Reconstruction of Holocene sea-surface salinity in the Skagerrak–Kattegat: a climatic and environmental record of Scandinavia

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ABSTRACT: Holocene sea-surface salinity in the Skagerrak–Kattegat is reconstructed using weighted averaging regression and calibration (WA) of diatom data from core Skagen 3. Diatom data from surface sediments together with 10-yr mean values of salinity and water temperature were used as a modern training set. Canonical correspondence analysis (CCA) was used to identify statistically significant directions of variation within the training set. The results of forward selection of the environmental variables and associated Monte Carlo permutation tests of the statistical significance of each variable, the canonical coefficients, and the intraset correlations of the environmental variables with the CCA axes suggest that summer and winter sea-surface salinities (SSS, WSS) are potentially reconstructable from fossil diatom assemblages. The changes in sea-surface salinity during the Holocene can be correlated with changes in climate of the circum-Baltic area, the current patterns of the Skagerrak–Kattegat, and the development of the Baltic Sea. Generally low SSS and large differences between WSS and SSS (ΔS_{w-s}) during 9000–6000 yr BP might have resulted from a climate with higher precipitation than today in the circum-Baltic area and its catchment, or a climate with maximum precipitation in late spring or early summer. The mechanism behind these patterns may be the combination of the northward shift of the jet stream and a stronger surface westerly penetration into the continent caused by a reduced latitudinal insolation gradient and enhanced land–sea contrast in the early to middle Holocene. It was, however, complicated by local events such as changes in the strength of various currents in the Skagerrak–Kattegat, successions of Baltic brackish and freshwater phases, and hydrodynamic conditions in the circum-Baltic area. © 1998 John Wiley & Sons, Ltd.

KEYWORDS: Holocene sea-surface salinity; canonical correspondence analysis (CCA); weighted averaging regression and calibration (WA); diatom; Skagerrak–Kattegat.

Introduction

Sea-surface salinity is highly correlated with regional sea-current patterns. Changes in sea-surface salinity should thus reflect variations in sea-current patterns. The Skagerrak–Kattegat is hydrographically characterised by the outflow of low saline water of Baltic origin in the southern Kattegat and along the Swedish and the Norwegian coasts, and the inflow of highly saline water from the North Atlantic on the North Jutland Shelf (Fig. 1). The interaction of these two major components determines sea-surface salinity. Based on the variation in freshwater supply of one of the larger rivers

to the Baltic Sea and surface salinity measured at Light Vessel *Schultz's Grund*, southwestern Kattegat, Svansson (1975) concludes that low precipitation in the Baltic Sea and its catchment gives rise to high salinity in the Kattegat. Schott (1966), who carried out Fourier analysis of time series of monthly means of surface salinity, shows that long-term fluctuations of surface salinity in the North Sea can be correlated with fluctuations in river discharge and in precipitation. Although the salinity pattern shows similar behaviour during winter and summer, the salinity in summer is about 2 g l^{-1} lower in the surface water entering from the Kattegat, and 1 g l^{-1} lower in the surface water entering from the North Sea than it is in winter (Rodhe, 1992). These results suggest that the outflow of water from the Baltic Sea has a greater influence on changes in sea-surface salinity in the Skagerrak–Kattegat than the inflow of water from the North Sea, in particular during summer. Hence, reconstruction of the sea-surface salinity in the Skagerrak–Kattegat could give

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Figure 1 Locations of core sites and the area investigated. Surface sediment cores are marked by bold circles and core Skagen 3 is marked by a bold square.

indications of both modifications in regional hydrography and climatic changes in the neighbouring areas.

Jiang (1996) studied the diatoms from surface sediments of the Skagerrak–Kattegat and their correlation with the spatial changes of environmental variables, such as salinity and temperature. Diatom study on ca. 116 m of marine sediments in the Skagerrak–Kattegat provides a continuous and detailed palaeoceanographic and palaeoenvironmental record of the last 11 000 yr BP in the area (Jiang *et al.*, 1997). In this paper we use diatom data from surface sediments and modern environmental data as a training set to reconstruct the Holocene sea-surface salinity (summer sea-surface salinity, SSS; winter sea-surface salinity, WSS; and differences between winter and summer sea-surface salinity, ΔS_{w-s}) from the Skagerrak–Kattegat.

We expect that changes in WSS during the Holocene most likely reflect variations in the strength of the highly saline water flowing into the Skagerrak–Kattegat, specifically at this site the Jutland current. The SSS is supposed to be strongly reduced by the Baltic Current because the SSS of the Baltic Sea is much lower than in the Skagerrak–Kattegat, even being totally fresh during the early Holocene (Björck, 1995). The changes in SSS of the Skagerrak–Kattegat mirror variations in the Baltic outflow, which is controlled by climatic factors in its catchment, mainly precipitation. We draw on observations of modern oceanography and climatology of the region to explain the changes in sea-surface salinity, and further we relate these changes to external climatic factors, including changes in insolation and local hydrodynamic events.

Material and methods

Modern data

Salinity and water temperature data used for the numerical analyses are the mean values for the period 1980–1990 at the surface and bottom of the water column in summer and winter, with a temperature range of between 0.3°C and 17.3°C and a salinity range of 13.7 g l⁻¹ to 35.2 g l⁻¹ (Jiang, 1996). These data were provided by the Oceanographic Laboratory of the Swedish Meteorological and Hydrological Institute. A few data covering the period between 1983 and 1993 were provided by the Geological Survey of Denmark. Nineteen diatom samples from surface sediments with environmental variables were used to develop a modern training set. In total, 117 taxonomic entities were distinguished. Diatom assemblages are dominated by temperate and/or cosmopolitan species. Canonical correspondence analysis (CCA) (ter Braak 1986, 1988, 1990) was used to identify statistically significant directions of variation within these samples. In the first screen of CCA analysis, water depth was excluded because it is almost perfectly correlated with other variables (variance inflation factor, VIF, is larger than 20) (ter Braak 1988, 1990). The VIF values of eight other variables are less than 10, suggesting that each of them makes a unique contribution to the regression equation (Jiang, 1996). After four to five screenings, three to four samples were deleted from palaeo-SSS and palaeo-WSS reconstruction based on the criteria proposed by Birks *et al.* (1990b), and zero to eleven species were deleted because of their unclear ecological information. This resulted in high root-mean-square error of prediction (RMSEP) in weighted averaging regression and calibration (WA). The eigenvalues for CCA axes 1 and 2 are 0.41 and 0.19 and the species–environment correlations for CCA axes 1 (0.98) and 2 (0.93) are high. Monte Carlo permutation tests (99 unrestricted permutations) indicate that there is only one significant major gradient captured by axis 1 ($p = 0.01$). The results of forward selection of the environmental variables and associated Monte Carlo permutation tests of the statistical significance of each variable, the canonical coefficients (as judged by an approximate *t*-test, *t* values larger than 2.1), and intra-set correlations of the environmental variables with the CCA axes, show that SSS, WSS, SBT (summer sea-bottom temperature), and WBS (winter sea-bottom salinity) are individually significant ($p = 0.01$ – 0.05 , 99 unrestricted permutations) and that SSS and WSS are the most important environmental variables, especially SSS. These two environmental variables explain about 37% of the total variance in the diatom data, of which SSS alone accounts for about 30%. Therefore, these two variables are potentially reconstructable from fossil diatom assemblages.

The fossil data

Diatom data from core Skagen 3 (Jiang *et al.*, 1997) were used for palaeo-SSS and palaeo-WSS reconstruction purposes (Fig. 1). The samples below 114.9 m are not included because the diatom assemblages from these samples are totally different from those in the training set, being dominated by sea-ice species. In total, 52 samples from 31.3 m to 114.9 m were analysed and they cover the period from ca. 10 000–1000 yr BP. The radiocarbon datings (AMS) are from Conradsen and Heier-Nielsen (1995) and are linearly

interpolated against core depths (Jiang *et al.*, 1997). A standard marine reservoir correction of 400 yr is subtracted from the dates. Some taxa at core Skagen 3 are absent from the training set and vice versa. Weighted averaging regression and calibration (WA) were used to reconstruct SSS and WSS separately. Classical regression was used to deshrink inferred SSS values and inverse regression to deshrink inferred WSS values because it minimized RMSEP in the training set (Birks *et al.*, 1990a).

In total, 76 species were used as active taxa in the numerical analysis. Seven diatom assemblage zones were distinguished (Table 1). During 10 100–9600 yr BP, temperate and/or cosmopolitan marine littoral species dominated the diatom assemblage. The main species are *Cocconeis scutellum* var. *parva*, *Cymatosira belgica*, *Delphineis surirella*, and *Campylosira cymbelliformis*. The diatom assemblage of 9600–8600 yr BP is composed mainly of marine tychoplanktonic species such as *Paralia sulcata*, *Podosira stelliger*, and *Actinopterychus senarium* (Hendey, 1964; Stabell, 1985; Jiang, 1996). Some marine littoral species that tolerate low salinity (e.g. *Grammatophora oceanica*, *Diploneis constricta*, and *Diploneis suborbicularis*) also occur in the zone. Jiang *et al.* (1997) suggest that the replacement of *Cocconeis scutellum* var. *parva* and *Cymatosira belgica* by *Paralia sulcata*, *Podosira stelliger* and *Actinopterychus senarius* at 9600–8600 yr BP might be a result of the increased influence of currents along the Norwegian and the Swedish west coasts, with relatively lower salinity but higher summer sea-surface temperature. *Cocconeis scutellum* var. *parva* and *Cymatosira belgica* became the main components of the diatom assemblage with increased numbers of *Thalassionema nitzschioides* at about 8600–7700 yr BP. An abrupt increase in the abundance of *Cyclotella striata* occurred at 7700 yr BP, which suggests decreasing sea-surface salinity and a strong influence of the coastal currents. At about 5100–2000 yr BP the numbers of marine littoral diatoms, mainly *Delphineis surirella* and *Cymatosira belgica*, increase greatly. The abundances of *Delphineis surirella* may suggest a period of acceleration of the currents along the Danish west coast.

Evaluation of reconstructed SSS and WSS

Plots of inferred SSS and WSS against observed SSS and WSS (Fig. 2) show a homogeneous scatter over most salinity ranges and residuals are randomly scattered. The inferred SSS values are, however, slightly lower than observed ones, probably because of the lack of sample sites with the highest sea-surface salinity (Jiang, 1996). As the root-mean-square of the error (RMSE) (observed X_i – inferred X_i) is invariably underestimated when based solely on the training set, bootstrapping (1000 cycles), a computer-intensive resampling procedure (Birks *et al.*, 1990a), was used to estimate a more reliable RMSEP for the training set. The RMSEP and the root-mean-squares of the two error (RMSE) components (s_1 , s_2) for the training set are shown in Table 2. The RMSEP values are 2.777 (SSS) and 2.034 (WSS). Sea-surface salinity reconstructed from diatom data of Skagen 3 ranges from about 24 g l⁻¹ to 30 g l⁻¹ for SSS, and 28 g l⁻¹ to 30.5 g l⁻¹ for WSS, with a high fluctuation at about 6000–9000 yr BP. Compared with RMSEP of the modern diatom training set, we think that reconstructed sea-surface salinity can explain large changes in current pattern and major local events, especially SSS. However, it is not suitable for correlating detailed changes in palaeoenvironment. The s_1 value is small

Table 1 Developments of palaeoclimate and palaeoceanography since 11 000 yr BP based on diatom and foraminiferal data from Skagen 3 (Conradsen and Heier-Nielsen, 1995; Knudsen *et al.*, 1996; Jiang *et al.*, 1997). Abbreviation of SST is summer sea surface temperature

Diatom zones (¹⁴ C yr BP)	Climate and oceanography indicated by diatoms	Foraminiferal zones (¹⁴ C yr BP)	Climate and oceanography indicated by benthic Foraminifera
VII (2000–1000)	Large influence of the South Trench Current	A ₁ (3300–1000)	Higher energy conditions, gradually shallower water
VIb (3000–2000)	Weakening of the South Jutland Current		
VIa (5100–3000)	Acceleration of the South Jutland Current, and relatively low SST	A ₂ (5500–3300)	Higher energy condition, strengthening of the Jutland Current and climatic cooling
V (7700–5100)	Formation of the South Jutland Current, stronger influence of coastal currents along the Swedish west and Norwegian coasts, and high SST	A ₃ (7600–5500)	Opening of the English Channel and establishment of the modern circulation pattern
IV (8600–7700)	Strengthening of the North Jutland Current, and possibly relatively low water temperature	B (8600–7600)	Sediments were derived from a westerly source
III (9600–8600)	Higher SST, and stronger influence of coastal currents along the Norwegian and Swedish west coasts	C, D (9600–8600)	Major temperature change to boreal condition in the bottom water
II (10 100–9600)	An abrupt warming of the sea surface water, and SST exceeded 10°C	E _{1,2} (10 100–9600)	Arctic–subarctic marine environment in the bottom water
I (10 900–10 100)	Cold saline water with SST of about 2°C	E ₃ (10 900–10 100)	Arctic–subarctic marine environment

Figure 2 Plots of inferred SSS and WSS against observed SSS and WSS (g l⁻¹).

Table 2 Root-mean-square of the error of prediction (RMSE) of the modern diatom training set for SSS and WSS for simple weighted averaging (WA) and tolerance downweighted weighted averaging (WA_(tol)) estimated by bootstrapping (1000 cycles) using all taxa

SSS	RMSE prediction	RMSE <i>s</i> ₁	RMSE <i>s</i> ₂	WSS	RMSE prediction	RMSE <i>s</i> ₁	RMSE <i>s</i> ₂
WA	2.777	1.139	2.533	WA	2.034	0.724	1.901
WA _(tol)	5.025	2.749	4.206	WA _(tol)	2.486	1.283	2.129

(1.139 SSS, 0.724 WSS) for WA but large (2.749 SSS, 1.283 WSS) for weighted averaging with tolerance downweighting WA_(tol). These RMSE values suggest that the training set is capable of producing reliable estimates of the taxon optima required in WA, but that it is not large enough for reliable

estimation of all the taxon tolerances used in WA_(tol). The second error component (*s*₂) is invariably larger than the first component and reflects both the considerable natural variation in diatom assemblages at given SSS and WSS, and the fact that very similar assemblages can occur at different SSS and WSS values.

Interpretation of palaeo-SSS, palaeo-WSS and Δ Sw-s and discussion

Regional climate

Figure 3 shows the Holocene WSS (Fig. 3a), SSS (Fig. 3b) and Δ Sw-s (Fig. 3c) curves inferred from the fossil diatom assemblages in the Skagen 3 core. The WSS and SSS values have the same distribution patterns during the Holocene with constantly higher values of WSS, which is similar to modern ones, as mentioned above (Rodhe, 1992). The SSS values are generally lower between 9600 and 6000 yr BP, indicating stronger freshwater influence during that period. The Δ Sw-s values are higher than those of today with high variations between 9600 yr BP and 6000 yr BP, and slightly lower than or close to the present during the rest of the period (Fig. 3), as modern Δ Sw-s in the area are usually between 1 and 2 g l⁻¹ (Rodhe, 1992).

On the time-scale of the Holocene, changes in the latitudinal and seasonal distribution of insolation and changes in terrestrial geography must be regarded as boundary conditions controlling climate (Yu and Harrison, 1995). The combined changes in Earth's precession, obliquity, and eccentricity produce changes in the seasonal cycle of solar radiation and, in turn, produce climate changes. Compared with our present regime, the seasonality of solar radiation was considerably greater during the interval from around 12 000 to 6000 yr BP, reaching a maximum around 9000 yr BP when solar radiation was greatest in northern summers (Kutzbach and Webb, 1993). Increased summer insolation has been shown by GCM experiments to cause major changes in atmospheric circulation (Kutzbach and Guetter, 1984, 1986; COHMAP Members, 1988), such as a reduced latitudinal insolation gradient in both seasons and enhanced land-sea contrast at all latitudes (Berger, 1978; Harrison *et al.*, 1992). The reduction in the insolation gradi-

ent would have resulted in a northward shift of the jet stream (Harrison *et al.*, 1992) and the enhanced land-sea contrast would have resulted in stronger surface westerly penetration into the continent (Yu and Harrison, 1995).

Moisture-bearing air currents other than the westerlies enter Scandinavia or parts of it and produce rain or snow at different times of the year. None of these air currents are, however, as moisture-bearing, strong, or persistent as the westerlies and southwesterlies. The precipitation of Scandinavia is, therefore, to a great extent determined by the amounts of water released within these air currents under the influence of topography and, furthermore, by intensities of the air currents. On the whole, mean annual precipitation decreases eastwards in Scandinavia (Wallén, 1970). The stronger surface westerly penetration into the continent, which resulted from the enhanced land-sea contrast, would have produced higher annual precipitation (as both rain and snow) in the circum-Baltic area and, in turn, produced lower sea-surface salinity in the Skagerrak-Kattegat. Furthermore, the variations of the amount of precipitation and temperature during the year, the snow accumulation during the winter, and snow melting in spring exert a strong influence on the hydrology of the rivers and lakes in the Scandinavian countries (Wallén, 1970). In this respect the mountain rivers of Norway and Sweden generally show similar conditions, having a minimum discharge in late summer and winter and a maximum discharge in spring and early summer, as do the rivers in the lowlands of eastern Norway, central Sweden, and Finland. Hence, the higher annual precipitation in the area not only produced lower salinity, in particular SSS, in the Skagerrak-Kattegat but also enlarged the Δ Sw-s. Dahl and Nesje (1996) studied the Holocene winter precipitation (1 October–30 April) in Hardangervidda, southern Norway and the Scandes Mountains. The mean winter precipitation derived from pine-tree limit data was, in general, high during 9000–5500 yr BP, low between about 5500 and 3000 yr BP, and close to present after 3000 yr BP, which is comparable

Figure 3 Reconstructed sea-surface salinity (g l⁻¹) are plotted against ¹⁴C age for the core Skagen 3: (a) WSS; (b) SSS; (c) Δ Sw-s. Sea-surface salinity (WSS = 30, SSS = 28.5 and Δ Sw-s = 1.5) are selected as modern data near the core site. Successions of the Baltic brackish and freshwater phases are also indicated.

with the sea-surface salinity curve. Based on the study of two species of Lusitanian/Mediterranean ostracods, Vork and Thomsen (1996) also suggest that the temperature maximum of the Atlantic chronozone in southern Scandinavia may be connected to a stronger westerly airflow. There are, however, almost no lake-level data with sufficiently high time resolution from the middle and northern Sweden to test this hypothesis. Furthermore, changes in lake-level are due to changes in the local water budget (the balance of precipitation minus evaporation over lake and its catchment). The strong evaporation would have given rise to low lake levels but would have had less influence on sea-surface salinity, which makes the test even more difficult.

A conspicuous feature in the climate of Europe is the increase in continentality from west to east. Scandinavia is exposed to the prevailing westerly and southwesterly winds of the mean Icelandic low-pressure circulation. The westerly or zonal type of circulation, therefore, is the most frequent one and brings in warm, moist Atlantic air over Scandinavia all year, although there is a continuous change, from the zonal to the meridional types of atmospheric circulation throughout the year (Wallén, 1970). In western Europe, the cyclonic type of precipitation is more dominant than further eastwards where the convective type of precipitation gradually becomes of greater significance. As cyclonic activity over western Europe is much more intense in autumn and winter than in summer, the precipitation maximum occurs in these seasons in the Atlantic areas and the western central parts. In the eastern, more continental parts of the region, the dominant convective precipitation gives rise to a maximum in late summer; in southeast Europe the maximum occurs in late spring or early summer. Northward shifts of the jet stream caused by a reduced latitudinal insolation gradient would probably have resulted in a climate similar to that in southeastern Europe, with maximum precipitation in late spring or early summer. Thus, low SSS and high ΔS_w -s in the Skagerrak–Kattegat could also be explained as a result of such a climate, with maximum precipitation in late spring or early summer. Furthermore, a northward shift of the jet stream would possibly have given rise to higher precipitation in northern Scandinavia, and consequently lowered the sea-surface salinity in the Skagerrak–Kattegat, even if precipitation might be low in southern Scandinavia during some periods. This could probably explain why we have low WSS and SSS in the Skagerrak–Kattegat when lake levels in southern Sweden were low (Digerfeldt, 1988).

Local events

The Holocene WSS (Fig. 3a), SSS (Fig. 3b), and ΔS_w -s (Fig. 3c) data can be further correlated with major local events such as changes in the strength of various currents in the Skagerrak–Kattegat, successions of Baltic brackish and freshwater phases, and hydrodynamic conditions in the circum-Baltic area. High WSS at 9800–9500 yr BP suggests the strong influence of the North Jutland Current. A reduced influence of water of Baltic origin is mirrored by high SSS and low ΔS_w -s, which generally agrees with the brackish phase of the Yoldia Sea stage, less meltwater from the ice because of relatively cold conditions (Björck, 1995) and the lowest lake levels in southern Sweden (Digerfeldt, 1988). Low SSS between 9500 and 8500 yr BP suggests a strong influence of Baltic water, which is in agreement with the diatom and foraminiferal data (Knudsen *et al.*, 1996; Jiang *et al.*, 1997). The changes in the components of the diatom

assemblages at 9600 yr BP suggest stronger influences of the currents along the Swedish west coast and the Norwegian coast, with relatively lower salinity and higher summer sea-surface temperature (Jiang *et al.*, 1997). Benthic foraminiferal data from the same core show that a significant temperature change from arctic/subarctic to boreal conditions occurred at about 9600 yr BP in the deeper parts of the Skagerrak–Kattegat (Knudsen *et al.*, 1996). The idea of warmer summers for northern Europe at about 9000 yr BP is also supported by evidence that taxa requiring warm summers, particularly aquatics, were already present north of their present limits in Scandinavia shortly after 10 000 yr BP (Berglund, 1966; Iversen, 1973; Berglund *et al.*, 1984; Kullman, 1995). In addition, some components of the temperate deciduous forest (notably *Tilia cordata*) were already north of their present limits in the Baltic region by 9000 yr BP (Huntley and Birks, 1983), suggesting that this region too was experiencing summers warmer than at present as early as 9000 yr BP (Huntley and Prentice, 1993). Low SSS values during this period, which are supposed to be a result of high precipitation, however, are inconsistent with low lake levels in southern Sweden (Digerfeldt, 1988). The reasons for this are complicated. Strong evaporation would have given rise to a low lake level but would have had less influence on sea-surface salinity. Northward shift of westerlies would have resulted in decreased precipitation in southern Sweden, but an increase in precipitation in middle and northern Scandinavia (Yu and Harrison, 1995), where most of the Baltic catchment is located. Local hydrodynamic events, such as the rising Ancylus Lake level, created a significant transgression in the southern Baltic at about 9500–9200 yr BP (Björck, 1995), and the associated drainage would have resulted in increased freshwater discharge into the Skagerrak–Kattegat at about 9200 yr BP and consequently lowered WSS and SSS. A large discharge from the Baltic was recorded by a lower sea-surface salinity during the period of 7700–5900 yr BP, although the Baltic was brackish during the Littorina Sea stage. It is consistent with diatom, foraminiferal, and lake-level studies, which suggest larger effects of the Norwegian Coast Current and the currents along the Swedish west coast (Jiang *et al.*, 1997) and a warm and humid climate (Digerfeldt, 1988). The following high salinity period of about 1000 yr must have resulted from a dry climate as indicated by low lake levels (Digerfeldt, 1988), and an acceleration of the South Jutland Current (Jiang *et al.*, 1997). There was no major change in sea-surface salinity until about 1200 yr BP, when a tendency to a gradual decrease in salinity occurred, which parallels the increased lake levels (Digerfeldt, 1988). A short period of high lake levels around 3000–2400 yr BP seems to have been accompanied by a slightly lower sea-surface salinity.

Conclusions

1. A combination of CCA and WA has been shown to be a good method for quantitative reconstruction of palaeo-environmental variables in the Skagerrak–Kattegat based on diatom data. Canonical correspondence analysis was used to identify statistically significant directions of variation within the surface samples and to find the most important environmental variables affecting the diatom distribution. Weighted average regression and calibration was used for quantitative reconstruction of palaeoenvironmental variables.

2. Inferred WSS and SSS were evaluated by observed WSS and SSS, and bootstrapping (1000 cycles), a computer-intensive resampling procedure. Root-mean-square error of prediction values are 2.777 (SSS) and 2.034 (WSS). Compared with RMSEP of the modern diatom training set, reconstructed sea-surface salinity could explain large changes in current pattern and major local events, especially SSS, but is not suitable for establishing correlations with detailed changes in palaeoenvironment. The results also show that the training set is adequate for generating reliable estimates of taxon optima required in WA, but that they are not large enough for reliable estimations of all the taxon tolerances used in WA_(tol).
3. General low SSS and high Δ Sw-s during 9000–6000 yr BP might have resulted from a climate with either higher annual precipitation than today in the circum-Baltic area, or a climate having maximum precipitation in late spring or early summer. Mechanisms behind this may be a combination of the northward shift of the jet stream and stronger surface westerly penetration into the continent in the early to middle Holocene. This could have been caused by a reduced latitudinal insolation gradient and enhanced land–sea contrast due to increased summer insolation. It was further complicated by local events, such as changes in the strength of various currents in the Skagerrak–Kattegat, successions of brackish and freshwater phases, and hydrodynamic conditions in the circum-Baltic area.
4. The changes in Holocene sea-surface salinity can be correlated with modifications of current patterns in the Skagerrak–Kattegat, development of the Baltic Sea, and lake-level fluctuations in southern Sweden. High WSS and SSS at 9800–9500 and 5700–4700 yr BP show two distinct periods when highly saline water flowed into the Skagerrak–Kattegat, which could be correlated with an acceleration of the Jutland Current. Low WSS and SSS between 9500 and 8500 yr BP coincide with stronger influences of the currents along the Swedish west coast and the Norwegian coast, along with a warming in the Skagerrak–Kattegat mirrored by diatom and foraminiferal data. This resulted in a significant change in bottom-water temperature in the deeper parts of the Skagerrak–Kattegat.

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