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Holocene trends in the foraminifer record from the Norwegian Sea and the North Atlantic Ocean

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Abstract

The early to mid-Holocene thermal optimum is a well-known feature in a wide variety of paleoclimate archives from the Northern Hemisphere. Reconstructed summer temperature anomalies from across northern Europe show a clear maximum around 6 ka. For the marine realm, Holocene trends in sea-surface temperature reconstructions for the North Atlantic and Norwegian Sea do not exhibit a consistent pattern of early to mid-Holocene warmth. Sea-surface temperature records based on alkenones and diatoms generally show the existence of a warm early to mid-Holocene optimum. In contrast, several foraminifer and radiolarian based temperature records from the North Atlantic and Norwegian Sea show a cool mid-Holocene anomaly and a trend towards warmer temperatures in the late Holocene. In this paper, we revisit the foraminifer record from the Vøring Plateau in the Norwegian Sea. We also compare this record with published foraminifer based temperature reconstructions from the North Atlantic and with modelled (CCSM3) upper ocean temperatures. Model results indicate that while the seasonal summer warming of the sea-surface was stronger during the mid-Holocene, sub-surface depths experienced a cooling. This hydrographic setting can explain the discrepancies between the Holocene trends exhibited by phytoplankton and zooplankton based temperature proxy records.

1 Introduction

A prominent feature in a wide variety of paleoclimate archives from the Northern Hemisphere is the existence of a period of Holocene warmth, the so-called Holocene thermal maximum (e.g. Kaufmann et al., 2004) or early to mid-Holocene optimum (e.g. Jansen et al., 2008). The length of the Holocene thermal maximum varies in literature. In its broadest sense the period between 11 000–5000 yrs before present (11–5 ka) corresponds to a period of relative warmth at high and middle latitudes of the Northern Hemisphere (Renssen et al., 2009). It is clear that proxy based reconstructions

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show differences in both timing and magnitude of peak Holocene warmth (Kaufmann et al., 2004; Renssen, et al., 2009). From the western Arctic (0–180° W) there are clear evidence of a warming of 1.6°C based on a large compilation of different proxy records, terrestrial, ice-core and marine. However, northeast Canada experienced a thermal optimum between 11–9 ka, about 4 kyr before the thermal maximum in north-eastern Canada (Kaufmann et al., 2004). The delay in warming in this region was likely caused by influences of the Laurentide ice-sheet. In other regions, which were dominated by orbital forcing, the thermal maximum occurred earlier (Kaufmann et al., 2004; Renssen et al., 2009). Reconstructed summer temperature anomalies from across a wide area of northern Europe show a clear maximum around 6 ka (Davis et al., 2003). For Scandinavia there are considerable evidence for a mid-Holocene thermal optimum (Davis et al., 2003). For the marine realm, Holocene trends in sea-surface temperature (SST) reconstructions for the North Atlantic and Norwegian Sea do not exhibit a consistent pattern of early to mid-Holocene warmth. Besides differences in the reconstructions that originate from local differences in oceanographic settings between coring locations, there are results that point towards proxy-related differences between the reconstructions. Proxies derived from photosynthesizing organisms, i.e. diatom and alkenone based SST reconstructions do often exhibit an early to mid-Holocene optimum, whereas zooplankton-based SST reconstructions do not. A compilation of North Atlantic SST proxy data from alkenones (Kim et al., 2004a, b) and foraminifers (transfer functions SST estimates) (Andersson, 2005) for 6 ka also show that the 6ka anomaly from these two SST proxies is quite different. The 6 ka anomalies from alkenone reconstructions are generally positive, i.e. 6 ka were warmer than the pre-industrial period, and there is also an indication of a polar amplification during the 6 ka anomaly (Marchal et al., 2002; Rimbu et al., 2003; Kim et al., 2004c; Lorenz et al., 2006). In comparison, the North Atlantic 6ka anomalies reconstructed using transfer function SST estimates from planktic foraminifers are not consistently positive and do not display any polar amplification (Andersson, 2005). One explanation for this is that there were a different evolution of surface ocean temperatures between the very sea-surface, occupied

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by phytoplankton, and waters closer to the thermocline, depths occupied by zooplankton throughout the Holocene in the North Atlantic and Norwegian Sea (e.g. Jansen et al., 2008). Hence, differences in depth habitat between zoo- and phytoplankton are responsible for the differences in terms of presence/absence of a Holocene thermal maximum and the different long-term trends in the SST reconstructions.

In this paper we revisit the Holocene record from the Norwegian Sea and compare this record to more recently published data from the North Atlantic in order to explore the trends in the foraminifer record in more detail. We also use model results for 6ka to look into the differences between reconstructed phytoplankton-based and zooplankton-based SST estimates for the Norwegian Sea and the northern North Atlantic.

2 Material and methods

Core MD95-2011 is located under the easternmost limb of the warm Norwegian Atlantic Current (the northern continuation of the North Atlantic Current; NAC). Multiple sea-surface temperature proxies have been developed and published for MD95-2011. The site was originally cored during IMAGES campaign MD101, and a 17.49 m long core was recovered from 1048 m water depth (66.97° N, 7.64° E) (Fig. 1) using a giant piston corer (CALYPSO). Due to overpenetration of the giant piston corer, a box core, JM97-948/2A, was later taken at the same position to sample the surface sediments lost during the piston coring. An age-depth model for the Holocene was developed using a combination of ^{210}Pb -dating and accelerator mass spectrometer (AMS) radiocarbon dating techniques (Andersson et al., 2003; Risebrobakken et al., 2003). Multiple proxies for surface-ocean reconstructions have been developed for MD95-2011. Stable oxygen and carbon isotope records from *Neogloboquadrina pachyderma* (dex) and *Neogloboquadrina pachyderma* (sin) were published by Andersson et al. (2003) and Risebrobakken et al. (2003). Census counts and foraminifer-based SST estimates for the Holocene are also published (Andersson et al., 2003; Risebrobakken et al., 2003). The foraminifer SST estimates were originally calculated using the modern

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analog technique. In this study we have used the same foraminifer census counts and recalculated the foraminifer SST estimates using the Maximum Likelihood technique. Modern SST values for 10 m water depth during summer (July, August, September) for the calibration dataset were taken from the World Ocean Atlas version 2 (WOA, 1998). In addition to the foraminifer-based record, SST estimates for MD95-2011 are available from alkenones (Calvo et al., 2002; Jansen et al., 2008), diatoms (Birks et al., 2002; Andersen et al., 2004), and radiolarians (Dolven et al., 2002). In this study we compare results from MD95-2011 with newly published foraminifer SST records from the northern North Atlantic. The locations for sites discussed in this paper are shown in Fig. 1. Genotype studies have suggested a renaming of *N. pachyderma* (dex) to *Neogloquadrina incompta* when the percentage of right coiling forms is between 3 and 97% (Darling et al., 2006). In this study we continue to use *N. pachyderma* (dex) to be able to easily draw cross-references to the already published data from the Norwegian Sea and the North Atlantic discussed in this paper.

In this study we compare temperature proxy reconstructions with model output that belongs to the Paleoclimate Modelling Intercomparison Project Phase II (PMIP2/MOTIF). The model used in this study is the Community Climate System Model 3.0 (CCSM3). The horizontal resolution in the ocean has a nominal grid spacing of $0.4^{\circ} \times 1.1^{\circ}$ (lat \times lon). The ocean model has 40 levels with finer resolution near the surface (15 levels in the first 250 m). Boundary conditions for the pre-industrial (PI, 1780 AD) and mid-Holocene (MH, 6 ka) follow the protocol established by PMIP2 (<http://pmip2.lsce.ipsl.fr>). In the PI simulations, the orbital configuration is set to 1950 A.D. values, the greenhouse gases correspond to 1750 A.D., and vegetation is suggested to represent present day distribution. In the MH simulations, the orbital configuration is set to 6 ka, when the summer insolation was much higher in the Northern Hemisphere, whereas the winter insolation was lower compared to the PI; the vegetation, the ice-sheet extent and greenhouse gas concentrations (except for the methane that are lower) are the same as in the PI. 100 years of monthly post-spin up ocean potential temperature data for the Atlantic basin (30° – 85° N/ 90° W– 45° E) are analyzed

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for both the MH and PI simulations. For further details see Braconnot et al. (2007).

We analyze North Atlantic sea-surface (10 m depth) and sub-surface (100 m depth) ocean potential temperature for winter (from January to March, JFM), summer (from July to September, JAS) and annual average in both climate states. We also consider the vertical profile for the four proxy locations.

3 Results and Discussion

3.1 Holocene SSTs in the Norwegian Sea

The record from the Vøring Plateau (MD95-2011) is among the Holocene records with the highest temporal resolution from the Norwegian Sea. From the multiple SST proxy records available for MD95-2011, it is clear that there is a distinct difference between SST estimates derived from phytoplankton based records, i.e. the diatom and alkenone records, and zooplankton based records (foraminifers and radiolarians) (Fig. 2). Most phytoplankton species of coccoliths and diatoms thrive in the upper photic zone corresponding to the upper 50 m and bloom when nutrients and light conditions in the upper mixed layer are favourable (Abrantes, 2007; Flores and Sierro, 2007). Zooplankton assemblages, however, like those from foraminifers and radiolarians, contain a combination of species with wide preferences in depth habitat. Foraminifer assemblages often consist of both near-surface (0–50 m) species and more deep-dwelling (>100 m) species (Dowsett, 2007). Radiolarians have an even wider range of depth habitats going from the upper few meters of the surface layer to abyssal depths (Lazarus, 2005). This means that SST estimates derived from foraminifers and radiolarians contain an integration of environmental conditions over a certain depth range.

The Holocene trends of the diatom and alkenone SSTs correspond with the trend of decreasing summer insolation throughout the Holocene. These data show a clear trend of decreasing summer temperatures since the mid-Holocene and indicate that summer temperatures were up to 2°C higher in the mid-Holocene in northern Scandinavia com-

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pared to at present (Fig. 2). A similar long-term trend of decreasing temperature is also often seen in terrestrial temperature reconstructions such as the pollen-based July SST reconstruction from northern Finland (Seppä and Birks (2001) (Fig. 2). The zooplankton-based records do not display an early to mid-Holocene warmth and declining temperatures towards the late Holocene. The transfer function based summer SST reconstruction from radiolarians (Dolven et al., 2002) and foraminifers (Anderson et al., 2003; Risebrobakken et al., 2003) exhibits trends towards slightly higher temperatures towards the late Holocene, in addition to a multi-decadal type of variability with several cooling events throughout the records. Kucera et al. (2005) point out that a level of disagreement between different SST proxies must be expected because each approach reflects different past environmental conditions. At the Vøring Plateau the observed difference in SST trends between the two plankton types is so large that it seems likely that these two proxies actually record quite different environmental conditions due to different ecological preferences of phyto- versus zooplankton. This difference is also too large to be the result of any methodological biases coming from different SST estimation techniques.

The Holocene foraminifer fauna in the eastern Norwegian Sea is dominated by *N. pachyderma* (sin), *N. pachyderma* (dex), and *Globigerina quinqueloba*. Simstich et al. (2003) found that in the Norwegian Current *N. pachyderma* (sin) calcify at depth below the pycnocline (70–250 m) where temperatures are generally lower by 2–3°C compared to the sea-surface. In polar waters the depth habitat of *N. pachyderma* (sin) appears to depend on the vertical stratification (Kohfeld et al., 1996). Only in areas with a deep (>300 m) mixed layer and minimal seasonal temperature changes would *N. pachyderma* (sin) record surface ocean conditions. Thus, it is likely that *N. pachyderma* (sin) is a deeper-dwelling species that calcify below the thermocline. Based on the offset between *N. pachyderma* (dex) and *N. pachyderma* (sin) in the stable oxygen isotope records (Risebrobakken et al., 2003) and the Mg/Ca records (Nyland et al., 2005) it seems likely that *N. pachyderma* (dex) calcify at shallower depth (and/or during a warmer part of the year) relative to *N. pachyderma* (sin). North of Iceland

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5 *N. pachyderma* (dex) calcifies throughout the year at water depth between 30 and 40 m (Osterman et al., 1999). However, North of Iceland *N. pachyderma* (sin) calcify at the same depth as *N. pachyderma* (dex), which makes it open to discussion if the depth habitat of *N. pachyderma* (dex) is the same in the eastern Norwegian Sea. Ot-
10 tens (1992) suggests that *N. pachyderma* (dex) calcifies at depth below 75 m in the northeast Atlantic, and according to Simstich et al. (2003) the calcification depth of *G. quinqueloba* is between 25 and 75 meters, matching the depth of the pycnocline. Recently, Fraile et al. (2009) used a global foraminifer model (PLAFOM) to evaluate the seasonal imprint on the sedimentary record. They found that for *N. pachyderma* (sin),
15 *N. pachyderma* (dex) and *Globigerina bulloides* the difference between the predicted value and the annual mean temperature was positive for all three species, indicating a bias towards summer temperatures for these species. Berstad et al. (2003) also suggested that calcification of *N. pachyderma* (dex) occur during summer (JAS) in the eastern Norwegian Sea.

15 Other foraminifer records from the eastern Norwegian Sea also share the Holocene trends in the foraminifer record SST from the Vøring Plateau. Hald et al. (2007) published a comparison between six published surface temperature proxy records, including MD95-2011, along a S-N transect on the Norwegian-Continental margin. This comparison shows that records from the southern part of the transect (60–69° N) have
20 stable SSTs or slightly increasing SSTs throughout the Holocene. The northernmost records (72–77.4° N) display a pronounced warming in the early Holocene followed by a long-term SST decrease and a subsequent weak warming in the latest Holocene. The different trends between the southern and northern transects were suggested to result from a polar amplification of early Holocene warmth for the northernmost records.

25 The lack of an early Holocene warm period in the south-eastern Norwegian Sea was suggested to reflect the influence of cooler subsurface water masses possibly related to increased seasonality caused by orbital forcing and increased stratification due to freshening (Hald et al., 2007). Risebrobakken et al. (2003) suggested that the long-term Holocene trend, as seen in the foraminifer record at site MD95-2011, is re-

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lated to horizontal migration of the Arctic water/Atlantic water interface (Arctic Front). The oceanography of the Vøring Plateau is governed by the presence of two water masses: the inflowing warm and saline North Atlantic surface water and the less saline and cooler Arctic intermediate water mass (see Risebrobakken, 2003 and references therein). Risebrobakken et al. (2003) suggested that the Arctic front and Arctic water masses were closer to the site MD95-2011 during the early and mid-Holocene than during the late Holocene. The stronger influence of Arctic water during the early Holocene would result in cooler sub-surface temperatures that would be recorded by planktic foraminifers. This interpretation was based on two observations in the planktic record. Firstly, in Arctic water there is no difference between the stable oxygen isotope composition in *N. pachyderma* (sin) and *N. pachyderma* (dex), while the differences increase towards east in The Nordic Seas (Johannessen, 1992). Hence, the varying stable oxygen isotope contrast between *N. pachyderma* (dex.) and *N. pachyderma* (sin) can be used as an indicator of horizontal migration of the Arctic water/Atlantic water interface. In MD95-2011 $\Delta\delta^{18}\text{O}$ values of *N. pachyderma* (dex) and *N. pachyderma* (sin) is lower during the early and mid-Holocene relative to the late Holocene, indicating an eastward migration of the Arctic Front. Secondly, high relative abundances of *G. quinqueloba*, a species strongly related to the Arctic Front (Johannessen et al., 1994), between 8–4 ka also indicate a more eastward location of the boundary between Arctic and Atlantic waters before 4 ka. During recent decades, sub-surface eastward migration of Arctic waters has been caused by an increase in the strength of the west-erlies (Blindheim et al., 2000). Stronger influence of sub-surface Arctic water could possibly also explain the observed difference between SSTs derived from phytoplankton and zooplankton at the Vøring Plateau. The relatively deeper dwelling zooplankton could have experienced cooler sub-surface conditions in the early- and mid-Holocene compared to the late Holocene.

According to Jansen et al. (2008) the difference between different SST proxies (basically, between diatom and alkenones SSTs and foraminifer and radiolarian SSTs) is due to the seasonality of orbital forcing, the habitat of the different biological prox-

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ies, and the vertical structure of the high-latitude ocean. A positive thermal anomaly during the summer season and a small negative anomaly during winter gave rise to enhanced seasonality during the early to mid-Holocene. The observed difference between zooplankton and phytoplankton SSTs can be explained as a response to the seasonality of the forcing. The long-term orbital trends during the Holocene could be reflected in both the phytoplankton SST records (summer insolation) and zooplankton records (winter insolation). Jansen et al. (2008) suggests that foraminifera living at or around the thermocline experience temperatures unrelated to the summer season, which would explain the observed difference between zooplankton and phytoplankton SST records. At Ocean weather Station Mike (Østerhus et al., 1996) (Figs. 1 and 4), there is a strong summer warming and stratification of the sea-surface. At 100 meter water depth mixing occurs during winter when the seasonal thermocline breaks down. Hence, species living at this depth would record a signal related to winter-ventilation. However, the seasonal variability is negligible below the thermocline, which means that all seasons are close to the annual mean temperature at this depth. As a result, although the maximum production of foraminifera in general occurs during spring and/or summer, deeper-dwelling species could record temperatures more comparable to the annual mean. In a modelling study of the upper ocean SST evolution and its response to orbital forcing through the Holocene, Liu et al. (2003) found negative mean annual temperature anomalies in the early and mid-Holocene at 100–300 m water depth for the mid-latitudes of the North Atlantic. However, this modelling experiment does not give any insight to the surface and sub-surface conditions of the Norwegian Sea.

3.2 North Atlantic versus Norwegian Sea SST record

SST records from the subpolar North Atlantic also share the observed trend of a warming since the early and mid-Holocene seen in the foraminifer SST records from the eastern Norwegian Sea. A recently published Mg/Ca SST record from MD99-2251 (Farmer et al., 2008) (Figs. 1 and 3) displays many similarities to the foraminifer faunal SST record from MD95-2011 for much of the last 9.5 ka. Both the overall trends as well as

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absolute SST values agree well between the two records. As pointed out by Farmer et al. (2008), mid-Holocene temperatures in MD99-2251 are cooler (1.5°C) than the average temperature for the last 3.5 ka (10.1°C at 6 ka relative to 11.6°C for the last 3.5 ka). To be consistent with mid-Holocene paleomodel results we define the mid-Holocene to be centred at 6 ka and calculated averages from paleo proxy data are averages spanning the interval 6±0.5 ka. The corresponding 6 ka average and the average for the last 3.5 ka in MD95-2111 are 10.7 and 11.6°C, respectively. A very important aspect of this comparison is that the Mg/Ca-based SST record from MD99-2251 was derived by analysis of *G. bulloides*. This species is generally regarded as being a near-surface living species. The depth habitat of *G. bulloides* is confined to the upper 60 m of the water column at the location of MD99-2251 (Farmer et al., 2008, and references therein). Hence, the SST record from *G. bulloides* is expected to reflect SST changes in the near-surface environment of the core locality. This was used by Jansen et al. (2008) who proposed that the more surface-dwelling species, like *G. bulloides*, which normally calcify above the seasonal thermocline, would respond to changes in summer insolation and show the same Holocene SST trends as phytoplankton-based SST proxies with decreasing SSTs since the early and mid-Holocene. This is apparently not the case with the SSTs from core MD99-2251 (Fig. 3). Farmer et al. (2008) found it difficult to reconcile the near-surface depth habitat and summer season reproduction of *G. bulloides* with the theory that wintertime insolation changes should govern the long-term trends in their SST record. Farmer et al. (2008) pointed out that this reasoning implies a discrete separation between phyto- and zooplankton communities. Assuming that the Mg/Ca record from MD99-2251 does reflect near-surface temperatures, the relatively cool 6 ka SST temperature average registered at site MD99-2251 has to be interpreted as either significant lower surface summer temperatures in the mid-Holocene or a shift in the calcification/productivity season of *G. bulloides* (Farmer et al., 2008). Despite uncertainties in the productivity season of *G. bulloides*, significantly lower 6 ka SSTs during late spring/summer are difficult to reconcile with the negative 6 ka SST anomaly displayed by many North Atlantic phytoplankton records. A change in the timing and/or

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composition of the phytoplankton bloom is as another possible explanation. However, since the productivity of *G. bulloides* occurs during or shortly after phytoplankton bloom events (Farmer et al., 2008), a shift in timing of these events to earlier during spring or summer would result in a cooling in the *G. bulloides* as well as in the phytoplankton records if it, for example, alkenone synthesizing *Haptophycean* species were involved.

Other foraminifer temperature records from the sub-polar North Atlantic, e.g. ODP 984 (Came et al., 2007) and RAPiD-12-1K (Thornalley et al., 2009) (Fig. 1) and NEAP 8K (Barker and Elderfield, 2002) (not shown), display the same lack of significant warmth in the early and mid-Holocene as the cores MD95-2011 and MD99-2251. Mg/Ca temperature data from *G. bulloides* (RAPiD-12-1K) and *N. pachyderma* (dex) (ODP 984) are shown in Fig. 3 along with MD95-2011 and MD99-2251. Long-term warming trends are apparent in all four records. In MD95-2011 and ODP 984 the increase in temperature seems to start around 8 ka years ago, while in MD99-2251 and RAPiD-12-1K the trends of increasing warmth starts between 7–6 ka. There is also a marked shift in the mode of variability in all four records taking place around 4–3.5 ka (Fig. 3). The Mg/Ca temperature record from ODP 984 is significantly cooler compared to the other three records. However, this record is based on Mg/Ca ratios in *N. pachyderma* (dex), which seems to have a calcification habitat at depth somewhere between the preferred depths of *G. bulloides* and *N. pachyderma* (sin) (see discussion above) and thus is expected to show somewhat cooler temperatures relative to *G. bulloides*. From the comparison between North Atlantic and Norwegian Sea foraminifer SST records, it is clear that they show no significant warmth during the early and mid-Holocene regardless of species or methods used to derive the SST records. With the existing data at hand it is not possible to rule out adaptations in species ecology, i.e. changes in depth habitat and/or shifts in seasonal productivity, at any of the sites discussed.

Farmer et al. (2008) concluded from comparisons between the Holocene trends in the Norwegian Sea and North Atlantic records that despite differences in the locations, proxy methods and species used, there seem to be a common climate linkage. All

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discriminate between possible changes in the character of the NAO (Gladstone et al., 2005).

At the two sites ODP 984 and RAPID-12-1K salinity reconstructions are available for the Holocene (Came et al., 2007; Thornalley et al., 2009). The records from ODP 984 and RAPID-12-1K (based on *N. pachyderma* (dex) and *G. bulloides*, respectively) agree well and show a trend of increasing near-surface salinity since about 9–8 ka. Came et al. (2007) explains the Holocene trend of increasing temperature and salinity at Site 984 with a possible northward retreat of the boundary between polar and North Atlantic water. Thornalley et al. (2009) suggested that changes in salinity of the near-surface water were related to changes in the position of the subpolar front, at least on centennial to millennial time scales. Due to the proximity of the subpolar front to the southern Icelandic region it is likely that changes in the position of this front will affect the near-surface hydrography of the southern Icelandic sites (Thornalley et al., 2009). Cooler and fresher subpolar waters would compete with water from the warmer and more saline NAC. However, the sub-thermocline temperature and salinity records from RAPID-12-1K, based on deep-dwelling *G. inflata*, display periods that were significantly warmer and more saline compared to the present. Thornalley et al. (2009) suggested that changes in relative contribution of waters drawn from the North Atlantic sub-polar gyre (SPG) and sub-tropical gyre (STG) could explain Holocene changes sub-thermocline salinity and temperature south of Iceland. At present, the salinity of the Atlantic inflow is linked to the dynamics of the SPG on decadal time scales (Hátún et al., 2005). When the gyre circulation is strong the volume transport of relatively fresh and cool SPG water is high relative to the warm and saline water from the STG. High sub-thermocline salinities and temperatures in the NAC will then be the result of a weaker SPG circulation, which will allow a larger contribution of STG water to the NAC. Decadal scale variations in salinity of the Atlantic Ocean have been recorded over the past few decades (Curry et al., 2003; Hátún et al., 2005). Over the most recent decade positive salinities have been recorded in the inflow areas (Hátún et al., 2005). These changes are related to changes in the dynamics of SPG circulation, and

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have also been simulated using the Miami Isopycnal Coordinate Ocean Model (Hátún et al., 2005). At Selvogsbanki monitoring transect south of Iceland the mean spring 0–50 m temperature and salinity increased during the period 1990–2007 (Gislason et al., 2009). Furthermore, at OWS Mike a warming and increase in salinity has also been recorded over the past decade (Drange et al., 2005). These changes are likely to be related to changes in the dynamics of the SPG and STG gyres (Svein Østerhus, pers. comm., 2009). Moreover, at OWS Mike, it is clear that the temperature and salinity increase is recorded in the entire Atlantic water mass, also at near-surface depths of 50 m. Hence, on shorter time-scales changes in SPG dynamics is likely to be recorded by near-surface as well as sub-surface dwelling foraminifers. However, on millennial time-scale a decoupling between near-surface and sub-surface waters south of Iceland has been suggested and that the near-surface waters were influenced by a southward migration of subpolar waters rather than changes in the gyre dynamics (Thornalley et al., 2009).

The cause of the thermal maximum in the phytoplankton records were suggested by Jansen et al. (2008) to be related to radiative forcing alone. A possible increase in advection of North Atlantic waters into the Norwegian Sea was ruled out as the thickness of Atlantic water in this area is 400–600 m (Nilsen et al., 2008), and that the depth habitat of zooplankton may extend to a few hundred meters (Bé, 1977). Hence, an increase in advection would affect depths inhabited by both phytoplankton and zooplankton resulting in a positive anomaly in both plankton groups. However, this is apparently not the case.

3.3 Modelling results versus data

To further investigate the differences in trends between the Holocene phytoplankton and zooplankton records, we turn to the PMIP2/MOTIF modelling results for the mid-Holocene (6 ka) were taken into account (Braconnot et al., 2007). In this preliminary study we use the CCSM3 model results.

For the Norwegian Sea, the model generally shows positive 6 ka sea-surface anoma-

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lies throughout the year, with a particularly pronounced anomaly during the summer season (Figs. 5, 6 and 7). This agrees well with the Holocene trends of estimated SSTs based on alkenones (Calvo et al., 2002; Jansen et al., 2008), and diatoms (Birks, 2000) (Figure 2). The CCSM3 results indicate no or a negative 6 ka anomaly at 100 m depth along the Norwegian coast, going from Skagerrak to Lofoten (Figs. 5, 6 and 7). The mid-Holocene modelled temperature depth profile for the Vøring Plateau (MD95-2011) is warmer at all depths for all seasons compared to PI values, except for a slightly cool anomaly between approximately 40–75 m water depth in summer (Fig. 8). By recalibrating the foraminifer training data set using annual mean temperatures for 100 m water depth, the estimated 6 ka annual 100 m foraminifer temperature for MD95-2011 is 6.8°C, which is slightly cooler than both the corresponding modelled PI and 6 ka temperature (Fig. 8). The resulting 6 ka 100 m annual anomaly (6 ka minus core top) for MD95-2011 is -0.6°C, whereas the modelled 100 m annual anomaly is 0±0.25°C (Fig. 7). Considering the uncertainties linked to both the faunal temperature estimates and the modelled temperatures, the model shows a fairly good agreement with the estimated temperature from MD95-2011.

For the area south of Iceland, where cores MD99-2251, ODP 984, and RAPiD-12-1K were retrieved, the model results indicate a strong positive summer temperature anomaly at the sea-surface between the mid-Holocene and PI period (Figs. 5 and 8), whereas it is negative in winter (Fig. 6). At sub-surface depth the model shows a cooling throughout the year and Fig. 8 shows that the temperature is cooler compared to the PI for all sites south of Iceland at sub-surface depth for all seasons. Given the uncertainties in foraminifer depth habitats, the negative 6 ka anomaly for sub-surface depths south of Iceland could explain the reconstructed temperature trends based on *N. pachyderma* (ODP 984). Calcification of *N. pachyderma* in the cooler sub-surface waters deeper than ca. 30 m (Fig. 8) would lead to the observed negative 6 ka anomaly in the proxy data. To explain the reconstructed temperature trends based on *G. bulloides* (MD99-2251, and RAPiD-12-1K) on the background of these modelling results, one may propose a somewhat deeper depth habitat for this species or advocate for a

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shift in productivity to earlier periods during summer or spring, as suggested by Farmer et al. (2008). However, the model results clearly show that the seasonal summer warming is restricted to the upper ca. 30 m. Below 30 m, the mid-Holocene temperature profile is cooler relative to the pre-industrial profile (Fig. 8). Schiebel et al. (1997) suggested that the reproduction of *G. bulloides* is mostly restricted to the upper 60 m in the North Atlantic. Plankton tow results, with the majority of the samples collected in May, June and August, show that cytoplasm bearing tests of *G. bulloides* is present down to 300 m, and that below 60 m (60–100 m) the average number of *G. bulloides* tests per cubic meter is about half of that of the upper 60 m (Schiebel et al., 1997). The reconstructed cool mid-Holocene anomaly for MD99-2251 can be explained if we assume that the majority of the *G. bulloides* population reside below ca. 30 m. If assuming a near-surface depth habitat of *G. bulloides* a shift in the productivity to cooler temperatures earlier during summer is only plausible if this is not linked to shifts in bloom involving a large fraction of the phytoplankton communities. For RAPID-12-1K the shift between a warm 6 ka anomaly at the surface to a negative 6 ka anomaly at sub-surface depths takes place at about 75 m water depth (Fig. 8), which is slightly deeper relative to sites ODP 984 and MD99-2251. At RAPID-12-1K the 6 ka cooling is also slightly less pronounced relative to the last 4–3.5 ka compared to MD99-2251 and MD95-2011 (Fig. 3). One scenario that could explain this is that *G. bulloides* at RAPID-12-1K integrated a larger portion of the warmer surface waters during calcification. However, during the mid-Holocene the seasonal thermocline was more pronounced due to the increase in summer warming relative to at present. It is difficult to estimate the effect of this change on the depth habitat of planktic foraminifers, but it cannot be excluded that this may have had an effect on the preferred depth habitat.

The comparison between foraminifer-based temperature estimates and model results show that the Holocene trends in the proxy data can be explained by changes in hydrography at surface and sub-surface depths during the summer season. Modelling results indicate that while the seasonal summer warming of the sea-surface was stronger during the mid-Holocene, sub-surface depth experienced a cooling below

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30–75 m (ODP 984, MD99-2251, and RAPID-1-12K) or over a certain depth range (40–75 m at MD95-2011) (Fig. 8). This can explain the observed difference between the Holocene trends in phytoplankton and zooplankton temperature reconstructions. The sub-surface cool anomaly is registered at depth intervals occupied by both near-surface and deeper dwelling foraminifer species. There are no large differences in trend between reconstructions from near-surface and deeper-dwelling foraminifer species, which is contrary to the suggestion by Jansen et al. (2008) that a cool mid-Holocene anomaly would be recorded by deeper-dwelling species only. Our explanation does not exclude the possibility of smaller shifts in reproductive season (towards cooler months) or shifts in depth habitat (towards deeper depths), in addition to changes in hydrography, to explain the mid-Holocene anomaly in the proxy records.

4 Conclusions

Foraminifer temperature proxy records from the eastern Norwegian Sea (MD95-2011), and the North Atlantic south of Iceland (MD99-2251, ODP 984, and RAPID-12-1K) show Holocene trends of increasing temperature from early/mid Holocene to late Holocene, in contrast to the mid-Holocene thermal maximum exhibited by many phytoplankton-based SST records (i.e. diatom and alkenone records). Based on comparisons between foraminifer temperature proxy data and CCSM3 model results the following results of local and regional importance are suggested:

1. Both records based on foraminifers with near-surface (*G. bulloides*) and deeper dwelling (*N. pachyderma*) habitat share the trend towards warmer late Holocene temperatures. The trend is also evident in records based on faunal assemblage changes as well as geochemical temperature proxies.
2. CCSM3 modelling results show a distinct 6 ka summer (JAS) warming of the sea-surface in the North Atlantic and Norwegian Sea. Modelling results for the area south of Iceland suggests negative 6 ka anomalies for all seasons but summer

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and for sub-surface depth (100 m) throughout the year. For the Norwegian Sea, the model generally shows positive 6 ka sea-surface anomalies throughout the year, an anomaly that is particularly pronounced during the summer season.

3. Model summer temperature profiles for site MD99-2251, ODP 984, and RAPiD-12-1K display cool 6 ka sub-surface anomalies. The strong summer warming appears to be restricted to the upper 30–75 m. For site the MD95-2011, the model temperature profile exhibits a cool anomaly between 40–75 m water depth.
4. The relatively cool mid-Holocene foraminifer-based temperatures can be explained by the presences of cool sub-surface waters during summer (JAS). This explanation does not exclude the possibility of shifts in productivity season or changes in depth habitat between 6 ka and the late Holocene. More extensive data-model comparisons are needed to test this hypothesis.
5. Several different suggestions have been made to explain the observed trends in the foraminifer records from the North Atlantic and Norwegian Sea. Changes in the dynamics of the subpolar gyre have recently been shown to have a great influence on the inflow of Atlantic water (Hátún et al., 2005). Changes in the supolar gyre circulation affect all the different branches of the Atlantic inflow, and could possibly be the common source of the temperature trends seen in the studied foraminifer records. However, the influence of the subpolar gyre circulation on the Atlantic inflow has only been examined on decadal time scales. Studies of proxy records with high temporal resolution are needed to examine how the dynamics of the subpolar gyre operates on longer time scales.

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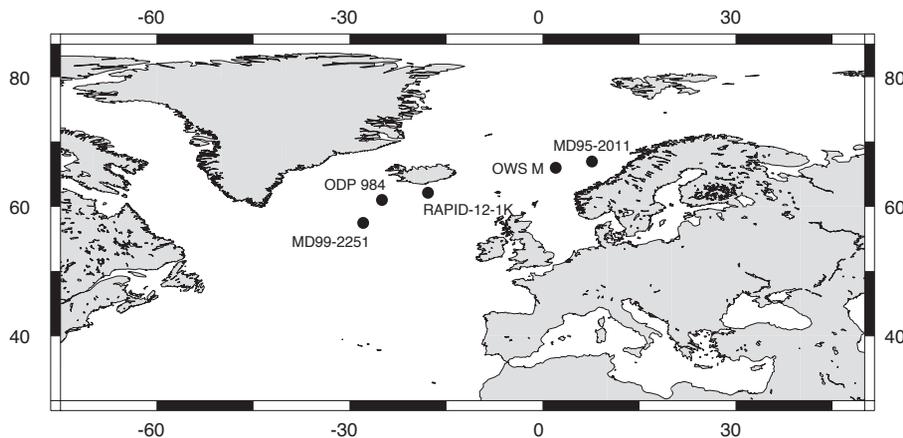


Fig. 1. Map showing the location of cores MD95-2011, MD99-2251, ODP 984 and RAPiD-12-1K. The position of Ocean Weather Station (OWS) Mike is also shown.

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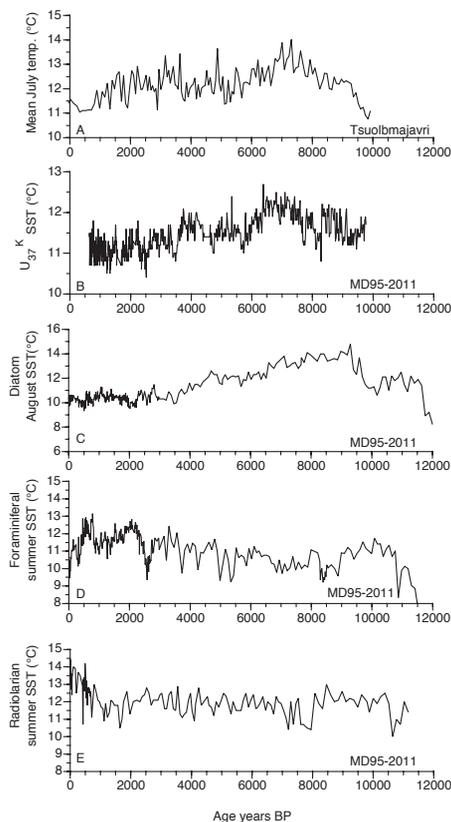


Fig. 2. (A) Mean July temperature based on pollen from Tsoulbmajavri, Finland (Seppä and Birks, 2001). (B) Alkenone derived sea-surface temperatures from the Vøring Plateau (MD95-2011) (Calvo et al., 2002; Jansen et al., 2008). (C) Diatom-based sea-surface August temperature estimates from MD95-2011 (Birks et al., 2002). (D) Foraminiferal-based transfer function sea-surface temperature estimates for summer (JAS) for MD95-2011 (Andersson et al., 2003; Risebrobakken et al., 2003). (E) Radiolarian-based transfer function sea-surface summer temperature estimates for MD95-2011 (Dolven et al., 2002).

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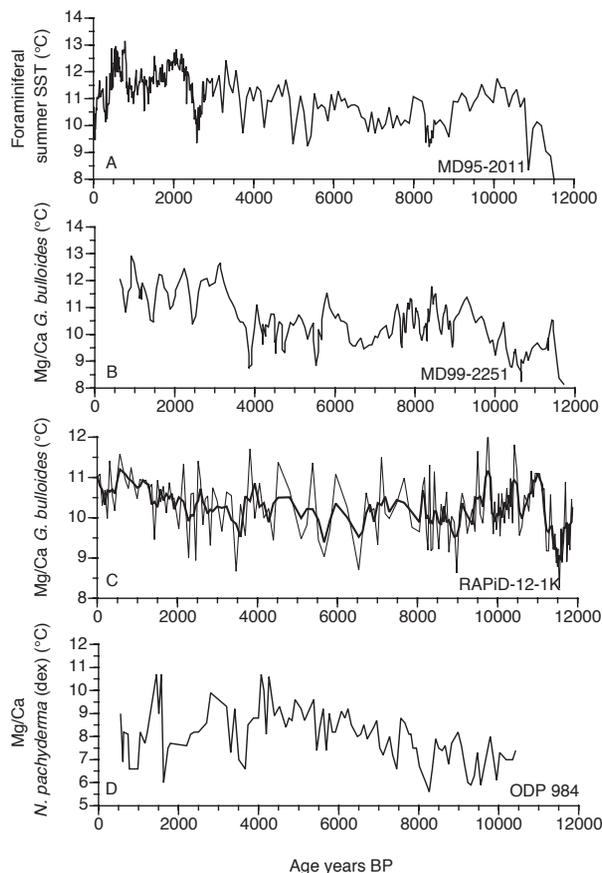


Fig. 3. Foraminiferal-based temperature records from the eastern Norwegian Sea and the northern North Atlantic south of Iceland. **(A)** Sea-surface temperature estimates for summer (JAS) for site MD95-2011 (Andersson et al., 2003; Risebrobakken et al., 2003). **(B)** Mg/Ca sea-surface temperatures for MD99-2251 based on *G. bulloides* (Farmer et al., 2008). **(C)** Mg/Ca sea-surface temperatures for RAPiD-12-1K based on *G. bulloides* (Thornalley et al., 2008). **(D)** Mg/Ca sea-surface temperatures for ODP 984 based on *N. pachyderma* (dex) (Came et al., 2007).

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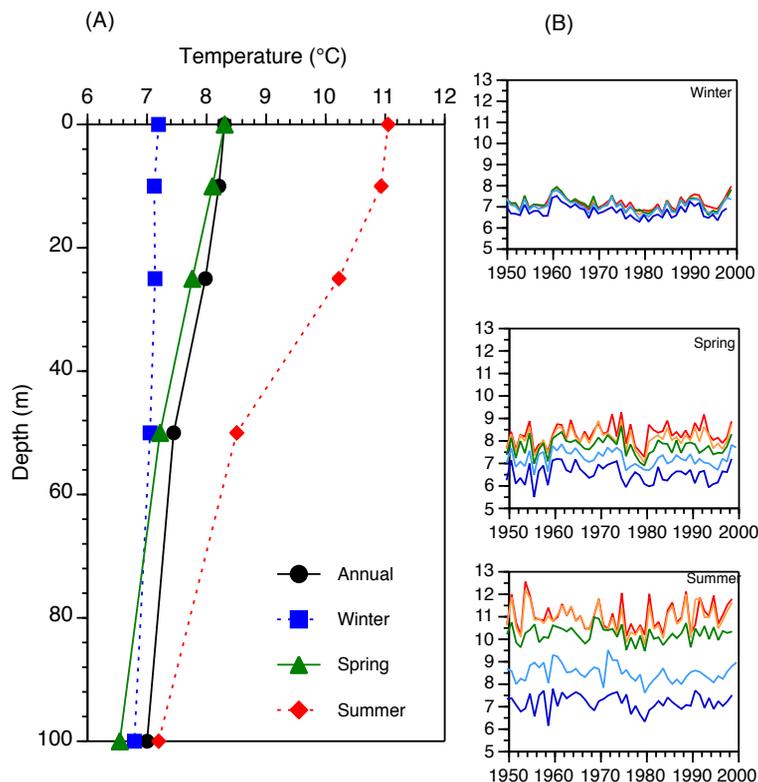


Fig. 4. (A) Seasonal and annual temperature averages for the last 50 years from Ocean Weather Station Mike in the upper 100 m of the water column. Averages are based on the temperature records presented in (B). From Nyland et al. (2006).

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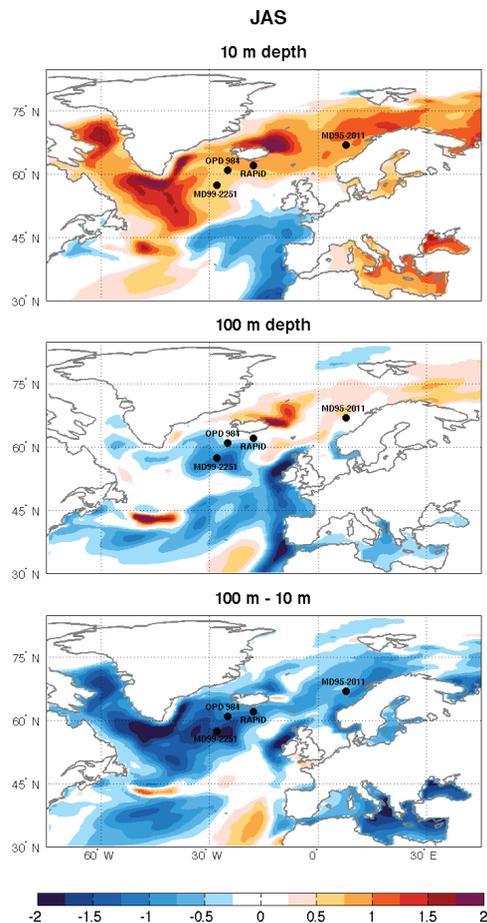


Fig. 5. Ocean potential temperature differences between MH and PI in CCSM3 for summer (JAS) at 10 m depth (upper panel) and 100 m depth (center). The lower panel shows the MH-PI anomaly for the difference between 100 m and 10 m depth.

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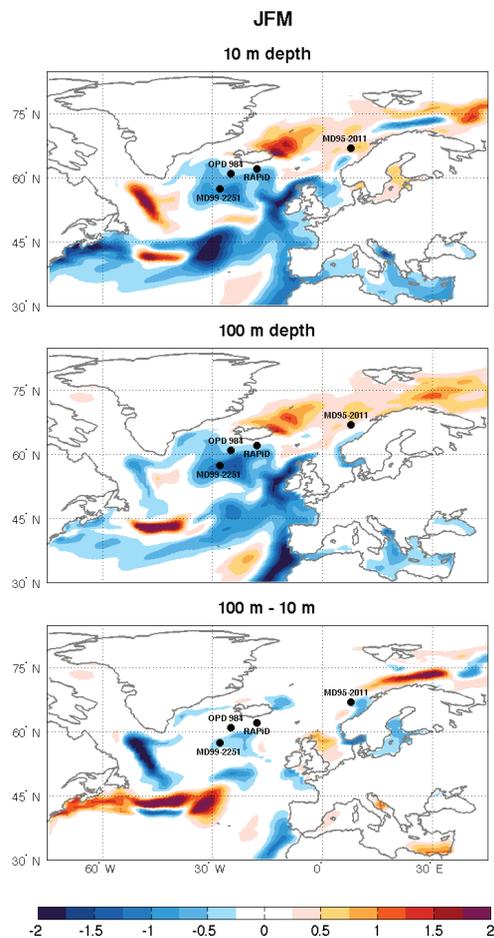


Fig. 6. 6 k–0 k CCSM3 model result for winter (JFM) temperature for 10 m and 100 m as well as the 6 k–0 k anomaly for the difference between 100 m and 10 m.

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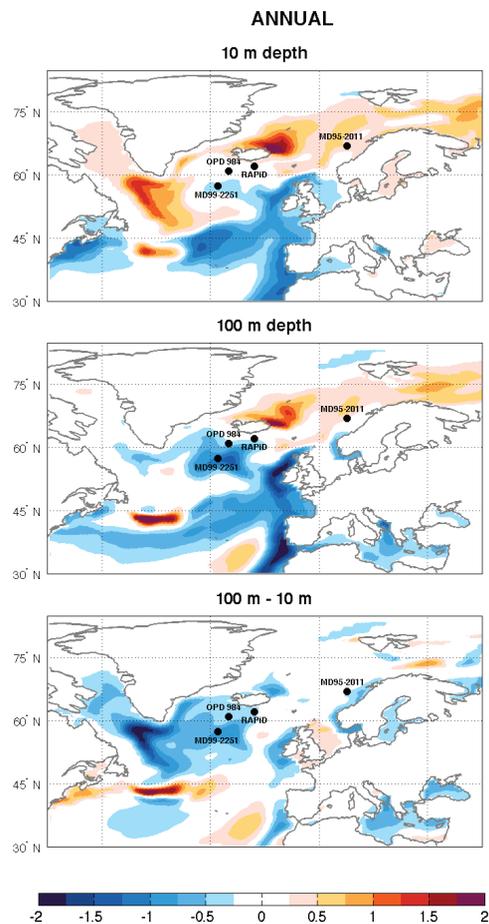


Fig. 7. 6k–0k CCSM3 model result for the annual mean temperature for 10 m and 100 m as well as the 6k–0k anomaly for the difference between 100 m and 0 m.

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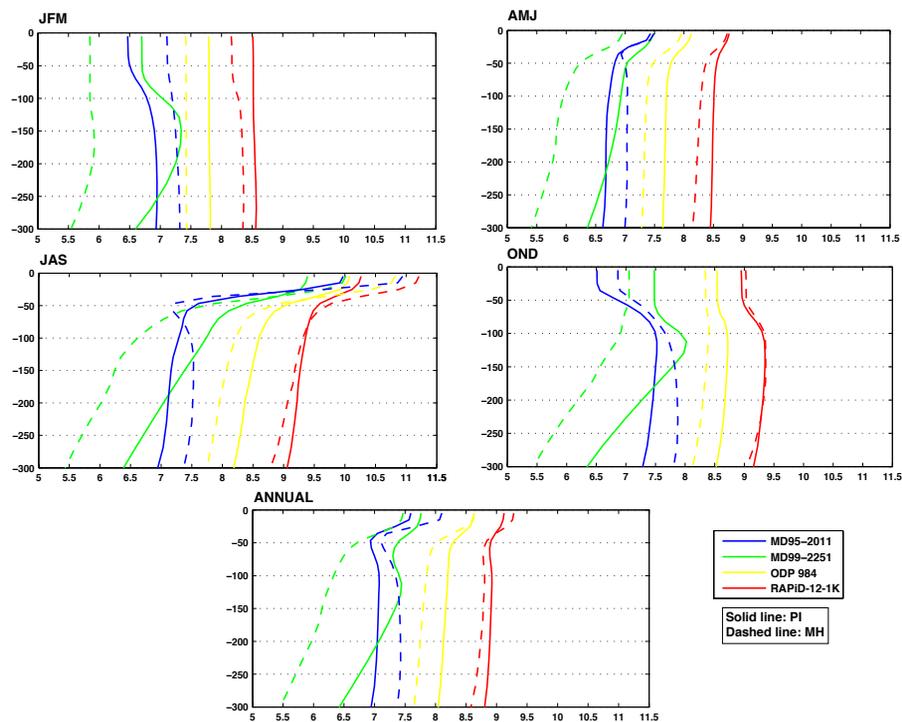


Fig. 8. Average annual and seasonal temperature profiles 0–300 m depth for site MD95-2011, MD99-2251, ODP 984, and RAPiD-12-1K from the CCSM3 model results.

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