Research paper

The Holocene
1–11

DOI: 10.1177/0959683617702223
journals.sagepub.com/home/hol

Regional climate change and the onset of farming in northern Germany and southern Scandinavia

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Abstract

In Europe, the transition from hunter–gatherer–fisher-based communities into societies mainly relying on farming was spread from the southeast towards the north and west during the Holocene. In central Germany, farming was adopted at ~7500 cal. yr BP, whereas the shift is evident at ~6000–5500 cal. yr BP in northern Germany and southern Scandinavia. Consequently, farming techniques were available for more than a millennium. Some studies argue that climate change might have played a role in the onset of farming in those areas. The aim of this study is to reconstruct the mid- to late-Holocene sea surface temperature (SST) evolution in the Skagerrak to document potential regional climatic impacts on changes in human economy. We compare our results with a record of human settlement activity in northern Germany and southern Scandinavia. Prior to ~6300 cal. yr BP, warm SSTs are documented throughout the Skagerrak, suggesting dominance of North Atlantic sourced water inflow providing mild climatic conditions. Between ~6300 and 5400 cal. yr BP, that is, concomitant with the shift in human economy, SSTs in the NE Skagerrak dropped by ~5–6°C, as also documented in mean annual air temperatures in central South Sweden, although less pronounced. The regional cooling suggests outflow of colder Baltic Sea water only affecting the NE Skagerrak and central South Sweden. Probably, numerous severe winters reflecting a continental-dominated atmospheric circulation pattern prevailed over the region. These changes most likely caused a gradual restriction in natural food sources, in particular from the marine realm. We thus suggest that hunter–gatherer–fishers were forced to adopt farming strategies to counter-balance this environmental stress. Our results indicate that regional changes in oceanography probably amplifying North Atlantic climate change in the western Baltic were an important factor that played a role in the adoption of farming in northern Germany and southern Scandinavia.

Keywords

agriculture, alkenones, Baltic Sea outflow, $C_{37:4}$, climate change, Holocene, northern Germany, sea surface temperatures, Skagerrak

Received 22 October 2014; revised manuscript accepted 17 February 2017

Introduction

In the frame of the interdisciplinary project 'Early Monumentality and Social Differentiation' at the University of Kiel, northern Germany, past regional climate and environmental conditions were reconstructed to comment on fundamental shifts occurring in regional human societies during the mid-Holocene period (~7500–4500 cal. yr BP). The transition from hunter–gatherer–fisher communities to societies with an economy mainly relying on animal husbandry and cereal cultivation was one of the most radical changes in recent human history, separating the Mesolithic from the Neolithic period. In Europe, farming was spread from the southeast towards the north and west during the Holocene period (past 12,700 cal. yr BP; Walker et al., 2012), whereas the transition took place as late as over the past three millennia in northern Scandinavia. In northern Germany and southern Scandinavia, first agricultural elements occurred at ~6000 cal. yr BP (Sørensen and Karg, 2012), and evidence for a fully developed agrarian society is documented at ~5500 cal. yr BP as manifested in cereal pollen and landscape opening (Dörfler et al., 2012; Feeser et al., 2012; Kirleis et al., 2012). In contrast, in adjacent regions more to the South, the agrarian economy was adopted much earlier at ~7500 cal. yr BP (Guilaine, 2000/2001; Schier, 2009). Consequently, the agrarian technology was most likely available to hunter–gatherer–fisher societies in northern Germany and southern Scandinavia for more than one millennium.

Many studies have proposed that climate and environmental changes potentially played a role in the onset of farming in northern Germany and southern Scandinavia (Bonsall et al., 2002; Gronenborn, 2007; Gronenborn et al., 2013; Hartz et al., 2007; Sørensen and Karg, 2012). The mid-Holocene period (~8000–4000 cal. yr BP) in the North Atlantic and northwestern Europe is typically described as a stable and mild climatic interval, with high temperatures, reduced precipitation and reduced or lacking glaciers (e.g. Hammarlund et al., 2003; Seppä and Birks, 2001;

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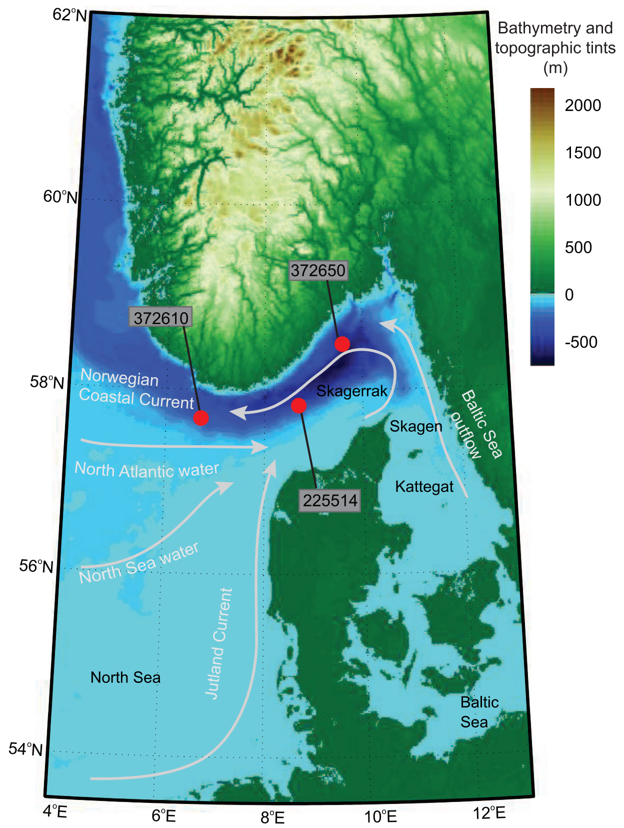

Figure 1. Core locations in the Skagerrak (core numbers in grey boxes). White solid arrows indicate present-day main surface currents in the Skagerrak and the Kattegat. The bathymetric and topographic lines are from IOC et al. (2003).

Seppä et al., 2005). These climate conditions were terminated by the Neoglacial cooling that occurred between ~6000 and 5000 cal. yr BP (Bakke et al., 2008; Bond et al., 2001; Jansen et al., 2008; Seppä et al., 2005; Zillén, 2003). Until now, the ultimate effect of climatic and environmental changes on shifts in the economic and cultural behaviour in human settlements in northern Germany and southern Scandinavia close to the Baltic Sea is still debated because of a dearth of high-resolution regional paleoenvironmental reconstructions.

Here, we reconstruct the mid- to late-Holocene sea surface temperature (SST; UK′37-SST) history from the western and central as well as from the northeastern Skagerrak (Figure 1), close to areas where the proper timing of settlements of first agrarian communities in northern Germany and southern Scandinavia is well documented. The coring sites allow us to comment on regional climate change that might have occurred during the mid-Holocene period and discuss the possible effects of such on the environment affecting the landscape where these communities settled.

Study site and regional climate

The Skagerrak

The Skagerrak forms the only marine connection between the North Atlantic and the landlocked Baltic Sea (Figure 1). In the northwest, the Skagerrak has a fjord-like shape (Thiede, 1987) and reaches maximum water depths of more than 700 m (Rodhe, 1987), thus representing the deepest part of the otherwise shallow North Sea. In the present-day NE Skagerrak, SSTs are determined by the interplay between the inflow of North Atlantic water and the Baltic Sea outflow. Therefore, sedimentary sequences from the NE Skagerrak provide excellent archives for paleo-climate reconstructions that reflect past changes in atmospheric circulation and precipitation pattern over the Baltic region, while those from the western Skagerrak are more indicative of the overall maritime climate of the North Atlantic realm.

In general, the modern current circulation pattern in the Skagerrak/North Sea is largely governed by the inflow of North Atlantic and North Sea water and the outflow of Baltic Sea water (Otto et al., 1990; Rodhe, 1987, 1988; Svansson, 1975; Figure 1). Saline North Atlantic water enters the Skagerrak/North Sea between Scotland and Norway and via the English Channel. The South Jutland Current, consisting of water from the English Channel and southern North Sea, flows northwards along the Danish coast and mixes with the North Jutland Current that originates from the North Atlantic and the central North Sea water. As the current passes Skagen (Figure 1) and enters the Skagerrak/Kattegat border, part of it mixes with fresher and colder Baltic Sea water. Thereupon, part of the current forms an anti-clockwise gyre that exits the Skagerrak, back flowing along the Norwegian coast as the Norwegian Coastal Current (Figure 1). The anti-clockwise current and the deep waters cause current speed reduction that allows fine-grained sediment to accumulate at high rates in the central and northeast parts of the Skagerrak (Rodhe and Holt, 1996; Van Weering, 1982).

Baltic Sea outflow

The Baltic Sea semi-enclosed brackish water body is located in the humid climatic zone of northern Europe. In the present day, it is connected to the North Atlantic Ocean via the Skagerrak through the narrow and shallow Kattegat and Danish straits, consequently having strongly restricted water exchange with the open ocean. As a consequence of the fresh water surplus and the strongly limited water exchange with the North Atlantic, the Baltic Sea has an estuarine circulation pattern characterized by outflowing low-salinity surface water and inflowing higher salinity bottom water (Figure 1). Today, the main outflow occurs during winter and after spring snowmelt (BACC, 2008). The onset of the estuarine circulation pattern took place during the early and the beginning of the mid-Holocene period after the so-called Littorina Sea transgression. The timing of this transgression is still a matter of debate (e.g. Rößler et al., 2011 and references therein).

Regional climate

The present-day climate in northwest Europe and the Baltic region is strongly governed by large-scale atmospheric pressure systems that drive variations in strength and direction of wind fields (BACC, 2008; Hurrell, 1995; Hurrell et al., 2003). Such pressure systems include the Icelandic Low, the Azores High and the winter High/summer Low over Russia, whereas variations in the occurrence of these pressure systems lead to a pre-dominance of maritime or continental climate. Periods of maritime-dominated climate are characterized by the strong influence of Westerlies directed towards northwest Europe that are driven by intensified pressure gradients between the Icelandic Low and Azores High. Such climate conditions cause mild and moist climate in northwest Europe that can affect large areas of the Baltic region. In contrast, a continental-dominated climate is marked by weaker Westerlies and a greater dominance of the continental anticyclone over Russia, thus provoking dry and warm summer and cold and dry winter conditions (BACC, 2008; Hurrell, 1995; Hurrell et al., 2003).

Material and methods

Skagerrak sediment cores

Two multi-cores (IOW372610 and IOW372650) and three gravity-cores (IOW372610, IOW225514 and IOW372650) located in the western, central and northeastern Skagerrak (Figure 1) were used to reconstruct SST changes during the past decades and for

Table 1. Age determination and core location/water depth/cruise of each gravity-core used in this study. The radiocarbon dates are published in Emeis et al. (2003) and Krossa et al. (2015) and supplemented by four radiocarbon dates (the past three radiocarbon dates in core IOW372650). Radiocarbon ages were calibrated (cal. yr BP) using the Calib Rev 7.0 software program and the Marine13 calibration set (Reimer et al., 2013) with an assumed standard marine reservoir age of 400 years.

Sample depth (cm)	Dated material	Age (^{14}C yr BP)	Calibrated age min–max (1σ range, cal. yr BP)	Calibrated age med. (1σ range, cal. yr BP)	Lab Ref.	C (mg)
Skagerrak GC 372610 (Krossa et al., 2015; 57°41.05′N, 06°41.00′E)						
2–3	Mixed benthic foraminifera	715 ± 25	314–397	359	KIA42411	0.7
20	Mixed benthic foraminifera	745 ± 35	333–432	386	Poz-34467	0.42
55–56	Mixed benthic foraminifera	940 ± 25	504–556	536	KIA42412	0.5
73–74	Mixed benthic foraminifera	1140 ± 50	647–731	693	LuS 9540	1.07
100	Mixed benthic foraminifera	1510 ± 40	1003–1123	1064	Poz-34553	0.37
124–125	Mixed benthic foraminifera	1960 ± 50	1438–1577	1514	LuS 9539	0.53
155–156	Mixed benthic foraminifera	2385 ± 25	1966–2060	2014	KIA 42413	1.0
174–175	Mixed benthic foraminifera	2550 ± 50	2161–2292	2221	LuS 9538	0.78
200	Mixed benthic foraminifera	2710 ± 30	2344–2444	2404	Poz-34468	0.67
255–256	Mixed benthic foraminifera	3195 + 35/−30	2935/2941–3055/3050	2995/2994	KIA 42414	0.8
300	Mixed benthic foraminifera	3820 ± 40	3705–3826	3768	Poz-34554	0.5
354–356	Mixed benthic foraminifera	4530 ± 35	4693–4807	4738	KIA 42415	0.6
424–426	Mixed benthic foraminifera	5505 ± 35	5851–5933	5891	KIA 42416	0.5
Skagerrak GC 225514 (Butruille et al., 2016; Emeis et al., 2003; 57°50.28′N, 08°42.226′E)						
10.5	Mixed benthic foraminifera	810 ± 30	429–483	454	KIA 14028	
105.5	Mixed benthic foraminifera	1780 ± 35	1284–1353	1323	KIA 14029	
135.5	Mixed benthic foraminifera	2710 ± 35	2342–2451	2407	KIA 14031	
155.5	Mixed benthic foraminifera	2755 ± 45	2368–2545	2481	KIA 14033	
218.5	Mixed benthic foraminifera	3545 ± 35	3377–3472	3431	KIA 43703	
250.5	Mixed benthic foraminifera	4280 ± 45	4337–4480	4397	KIA 14034	
300.5	Mixed benthic foraminifera	4250 ± 60	4257–4430	4353	KIA 43704	
375.5	Mixed benthic foraminifera	5680 ± 45	6022–6160	6088	KIA 14036	
Skagerrak GC 372650 (Krossa et al., 2015; this study; 58°29.76′N, 09°35.91′E)						
24–26	Mixed benthic foraminifera	900 ± 50	472–547	513	Poz-34465	0.26
55–57	Mixed benthic foraminifera	1200 ± 25	699–767	736	KIA 42417	0.6
105–107	Mixed benthic foraminifera	1655 ± 30	1186–1255	1222	KIA 42418	0.6
155–157	Mixed benthic foraminifera	2155 ± 30	1703–1796	1749	KIA 42419	0.5
199–201	Mixed benthic foraminifera	2620 ± 50	2240–2356	2303	Poz-34551	0.23
223–225	Mixed benthic foraminifera	2985 ± 50	2713–2806	2762	LuS 9537	0.82
244–246	Mixed benthic foraminifera	3150 ± 50	2855–3003	2935	Poz-44174	0.6
255–257	Mixed benthic foraminifera	3470 ± 35	3308–3404	3352	KIA 42420	0.5
273–275	Mixed benthic foraminifera	3155 ± 70	2847–3040	2946	LuS 9536	0.36
284–286	Mixed benthic foraminifera	3760 ± 50	3619–3770	3695	Poz-44175	0.2
299–301	Mixed benthic foraminifera	3660 ± 50	3492–3630	3566	KIA 42421	0.7
323–325	Mixed benthic foraminifera	4230 ± 90	4186–4440	4324	LuS 9535	0.27
355–357	Mixed benthic foraminifera	4945 ± 35	5234–5325	5289	KIA 42422	0.6
384–385	*Mixed benthic foraminifera*	*5130 ± 70*	*5428–5578*	*5503*	*Poz-48329*	
415–417	*Mixed benthic foraminifera*	*5880 + 40/−35*	*6256–6346*	*6298*	*KIA 42423*	*0.4*
427–430	*Mixed benthic foraminifera*	*6730 ± 50*	*7202–7314*	*7261*	*Poz-44176*	*0.3*
453–454	*Mixed benthic foraminifera*	*8170 ± 35*	*8583–8706*	*8706*	*Poz-51561*	

Omitted radiocarbon ages are in italics.

the past 8000 years, respectively. The cores were retrieved during the cruises of ‘R/V Alkor’ in 2000 and ‘R/V Maria S. Merian MSM’ in September 2009 (Table 1).

UK′37 SST estimates

The total lipids were extracted from approximately 2–3 g of freeze-dried and homogenized bulk sediment, using an Accelerated Solvent Extractor (Dionex ASE-200) with a mixture of 9:1 (v/v) of dichloromethane:methanol (DCM:MeOH) at 100°C and 100 bar N_2 (g) pressure at the Biomarker Laboratory of the Geoscience Institute, Christian Albrechts University, Kiel. Extracts were cooled to −20°C and thereupon brought to near dryness by vacuum rotary evaporation at 20°C and 65 mbar. We used a multi-dimensional, double gas column chromatography (MD-GC) set up with two Agilent 6890 gas chromatographs for $C_{37:3}$ and $C_{37:2}$ identification and quantification. The method is fully described in Etourneau et al. (2010). Quantification of the organic compounds was achieved with the addition of an internal standard prior to extraction (cholestane ($C_{37}H_{48}$) and hexatriacontane ($C_{36}H_{74}$)). The alkenone unsaturation index (UK′37) was obtained by quantifying the peak areas of $C_{37:3}$ and $C_{37:2}$ and subsequently applying the equation of Prahl and Wakeham (1987):

$$UK'37 = \frac{C_{37:2}}{(C_{37:3} + C_{37:2})}$$

The UK′37 index was translated into SST using a calibration based on a global set of 149 surface samples (Müller et al., 1998):

$$SST(^{\circ}C) = \frac{(UK'37 - 0.044)}{0.033}$$

The proportion of the $C_{37:4}$ compound in the total amount of C37 ketones in one sample is expressed as $C_{37:4}$%:

$$C_{37:4}\ \% = \left(\frac{C_{37:4}}{(C_{37:4} + C_{37:3} + C_{37:2})} \right) \times 100$$

Analytical precision based on duplicate analyses of internal laboratory sediment standards during the whole procedure was approximately 0.12°C and 0.30 units of $C_{37:4}$, respectively.

Chronology

The surface sediments derived from multi-cores (Krossa et al., 2015) and gravity-cores (Butruille et al., 2016; Emeis et al., 2003; Krossa et al., 2015) were dated using AMS ^{14}C dates (Table 1).

The radiocarbon dates of both multi-cores indicate a 'modern age' ('post bomb') of surface and subsurface sediments, thus allowing a comparison of estimated SST at the core-top with modern instrumental data (Krossa et al., 2015). Chronologies of the gravity-cores presented in this study are based on ^{14}C ages converted into calendar years using the online software Calib Rev 7.0 and the Marine13 calibration curve (Reimer et al., 2013). The application of the standard marine reservoir age of 400 years allows direct comparison with previously published paleo-climate records from the Skagerrak (e.g. Butruille et al., 2016; Erbs-Hansen et al., 2012; Gyllencreutz, 2005; Gyllencreutz and Kissel, 2006; Krossa et al., 2015). Our results are presented on a calibrated age scale before present (cal. yr BP, AD 1950). We used previously published age–depth models based on linear interpolation between each calibrated radiocarbon dates (Butruille et al., 2016; Emeis et al., 2003; Krossa et al., 2015). In gravity-core IOW372650 in the northeastern Skagerrak, we added four new radiocarbon dates to establish an age–depth model ranging back to ~8000 cal. yr BP (Table 1). The depth intervals 273–275 and 299–301 cm indicate too low radiocarbon ages and were therefore not included in the linear interpolation (Krossa et al., 2015). However, these depth intervals do not affect the time series pattern older than 4700 years mainly discussed in this study (Figure 2).

Calculating human settlement activity

We used 'Summed Calibrated Date Probability Distributions' (SCDPD) proposed by Rick (1987) to estimate the activity of human settlements in northern Germany and southern Scandinavia. In our record covering the time interval between ~7500 and 4500 cal. yr BP, we used 3170 ^{14}C dates from northwestern Germany and southern Scandinavia previously published by Hinz et al. (2012) and refined for this study. We thereby considered possible biases such as sampling strategy, sample size, effects of the ^{14}C calibration curves and taphonomic loss as discussed by Williams (2012).

To avoid or reduce the impact of archaeology projects with a large number of ^{14}C dates, we sum-calibrated the radiocarbon dates for each site and used the result as a single date. Consequently, regardless of the number of radiocarbon dates at a single excavation site, all archaeological sites have the same impact on the resulting total sum distribution. The calculation is described in detail in Hinz et al. (2012).

Over the past years, the potential effects of time-decay on radiocarbon summed probability plots (taphonomic loss) have been increasingly considered in many studies as such records reveal a monotonically increasing pattern towards present day (Peros et al., 2010; Surovell and Brantingham, 2007; Surovell et al., 2009). To avoid such effects, Surovell et al. (2009) developed an equation for the correction of taphonomic loss. When applying the formula (Surovell et al., 2009; Williams, 2012) on our data set, the difference between the Mesolithic and late Neolithic period results in a loss of around 10%. This is considered to be low as the differences of population densities between those periods were of orders of magnitudes higher. Therefore, in addition to the rather short period presented in this study (approximately between 7500 and 4500 cal. yr BP), we do not consider taphonomic loss as a major issue and did not apply any taphonomic correction to our data.

Results

Mid- to late-Holocene SST evolution in the Skagerrak

Modern data suggest SSTs ranging from approximately 4°C during winter to 16°C during summer months, with an annual average of approximately 9–10°C for the Skagerrak region (Locarnini et al., 2010). Our surface and subsurface sediments (upper 5 cm in 0.5 cm intervals of multi-cores in the western and northeastern Skagerrak, respectively) reveal a mean SST value of 9.2 ± 1.1°C that is comparable with present-day mean annual SST in the Skagerrak. The gravity-core SST records, which are located in the western (IOW372610), central (IOW225514) and northeastern Skagerrak (IOW372650; Figure 1), reveal similar absolute SST values prior to ~6300 cal. yr BP and periodically over the past ~4700 cal. yr BP (Figure 3a and b).

In general, all Skagerrak SST records show the typical orbitally forced mid- to late-Holocene cooling trend as documented in several North Atlantic and northern European paleoclimate records (e.g. Calvo et al., 2002; Jansen et al., 2008; Moros et al., 2004; Seppä and Birks, 2001; Seppä et al., 2005). The records reveal an overall cooling of 3.5–4.5°C from ~12.5–13.5°C at ~6500 cal. yr BP to ~9°C at ~500 cal. yr BP (Figure 3a and b). In contrast to the western and central Skagerrak records, the SST evolution in the northeastern Skagerrak diverged towards much lower SST values for several periods after ~6300 cal. yr BP (Figure 3b).

A prominent SST drop from ~13 to ~7°C that occurred between ~6300 and 5400 cal. yr BP disconnected the NE Skagerrak SST evolution from that in the western and central Skagerrak and is not observed in any other North Atlantic SST record. This SST drop is in harmony with a mean annual air temperature (MAT) cooling in central South Sweden (Seppä et al., 2005), although much more pronounced than in the land-based pollen record. The NE Skagerrak cooling was followed by a warming of ~2–3°C reaching maximum at ~4700 cal. yr BP, as also documented in the central South Sweden MAT record (Figure 3b).

After the prominent 5–6°C SST drop, the NE Skagerrak SST record showed absolute temperatures ranging between ~10.5 and 5°C, being periodically much lower than the western/central SST records and in harmony with the central South Swedish MAT record (Seppä et al., 2005). This was particularly prominent during several shorter periods centred at ~2600, 2200 and 1500 cal. yr BP, when the SSTs in the NE Skagerrak were in harmony with the MAT record (Figure 3b). After ~1000 cal. yr BP, the gravity- and multi-core SST records from all Skagerrak locations approached modern-time mean annual SSTs of ~9–10°C, diverging again from MATs of ~6°C recorded in central South Sweden (Seppä et al., 2005).

Mid- to late-Holocene Baltic Sea outflow in the Skagerrak

In the Skagerrak, in particular in the NE Skagerrak, increases in tetra-unsaturated ketones ($C_{37:4}$%) have been shown to be a good indicator of outflowing Baltic Sea surface water (Krossa et al., 2015). Until ~6500 cal. yr BP, the $C_{37:4}$% varied between 1% and maximum 1.5%. Between ~6500 and 4500 cal. yr BP, the

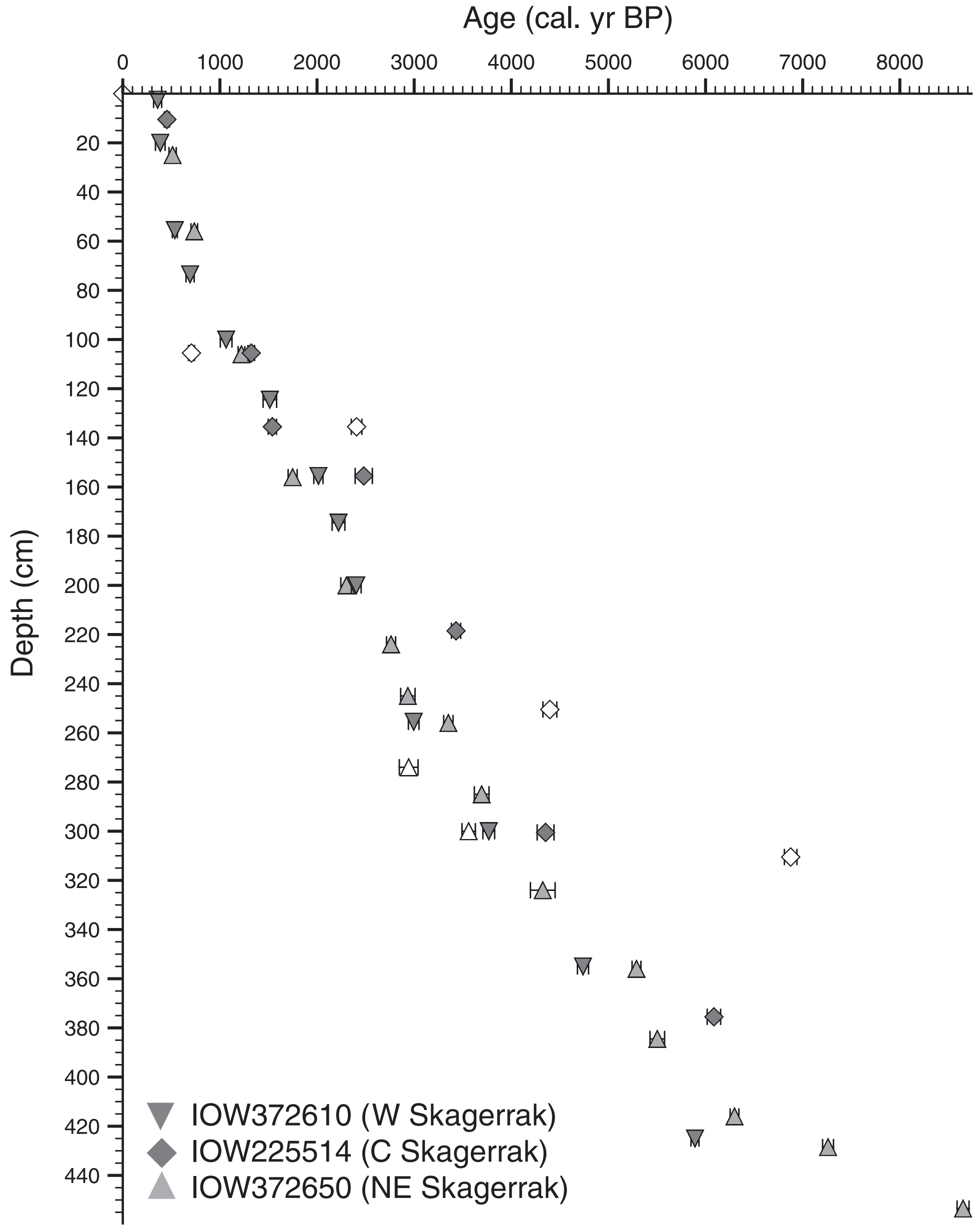

Figure 2. Age–depth profiles of all Skagerrak gravity-cores (see also Table 1). The radiocarbon ages were converted into calendar years (cal. yr BP) using the online software Calib Rev 7.0, thereby applying the Marine13 data set and a standard reservoir age of 400 years (Reimer et al., 2013). All age–depth models are based on linear interpolations between individual calibrated radiocarbon tie-points (Butruille et al., 2016; Emeis et al., 2003; Krossa et al., 2015; this study). Discharged radiocarbon points are marked by open symbols.

prominent SST decrease observed in the same core is accompanied by several pulses of outflowing Baltic Sea water centred at ~6200, ~5500 and ~5200 cal. yr BP (Figure 3c). The values are reaching a maximum of ~4.5%. Over the past ~3500 cal. yr BP, an increase from ~1% to ~5% in $C_{37:4}$% is documented (Krossa et al., 2015). Superimposed on the overall increase, several smaller increases in $C_{37:4}$% are recorded centred at ~2700, ~2100, ~1500 and ~600 cal. yr BP (Figure 3c).

Discussion

Long-chain alkenone-derived SSTs in the Skagerrak

Long-chain alkenones (C_{37}–C_{39}) are unsaturated ketones exclusively biosynthesized by coccolithophorids, mainly the cosmopolitan species *Emiliania huxleyi* and *Gephyrocapsa oceanica*. The proportion of di-unsaturated ($C_{37:2}$) to tri-unsaturated ($C_{37:3}$) C_{37} alkenones (expressed as the UK′37index) shows a linear correlation to algal growth temperature (Conte et al., 1998; Prahl et al., 1988; Prahl and Wakeham, 1987). Global core-top studies suggest that the correlation between the UK′37index and sea temperature is strongest when mean annual SSTs are considered (e.g. Conte et al., 2006; Müller et al., 1998; Rosell-Melé and Prahl, 2013). However, many studies argue that reconstructed SSTs are seasonally skewed, as the algae growth strongly depends on light conditions and nutrient availability (e.g. Leduc et al., 2010; Lohmann et al., 2013; Schneider et al., 2010). Although the maximum of coccolithophorid bloom occurs during late spring and early summer in the modern Skagerrak area (Blanz et al., 2005; Nanninga and Tyrrell, 1996), our core-top SST estimates (upper 5 cm) match with observed mean annual SST (approximately 9–10°C) and are slightly lower than spring/summer temperatures (approximately 10–11°C; Locarnini et al., 2010). Also, Rosell-Melé and Prahl (2013) showed that the seasonality of maximum alkenone flux in globally distributed sediment traps does not follow any coherent spatial pattern and conclude that alkenone-derived SST estimates are reflective of mean annual SSTs. As we have no way to infer the seasonality of alkenone fluxes through the water

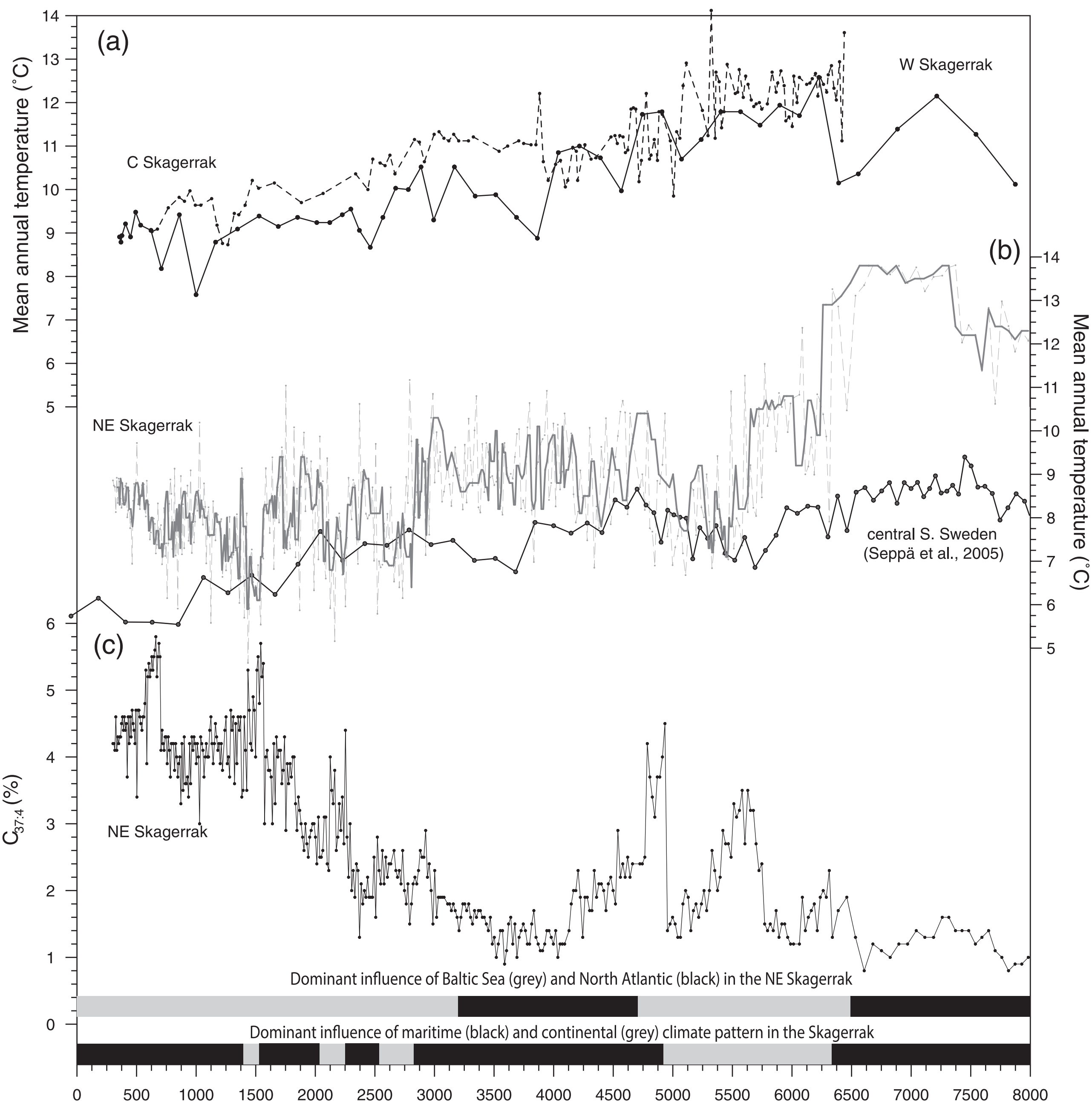

Figure 3. Comparison of the mid- to late-Holocene SST evolution (a) in the western (solid line)/central (dashed line) and (b) in the northeastern (dark grey line representing a three-point running mean average, light grey dashed line representing each single measurement) Skagerrak. The solid line in (b) represents the pollen-derived temperature estimations from central South Sweden (Seppä et al., 2005). Prior to ~6300 cal. yr BP, the Skagerrak SST records reveal similar absolute SST values, followed by diverging SST trends in the northeastern and western/central Skagerrak over the mid- and late-Holocene. (c) Between ~6300 and 5400 cal. yr BP, a notable ~5–6°C SST drop is recorded in the NE Skagerrak, probably largely a result of colder Baltic Sea outflow, as also supported by several increases in $C_{37:4}$% in the NE Skagerrak record. Over the past ~4700 cal. yr BP, similar SSTs and an increase in $C_{37:4}$% in particular over the past ~3500 cal. yr BP suggest an overall dominance of North Atlantic conditions and enhanced Baltic Sea outflow in the Skagerrak.

column in the Skagerrak, we consider the UK′37-derived SST values as a proxy for the mean annual temperature at this site, although bearing in mind that the reconstructed SST signal might be slightly skewed towards spring and summer as suggested for the modern Skagerrak (e.g. Blanz et al., 2005).

Mid- to late-Holocene diverging SST trends in the western and northeastern Skagerrak and the prominent SST drop between ~6300 and 5400 cal. yr BP

All Skagerrak SST records presented in this study reveal similar absolute SST values prior to ~6300 cal. yr BP and during the past millennium (Figure 3a and b). Additionally, they all document a general cooling of ~3.5–4.5°C from the mid- to late-Holocene. This magnitude of cooling is observed in many North Atlantic and north European paleo-climate records (see e.g. Magny and Haas, 2004; Wanner et al., 2008) and follows the typical orbital-related Holocene decrease in temperature at such northern hemispheric latitudes. In contrast, the SST evolution from ~6300 to 4700 cal. yr BP and periodically between ~4700 and 1000 cal. yr BP in the NE Skagerrak, which diverged from that in the western and central Skagerrak towards much lower absolute temperatures (Figure 3a and b), requires a regional forcing, in particular to explain the prominent ~5–6°C drop between ~6300 and 5400 cal. yr BP.

Nowadays and probably over the past ~8500 years, varying contributions of North Atlantic water inflow (Gyllencreutz, 2005; Gyllencreutz and Kissel, 2006; Klitgaard-Kristensen et al., 2001) and Baltic Sea water outflow (Krossa et al., 2015) dominated the Skagerrak circulation pattern as schematically indicated in Figure 1. Therefore, the SST evolution occurring in the western and central Skagerrak is likely determined by inflowing North Atlantic waters and follows the overall North Atlantic mid- to late-Holocene SST trend (e.g. Calvo et al., 2002; Moros et al., 2004). As the NE Skagerrak is exposed to outflowing Baltic Sea water (Figure 1), climatic and oceanographic changes within and in the Baltic Sea region would impact the SST evolution in the NE Skagerrak to a much stronger extent than the central/western sites (Krossa et al., 2015).

Similar absolute and warmer-than-modern SSTs prior to ~6300 cal. yr BP recorded at all Skagerrak sites (Figure 3a and b) suggest that inflow of warm North Atlantic waters affected the entire Skagerrak. This is corroborated by multiple regional studies (Butruille et al., 2016; Gyllencreutz, 2005; Gyllencreutz and Kissel, 2006; Klitgaard-Kristensen et al., 2001). Supportingly, paleo-climate records from the open North Atlantic and adjacent landmasses also indicate warmer-than-modern conditions prior to ~6000 cal. yr BP (e.g. Calvo et al., 2002; Jansen et al., 2008; Seppä et al., 2005), most likely largely driven by high summer insolation prevailing during the mid-Holocene as discussed above (e.g. Leduc et al., 2010; Schneider et al., 2010).

A marked ~5–6°C temperature drop occurring between ~6300 and 5400 cal. yr BP in the northeastern Skagerrak SST record (IOW372650) documents the onset of a longer-lasting disconnection between the SST evolution in the NE and western/central Skagerrak (Figure 3a and b). A cooling trend, although less pronounced in magnitude, is also recorded in a pollen-based MAT record from central South Sweden (Seppä et al., 2005) during that period. In both records, a smooth warming phase followed the cooling reaching highest temperatures at ~4700 cal. yr BP (Figure 3a and b). This suggests that regional features probably of oceanographic and climatic origin not affecting the western/central Skagerrak records provoked the cooling. Surface and gravity-core studies in the Skagerrak covering the past three millennia strongly indicate that changes in the strength of Baltic Sea outflow can be recorded in the NE and to a lower extent in the central/western Skagerrak using the relative amount of $C_{37:4}$ compounds over the sum of C_{37} ketones ($C_{37:4}$%; Krossa et al., 2015). Accordingly, several increases in $C_{37:4}$% centred at ~6200, 5500 and 5200 cal. yr BP (Figure 3c) in the NE Skagerrak sediment core indicate enhanced Baltic Sea outflow. In the southwestern Baltic Sea, a study documents several pulses of the Littorina transgression between ~6400 and 5400 cal. yr BP (Yu et al., 2003). Therefore, we argue that the prominent SST cooling occurring in the NE Skagerrak between ~6300 and 5400 cal. yr BP (Figure 3b) was a response to oceanographic changes occurring in the Baltic Sea and consequently affecting the water exchange dynamics to the Skagerrak.

The SST drop at the NE Skagerrak site is much more prominent than in the central South Swedish MAT record (Figure 3b). Its magnitude might be explained by the outflow of generally colder Baltic Sea water. Today, strongest Baltic Sea outflow occurs during winter and after spring snowmelt (BACC, 2008). Therefore, outflowing Baltic Sea water during periods of severe winters would produce a generally colder (mean annual) SST signal as recorded at the NE Skagerrak site. This is supported by the reconstruction of colder winter conditions in Lake Belau in northern Germany (Dreibrodt et al., 2012) as well as in the central/western Skagerrak (Butruille et al., 2016) during that particular period. Antonsson et al. (2009) argue that a long-lived and recurrent high-pressure system that prevailed in the latitudinal belt of the Westerlies during the mid-Holocene period (Rimbu et al., 2007) blocked the winds bringing moist and mild air masses towards northern Europe, inducing a continental-dominated atmospheric circulation pattern above northern Europe. This shift is associated by colder winters and warmer summers over the Baltic region (Hurrell, 1995; Hurrell et al., 2003). Therefore, we hypothesize that the prominent cooling was related to an increased outflow of generally colder Baltic Sea water during the Littorina transgression, probably amplified by the dominance of a more continental-like atmospheric circulation pattern. However, the extent of the climatic impact on the probably largely circulation-driven SST drop in the NE Skagerrak cannot be fully resolved with our data set.

Over the past ~4700 cal. yr BP and in particular over the past millennium, the SST evolution in the western, central and northeastern Skagerrak periodically approached similar temperature values (Figure 3a and b), suggesting an overall dominance of more maritime climate conditions. This is supported by regional and local studies indicating a period with less seasonal contrast (Butruille et al., 2016; Dreibrodt et al., 2012; Krossa et al., 2015). Also, enhanced Baltic Sea outflow over the past 3500 cal. yr BP is recorded in the NE Skagerrak (Figure 3c), probably as a response to increased precipitation and river runoff associated with a more maritime-dominated climate circulation pattern (Krossa et al., 2015). In contrast, during several time intervals, the NE Skagerrak SST record shows lower absolute SSTs compared with those in the central and western Skagerrak (~2800–2500, ~2200–2000 and ~1500–1400 cal. yr BP), thereby approaching MAT values recorded in central South Sweden (Figure 3b). During those periods, elevated $C_{37:4}$% values are documented (centred at ~2700, ~2100 and ~1400 cal. yr BP). This suggests that outflow of generally colder Baltic Sea water, probably amplified by a more continental-dominated climate prevailing over the Baltic region, impacted the SSTs at that site. Over the past 1000 cal. yr BP, similar absolute SSTs occurred, suggesting a dominance of a maritime climate circulation pattern (Figure 3a and b).

Regional climate change and development towards an agrarian-based society in northern Germany and southern Scandinavia during the mid-Holocene period

Between ~6000 and 5500 cal. yr BP, evidence for the development towards an agrarian-based society in northern Germany and southern Scandinavia is documented by a concomitant increase in cereal pollen and landscape opening in a lake sedimentary sequence from Lake Belau, northern Germany (Dörfler et al., 2012; Feeser et al., 2012; Kirleis et al., 2012; Sørensen and Karg, 2012). Also, the demographic record from northern Germany and southern Scandinavia (Figure 4c) documents a prominent increase in human settlement activity after ~6000 cal. yr BP reaching highest values at ~5600 cal. yr BP, suggesting a shift towards an agrarian-based society in those areas (Hinz et al., 2012).

Many studies attribute the shift in human economy in northern Germany and southern Scandinavia at ~6000 cal. yr BP to climate and environmental change. Thereby, they argue that the very adapted and specialized economic system of late Mesolithic hunter–gatherer–fishers was particularly vulnerable to such changes (e.g. Bonsall et al., 2002; Gronenborn, 2007; Hartz et al., 2007; Sørensen and Karg, 2012). In contrast, Shennan et al. (2013) found no correlation between demographic evolution from several European sites and northern high-latitude climate change. This study, however, compares European demographic results with climate records located at large geographical distances from the excavation sites, so that the paleo-climate proxies presented in Shennan et al. (2013) might not reflect the regional climate situation occurring near the landscape where these people settled. We posit that the potential effect of climate and environmental change on the development occurring in human settlements in northern Germany and southern Scandinavia is best expressed in climate records situated close to the landmass and also to the Baltic Sea.

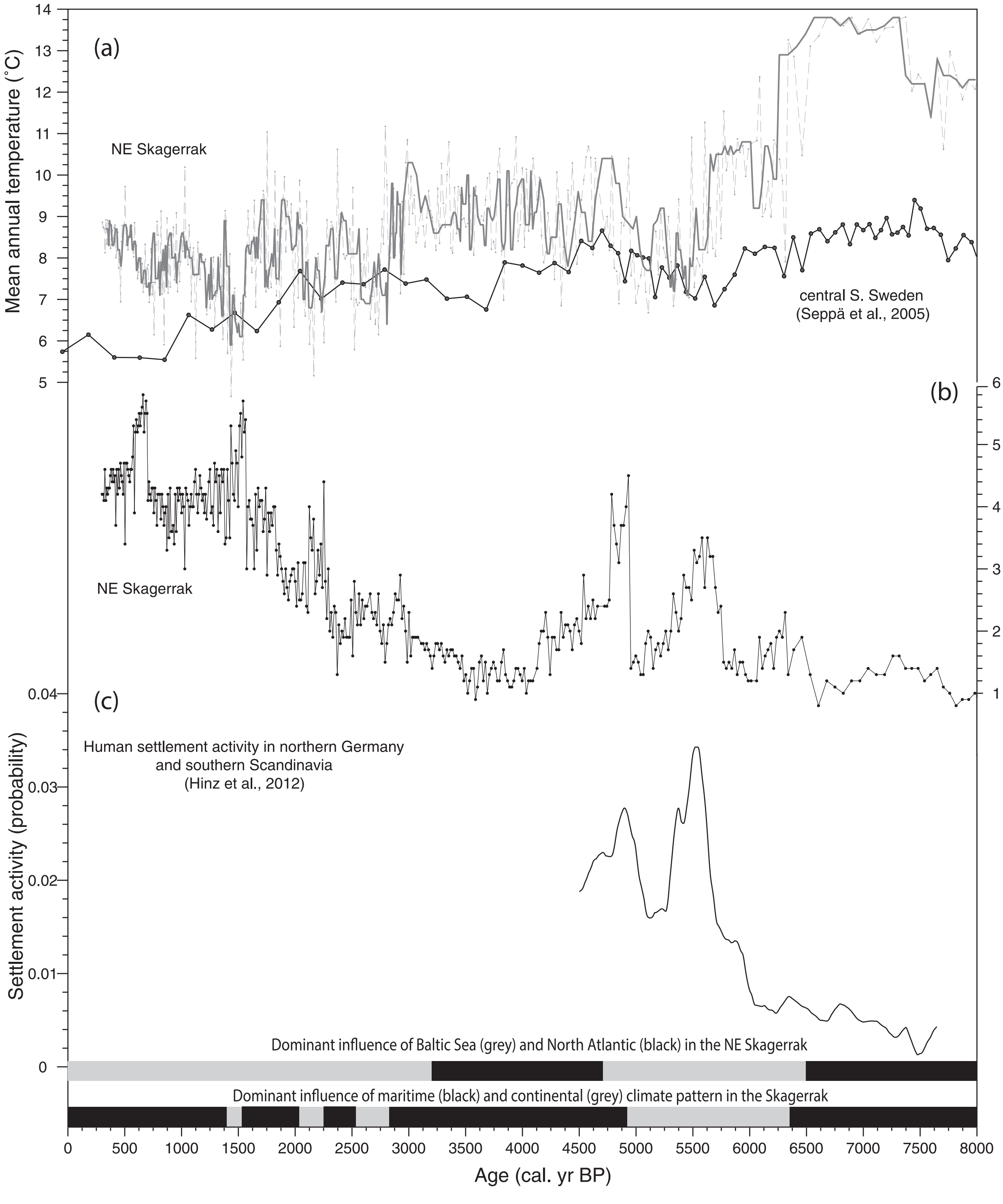

Figure 4. (a) UK′37-SST from the northeastern Skagerrak (dark grey; IOW372650) and pollen-based MAT from central south Sweden (black solid line; Seppä et al., 2005), (b) $C_{37:4}$% from the NE Skagerrak indicating outflowing Baltic Sea water and (c) probability of human settlement activity in northern Germany and southern Scandinavia used as a demographic proxy (Hinz et al., 2012). The regional paleo-climate records (a) demonstrate a temperature drop occurring between ~6300 and 5400 cal. yr BP associated with an increased outflow of colder Baltic Sea water (b) and probably amplified by a climate cooling in general (see text and Figure 3). This matches the transition from a hunter–gatherer–fisher economy towards an economy based on farming in north-central Europe starting at ~6000 cal. yr BP as evident in several studies (e.g. Dörfler et al., 2012; Feeser et al., 2012; Kirleis et al., 2012; Sørensen and Karg, 2012). An increase in settlement activity (c) occurring after the onset of farming indicates that farming was sufficient enough to sustain a growing population even during periods of severe winters as suggested by lake studies in northern Germany (Dreibrodt et al., 2012) and in the Skagerrak (Butruille et al., 2016). Note that the data used in (c) only represent the settlement development until ~4500 cal. yr BP because of data collection strategy. The drop at ~5300 cal. yr BP documents changes in settlement behaviour rather than a drop in human activity (Hinz et al., 2012).

Our results suggest a connection between the establishment towards modern water exchange processes between the Skagerrak and Baltic Sea, amplified by a period of more severe winters, and the fundamental change in human strategies in northern Germany and southern Scandinavia (Figure 4a–c). The cooling documented in the NE Skagerrak was most likely an expression of enhanced Baltic Sea outflow of colder waters during a period of severe winters. These changes might have had a pronounced impact on the natural ecosystems, probably limiting food resources, in particular in the marine realm close to the areas where changes in human settlements are documented. This consequently affected the then stable economy in late Mesolithic societies that was largely based on fishing, and also on hunting and gathering. Therefore, new food supply techniques such as cereal cultivation and animal husbandry became increasingly efficient or even necessary to counter-balance climate-induced diminution of natural food resources (Andersen, 2008; Bailey and Milner, 2008; Bonsall et al., 2002; Gronenborn, 2007; Hartz et al., 2007; Rowley-Conwy, 1984). For instance, a decline in dominant Mesolithic food sources such as oysters, fish and seals at sites close to the SW Baltic Sea (e.g. Fischer et al., 2008; Price et al., 2007; Richards et al., 2003; Tauber, 1981) is documented in the human diet after ~6000 cal. yr BP (Bailey and Milner, 2008; Hartz et al., 2007) that largely matches the SST drop in the NE Skagerrak. Also, because of farming techniques, Neolithic societies were able to store food (cereals and animals 'on the hoof') during harsh winters that, in turn, might sustain a larger growing population as documented in an increase in human settlement activity during coldest SSTs in the Skagerrak (Hinz et al., 2012; Figure 4a and c). However, as the cooling had already begun prior to the adoption of farming techniques, it implies that regional climate change was probably not the ultimate factor for explaining the shift in economy, and therefore other factors, for example, social nature, should also be considered. Nevertheless, most likely, the specialization of the Mesolithic strategy made the economic system vulnerable to environmental changes, so the socio-economic development during the early Neolithic can be regarded as a response to environmental deterioration.

Conclusion

We used three marine sediment cores in the Skagerrak to comment on regional changes in SST over the past 8000 years, in particular focusing on the mid-Holocene interval. Multi-core samples collected at sites in the western and northeastern Skagerrak, respectively, document a good match between estimated SSTs and modern mean annual SSTs. Gravity-cores show an overall SST decrease in the Skagerrak during the mid- to late-Holocene related to orbital-forced cooling. Prior to ~6300 cal. yr BP, the SST records document similar absolute values, suggesting a strong influence of North Atlantic water in the Skagerrak. Over the past ~6300 cal. yr BP and in particular between ~6300 and 5400 cal. yr BP, the NE Skagerrak record shows lower SSTs and is partly disconnected from the SST evolution in the western and central Skagerrak. A notable SST drop of ~5–6°C occurring between ~6300 and 5400 cal. yr BP in the NE Skagerrak is most likely related to the outflow of generally colder Baltic Sea water after the Littorina transgression and amplified by a dominance of a more continental-dominated atmospheric circulation pattern associated with stronger seasonal contrast. After ~4700 cal. yr BP, the SST evolution in the entire Skagerrak largely documents similar absolute values in addition to enhanced Baltic Sea outflow over the past ~3500 cal. yr BP. This indicates a shift towards a more maritime-dominated atmospheric pattern associated with less seasonal contrast. The prominent increase in outflow of colder Baltic Sea water between ~6300 and 5400 cal. yr BP matches a fundamental change in economic strategies in northern Germany and southern Scandinavia. We hypothesize that a succession of several events led to the onset of farming in those areas and posit that changes in surface circulation in the Baltic Sea amplifying the climate situation prevailing during the mid-Holocene period were important factors. Probably, these changes progressively modified the environment to such an extent, in particular in the marine environment, so that farming and food storage during severe winters became an efficient strategy to counter-balance environmental-related stress. Once fully adopted, the societies were able to sustain a larger growing human population as evident in an increase in human settlement activity. As the apparent cooling occurring in the NE Skagerrak starts earlier than the onset of first farming techniques in the area, our results suggest that climate change was not the only factor for explaining the recorded shift in economy.

Acknowledgements

The authors thank the crews of Alkor and Maria S. Merian research vessels for technical support during coring operations. They thank S Koch for assistance with alkenone analysis. They thank Dr Jeremy Lloyd and Durham University for radiocarbon dates. They are also thankful to all INFLOW and SPP 1400 members. The authors are grateful to an anonymous reviewer for constructive improvements and suggestions.

Funding

This work was funded by the DFG SPP 1400 'Early Monumentality and Social Differentiation' and the EU BONUS+ 'Inflow' project.

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