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Meltwater pulses in the northern North Atlantic: retrodiction and forecast by numerical modelling

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Abstract Changes in sea surface salinity, especially by sudden meltwater pulses, are the most effective process to modify the circulation in the Greenland–Iceland–Norwegian (GIN) seas. With "Sensitivity and Circulation of the Northern North Atlantic" (SCINNA), a three-dimensional ocean general circulation model, several experiments addressing the possible effects of meltwater inputs of different intensities were carried out. The experiments used (a) the last glacial maximum (LGM) reconstruction based on oxygen isotopes data from sediment cores and (b) the modern conditions of the GIN seas for their initial states. Meltwater inputs from Europe as recorded during the last deglaciation succeeding the LGM change the circulation pattern drastically. These pulses can push the high-salinity inflow from the northeast Atlantic away from Europe over to the southern coast of Iceland, thus allowing the low-salinity meltwater to spread all over the GIN seas. As a result, the deepwater formation in this region can be turned off and the circulation system shifts from the normal cyclonal-antiestuarine into an anticyclonal-estuarine mode. On the contrary, meltwater pulses originating from Greenland due to global warming mainly intensify the East Greenland Current without altering the overall circulation and temperature/salinity patterns significantly because they chiefly enhance the salinity minimum off the Greenland coast.

Key words Numerical modelling · Meltwater pulses · Paleoceanography · Circulation changes · Norwegian–Greenland seas

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Introduction

The stratigraphic record from sediment cores supplies evidence for several meltwater pulses during the transition from the last glacial maximum (LGM; 18 000 ^{14}C years BP) to the Holocene climatic state (from 9000 ^{14}C years BP onwards) in the Greenland–Iceland–Norwegian (GIN) seas. Major meltwater events (MWE) resulted from the breakdown of the Laurentide, the Barents, and later, the Scandinavian ice sheets. Evidence is given by stable isotope analysis from planktonic foraminifera for salinity anomalies, and by coarse-clastic sediment layers from melting icebergs, the Heinrich layers (Bond et al. 1992; Sarnthein et al. 1995; Weinelt 1993). These meltwater pulses varied in duration and intensity; some estimates are given in Fig. 1 (cf. Fairbanks 1989; Sakai and Peltier 1996). Global warming may induce a future meltwater pulse in the GIN seas by melting the Greenland ice cap.

Prescribing meltwater pulses of varying intensity and provenance to an oceanic circulation model offers the possibility to simulate the influence of such pulses on the oceanic circulation. We present two numerical experiments: (a) retrodiction of the first big MWE after the LGM 13 500 ^{14}C years BP; and (b) prediction of a future MWE by melting ice from Greenland.

The model

"Sensitivity and Circulation of the Northern North Atlantic" (SCINNA; Schäfer-Neth 1994), the model we used for our experiments, is a three-dimensional prognostic ocean general circulation model, employing the primitive equations, based on the Modular Ocean Model by Pacanowski et al. (1993). For computational efficiency, it does not use conventional geographical coordinates but a rotated spherical grid where the

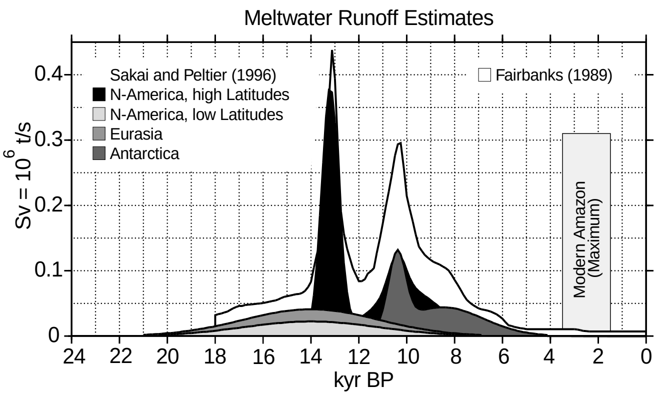

Fig. 1 Meltwater spikes of the past 24 000 years as reconstructed from the Barbados sea-level data (Fairbanks 1989) and modelled with the Ice4G glacier model of Sakai and Peltier (1996). Values are given in Sv = 10^6 t/s. For comparison the maximum discharge of the modern Amazon is indicated by the *vertical bar* to the right

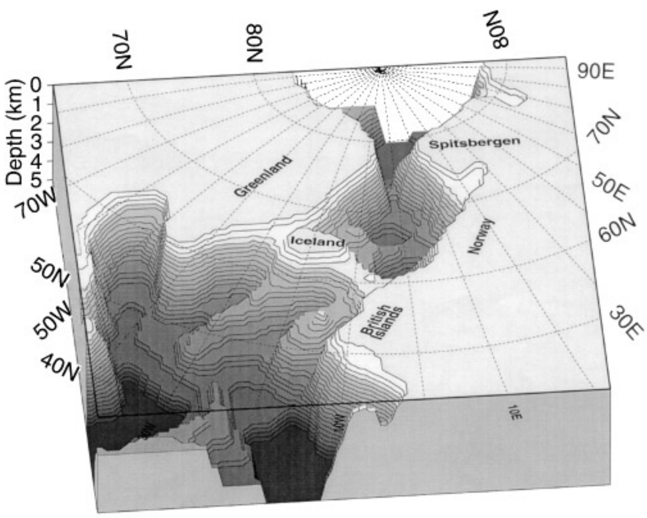

Fig. 2 SCINNA's last glacial maximum (LGM) topography shown in three dimensions from the southwest. Contour interval is 50 m

model's north pole is located at 180°W/30°N, thus minimizing the convergence of meridians. The model domain covers the GIN seas and parts of the neighboring basins. It is resolved with 0.5° (ca. 55 km) in latitude and longitude and vertically by 17 levels with thicknesses increasing from 50 m at the top to 1000 m at the bottom of the deepest basins, thus representing the topography realistically. During test runs forced with modern sea-surface temperatures, salinities, and wind stress, SCINNA proved to reproduce the modern oceanography reasonably well (Haupt et al. 1994, 1995).

Until now, the model's main purpose was to aid paleoceanographic reconstructions of the last glacial maximum (LGM), i.e., to reconstruct physically consistent temperature and salinity distributions with the associated circulation patterns from the proxy data (Schäfer-Neth 1994, 1997). For the first part of the experiments presented herein, a modified topography (Fig. 2) was employed to take into account the 100-m glacial sea-level lowering (Fairbanks 1989) and the continental-shelf glaciation down to a mean depth of 200 m with respect to glacial sea level (CLIMAP 1981; Lehman et al. 1991; Mienert et al. 1992). In the LGM topography, the straits between Greenland and Scotland, especially the Denmark Strait, are narrower and shallower than at present, and the Barents and North Sea have been removed.

SCINNA's southern and northern boundaries are closed. To include the effects of the global ocean, temperatures and salinities are damped to prescribed values within restoring zones five gridpoints wide along these boundaries. These zones extend over the whole vertical water column of the respective grid points.

Experiments and results

We discuss two meltwater experiments starting from (a) the reconstructed LGM summer scenario (Schäfer-Neth 1994, 1997), the best documented time slice, and (b) the modern winter situation, the season during which the formation of the main water masses takes place. Both experiments were carried out in two stages. Firstly, the model was integrated using fixed surface T and S until it reached an equilibrium state, from which the sea-surface heat and freshwater fluxes were diagnosed. For the second stage, additional meltwater inputs were incorporated into the system by modifying the freshwater fluxes, and SCINNA was integrated further on for 50 years with flux boundary conditions. In the upper 750 m of the model the meltwater-induced variations occur very rapidly, and the model reaches a new stable state after only two decades, which lasts until the meltwater supply is turned off.

Experiment 1: MWE 13 500 ^{14}C years BP

The first stage of this experiment was initialized with the three-dimensional T and S reconstruction of the glacial summer by Schäfer-Neth (1997). This reconstruction was based on a total of 133 deep-sea cores with oxygen-isotope measurements from planktonic foraminifera and 25 cores with new sea-surface T estimates from faunal assemblages (Weinelt et al. 1996, Pflaumann et al. 1996). According to this reconstruction, both T (Fig. 3) and S (Fig. 4) of the GIN seas were relatively high during the glacial summer. These distributions lead to a glacial circulation (Fig. 5) quite

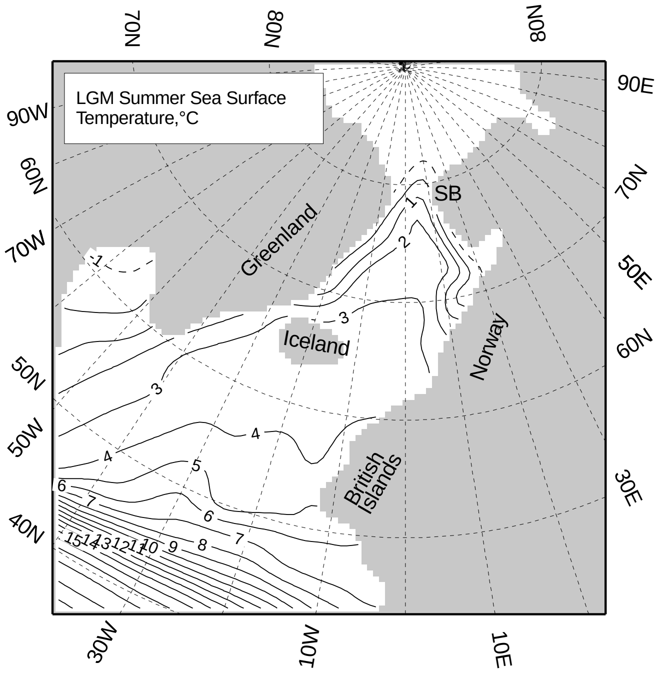

Fig. 3 Sea-surface temperature of the glacial summer, reconstructed from faunal assemblages. Contour interval is 1°C. *SB* Spitsbergen

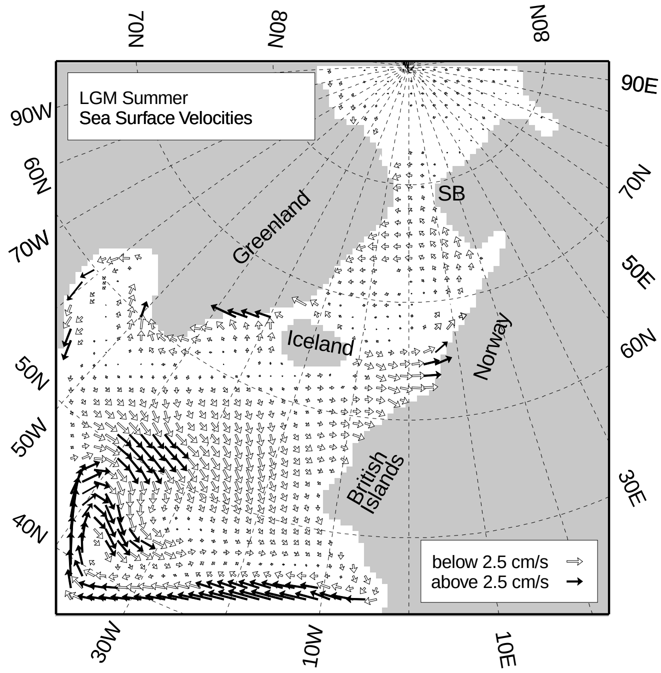

Fig. 5 Glacial summer circulation at the surface. The *shortest black arrows* and *longest white arrows* indicate 2.5 cm/s

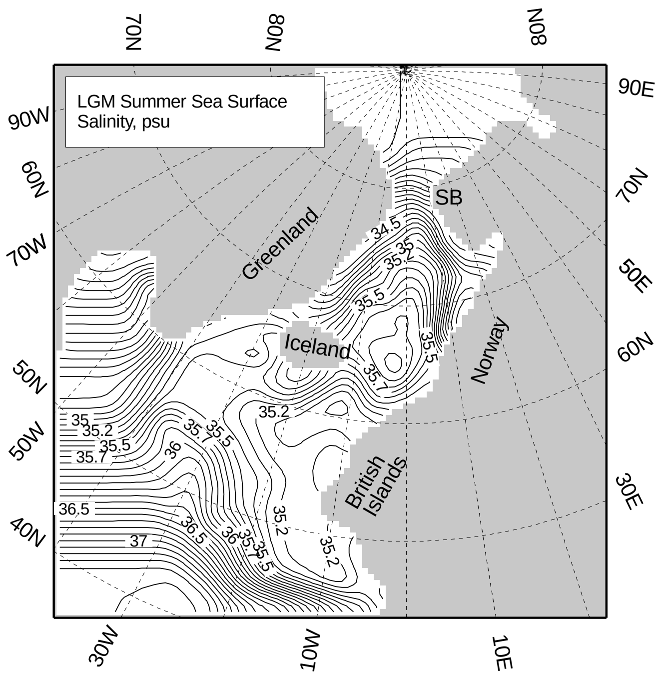

Fig. 4 Sea-surface salinity of the glacial summer, reconstructed from oxygen isotopes and surface temperature. Contour interval is 0.1 psu

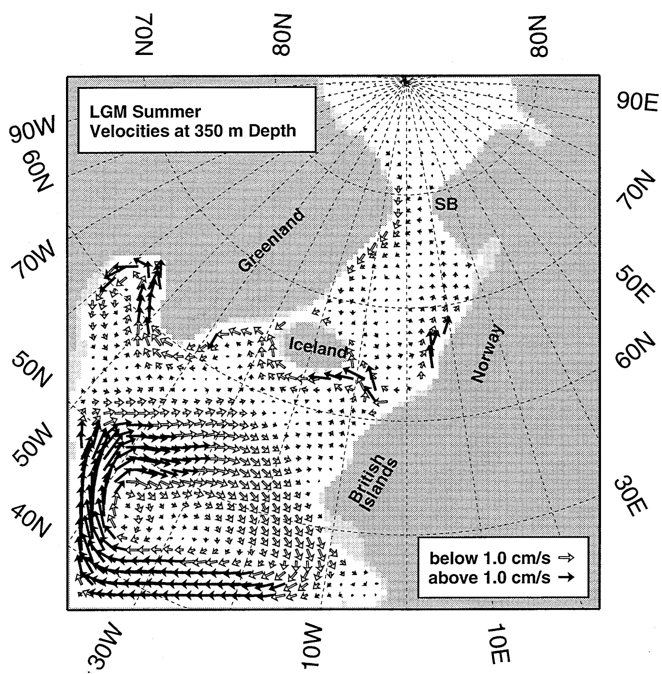

Fig. 6 Glacial summer circulation at 350 m depth. *Shortest black arrows* and *longest white* arrows = 1.0 cm/s

similar to the modern circulation, exhibiting the cyclone in the GIN seas, the East Greenland and Norwegian currents, and the subpolar and subtropical gyres. The circulation at deeper levels resembles the modern circulation also. At 350 m depth (Fig. 6) outflows from the GIN seas into the North Atlantic known from the present can be seen. For surface forcing and restoring at the boundaries, the respective parts of this data set were used. The wind forcing was taken from the glacial July reconstruction that was modelled by Hoffmann (pers. commun.) with the ice-free GIN seas.

Proxy data from the 13 500 ^{14}C-year time slice are scarce and give no physically consistent patterns because of stratigraphic uncertainties by comparing meltwater spikes from different cores within a 1000-year interval. Thus, they cannot be used for salinity reconstructions and numerical modelling in the same way as for the LGM. To tackle this problem from a different point of view, we study meltwater inflows at the surface. The sea-level reconstructions of Fairbanks (1989) and the model results of Sakai and Peltier (1996) give peak deglaciation rates of approximately 0.5 Sv for the past 20 000 years (see Fig. 1). From these findings, we imposed additional freshwater inputs of 0.5 Sv each at the coasts of Greenland, northern Europe, and Scotland during the second stage of this experiment (Fig. 8, circles). The wind and restoring fields were kept unchanged.

Within 20 years of integration under meltwater conditions, the circulation changes dramatically. At the surface (Fig. 7), the currents switch from a cyclonal into an anticyclonal mode in the Greenland Sea. Off Scotland, an outflow from the GIN seas exists instead of the former inflow, and the East Greenland Current is heavily intensified. These changes shift the warm and salty inflow into the GIN seas to the west, thus cutting the former GIN Sea cyclone short along Iceland. As a consequence, the low-saline meltwater can spread (Fig. 8) far southward. This causes a strong density stratification at the surface, thereby turning off the deep water formation in the GIN seas. In turn, the outflows over the Greenland–Iceland-Scotland ridges into the North Atlantic cease as well and inflows into the GIN seas are established (Fig. 9).

In short, the meltwater input pushes the overall circulation of the GIN seas from a cyclonal-antiestuarine state to an anticyclonal-estuarine. After turning off the

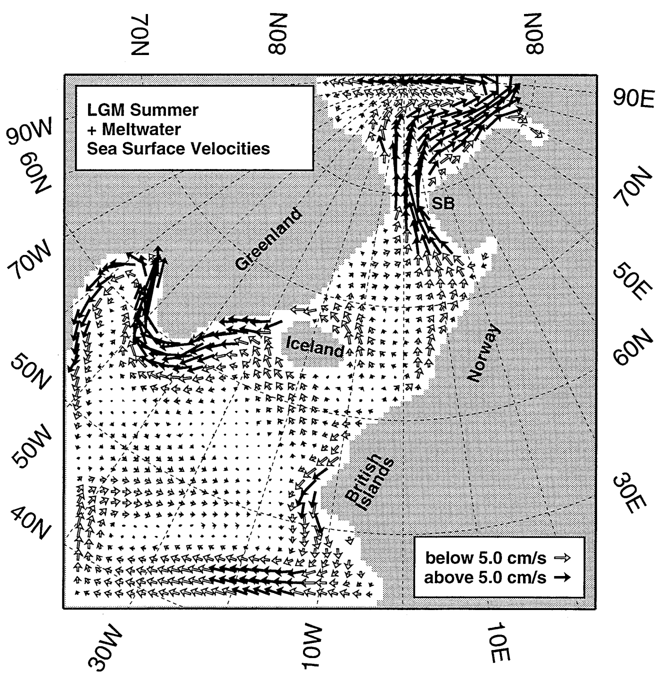

Fig. 7 Surface circulation after 20 years under meltwater conditions superimposed on the LGM state. *Shortest black arrows* and *longest white arrows* = 5.0 cm/s

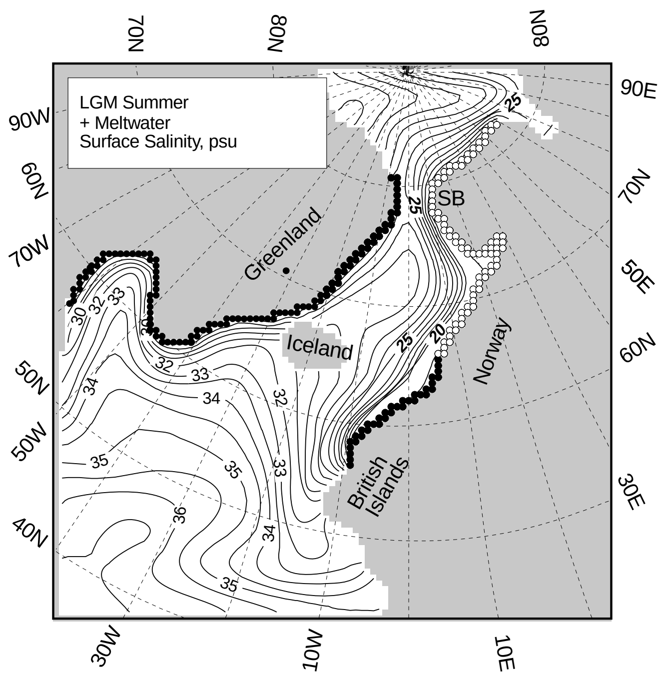

Fig. 8 Sea-surface salinity under meltwater conditions (cf. Fig. 7). *Filled* and *open circles* meltwater inputs along Greenland, northern Europe, and Scotland, 0.5 Sv at each coastline. Contour interval is 5 psu below 20, 1 psu between 20 and 33, and 0.5 psu above 33

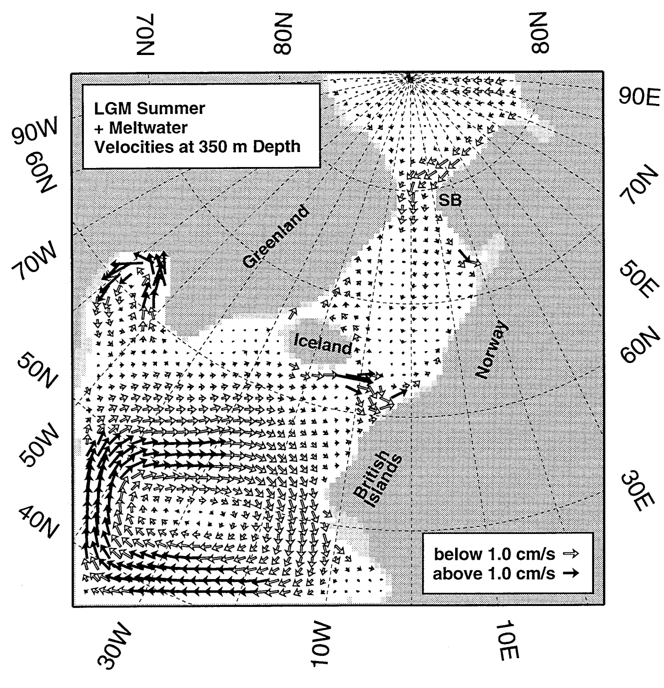

Fig. 9 Circulation at 350 m depth under meltwater conditions (cf. Fig. 7). *Shortest black arrows* and *longest white arrows* = 1.0 cm/s

meltwater inflow, the system flips back to the old cyclonal-antiestuarine scenario of the LGM within 20 years.

Experiment 2: “future” MWE

The sea-surface temperatures and salinities for driving the experiment’s first stage were taken from the Levitus (1982) winter data that were superimposed in the GIN seas (Seidov et al. 1996) with the *T* (Fig. 10) and *S* (Fig. 11) fields after Dietrich (1969) to account for the local hydrography not represented in the Levitus climatology, namely the salinity minima along the coasts of Norway and Greenland. The temperature field was further modified by freezing point (–1.9°C) conditions in the area of the mean winter ice cover (Wadhams 1986). This combined data set was used as well for initialization and boundary restoring. The Hellerman and Rosenstein (1983) January wind stress was employed for wind forcing. With these data, SCINNA produces modern circulation very well, shown in Fig. 12 for the surface.

In the second stage an additional freshwater flux of totally 1 Sv was imposed along the coast of Greenland (Fig. 13, circles) to check whether the dramatic changes found in the first experiment can be attributed solely to one of the pulses originating from Greenland or Eurasia. Doing so, we can find out possible consequences of the present warming of the atmosphere that might cause a melting of the Greenland ice sheet. (The effect of this melting on the sea level is not considered herein.) As in experiment 1, the wind and restoring data were not changed. Although a 1-Sv freshwater input is an intense pulse, corresponding to a complete melting of the Greenland ice sheet within some 200 years, its effect is limited to a salinity reduction (Fig. 13)

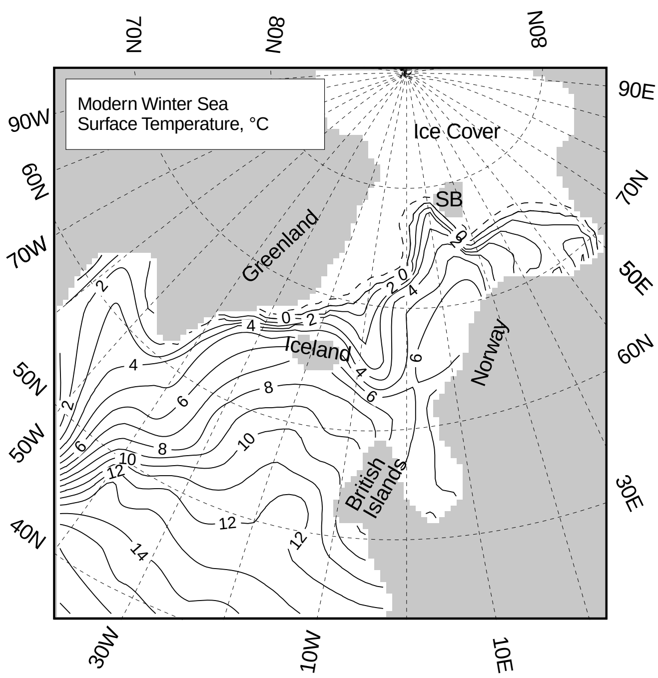

Fig. 10 Modern winter sea-surface temperature after Levitus (1982), Dietrich (1969), and Wadhams (1986). Contour interval is 1°C

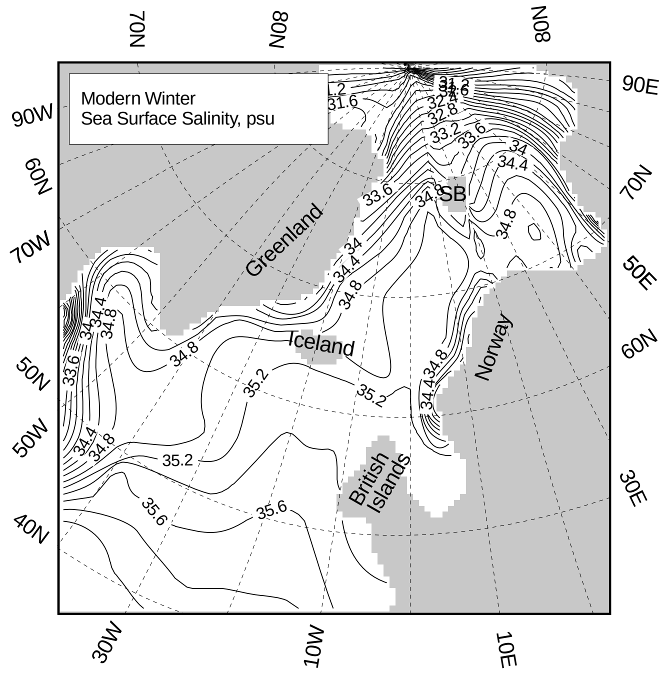

Fig. 11 Modern winter sea-surface salinity after Levitus (1982) and Dietrich (1969). Contour interval is 0.2 psu

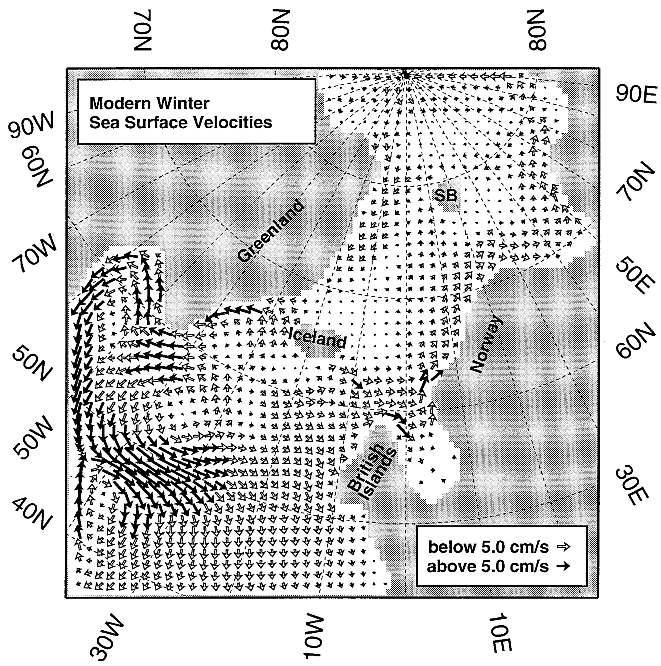

Fig. 12 Modern winter circulation at the surface. *Shortest black arrows* and *longest white arrows* = 5.0 cm/s

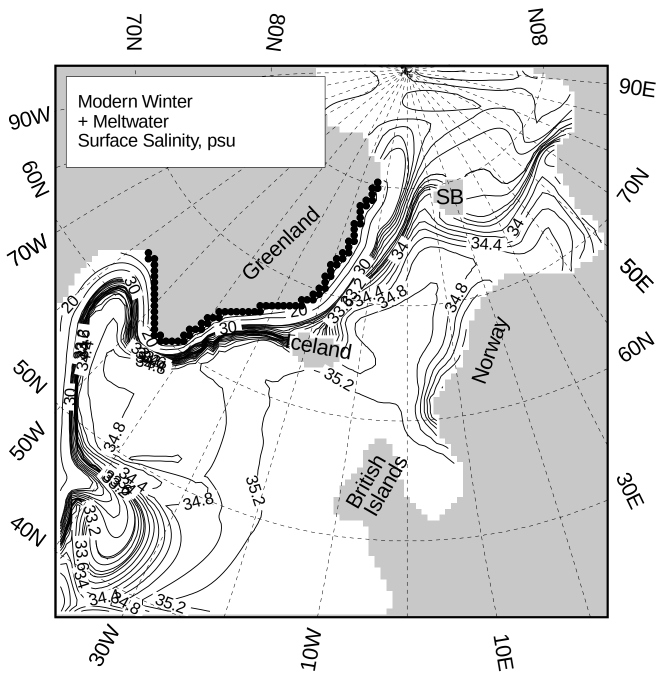

Fig. 13 Sea-surface salinity after 20 years under meltwater conditions superimposed on the modern winter scenario. *Circles* 1-Sv meltwater inflow from Greenland. Contour interval is 5 psu below 30, 0.5 psu between 30 and 33.5, and 0.2 psu above 33.5

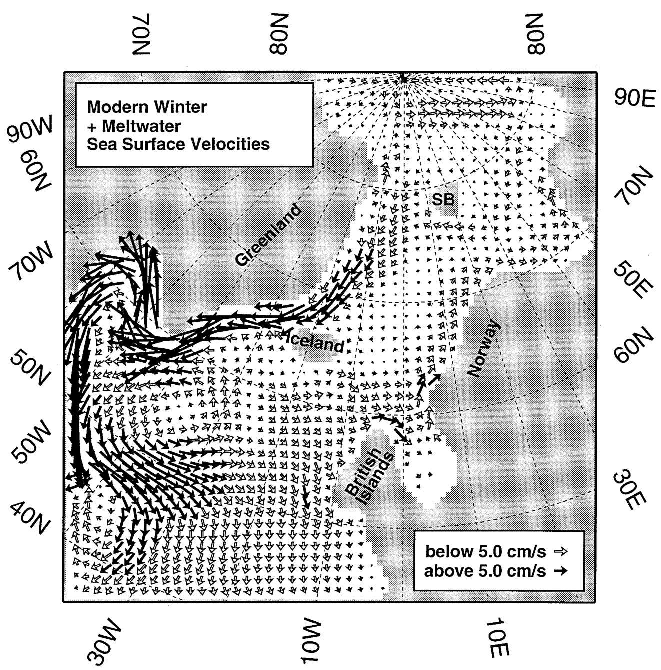

Fig. 14 Surface circulation after 20 years under meltwater conditions (cf. Fig. 13). *Shortest black arrows* and *longest white arrows* = 5.0 cm/s

along the Greenland coast and in the Labrador basin. Except for a remarkable strengthening of the East Greenland Current (Fig. 14), the circulation remains unchanged.

These comparably small effects of the meltwater pulse originating from Greenland can be explained by the fact that this inflow mainly enhances the salinity gradients off the coast of Greenland, thereby increasing the density contrasts and the associated current velocities. On the other hand, the spatial patterns of the salinity gradients remain essentially unchanged, which keeps the current locations fixed.

Conclusions

Our meltwater experiments superimposed on the LGM and on the modern state result in two different scenarios:

1. If meltwater is derived from the western and eastern margins of the GIN seas, the surface circulation switches from the cyclonal-anitiestuarine into the anticyclonal-estuarine mode. The spreading of the light meltwater leads to a strong density stratification which suppresses deep water formation heavily.
2. On the contrary, if meltwater is available only from Greenland as it is presently, it will cause no major change in the general circulation pattern, except for an intensification of the East Greenland Current. This does not allow spreading of meltwater over the GIN seas, and deep water formation is not suppressed. Triggering a new meltwater event by global warming is therefore expected to have only minor influence on the general oceanic circulation pattern in the GIN seas.

Further experiments will include the melting of iceberg flotillas in producing meltwater corridors and Heinrich layers as sedimentary response.

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