The Holocene 16,7 (2006) pp. 937–947

Mid-latitude shelf seas: a NW European perspective on the seasonal dynamics of temperature, salinity and oxygen isotopes

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Abstract: Pronounced seasonal variability, particularly in the surface ocean heat flux, imparts an important control that drives thermal stratification of the tide-dominated middle- and high-latitude shelf seas. Bottom water temperature and salinity data, resolved on a grid 20′ latitude by 30′ longitude, were combined with a regional synthesis of the salinity:δ^{18}O relationship in order to generate a spatial and temporal understanding of oxygen isotopes in seawater around the shelf seas of NW Europe. The data are expressed according to equilibrium calcite ($\delta^{18}O_{Eq.calcite}$) and, in the shallow mixed water column, exhibit large seasonal changes that are primarily driven by bottom water temperature. Annual bottom water temperature varies from <3°C to >17°C in the southern North Sea, generating a seasonal $\delta^{18}O_{Eq.calcite}$ signal of up to 3.2‰. The amplitude of the seasonal $\delta^{18}O_{Eq.calcite}$ signal is significantly damped (0.1–0.2‰) in deeper, thermally stratified shelf waters. Maps of the monthly distribution $\delta^{18}O_{Eq.calcite}$ provide the first systematic overview of the spatial and temporal changes on the NW European shelf and highlight the importance of understanding seasonal growth on the incorporation of geochemical signatures into marine organisms.

Key words: Shelf seas, oxygen isotopes, temperature, salinity, seasonality, HOLSMEER project.

Introduction

Shelf seas, particularly in the tide-dominated middle and high latitudes, are characterized by seasonal thermal stratification of the water column. On the shelf, dissipated tidal energy predominantly drives mixing through the water column, but may be opposed by thermal stratification causing the development of a seasonal thermocline in response to marked seasonal variability of the surface heat flux (eg, Pingree and Griffiths, 1978). During the summer months, well-defined fronts representing the surface expression of the thermocline, separate areas of stratified and mixed water on the shelf. During the autumn, as the surface heat flux diminishes, tidal energy causes a return to mixing and the fronts are broken down.

In NW European shelf areas where the water column remains mixed throughout the year, the temperature difference between bottom and surface water is relatively small, typically 1–2°C, but in regions where the water column is stratified, significant thermal gradients, up to 5–6°C, are recorded (Elliot *et al.*, 1991). As a result, summer bottom water temperatures can be lower in a stratified than in a well-mixed water column. For example, a bottom water temperature gradient of 1–2°C across the Celtic Sea front in September contrasts with gradients of between 7 and 9°C in the southern North Sea during the same month (Elliot *et al.*, 1991). Therefore, while both seasonal and geographical variations exist in bottom water temperatures throughout the shelf seas of NW Europe, these are often most pronounced in late summer across frontal regions (eg, Austin and Scourse, 1997).

Numerical models of the M_2 tide (ie, the lunar semi-diurnal ocean tide component) on the NW European shelf provide a predictive capability in assessing basic tidal dynamics (amplitude, current, bed stress), including tidal mixing, from bathymetry, coastline configuration and a known ocean tide at the shelf edge. The pattern of frontal development in the shelf seas of NW Europe at the present day can be predicted with considerable accuracy (Pingree and Griffiths, 1978; Belderson *et al.*, 1986; Austin, 1991; Scourse and Austin, 1995) and such models therefore provide a means to predict frontal evolution in the past. Austin (1991) used one such model to predict the tidal regime on the NW European shelf at successive stages during the Holocene transgression by incorporating inputs derived from interpretations of geological data (eg, relative sea-level reconstructions).

Austin and Scourse (1997) tested the predictions of this model using faunal and stable isotopic data from British Geological Survey (BGS) vibrocore 51/-07/199 from the central Celtic Sea. More recently, Scourse *et al.* (2002) re-evaluated the stratigraphy of vibrocore 51/-07/199 after obtaining additional Accelerator Mass Spectrometry (AMS)

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10.1177/0959683606hl985rp

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^{14}C dates and placed the timing of the onset of seasonal stratification in the central Celtic Sea at 8720 cal. yr BP. Despite these promising results, there have been relatively few palaeoceanographic studies that have documented the evolution of shelf sea fronts and thermoclines. A widespread conviction exists that continental shelves are zones of net erosion, unconformities in the making (Curry, 1989), and are therefore unlikely to preserve sedimentary records suitable for palaeoceanographic investigation. However, shelf sea environments do hold the potential to preserve important palaeoceanographic archives (eg, Scourse and Austin, 2002) and the HOLSMEER project (this issue) illustrates their significance in reconstructing climatic and oceanographic change over the last two millennia.

The aim of this study is to provide the first systematic review of the long-term averaged (modern) spatial and temporal pattern of oxygen isotopes in seawater, expressed according to equilibrium calcite, around the shelf seas of NW Europe. In compiling these data, we provide a monthly overview of the calculated isotopic composition of calcite grown in equilibrium with seawater, together with the first comprehensive review of salinity:oxygen isotope mixing relationships in the coastal ocean. The data are likely to be of interest to anyone studying the incorporation of geochemical signatures into marine organisms.

The salinity:oxygen isotope relationship

As described in the classic papers of Craig (1961) and Dansgaard (1964), the isotopic composition of precipitation is depleted in ^{18}O relative to the oceans. The extent of ^{18}O depletion in precipitation varies throughout Europe (Figure 1) and the $\delta^{18}O$ of precipitation, captured by the Global Network for Isotopes in Precipitation (GNIP) station data (http://isohis.iaea.org, last accessed 21 June 2006), exhibits two pronounced features. First, a notable trend towards isotopic depletion from west to east as the heavy isotope ^{18}O is preferentially and progressively rained out; the same progressive isotopic depletion is also observed towards higher latitudes (Figure 2). Second, a strong seasonality in the $\delta^{18}O$ of precipitation, with a winter depletion and summer enrichment in ^{18}O and a tendency for the amplitude of this isotopic variation to increase with distance (and altitude) from the maritime stations (Figure 2). Darling (2004) provides a useful review of some of the key hydrological factors that govern the isotopic composition of surface and groundwaters throughout Europe.

Therefore, throughout the coastal regions of NW Europe, freshwater runoff and groundwaters (depleted in ^{18}O) mix with shelf water (enriched in ^{18}O) to define a regional salinity:oxygen isotope relationship (eg, Mikalsen and Sejrup, 2000; Austin and Inall, 2002; Owen et al., 2002; Scheurle and Hebbeln, 2003). Regional salinity:$\delta^{18}O_{water}$ mixing-lines are defined by the following relationship:

$$\delta^{18}O_{water} = m*S + c \qquad (1)$$

where m is slope of the mixing-line; S is salinity of coastal water and c is the isotopic composition of freshwater entering the coastal environment. These seawater and freshwater data are all reported relative to Vienna Standard Mean Ocean Water (VSMOW); however, care should be taken to check specific references for detailed information regarding analytical precision (see Table 1).

As one might expect from the GNIP data (Figure 1), estimates of the freshwater end-member (c) vary greatly throughout European and northern waters (Table 1), with the least fractionated values typically reported from the west coast regions, eg, −6.0‰ Scottish west coast (Austin and Inall, 2002); −7.42‰ Irish/Celtic Seas (Owen *et al.*, 2002; Scourse *et al.*, 2004). Values of c around the North

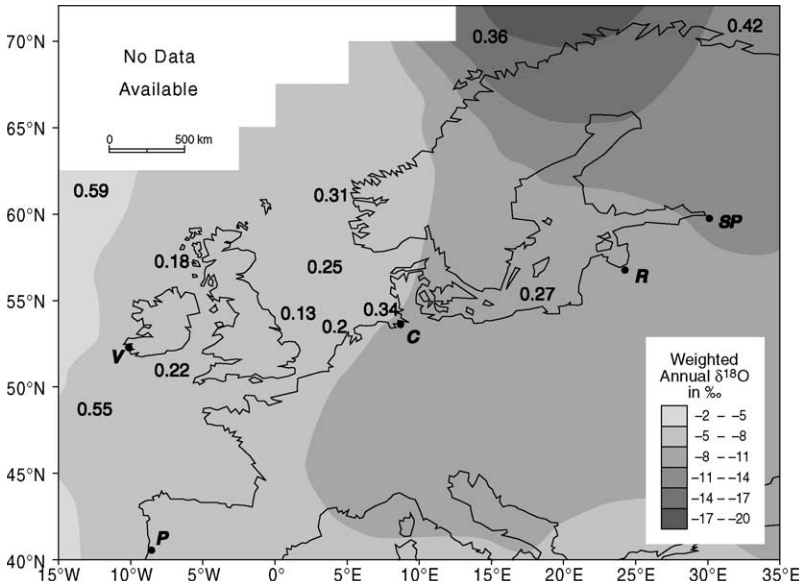

Figure 1 Location map, showing the weighted annual $\delta^{18}O$ (‰ VSMOW) in precipitation over NW Europe (modified from IAEA, 2001). Individual GNIP stations that illustrate pronounced latitudinal and longitudinal gradients in $\delta^{18}O$, air temperature and precipitation amount (see Figure 2) are indicated as follows: P, Porto; V, Valentia; C, Cuxhaven; R, Riga; SP, St Petersberg. Regional salinity:$\delta^{18}O$ mixing-line gradients (m) for coastal and shelf waters are shown (see Table 1)

Figure 2 Selected GNIP station data showing averaged monthly $\delta^{18}O$ in precipitation (solid line), air temperature (grey squares) and precipitation amount. Station locations are shown in Figure 1. AWM is annual weighted mean $\delta^{18}O$ (‰ VSMOW) value

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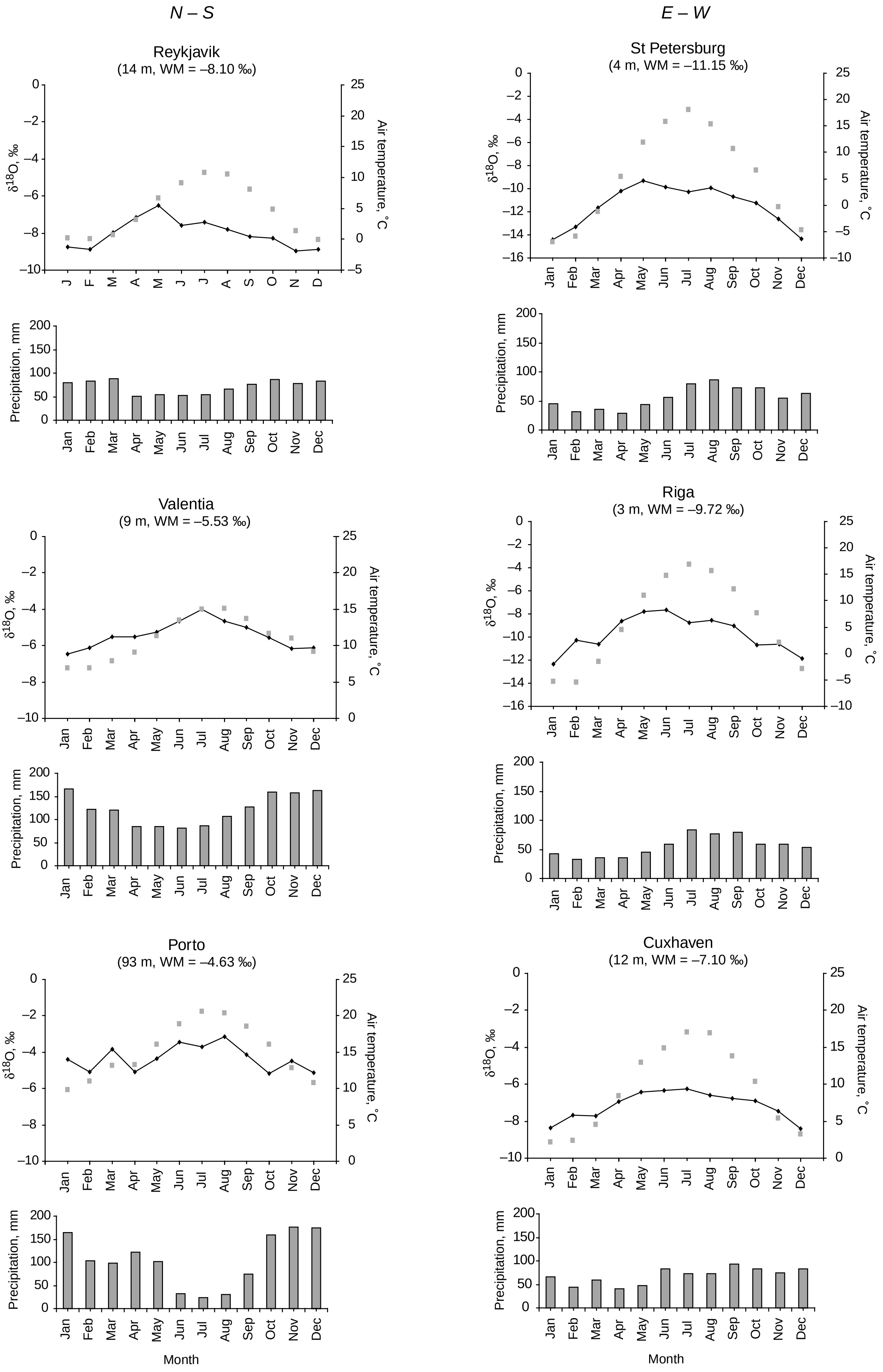

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Sea are variable, ranging from $-8.91‰$ in the Baltic Sea (Fröhlich *et al.*, 1988), $-9.36‰$ in the German Bight (Scheurle and Hebbeln, 2003) and $-14.55‰$ in the central North Sea (Ganssen in Witbaard *et al.*, 1994). Smith *et al.* (2005) report a value of *c* on the Iceland Shelf of $-10.99‰$; whilst Mikalsen and Sejrup (2000) report a value of $-10.49‰$ from the Sognefjord, western Norway and Polyak *et al.* (2003) report a value of $-14.84‰$ from the Arctic (Pechora Sea). North Atlantic and northern North Atlantic values are reported as $-19.45‰$ and $-23.0‰$, respectively (Ganssen and Kroon, 2000; Frew *et al.*, 2000).

Austin and Inall (2002) highlighted the fact that *c* is not constant, and although various authors (eg, Soulsby *et al.*, 2000) suggest that the seasonal precipitation differences in $\delta^{18}O_{water}$ are damped in stream waters, 'flashy' isotopic responses (eg, Lawler, 1987) and seasonal variation (eg, Mook, 1970; Ricken *et al.*, 2003) in the larger European rivers draining into the southern North Sea are known to arise when summer snowmelt occurs. Other factors, such as sea ice formation and melting at differing times of the year may significantly alter the seasonal salinity:$\delta^{18}O_{water}$ relationship, particularly in the high latitudes (eg, Strain and Tan, 1993). The changing seasonal balance between evaporation and precipitation and its effect upon the salinity:$\delta^{18}O_{water}$ relationship in European coastal waters is poorly studied, but these processes are likely to have a limited impact on bottom waters.

Despite these uncertainties, the effects of the seasonal evolution of the salinity:$\delta^{18}O_{water}$ relationship over most of the NW European shelf can largely be ignored, except in the lowest salinity environments. At higher, normal marine, salinities the seasonal changes in *c* are unlikely to impart a major signal to the $\delta^{18}O_{water}$, but the slope of the mixing-line (*m*) becomes critical as salinity decreases. In this study, the most sensitive regions appear to be the coastal waters of the southern North Sea, from the German Bight (Scherule and Hebbeln, 2003) towards the Baltic (Fröhlich *et al.*, 1988) and along the west Norwegian coast (Mikalsen and Sejrup, 2000). European coastal waters least likely to be affected by marked salinity:$\delta^{18}O_{water}$ relationships are those to the west, where the freshwater end-member (*c*) is least depleted (Austin and Inall, 2002; Owen *et al.*, 2002; Scourse *et al.*, 2004).

Bottom water temperature data

The temperature data used in this study were compiled from 45 000 XBT (eXpendable BathyThermograph) profiles by Elliot *et al.* (1991) to generate monthly average measurements in the NW European shelf seas. The data are positioned and averaged on a 37.1 km (20 nautical mile) grid (20′ latitude by 30′ longitude), covering an area from 47°N to 62°N and 12°W to 9°E. Bottom water temperatures during February (Figure 3a) reveal the warmest waters (11°C) in the South West Approaches and coolest temperatures (<3°C) in the shallow (<30 m) southern North Sea. During August (Figure 3b) summer bottom water temperatures are completely reversed, with the mixed, shallow southern North Sea warming to >17°C, but the South West Approaches bottom temperatures rising little above 11.5°C. In general, those regions of the shelf that develop seasonal thermal stratification of the water column (Elliot *et al.*, 1991) exhibit significantly less intra-annual bottom water temperature variation than mixed regions. Over the NW European shelf, the largest widespread intra-annual bottom water temperature changes are observed in the southern North Sea, but similarly large temperature changes are likely in a number of shallow coastal locations.

Predicting $\delta^{18}O_{water}$

Gridded monthly bottom salinity data for the NW European shelf were not readily available and we therefore used mean bottom salinity (summer and winter) maps (Lee and Ramster, 1981). Where winter salinity data were not available, for example to the west of Ireland and Scotland, mean summer bottom salinity data were used. The winter map, which is based on the mean bottom salinity distribution in February, shows an expected pattern, with North Atlantic water (≥ 35) filling much of the northern and central North Sea, the deep Skagerrak and the South West Approaches (Figure 4a). The mean bottom salinity in summer is based on the distribution of August data and there is very little difference between the summer (Figure 4b) and winter (Figure 4a) months, except for a small retreat of the 35 isohaline in summer. However, these movements are small when compared with the movements of the surface salinity fields (Lee and Ramster, 1981).

Table 1 Regional NE Atlantic–Arctic salinity:$\delta^{18}O$ mixing-line relationships. Values of the freshwater intercept (*c*) are omitted here when not available from the primary reference

Region	Salinity:$\delta^{18}O$ gradient	Intercept	R^2	Reference
North Sea (UK coast)	0.16 (winter) 0.1 (summer)	NA		Hickson *et al.* (1999)
NW Scottish coastal waters	0.18	−6	0.998	Austin and Inall (2002)
Southern North Sea	0.2	NA		Mook and Vogel (1968)
Celtic Sea/Irish Sea	0.22	−7.419	0.902	Owen *et al.* (2002); Scourse *et al.* (2004)
North Sea	0.25	NA		Israelson and Buchardt (1991)
Baltic Sea	0.272	−8.91	0.978	Fröhlich *et al.* (1988)
Nordic Seas	0.2–0.3	NA		Østbø, (2000) (cited from Risebrobakken *et al.* (2003))
Sognefjord	0.31	−10.497	0.88	Mikalsen and Sejrup (2000)
Iceland shelf	0.32	−10.99	0.99	Smith *et al.* (2005)
German Bight	0.34	−9.36	0.86	Scheurle and Hebbeln (2003)
East & Central Nordic Seas	0.36	−12.17	0.72	Simstich *et al.* (2003)
Pechora Sea (Arctic, Barents Sea)	0.42	−14.84	0.97	Polyak *et al.* (2003)
East Greenland Current (west of 19°W)	0.495	−17.11	0.96	Simstich *et al.* (2003)
North Atlantic	0.55	−19.45	0.938	Ganssen and Kroon (2000)
Northern North Atlantic	0.59	−23	0.89	Frew *et al.* (2000)
Open Atlantic Ocean	0.61	NA		Craig and Gordon (1965)

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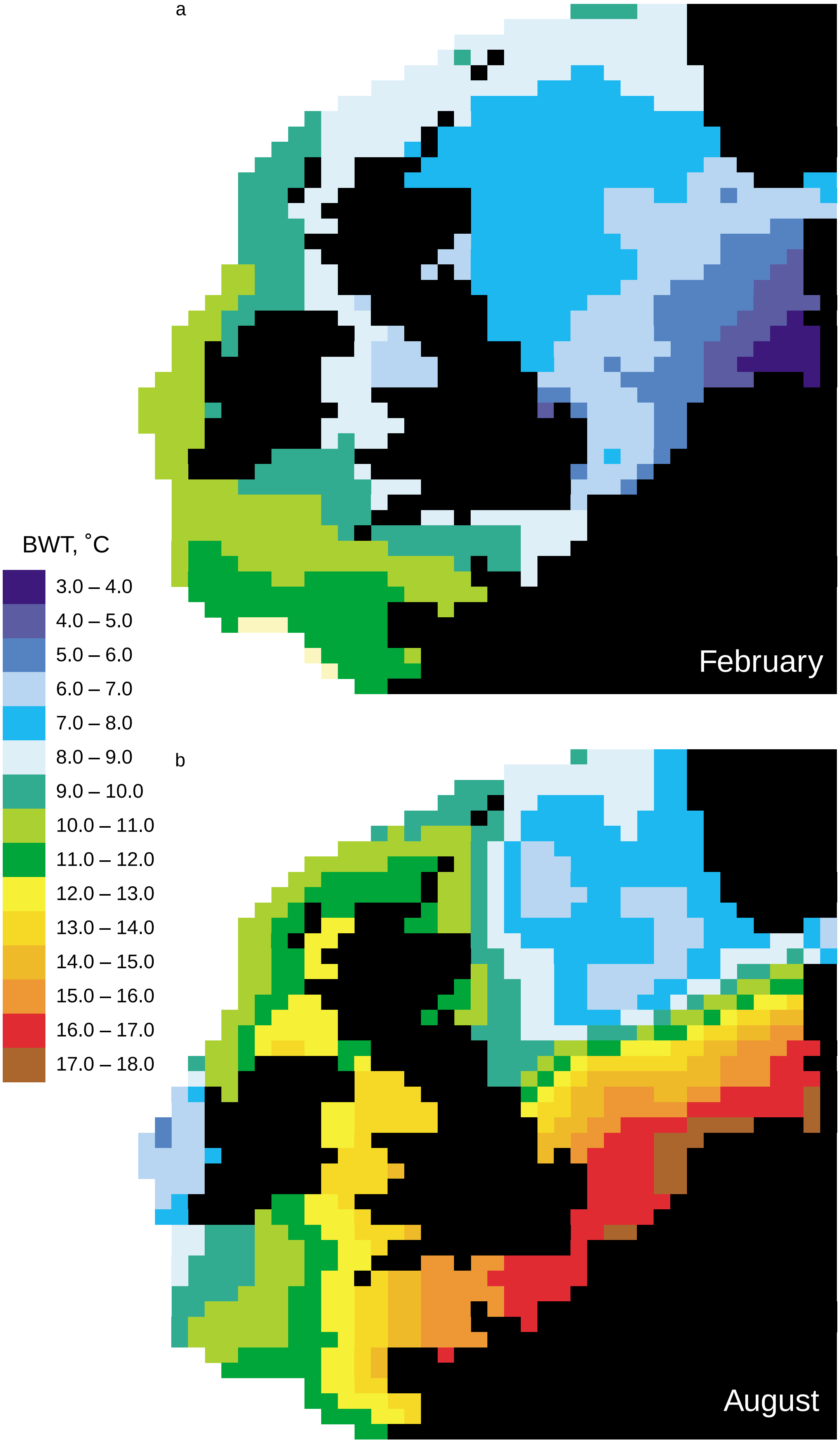

Figure 3 (a) Bottom water temperatures during winter (February); (b) bottom water temperatures during summer (August)

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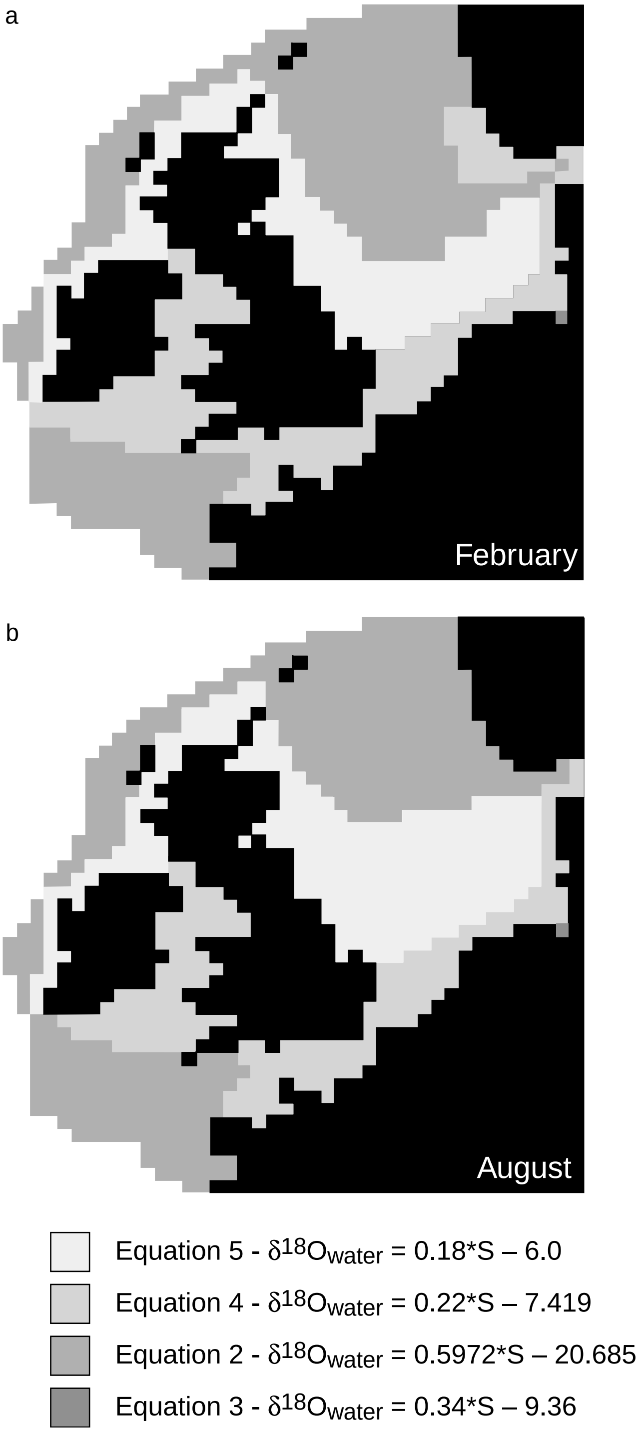

Figure 4 Salinity:$\delta^{18}O_{water}$ mixing-lines are based on Equation (5) (lightest shading); Equation (4) (pale grey shading); Equation (3) (darkest shading); Equation (2) (intermediate grey shading); see text for further explanation (values are ‰ VSMOW). (a) Salinity:$\delta^{18}O_{water}$ mixing-lines with superimposed bottom water salinity during winter (February); (b) salinity:$\delta^{18}O_{water}$ mixing-lines with superimposed bottom water salinity during summer (August)

The regional salinity:$\delta^{18}O_{water}$ mixing-lines (Table 1) provide a means to predict the $\delta^{18}O_{water}$ composition of coastal water from the observations of summer and winter salinity (Figure 4a, b). Unfortunately, because of the scarcity of directly measured $\delta^{18}O_{water}$ data from the NW European shelf seas, the most appropriate salinity:$\delta^{18}O_{water}$ mixing-lines have been chosen, primarily to reflect the salinity regime and gross pattern of circulation. These mixing-lines are shown for both winter (Figure 4a) and summer (Figure 4b) and include:

$$\delta^{18}O_{water} = 0.5972*S - 20.685 \quad (2)$$

$$\delta^{18}O_{water} = 0.34*S - 9.36 \quad (3)$$

$$\delta^{18}O_{water} = 0.22*S - 7.419 \quad (4)$$

$$\delta^{18}O_{water} = 0.18*S - 6.0 \quad (5)$$

Throughout much of the central and northern North Sea, the shelf waters to the west of Scotland and Ireland and the South West Approaches, where bottom water salinities are ≥ 35, we apply Equation (2), which is modified after Frew *et al.* (2000) (see Table 1). Around the coastline of western Ireland, Scotland and the east coast of England, extending eastwards into the southern-central North Sea, we apply Equation (5), based on Austin and Inall (2002). However, given that Darling (2004) demonstrates an isotopic gradient of depletion in ^{18}O of about 1‰ from west to east across northern Britain, it may be that a small, progressive adjustment to Equation (5) is necessary for the coastal waters of the North Sea, which are influenced by river waters that drain the major catchments of eastern Britain. In the Irish Sea, northern Celtic Sea, English Channel and much of the southern North Sea coastline, extending to the southern coastline of Norway, we apply Equation (4), based on Owen *et al.* (2002) and Scourse *et al.* (2004). Deep within the German Bight, where summer salinity drops to 27.0, we apply Equation (3), which is based on the work of Scheurle and Hebbeln (2003).

In any gridded data set, there is a danger of creating artificial ‘fronts’ between adjacent cells in which different regional salinity:$\delta^{18}O_{water}$ mixing-lines are employed. The total salinity range employed within the NW European shelf data set is 27.0 to 35.5 and in the majority of boxes adjacent salinities differ by less than 1, with the exception of a few coastal locations. At a salinity of 35.0, the different regional salinity:$\delta^{18}O_{water}$ mixing-lines predict the $\delta^{18}O_{water}$ to be 0.217‰ (Equation 2), 2.54‰ (Equation 3), 0.281‰ (Equation 4) and 0.3‰ (Equation 5) (Figure 5). The relationship established for the German Bight by Scheurle and Hebbeln (2003) yields anomalous $\delta^{18}O_{water}$ values at normal marine salinities and does not therefore appear to be appropriate for use over most of the NW European shelf. The uncertainties associated with the $\delta^{18}O_{water}$ calculations in this study are most likely to arise within the salinity range 34.0 to 35.0, where we chose to apply Equations 2, 4 or 5 (Figure 4). At a salinity of 34.0, for example, predicted $\delta^{18}O_{water}$ values are -0.38‰ (Equation 2), 0.06‰ (Equation 4) and 0.12‰ (Equation 5) and it is therefore clear that the choice of regional salinity:$\delta^{18}O_{water}$ mixing-lines have implications for the uncertainty associated with subsequent calculations (see the next section). However, it should be noted that Equation (2) is only used in this study when salinities are ≥ 35 and that the differences arising from the use of Equation (4) and Equation (5) are relatively small (Figure 5).

The most enriched waters are predicted in the South West Approaches (+0.5‰; Equation (2)) and the most depleted waters adjacent to the German Bight (-1.0‰; Equation (4)). Much of the North Sea and the British and Irish coastal waters exhibit $\delta^{18}O_{water}$ values typically ranging from around 0.0 to 0.4‰. Further direct measurements of $\delta^{18}O_{water}$ from the region, particularly from the North Sea, would be extremely valuable.

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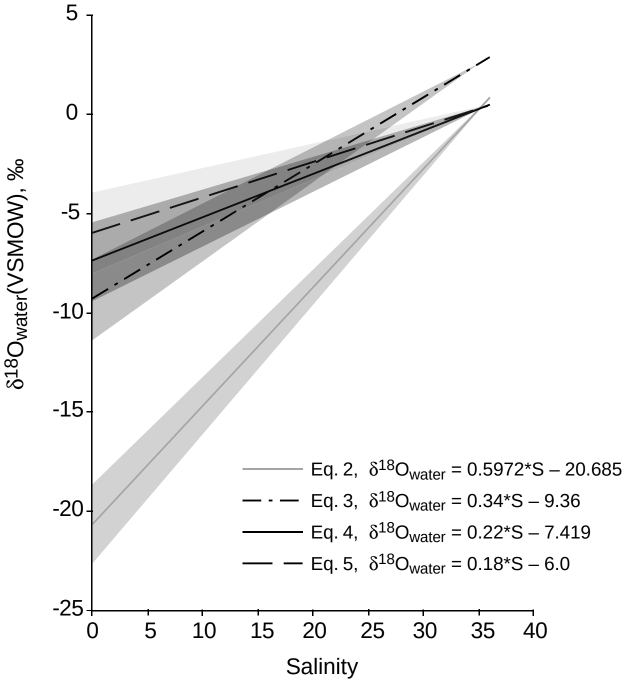

Figure 5 Salinity:$\delta^{18}O_{water}$ mixing-lines for NW European waters (see text for details)

Predicting $\delta^{18}O_{Eq.calcite}$

The incorporation of the $\delta^{18}O_{water}$ signal into the skeletal structure of marine organisms ($\delta^{18}O_{calcite}$) is temperature dependent (eg, Urey, 1947). The first empirical temperature: $\delta^{18}O$ relationship was developed by McCrea (1950) and the first 'palaeotemperature' equation was published by Epstein *et al.* (1953). Changes in both salinity and temperature therefore have the potential to be recorded in the palaeoclimate record of marine organisms ($\delta^{18}O_{calcite}$). In this study, the temperature: $\delta^{18}O$ relationship adopted (Equation (6)) comes from Bemis *et al.* (1998), but it should be noted that the calibration temperature range employed in this relationship is relatively narrow (15–25°C) when compared with the range of observed bottom water temperatures from the NW European shelf (2.4–17.8°C).

$$T(^{\circ}\mathrm{C}) = 16.5 - 4.8(\delta^{18}O_{calcite} - \delta^{18}O_{water}) \qquad (6)$$

In order to explore the impact of seasonal temperature changes on 'equilibrium' calcite ($\delta^{18}O_{Eq.calcite}$), the $\delta^{18}O_{water}$ correction of $-0.27‰$ (Hut, 1987) is employed to convert from the VSMOW to the Vienna Pee Dee belemnite (VPDB) scale:

$$\delta^{18}O_{water(VPDB)} = \delta^{18}O_{water(VSMOW)} - 0.27 \qquad (7)$$

From these equations (ie, 1, 6 and 7), it is possible to derive estimates of the theoretical 'equilibrium' calcite ($\delta^{18}O_{Eq.calcite}$) from any given observation of salinity and temperature. Using the gridded salinity/temperature data, we have constructed maps to trace the evolution of $\delta^{18}O_{Eq.calcite}$ in bottom waters month by month throughout the shelf seas of NW Europe (see Supplementary Data link at http://hol.sagepub.com/content/vol16/issue7/). These are summarized as winter (Figure 6a) and summer (Figure 6b) maps and reveal large seasonal differences in $\delta^{18}O_{Eq.calcite}$ in some shelf regions. For example, predicted $\delta^{18}O_{Eq.calcite}$ in the non-stratified bottom waters of the central North Sea vary from 0.5‰ in August to nearly 2.3‰ in February; the stratified deeper waters of the northern North Sea record the same (2.1‰) values in both February and August; while the shallow waters adjacent to the Dutch coastline vary from nearly $-1.0‰$ in August to nearly 2.2‰ in February.

Since summer and winter bottom water salinity are very similar (Lee and Ramster, 1981), the differences in $\delta^{18}O_{Eq.calcite}$ are primarily driven by bottom water temperature. In a similar manner, it can also be argued that the density of shelf water is largely controlled by temperature. The largest amplitude in the seasonal $\Delta\delta^{18}O_{Eq.calcite}$ record (ie, the difference between winter (February) and summer (August) $\delta^{18}O_{Eq.calcite}$ values) may therefore be expected in the shallow and mixed water column of the shelf, while the smallest signal in $\delta^{18}O_{Eq.calcite}$ is likely to occur in deeper, stratified water (Figure 7). Since seasonal thermal stratification of the water column is largely a summer phenomenon in the NW European shelf seas, the steepest spatial gradients in $\delta^{18}O_{Eq.calcite}$ are often observed across frontal regions (compare Figure 3b and Figure 6b).

Seasonality and $\delta^{18}O_{Eq.calcite}$

Much of the enhanced biological productivity of shallow water marine environments is associated with seasonal thermal stratification (Holligan, 1981; Scott *et al.*, 2003). The effects of vertical stability on phytoplankton distributions during the summer months on the NW European shelf are well-established (Pingree *et al.*, 1975; Houghton, 1988). Nutrient renewal along fronts during the summer due to mixing by wind and tide combined with surface stabilization during settled weather and neap tides intermittently create conditions suitable for rapid phytoplankton growth (Pingree *et al.*, 1975; Tett *et al.*, 1986). Such growth in turn leads to enhanced particulate flux to the sea bed in the vicinity of the frontal region (Jones *et al.*, 1998).

Many marine calcareous-shelled organisms (eg, foraminifera, bivalved molluscs) exhibit a marked seasonality in their growth, often triggered in response to the spring or autumn bloom of phytoplankton (eg, Gooday, 2002). Recently, Scourse *et al.* (2004) have speculated on the significance of the 'seasonal effect' upon the stable isotopic composition of benthic foraminifera living in the Celtic Sea. Seasonally triggered reproduction in foraminifera often follows the spring-bloom in April, so that subsequent test (shell) growth integrates a record of significant change in $\delta^{18}O_{Eq.calcite}$, particularly where bottom water temperatures are increasing throughout the summer months.

Further work will be required to determine the extent to which the seasonally integrated $\delta^{18}O$ signal recorded in marine organisms can deviate from the annual mean $\delta^{18}O_{Eq.calcite}$ value, but the potential nature of this effect is highlighted by contrasting a stratified and mixed water column location from the central North Sea (Figure 8). At 53°N, the water column is mixed and both surface and bottom water temperatures record a marked seasonality; bottom water temperatures ranging from 4.7°C in March to 16.9°C in August. Calculated bottom water $\delta^{18}O_{Eq.calcite}$ values at 53°N reflect this strong temperature dependency, ranging from 2.4‰ in March to $-0.14‰$ in August. However, the contrast (0.74‰) between the annual $\delta^{18}O_{Eq.calcite}$ mean value (1.17‰) and May–October $\delta^{18}O_{Eq.calcite}$ mean value (0.43‰) is significantly greater than the contrast (0.11‰) between these same values (1.67‰ and 1.56‰, respectively) in the deeper, stratified waters of the central North Sea at 57°N. As one might expect, the 'seasonal effect' is likely to be most pronounced in the shallow, mixed water column of middle and high latitude shelf seas.

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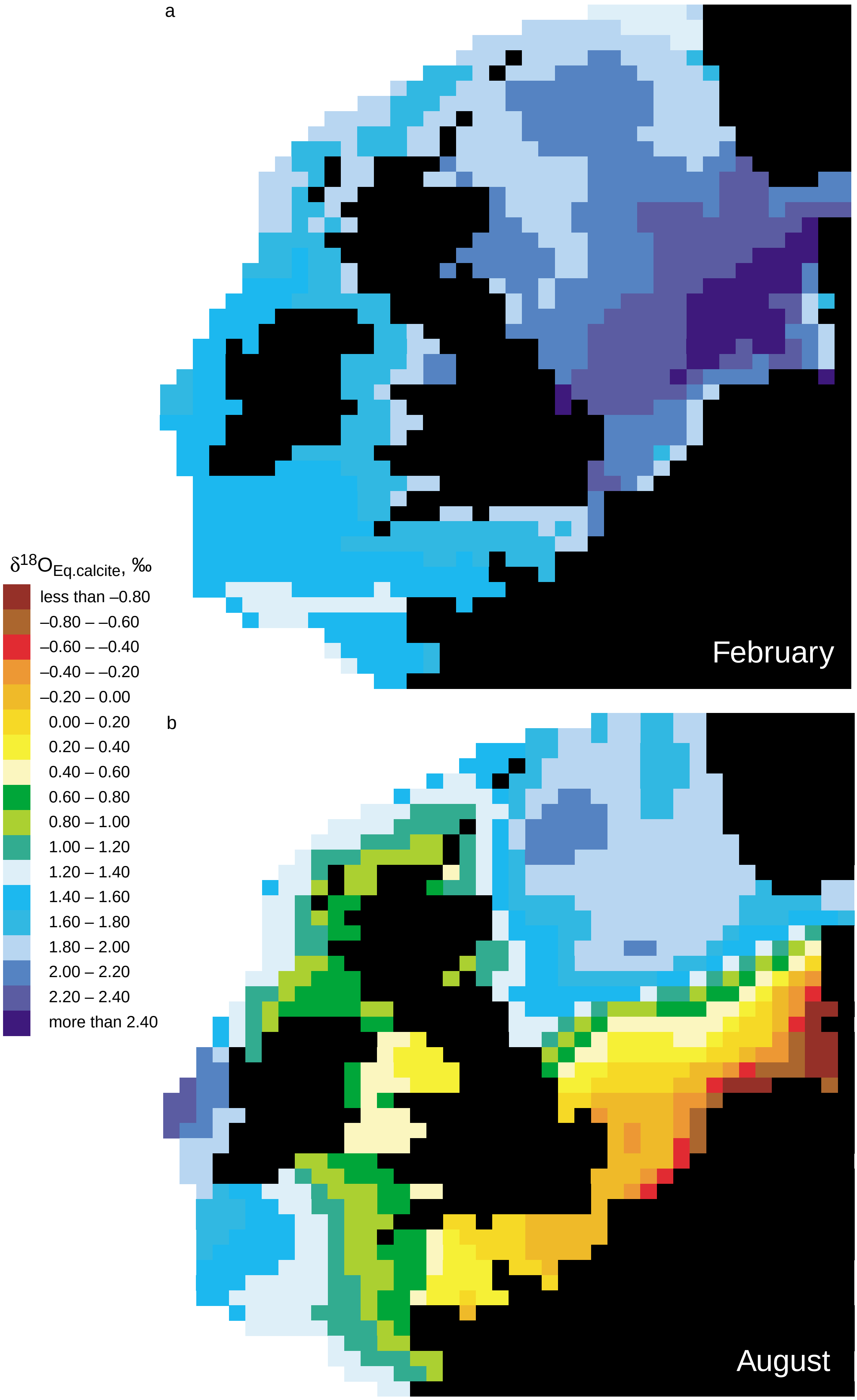

Figure 6 (a) Calculated oxygen isotopes in equilibrium calcite ($\delta^{18}O_{\mathrm{Eq.calcite}}$) during winter (February); (b) calculated oxygen isotopes in sea water ($\delta^{18}O_{\mathrm{Eq.calcite}}$) during summer (August) (values are ‰ VPDB)

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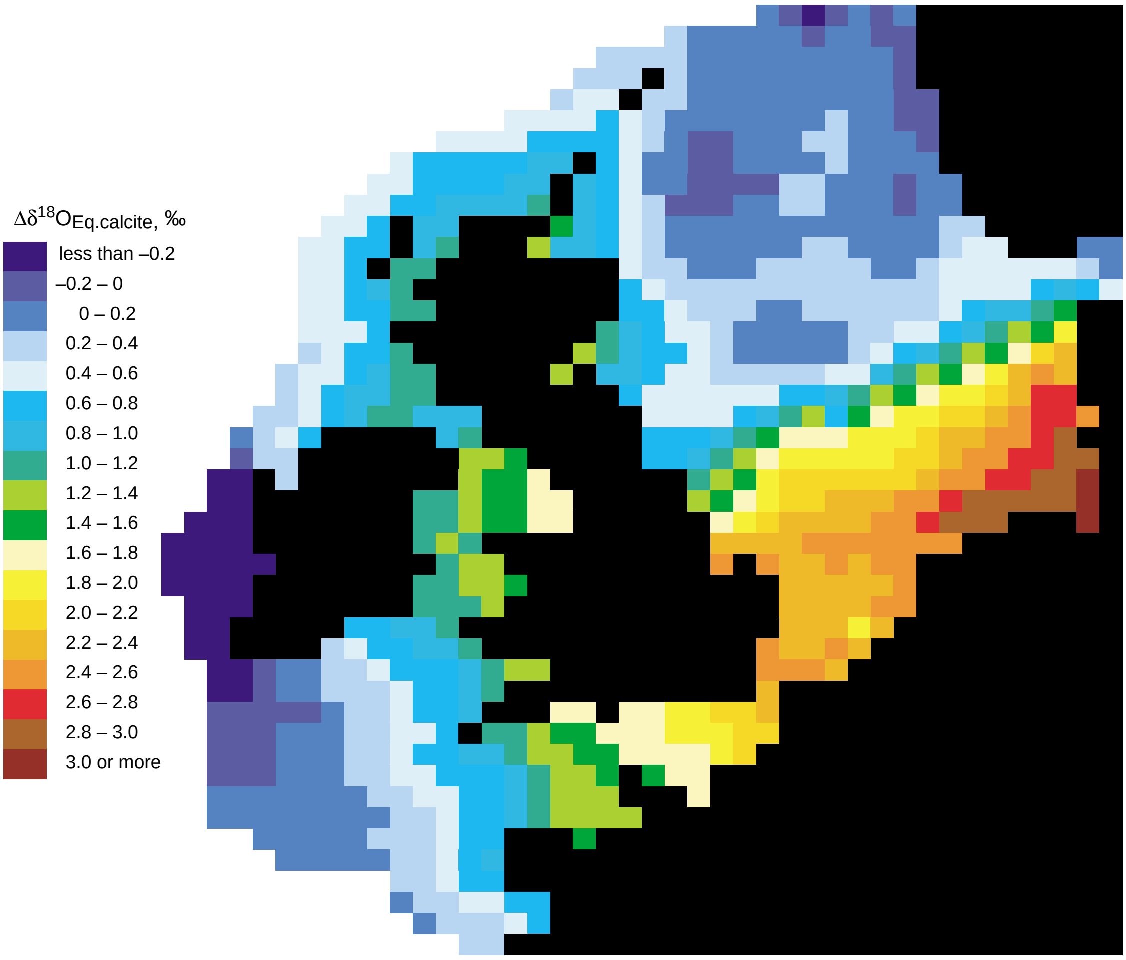

Figure 7 $\Delta\delta^{18}O_{Eq.calcite}$ record showing the difference between winter (February) and summer (August) $\delta^{18}O_{Eq.calcite}$ values for the NW European shelf (values are ‰ VPDB)

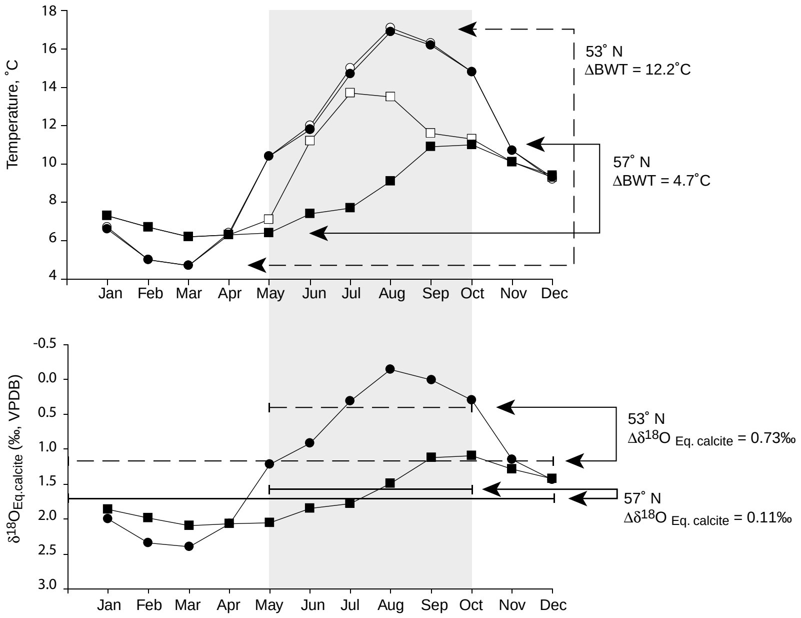

Figure 8 Seasonal changes in temperature (upper panel) and $\delta^{18}O_{Eq.calcite}$ (lower panel) for a mixed water column site at 53°N (square symbols) and a stratified water column site at 57°N (round symbols) from the central North Sea. Surface (open symbols) and bottom (solid symbols) water temperatures, together with seasonal differences (ie, ΔT), are shown in the upper panel. Bottom water $\delta^{18}O_{Eq.calcite}$ values and the differences (ie, $\Delta\delta^{18}O_{Eq.calcite}$) between annual average $\delta^{18}O_{Eq.calcite}$ values and May–October (ie, typical growth season) $\delta^{18}O_{Eq.calcite}$ values are shown in the lower panel

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Conclusions

The shelf seas of NW Europe reveal pronounced changes in $\delta^{18}O_{Eq.calcite}$, both spatially and temporally. These changes primarily reflect the control of bottom water temperature on $\delta^{18}O_{Eq.calcite}$. The development of seasonal thermal stratification of the water column plays an important role in damping the bottom water response to marked seasonal variability of the surface heat flux. As a result of stratification, steep spatial gradients in $\delta^{18}O_{Eq.calcite}$ exist across shelf sea fronts and such gradients are readily resolved in the geological record. The evolution of a pronounced seasonal signal in $\delta^{18}O_{Eq.calcite}$ on some parts of the NW European shelf has important implications for understanding stable isotope records obtained from marine calcareous-shelled organisms, whose growth and calcification may vary seasonally. Further work will be required to evaluate the interannual variability in $\delta^{18}O_{Eq.calcite}$ on both smaller spatial and longer temporal scales.

Acknowledgements

We thank A. Elliot for his help in accessing the temperature data and J. Evans, who contributed to the data entry effort. Luke Skinner and Mark Chapman provided constructive reviews. This work was partly supported by NERC (GR3/11467) and the EU Framework V HOLSMEER project.

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