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Reconciling Bølling warmth with peak deglacial meltwater discharge

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Abstract. Paleoclimatic data indicate warm conditions during the Bølling period, whereas climate modeling studies predict significant cooling, triggered by the concomitant deglacial meltwater flux into the Atlantic Ocean. We suggest that the lack of an adequate representation of deep water flow over the Greenland-Scotland Ridge in ocean circulation models can account for this discrepancy.

Sea-level reconstructions indicate a massive input of meltwater during the early stage of the last deglaciation. During the Bølling period, 14.7–14.1 cal. kyr B.P. (thousand calendar years before present), up to ~ 0.5 Sv ($1\ \mathrm{Sv}=10^6\mathrm{m}^3\mathrm{s}^{-1}$) of meltwater entered the ocean [*Fairbanks et al.,* 1992] (Figure 1). Most of the meltwater likely originated from the decaying Laurentide ice sheet; the inferred freshwater pulse out of the Mississippi river entered the Atlantic via the Gulf of Mexico [*Fairbanks et al.,* 1992]. Various modeling studies indicate that such massive meltwater input should lead to the cessation of deep water formation in the North Atlantic and the large-scale thermohaline circulation [e.g., *Stocker et al.,* 1992; *Mikolajewicz and Maier-Reimer,* 1994; *Rahmstorf,* 1996; *Manabe and Stouffer,* 1997; *Schiller et al.,* 1997]. In these models the associated drop in northward heat transport results in a dramatic cooling in the North Atlantic region.

In contrast to these model results, paleoclimatic proxy data indicate that the Bølling was a remarkably warm period: Sea surface temperatures in the North Atlantic reached almost interglacial values, and mild temperatures persisted in Europe [e.g., *Berger and Jansen,* 1995]. These findings are reflected in the δ^{18}O record from the Greenland ice sheet (Figure 1) and are consistent with active deep water formation, which is corroborated by benthic δ^{13}C data [*Sarnthein et al.,* 1994]. Incursion of warm Atlantic water into the Norwegian Sea [e.g., *Sarnthein et al.,* 1995; *Hald et al.,* 1996] and high surface water density in the Icelandic Sea [*Sarnthein et al.,* 1995] suggest that deep water was formed in the northern North Atlantic during the Bølling. Thus the coincidence of a warm climate period in the North Atlantic region with a massive meltwater input raises a puzzling question regarding the last deglaciation [*Sarnthein et al.,* 1994, 1995; *Berger and Jansen,* 1995]. On the basis of the seemingly incompatible evidence from models and data, *Clark et al.* [1996] concluded that it is unlikely that the meltwater source was the Laurentide ice sheet; instead, these authors envisioned an Antarctic source. However, on the basis of a new modeling study we suggest that meltwater influx into the North Atlantic and warm climate in the North Atlantic realm during the Bølling may be reconciled.

The sensitivity of the thermohaline circulation (THC) to meltwater input has been studied with ocean general circulation models (OGCMs) coupled to atmospheric components of different complexity [e.g., *Rahmstorf,* 1996; *Manabe and Stouffer,* 1997; *Schiller et al.,* 1997]. In these models, deep water is largely formed south of the Greenland-Scotland Ridge, whereas oceanographic observations indicate that a considerable fraction of the deep water is actually produced in the Greenland-Iceland-Norwegian (GIN) Sea [*Dickson and Brown,* 1994]. Part of the water formed in the GIN Sea flows over the Greenland-Scotland Ridge, contributing to deep water renewal. Current large-scale OGCMs have very strong numerical entrainment on slopes and cause a significant loss of bottom-water mass characteristics [*Gerdes,* 1993]. Since overflow is frequently underestimated in these models, deep water formation regions in the models are shifted southward compared to the real ocean. *Beckmann and Döscher* [1997] formulate a bottom boundary layer model which parameterizes explicitly the near-bottom transport over sloping topography improving the representation of descending dense-water plumes. In this model concept, adjacent bottom tracer boxes are "diagonally" connected over

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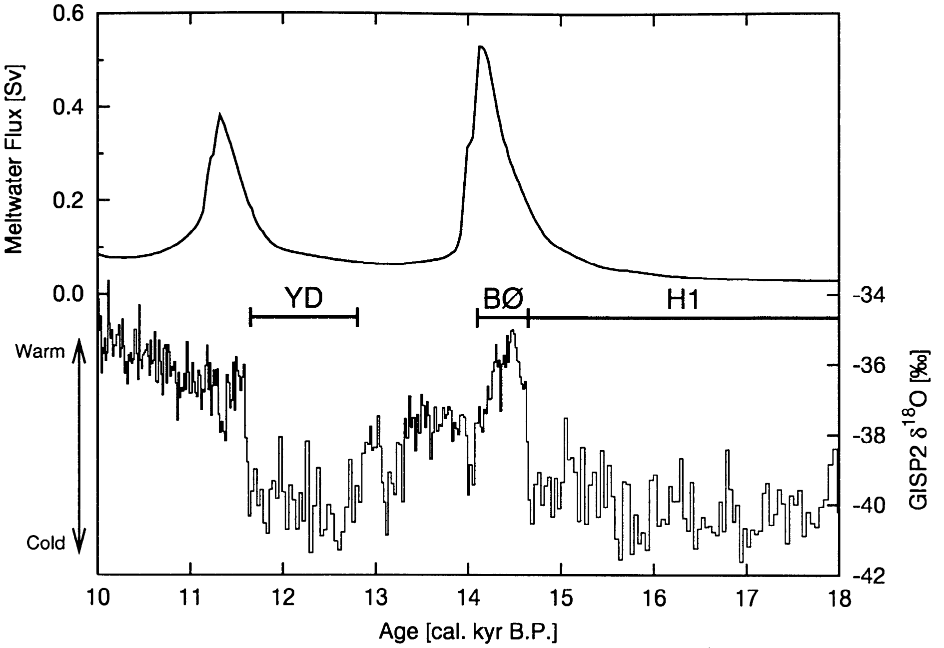

Figure 1. Sea level derived rate of deglacial meltwater discharge [*Fairbanks et al.,* 1992] (top line) and oxygen isotope record from Greenland GISP2 ice core [*Grootes and Stuiver,* 1997], reflecting air temperature (bottom line). Meltwater influx is maximum during the Bølling warm period (BØ) and minimum during Heinrich event 1 (H1) and Younger Dryas (YD).

topographic slopes (solid arrows in Figure 2) and overflow water can contribute to deep water formation, in addition to a source linked to open ocean convection (shaded arrow in Figure 2).

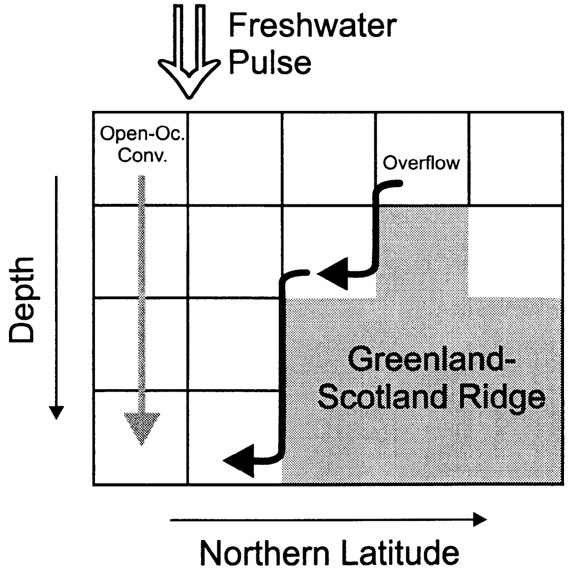

Figure 2. North Atlantic Deep Water fed by open ocean convection south of the Greenland-Scotland Ridge (shaded arrow) and overflow water from the GIN Sea. Parameterization of near-bottom transport allows for "diagonal" exchange between model grid cells over topography (solid arrows). In experiments a and b, a freshwater pulse south of the Greenland-Scotland Ridge has been applied which effectively interrupted convection south of the ridge.

Recently, *Lohmann* [1998] applied this parameterization to a coupled atmosphere-ocean-sea ice mode [*Lohmann and Gerdes,* 1998] with idealized geometry of the Atlantic Ocean. The basic result of this sensitivity study is that the system with the near-bottom transport allows a coupling of the circulation over the ridge. Without parameterization of the near-bottom transport a subpolar freshwater perturbation south of the Greenland-Scotland Ridge (schematically shown in Figure 2) caused the northward heat transport to be strongly reduced and deep water formation to almost collapse (Figure 3a). Sea surface temperature in the northern North Atlantic is reduced by several degrees As a result of including the effect of the near-bottom transport, the freshwater perturbation caused a significant circulation anomaly, but the influence of the overflow water was sufficient to keep the THC active (Figure 3b). Entrainment by ambient water reduced the buoyancy anomaly and the circulation returned to norma (Figure 3b). The experiments suggest that if the northern deep water source is active, deep convection south of the ridge is not the dominant forcing of the THC (see Figure 3).

On the basis of paleoceanographic data, which indicate active deep water formation during the Bølling in the Icelandic Sea [*Sarnthein et al.,* 1995], we suggest that this deep water mass crossed the Greenland Scotland Ridge and stabilized the THC and inhibited its complete breakdown during the Bølling. The stabilization of the THC helped to maintain mild climate condi

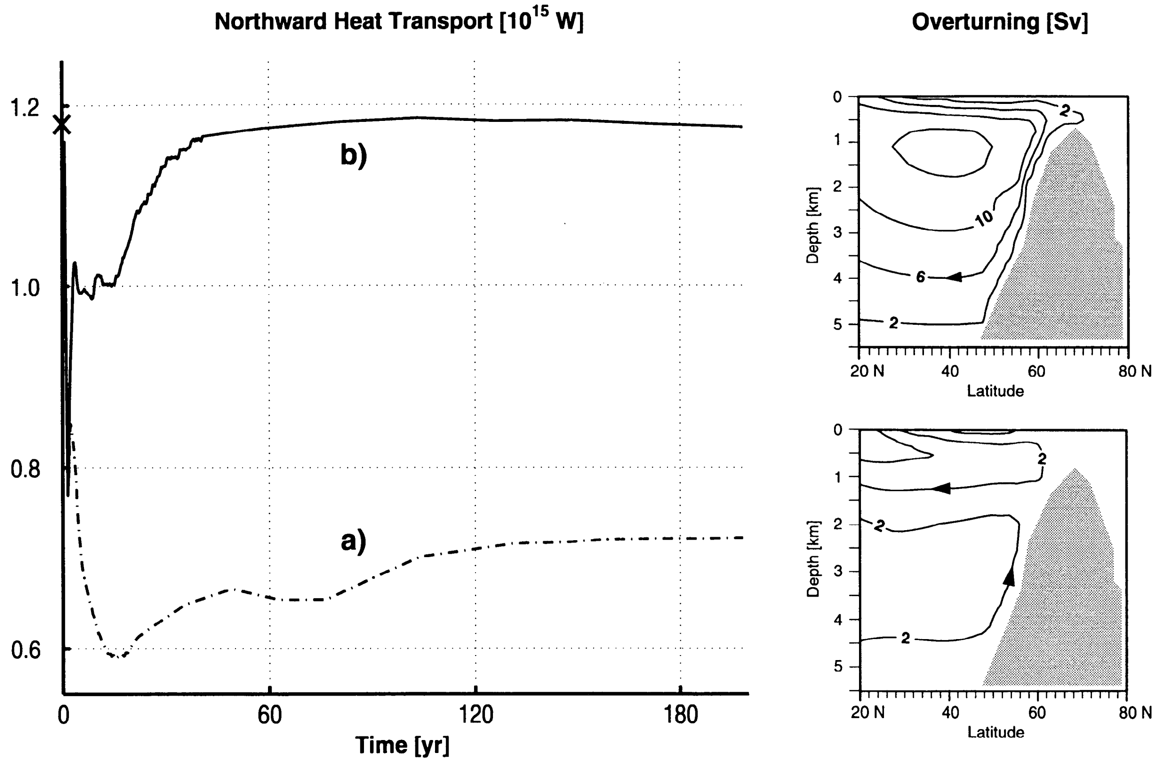

Figure 3. Time-series of maximum oceanic heat transport after an initial salinity perturbation in the North Atlantic surface layer, south of the ridge [*Lohmann,* 1998]. In experiment a, deep water formation almost collapses and does not recover. With bottom boundary layer parameterization, experiment b, the initial perturbation is damped out after a few decades and the northward heat transport recovers almost to the initial value. Initial states in the experiments have nearly the same northward heat transport (cross in the figure). Plots on the right show the meridional overturning stream function 15 years after perturbation. (The initial meridional overturning in experiment b is slightly weaker (~ 2 Sv) than in experiment a due to the contribution of relatively fresh overflow water to North Atlantic Deep Water formation; not shown.)

tions in Europe during the Bølling despite the massive meltwater input. (It is, however, tempting to speculate if the brief cooling at ~14 cal. kyr B.P. (Figure 1) was triggered by the meltwater pulse [*Bard et al.,* 1996].) This situation contrasts with the sea-surface hydrography during Heinrich event 1, 14.7-18.1 cal. kyr B.P., when surging ice sheets delivered meltwater to the central North Atlantic [*Bond et al.,* 1992] and the GIN Sea [*Sarnthein et al.,* 1995]. The associated suppression of deep water formation north of the Greenland-Scotland Ridge deprived the THC of its stabilizing mechanism, making it extremely vulnerable to meltwater input from the Laurentide ice sheet. As a result, deep water formation in the North Atlantic ceased completely [*Sarnthein et al.,* 1994].

These inferences highlight the importance of the representation of deep water formation and adequate overflow in OGCMs for paleoclimate studies. The modeling results and the proxy data suggest two players, a northern (GIN Sea) and a southern (Labrador Sea) source, in ventilating the deep interior of the Atlantic Ocean. We propose that this characteristic feature of the THC is also relevant for the estimation of natural climate variability and future climate change.

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