Modeled glacial North Atlantic ice-rafted debris pattern and its sensitivity to various boundary conditions

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Abstract. An iceberg drift and decay model is used to compute the ice-rafted debris (IRD) flux to the glacial North Atlantic under steady iceberg discharge from the Croenland and Laurentide Ice Sheets. I investigate the sensitivity of modeled IRD distribution pattern to formulation of glacial iceberg decay, meltwater drainage of Laurentide Ice Sheet at its southern margin, and the choice of ocean current and wind fields used as model boundary conditions. Modeled IRD patterns are compared with the observed "basic glacial" mode IRD pattern [Ruddiman, 1977] and the last five Heinrich layer patterns [Grousset et al., 1993]. Model results show that the first-order control on IRD deposition pattern is the prevailing ocean currents, and the choice of current fields is critical in determining the results. Winds can have significant effect when they exert drag in concert with ocean currents. Formulation of glacial iceberg decay directly affects its survival and the expanse of IRD distribution, but the formulation is perhaps one of the largest uncertainties in the model. Drainage of the southern margin of the Laurentide Ice Sheet through the Laurentian Channel by meltwater instead of glaciers predicts no significant IRD deposition in the open North Atlantic in contrast to observations, suggesting that glacier (i.e., iceberg) drainage through the Laurentian Channel was significant during the times of observed IRD deposition. In most experiments, the model predicts a high IRD deposition band that roughly coincides with the latitudinal band of high Heinrich layer deposition but are measurably south of the basic glacial mode high IRD deposition band. This discordance suggests either that the flow fields used as model boundary conditions are inaccurate or that much of the basic glacial mode IRD was not delivered by icebergs but perhaps sea ice.

Introduction

Icebergs in the glacial North Atlantic are important in paleoclimateology for two reasons. First, the timing and spatial distribution of ice-rafted debris (IRD) deposition by icebergs to the sea floor help constrain the regional ocean-surface conditions and surrounding ice sheet activity during the times of IRD delivery. Second, the North Atlantic thermohaline circulation, which strongly influences the northern hemisphere climate by transporting heat meridionally from the tropics to high latitudes, is shown to be highly sensitive to freshwater flux [e.g., Manabe and Stouffer, 1995; Rahnistorf, 1995]. Iceberg meltwater input from massive iceberg discharges (i.e., Heinrich events) is suggested as the source of freshwater that caused the thermohaline circulation to weaken in the past [Broecker, 1994].

Our understanding of iceberg drift and melting behavior is incomplete, particularly in the open ocean where iceberg observations decline in quantity and quality. The International Ice Patrol (IIP) has been observing icebergs in the vicinity of Grand Banks since the Titanic sank in 1912, but IIP's spatial coverage is limited to regions of navigational interests, fairly close to land [Vickman and Bannier, 1995]. From paleoclimatological interests, understanding the iceberg behavior in the open ocean is perhaps more important because most mapped IRD deposition patterns are from the open ocean [e.g., Ruddiman, 1977; Grousset et al., 1993]. As for modeling studies of icebergs, most are too limited in spatial and temporal domain from a paleoclimatological perspective. The spatial coverage is typically a few degrees in latitude and longitude, and model run time is of the order of days to weeks [Marko et al., 1988]. A recent modeling study by Matsumoto...
[1996] on icebergs under interglacial conditions has sufficient spatial and temporal domain, and here I take a similar approach at modeling icebergs but under glacial conditions.

With gaps in our knowledge of the glacial climate conditions that affect model results, various assumptions are made in the model construct. Therefore emphasis is placed on understanding the sensitivity of glacial IRD distribution to the assumptions made rather than on "simulating" the glacial IRD distribution pattern. Modeled IRD results are compared with the "basic glacial" pattern observed by Ruddiman [1977] and with deposition patterns of last five Heinrich layers (H1 through H5) traced by Grouset et al. [1993]. The comparisons are not entirely appropriate because the conditions under which the observed IRD was deposited were possibly different from the Last Glacial Maximum (LGM) conditions under which the model is run. Therefore inferences made from such comparisons must be treated with caution.

Model Description

An iceberg drift and decay model used to compute the IRD distribution and iceberg meltwater flux under interglacial conditions [Matsumoto, 1996] is modified in this study for glacial North Atlantic. The model requires ocean current and wind fields and predicts iceberg drift, decay, and IRD release given the month and iceberg position. Here I abbreviate the general description and validation of the model detailed by Matsumoto [1996] and discuss the model modifications appropriate for glacial North Atlantic.

Iceberg drift is modeled dynamically with a set of equations of motion that account for the major forces on icebergs: water drag, wind drag, Coriolis force, and the gravitational force due to sea surface slope (i.e., the dynamic topography). Scale analysis of the forces shows that water drag is the most important force followed by wind drag, with the two remaining forces canceling each other to a large extent. The choice of ocean and atmospheric flow fields is therefore critical in determining model results. The required flow fields are taken from general circulation models simulating glacial and modern conditions (Figure 1). The accuracy of glacial fields is contestable because various aspects of circulation models such as the glacial sea surface boundary conditions contain ambiguities, and the use of such glacial fields in this study introduces uncertainties. Therefore I use different sets of flow fields to assess the sensitivity of model results to the choice of flow fields. I use annually averaged glacial and modern ocean current fields by Seidov et al. [1996] and Toggweiler [1994], respectively. Seidov et al. [1996] used a regional North Atlantic ocean circulation model with a relatively high 1° × 1° resolution, making their data most appropriate for this iceberg modeling study. Attempts to obtain different glacial ocean current fields from other researchers were largely unsuccessful because their data had been lost or were not in a form ready for this study. Therefore I use a set of modern current fields predicted by Toggweiler [1994], which were readily available from a previous iceberg study [Matsumoto, 1996]. As for winds, I use seasonally varying glacial wind fields from Kutsbach and Gruetter [1986]. For alternative wind fields, I use a set of modern fields from Trenberth et al. [1989]. The two sets of wind fields are substantially different, making them suitable to understand the effect of winds on model results. Since ocean current and wind fields were generated independently by uncoupled circulation models, they are not necessarily compatible.

Unlike iceberg drift dynamics, which is basically the same under any condition, iceberg decay under glacial conditions would likely be significantly slower than under interglacial conditions because of lower sea surface temperatures (SSTs). Iceberg decay involves various mechanisms such as mechanical erosion from wave actions, basal melting by buoyancy convection, and surface melting by solar radiation [El-Tahhan et al., 1987]. Without detailed knowledge of glacial environmental conditions, it is difficult to determine the appropriate glacial iceberg decay rates. Iceberg decay therefore is a large uncertainty in this modeling study. I formulate glacial iceberg decay in two distinct methods to assess the sensitivity of model results to decay formulation. The first method scales today's monthly iceberg decay rates for various model subdomains [Matsumoto, 1996] by glacial SSTs reconstructed by CLIMAP Project Members [1981]. In this formulation, the lowest modern iceberg decay rate from ice covered region, typically from the Labrador Sea during March, is assigned to those glacial model grid points where Climate: Long Range Investigation, Mapping, and Prediction (CLIMAP) LGM SST is 0°C (i.e., sea ice covered). Where modern and CLIMAP SSTs are the same, modern iceberg decay rate is assigned. The remaining grid points have CLIMAP SSTs between 0°C and the modern temperature, and I scale the iceberg decay rates proportionally to the CLIMAP and modern SST difference. For model months of January to June, I use CLIMAP February LGM SSTs, and for model months July to December, I use the CLIMAP August LGM SSTs. The lack of complete seasonal cycle in the CLIMAP SSTs has the effect of muting the seasonal variation in iceberg meltwater flux as discussed below. The second glacial iceberg decay formulation assigns glacial iceberg decay rates by uniformly shifting the modern rates by an amount equivalent to 10° in latitude. For example, the glacial iceberg decay rate at 10°N at some longitude is equivalent to the modern iceberg decay rate at 50°N along the same longitude.
IRD release is modeled with an equation that relates by a power law constant the proportion of iceberg debris release to the proportion of iceberg decay [Matsumoto, 1996]. The equation accounts for the fact that icebergs melt from outside inward and that debris is essentially contained in the “outer shell” of icebergs; the net result being that more debris is released early in iceberg decay history. The power law constant determines the rate of debris release in relation to iceberg decay history. Here I present results using a power law constant of 5, determined to give a reasonable result under interglacial conditions [Matsumoto, 1996]. Although the choice of this constant affects the spatial gradient of IRD distribution, model sensitivity to this constant is relatively minor compared to other uncertainties, and hence it will not be discussed.

The model domain is bounded by latitudes 70°N and 30°N and longitudes 80°W and 20°E. All icebergs in the model calve from Laurentide and Greenland Ice Sheets. The steady state glacial Greenland iceberg production rate is assumed to be the same as the modern rate at 2.25 × 10^{14} kg yr^{-1} (Table 1). Glaciers from the steady state Laurentide Ice Sheet that ultimately enter the model domain as icebergs are assumed to drain into either the Hudson Strait or Laurentian Channel catchment basin [Dowdeswell et al., 1995]. I calculate the iceberg production rate from Laurentide Ice Sheet by mass balance using a net snow accumulation of 20 cm yr^{-1} and catchment basin areas predicted according to both the rigid bed and deformable sediment conditions suggested by glaciological analysis. An iceberg production rate of 3.88 × 10^{14} kg yr^{-1}
Table 1. Calculations of the Rates of Glacial North Atlantic Iceberg Production From Laurentide and Greenland Ice Sheets

<table>
<thead>
<tr>
<th>Catchment Basin/Ice Sheet</th>
<th>Basin Area, km²</th>
<th>Iceberg Production Rate, kg yr⁻¹</th>
<th>Total, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hudson Strait</td>
<td>2.13 × 10⁶</td>
<td>3.88 × 10¹⁴</td>
<td>52</td>
</tr>
<tr>
<td>Laurentian Channel</td>
<td>0.7 × 10⁶</td>
<td>1.27 × 10¹⁴</td>
<td>18</td>
</tr>
<tr>
<td>Greenland</td>
<td></td>
<td>2.25 × 10¹⁴</td>
<td>30</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>7.40 × 10¹⁴</td>
<td>100</td>
</tr>
</tbody>
</table>

Iceberg production from Laurentide Ice Sheet to the North Atlantic is partitioned into that which drain to Hudson Strait and to Laurentian Channel after Dowdeswell et al. [1995]. Net snow accumulation rate of 20 cm yr⁻¹ is assumed.

aAverage of Hudson Strait catchment basin areas assuming rigid bed (1.56 × 10⁸ km²) and assuming deformable sediments (2.7 × 10⁸ km²).

bFrom observations and mass balance calculation of modern Greenland iceberg production rate [Roe, 1980].

is assigned to Hudson Strait, which is 52% of the total annual iceberg production to the glacial North Atlantic, and 1.27 × 10¹⁴ kg yr⁻¹ is assigned to Laurentian Channel, which is 18%. The remaining 30% is from Greenland. The iceberg production rates from the Hudson Strait, Laurentian Channel, and Greenland are further partitioned into nine geographical locations in the model (Figure 2). The outlined iceberg production precludes any ablation of Laurentide Ice Sheet and meltwater removal of ice, where in reality ablation zones might have existed around the southern margin of the ice sheet and possibly at low altitudes to the north. Ablation zone around the southern margin would affect the Laurentian Channel, with the limiting case of the channel being completely drained by meltwater rather than glaciers (i.e., icebergs). To assess the sensitivity of model results to this uncertainty in ice sheet boundary condition, I run the model with and without iceberg production from the Laurentian Channel.

Icebergs enter the ocean at their source locations every month for the first 8 years, and the model continues to run until all icebergs melt. Monthly iceberg meltwater fluxes are computed when the model reaches steady state after the first 3 years. During steady state, when the total annual iceberg production roughly equals total removal by decay, the model drifts between 600 and 800 icebergs at any one time. In total, the model runs approximately 13 to 15 years and drifts 3456 icebergs. The computed IRD and iceberg meltwater fluxes from a 13 to 15-year run adequately represent the steady state glacial fluxes because the model's year-to-year variations in the computed fluxes are minimal when the model is steady. The model drifts only nontabular icebergs that range in size from small (75 × 10⁶ kg) to large (5500 × 10⁶ kg) as classified by Mountain [1980]. Glacial icebergs from northern sources may have been much larger like the modern Antarctic tabular icebergs, but I do not model tabular icebergs because physical properties and proportion of such icebergs are unknown. The neglect of larger tabular icebergs reduces the possibility of very long iceberg survival and drift, which would make the modeled IRD distribution conservative. The presence of extensive sea ice during the LGM (Figure 3) may also strengthen the model bias against longer iceberg drift, although this is not entirely clear. From a demonstrated statistical relationship between seasonal changes in sea ice extent and variation in iceberg num-

Figure 2. Location of iceberg sources and their relative contributions to the total annual glacial North Atlantic iceberg production assigned in the model. See Table 1. Following Matsumoto [1996], Greenland iceberg production does not add up to 30% of the total iceberg production because 40% of Greenland icebergs (i.e., 12% of the total glacial icebergs) produced in the northwest are shown by model results to completely melt before reaching the Labrador Sea and do not contribute to ice-rafted debris and iceberg meltwater fluxes to the North Atlantic. (Polar stereographic projection.)
bers off eastern North America, Marko et al. [1994] note that sea ice enhances iceberg survival and drift by preventing iceberg grounding and suppressing SSTs and wave erosion but that sea ice can significantly slow down iceberg movement by entrapment.

Experiments

The emphasis of this paper, as mentioned above, is on understanding the sensitivity of model results to model uncertainties and assumptions. The experiments therefore are designed accordingly.

I present model results from five experiments (Table 2). The control experiment uses glacial ocean current fields predicted by Seidov et al. [1996] and glacial wind fields predicted by Kutzbach and Guetter [1986], scales iceberg decay by CLIMAP SSTs, and models icebergs from all source locations. From this experiment, ice sheet boundary condition, iceberg decay formulation, wind fields, and ocean current fields are modified one at a time to assess their effect on model results. The ice sheet boundary condition is altered in the No Laurentian Icebergs experiment (NLI), which excludes all icebergs from the Laurentian Channel. The iceberg decay formulation is changed to a uniform $10^9$ shift in latitude in the Decay by $10^9$ Shift experiment (D10S). Modern wind fields by Trenberth et al. [1989] are used instead of glacial fields in the Modern Winds experiment (MW). Finally, glacial ocean currents are replaced by modern currents predicted by Toggweiler [1994] in the Modern Currents experiment (MC).

Iceberg Meltwater Flux

Average monthly meltwater flux to the glacial North Atlantic computed by experiments that modeled all glacial icebergs is approximately 20 mSv (1 millisilver- bubble = 1000 m$^3$ s$^{-1}$), roughly 5 times greater than that to the interglacial North Atlantic of approximately 4 mSv [Matsumoto, 1996] (Table 3). Experiment NLI (no icebergs from the Laurentian Channel) has an average monthly flux of 16.7 mSv, roughly 4 times the interglacial value.

Although the average monthly iceberg meltwater flux to the glacial North Atlantic is 4 to 5 times that to the interglacial North Atlantic, it is unclear from the modeling results whether the total freshwater flux (i.e., flux sum of iceberg meltwater, river runoff, and direct precipitation to the ocean) is appreciably different between glacial and interglacial climates. Presumably, most precipitation on continents is drained as river runoff during interglacial periods and by glaciers during glacial peri-

![Figure 3](image_url)

**Figure 3.** Position of "basic glacial" mode of IRD deposition from isotopic stage 4 [Ruddiman, 1977] and high-deposition band of Heinrich layer [Grousset et al., 1993]. Stage 4 IRD band shading enclose the sedimentation rate of 150 mg cm$^{-2}$ kyr$^{-1}$ and higher. Also shown are the CLIMAP [1981] reconstruction of the Last Glacial Maximum sea ice limit in February (labeled LGM2) and August (LGM8). (Oblique orthographic projection with standard latitude at 40° N and standard longitude at 40° W.)
Table 2. Boundary and Environmental Conditions for Experiments

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Currents</th>
<th>Iceberg Decay</th>
<th>Winds</th>
<th>Laurentian Icebergs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>LGM</td>
<td>CLIMAP\textsuperscript{a}</td>
<td>LGM</td>
<td>included</td>
</tr>
<tr>
<td>No Laurentian Icebergs (NL1)</td>
<td>LGM</td>
<td>CLIMAP\textsuperscript{a}</td>
<td>LGM</td>
<td>excluded</td>
</tr>
<tr>
<td>Decay by 10° Shift (D10S)</td>
<td>LGM</td>
<td>10° shift</td>
<td>LGM</td>
<td>included</td>
</tr>
<tr>
<td>Modern Winds (MW)</td>
<td>LGM</td>
<td>CLIMAP\textsuperscript{a}</td>
<td>Modern included</td>
<td></td>
</tr>
<tr>
<td>Modern Currents (MC)</td>
<td>Modern</td>
<td>CLIMAP\textsuperscript{a}</td>
<td>LGM</td>
<td>included</td>
</tr>
</tbody>
</table>

Last Glacial Maximum (LGM) ocean current fields are from Seidov et al. [1996], and modern ocean current fields are from Toggweiler [1994]. As explained in text, glacial iceberg melting rates are either scaled to Climate: Long Range Investigation, Mapping, and Prediction sea surface temperatures (CLIMAP SSTs) or shifted 10° latitude to south from modern iceberg melting rates. LGM surface wind fields are from Kutzbach and Guetter [1986], and modern surface wind fields are from Trenberth et al. [1989]. As explained in text, iceberg production from the Laurentian Channel is excluded in experiment NL1 to model the limiting case of ablation of southern margin of the Laurentide Ice Sheet.

\textsuperscript{a}Iceberg melting rate scaled by CLIMAP SSTs.

Changes in iceberg meltwater flux may be compensated by changes in river flux with no net change in the total freshwater flux. To address the total freshwater budget in the North Atlantic region, the entire regional hydrological cycle including the effect of ice sheet and vegetation on precipitation needs to be investigated. Since the thermohaline circulation is sensitive to surface salinity changes, for which the total freshwater flux is important, the computed iceberg meltwater flux alone is insufficient to speculate on the behavior of the thermohaline circulation. Nevertheless, since icebergs can deliver freshwater directly to sensitive convective regions of the thermohaline circulation, as opposed to rivers which discharge along the boundary, iceberg meltwater flux can possibly be a more potent perturbation on the circulation.

Experiment D10S, which uses modern iceberg decay rates shifted by 10° in latitude to the south, shows minimum iceberg meltwater flux of 7.5 mSv in March when low SSTs enable icebergs to avoid appreciable melting. D10S also shows the highest flux in September at around 40 mSv when icebergs decay most rapidly because of high SSTs during the summer. This temporal variation is a direct consequence of leaving intact the overall modern iceberg decay rates, which are higher during the summer than the winter. In all other experiments, this seasonality in meltwater flux is largely subdued because iceberg decay is scaled to CLIMAP LGM SSTs, for which only February and August reconstructions are available. In reality, there must have been a full seasonal cycle in glacial SSTs and sea ice coverage as suggested by the sea ice extent at both poles.

Table 3. Iceberg Meltwater Fluxes to the Glacial North Atlantic

<table>
<thead>
<tr>
<th>Month</th>
<th>Control</th>
<th>NL1</th>
<th>D10S</th>
<th>MW</th>
<th>MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>22.6</td>
<td>20.1</td>
<td>18.1</td>
<td>12.2</td>
<td>24.1</td>
</tr>
<tr>
<td>February</td>
<td>12.2</td>
<td>9.6</td>
<td>8.2</td>
<td>11.8</td>
<td>16.7</td>
</tr>
<tr>
<td>March</td>
<td>12.0</td>
<td>8.6</td>
<td>7.5</td>
<td>13.9</td>
<td>16.2</td>
</tr>
<tr>
<td>April</td>
<td>11.7</td>
<td>9.0</td>
<td>8.5</td>
<td>12.8</td>
<td>14.5</td>
</tr>
<tr>
<td>May</td>
<td>11.5</td>
<td>7.4</td>
<td>9.5</td>
<td>15.0</td>
<td>15.7</td>
</tr>
<tr>
<td>June</td>
<td>15.0</td>
<td>9.7</td>
<td>15.6</td>
<td>19.0</td>
<td>16.4</td>
</tr>
<tr>
<td>July</td>
<td>27.2</td>
<td>22.1</td>
<td>24.5</td>
<td>33.0</td>
<td>22.9</td>
</tr>
<tr>
<td>August</td>
<td>25.1</td>
<td>19.5</td>
<td>32.3</td>
<td>27.1</td>
<td>21.4</td>
</tr>
<tr>
<td>September</td>
<td>25.6</td>
<td>21.0</td>
<td>40.9</td>
<td>26.9</td>
<td>21.7</td>
</tr>
<tr>
<td>October</td>
<td>22.0</td>
<td>18.3</td>
<td>27.7</td>
<td>24.4</td>
<td>21.7</td>
</tr>
<tr>
<td>November</td>
<td>26.0</td>
<td>22.8</td>
<td>26.3</td>
<td>22.7</td>
<td>23.7</td>
</tr>
<tr>
<td>December</td>
<td>27.2</td>
<td>23.1</td>
<td>21.0</td>
<td>21.7</td>
<td>26.0</td>
</tr>
<tr>
<td>Average</td>
<td>19.9</td>
<td>16.7</td>
<td>20.1</td>
<td>20.0</td>
<td>20.1</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Flux values computed from model run years under steady state when iceberg addition to the glacial North Atlantic by iceberg calving roughly equals removal by decay.

\textsuperscript{b}One millisverdrup is 1000 m$^3$ s$^{-1}$. 
today that vary monthly. Such cycles in SSTs and sea ice coverage would naturally lead to changes in iceberg decay rates and iceberg meltwater flux over the year. Therefore this muting of seasonality in experiments using CLIMAP SST-scaled iceberg decay is rather unrealistic and thus so are these monthly fluxes.

**IRD Deposition**

Modeled IRD deposition rate is given in units of mg cm$^{-2}$ kyr$^{-1}$ following Ruddiman [1977], who demonstrated that the basic glacial mode of IRD deposition preferentially occurred in the latitudinal band between 40$^\circ$N and 55$^\circ$N with maximum accumulation trending about 50$^\circ$N (Figure 3). His basic glacial mode is averaged over a 10,000-year period from isotopic stage 4 between 80,000 and 70,000 years B.P. and represents an average of possibly various glacial IRD deposition patterns. A nearly identical IRD pattern from stage 2 between 25,000 and 13,000 years B.P. is also presented in the work of Ruddiman [1977] with the same maximum accumulation trend around 50$^\circ$N but with higher IRD input. He infers from the glacial mode IRD pattern that icebergs drifted southward along eastern North America in the Labrador Current, the western limb of North Atlantic subpolar cyclonic gyre, before turning eastward from around 55$^\circ$N and entering the high-deposition band, which extends east across the North Atlantic. More recently, Grousset et al. [1993] traced the last five Heinrich layers (H1 through H5) from the last glacial period across the open North Atlantic. They find that Heinrich layers extend eastward across the glacial North Atlantic roughly within the latitudinal band identified by Ruddiman [1977] with most debris accumulation at approximately 45$^\circ$N (Figure 3). Together, these results demonstrate that most IRD deposition during the last glacial period was confined in the North Atlantic to the north of 40$^\circ$N and south of 55$^\circ$N. Modeled results are compared with these observations; however, as mentioned above, the comparison may not be entirely appropriate because the conditions under which the observed IRD was deposited possibly differed from the LCM conditions under which the model is run.

The control experiment predicts an eastward extending lobe of high IRD deposition between latitudes 40$^\circ$N and 48$^\circ$N (Figure 4), agreeing roughly with maximum Heinrich layer band but south of maximum stage 4 IRD band. The lobe extends east-southeast into the open ocean, largely reflecting the prevailing ocean currents (Figure 1b). The maximum limit of the predicted IRD distribution, indicated by the 0 mg cm$^{-2}$ kyr$^{-1}$ contour, shows IRD reaching as far east as 26$^\circ$W longitude. This contrasts with 34$^\circ$W predicted under interglacial conditions [Matsumoto, 1996] and 30$^\circ$W observed by decades of regular monitoring by IIP [Vickerman and Baumer, 1996; D. Murphy, personal communication, 1995], although U.S. Naval Oceanographic Office [1968] notes some exceptional sightings east of 30$^\circ$W. To the south, the control experiment predicts glacial IRD to almost 37$^\circ$N latitude, while the predicted interglacial IRD extends only to 45$^\circ$N. These results show that indeed with CLIMAP SST-scaled iceberg decay, glacial icebergs have longer drift than modern icebergs as expected. The stage 4 and Heinrich IRD deposition patterns, however, were more expansive than that predicted by the control experiment, suggesting that the CLIMAP SST-scaled iceberg decay is still too high for glacial conditions. This underestimation is most likely due to assigning iceberg decay rates from modern sea ice covered regions to grid points where CLIMAP LGM SST indicates sea ice coverage. Sea ice covered regions in glacial climates were probably colder and more conducive to iceberg survival than the modern sea ice covered regions.

Experiment D10S, which uses an entirely different formulation of iceberg decay, also shows high IRD deposition band trending east-southeast (Figure 5), again reflecting the prevailing ocean currents. IRD deposition of D10S, however, is more expansive than that of the control experiment, indicating that iceberg decay formulation of D10S apparently results in slower decay and longer iceberg drifts. Like the control experiment, the position of predicted high IRD deposition lobe of D10S compares favorably with the observed pattern of Heinrich layer but is located south of stage 4 maximum deposition band.

The high IRD deposition lobe in the open ocean predicted by the control experiment and D10S is largely absent in experiment NLI, which excluded all icebergs from the Laurentian Channel (Figure 6). Most icebergs decay within 10$^\circ$ of the coast as indicated by the 100 and 1000 mg cm$^{-2}$ kyr$^{-1}$ contours. The 0 mg cm$^{-2}$ kyr$^{-1}$ contour, nevertheless, indicates the same east-southeast trend of IRD deposition. The absence of high-deposition lobe in the open ocean shows that ablation of the southern margin of Laurentide Ice Sheet is an important factor in determining the IRD deposition in the glacial North Atlantic. The observed high deposition of Heinrich and stage 4 IRD in the open ocean therefore suggests that the Laurentian Channel was an important source of icebergs during the times of observed deposition. However, the apparent absence of high deposition is partly an artifact of model assumption. The model assumes that the glacial and modern icebergs have the same debris content. If icebergs produced under glacial conditions had higher debris concentration, which is not unlikely, the model would predict proportionally more IRD deposition.

The apparent association between the prevailing ocean currents and IRD deposition is further exemplified in the IRD deposition pattern predicted by experiment...
MC (Figure 7), which used modern ocean current fields. The high IRD deposition lobe in the open ocean trends east in the mid 40°N with no apparent southward component. This trend is coherent with the strong eastward current in those latitudes (Figure 1a). The lobe reaches almost 30°W longitude as indicated by the 100 mg cm⁻² kyr⁻¹ contour, which is significantly more eastward than 37°W predicted by the control experiment. This is apparently due to the stronger eastward flow of the modern ocean current than the glacial flow (Figure 1b). Although not presented here, IRD deposition pattern from MC with no Laurentian Channel icebergs shows that the high IRD deposition trend is unchanged but with reduced expanse, much like the results from experiment NLI. Comparison of MC's predicted high IRD deposition band with the observed IRD deposition patterns shows the same result: the predicted band roughly coincides with the high Heinrich IRD deposition band but is offset to the south of stage 4 IRD maximum deposition band.

Finally, model sensitivity to the choice of wind fields is highlighted by experiment MW, which used modern instead of glacial winds (Figure 8). Compared to the control experiment, MW predicts a stronger eastward
IRD deposition as indicated by the 0 mg cm$^{-2}$ kyr$^{-1}$ contour, which extends almost to 16°W. The 100 and 1000 mg cm$^{-2}$ kyr$^{-1}$ contours also exhibit a strong eastward component although the trend is still more or less east-southeast, indicating the persistent dominance of the ocean currents. The more extensive eastward IRD deposition suggests faster iceberg movement, which is apparently due to the strong modern southwesterly winds (from SW to NE) in the open ocean (Figure 1c). While the northward component of the winds is largely negated by the southern component of the currents (Figure 1b), the eastward wind component is reinforced by current component in the same direction. This shows that the effect of winds on IRD distribution can be significant when winds act in concert with the currents; this effect is particularly accentuated in this experiment because the prevailing glacial winds in the control experiment over the open ocean were much weaker (Figure 1d). Like other experiments, MW predicts high IRD deposition in the latitudinal band of high Heinrich IRD deposition but to the south of stage 4 maximum IRD deposition band.

Conclusions

An iceberg drift and decay model was used to compute the IRD and iceberg meltwater flux to the glacial North Atlantic under steady state Greenland and Laurentide Ice Sheets. Because of a number of assumptions and uncertainties in the model construct and boundary conditions, emphasis was placed more on understanding the sensitivity of model results to such assumptions and uncertainties rather than "simulating" the glacial IRD distribution pattern. Therefore strong conclusions about the glacial conditions that relate to icebergs are not possible.

Average monthly iceberg meltwater flux to the glacial North Atlantic ranged approximately between 17 and 20 mSv depending on whether the icebergs from the Laurentian Channel was included or not. This meltwater flux range is roughly equivalent to 4 to 5 times that to the interglacial North Atlantic, but it is unclear from model results whether the total freshwater flux (i.e., cumulative flux of iceberg meltwater, river runoff, and direct precipitation to the ocean) is appreciably more during glacial than during interglacial conditions.

Sensitivity experiments showed that the first-order control on IRD distribution pattern is the prevailing ocean currents. Currents determined the overall pattern and the trend of high deposition. Winds are shown to affect IRD distribution significantly if strong winds share a directional component with the prevailing ocean currents. Formulation of iceberg decay directly affected iceberg survival and the expanse of IRD distribution. Iceberg decay scaled to CLIMAP SSTs underestimated the glacial iceberg decay and produced too limited an IRD distribution. An alternative formulation of glacial iceberg decay by a 10° latitudinal shift in modern iceberg decay rates predicted a more expansive distribution. Drainage of the southern margin of the Laurentide Ice Sheet through the Laurentian Channel by meltwater instead of glaciers essentially removed the high IRD deposition from the open ocean and confined much of the deposition close to land, although parameterizing an enhanced debris concentration in glacial icebergs would proportionally increase IRD deposition. Nevertheless, the observed high deposition of Heinrich and stage 4 IRD in the open ocean suggests that drainage by icebergs through the Laurentian Channel significantly contributed to the observed IRD deposition.

With the exception of the experiment which produced no high IRD deposition in the open ocean, all experiments predicted high IRD deposition that roughly coincided with the latitudinal band of high Heinrich IRD deposition at around 45°N. The "basic glacial" mode (stage 4) maximum IRD deposition, in contrast, is located farther to the north at around 50°N. If the ocean current and wind fields used in this study are assumed to reasonably encompass those conditions under which the basic glacial mode IRD was deposited, it is difficult to explain how icebergs could deliver IRD to those regions where IRD is found. In light of this, it is interesting to note that the basic glacial mode high IRD deposition band is almost entirely enclosed by the two extreme positions of CLIMAP reconstructed sea ice limit (Figure 3). The basic glacial mode high IRD deposition thus can be explained if a significant portion of those IRD was delivered by sea ice instead of icebergs. Alternatively, the differences between model and observed data might be explained by ocean currents significantly
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