Coastal primary productivity changes over the last millennium: a case study from the Skagerrak (North Sea).

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Abstract. A comprehensive multi-proxy study on two sediment cores from western and central Skagerrak was performed in order to detect the variability and causes of marine primary productivity changes in the investigated region over the last 1100 years. The cores were dated by Hg pollution records and AMS ^{14}C dating and analysed for palaeoproductivity proxies such as total organic carbon, δ^{13}C, total planktonic foraminifera, benthic foraminifera (total as well as abundance of *Brizalina*

5   *skagerrakensis* and other palaeoproductivity taxa) and palaeothermometers such as Mg/Ca and δ^{18}O. Our results reveal three periods with changes in productivity in the Skagerrak region: i) moderate productivity at ~ CE 900 – 1200; ii) low to moderate productivity at ~ CE 1200 – 1600 and iii) high productivity at ~ CE 1600 – present. During ~ CE 900 – 1200, moderate productivity was likely driven by the nutrients transported with the warm Atlantic water inflow associated with a tendency for a persistent positive NAO phase during the warm climate of the Medieval Climate Anomaly. The following low productivity

10 period at ~ CE 1200 – 1600 was likely caused by a lower contribution of nutrient-rich Atlantic water due to a generally more negative NAO phase and a shift to the more variable and generally cooler climate conditions of the Little Ice Age. At that time the nutrient supply was largely sustained by the Baltic Sea outflow and river runoff associated with land-use changes. Since ~ CE 1600 towards present day our data point to an increased nutrient content in the Skagerrak waters. This increased nutrient content was likely caused by enhanced inflow of warm Atlantic water, increased Baltic outflow, intensified river runoff and

15 enhanced human impact through agriculture expansion and industrial development. Intensified human impact likely increased nutrient transport to the Skagerrak and caused changes in the oceanic carbon isotope budget, known as the Suess effect, which is clearly visible in our records as a negative shift in δ^{13}C values from ~ CE 1750. In addition, a higher benthic foraminiferal Mn/Ca suggests slightly decreased bottom water oxygen conditions between ~ CE 1050 and 1400 in the central Skagerrak and in the last 70 years at both studied locations.

1 Introduction

Growth of marine microalgae is stimulated by enhanced concentrations of major nutrients like nitrogen and phosphorus in the photic zone (e.g. Sigman and Hain, 2012). Microalgae in the oceans are primary producers, which provide food for consumers at higher trophic levels and oxygen for respiration (e.g. Micheli, 1999). Through photosynthesis and the biological pump,

5   marine primary producers also extract CO_2 from the atmosphere. Carbon, nutrients and trace elements, which are fixed by primary producers are further ingested by higher organisms or sink to the ocean floor where they are stored in the form of organic matter. The organic matter will eventually be remineralised, releasing the carbon, nutrients and trace elements to the bottom water (e.g. Sigman and Hain, 2012). Supply of carbon to the oceanic ecosystems is an important part of the biogeochemical cycles, which presently are being disturbed by the human impact. Since primary producers require CO_2 for

10   photosynthesis, they naturally help to reduce the atmospheric CO_2 increase following anthropogenic greenhouse gas emissions. However, increasing levels of dissolved CO_2 in the oceans associated with so-called "ocean acidification" negatively impact ocean's carbonate producers (e.g. Doney et al., 2009; Haynert et al., 2012), their survival and fitness (e.g. Thomsen et al., 2017). Excessive production of organic matter furthermore changes the oxygen condition at the sea floor due to decay of organic matter, which lowers the dissolved oxygen content, in turn, negatively influencing life regime (e.g. Kristiansen and

15   Aas, 2015 and references therein).

Coastal zones are among the most productive marine regions characterised by high, organic matter accumulation and decomposition (e.g. Hjalmarsson et al., 2010). The Skagerrak, located between the North Sea and the Baltic Sea and in the close proximity to land, has many potential nutrient sources, such as the North Atlantic, Baltic Sea, North Sea, as well as continental discharge and river runoff (Aure and Dahl, 1994; Andersson, 1996; Gustafsson and Stigebrandt, 1996). Upwelling,

20   increased atmosphere-ocean gas exchange and precipitation further increase the nutrient supply to the surface waters, additionally stimulating productivity in this region (Pingree et al., 1982; Aure and Dahl, 1994; Fonselius, 1996). Effects of increased primary production range from positive impacts on growth, size and reproduction of fish and shellfish populations to disruptive alterations in the food webs, thus yielding or reducing the profit rates of fisheries (Hop et al., 1992; Micheli, 1999; Iversen et al., 2002; Olsen et al., 2004, 2005; Breitburg et al., 2009; FAO, 2016). Negative changes in trophic levels of

25   the Skagerrak ecosystem have been attributed to overfishing (Cardinale and Svedäng, 2004), however, ongoing studies alert about adverse impact of increased nutrient inputs driving heavy phytoplankton blooms and eutrophication in the region (e.g. Baden et al., 1990; Aure et al., 1996; Breitburg et al., 2009). Eutrophication causes high demand and depletion of oxygen in the bottom waters, which affect species diversity, morphology and population growth, and forces organisms to migrate (Rosenberg et al., 1990; Conley, 2009).

30   Although the Skagerrak is a well-investigated area, retrospective studies from this region have focused on climate change instead of productivity, and hence, past primary productivity changes are not well known (Polovodova Asteman et al., 2018). Previous studies suggested that among the processes driving primary productivity changes in the Skagerrak are 1) the North Atlantic Oscillation (NAO), 2) an input of anthropogenic nutrients from the Skagerrak catchment area and 3) nutrients

transported from the Baltic Sea. Thus, while the NAO naturally influences the inflow of the nutrient-rich Atlantic water mass into the Skagerrak (Gil et al., 2005; Brückner and Mackensen 2008), anthropogenic activities in the Skagerrak catchment area such as e.g. land-use changes also cause an increased nutrient input and high organic matter flux to the basin (e.g. Filipsson and Nordberg, 2010). In addition, eutrophication of the Baltic ecosystem and resulting transport of nutrient-rich water with the

5   Baltic Current through surface water exchange processes represents potentially an additional nutrient source (Andersson, 1996; Hjalmarsson et al., 2010; Filipsson et al., 2017; Krossa et al., 2015; Polovodova Asteman et al., 2018). In its turn, a nutrient-overloaded ecosystem in the Skagerrak may further supply dissolved inorganic nitrogen (DIN) to the Kattegat bottom waters (Carstensen et al., 2006) and increase the nutrient level in the coastal waters of Norway (Rosenberg et al., 1987; Rydberg et al., 2006). The last two processes involve human induced influences on the ecosystem, while the NAO relates to effects

10   following natural variability in the climate system. Over the last 1100 years the interaction between these processes has changed, as human influence have increased. In perspective of the last 4500 years, it is seen that productivity and its variability has increased from 50 BCE towards present day (Polovodova Asteman et al., 2018). The increased productivity occurred as a response to enhanced local runoff coinciding with high winter rainfall and general cooling in Scandinavia, as well as intensified Baltic outflow, which may have significantly contributed to the nutrient supply in the Skagerrak in the past (Polovodova

15   Asteman et al., 2018).

Our study aims to detect the variability and causes of marine primary productivity changes in the Skagerrak over the last 1100 years. We address this aim through a comprehensive multi-proxy study of two sediment cores from the central and the western Skagerrak, integrating records of the total organic carbon (TOC), foraminifera, stable carbon and oxygen isotopes (δ^{13}C, δ^{18}O) and trace element ratios (Mg/Ca, Mn/Ca). In addition we evaluate our results in context of the long-term productivity changes

20   described previously in Polovodova Asteman et al. (2018).

2 Study area

The Skagerrak is located in the northeastern part of the North Sea, connected to the Baltic Sea through the Kattegat (Fig. 1). The Skagerrak has a mean depth of 210 m and with a maximum depth of 700 m it represents the deepest part of the Norwegian Trench (Rodhe, 1996). The area is characterised by an anticlockwise circulation and complex hydrography dominated by three

25   water masses. The inflowing North Sea Water (NSW ~31 – 35 psu) flows from the west, the North Atlantic Water (AW >35 psu) flows from the northwest and is governed by the sill located in the Norwegian Trench (southwest of Norway) at 270 m water depth, while the outflowing Baltic Sea water (BW ~20 – 30 psu) flows as the Baltic Current (BC) along the Swedish west coast towards the Skagerrak, where it merges with the Northern Jutland Current (NJC) and turns to the northwest as low saline Norwegian Coastal Currant (NCC) (Rodhe, 1996; Rydberg et al., 1996). The outflowing water from the Skagerrak

30   towards the Norwegian Sea partly recirculates to the western Skagerrak (Rodhe, 1996). The surface water masses driven by the Southern Jutland Current (SJC), NJC and the BC have a high nutrient concentration due to the freshwater input via rivers draining from the German and Danish east coasts and the Baltic catchment area (Gustafsson and Stigebrandt, 1996; Rodhe, 1996). Together with discharges from the major Norwegian rivers, these freshwater supplies enhance vertical salinity

differences between the less saline surface layer (<35 psu) and underlying high saline Atlantic water (>35 psu), hence, strengthening stratification of the water column (Gustafsson and Stigebrandt, 1996). In addition, internal processes such as e.g. the upwelling of the nutrient-rich underlying Atlantic water (Danielssen et al., 1997) and a wind-forced recirculation of the Skagerrak surface water (Gustafsson and Stigebrandt, 1996) take place on shorter time scales.

5   Large-scale atmospheric systems and regional meteorological factors (e.g. precipitation, storms) influence the flow regime creating a high-dynamic system in the upper layer of the water column (0 – 30 m) where water mixing is largely caused by the southwesterly winds (Gustafsson and Stigebrandt, 1996). At the same time, the calmer hydrographic conditions are typical for the intermediate layers (30 – 150 m) with a maximum water residence time of 3 months (Andersson, 1996). Renewal of the deep water (below sill depth) occurs every 1 to 3 years depending on the strength of the Atlantic water inflows (Aure and Dahl,
10   1994), which closely correlate with the NAO index (Brückner and Mackensen, 2006).

3 Material and methods

Two gravity cores (GC) were retrieved from the Skagerrak during a R/V Elisabeth Mann-Borgese cruise in May 2013. Core EMB046/20-3GC (4.8 m long) was taken from the central Skagerrak (SE Norwegian Trench; 58°31.75´N, 09°29.13´E; 533 m water depth), while core EMB046/10-4GC (4.62 m) comes from the western Skagerrak (SW Norwegian Trench; 57°49.73´N,
15   07°17.62´E; 457 m water depth) (Fig. 1). The cores were cut in 1-m sections on board before being split and subsampled every 1 cm ashore. In this study we present results from the upper 170.5 and 164.5 cm, in cores EMB046/20-3GC and EMB046/10-4GC respectively, covering the last 1100 years. Here we present new stable isotope (δ^{13}C, δ^{18}O), and trace element ratios (Mg/Ca, Mn/Ca) data covering the last 1100 years, in combination with foraminiferal assemblage data and multivariate statistics. A part of the foraminiferal dataset and the TOC data were previously published in Polovodova Asteman et al. (2018).
20   The TOC was determined using 'Rapid CS cube –Elementar' analyser (Department of Geology and Paleogeography, University of Szczecin, Poland) for detailed methodology of geochemistry measurements (TOC) see Polovodova Asteman et al. (2018).

For the stable carbon and oxygen isotopes (δ^{13}C, δ^{18}O) and trace elements analyses, well-preserved tests of benthic foraminifera *Melonis barleeanum* were picked from the dried sediment (fraction >150 µm). *Melonis barleeanum* was selected
25   for the analyses due to its relatively high abundance in the whole study record at both sites and its proved potential for geochemical palaeoreconstructions (Mackensen et al., 2000; Kristjánsdóttir et al., 2007; Brückner and Mackensen, 2008; Butruille et al., 2017). Stable isotopes measurements were performed at 1 cm intervals and the trace elements analyses were done at 1 – 2 cm intervals from both gravity cores down to 170 cm (EMB046/20-3GC) and 164.5 cm (EMB046/10-4GC). No stable isotope or trace element analyses were done between 4.5 cm and 7.5 cm in EMB046/10-4GC, since most of foraminifera
30   from that interval where used for ¹⁴C AMS dates.

Stable isotope analyses were done on a Finnigan MAT 253 mass spectrometer equipped with an automatic Kiel device at the FARLAB of the University of Bergen. Prior to measurement the tests of *M. barleeanum* were lightly crushed, cleaned

with methanol using an ultrasonic bath and dried at 60 ºC. For each measurement 2 – 4 specimens were used. All results are reported in ‰ versus Vienna Pee Dee Belemnite standard (V-PDB), using the National Bureau of Standards (NBS) 19 and 18, in combination with the lab internal standard CM12. The analytical uncertainty is ±0.08‰ and ±0.03‰ for oxygen and carbon isotopes, respectively.

5   Shells of *M. barleeanum* were also cleaned and analysed for trace elements at the Trace Element Lab (TELab) at Uni Research Climate, Bergen (Norway). For each analysis, approximately 15-20 specimens were gently crushed between two glass plates under a microscope to allow the contaminants to be removed. The samples were cleaned following the procedure described by Barker et al. (2003). The cleaning method includes clay removal steps, oxidation of the organic matter and surface leaching. Samples containing enough material were mixed and split into two subsamples to allow duplicate analysis. All

10   samples were dissolved in trace metal pure 0.1M HNO_3 and diluted to a final volume of 350 μL.

The trace elements (Mg, Mn, Al, Fe) were measured on an Agilent 720 inductively coupled plasma optical emission spectrometer (ICP-OES). Further, Fe/Ca and Al/Ca values have been checked and show no correlation with the measured Mg/Ca values. The correlation coefficients (R^2) between Mg/Ca and, Fe/Ca and Al/Ca ratios are respectively, for the core EMB046/20-3GC, 0.012 and 0.095, and for the core EMB046/10-4GC, 0.020 and 0.067, indicating no contamination due to

15   insufficient cleaning. The Mn/Ca values in our samples are higher than the recommended maximum (<105 μmol mol^{-1}) (Boyle, 1983), indicating that diagenetic coatings might also affect our results. The Mn/Ca values, however, show no significant correlation with the measured Mg/Ca values ($R^2 = 0$ for EMB046/20-3GC and $R^2 = 0.021$ for EMB046/10-4GC).

For every eight samples, known standard solutions were analysed to correct for instrumental biases and analytical drift of the instrument. Long-term instrumental precision is ±0.016 mmol mol^{-1} or 3.11% (relative standard deviation) for Mg/Ca.

20   Duplicate measurements obtained for 41 *M. barleeanum* samples show a good reproducibility. The pooled standard deviation of the duplicate Mg/Ca determination is equivalent to an overall average precision of 4.09%. The average Mg/Ca of long-term international limestone standard (ECRM752-1) measurements was 3.76 mmol mol^{-1} ±0.07 mmol mol^{-1} with the average published value of 3.75 mmol mol^{-1} (Greaves et al., 2008). The published *Melonis* spp. Mg/Ca - Bottom Water Temperature (BWT) is calculated from the measured Mg/Ca using the new *Melonis* spp. calibration (Mg/Ca = 0.113(±0.005)*BWT +

25   0.792(±0.036)), based on core top data covering a Mg/Ca range of 0.68 – 3.66 mmol mol^{-1} for a temperature range of -0.89 – 15.58°C (Hasenfrantz et al., 2017). Our Mg/Ca results fit well within the range of the Hasenfratz's calibration. Further discussion on Mg/Ca-derived BWT within this article will use the Hasenfratz's calibration.

The foraminiferal analysis was carried out on 5 – 10 g wet sediment, gently sieved over a 63-μm sieve and wet-counted for foraminifera immediately afterwards. The two Skagerrak records over the targeted time interval covering the last 1100 years

30   were counted at 1 – 5 cm and 1 – 2 cm resolution for EMB046/20-3GC and EMB046/10-4GC, respectively. In the >63 μm fraction, at least 300 benthic and 300 planktonic (where possible) specimens were counted under a stereomicroscope and identified to a species level. Both relative (%) and absolute (individual per gram in wet sediments, as n g^{-1}wet sed.) abundances were calculated. The benthic foraminiferal species were categorised depending on their relative abundance in the assemblage to dominant (>10%), accessory (5% – 10%) or rare (<5%). Only dominant and accessory species are discussed in this study

(Fig. 2, Table 1). Benthic species with relative abundance of >5% in at least two samples were subject to multivariate statistics using simple CABFAC factor analysis with varimax rotation (Table 1), performed by the PAST software (Hammer et al., 2001). This statistical tool provides a reliable method to distinguish the statistically significant foraminiferal units dominated by different species (e.g. Polovodova Asteman et al., 2013). In addition, benthic foraminiferal species indicative of increased

5 organic matter fluxes to the sea floor and, hence, algal blooms, were grouped as '*palaeoproductivity fauna*' and included: *Alabaminella weddelensis, Brizalina skagerrakensis, Bulimina marginata, Epistominella* spp.*, Nonionella iridea* and *Uvigerina* spp. (Polovodova Asteman et al., 2018 and references therein). The planktonic foraminifera are presented as total planktonic individuals.

4 Chronology

10 The age constraints follow Polovodova Asteman et al. (2018), where a common age model was established for both cores based on a total of 30 AMS ^{14}C dates on mixed benthic foraminifera, as well as correlations of percent total inorganic carbon, relative abundance of *B. skagerrakensis* and mercury (Hg) records from both cores. All AMS ^{14}C samples were dated at the Poznan Radiocarbon Laboratory (Poland), and the obtained dates were calibrated using Calib 7.1.0 software (Stuiver et al., 2017), marine calibration data set 'Marine13' (Reimer et al., 2013) and a reservoir age $\Delta R = 0\pm50$. The Hg-profiles from the

15 cores confirm that the top of both cores were deposited later than the 1960 – 70s (Polovodova Asteman et al., 2018), when peaks in Hg values are seen in association with the anthropogenic induced pollution maximum (Moros et al., 2017). In this study we target the time interval after CE 900. For in-depth information about the full age model we refer to Polovodova Asteman et al. (2018).

5 Results

20 ### 5.1 Organic geochemistry of bulk sediment

Both records show low TOC values until ~ CE 1600, around 1.7 – 2.1% and 1.5 – 1.8% in EMB046/20-3GC and EMB046/10-4GC respectively (Fig. 4). From ~ CE 1600, the TOC content strongly increases towards the core tops, where ranges 1.9 – 2.5% (EMB046/20-3GC) and 1.75 – 2.3 (EMB046/10-4GC) are recorded. In addition, a distinct increase in the TOC values between ~ CE 1050 and 1200 in the EMB046/20-3GC is noticed. When comparing the two cores, the TOC values are higher

25 for the EMB046/20-3GC record than for EMB046/10-3GC (Fig. 4).

5.2 Carbon isotopes

Overall, lower absolute δ^{13}C values are recorded in EMB046/10-4GC than in EMB046/20-3GC, except between CE 1550 and 1650 where there is a distinct increase of δ^{13}C values for EMB046/10-4GC and a sharp decrease for EMB046/20-3GC. Both δ^{13}C records do, however, show similar long-term trends through the study interval. Mean δ^{13}C values of the time interval

between ~ CE 900 and 1600 are generally higher (-0.55‰ on average in EMB046/10-4GC and -0.34‰ on average in EMB046/20-3GC), than during ~ CE 1600-2000 with mean $\delta^{13}C$ values of -0.78‰ (EMB046/10-4GC) and -0.67‰ (EMB046/20-3GC) (Fig. 4). From~ CE 1600 towards the present, both records document a strong decreasing trend from ca. -0.3‰ to -1.6‰ (Fig. 4).

5.3 Oxygen isotopes

Both Skagerrak records display similar $\delta^{18}O$ values, ranging from around 1.7 to 2.7‰ (Figs 3, 4). The $\delta^{18}O$ long-term trend common for the both records is interrupted between ~ CE 1150 and 1350 by a $\delta^{18}O$ increase in EMB046/10-4GC and a $\delta^{18}O$ decrease in EMB046/20-3GC. In general, there are three distinct periods which can be distinguished for both records, two of relatively low $\delta^{18}O$ values: at ~ CE 900 – 1150 and at ~ CE 1350 – 1450, and one of relatively high $\delta^{18}O$ values ~ CE 1450 – 1600. After ~ CE 1550, the $\delta^{18}O$ gradually decrease until ~ CE 1675 in EMB046/20-3GC and until ~ CE 1775 in EMB046/10-4GC, and is followed by the $\delta^{18}O$ steady increased in EMB046/20-3CG and more variable but overall lower $\delta^{18}O$ values in EMB046/10-4GC towards the core top (Figs. 3, 4).

5.4 Mg/Ca analyses and BWT

The Mg/Ca values vary from 1.33 to 1.87 mmol mol^{-1} in EMB046/20-3GC record and from 1.37 to 1.97 in EMB046/10-4GC, in general giving the estimated BTW range between 4.7 and 8.1 ºC, which is within the range of instrumentally recorded temperatures (ICES, 2010; Fig. 3). This comparison and further interpretation refer to the smoothed data, while the raw data are mostly within the range of the instrumental records, but not completely. Through the records, there is a general correlation between the BTW changes and variability of $\delta^{18}O$ values, showing similar patterns with periods of higher BWT corresponding to those with decreased in $\delta^{18}O$ values and vice versa (Fig. 3). Both records show generally higher BWTs during ~ CE 900 – 1200, somewhat lower or variable BWTs between ~ CE 1400 and ~ CE 1600 and again warmer BWTs are shown for the youngest part of the record (~ CE 1600 – 1950) (Figs. 3, 4).

5.5 Mn/Ca analyses

Both Mn/Ca records show a range between 0.15 and 0.8 mmol mol^{-1} (Fig. 4). The Mn/Ca ratios for the both cores present similar trends with an exception between ~ CE 1050 and 1400 were Mn/Ca values in EMB046/20-3GC are noticeably higher than in EMB046/10-4GC. The Mn/Ca ratios show slightly higher values in the last 70 years.

5.6 Foraminifera assemblages

Eight planktonic foraminiferal species are identified in both records. *Globigerinita uvula* and *G. glutinata* are the most abundant species, while *Globorotalia inflata*, *Globigerina bulloides*, *Neogloboquadrina pachyderma*, *Neogloboquadrina*

incompta, *Turborotalia quinqueloba* and *Orbulina universa* are less abundant. However, in this study all planktonic species are presented together as total number per gram of wet sediments (Fig. 2) due to their overall low absolute abundance, varying between 0 and 49 n g^{-1} wet sediment (EMB046/20-3GC) and 1.6 – 110 n g^{-1} wet sediment (EMB046/10-4GC). In both records, the planktonic foraminifera are most abundant in the interval between ~ CE 900 and 1200, after which they decrease towards

5   the top of the cores and almost disappear after ~ CE 1850 (Figs. 2, 4).

The benthic foraminiferal record from the core EMB046/10-4GC is characterised by consistently high absolute abundances (123 – 455 n g^{-1} wet sed.) and less fluctuating values than in the core EMB046/20-3GC (43 – 527 n g^{-1} wet sed., where the highest value represents an individual peak above 361 n g^{-1} wet sed. significantly sticking out from the rest of the record). In EMB046/20-3GC, the absolute abundance of benthic foraminifera is high until ~ CE 1050. At CE 1050, the values

10   drop below 125 n g^{-1} wet sediment for the next ~ 300 years. After ~ CE 1350 the absolute abundances gradually increase to reach the highest recorded values between CE 1600 and 1950. A similar absolute abundance trend is shown for agglutinated foraminifera, however, those appear in higher numbers in core EMB046/10-4GC then in EMB046/20-3GC (Fig. 2).

The benthic foraminiferal assemblages consist of up to 61 and 57 species in the cores EMB046/20-3GC and EMB046/10-4GC, respectively. Among those, eight species are dominant (>10%) and nine are accessory (5-10%) in the core

15   EMB046/20-3GC while the EMB046/10-4GC record has six dominant and five accessory taxa (Table 1). The common dominant species for both cores include *Brizalina skagerrakensis*, *Cassidulina laevigata*, *Eggereloides medius*, *Nonionella iridea*, *Pullenia osloensis* and *Stainforthia fusiformis* (for a full list of dominant and accessory species see Table 1). In general for both cores, the relative and the absolute abundance of the benthic foraminifera follow similar trends, showing a distinct variability of species *B. skagerrakensis* (Fig. 2).

20   The CABFAC factor analysis distinguished three factors for each of the cores (Fig. 4), which together explained 95% (EMB046/20-3GC) and 97% (EMB046/10-4GC) of the total variance (Table 2). The foraminiferal species with absolute value of factor scores >1 were considered to contribute significantly to the defined foraminiferal assemblages (Table 3) and were used to name the distinguished factors (assamblages). Thus, "*Pullenia osloensis* assemblage" associated with Factor 1 explained 81% (EMB046/20-3GC) and 86% (EMB046/10-4GC) of variance, and included species *P. osloensis* and *Nonionella*

25   *iridea* defined for both records with an addition of *Cassidulina laevigata* in the EMB046/10-4GC dataset. The "*Brizallina skagerrakensis* assemblage" associated with Factor 2 is dominated by species *B. skagerrakensis* and explained ~11% (EMB046/20-3GC) and ~9% (EMB046/10-4GC) of variance. Finally, factor 3 explained ~3% (EMB046/20-3GC) and ~1.8% (EMB046/10-4GC) of variance and included *N. iridea* as a common species for both records, with *P. osloensis* as the second dominant species for the EMB046/20-3GC record and *Stainforthia fusiformis* for the EMB046/10-4GC record, consequently

30   resulting in "*N. iridea - P. osloensis*" (EMB046/20-3GC) and "*N. iridea - S. fusiformis*" (EMB046/10-4GC) assemblages (Table 3). The factor analysis showed that both records are defined by a clear dominance of *P. osloensis* factor alternating with *B. skagerrakensis* factor between CE 900 and 1600. The most pronounced changes in the foraminiferal assemblages occurred between CE 1600 and the present day where the *P. osloensis* factor is to a large extent replaced by *B. skagerrakensis* factor. Similar long-term variability is seen in the '*palaeoproductivity fauna*' group due to a strong dominance of *B. skagerrakensis*

in this group (Fig. 4). In addition, *palaeoproductivity fauna* appears in higher abundance between ~ CE 900 and 1200. In the uppermost part (~ CE 1900) of the EMB046/10-4GC record the *N. iridea- S. fusiformis* factor distinctly increased, while the *N. iridea- P. osloensis* factor of the EMB046/20-3GC record shows less variability (Fig. 4).

6 Discussion

6.1 Productivity changes in the last millennium

All dominant species in our benthic foraminiferal assemblages, grouped into factors, have proven association with quality and availability of organic matter at the sea floor (e.g. Conradsen et al., 1994; Alve and Murray, 1995, 1997; Alve, 2003; Gustafsson and Nordberg, 2001; Duffield et al., 2015). The absolute abundance of planktonic foraminifera, stable carbon isotopes and total organic carbon also inform on past variability of productivity. We combine these proxies to assess productivity changes in the Skagerrak. Three periods with differing productivity in the Skagerrak region are identified: i) moderate productivity between ~ CE 900 and 1200; ii) low to moderate productivity from ~ CE 1200 to 1600 and iii) high productivity from ~ CE 1600 towards present (Fig. 4). For each defined period, we discuss the level of, and changes in, primary productivity and potential causes behind these productivity changes. Throughout the discussion we refer to the smoothed data of stable isotopes and Mg/Ca-derived BWT records as palaeothermometry proxies.

6.1.1 Moderate primary productivity (~ CE 900 – 1200)

The highest absolute abundance of planktonic foraminifera and an intermediate absolute abundance of benthic palaeoproductivity fauna are recorded between ~ CE 900 and 1200 (Fig. 4). High abundance of planktonic foraminifera is strongly correlated with nutrient-rich water, making them a good proxy for productivity changes (Boltovskoy and Correa, 2016). Furthermore, the *B. skagerrakensis* factor also peaks occasionally within this interval (Fig. 4). The *B. skagerrakensis* factor relates to ecological preferences of the epifaunal to shallow infaunal benthic species *B. skagerrakensis*, a species associated with high fresh phytodetritus fluxes to the sea floor accompanied by a continuously high oxygen content in the sediments (Duffield et al., 2015). The abundant occurrence of *B. skagerrakensis* in the Skagerrak and Oslofjord area is restricted to water masses with temperatures between 5 and 7 °C and salinity around 35 PSU (Qvale and Nigam, 1985 and references therein; Alve and Murray, 1995, 1997; Duffield et al., 2015). In contrast to *P. osloensis*, *N. iridea* and *C. laevigata*, taxon *B. skagerrakensis* does not feed on decaying organic matter but prefers freshly settled algal material (Duffield et al., 2015).

At both sites, warm BWT and light $\delta^{18}O$ are recorded when high absolute abundance of planktonic foraminifera is seen between CE 900 and 1200 (Fig. 4). The correspondence between warm bottom water and high productivity of planktonic foraminifera suggests that the primary productivity was driven by nutrient-rich Atlantic water and abundant phytodetritus fluxes rather than enhanced nutrients entering the area through the Baltic outflow feeding the NCC. This interpretation is

supported by a study from the Northern North Sea, where Klitgaard-Kristensen and Sejrup (1996) argued that the Atlantic water is favourable for planktonic foraminifera, while the low salinity of the NCC reduces their abundance. Our interpretation is further supported by previous studies based on foraminiferal (Erbs-Hansen et al., 2011) and diatom (Gil et al., 2006) assemblages, as well as a multiproxy study by Hebbeln et al. (2006), which all report on an onset of enhanced Atlantic water

5   advection to the Skagerrak at ~ CE 900. Gil et al. (2006), documented an increase in diatom species associated with high salinity water in the Skagerrak and argued for enhanced productivity caused by inflow of nutrient-rich, high-salinity water via the NJC. The higher absolute abundance of planktonic foraminifera in EMB046/10-4GC than in EMB046/20-3GC can therefore be explained by an advantageous exposure to Atlantic water and smaller contribution of the low salinity Baltic Sea water within the NCC in the western, than in the central Skagerrak.

10   The stable carbon isotope composition recorded in calcareous benthic foraminiferal shells can be used to reconstruct past bottom water environments modified by fluxes of organic matter (Rohling and Cooke, 1999; Ravelo and Hillaire-Marcel, 2007). Marine organisms preferentially take up more ^{12}C than ^{13}C in their biomass. When this organic matter disintegrates after it is deposited at the ocean floor, more ^{12}C is released to the surrounding water. Hence, enhanced degradation at the bottom, e.g. related to enhanced primary productivity in the surface waters, will increase the ^{12}C concentrations in the

15   bottom/pore water, in addition to increasing the nutrient content. Foraminifera that calcify in such a ^{12}C enriched water mass will record lower $\delta^{13}C$ values than if less degradation of organic matter took place (Ravelo and Hillaire-Marcel, 2007; Filipsson and Nordberg, 2010). Hence, if the high absolute abundance of planktonic foraminifera is linked to enhanced productivity in the Skagerrak surface water between ~ CE 900 and 1200, a corresponding depletion of the benthic $\delta^{13}C$ would be expected. In EMB046/20-3GC record the $\delta^{13}C$ values are slightly lower during the first 150 years (~ CE 900 – 1050), when the absolute

20   abundance of planktonic foraminifera is highest in the same core. For EMB046/10-4GC there is no clear relationship between abundance of planktonic foraminifera and benthic $\delta^{13}C$ (Fig. 4). The lack of a clear response in the benthic $\delta^{13}C$ to high primary productivity in the surface water can in general be explained by a counteracting effect of high amounts of organic matter deposited at the sea floor and its further reduced remineralisation due to the oxygen depletion (McCorkle and Emerson, 1988; Fontanier, 2006; Brückner and Mackensen, 2008). We do, however, consider this to be an unlikely scenario. Low oxygen

25   conditions would be indicated by a decreased abundance of the oxygen deficiency sensitive species *C. laevigata* accompanied by peaks of *S. fusiformis*, which rapidly proliferates in oxygen depleted environments (e.g. Alve, 2003; Filipsson and Nordberg, 2004).

Based on the combined high absolute abundance of planktonic foraminifera, intermediate abundance of benthic palaeoproductivity species, occasional peaks in the *B. skagerrakensis* factor and an inconsistent relation between these and the

30   benthic $\delta^{13}C$ we conclude that the time interval CE 900 – 1200 was characterised by moderate palaeoproductivity in the Skagerrak. Furthermore, we argue that the moderate productivity was sustained by warm, nutrient-rich and highly saline Atlantic water bathing the sites.

The warm bottom water temperatures and moderate productivity found at CE 900 – 1200 correspond well to the overall stable and relatively warm temperatures at the Northern Hemisphere (CE 830 – 1100) (PAGES 2k Consortium, 2013)

associated with the early stage of the Medieval Climate Anomaly (MCA) (e.g. Hass, 1996). Hass (1996) argued that the MCA lasted until CE 1300 in the Skagerrak area. Based on granulometric analyses he suggested that the MCA was associated with a decreased strength of south-westerly winds as a result of a more northerly located cyclonic track causing weaker bottom currents. In contrast, the North Atlantic Oscillation (NAO) reconstruction by Trouet et al. (2009) suggests a tendency for

5   prevailing positive NAO conditions during the MCA and hence, south-westerlies dominating the hydrographic and meteorological regimes during winter. During a positive NAO phase, strong south-westerlies result in warm and wet winters over the Northern Europe (Hurrell, 1995; Hurrell et al., 2001; Trouet et al., 2009) and coincide with intensification of water mass exchange (inflows and outflows) in the Skagerrak (Winther and Johannessen, 2006). Hence, our warm BWT favours an interpretation of a positive NAO phase. Predominant positive NAO conditions would, however, also intensify the river runoff

10   and the outflow of brackish water from the Baltic Sea to the Skagerrak due to increased precipitation over the catchment area. Increased riverine input and Baltic Sea outflow would in turn enhance the nutrient supply to the surface waters of the Skagerrak, and hence, increase the primary production. However, the high absolute abundance of planktonic foraminifera recorded at our sites between ~ CE 900 and 1200 (Fig. 4) does not support increased Baltic Sea outflow since their abundance usually decreases in areas with increased brackish water conditions and decreased water transparency due to e.g. runoff (Murray, 1976;

15   Klitgaard-Kristensen and Sejrup, 1996).

Hence, to conclude it is likely that moderate productivity during ~ CE 900 – 1200 was primarily driven by nutrient-rich Atlantic water likely during the predominant positive NAO, where the Atlantic inflow was stronger than the Baltic Sea outflow creating favourable conditions for planktonic foraminifera in the region.

6.1.2 Low to moderate primary productivity (~ CE 1200 – 1600)

20   The low absolute abundance of planktonic foraminifera and benthic palaeoproductivity fauna accompanied by low TOC between ~ CE 1200 and 1600 indicate lower primary productivity than between ~ CE 900 and 1200 (Fig. 4). At the same time, a clear dominance of the *P. osloensis* factor including species *P. osloensis* and *N. iridea*, with an addition of *C. laevigata* in EMB046/10-4GC is documented throughout, in line with the previously identified *C. laevigata – P. osloensis* cluster (Erbs-Hansen et al., 2011) and *N. iridea – C. laevigata* category (Alve, 2010). These three species have an ecological preference for

25   nutrient-rich environments, preferably with oxic bottom water conditions (Alve, 2003, 2010; Duffield et al., 2015). Hence, overall nutrient-rich conditions likely prevailed in the Skagerrak. The δ^{13}C values seen during the interval ~ CE 1200 to 1600 are overall comparable to the previous interval (~ CE 900 – 1200) (Fig. 4). Hence, while δ^{13}C and the factor analysis do not show any major change, the interpretation of decreased primary productivity from CE 1200 is supported by the reduced absolute abundances of planktonic and benthic foraminifera (Fig. 4).

30   Within the period of overall decreased primary production after CE 1200, EMB046/20-3GC shows warmer BWT and lighter δ^{18}O than in EMB046/10-4GC ~ CE 1150 – 1350. This suggest that more of warm and well-oxygenated Atlantic water reached the central Skagerrak than its western part. However, a corresponding drop in absolute abundance of total benthic

foraminifera in EMB046/20-3GC and higher Mn/Ca values in EMB046/20-3GC in contrast to EMB046/10-4GC, suggest that bottom water oxygen conditions in the central Skagerrak may have become somewhat less favourable for benthic foraminifera due to reduced inflow of well-oxygenated Atlantic water or enhanced oxygen consumption after intense nutrients fluxes of various origins (Fig. 2, 4). It is likely that the Mn/Ca ratio increases during periods of lower bottom-water oxygen concentration

5   (Groeneveld and Filipsson, 2013). It has to be noticed, however, that generally low Mn/Ca values (0.15 – 0.8 mmol mol-1) in our records suggest slight changes in dissolved bottom water oxygen in comparison to a severe oxygen depletion recorded in a NE Skagerrak fjord as indicated by high Mn/Ca values (0.20 – 5.8 mmol mol-1) (Groeneveld and Filipsson, 2013). Thus, in our study we only use the Mn/Ca as a supportive indicator for seafloor oxygen conditions when the ratio corroborates changes seen in benthic foraminiferal assemblages.

10   Reduced Atlantic inflow to the central Skagerrak is further supported by the differences in foraminiferal assemblages between the cores at CE ~ 1200 – 1400. It is likely that the higher abundance of *C. laevigata* in core EMB046/10-4GC than in the EMB046/20-3GC reflect a higher contribution of well-oxygenated Atlantic waters to the western Skagerrak as compared to its central part (Fig. 2). The *C. laevigata* and *P. osloensis* are mostly recorded in the Skagerrak and Norwegian Trench area and are associated with Atlantic water influence (Van Weering and Qvale, 1983; Conradsen et al., 1994; Alve and Murray,

15   1995; Klitgaard-Kristensen et al., 2002; Wollenburg et al., 2004). In EMB046/20-3GC, the *C. laevigata* is largely replaced by dominance of *N. iridea* which is commonly present in the Skagerrak and the Scandinavian fjord waters with a salinity >35 PSU and a temperature range of 6 – 6.5 °C (Polovodova Asteman et al., 2013 and references therein). In addition, *N. iridea* is capable of growth under hypoxic-suboxic conditions (Duffield et al., 2015). Hence the dominance of *N. iridea* over *C. laevigata* in EMB046/20-3GC may be related to the less favourable bottom water oxygen conditions due to the lower contribution of

20   well-oxygenated Atlantic waters to the central Skagerrak than in its western part.

Consequently, the reduced Atlantic inflows and, perhaps, intensified input of freshwater via e.g. river runoff and precipitation could lead to reduced salinity in the central Skagerrak which influence the δ^{18}O and BWT signals (Ravelo and Hillaire-Marcel, 2007; Brückner and Mackensesn, 2008; Erbs-Hansen et al., 2011; Butruille et al., 2017). Thus, it is possible that the distinct differences in BWT and δ^{18}O between the sites at ~ CE 1150 – 1350 were an effect of a salinity, which biases

25   on the temperature signal. Enhanced river input can also explain observed differences in δ^{13}C between the sites. Depleted δ^{13}C seen at both sites after ~ CE 1200, and the lower δ^{13}C values in EMB046/20-3GC than in EMB046/10-3GC between CE 1300 and 1450, could be caused by an increased input of terrestrial organic carbon via enhanced river runoff due to land-use changes such as deforestation and strong agricultural expansion, documented at that time in Scandinavia (e.g. Lagerås, 2013). Thus, the more inland-located EMB046/20-3GC would be more affected by terrestrial influence than EMB046/10-3GC. In contrast,

30   the most depleted δ^{13}C are recorded in EMB046/10-4GC from ~ CE 1450. This can be associated with reduced terrestrial input to the central Skagerrak due to agriculture decline and vegetation changes in Scandinavia caused by a massive population decline in 14th century due to an outbreak of Black Death (e.g. Lagerås, 2013). In the second part of the 14th century BWT and δ^{18}O curves match again between both sites, suggesting decreased influence of local processes.

Despite a temperature drop indicated by a decrease in BWTs after ~ CE 1400 and eventually increase in $\delta^{18}O$ values (Fig. 4), bottom water conditions at both locations likely become more oxygenated, when the *B. skagerrakensis* factor and abundance of total benthic foraminifera both increase, and Mn/Ca records show lower values (Fig. 4).

The *B. skagerrakensis* factor peaks in EMB046/20-3GC between ~ CE 1400 and 1600, whereas similar variability is
5   not visible in EMB046/10-4GC record, which instead is dominated by *P. osloensis* factor (Fig. 4). Generally lower organic fluxes indicated by the lower TOC values in core EMB046/10-4GC (Fig 5), might have caused a food-competitive environment where the herbivorous *B. skagerrakensis* was likely outcompeted by a more omnivorous to detritivorous species *C. laevigata*, *P. osloensis* and *N. iridea*, which are all able to feed on both fresh and decaying organic matter (Alve, 2010; Duffield et al., 2015).
10   The pronounced appearance of *B. skagerrakensis* and increase in absolute abundance of total benthic foraminifera after ~ CE 1400 in EMB046/20-3GC, as well as low Mn/Ca values at the both sites (Fig. 4), likely indicate a period of well-oxygenated bottom water conditions with high fresh phytodetritus fluxes. Such favourable environmental conditions in the central Skagerrak in comparison to the preceding period (CE 1200 – 1400) and despite the colder BWTs at the both sites, were likely sufficient to satisfy most of foraminiferal needs required for growth and reproduction. The high oxygen and favourable
15   nutrient conditions were likely associated with an intense mixing of the water column and enhanced productivity. Gil et al. (2006) and Hebbeln et al. (2006) suggested increased storminess that entailed intense mixing of the water column at this time (Erbs-Hansen et al., 2011), in line with our results. The colder BWTs at both sites can be indicative of weaker Atlantic water inflow. Hence, the nutrients of Atlantic origin that previously triggered primary production in the Skagerrak region were likely, to a large extent, replaced by nutrients transported by local river runoff and the Baltic Sea outflow after ~ CE 1400. This is
20   supported by a period of minimum salinity in the Skagerrak surface water identified for CE 1400 – 1550 by Hebbeln et al. (2006).

From the discussion above it is seen that several processes took place between CE 1200 and 1400, including changes in bottom water circulation, oxygen fluctuation or carbon fluxes. Each of the causes may in turn have been influenced by anthropogenic,
25   climatic and/or oceanic factors (Brückner and Mackensen, 2008; Filipsson and Nordberg, 2010). The changing climate conditions during the transition between MCA and the Little Ice Age (LIA), likely accompanied by increased storminess (Gil et al., 2006), were important for the difference between the central and western Skagerrak records. The second part of the 'low to moderate productivity' period (CE 1400 – 1600) is characterised by a temperature drop at the both sites (Fig. 4). This cooling in the Skagerrak is consistent with a temperature decline in the North Atlantic after ~ CE 1350, marking the onset of the LIA
30   in northern Europe (Berstad et al., 2003; Brückner and Mackensen, 2006; Büntgen et al., 2011; Erbs-Hansen et al., 2011). Among other reconstructions, Trouet et al. (2009) proposed that during the LIA the NAO index was predominantly negative and was characterised by weaker westerly airflows resulting in a reduction of the Atlantic water inflows. Reduced advection of warm Atlantic water to the Skagerrak may explain the colder bottom water conditions seen in our records.

Based on our combined multi-proxy records and the discussion above, we conclude that the time interval CE 1200 – 1600 was characterized by generally low to moderate primary productivity in the Skagerrak during variable climate conditions, which are characteristic for the beginning of the Little Ice Age followed by a more stable but colder climate between ~ CE 1400 and 1600. Nutrients present in the Skagerrak were likely transported with the Baltic outflow, river runoff or were generated internally via mixing of the water column due to storms.

6.1.3 High primary productivity (~ CE 1600 – present)

A prominent change in benthic foraminiferal assemblages, $\delta^{13}C$ and TOC took place around CE 1600 in both cores, suggesting a shift in environmental conditions in the Skagerrak. The palaeoproductivity related foraminiferal fauna increased and the values of *B. skagerrakensis* factor largely replaced the *P. osloensis* factor (Fig. 4). These changes in foraminiferal assemblages were accompanied by a gradual depletion of $\delta^{13}C$ and a continuous increase in TOC in both cores (Fig. 4). All proxies suggest enhanced primary productivity from CE 1600 towards present day.

The increased primary productivity after ~ CE 1600 corresponds well with increased BWT and lower $\delta^{18}O$ (Fig. 4). This warming of the bottom water reflects naturally-induced environmental changes in the Skagerrak region accompanied by a gradually increasing human activity. The warming seen in our records is consistent with intensified heat transport to the Northern Hemisphere (Brückner and Mackensen, 2006), overall warm climate in Fennoscandia (Briffa et al., 1992) and warm spring conditions recorded between CE 1700 and 1920 off the Norwegian continental margin (Berstad et al., 2003). Furthermore, our results are supported by similar $\delta^{18}O$ changes recorded in the same area and at the same time by Hass (1995). The bottom water warming was associated with the termination of the coldest LIA phase in the Skagerrak region (Berstad et al., 2003; Brückner and Mackensen, 2006), a transition to a more positive NAO mode that would entail wetter and warmer winters over Scandinavia (Hurrell et al., 2001), or both. Either way, our data demonstrate a long-term intensification of nutrient supply likely due to increased inflows of Atlantic water to the Skagerrak.

Associated with a generally more positive NAO phase it is expected that changes in atmospheric and oceanic circulation systems would result in enhanced surface water outflow from the Baltic Sea (e.g. Gustafsson and Stigebrandt, 1996; Zorita and Laine, 2000). As a consequence of increased precipitation and thus enhanced river runoff over the large Baltic Sea catchment area, the outflowing low saline Baltic Sea water would supply the Skagerrak surface water with nutrients (Svansson, 1975; Aure et al., 1998; Krossa et al., 2015). The total freshwater riverine discharge from the Baltic Sea together with the contributions from the major Norwegian rivers to the Skagerrak contribute with much less nutrients to the Skagerrak waters than nutrient transport via the inflows from the North Sea (Danielssen et al., 1997). However, Krossa et al. (2015) still showed a good correlation between the increased Baltic outflow and enhanced productivity in the Skagerrak on timescales longer than 1100 years, based on increased alkenone $C_{37:4}$ concentration, a proxy for the influence of brackish water. Furthermore, Polovodova Asteman (2018), documented increased palaeoproductivity over the last 1700 years that corresponded in time with the increased alkenone $C_{37:4}$ concentration (Krossa et al., 2015). They argued that the nutrient-rich water causing enhanced

productivity in the central Skagerrak was to a large extent of Baltic origin. Thus, the Baltic outflow can play an important role in the Skagerrak nutrients budget.

Zillén et al. (2008) showed that a widespread oxygen deficiency in the Baltic Sea was stimulated by an increased nutrient loading associated with a growing population and intensification of land use changes, which all began around CE 1600 and were followed by an industrial development at around CE 1800. In more recent times (after ~ CE 1900), the land use changes in Scandinavia caused an increased terrestrial runoff through either sparsely cultivated lands after massive deforestation or an extensive farming in southern Sweden (Zillén et al., 2008 and references therein; Kaplan et al., 2009). Hence it is likely that superimposed on the natural variability in volume of the outflowing Baltic water, the concentration of nutrients in the outflowing water has changed after ~ CE 1600 towards present due to a gradually increased human impact.

At the same time as increased primary production caused eutrophication in the Baltic Sea, our data shows a clear decrease in the δ^{13}C values at both Skagerrak sites (Fig. 4). This distinct depletion in δ^{13}C provides evidence for a change from the ocean-atmospheric relationship established for the preceding periods towards an additional contribution of the lighter carbon isotope (^{12}C) to the sea water from the atmosphere due to the increase in atmospheric CO_2 concentration caused by anthropogenic emissions. This effect of increased anthropogenic CO_2 emissions is known as the Suess effect, manifested as a shift in the marine δ^{13}C towards much lower values (e.g. Cage and Austin, 2010; Filipsson and Nordberg, 2010; Eide et al. 2017). Both the increased primary productivity and the Suess effect may cause the depletion in benthic δ^{13}C. However, the decrease of ca 0.9‰ seen in our δ^{13}C records from ~ CE 1750 towards present is likely to a large extent explained by the Suess effect, in line with the ca 0.8‰ δ^{13}C decrease between the preindustrial and modern period observed in the North Atlantic (Eide et al., 2017).

During the last 70 years the water conditions in Skagerrak changed as indicated by a slightly increased Mn/Ca in our records (Fig. 4). At the same time *B. skagerrakensis* starts to decrease in favour of higher *S. fusiformis* abundances (Fig. 2). *Stanforthia fusiformis* is considered as an indicator of trophic changes in Scandinavian waters due to its high tolerance of oxygen-depleted and organic-rich conditions (e.g. Alve, 2003 and references therein). This opportunistic species has the highest reproduction (up to 7 times/month) and growth rates after the phytoplankton blooms followed by an enhanced food supply to the sea floor and decay of organic matter (Gustafsson and Nordberg, 2001). This explains the taxon's food preferences recognised as fresh phytodetritus and microbes associated with degradation of organic matter (Duffield et al., 2015). Therefore, the increased abundance of *S. fusiformis* during the last 70 years in our records may suggest changes in bottom water oxygenation regime during the continuously high nutrients content as it has been shown for the Skagerrak fjords with sluggish bottom water circulation (e.g. Alve, 2003; Filipsson and Nordberg, 2004). In addition, the increased Mn/Ca in the last 70 years in our records likely point to slightly decreased bottom water oxygen (Fig. 4). The assumption of a gradual decline in oxygen concentration in the Skagerrak during the last 70 years is supported by other studies (e.g. Rosenberg, 1990; Johannessen and Dahl, 1996).

To summarize, from ~ CE 1600 towards present day changes in palaeoproductivity proxies indicate increased primary productivity likely caused by a combination of inflow of warm Atlantic water, the Baltic outflow, intensified river runoff and

enhanced human impact through agriculture expansion and industrial development. This increase in primary production occurred during a warm period associated with a generally more positive NAO phase.

7 Conclusions

This study provides evidence for changes in primary productivity in the Skagerrak during the last millennium. Our multi-proxy
5 records show that the time interval ~ CE 900 – 1200 was characterised by moderate primary production with nutrients largely sustained by warm Atlantic water, as revealed by high abundance of planktonic foraminifera, warm BWT and depleted $\delta^{18}O$ in foraminiferal shells. This was likely associated with the warm Medieval Climate Anomaly, during which a persistent positive NAO strengthened westerlies resulting in mild and wet winters over the Northern Europe.

The transition to a low primary productivity period after ~ CE 1200 coincides with variable climate conditions which
10 are characteristic for the beginning of the Little Ice Age followed by a more stable, but colder, climate between ~ CE 1400 and 1600. The latter is consistent with a decrease in BWT and increased $\delta^{18}O$ values in our records. The period of lower primary productivity seen in our records between ~ CE 1200 and 1600 is characterized by a dominance of *P. osloensis* factor, low TOC, low abundance of both planktonic and benthic palaeoproductivity fauna. At that time, fluctuations of organic matter input were likely associated with land-use changes, water column mixing, low Atlantic water inflows, together with local river
15 runoff and the Baltic outflow, with the last two likely being the most dominant nutrients sources.

Finally, the high primary productivity period between ~ CE 1600 and 1950 is documented by both increased TOC and *B. skagerrakensis* factor, high absolute abundance of palaeoproductivity fauna and decreased $\delta^{13}C$ values. Enhanced nutrient availability was likely caused by a stronger Baltic Sea outflow, increased river runoff, intensified inflows of the nutrient-rich Atlantic water, together with agricultural and industrial expansion. Simultaneously, an increase in human induced
20 CO_2 emission caused great change in oceanic carbon isotope budget, indicated by the Suess effect, shown in our records by strongly negative $\delta^{13}C$ values since ~ CE 1750. The increase in primary production at ~ CE 1600 – 1950 occurred during a warm period with a more positive NAO, wetter and warmer winters in Scandinavia as shown by an increase in BWT and decrease in $\delta^{18}O$ in our records.

A comparison between two records shows slight differences in species composition likely due to more favourable
25 habitat in the western Skagerrak, with a better exposure to high-saline, oxygenated and nutrient-rich Atlantic water while the higher TOC in the central Skagerrak mostly results from a better exposure to the Baltic outflow and terrestrial runoff due to a more inland location.

Competing interests

The authors declare that they have no conflict of interest

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Tables

Table 1: List of dominant (bold) and accessory benthic foraminiferal species. The species names marked by "*" represent foraminiferal species with relative abundance >5% in only one sample, thus were excluded from statistic classification.

Core EMB046/10-3GC
Brizalina skagerrakensis Qvale & Nigam, 1985
Bulimina marginata d'Orbigny, 1826
Cassidulina laevigata d'Orbigny, 1826
Cassidulina neoteretis Seidenkrantz, 1995
Eggereloides medius (Höglund, 1947)
Epistominella sp. including *E. exigua* (Brady, 1884) *E. vitrea* Parker, 1953
Hyalinea balthica (Schröter in Gmelin, 1791)
Melonis barleeanum (Williamson, 1858)
Nonionella iridea Heron-Allen & Earland, 1932
Pullenia osloensis Feyling-Hanssen, 1954
Stainforthia fusiformis (Williamson, 1848)

Core EMB046/20-4GC
*Bolivina spathulata (Williamson, 1858)
Brizalina skagerrakensis Qvale & Nigam, 1985
*Bulimina elegantissima d'Orbigny, 1839
*Bulimina marginata d'Orbigny, 1826
Cassidulina laevigata d'Orbigny, 1826
Cassidulina neoteretis Seidenkrantz, 1995
*Cassidulina norcrossi Cushman, 1933
Eggereloides medius (Höglund, 1947)
Epistominella sp. including *E. exigua* (Brady, 1884) *E. vitrea* Parker, 1953
Hyalinea balthica (Schröter in Gmelin, 1791)
Melonis barleeanum (Williamson, 1858)
Nonionella iridea Heron-Allen & Earland, 1932
Pullenia osloensis Feyling-Hanssen, 1954
Recurvoides laevigata Höglund, 1947
Stainforthia fusiformis (Williamson, 1848)
*Triloculina tricarinata d'Orbigny, 1826
*Trochammina sp. Parker & Jones, 1859

Table 2: The factor results from a CAB-FAC factor analyses.

EMB046/10-4GC		
Factors	Eigenvalue	Variance (%)
1	88.665	86.08
2	9.1984	8.93
3	1.8953	1.84
EMB046/20-3GC		
Factors	Eigenvalue	Variance (%)
1	45.2	80.72
2	6.4351	11.49
3	1.3995	2.5

Table 3: The varimax scores for factors 1 – 3. The bold numbers indicate foraminiferal species with absolute value of factor scores >1.

EMB046/10-4GC					EMB046/20-3GC			
Foram. species	Factor 1	Factor 2	Factor 3		Foram. species	Factor 1	Factor 2	Factor 3
B. skagerrakensis	-0.95083	**3.1052**	0.11006		*B. skagerrakensis*	-0.81099	**3.1907**	-0.01581
B. marginata	0.28721	0.29398	-0.18906		*C. laevigata*	0.55287	0.27574	-0.19865
C. laevigata	**1.3438**	0.45052	**-1.234**		*C. neoteretis*	0.030673	0.23185	-0.11031
C. neoteretis	0.036824	0.15451	-0.01801		*E. medius*	0.38736	0.13685	-0.15638
E. medius	0.13292	0.57788	0.48831		*Epistomienlla sp.*	0.26935	0.1446	0.47431
Epistominella sp.	0.18666	0.15052	0.2312		*H. baltica*	0.31697	0.33722	0.73552
H. baltica	0.18637	0.35011	-0.25495		*M. barleeanum*	0.30047	0.062139	-0.09968
M. barleeanum	0.25854	0.14265	-0.13135		*N. iridea*	**1.8606**	0.35752	**2.357**
N. iridea	**1.0553**	0.25077	**1.8493**		*P. osloensis*	**2.3155**	0.54091	**-2.0843**
P. osloensis	**2.4565**	0.68666	-0.91334		*R. laevigatum*	0.202	0.007055	-0.31694
S. fusiformis	0.95088	0.10359	**2.191**		*S. fusiformis*	0.87063	0.33472	0.38467

Figures
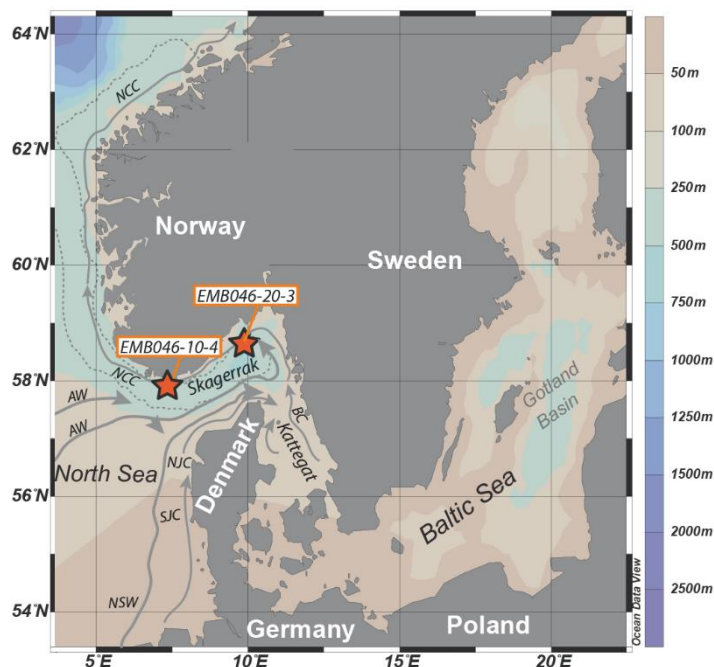
Figure 1: Map of cores locations (stars) in the Skagerrak, the NE North Sea (modified from Polovodova Asteman et al. 2018). Norwegian Trench is outlined by a thin grey dotted line along the coast of Norway. Major current systems and water masses in Skagerrak are indicated by arrows: the Baltic Current (BC), Northern Jutland Current (NJC), Southern Jutland Current (SJC), Norwegian Coastal Current (NCC), North Sea Water (NSW) and Atlantic Water (AW).
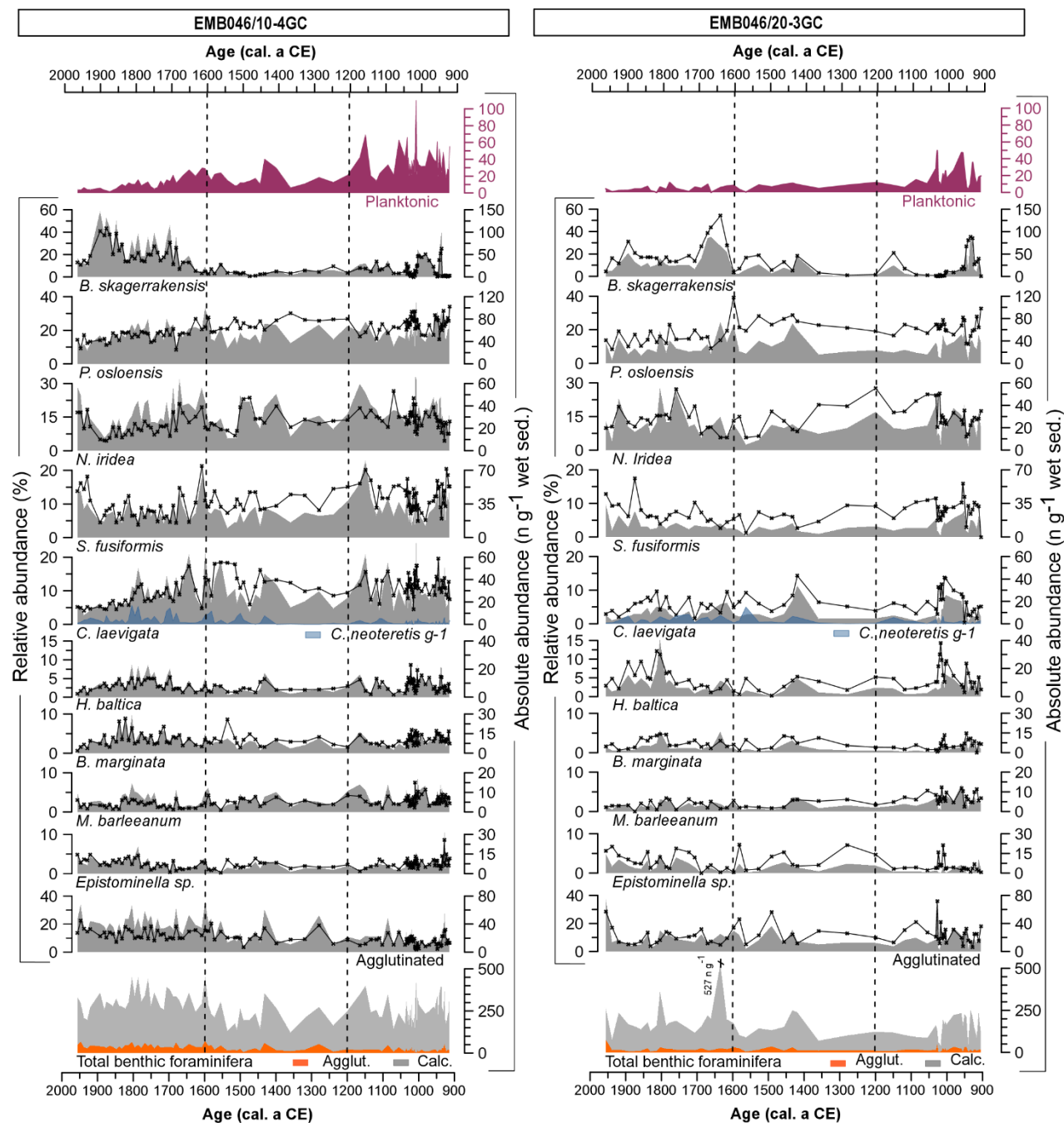
Figure 2: Foraminiferal assemblages including dominant and accessory benthic species for both cores (EMB046/10-4GC and EMB046/20-3GC). Absolute abundance is shown as grey filed, while relative abundance as black curve with symbols. The absolute abundance of total benthic foraminifera is a sum of all species: agglutinated (Agglut.) and calcareous (Calc.). Dashed lines divide record into 3 periods of most pronounced palaeoproductivity changes, which are discussed in the text.
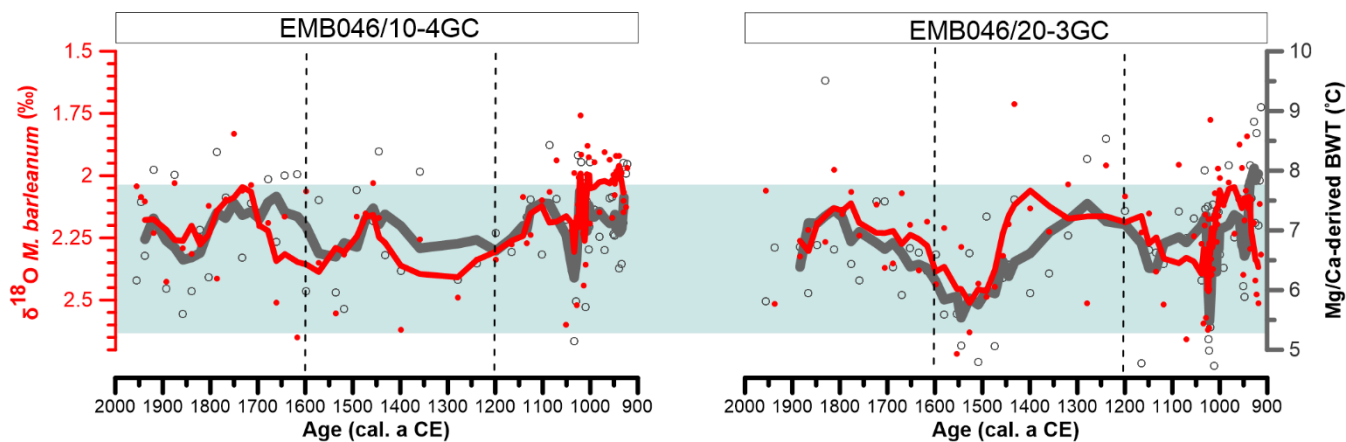
Figure 3: Oxygen stable isotopes (δ18O, red) and the Mg/Ca-derived bottom water temperature (Mg/Ca-derived BWT, grey) of both studied cores against age. Figures include data from depths at which data of both proxies (δ18O and Mg/Ca-derived BWT) are available (symbols). The curves correspond to 5-points running average. Grey box indicates range of instrumentally recorded temperatures of the time period between 2009 and 1924 years from the area between 57°.17–58°´N and 8°–9°.79´E at 300 – 340 dbar (ICES 2010).
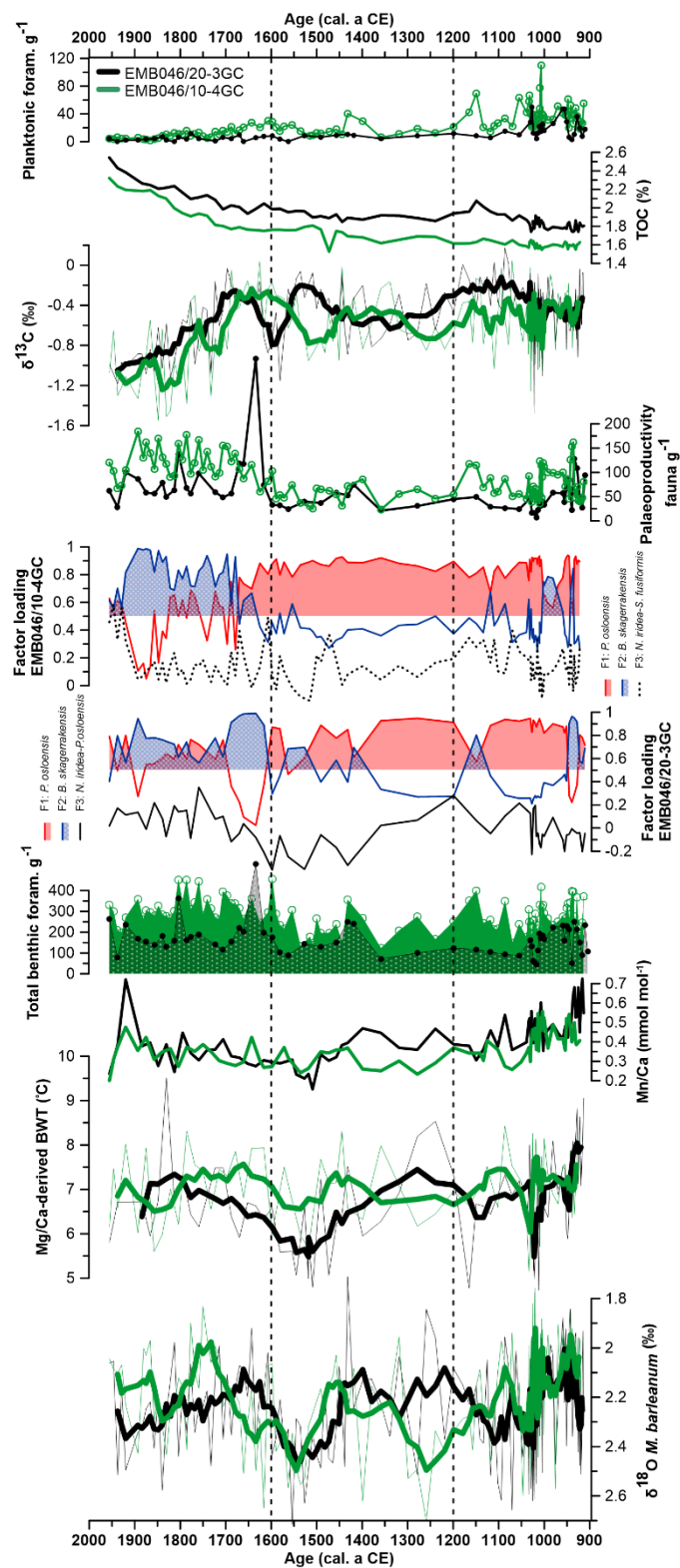
Figure 4: Comparison of absolute abundances of planktonic foraminifera, total organic carbon (TOC), stable carbon isotope (δ13C), absolute abundance of palaeoproductivity fauna, CABFAC results, absolute abundance of total benthic foraminifera, the Mn/Ca ratio, Mg/Ca-derived bottom water temperature (Mg/Ca-derived BWT), oxygen stable isotope (δ18O) between two studied sediment cores EMB046/10-4GC (green curves) and EMB046/20-3GC (black curves). The thicker curves correspond to 5-points running average. Dashed lines divide record into 3 periods of most pronounced palaeoproductivity changes, which are discussed in the text.