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Change in atmospheric and oceanic circulation reflected in North Sea sediments during the late Holocene

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With 5 figures in the text

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Abstract: The results from two of a total of four long sediment cores from high accumulation areas of the southern flank of the Skagerrak (NE North Sea) are given to further elucidate the interplay of atmospheric and ocean current circulation during the past ca. 1300 years.

Strong westerlies, emerging from the Northern Hemisphere main westerly wind stream (MWWS), are likely to amplify current intensities, while easterly wind directions can hamper the water mass circulation in the Skagerrak. Changes in current energies can be traced by the granulometric composition of the sediments.

Earlier investigations regarding the movement of the cyclone tracks (northwards during warm and southwards during cold periods; see e. g. LAMB 1969) can be confirmed: the Medieval Warm Period (ca. 800/1000-1350 AD) is characterized by generally finer sediments indicating lower bottom current energies. Thus, minor wind-forcing and a northern position of the MWWS can be inferred. During the Little Ice Age (ca. 1350-1900 AD) a southward movement of the MWWS as far south as the Skagerrak system and probably further south can be traced.

Zusammenfassung: Am Beispiel zweier von vier langen Sedimentkernen aus Hochakkumulationsgebieten der Südflanke des Skagerraks (NE-Nordsee) wird das Zusammenspiel von atmosphärischen und Wassermassenzirkulationsmustern während der letzten ca. 1300 Jahre dargestellt.

Starke Winde der nordhemisphärischen Westwinddrift (MWWS) sind in der Lage, die Wassermassenzirkulation im Skagerrak zu verstärken, während Winde aus östlichen Richtungen die Zirkulation behindern können. Veränderungen in der Strömungsenergie dokumentieren sich durch Veränderungen in der granulometrischen Zusammensetzung der Sedimente.

Frühere Untersuchungen der N-S-Bewegungen der Zyklonenzugbahnen (nordwärts während warmer und südwärts während kalter Klimaperioden;

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siehe z. B. LAMB 1969) können durch die vorliegenden Untersuchungen bestätigt werden: Die Mittelalterliche Wärmeperiode (ca. 800/1000-1350 AD) ist durch generell feinere Sedimente gekennzeichnet, die den Schluß auf schwächere Bodenströmungen zulassen. Daraus kann geringere Westwindbeeinflussung und daher eine nördliche Lage der MWWS abgeleitet werden. Während der Kleinen Eiszeit (ca. 1350-1900 AD) kann eine Südbewegung der MWWS interpretiert werden. Möglicherweise hat die Kernzone der MWWS zeitweise über den Skagerrak hinweg nach Süden gereicht.

1. Introduction

The late Holocene is characterized by various climate fluctuations which appear to have had most prominent effects on the latitudes of the planetary frontal zone, at least of the Northern Hemisphere. The planetary frontal zone marks the latitudes of greatest temperature and pressure gradients and is situated between the 35th and 65th latitude. The pressure gradients increase with increasing distance to the earth's surface and, thus, under the influence of the fictitious Coriolis force strong westerlies mark the planetary frontal zone (WEISCHET 1977). The Boreal climate zone links the high arctic and the temperate latitudes in the form of a dynamic front quite similar to the front systems in the North Atlantic Ocean. The zone is of exceptional importance for the climatic development of the Northern Hemisphere, because the higher temperate latitudes show extremely continental features which do not have any counterpart in the Southern Hemisphere.

The zone of the main westerly windstream plays an important role in the development and the migration tracks of anticyclones affecting the Boreal climate zone. By no means can this zone be regarded as being staticly (GRAEDEL & CRUTZEN 1993). It is characterized by migrating or standing waves (Rossby waves) which lead to zonal differences in the characteristics of short-term climate periods. Blocking of the westerly windstream due to stationary cyclones or anticyclones may cause partly persistant weather anomalies (see GRAEDEL & CRUTZEN 1993).

Climate periods like the Little Ice Age (1350-1900 AD) or the Medieval Warm Period (800/1000-1350 AD) have dramatically affected human life during the past 2000 years. Models of future climate development predict fluctuations similar to those of historical times, but even higher in amplitude (HOUGHTON et al. 1990, JONES & WIGLEY 1990).

Such climate fluctuations can be related to the variability of the main westerly windstream and the cyclone tracks, moving northward during warmer and southward during cooler periods (LAMB 1969, 1977). These movements are accompanied by changing mean wind directions on the earth's surface and, thus, are likely to affect strengths and directions of surface currents as well as bottom currents which can be traced by means of sedimentological working methods. The Skagerrak (NE North Sea) was chosen for the analysis of climate-forced changes in the circulation of water masses, because the intensity and pattern of surface and bottom currents between the North and Baltic Seas and the North Atlantic have recently been found to be very sensitive to climatic variations during late Holocene (HASS 1993, in press). Thus, the Skagerrak appears to be

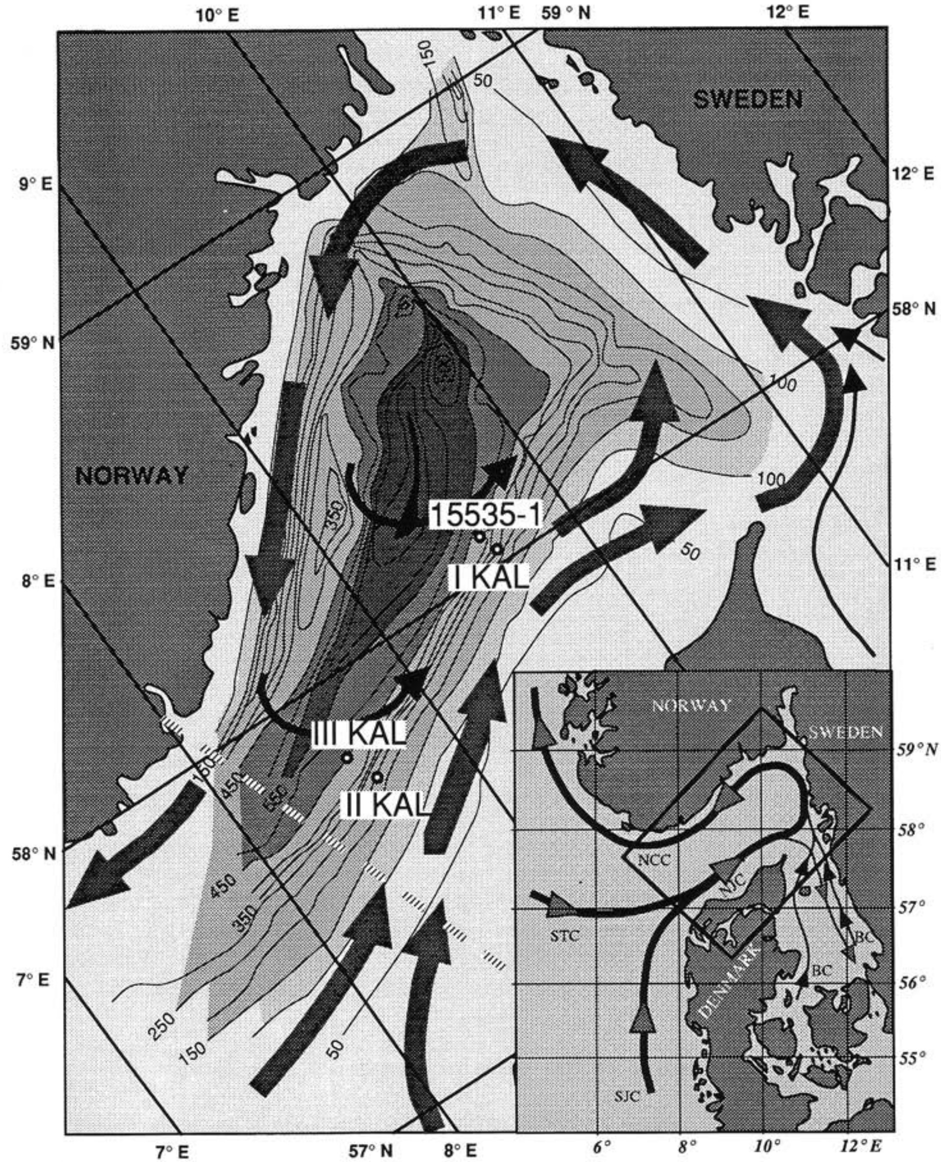


Fig. 1. The Skagerrak. Current circulation system (after SVANSSON 1975) (SJC = South Jutland Current, NJC = North Jutland Current, STC = South Trench Current, BC = Baltic Current; NCC = Norwegian Coastal Current, after NORDBERG 1991); bathymetry (after HEMPEL 1985) and core locations (Stations 15535 and III are referred to in this paper).

a suitable region to provide a means for correlation of terrestrial (e. g. ice cores) and marine records of short-term climate change which is one of the major goals in Global Change research.

2. Study area, material and methods

The Skagerrak forms the deepest part (>700 m water depth) of the Norwegian Trench (Fig. 1). Water mass exchange between the Baltic Sea and the World Ocean runs exclusively through Kattegat and Skagerrak via the Baltic Current (BC). North Sea water masses are transported into the Skagerrak domain by the South Jutland (SJC) and the South Trench Currents (STC) (see NORDBERG 1991, SVANSSON 1975). Currents may accelerate up to 150 cm/s (North Jutland Current = NJC; FONSELIUS 1990) along the northern Danish coastline due to the strength of prevailing winds. Hence, bedload sediment in the shallower areas is forced to move as large sand waves partly grounded on outcropping glacial strata (see KUIJPERS et al. 1993). Further east currents decelerate dramatically, discharging huge masses of suspended matter onto the southeastern flank of the Skagerrak (VAN WEERING 1981). Brackish water masses originating from the Baltic Sea enter via the mouth of the Kattegat, mix with Skagerrak waters and then slowly leave the Skagerrak along the southern Norwegian coastline as Norwegian Coastal Current (NCC).

Various investigations (e. g. AURE & SAETRE 1981, RODHE 1987, FONSELIUS 1989) have shown that westerly and southwesterly winds intensify water mass circulation in the Skagerrak. The high velocity core of the Jutland Current was observed to move downslope during the stormy winter season (RODHE 1987). Easterly winds, however, are not able to amplify the circulation and are more likely to hamper the circulation by slowing down current velocities.

High resolution granulometry and a variety of further sedimentological and micropaleontological methods were applied to a set of four long cores and corresponding box cores (see HASS in press). The classic 'excess' ^{210}Pb dating method combined with a recently developed method of 'supported' ^{210}Pb (see ERLENKEUSER & PEDERSTAD 1984, ERLENKEUSER 1985) was applied for age determinations of the past 3.5 ky.

3. Sedimentation rates and sediment transport

Datings yielded sedimentation rates between 0.7 (Core II KAL, western Skagerrak) and 54 mm/y (Core 15535-1, eastern Skagerrak). The westerly and easterly locations can both be regarded as high accumulation areas. Fig. 2 shows age-depth relationships for Cores III KAL and 15535-1 as an example. Plateaus indicate periods of high sedimentation rates, while steeper curves suggest lower sediment accumulation. The base of Core 15535-1 was dated to ca. 700 AD (i. e. an age of ca. 1300 years). Core III KAL, however, exceeds the limiting value of the dating function (about 3500 years) at 3 m core depth. Hence, high accumulation is much more prominent in the eastern Skagerrak. Core 15535-1 is characterized by a sequence of plateaus and steeper sections in the age-depth relation curve. This can be explained by a "Mud Conveyor Belt" (MCB; HASS in press).

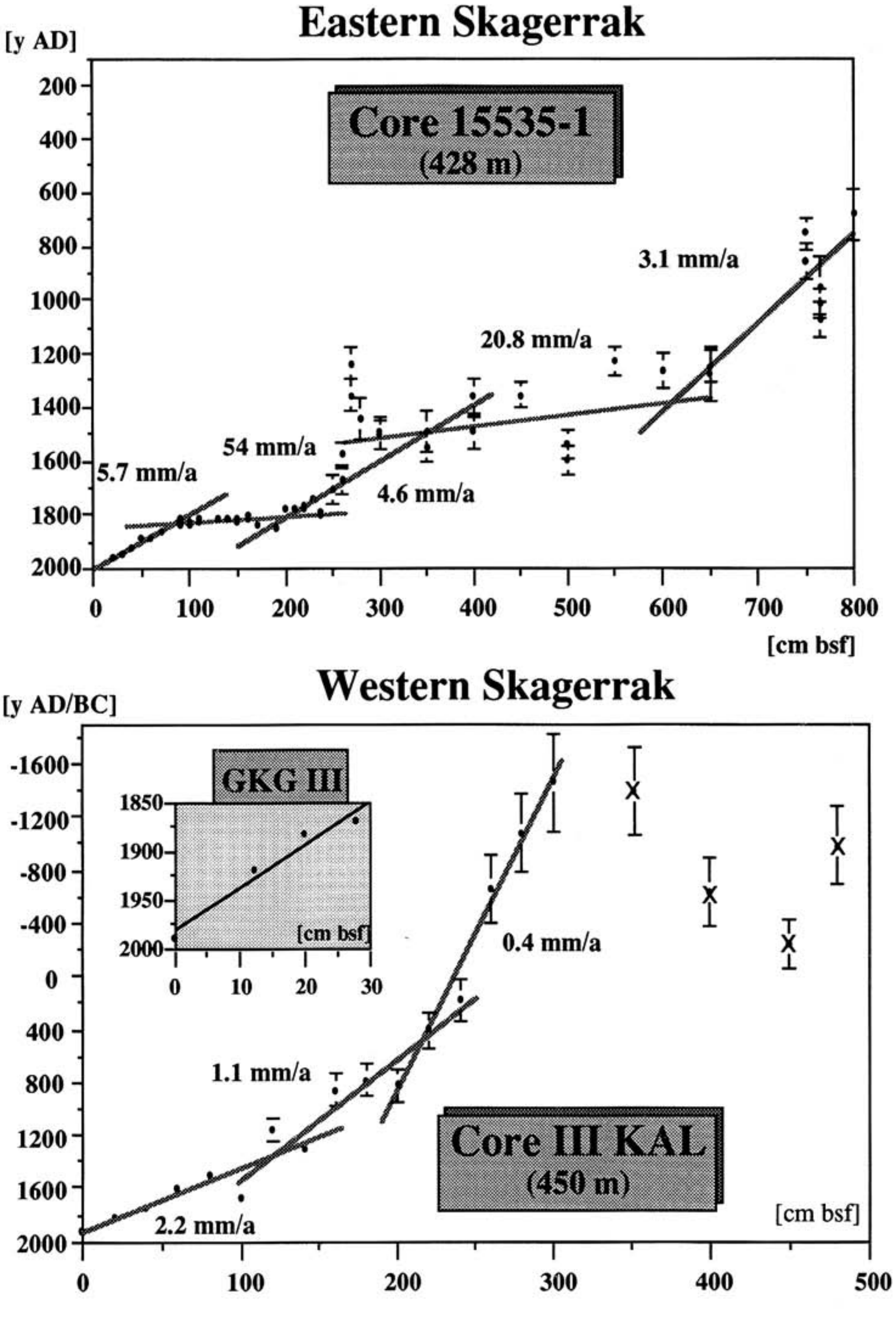


Fig. 2. Age-depth relationship of Cores 15535-1 and III KAL (III GKG is the corresponding box corer for surface samples). Age determinations of surface Core 15535-2 (ERLENKEUSER unpubl. data) are included in the upper diagram (measurements: C14 Laboratory, Kiel).

During periods of intensified water mass circulation in the Skagerrak high quantities of suspended load accompanied by a significant amount of coarser bedload are transported over the southwestern flank of the Skagerrak from West to East. In the eastern Skagerrak, however, where currents decelerate bedload and a great portion of the suspended material settles, thus producing extremely high sedimentation rates (MCB strong). Low energy periods, however, are marked by reduced sediment transport which causes decreased sedimentation rates in the eastern Skagerrak (MCB weak).

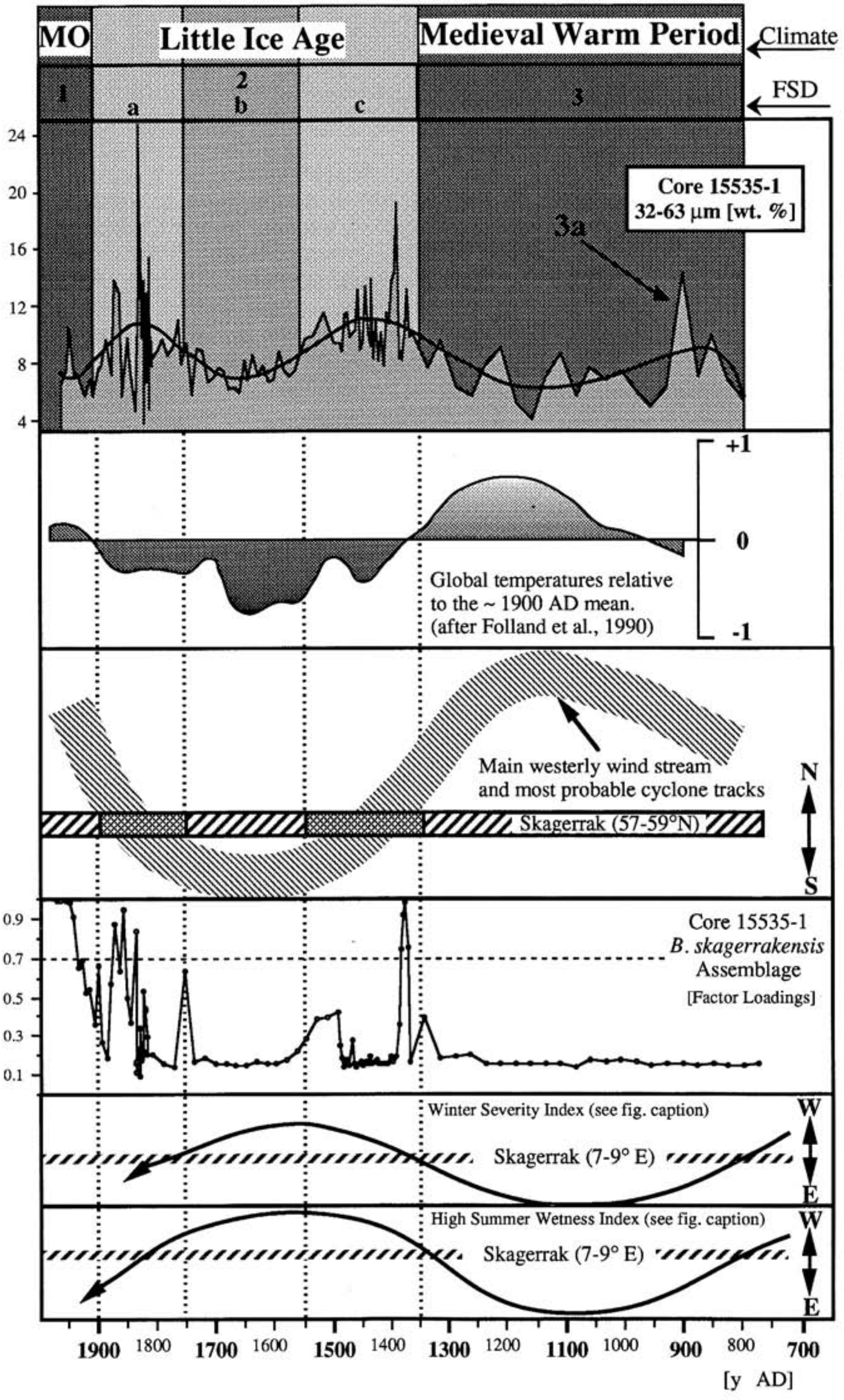
From the sedimentation rates it can, thus, be inferred that at least between ca. 1350 and 1500 AD and between 1800 and 1850 AD the MCB was highly active indicating intensified bottom current circulation due to the influence of forcing westerly winds.

4. Sensitive grain-size classes

High-resolution grain-size analyses of the four cores from the southern flank of the Skagerrak were given by HASS (1993, in press). Those grain-size classes which mark the transition between bedload and suspended load related to the predominant bottom current velocities were called "sensitive grain-size classes". Under high-energy conditions the bottom currents take up maximum amounts of suspended matter, while a significant quantity of coarser material is rolled and saltated over the ground as bedload (high MCB activity). The amount of transported bedload is likely to have a strong relation to the prevailing current energy. Yet, when the currents slow down the so-called sensitive grain-size classes settle, being replaced by another (finer) grain-size class which is indicative of the new current energy.

If the mean long-term current energy does not change significantly the sensitive grain-size class can be outlined by a simple trend analysis. Firstly a "mean" grain-size class related to current energies must be determined. Within the grain-size spectrum it is situated where the next finer grain-size class shows a positive or a negative percentage trend and the next coarser grain-size class shows the opposite trend. The sensitive grain-size class, then, is the next coarser or next finer to the "mean" grain-size class. Numerous analyses and comparisons suggested the next coarser grain-size class to be most indicative of current velocity fluctuations.

Fig. 3. From top to bottom: interpreted climate periods; lithofacies subdivisions (FSD); sensitive grain-size class of Core 15535-1; global temperature variations relative to the ~1900 AD mean (after FOLLAND et al. 1990); interpreted movement of the main westerly windstream; dominance of the benthic foraminifer *B. skagerrakensis* (result of the q-mode factor analysis of the benthic foraminifer fauna carried out by HASS (in press), this factor (benthic foraminifer assemblage) is formed by *B. skagerrakensis* alone); LAMB's Winter Severity Index and Summer Wetness Index: movement of maximum anomalies (redrawn after LAMB 1969).


MO
Little Ice Age
Medieval Warm Period
Climate
1
2
a
b
c
3
FSD
24
20
16
12
8
4
Core 15535-1
32-63 μm [wt. %]
3a
+1
0
-1
Global temperatures relative
to the ~ 1900 AD mean.
(after Folland et al., 1990)
Main westerly wind stream
and most probable cyclone tracks
Skagerrak (57-59°N)
N
S
0.9
0.7
0.5
0.3
0.1
Core 15535-1
B. skagerrakensis
Assemblage
[Factor Loadings]
Winter Severity Index (see fig. caption)
Skagerrak (7-9° E)
W
E
High Summer Wetness Index (see fig. caption)
Skagerrak (7-9° E)
W
E
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
[y AD]

The sensitive grain-size classes for the investigated cores are in the coarse silt and very fine sand classes (HASS in press). Fig. 3 depicts the sensitive grain-size fraction of Core 15535-1 versus years AD. The general trend is visualized by a multigrade polynomial curve fit. Fluctuations in the sensitive grain-size class are marked by lithofacies subdivisions (FSD). Three FSDs are recognized:

FSD 3 marks a period of reduced bottom current velocity. Fig. 3 indicates a lower sedimentation rate; the percentage of the sensitive grain-size fraction is generally lower compared to the rest of the core. Hence, it can be postulated that the MCB was weak and that there was no prominent influence of strong westerly winds and storms. Oxygen isotope analyses ($\delta^{18}O$; HASS in press) indicate a warmer water body during FSD 3 which temporally covers the Medieval Warm Period. However, between 800 and 900 AD a conspicuous peak in the coarse silt fraction (marked FSD 3a) suggests a short interval of probably increased atmospheric forcing, which could either be the ending of the preceding "climate deterioration of the migration of peoples" (SCHÖNWIESE 1979) or a cold spell within the Medieval Warm Period.

FSD 2 covers the climate deterioration of the Little Ice Age between 1350 and 1900 AD. The sensitive grain-size record suggests two phases of intensified bottom current circulation: FSD 2c and FSD 2a. The maximum of the Little Ice Age, however, is characterized by reduced bottom current energy. It can, therefore, be inferred that at the beginning and at the end of the Little Ice Age strong and stormy westerly winds accelerated the water mass circulation in the Skagerrak. While sedimentation rates during FSD 2b were comparatively low (4.6 mm/y), they increased to 20.8 mm/y (FSD 2c) and even 54 mm/y (FSD 2a) at the beginning and the end of the Little Ice Age. Thus, during the stormy phases the MCB was highly active. The maximum of the Little Ice Age, however, was probably not influenced by stormy westerlies since sedimentation rates and the amount of the sensitive grain-size class indicate a weak MCB.

FSD 1 is marked by a trend to lower circulation energies. All cores investigated so far reveal decreasing amounts of the sensitive grain-size fraction indicating the weakening of the MCB after the last and most turbulent phase of the Little Ice Age. FSD 1 covers the period of the Modern Climate Optimum.

5. Benthic environments

Periods of strong bottom current pulses most probably triggered and supported the immigration of the benthic foraminifer *Bolivina skagerrakensis* QVALE & NIGAM, 1985 into the Skagerrak area. The genus *Bolivina* is interpreted to be opportunistic, dominating benthic foraminiferal assemblages in physical disturbed areas, such as in areas with occasionally strong bottom currents or in areas of high sedimentation rates. For example, the living benthic foraminiferal fauna collected from box cores in the South China Sea two years after the Pinatubo volcanic ash fall were dominated by species of *Bolivina* which confirms our interpretation that this species is an opportunist (KUHNT pers. comm. 1994). *Bolivina* dominated faunas are also well developed under eutrophic conditions and in areas that experience seasonal dysoxia such as the northern Gulf of Mexico and the California borderland basin (MACKENSEN & DOUGLAS 1989). Its record in the Skagerrak, therefore, signals periods of disturbed conditions at the sea floor. *Bolivina skagerrakensis* shows a sudden increase in percentage as well as in frequency during stormy FSD 2c (Fig. 3, expressed in factor loadings). Values then decrease parallel to the 'calm' Little Ice Age maximum but increase again during the most turbulent last phase of the Little Ice Age (FSD 2a). After a short-term decline *B. skagerrakensis* becomes abundant again and after few decades it dominates the foraminifer fauna with more than 70 grain %, while it can be inferred that the *B. skagerrakensis* spikes during the stormy phases of the Little Ice Age reflect intensification of bottom currents. In contrast, its dominance since the onset of the present century may result from a strong increase in eutrophication associated with increased agricultural runoff into the North Sea and Skagerrak waters.

6. The atmosphere in motion: consequences for the Skagerrak circulation system

6.1 The Medieval Warm Period

The sedimentological data indicate that during the Medieval Warm Period mean wind velocities from westerly directions were decreased or wind directions were more easterly in nature. Investigations by LAMB (1977; see also FLOHN 1985) revealed that Middle Europe was frequently affected by persistent anticyclones during the Medieval Warm Period. This anticyclonic circulation pattern was able to push the main westerly windstream (i. e. the most probable cyclone tracks) about 3-5° to the North. Consequently, the Skagerrak was affected by only weak meridional anticyclonic southwesterlies on the average, which did not have significant effects on the water mass circulation intensity of the Skagerrak. Additionally, the zone of wet summers and severe winters which predominated until ca. 800 AD appears to have moved eastwards, thus suggesting especially mild conditions between 1000 and 1200 AD (LAMB 1969: fig. 3).

FSD 3a which indicates a cold spell around 900 AD (HASS in press) can be regarded either as a cold spell within the Medieval Warm Period or as the final part of a cold phase preceding the Medieval Warm Period. BRIFFA et al. (1992) suggested a colder interval at least for northern Sweden between 800 and 900 AD according to tree ring analyses. Greenland's Ice Cores Camp Century and Crête reveal similar features (DANSGAARD et al. 1975). Ice Core GISP2 shows two colder phases between 900 and 1000 AD which, however, are assigned to a preceding climate deterioration (O'BRIEN pers. comm. 1994, unpubl. data). Hence, one or more cold spells undoubtedly took place; only the assignment appears to be a problem.

6.2 The Little Ice Age and the Modern Climate Optimum

Between 1300 and 1400 AD (between 1200-1300 and 1600-1700 AD according to LAMB 1965) the Polar climate zone began to expand toward the south. This process also forced the main westerly wind stream and the cyclone tracks to move southwards. Synchronously, LAMB's Winter Severity and High Summer Wetness indices (Fig. 3; LAMB 1969, 1977) indicate increasing summer wetness and the beginning of a period of cold winters. It can be postulated that in the mid-14th century AD the outer margins of the cyclone tracks came in contact with the Skagerrak circulation system. Strong westerly winds and frequent storms are reported from the North Sea region during the onset of the Little Ice Age (LAMB 1977, 1991). Already as early as the 13th century AD scattered severe storms affecting the German and Danish coastlines led to death tolls of more than 300,000 (LAMB 1982). The granulometric and micropaleontologic data suggest a period of strong current pulses which disturbed the benthic environment and probably generally increased current velocities during this period. This is assigned to the first phase of the Little Ice Age (FSD 2c, 1350-1550 AD). The global temperature curve given by FOLLAND et al. (1990) shows a first temperature minimum characterizing the first phase of the Little Ice Age around 1450 AD. Sodium flux data from the Greenland Ice Core GISP2 indicate a first maximum phase of the Little Ice Age between 1400 and 1550 AD (O'BRIEN pers. comm. 1994, unpubl. data).

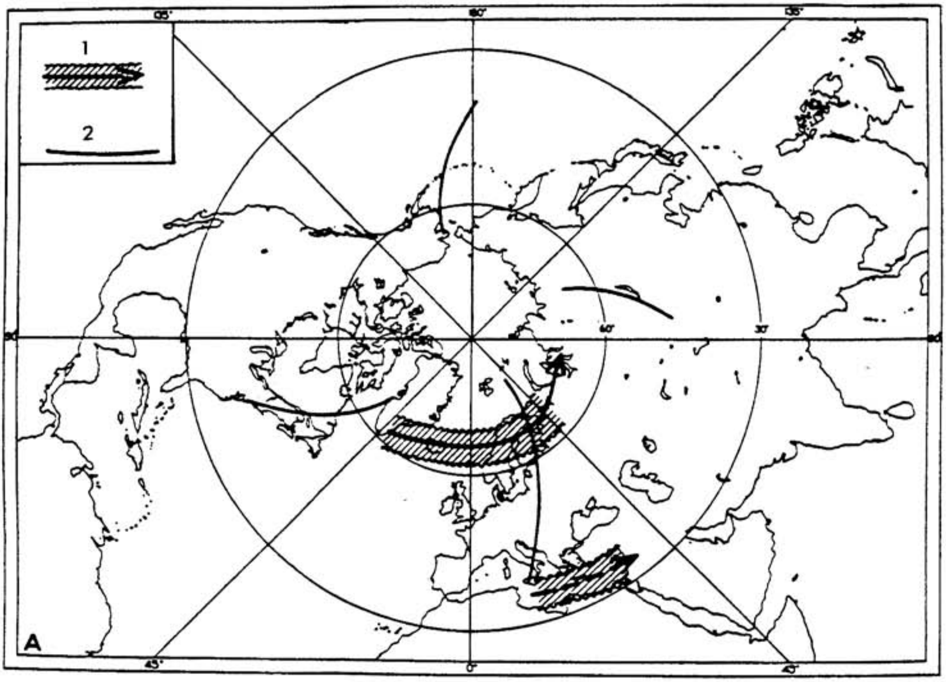


Fig. 4. Probable zones of most frequent depression passages and probable preferred longitudes for axes of cold upper troughs: summer 1000-1100 AD (LAMB 1969). 1: Approximate zone of most frequent depression. 2: Approximate longitude of most frequent upper trough axes.

Global temperature data (FOLLAND et al. 1990) show the maximum for the Little Ice Age to be between 1550 and 1750 AD. This is in excellent agreement with data from the Skagerrak. However, the granulometric data indicate that the Little Ice Age maximum should have been a calm and not very stormy phase, at least not affected by strong westerlies like the first phase between 1350 and 1550 AD. LAMB (1969) depicted the movement of the most probable depression tracks for two periods of the Little Ice Age (Figs. 4 and 5). Thereafter, it is evident that the cyclone tracks approximated the Skagerrak region and even covered it at a certain interval during the Little Ice Age maximum. The data shown in this paper, however, indicate decreased westerly wind forcing. This may be explained by the continuous southward migration of the main westerly windstream or a probable formation of a semipermanent (Rossby-) wave trough over northern Europe. In both cases and under the supporting influence of frequent formations of anticyclones over northern Russia (LAMB 1977) the Skagerrak system could have been subjected to more easterly wind directions, thus causing a decrease in current strengths and probably heavier weather conditions south of the Skagerrak over the North Sea area. The temperature minimum can be explained by frequent episodes of cold arctic air travelling southwards due to this special atmospheric setting (see also LAMB 1969).

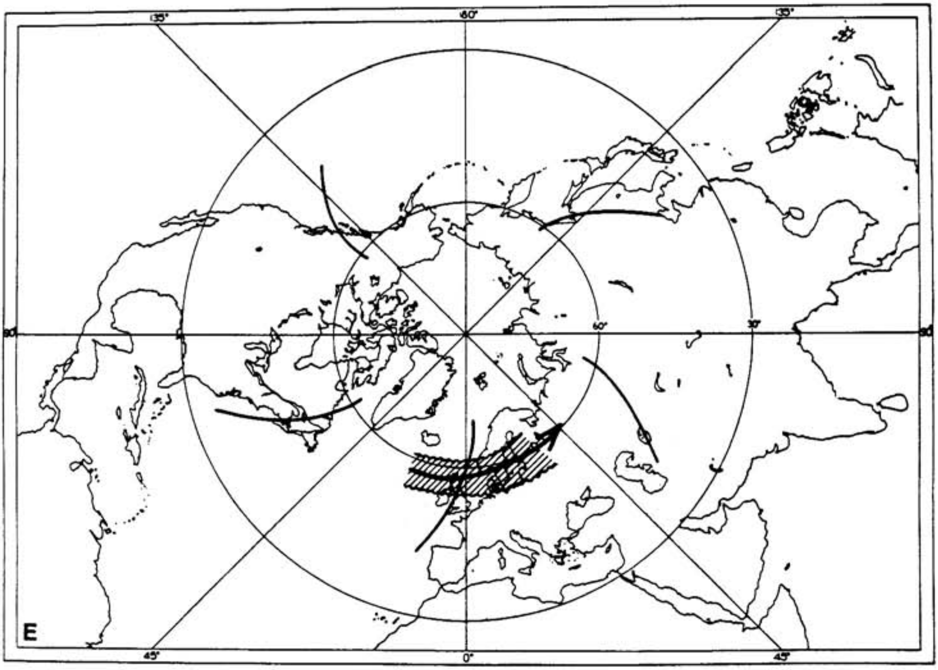


Fig. 5. Probable zones of most frequent depression passages and probable preferred longitudes for axes of cold upper troughs: summer 1550-1600 AD (LAMB 1969).

The last phase of the Little Ice Age is marked by another minor temperature minimum (FOLLAND et al. 1990). High amplitude and high frequency variations in the granulometric record and a return of opportunistic benthic foraminiferal assemblages indicates strongly intensified water circulation and turbulence during this phase. Hence, strong and stormy westerlies can be inferred. The movement of the atmospheric front systems obviously reversed during the Little Ice Age maximum. Thus, moving back northwards, storms and strong westerly gales again affected the Skagerrak region as in the first phase of the Little Ice Age.

After 1900 AD the main westerly windstream progressed further North and, consequently, storminess decreased. Lower sedimentation rates and decreasing amounts of the sensitive grain size mark the lower current energy period of the Modern Climate Optimum.

7. Conclusions

The Skagerrak appears to be a key area for understanding much of the late Holocene climatic evolution, at least for the region of the North and Baltic Seas. It can be shown that climate-forced changes in wind direction and strength affected the circulation in the Skagerrak system to a strong degree and left a clear record in the sediments.

Most of the colder periods during the past ca. 1300 years are characterized by strong and probably stormy westerlies which result from the southward movement of the main westerly windstream (see LAMB 1969). The opposite is true for the warmer climate phases: due to various processes the cyclone tracks moved northward, hence, strong westerlies became rare over the Skagerrak region.

The Medieval Warm Period is characterized by generally lower sedimentation rates and finer sediments. We conclude that the main westerly windstream was situated further north. The northernmost situation may have been reached between 1000 and 1100 AD. Between 800 and 900 AD a stormy episode can be outlined. Between 1300 and 1400 AD the cyclone track zone began to move southward. The termination of the Medieval Warm Period and the onset of the Little Ice Age can thus be dated at 1350 AD.

The first phase of the Little Ice Age is marked by sediments which indicate higher current energy conditions. During the period between 1350-1550 AD the cyclone track zone had great influence on the Skagerrak current system as a part of it crossed the Skagerrak (see LAMB 1969). It can be speculated that the core of the main westerly windstream moved further southward during the Little Ice Age maximum (1550-1750 AD) which resulted in more easterly wind directions over the Skagerrak and generally lower temperatures (see FOLLAND et al. 1990). The last phase of the Litte Ice Age (1750-1900 AD) was again characterized by stormy westerlies which were likely to amplify water circulation in the Skagerrak system. Thus, the movement of the main westerly windstream reversed and, moving back northwards, it caused a second stormy phase over the Skagerrak. The presence of benthic foraminiferal assemblages comprised of opportunistic forms indicates unstable substrates at the sea floor during the stormy phases of the Little Ice Age.

Around 1900 AD the cyclone track zone moved beyond the limits of the Skagerrak system in the course of the beginning of the Modern Climate Optimum.

Models of future climate development indicate a worldwide warming over a temperature range which exceeds by far natural temperature fluctuations of at least the past several thousand years (JONES & WIGLEY 1990, HOUGHTON et al. 1990); most probably the planet will experience temperatures not seen for about 120 ky (GRAEDEL & CRUTZEN 1993). Since it can be shown that with rising temperatures storm and wind activities decrease at certain latitudes because of the movement of the main westerly windstream, we can speculate that e. g. the Baltic Sea will suffer serious ecological problems in the next few decades. By decreasing storm activities injections of oxygenated water into the Baltic Sea via the Skagerrak will be strongly limited, whereas increasing temperatures and continuing pollution will most probably cause intensive eutrophication.

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