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Power Spectrum Analyses of Storm Layers in Marine Silty Sediments: A Tool for a Paleoclimatic Reconstruction?

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ABSTRACT

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Climatic events are imprinted on the sedimentary record of the Baltic Sea. In these sediments, storm events are documented by sandy horizons within the mud sequences which dominate the deeper basins. The spectral characteristics of the storm layer sequences were determined through analyses of the optical density of sediment X-radiographs. Previously the evaluation of X-radiographs was done visually and provided qualitative rather than quantitative information. In order to enable a more objective analysis, an optical scanner was developed. Subsequently the digitized sequence was analysed using Fast Fourier Transformation procedures. The results show that the observed cycles which lead to the formation of alternating layers can be attributed to calendar and solar band frequency variations.

ADDITIONAL INDEX WORDS: *Marine geology, Holocene, Baltic Sea, X-radiographs, time series analyses.*

INTRODUCTION

Cyclical variations in sedimentary sequences are a widespread phenomenon in many depositional environments, from all geological periods (KREISA, 1981; FISCHER and HERBERT, 1986; HILL and NADEAU, 1989; FISCHER and ROBERTS, 1991; RIPEPE *et al.*, 1991). Recent cyclostratigraphic research (FISCHER and BOTTJER, 1991) has shown that spectral analysis can be used to distinguish the calendar band (including lunar and annual cycles), the solar band (dominated by phenomena such as sunspot cycles), and the Milankovitch band (comprising secondary aspects of the Earth's orbital cycle such as eccentricity, obliquity and precession). All these cycles affect environmental conditions and are imprinted on the rock record in a specific way.

Investigations involving the history of Holocene sediments in the western Baltic Sea (SEIBOLD *et al.*, 1971; SMETACEK, 1980; WERNER *et al.*, 1987) (Figure 1) show that the predominant effect of variations is expected to be changes in seasonal variations. Under calm summer conditions, uniform mud sedimentation occurs in the deeper basin. Storm events during autumn and winter mix the 'normal' sedimentation. These events are documented as more or less regularly alternating sandy laminae in the muddy sequence (WERNER, 1968; KHANDRICHE *et al.*, 1986; MILKERT, 1994).

In this paper we present a test-method for the application of spectral analyses of the storm layer signal in the sediments of Kiel Bay (Figure 1). Furthermore, we discuss whether this method is suitable to depict certain frequency domains in the short spectral bands of the last decades and whether potential cycles can be attributed to particular oscillation forcing factors.

Environmental Setting

In geological terms, Kiel Bay is a very young structure, mainly shaped by the Scandinavian ice during the Pleistocene. Its recent morphology of sills and basins developed at the end of the Weichselian glaciation, 25,000 years ago (GRIPP, 1964). Glaciers excavated Eckernförde Bay among other fjords (Figure 1). When the ice withdrew around 14,000 BP, the area was subaerial. Around 8,500 BP during the Ancylus Lake Freshwater Period, a large river ran through the Fehmarn Belt and Great Belt and transported freshwater towards the Kattegat. Rising sea level during the Holocene led to a transgression of marine water, and the Baltic Sea changed into the brackish Littorina Sea. Present sea level was achieved around 3,000 BP (SEIBOLD *et al.*, 1971; BABENERD and GERLACH, 1987).

Sediments

In Kiel Bay, a close correlation between the distribution of sediment types and different water depths is visible (SEIBOLD *et al.*, 1971). Principally, the sediments above wave base consist of sand and till; whereas, the deeper parts of the

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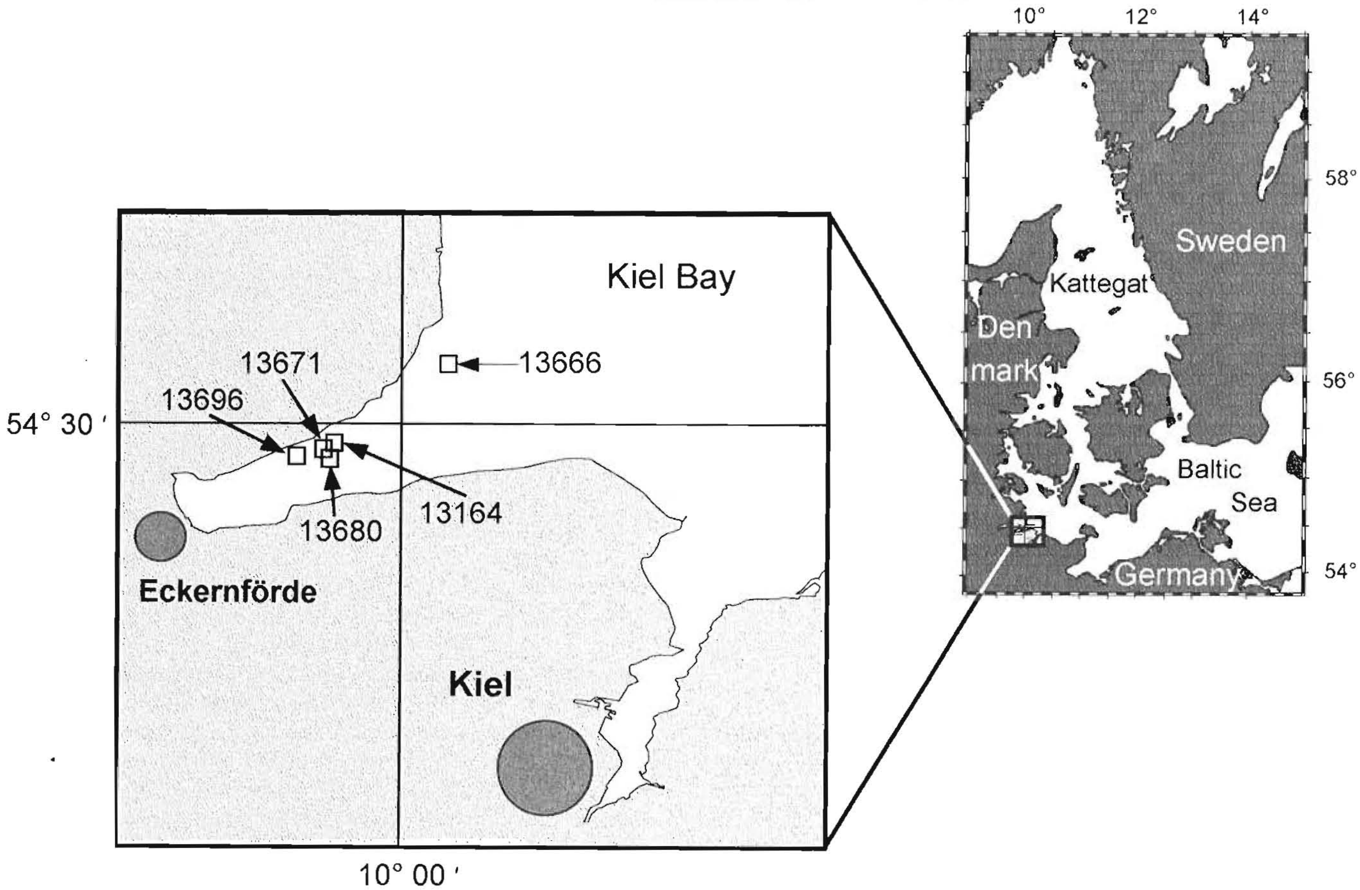

Figure 1. Generalized map of northern Europe with the investigation area including sample locations of box cores in Eckernförde Bay.

truncated fjords are covered by mud, with various mixtures from muddy sand to sandy mud downslope. The sedimentary material is derived from the erosion of submarine till ridges and cliffs (HEALY and WERNER, 1987).

Hydrography

The hydrographical setting of Kiel Bay within the Baltic is characterized by the interaction of fresh and salt water sources. At the eastern edge of the Baltic, river-inflow provides a continuous excess of fresh water into the surface layer (GERLACH, 1990). Depending on the excess supply of freshwater, a more or less stable halocline is present during the year. Stability of the water column increases during the summer with the formation of a stable thermocline. Oxygen depletion in the bottom water is common during summer and autumn. This leads to the occurrence of hydrogen sulfide below the thermocline and reduces benthic activity.

The stratification of the water column is broken up by meteorological events. This occurs because surface currents are controlled by the large-scale wind field (DIETRICH, 1951). After westerly storms, inflow of oxygen-enriched, salt water through the Skaggerak and Kattegat (DIETRICH, 1951) replaces the "old", oxygen depleted bottom water. Strong easterly winds can also lead to the formation of bottom currents in the easterly exposed fjords.

Meteorology

The Baltic Sea weather system is strongly influenced by the Atlantic circulation system, which provides mainly westerly winds during all parts of the year (DEFANT, 1974). The main direction for winter storms is west and correlates to the major pathways of Atlantic depressions. They do not affect this coastline because it is on the lee side. Less common storms from an easterly direction have a significant impact on the coastal zone of the western Baltic.

Regular and continuous daily weather observations did not start until 1870. Earlier historic storm events are only remembered when loss of human lives and destruction occurred, therefore the pre-1870 record of storm events is very incomplete. Four major floods, connected to easterly storm events, affected the coastline of Kiel Bay during the last 150 years, occurring in 1872, 1904, 1954 and 1978. The storm floods in January, 1954 (KANNENBERG, 1955) and December/New Year, 1978/1979 (KHANDRICHE *et al.,* 1986; EIBEN and SINDERN, 1979) which both affected the Northern German shoreline were investigated in detail. Both floods were char-

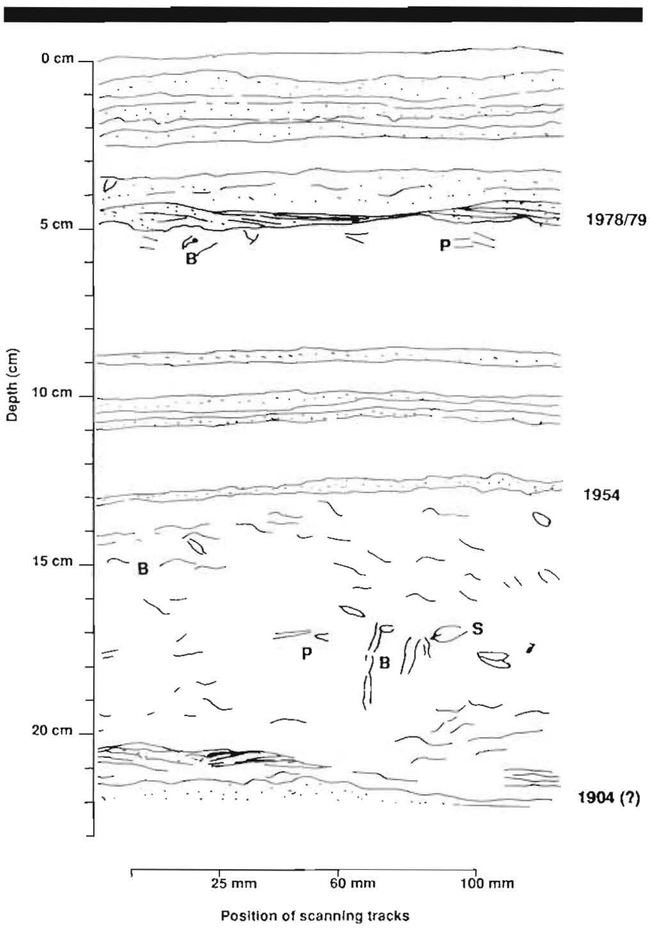

Figure 2. Sedimentary structure of Box core GIK 13680, taken in 26 m water depth with original depth scale and scanning tracks. The dates are determined by ^{210}Pb and placed at the base of the observed coarser grained stormlayers. B = Bioturbation, P = Shells of *Pectinaria korenii,* S = Shells of *Abra alba.*

Table 1. *Flow chart of the analysing and processing procedure.*

Analyses	Processing
Sediment coring	Linearization
↓	↓
Preparation of the X-radiography	Autocorrelation
↓	↓
Exposure to xrays	Interpolation to the power
↓	↓
Scanning/ digitizing	Matching the time scale
↓	↓
Storage on PC	Fast Fourier Transformation
	↓
	Estimation of periodicity

acterized by the amplified effects of seiches, begun when strong southwesterly wind forced a movement of the water masses in easterly direction and generated an additional inflow of North Sea water into the Baltic. Subsequently, the low pressure area moved to the southeast generating a heavy storm from an east–northeasterly direction. The long fetch resulted in a forced movement of the water masses in a westerly direction. During these extreme events, water level can increase up to 3 m above mean sea level.

METHODS

Sampling Procedure

Our investigation is based on several box cores (maximum length 45 cm) taken from Eckernförde Bay (Figure 1) between 1988 and 1990 (MILKERT, 1994), giving a complete, undisturbed sediment profile for the last 100 years (Figure 2). Up to 5 sediment slabs for X-radiographs were taken from each core. A flow chart of the analytical procedure is summarized in Table 1. All analysed box cores were taken from localities below 25 m water depth to ensure similar hydrographic conditions.

Marker horizons were dated by using the ^{210}Pb technique (MILKERT, 1994) (Figure 2). ^{210}Pb Geochronology has become a commonly used technique for ascertaining rates of sedimentation processes in lakes (*e.g.,* KRISHNASWAMI *et al.,* 1971; BRULAND *et al.,* 1975), estuaries (*e.g.,* GOLDBERG *et al.,* 1977) and coastal marine sediments (*e.g.,* KOIDE *et al.,* 1972; CHANTON *et al.,* 1983). To prove an undisturbed signal, recent sediment mixing via bioturbation has to be shown to be unimportant as is the case in the inner parts of Eckernförde Bay. Otter trawl fishery (KROST *et al.,* 1990; WERNER *et al.,* 1990) is common and affects surface sediments all over Kiel Bay, except in our investigation area where trawl net fishery is prohibited.

Physical Procedure

X-radiographs have proved to be an important tool for investigating the structure of muddy and silty sediments (CALVERT and VEEVERS, 1962; WERNER, 1968; BOUMA, 1969). The principle of this method is to radiate (40 keV) a defined sediment slab (here 250*100*7.5 mm). Attenuation is made visible on an attached film. Different physical sediment properties (*e.g.,* water content, texture, content of clay minerals) give rise to different levels of attenuation and thus different blackening of the film, which also depends on the exposure time and X-ray intensity.

Transparency of a certain layer is defined as the ratio of the intensity of the transmitted light to the incident light.

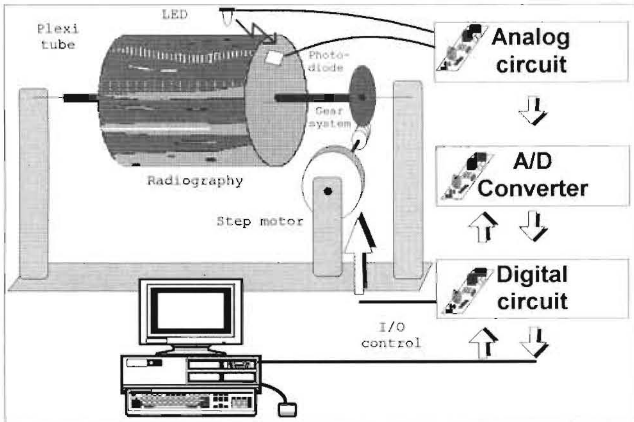

Figure 3. Hardware components of the scanning system (after HENTSCHKE and TALMAT, 1992).

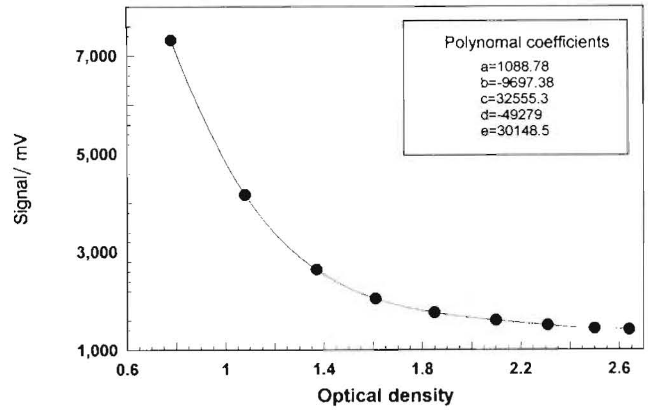

Figure 4. Correlation of the signal (mV, y-axis) and the corresponding optical density (x-axis).

The Opacity of a layer is defined as the ratio of the intensity of the incident light to the transmitted light. Optical density is the logarithm of the opacity (WEAST, 1987).

Thus, Transparency = I(t)/I(i), Opacity = 1/Transparency = I(i)/I(t), and Optical density = log10 (I(i)/I(t)) where I(i) = Intensity of incident light and I(t) = Intensity of transmitted light.

In order to evaluate the X-radiographs, a PC-controlled scanner system was developed which determines the optical density (HENTSCHKE and TALMAT, 1992, Figure 3). The principle of this method is to fix the radiography film (negative) on a rotating glass tube and to detect the transmission characteristics using a photodiode/LED system. The spatial resolution is limited by the dimension of the photodiode enabling the detection of horizontal layers down to 1.5 mm in thickness. Optionally, a higher resolution of 0.1 mm can be achieved by focusing the emitted radiation. The present data set was correlated to a calibrated grey scale (Figure 4) which is commercially available (German Federal Agency for Material Research, Berlin, Germany). It is calibrated to the PTB-Normal NBS (USA), Standard Reference Material 1001, X-ray film step tablet ID No: 067815. The grey scale is divided into 15 steps and covers a range in the optical density from 0.27–5.0 with an accuracy <0.05. The digitized data set is stored in ASCII-Code and can be integrated into any statistical program for further processing. Each film was scanned along a minimum of 3 tracks, depending on the internal variations of the X-radiograph, to give a representative data set (Figures 2, 5 and 6).

Statistical Procedure

The identification of signals in the sedimentary record has become an important target in Geoscience (BLACKMAN and TUKEY, 1958; RIPEPE *et al.,* 1991). The aim is to understand the rhythmicity which orbited cycles have imprinted into the sedimentary rocks (BLACKMAN and TUKEY, 1958; JENKINS and WATTS, 1968; BOX and JENKINS, 1970). Fast Fourier Analysis (FFT) provides a suitable procedure with which to identify the spectral characteristics of a time series. An update of the actual processing technique is published and critically reviewed by HINNOV and GOLDHAMMER (1991). Our processing was done by using Stanford Graphics.

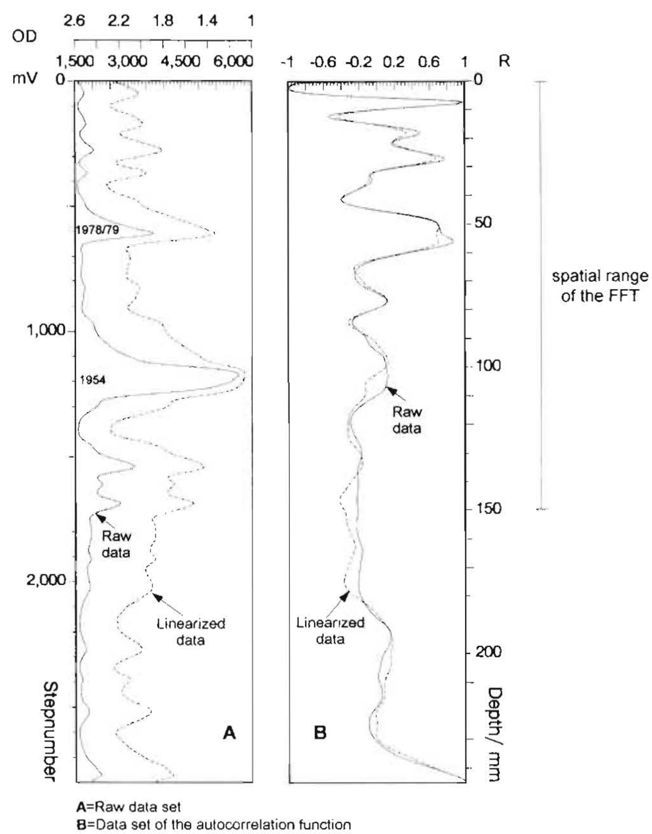

Figure 5. XY-Plot of the raw data set, the linearized data set and the corresponding autocorrelation function. The range for spectral estimation is indicated. Depth scale in millimetres.

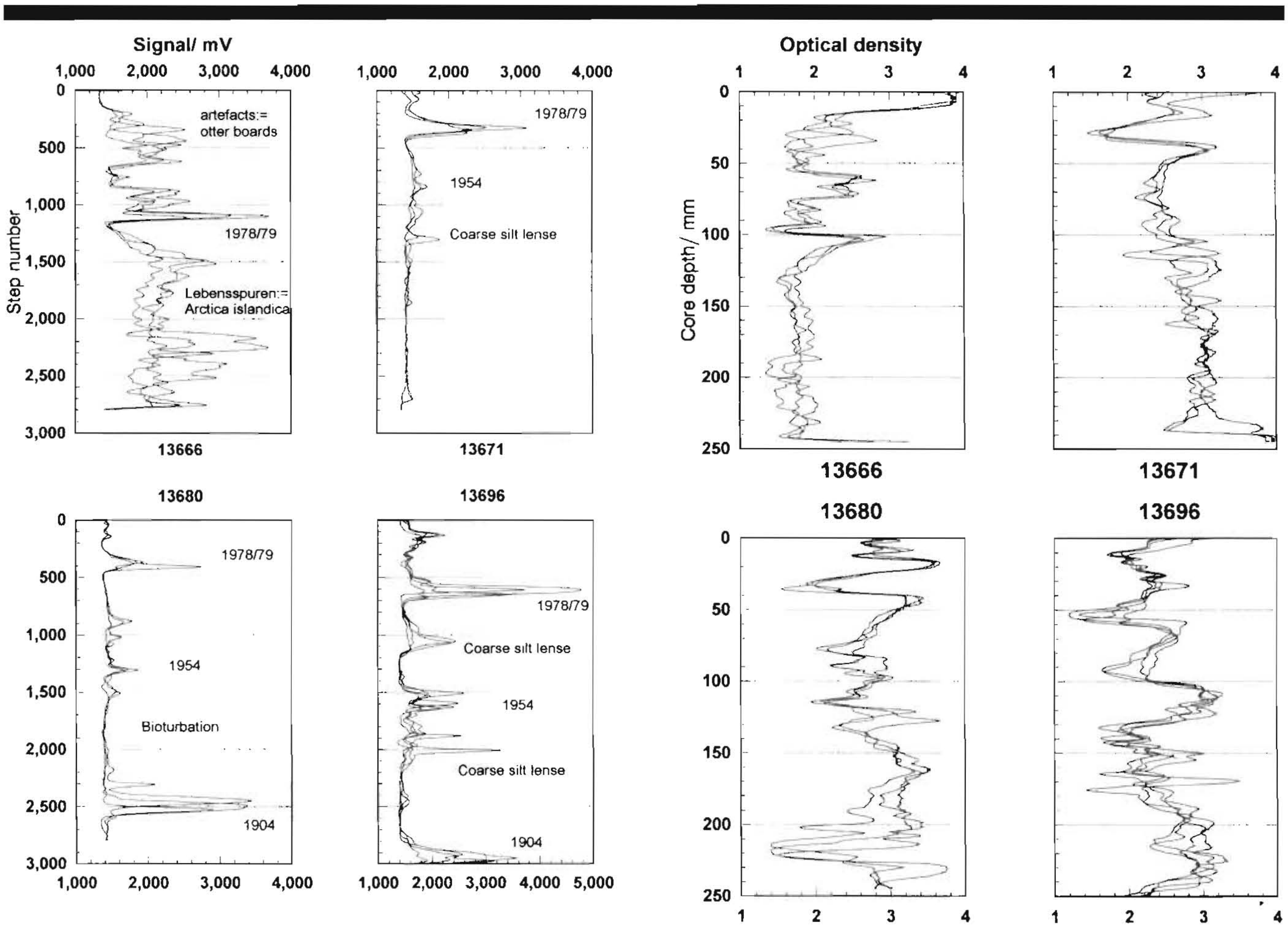

Figure 6. Raw data (6A) and linearized data set (6B) from 4 examples (for position see Figure 1). The marker horizons older than 1978 are determined by ^{210}Pb (MILKERT, 1994).

In this study the procedure of BLACKMAN and TUKEY (1958) was preferred for processing the digitized radiograph. Using this procedure, standardisation gives the advantage that raw data sets from archives containing non-calibrated radiographs can also be calibrated. Figure 5 exhibits a comparison of autocorrelation between the raw data and the fitted data. Variations between both results can be neglected. The autocorrelated series in the range between -1 and $+1$ is calculated by shifting and correlating the time series with $t = 0, 1, \ldots, M < n$ (n = number of data points). At each shift new average values and variances for the correlation coefficient have to be calculated due to the decreasing amount of data set.

Subsequently, the number of steps correlatable to the sediment depth can be interpolated by splining power and matched to the time scale using dated horizons. The number of data values is derived from the single steps of the motor and is correlated to the depth of the core and the time scale respectively. The depth scale was converted to a time scale by linking marker horizons (Figure 2) dated with ^{210}Pb (MILKERT, 1994). Combing the FFT to a discrete data set, the calculated spectrum represents an estimate of the distribution of the variance in a defined frequency domain which is limited for our data set by the Nyquist frequency $f_{max} = 85$ years. The maximum depth of the undisturbed sedimentary sequence in the box core corresponds to a time scale of about 90 years. Depending on the resolution of the photodiode, the minimum frequency is 0.5 years. In Figure 7, the non-smoothed magnitude $|z| = SQR(Re^2 + Im^2)$ of the relative variance which can be expressed as spectral density, amplitude or magnitude (HINNOV and GOLDHAMMER, 1991) is plotted versus the frequency at a half logarithmic scale.

Table 1 demonstrates the processing procedure for a single core (GIK 13164). During the first post-processing step (linearization), the stored raw data need to be correlated to the optical density by using a calibrated grey scale (Figure 5). The second post-processing step leads to calculate the autocorrelation function in the range of -1 to $+1$. This shows that the linearization step may be unnecessary, because there is only a minor difference between the autocorrelation function of the raw data and the linearized data set as can be seen in the diagram of Figure 6 for different box cores. Subsequently,

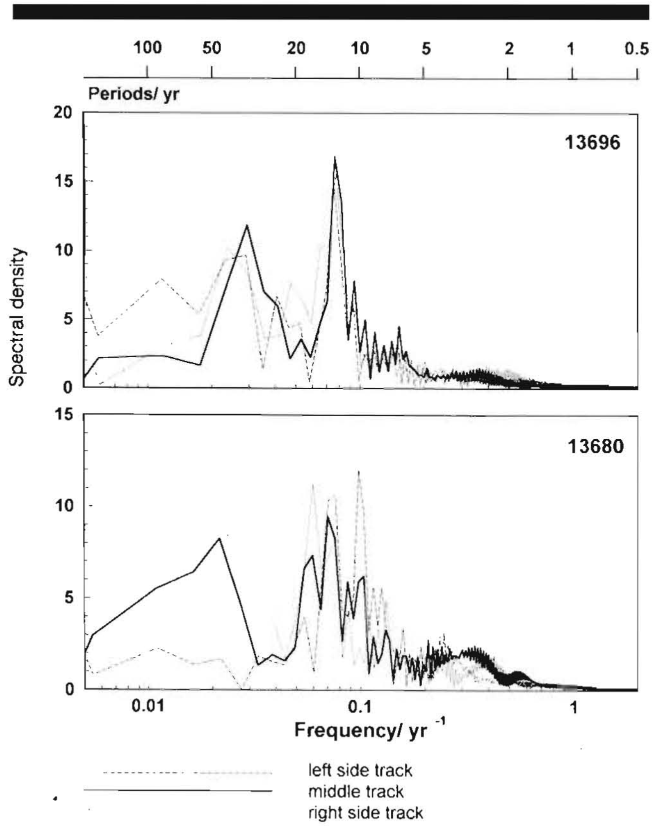

Figure 7. Distribution of the spectral density in half logarithmic scale. The periods are calculated by 1/f. The periodigrams are not smoothed.

Table 2. *Comparison of the occurrence of storm layers to the probability of storm flood events (columns 1, 2: MELF data, columns 3 to 5 from Figure 5).*

Flood water level above average/ cm	Probability of storm frequency f/yr^{-1}
>285	150
>200	17
>175	9
>150	6
>100	0.5-1

Estimated periods/ years taken from fig. 5 for the box cores:

13164	13680	13696
n.d.	40	34
n.d.	16	n.d.
10	12	13
8	7	7
6	4.8	4.9
2.9	3.9	3.5
1.25	n.d.	n.d.

the data taken from a defined range of the section were interpolated for the longer FFT-ranges and matched to a defined time scale as indicated in Figure 7.

RESULTS

Storm layers in the sedimentary column represent a regular contribution of sediment input with strong regional effects (WERNER *et al.,* 1987; MILKERT, 1994). The importance of this contribution may be assessed from the time series of highly fluctuating sedimentation rates measured with sediment traps moored in Eckernförde Bay (SMETACEK, 1980). During storm events, sedimentation rates suddenly increase due to the mixing of minerogenic material. The evidence from sediment cores shows that storm layers, due to the mixing processes of bioturbation, have little chance of being preserved. The probability of preservation increases both with increased water depth and from the outer, better ventilated areas of Eckernförde Bay to the sheltered inner parts where benthic life is reduced. The inner parts of the bay appear almost undisturbed by anthropogenic influence, *e.g.,* otter trawl fishery or moorings (KROST *et al.,* 1990; WERNER *et al.,* 1990). Thus, it is possible to show that at least major (century) storm layers remain undisturbed for a longer period (MILKERT, 1994).

All analysed box cores contained dominantly mud sediments and were taken from the same water depth (25 m) to ensure similar hydrographic conditions. Figure 2 shows an example for the lithological interpretation of a core (GIK 13680) and includes horizons/storm layers dated with ^{210}Pb. The upper 5 cm of the sedimentary section are characterized by three largely homogeneous, up to 5 mm thick, coarse silt layers without internal structure which alternate with mud. At 10 cm sediment depth, a fine sandy, ripple layer occurs. This layer is recognized as the New Year, 1978/1979 storm layer (KHANDRICHE *et al.,* 1986; MILKERT, 1994). It is underlain by a horizon formed by the polychaete *Pectinaria korenii,* which resulted from a mass extinct in summer 1976 (DOLD, 1980). Below 15 cm sediment depth, several homogeneous coarse silt to fine sand layers occur. They are storm layers of the 1954 storm. The signal measured by the photodiode correlates to the amount of sand in the X-radiography picture (Figure 6A). The storm layers of this major storm can be recognized in several box cores all over the bay, as shown in Figure 6.

Sandy layers (mainly storms of 1954 and New Year 1978/1979) show low optical densities (high signal) whereas the clay enriched parts show high values (low signal) and are marked by strong peaks (Figure 5). Different storm layers always show similar density curves with a rapid increase at the bottom of each layer and a slow smooth decrease at the top. This can be interpreted as a grain-size sorting effect.

Applying FFT on this recalculated data gives the spectral variance of the sine and cosine composition. After estimating the magnitude or spectral density of the sedimentary sequence, the overall distribution generally shows a stochastic red-noise pattern. Significant frequencies peak out of the noise and preferred periodicities can be distinguished (Table 2, Figure 7).

Figure 6A presents the data from four different box cores (for positions see Figure 1) showing every data track. Core disturbance is variable, but nevertheless, the major storm layers can be recognized in each core and appear to be excellent marker horizons. Figure 6B shows the linearized data. The top of GIK 13666 (Figure 6A), located close to the western edge of the fjord, is strongly affected by otter trawl fishing (WERNER *et al.*, 1990; KROST *et al.*, 1990). The New Year, 1978/1979 storm layer can still be distinguished, but the bottom of this core is almost completely bioturbated by *Arctica islandica* (WERNER *et al.*, 1987). The signals from the digitized tracks show wide variations and several peaks which cannot be correlated between the tracks or to the other cores. Only a minor sequence with lebensspuren can be observed in GIK 13680 (Figure 6A) and the three tracks match well. A few lenses of coarse silt occur in GIK 13696 (Figure 6A), making it impossible to correlate scanned tracks. GIK 13680 and GIK 13696 (Figure 6A) show only minor disturbances, whereas GIK 13671 gives a clear signal in the upper part of the core but is highly influenced by bioturbation in the lower part.

The applied FFT-procedure on the digitized data sets shows (Figure 7) a general stochastic character overlaid by significant periodicities. Uncertainties in the estimated spectral pattern have to be considered due to irregularities in the formation of layering. The most significant cycles are listed in Table 2.

By correlating the significant peaks of the probability of storm flood events to the data set given by the local agencies for coastal affairs (MELF, 1981), the estimated frequency of the storm layers corresponds to the frequency of meteorological observations (Table 2). However, due to the limited investigated time scale, a correspondence to cycles longer than 80 years cannot be presented. When estimating and comparing these periodicities, it must be considered that the time interval of the periods could vary in a wide range (KANNENBERG, 1955). Our results show that major peaks can be correlated to a defined layer. By using statistical procedures, it is possible to determine an age/frequency correlation for semi-enclosed fjords in the western Baltic Sea. Comparing the probability of storm frequencies to the estimated periods taken from box core data (Table 2) shows that the core data are generally lower with a difference between 2 to 4 years.

DISCUSSION

Storm dominated sedimentary deposits are a well known phenomenon from tropical to polar Shelf Seas (HAYES, 1967; BALL *et al.*, 1967; KREISA, 1981; HILL and NADEAU, 1989; GAGAN *et al.*, 1990). They are important agents for the erosion and deposition of sedimentary material. The frequency and tracks of intense storms and hurricanes are expected to have varied historically as a function of global climatic variations (BARRON, 1989; HOBGOOD and CERVENY, 1988). Thus, the understanding of variations in storm intensities is of great theoretical and practical value.

Sedimentary Features Not Related to Storm Depositional Processes

To understand storm dominated processes in the investigation area it was necessary to distinguish between storm related structures and other sedimentary features. Storm layers are characterized by coarser grain size and a widespread extension through the basin (MILKERT, 1994). Other sedimentary features are mainly caused by bioturbation (WERNER *et al.*, 1987). Areas where the water depth exceeds 20 m are strongly influenced by limited to reduced oxygen conditions in the bottom water and therefore contain a restricted bottom fauna. The influence of bioturbation on the surface sediment is generally low, and the marker species are well-known (DOLD, 1980; WERNER *et al.*, 1987). Ice-rafted, coarser material has no influence on the surface sediments in the western Baltic. Formation of ice is restricted to sea ice formation without a major input of sediment (DEFANT, 1974). Formation of sea ice minimizes the effects of storms.

Another important sedimentary feature is the geochemical formation of laminated sediments in anoxic basins, which is common in Santa Barbara Basin (GORSLINE *et al.*, 1993) and the central parts of the Baltic Sea (AXELSSON, 1987). In the Santa Barbara Basin, the lack of bioturbation preserves annual light-dark couplets (varves) of differing relative density that may be the result of periodic formation and destruction of bacterial mats on the sediment surface (GORSLINE *et al.*, 1993; CHRISTENSEN *et al.*, 1994); whereas, occasional storms induce transport of coarser material into the basin. In the western Baltic Sea, the formation of laminated sediments is restricted to summer periods with a clearly stratified water column. These laminated horizons are much smaller than those originated after storm events (RUMOHR, 1993; MILKERT, 1994).

The influence of compensational bottom currents in the western Baltic Sea, originated after the storm event, is still not fully understood. Field observations (MILKERT, 1994) proved that almost the same amount of material is eroded and transported in suspension by bottom current activity.

Factors Influencing the Signal Quality

Several factors influence the signal quality which is the basis of the statistical procedure. Shells, small dropstones or even mechanical disturbance of the X-radiography produce density values similar to the storm layer itself. It is important to measure several parallel tracks to gain representative averages, which allows storm layers and small scale disturbances to be distinguished. Furthermore, factors such as compaction or brightness of the original X-radiography must be eliminated to achieve good correlation between different box cores across the area. Nevertheless this non-destructive method provides an easy and inexpensive way of transferring the information stored on the original X-ray film into a digitized sequence, which allows further processing.

Matching the Local Time Scale

In this investigation, the validity of the data is linked to sediment cores sampled from a small local area. Long-term variations in local sedimentation patterns influence the time matching and cause uncertainties. For this reason, the determination of the local time scale is the most important problem in estimating the spectral characteristics of marine sedimentological sequences. We are able to show that the estimated periods roughly correspond to the meteorological probability of storm frequencies at the German Baltic coast (Table 2).

Linearization of the Time Series

The primary orbital parameters find expression in the "calendar band" (FISCHER and HERBERT, 1986) which includes the tidal, diurnal, semi-lunar, lunar and annual cycles. Solar phenomena and atmospheric and magnetospheric reactions to them dominate the "solar frequency band" expressed in the El Nino cycle, sunspot cycle, Gleisberg cycle, *etc.* (FISCHER and BOTTJER, 1991). The Milancovitch band is of minor importance for the observed short term variations (Figure 7) throughout the last century. Our results show that the observed cycles can be attributed to calendar and solar band frequency variations. However, the transformation of algorithms which were originally developed for unlimited time series into a series with a limited time scale may cause uncertainties. Statistical processing of a constant time interval is adopted for the depth respective to the time scale which is not strictly accurate but is the only possible way to analyse the geological time scale.

According to the investigations of FISCHER and ROBERTS (1991) and RIPEPE *et al.* (1991) on varved laminations from lacustrine oil shales, cycles in the frequency range of 10.4–11.7 years could suppose a correlation to sunspot cycles and shorter cycles of 4.8–5.6 years to ENSO (El Nino Southern Oscillation) events. The short period of approximately 1 year represents a seasonal driven oscillation; the longer periods up to 6 years show similarities to the ENSO frequency range (QUINN and NEIL, 1987). The intense hurricane activity in the western Atlantic and the Gulf of Mexico region is part of global teleconnections and may be linked to sub-Saharan droughts and ENSO events (LIU and FEARN, 1993; GRAY, 1990; CAVIEDES, 1991). It is now known that strong ENSO events affect the climate over a much larger region, reaching up to western North America and into Eastern Asia (LIU and FEARN, 1993), but it is speculative to transfer an influence on the European climate on the basis of our limited data set.

CONCLUSION

Intense storms are rare events, but they play an important role for the formation of coastal and shelf environments because of their highly destructive force and as active ecological agents. The statistical analyses of the storm layer sequence in a semi-enclosed bay gives us information about cyclic, transient or stochastic characteristics of the climatic conditions. This information can be essential for the interpretation of processes affecting the coastal zone.

Under the assumption that the sedimentary sequence is undisturbed, the spectral characteristics of different storm layer sequences through time provides information about phases with increased storm activities, respectively climatic variations.

We need to improve our knowledge on the sedimentation processes of storm layers, to correct the non-linear sections in the cores, which will give a much higher resolution and accuracy in the frequency range. In consequence, we probably could model climatic sceneries by reconstructing older series with similar characteristics and assess the meteorological impact on the coastal zone.

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ZUSAMMENFASSUNG

Extreme Klimaereignisse, wie etwa Stürme, lassen sich in den Schlicksedimenten der westlichen Ostsee nachweisen. In den sonst gleichförmigen Schlicke der tieferen Bereich bilden sich Sturmlagen in der Regel als grobsiltige bis feinsandige Horizonte ab. Die spektralen Charakterstika von Sturmlagensequenzen konnten durch die Digitalisierung und Analyse der optischen Dichte von Röntgenradiographien erfaßt werden. Bislang wurde die Interpretation der Röntgenradiographien ausschließlich visuell durchgeführt, was zu einer qualitativen anstelle einer quantitativen Interpretation führt. Aus diesem Grund wurde ein optischer "Scanner" entwickelt. Die digitalisierte Sequenz wurde anschließend in mehreren Schritten einer Fast Fourier Transformation unterzogen. Die Ergebnisse zeigen, daß zyklische Variationen, die zu Wechsellagerung im Sediment führen, mit Frequenzmodulationen im Kalenderband und im Solarband in Verbindung gebracht werden können.