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# Recent Changes of the Coastline and Nearshore Zone, Vejrø Island, Denmark: Possible Consequences for Future Development

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**ABSTRACT**

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This case study deals with coastal changes and their causal relationships. The study site is the island Vejrø situated in the Kattegat, the gateway between the North Sea and the Baltic. The observation period is 1954 to present. The small island presents different kinds of coastal types: bluffs fronted by narrow beaches, a low relief foreland of beach ridges, and a partly submarine, sandy and gravelly spit. In recent decades erosion has dominated on most of the coastal sections. The erosion is ascribed to natural as well as man-induced processes. These results from: An increase of the wind energy, higher frequency of strong winds, rise of the mean sea level, larger variability of the sea level, and dredging of raw materials from the outer spit area. A prediction of future coastal development is hampered, among others, by a break in coherence between sunspot activity and wind energy, coinciding with enhanced rise of sea level since mid 1970's.

**ADDITIONAL INDEX WORDS:** *Sunspot activity, changing wind climate, accelerated sea-level rise, dredging.*

## INTRODUCTION

"Coastal changes and their causal relationships" is a topic, which has been a subject of much interest in recent time. This is not surprising, when focusing on the animated debate on increasing greenhouse effects. These are, amongst others, changes in the wind climate and a rising sea level, which may both have consequences for the coastal development. Moreover, the dredging of raw materials from the sea bottom for *e.g.* building materials and beach nourishment, can affect the coastal development as well. Some studies have focused on the coastal development particularly with reference to changes in the wind climate (CHRISTIANSEN and BOWMAN, 1990; NIELSEN, 1990; SCHEFFNER, 1989), while others have studied the effects caused by sea level changes (BIRD, 1993; CARTER, 1982; CHRISTIANSEN and BOWMAN, 1986; CHRISTIANSEN *et al.*, 1985; GORNITZ and KANCIRUK, 1989; HUISKES, 1990; JELGERSMA *et al.*, 1993; ORFORD *et al.*, 1991; SIEFERT, 1990), or different climatic changes (KUHN and OSBORNE, 1989, MISDORP *et al.*, 1990).

In 1991 the Danish National Forest and Nature Agency (NFNA), which administrate "The Raw Materials Act," initiated an investigation on the possible effects of dredging of near-shore materials on nearby coastal stretches. The island Vejrø was chosen as target area for the case study.

A study of the historical coastal changes was based on aerial photographs and old maps. A detailed hydrographic survey including grain-size analysis, wave refraction patterns and sediment mobility in the spit area was carried out by NFNA. Results of the case study have previously been reported in BINDERUP (1991a, b), NFNA (1991) and CHRISTIANSEN *et al.* (1992). These papers focus on the effects of a changing wind climate and nearshore dredging, primarily concerning the spit area. Sea level variations have been reinterpreted since (BINDERUP and FRICH 1993), while the wind climate is further analysed.

The purpose of the present paper is to report on changes along the coast of the island Vejrø and their causal relationship. Possible future shoreline displacements are discussed as well as the link between sunspot activity, the wind energy and the sea level variations.

## ENVIRONMENTAL SETTING

Vejrø is a small uninhabited island of about ½ km$^2$, situated in the southwestern part of the Kattegat, Figure 1. The semidiurnal tide is only 0.3–0.4 m (CHRISTIANSEN *et al.*, 1992), while meteorologically induced sea level variations can range between +1.9 and −1.5 m DNN (Danish Ordnance Datum, CHRISTIANSEN *et al.*, 1985; CAPPELEN *et al.*, 1989). Generally, long-lasting westerly winds force the water from the North Sea into the Kattegat and the Belts and produce high sea levels, while corresponding easterly winds produce low sea levels.

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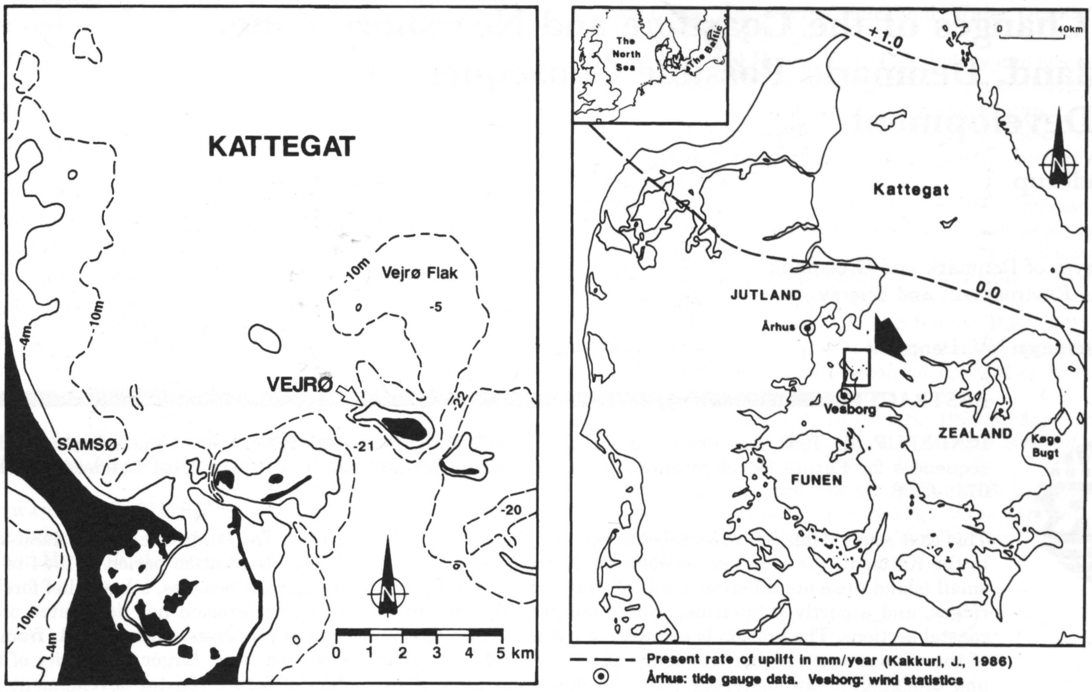

Figure 1. Location Map. Left: Regional setting of Vejrø. Right: an overview.

The postglacial isostatic rebound of the region is less than the eustatic sea level rise, resulting in a rise in the relative mean sea level. The rate of sea level rise is known from tide gauge data from Århus (Figure 1). The rise was only +0.06 mm/year in the period 1944–1973, while a fast sea level rise of +4.46 mm/year characterized the period from 1974 to 1990. This situation is not a special phenomenon for Århus tide gauge station. Almost exactly the same values are found from analyses of data from five other mareograph stations in the interior Danish waters (Binderup and Frich, 1993).

Wind climate analysis is based on data from Vesborg Lighthouse, situated 20 km SW of Vejrø (Figure 1). The total wind energy (all directions, more than 4 B, Beaufort Scale) has varied throughout the last century. The high values are found in the first quarter of the century and again recently, from 1960 onwards. A tendency of higher cyclonic activity during the last three decades is reported by Abild and Nielsen (1991), and the post 1960 rise in wind energy is known from Bergen, Norway too (Paetzel and Schrader, in Paetzel, 1993), as is a change in the prevailing wind direction in NW Jutland (Christiansen and Bowman, 1990). The period from 1925 to 1960 was characterized by a calmer although varying, wind climate (Figure 2). The energy of the strong winds (more than 9 B) follows the same pattern, except for the period 1930 to *c.* 1970, when the frequency of strong winds was very low.

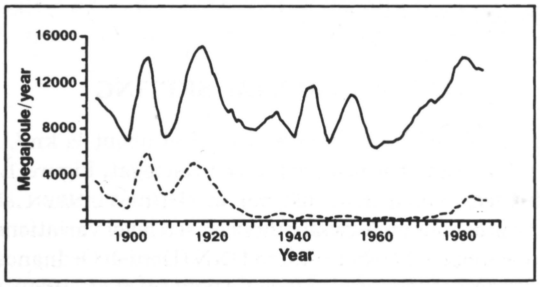

Figure 2. Wind energy at Vesborg, Samsø (see figure 1 for location). Solid line: Sum of wind energy from all directions, ≥4 B (Beaufort Scale). Dotted line: Sum of wind energy from all directions, ≥9 B. Both curves: 5 year running mean.

## Geomorphology of Vejrø

A core of clayey till and fluvio-glacial deposits form the largest part of Vejrø. The north facing coast is an erosive, almost straightlined sea cliff, oriented W–E (Figure 3), with a maximum height of 22.5 m DNN. In the eastern part of the island an old inactive bluff is surrounded by a foreland of beach ridges, partly vegetated. Toward the south and southwest another sea cliff is found. The southern part is erosive and alined, about 10 m high and oriented WNW-ESE. Where the cliffs are erosive, the beaches are very narrow. Most of the southwest facing bluff is overgrown, inactive and fronted by a few beach ridges. A partly submarine, sandy and gravelly spit extends toward northwest. The geology and sedimentary composition of the spit is known from a coring in the NW part of the submerged spit. The coring indicated, that a basement of till is overlain by a 5 to 10 meter thick layer

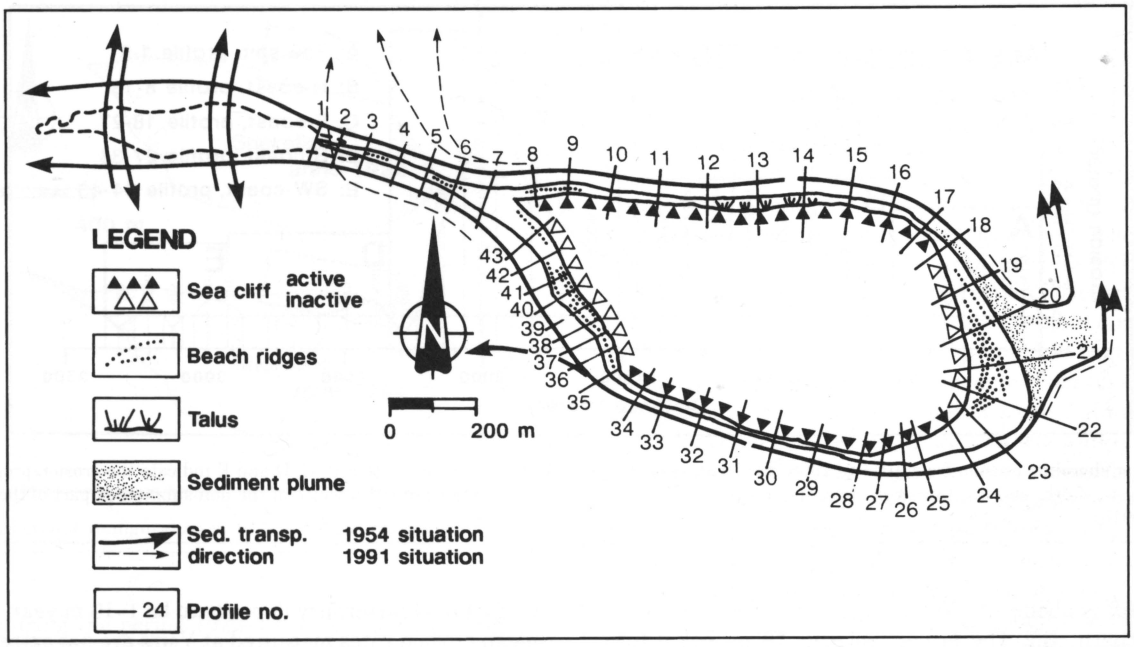

Figure 3. Geomorphology of Vejrø. Sediment transport direction is shown for two situations. The thick arrows illustrate the 1954 intact situation, while the dotted arrows indicate the 1991 situation, after the spit has been destroyed and eroded. In situations with strong wind and waves from northwest a sediment plume is seen east of the island on aerial photographs. It turns sharply toward the north and can be followed in this direction for more than one kilometer. (After Binderup, 1991a and NFNA, 1991).

of marine sand, gravel and stones of postglacial age (NFNA, 1987). These sediments most likely cover most of the spit area, and derive primarily from the erosion of Vejrø. Presumably, most of the sedimentation took place concurrently with the Littorina transgression and continued, but with a lower rate, since then. In the uppermost part of the submerged spit a narrow zone of gravel occurs, but on its flanks, the sediment is medium to coarse sand (NFNA, 1991).

## METHOD

Coastal changes in the period 1954 to 1988 are detected with a Peak Scale lupe (15×, scale 0.1 mm engraved) on aerial photographs from 7 years. All photos were corrected for distortions and enlarged to approximately 1:5,000. So, the accuracy of measurements is within ±5 meters. However, the accuracy of the displacement calculations is depending on changes in sea level and the beach slope, and these parameters are not known. Unfortunately the scale is slightly different from photo to photo. For this reason, and because the lack of any reference points in the northern and the southern part of the island, it was only possible to calculate the net shoreline displacements and the net cliff erosion. In the western and eastern part of the island several reference points made it possible to calculate the coastal changes between the years of the photographs. The topography is known from maps (scale 1:25,000), with contour intervals of 2.5 m.

The different kinds of coastal types presented at Vejrø demand the use of different methods to analyse the coastal changes and their causal relationships. These are descriped in further detail in the individuel sections.

## RESULTS

### Net Shoreline Displacements

The net shoreline erosion was determined in 43 locations. The results are outlined in Figure 4. The northern and the eastern shoreline have receeded markedly, by a maximum of 30 and 66 m, respectively. In contrast, the southern and the south-western shoreline seem to have been almost stable throughout the period. In 1988 the distal part of the spit is narrow and more than 100 m shorter than in 1954. But the proximal part of the spit seems to be unaltered. The total area of erosion calculated in this way is 50,200 m², the area of progradation is only 650 m², which give a net loss of approximately 49,550 m².

### Sea Cliff Erosion

The 1954–88 net erosion of the north and south facing cliffs has been calculated by measuring the retreat of the cliff top edge, which may be a usefull shoreline indicator when monitoring changes of shorelines characterized by high cliffs (CROWELL *et al.*, 1991). These measurements included section 9–18 and 27–35. The altitudes of the cliffs are known from maps, and the overall geometry of the cliff-fronts are assumed unaltered from 1954 to 1988 (SUNAMURA, 1983, 1992).

The results are shown in Figure 5. The total erosion of the

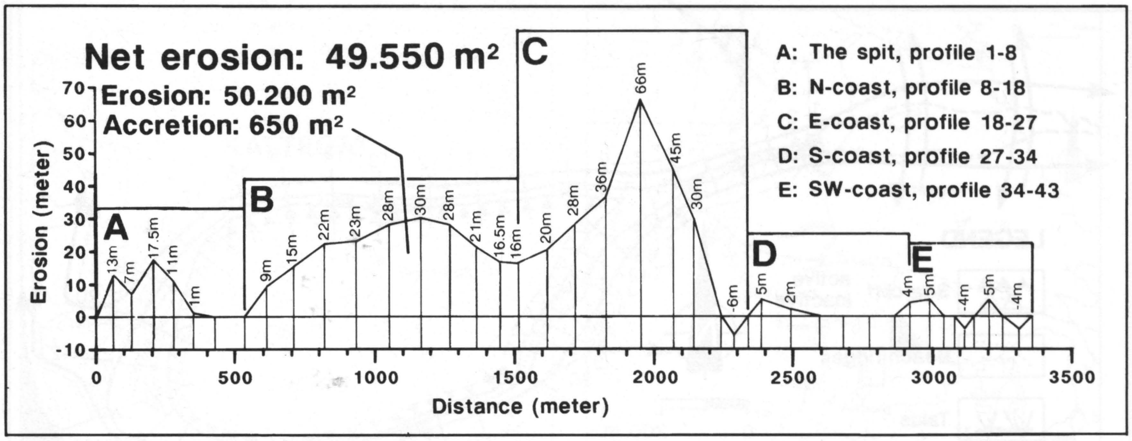

Figure 4. Net shoreline erosion from 1954 to 1988. For location of the profiles, see Figure 3. Section B, C, D and E indicate the erosion/progradation of the north-, east-, south- and southwestern shoreline, respectively. Section A indicates the changes in width of the non-submerged part of the spit. (After Binderup, 1991b).

northern cliff is about 193,300 m³, while it is only 18,800 m³ in the southern cliff. The largest retreat, 19 m, equal to a mean value of about 0.5 m/year, took place in section 13–15, where the highest bluffs are found.

The largest retreat of the southern cliff of Vejrø was only about 6 m, or approximately ⅓ of the northern cliff retreat. These retreat rates support the correctness of the above described pronounced receeding northern shoreline and an almost stable southern shoreline in the same period.

The recession rates of the northern sea cliff are comparable with the long-term retreat rates of 0.3–0.4 m/year found at the low-energy coast near Kilkeel, Northern Ireland (McGreal, 1979). According to Komar (1976) cliff erosion rates in general appear to be less than 1 m/year, while Sunamura (1983) found the generally expected erosion rates of cliffs formed in Quarternary deposits to be 1–10 m/year. Thus, the mean erosion rates measured at Vejrø are not extreme in any way.

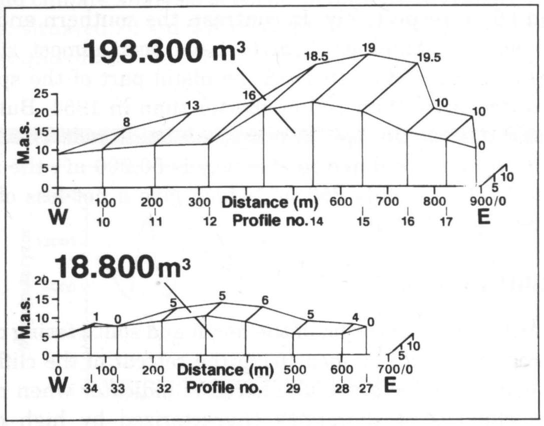

Figure 5. The 1954 to 1988 erosion of the north (top) and south facing (bottom) sea cliff. All figures in meter. Exaggerated 12 times. The profile numbers are indicated beneath the X-aces, the altitude of the cliff-fronts can be read by the Y-axes. The retreat of the cliff-top in each profile is shown by the thick diagonals and the numbers in top of these.

Natural and man-induced cliff-forming processes are numerous (Sunamura, 1992), but the main factors governing cliff-toe erosion are the resisting force of the bluff material and the assailing force of the waves at the cliff foot (Sunamura, 1983).

According to Houmark-Nielsen (1987) the stratigraphy of the northern bluff consists of an alternation of glacial clayey tills and meltwater deposits of varying grain-size, with marine Eemian clay and silt intercalated in the lower part of the section. More than half of the cliff-front is formed by sand and coarser materials which is less resistant than massive clayey till. The alternation of fine and coarse grained materials throughout the profile presumably promotes groundwater seepage. This may locally enhance erosion of these layers (Komar and Shih, 1993). Finally, the presence of thrusts and folds in the glacial sequence might cause further instability of the cliff-fronts. Thus, the overall impression is that the sea cliffs at Vejrø are easily erodible, but no measurements of the geotechnical proporties exists.

The recession rates, the steeply sloping and non-vegetated cliff-faces, and the narrow beaches in front of the cliffs of Vejrø indicate (according to theory by Emery and Kuhn, 1982) that active marine erosion rather than subaerial processes dominate coastal erosion here.

On the long term, there are natural as well as anthropogenic causes for the sea cliff erosion at Vejrø. The most essential natural causes are a change in the wind climate with more energy and a higher frequence of stronger winds, and sea level rise. Erosion is particularly promoted by wave convergence around a headland. Unfortunately it is not possible to separate and quantify the respective contributions of these processes from one another.

From earlier analysis of maps and aerial photos (Binderup, 1991a) it is known, that both sea cliffs receeded some

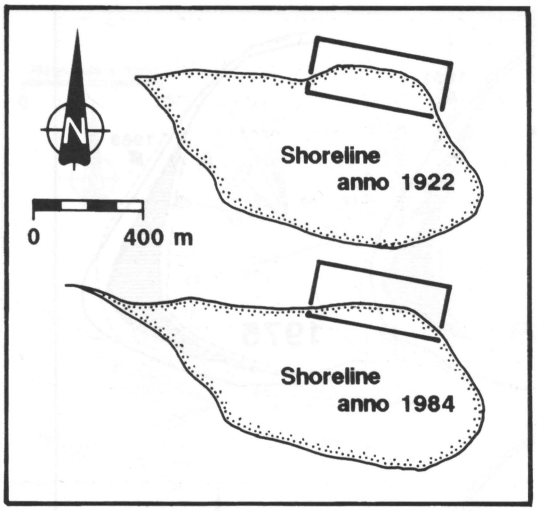

Figure 6. Shoreline configuration in 1922 and 1984 respectively.

20–30 m during the period 1922–1954. As seen from Figure 6, the configuration of the northern shoreline was characterized by a large headland 70 years ago, while the southern sea cliff was already linear. A larger part of the headland disappeared from 1922 to 1984, probably because of erosion from wave convergence due to refraction at the headland, a process which has been well described (KOMAR, 1976, 1983; CARTER, 1988; SUNAMURA, 1992). From the analysis of bluff erosion during the period 1954–1988 the largest recession rates are found where a minor bulge of the shoreline still exists, while erosion of the south facing coast was unsignificant. The difference in shoreline configuration between the north and south facing sea cliff is thougth to be the main reason for the distinct difference in recent erosion rates.

There has been a steady rise in the wind energy from 1960 to the mid 1980's in the W-, NW-, SW- and SE-erly directions (Figure 7A and C), and from the late 1970's onwards a marked rise in the frequence and/or duration of strong winds from W and NW (Figure 7B). From 1970 the frequence of strong winds from SW was rising to (Figure 7D). So one should expect an intensified erosion of both sea cliffs from 1960 onwards, and especially since the late 1970's because higher waves have been more frequent. Nevertheless, the south facing sea cliff remained almost stable during the period 1954–1988. The reason for this could be that winds from southerly directions normally cause low sea level in the region, causing the waves to break at some distance from the sea cliff. Otherwise, winds from westerly and northerly directions generally cause high sea level, favouring the storm waves to reach the cliff without losing much energy. This is another major reason for the difference in the erosion rates.

It is widely documented, that sea level rise cause an accelerated erosion rate of sea cliffs (SUNAMURA, 1992; BIRD, 1993). Because the erosion rate is depending on many factors, there is no simple relationship between the size of the sea level rise, and the quantity of sea cliff erosion. Therefore it is not known, how much erosion the sea level rise of c. 7.7 cm from 1954–88 (BINDERUP and FRICH, 1993, Table 3) actually caused.

The anthropogenic causes for the sea cliff erosion of Vejrø are quite atypical. Formerly, the cliffs were used as military targets for shells fired from naval vessels. The start of these activities is unknown, but it has ceased now. From c. 1920 to c. 1960, when cattles were grazing at Vejrø, the overhanging

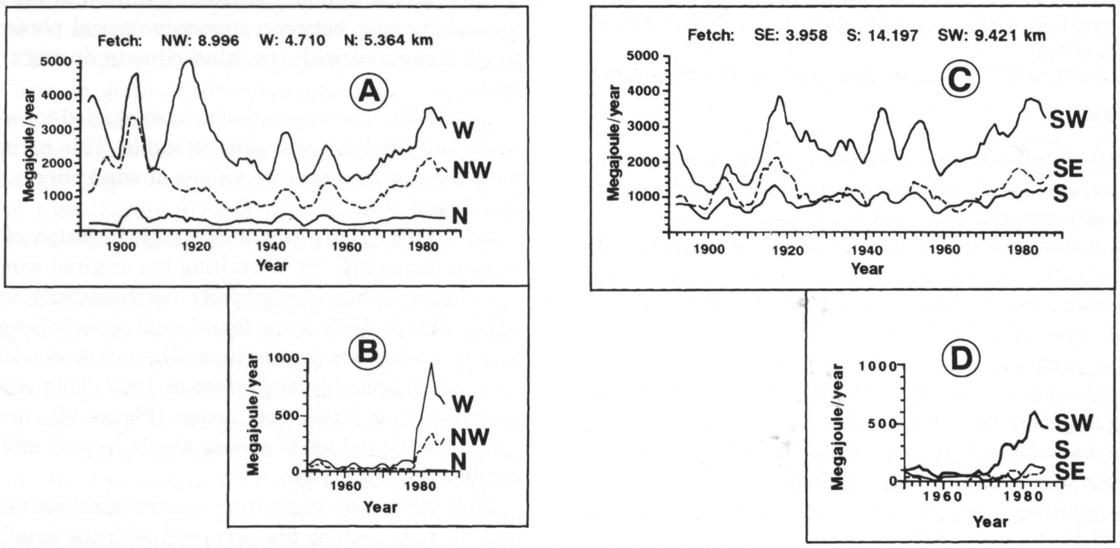

Figure 7. Wind energy and the mean effective fetch. A and B: The directions concerning the north facing sea cliff; the sum of wind velocity ≥4 and ≥9 B, respectively. C and D: The directions concerning the south facing sea cliff; the sum of wind velocity ≥4 and ≥9 B, respectively. All curves: 5 year running mean of data.

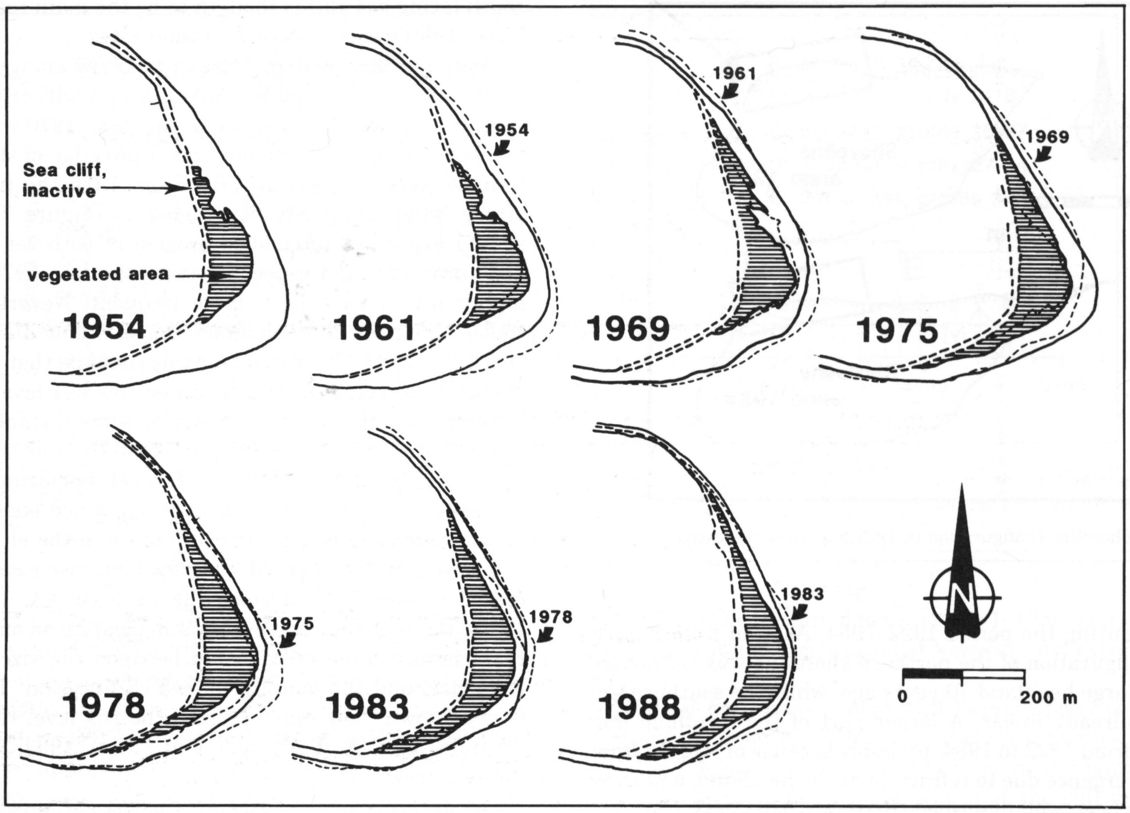

Figure 8. The 1954 to 1988 evolution of the shoreline and the vegetated part of the marine foreland, on the eastern part of Vejrø. (Partly from Binderup, 1991b).

parts of the cliffs were broken off to avoid the cattles from falling down the cliffs (H. Christoffersen, personal communication 1991). It is unquestionably that these activities have caused an erosion of the sea cliffs, but it is not possible to quantify the effect.

## The Foreland

The inactive bluff and beach ridges and small ponds constitute a system of bench-marks for measuring coastal changes on sequential aerial photographs.

The high water line (HWL) has been demonstrated to be the best indicator of the land-sea interface for historical shoreline comparison studies (CROWELL *et al.*, 1991). But the HWL is not expected to be constant. The position of HWL is depending on profile slope, wave period, tide and meteorologically induced sea level variations (CHRISTIANSEN, 1985), the latter being important in the Kattegat. An other problem concerning the use of the HWL or WL is, that the long term trend of beach width might be misleading, *i.e.*, identical beach width may manifest very different coastal trends (CHRISTIANSEN and BOWMAN, 1990).

To avoid these problems, it was decided to use the frontline of the vegetated area as the principal indicator of coastal changes in this part of the island. The position of the frontline reacts immediatly to erosion. In case of coastal accretion a timelag has to be considered. The timelag is less than 3 years in this area, as can be seen from the photos. But it might be as short as one summer season. In the following, the detected coastal changes between successive aerial photos are tentatively compared with the wind climate during the same periods.

**1954–1961.** The vegetation area expanded toward E and SE while the NE-limit was almost stable. This agrees very well with the low to moderate values of wind energy, Figures 9A and B and 10A.

**1961–1969.** There was a distinctive erosion of the coastal section facing NE. By consulting the original wind data some very large values of especially north-easterly wind in February–March 1969 were found, and it is believed, that the erosion took place at this time. The minor erosion at the SE coast most probably took place in 1967. This year was characterized by a large wind action (Figure 9B) from SSW but also by large values of strong winds from S and SW in November the same year.

**1969–1975.** The vegetation was reestablised along the NE and SE coast, which fits very well with the small to medium sized wind energies, Figure 9B and C and 10A. The long 1969-wind vector (Figure 9B) is primary caused by large February–March wind energies, and therefore prior to this period.

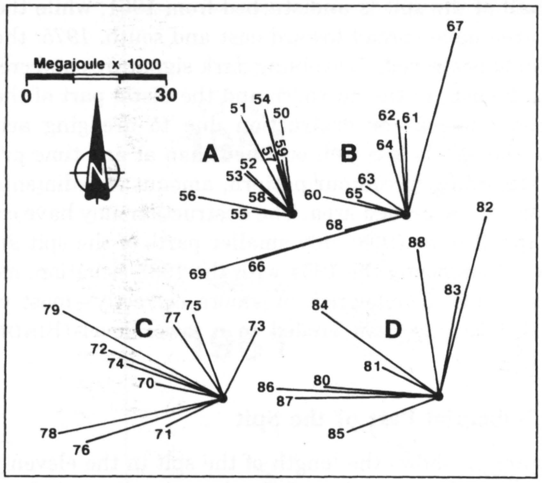

Figure 9. The resulting wind energy vector for each year, 1950 to 1988, compiled for the eastern shoreline at Vejrø. All velocities ≥4 B and all directions are included in the calculations. The energy from each wind direction has been multiplied with the mean effective fetch prior to the final calculation. A: 1950–1959. B: 1960–1969. C: 1970–1979. D: 1980–1988.

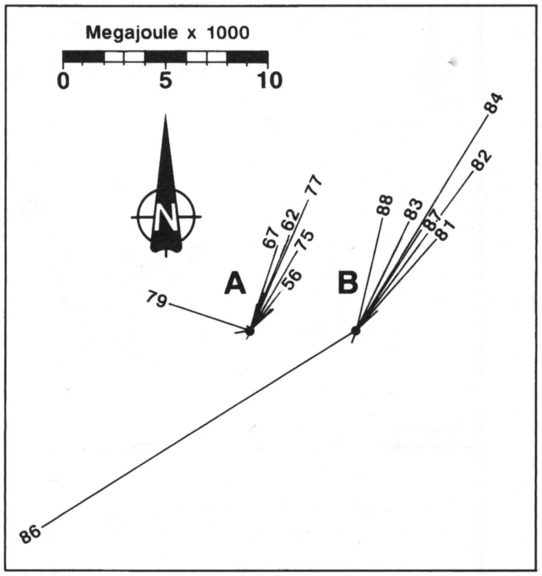

Figure 10. As figure 9, but only the wind velocities ≥9 B are included in the calculations. A: 1950–1979. B: 1980–1988.

**1975–1978.** The vegetation slightly expanded in the NE section in spite of a medium to large vector from ENE in 1976 (Figure 9C). The reason for this is probably, that the 1976 value is formed by a high frequence of relatively weak winds, while stronger winds are infrequent. The erosion of the SE section most likely took place in November 1977, which was characterized by strong SW winds.

**1978–1983.** The erosion in the NE and E part of the vegetation is in agreement with the relatively large wind vector of 1978, 1979 and 1980 toward WSW, W and WNW, respectively (Figure 9C and D) and with the 1979 vector of strong winds from ESE (Figure 10A). The vegetation expanded in the SE-erly area in spite of the relatively large 1982 wind vectors (Figure 9D and 10B).

**1983–1988.** The vegetation borderzone was almost stable in spite of generally large wind vectors and an extraordinary large value of 1986 (Figure 9D and 10B). Most probably, the vegetation was eroded during 1986 and reestablished afterwards.

In spite of the changing wind climate having a tendency toward a higher energy input throughout the period 1954–1988, the vegetated area had a net increase over the period. The reason for this is believed to be the elevation of the vegetated area above msl. By comparing this area (the 1988-photo) with the topography as shown on the map from 1863, it can be seen, that the eastern 1988-vegetation border is almost identical with the 1.5 m contour and the vegetation is only eroded in situations of high waves combined with high sea level. As seen in figure 8, the width of the beach, from the bluff to the waterline, has further diminished, except for the progress in the relatively calm period 1969–1975.

It must be concluded, that the use of only one single indicator of the land-sea interface for historical shoreline comparison studies might result in misleading conclusions.

## The Submarine Part of the Spit

The outline of the submarine part of the spit is known from two maps, Figure 11,A and B. In 1991 a new detailed mapping of the central spit area was performed, Figure 11C. In the 1870's smoothed contour lines characterize the submarine spit area. The nearshore falls rather steeply toward S, W and NW, while the N part is characterized by much smaller gradients.

The length of the spit, defined as the distance from the −2 m contour line in W to the ruin in E, is *c.* 930 m. From the 1870's to 1982 this distance was reduced by approximately 300 m, while the position of the −4, −6 and −10 m contour lines to the west was almost unaltered. Towards the south the contour lines have become much more curved. An effect, which may primarily be due to a change in recording methods, in that continuous echosounding has replaced the handwork of the 1870's.

North of the spit the −4 and −6 m contour lines have moved markedly towards N and NW indicating a significant sediment supply. It is not known wether the sedimentation in this area continued after 1982. The central spit area has undergone pronounced changes during the last decade, Figure 11C. Practically all contour lines are displaced landward, and its nearshore zone is now narrow and very steep, in particular towards NW. In contrast, the proximal part of the spit and the length of the spit as defined above, are almost unaltered, except for a displacement of the −2 m contour line toward N.

The uppermost part of the submerged spit was studied from aerial photos too. The quantity and quality of informa-

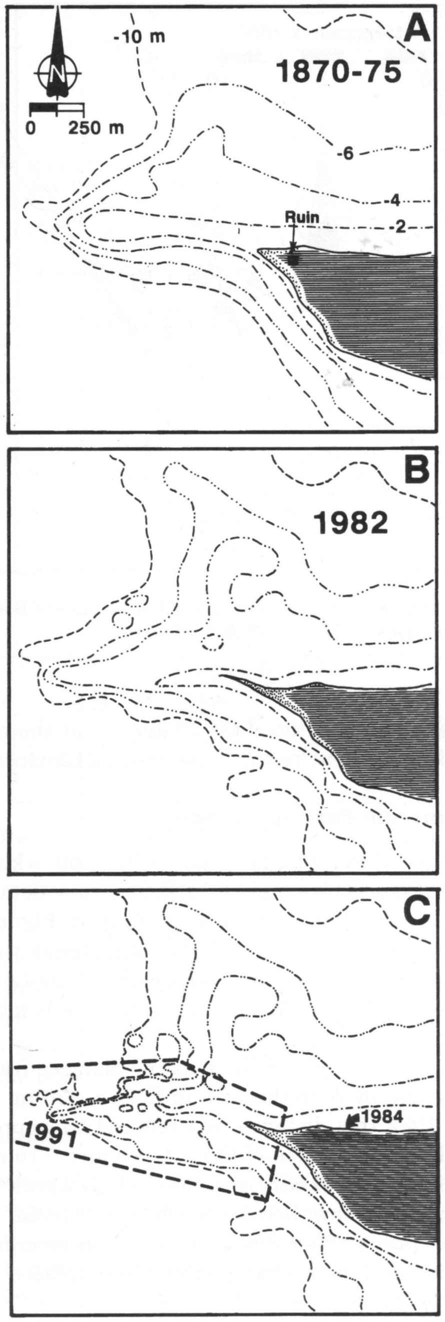

Figure 11. The bathymetry of the spit area in the beginning of the 1870ies (A), in 1982 (B) and in 1991 (C). (C: The fat line markes the area of the mapping performed in 1991. After NFNA, 1991. The contour lines outside this area represent the 1982-situation).

tions depended on the visibility of the water column and the quality of the photos. Six corrected and enlarged sets of photos from 1954 to 1988, Figure 12, were found useful for interpretations. They show the following development:

*1954:* the spit is very distinct and well developed all over. *1961:* the distal part has been eroded, while the remainder part appears as stable and intact as in 1954. *1969:* the northern half of the spit is undisturbed from 1961, while the erosion area have spread toward east and south. *1975:* the spit is widely destroyed. Traversing dark signatures and crescentic dark spots in the northern and the distal part of the spit indicate erosion—or destruction due to dredging activity. *1983:* the spit is less well outlined than at any time prior to this, according to contour-pattern, amount of sediments and the size of the eroded area. The destruction may have continued up till now. *1988:* only smaller parts of the spit are observed. Comparing the 1954 with the 1988-situation, most of the spit has disappeared, or—more correctly—most of the spit-surface has been eroded to a lower level (BINDERUP, 1991b).

## The Subaerial Part of the Spit

Figure 13 shows the length of the spit in the eleven years referred to. The length is defined as the distance from the shoreline in W to the ruin in E. Even though the data only presents 11 point measurements made in a time span of 34 years, there is a pattern in the data.

The maximum spit lengths are reduced in size throughout the period (Figure 13). On the contrary, the proximal part of the spit shows a tendency to grow. This indicates a progressive narrowing of the variability. A continuous and abundant sediment supply, primary from the erosion of the north facing bluff, to the proximal part of the spit, is the reason for the growth in this inner section. This agrees with the results presented in NFNA (1991), which show a net sedimentation in the inner spit area from the beginning of the century till 1991.

The submerged distal part of the spit area has been eroded throughout the period 1954–1988. This applies both to elevation and width of the spit (Figures 11 and 12). NFNA (1991) explains the erosion of the outer spit area as a concequence of several factors. It is presumed that the spit area was kept intact (situation A, Figure 11) by sediment supply from both sea cliffs, and that the sediment transport across the spit could take place in both directions (north and south) depending on the wave situation. In the period 1922–1961 the retreat of the north and the south facing sea cliff was of almost equal size, amounting to more than 20 meters each (BINDERUP, 1991a). From 1954 to 1988 the south facing cliff was almost stable, while the erosion rate of the north facing sea cliff was larger than in the first period studied (BINDERUP, 1991b). This decrease in sediment supply from the south facing sea cliff to the southern part of the spit has resulted in deterioration of the spit. Dredging of nearshore materials from the northern part of the spit has resulted in very steep gradients, a deepening of the sea bottom in this area (Figure 11C), the development of new sediment transport routes, *i.e.* current channels crossing the spit (Figure 3), and an intensified erosion (NFNA, 1991).

## PREDICTING FUTURE COASTAL CHANGES—A DISCUSSION

From the analysis it is obvious, that it is difficult to ascribe past coastal changes to have been induced by single natural

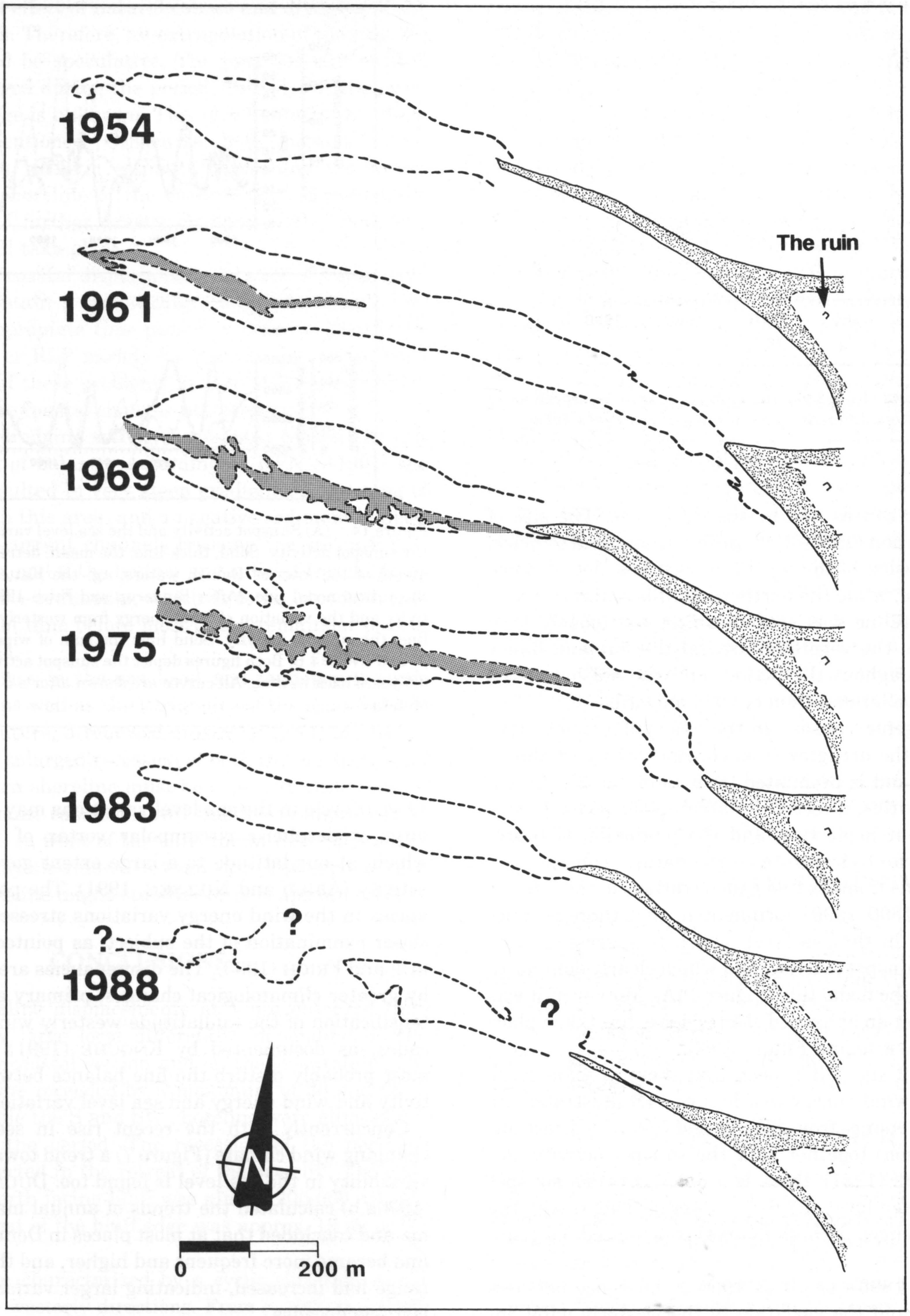

Figure 12. The evolution of the submerged part of the spit, from 1954 to 1988, as interpreted from aerial photographs. The fat dashed line represents the limit of the visible submerged spit-area, and is not a direct expression of the stability of the spit. The dark signature (1961, 1969 and 1975) represent depressions and hollows in the surface. (After Binderup, 1991b).

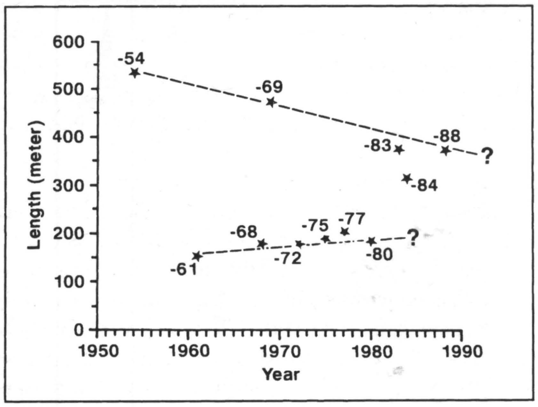

Figure 13. The length of the subaerial part of the spit. Measured on 11 aerial photographs from different years in the period 1954 to 1988.

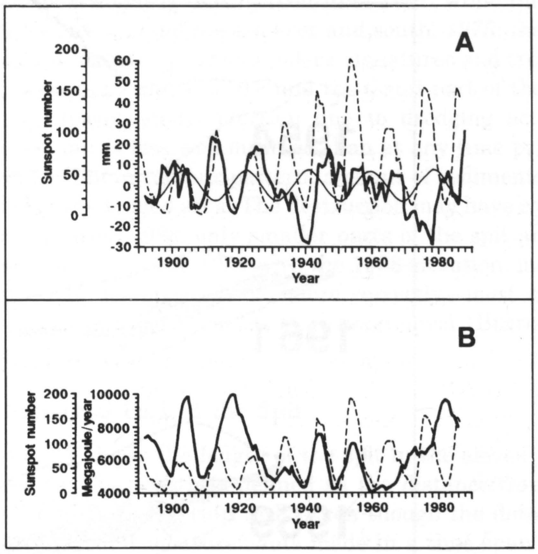

Figure 14. (A) Sunspot activity and the sea level variations. Dashed line: the sunspot activity. Solid, thick line: the mean, detrended sea level variations of the interior Danish waters, *e.g.* the Kattegat. Thin line: the theoretical nodal tide. (After Binderup and Frich 1993). (B) Sunspot activity and the variation of wind energy from westerly directions. Dashed line: the sunspot activity. Solid line: the sum of wind energy from NW, W and SW; ≥4 B. Both figures depict the sunspot activity curve displaced 3.6 years back in time. All curves are shown after a 5 year running mean of data.

or anthropogenic causes and to quantify these. The size of the shoreline erosion (1954–1988) differs from place to place. The former recession of the southern bluff has slowed down a few decades ago, while the northern bluff is still retreating. The eastern shoreline was eroded almost continously from 1954–1988, while the vegetated area of the foreland had a net increase throughout the period; and the erosion of the spit area was accellerated from *c.* 1975 onwards.

The anthropogenic causes for the sea cliff erosion have ceased now and the dredging from the spit area had almost stopped in 1992 and is prohibited from 1994. So, all the anthropogenic activities, directly threatening the coastal zone, are at the present neglective, and the prediction of future coastal changes can concentrate on the natural causes.

Sea level records from six tide gauge stations in the interior Danish waters (1890–1990) documented, that there is a periodic oscillation in the sea level, which is suggested to be connected with sunspot activity, and which clearly dominates the oscillation of the nodal tide (Figure 14A). Moreover, it was demonstrated that an enhanced sea level rise has taken place after 1974 (Binderup and Frich, 1993).

From Figures 2 and 7 it is seen that there is some cyclic variation in the wind energy too. Figure 14B illustrates the sum of the wind energy from SW, W and NW (the directions of largest variation) together with the sunspot activity. According to Currie (1981), there is a delay between sunspot activity and the sea level of 3.6 ± 0.1 years. This is why the sunspot activity curve (in both figures) is displaced 3.6 years back in time.

From the late 1890's to about 1960 a coherence between sunspot activity and the variation in the westerly wind energies is apparent, with a deviation around 1920. In the period from 1960 to 1988, the curves are opposite in phase or displaced by a period other than 3.6 years. A condition that characterized the later part of sea level variations too. Obviously, the connection between sunspot activity and the wind energy is even better than the connection between the sunspot activity and sea level variations. This fact supports the suggestion of Currie (1981), that the mechanism for the 11-year cycle in the sea level variations may be sought in the large tropospheric circumpolar vortex of westerly winds, which, at our latitude to a large extent govern the cyclonic activity (Abild and Nielsen, 1991). The post-1960 discrepancies in the wind energy variations stresses the need for a closer examination of the subject, as pointed out by Binderup and Frich (1993). The discrepancies are possibly caused by greater climatological changes, primary a substantial intensification of the midlatitude westerly winds in recent decades, as documented by Knoche (1991). These changes most probably disturb the fine balance between sunspot activity and wind energy and sea level variations, respectively.

Concurrently with the recent rise in sea level and the changing wind climate (Figure 7) a trend toward an increased variability in the sea level is found too. Duun-Christensen (1990a,b) calculated the trends of annual maxima and minima and concluded that at most places in Denmark large maxima became more frequent and higher, and that the max-min range had increased, indicating larger variability during the last few decades.

When predicting future natural coastal changes a normal procedure is to extrapolate past trends estimates using one or several prediction models: Linear Regression (LR), the End Point Rate (EPR) model, a Nonlinear Polynomial Regression (NPR), or—very recently introduced—a Robust Linear Prediction model (RLP), see Fenster *et al.* (1993). However, none of these methods are suitable in the case of Vejrø. The LR and the EPR models are useless for the spit area and for the sea cliffs, because the disintegration of the spit area has been a combined effect of natural causes and dredging of sea bottom materials. Therefore, an extrapolation of the past development would be speculative. The past sea cliff erosion rates have changed during the period studied, but the exact time of the change is unknown. This also hampers the use of the methods mentioned. Otherwise, both methods might come up with a realistic estimate concerning the future changes of the shoreline of the eastern part of the island, provided that no further drastic changes in the wind and wave climate will take place.

Moreover, the coastal displacement data set of Vejrø, however, neither contain a statistically acceptable sample size nor spans an appropiate time period in order to justify the use of the NPR or RLP models for the purposes of extrapolation. In spite of these problems, it may still be possible to predict the future coastal changes tentatively.

Although the dredging activity has almost ceased, the spit area is still out of balance. According to NFNA (1991) the dredging has resulted in very steep gradients, a lowering of the sea bottom in this area, and a negative sediment budget. If the observed current channels crossing the spit are permanent features, and if the bottom and sides of the channels consist of erodable sediments, which is to be expected, it is only a question of time before most of the remainder part of the spit is eroded.

If the recent rise in the sea level and tendency towards stronger winds, as well as the variability of the sea level will proceed in the future, a renewed erosion of the south facing sea cliff, and an enlarged recession of both the northern bluff and of the eastern shoreline must be expected. Otherwise, if sea level and climate conditions will stabilize or improve, protective platforms in front of the cliffs might develop and the cliff recession may slow down or even stop. Correspondingly, the eastern shoreline might stabilize or perhaps prograde.

## CONCLUSIONS

The net shoreline displacements at Vejrø observed from 1954–1988 show large local differences, depending on the character of the coastal section and on the orientation. The N and E shoreline receeded by a maximum of 30 and 66 m respectively, while the S and SW shoreline were allmost stable throughout the period. The recession of the northern shoreline is reflected in the retreat of the sea cliff. The total erosion of the north facing bluff was almost 200,000 $m^3$, and the largest retreat of the bluff edge was approx. 19 m, or 0.5 m/year.

Wind data are characterized by a cyclic variation in the energy from the westerly directions. From *c.* 1900 to *c.* 1960 there is a convincing coherence between the sunspot activity and the wind energy. This relation might be an important part of the explanation for the connection between sunspot activity and the sea level variations of the interior Danish waters, recently demonstrated by BINDERUP and FRICH (1993). During the last few decades, the rate of sea level rise has increased, while wind energy also increased, and the connection to the sunspot activity is disturbed. The erosion of the northern shoreline and the bluff is ascribed to this increase of the wind and wave energy and to the sea level rise.

This caused the recession of the eastern shoreline too. In spite of the shoreline erosion in this part of the island, the vegetated area of the beach ridges actually expanded. Therefore it must be concluded, that the use of one single indicator of the land-sea interface for historical shoreline comparison studies might result in misleading conclusions.

The south facing sea cliff was eroded earlier in this century, but in the 1954–1988 period the total erosion was only about 20,000 $m^3$ or 1/10 of the northern sea cliff. The largest retreat of the sea cliff edge was only *c.* 6 m, hardly exceeding the accuracy of measurement, and reflecting the stability of the shoreline. The reason why the southern part of the island was allmost stable in spite of the increase of wind and wave energy from the SW and SE directions during the period, is explained by low sea level which is normally associated with southerly wind directions.

The submerged distal part of the spit area was densely eroded throughout the period, in particular since the mid 1970's. Although the length of the subaerial part of the spit is fluctuating according to variations in sediment supply and in sea level, the entire spit length is getting progressively shorter. The disintegration of the spit area is caused by a reduction in the sediment supply from the erosion of the southern sea cliff and by dredging of sea botton materials from the outer spit area. Current channels crossing the spit have formed, and the sediment transport directions have also changed. Under these conditions, a reestablishment of the spit area is solely hypothetical.

With the changed spit configuration and recent change in both sea level rise and wind energy, an estimation of future coastal displacements would be purely specualtive.

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