative Brandwellen stark beeinflußt sein kann. Während eines intensiven Sturms bilden sich meist fortschreitende Brandungswellen, bei einem weniger intensiven Sturm sind es eher ortsfeste. In beiden Fällen wird das Energiespektrum bestimmt vom Modus einer einzelnen Brandungswelle. Die Ausmaße dieser Welle seewärts und parallel zum Strand sind ziemlich deckungsgleich mit dem Muster der Sandbänke. In Regionen mit geringerer Wellenenergie treten stationäre Randwellen auf. In diesen Fällen haben die Wellen jedoch eine größere Häufigkeit und geringere Ausmaße, worauf wahrscheinlich die geringeren Dimensionen der inneren Barren zurückzuführen sind. Äußere Sandbänke sind daher vornehmlich das Abbild sehr großer Energieentfaltung, während die innere Bank mit einem geringen Energieniveau zusammenhängt.—*Dieter Kelletat, Essen, Germany.*