An iceberg drift and decay model to compute the ice-rafted debris and iceberg meltwater flux: Application to the interglacial North Atlantic

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Abstract. An iceberg drift and decay model that computes the long-term ice-rafted debris (IRD) and iceberg meltwater flux over an entire ocean basin is presented. The model requires atmospheric and oceanic flow fields and has three main operations: iceberg drift, decay, and debris release. Using present atmospheric and oceanic flow fields in the North Atlantic, the model is able to reproduce modern iceberg drift paths and seasonal iceberg occurrences. Using the same flow fields, IRD and iceberg meltwater flux to the North Atlantic are computed. Core-top data do not preserve an adequate record of present-day IRD distribution on the ocean floor; thus modeled IRD results are compared with IRD results from marine isotopic stage 5e (the last interglacial), a period most similar to present interglacial conditions. Similarity between the modeled and observed IRD patterns confirms that present ocean surface conditions affecting iceberg drift and decay are similar to those of stage 5e. Detailed comparison reveals icebergs from stage 5e reaching as far east as 20°W, which is not reproduced by the model under existing oceanographic conditions. This discordance suggests that the 5e IRD data set includes deposits from times colder than today, either because of truly colder intervals in 5e or because of dating uncertainties in the data. Modeled meltwater flux to the North Atlantic exhibits large seasonal and spatial variations. Using results from a recent study of North Atlantic Deep Water (NADW) circulation sensitivity to freshwater forcing and assuming a steady Greenland ice volume, iceberg meltwater forcing is insufficient during interglacial conditions to produce even a partial NADW collapse.

Introduction

Recent studies of deep-sea sediments in the North Atlantic document cyclic ice-rafted debris (IRD) deposition, signifying multiple massive iceberg discharges, on millennial timescales and at times of major climate boundaries (e.g., isotopic stage shifts) during the last glacial cycle [Heinrich, 1988; Bond and Lotti, 1995]. Causal relationship between iceberg discharge and major climate shifts is still much in debate, but suggestions have been made that link the two via the North Atlantic conveyor [Broecker, 1994]. Heat release from the ocean surface that occurs during North Atlantic Deep Water (NADW) formation strongly influences the climate, especially in the high latitudes, and modeling studies demonstrate that changes in NADW production can be triggered by freshwater fluxes, possibly from iceberg melt. Though the link seems reasonable, questions remain as to the ability of icebergs to transport sufficient freshwater to weaken the conveyor.

Icebergs are important as transport agents for both IRD and freshwater. Pioneering work by Ruddiman [1977] and subsequent studies [e.g., Grouset et al., 1993; Dowdswell et al., 1995] have mapped past IRD distribution in the North Atlantic in such a manner as to allow inferences about iceberg sources and drift paths in the past. We understand modern iceberg behavior from observational studies mostly along the continental margins, where many shipping lanes and petroleum drilling platforms are located, and from a limited number of theoretical studies. Sighting of icebergs and iceberg tracking by the use of beacons transmitting to satellites provide direct evidence for the position and path of icebergs [e.g., U.S. Naval Oceanographic Office, 1968; Marko et al., 1982], while iceberg scour marks on continental shelves provide indirect evidence. Lewis and Woodworth-Lynas, 1990]. Observational studies of
icebergs, however, are difficult and often spatially limited because of their remote occurrences, large size, slow motion, and their largely underwater existence. Our understanding of modern icebergs therefore appears qualitative in nature, particularly away from the coast as the number of iceberg sightings and scour marks declines. Modern IRD distribution pattern in the North Atlantic is even less understood. Despite the large number of deep-sea sediment cores retrieved over the years, core-top data representing present-day IRD are rare or have not been studied over the entire ocean basin, and modern IRD distribution pattern is unavailable (G. Bond, personal communication, 1996; W. Ruddiman, personal communication, 1996). Without the knowledge of modern IRD distribution, the relationship between iceberg drift and decay at the surface and IRD deposition on the ocean floor is unclear. Most modeling studies of icebergs have fairly limited spatial coverage, with only a few degrees in latitude and longitude, and model runtimes are typically of the order of days to weeks [Markov et al., 1988]. Limited spatial and temporal extent render such models unsuited to study iceberg behavior over an entire ocean basin and complete life span of icebergs. From paleoclimatological perspectives, long-term iceberg behavior is perhaps most important, especially in relation to iceberg deterioration and its meltwater impact on NADW. Understanding the nature of meltwater flux is important in order to realistically parameterize freshwater flux in ocean general circulation models (GCMs) that include freshwater flux as model forcing.

In this paper, I present an iceberg drift and decay model used to investigate the long-term iceberg behavior over the entire North Atlantic, focusing on the IRD deposition pattern and iceberg meltwater flux. The model is applied to the interglacial North Atlantic by using the present atmospheric and oceanic surface flow fields. The model involves a few parameters poorly constrained by observations, so model results using various parameter values are compared to gain a sense of uncertainty in model results. Model results are also compared with modern iceberg drift and marine isotopic stage 5e IRD deposition pattern. Although modeled IRD deposition pattern should ideally be compared with modern IRD deposition pattern, modern IRD pattern is unavailable. Modeled IRD pattern is instead compared with that from stage 5e, a period most similar to the present interglacial conditions. The comparison is not entirely appropriate since the last and present interglacial are not the same, particularly because the modern environmental conditions may be partly anthropogenic; nevertheless, IRD distribution pattern from stage 5e is the best and only one available today for comparison with modeled IRD distribution pattern.

Model Description

The model consists of three routines to predict IRD and iceberg meltwater flux. First, it predicts iceberg drift as a function of four main forces described below. Second, it predicts iceberg melt flux based on an empirical relation between iceberg life expectancy and its environment. Third, it predicts IRD release to the ocean floor as a function of iceberg mass. Model domain is bounded by latitudes 40°N and 80°N and longitudes 180°W and 20°E, with 1° x 1° resolution.

In simulating interglacial conditions, I take the present northern hemisphere iceberg production rates and tidewater calving fronts as model boundary conditions (e.g., sources of iceberg drift trajectories). All icebergs in the model originate from Greenland, by far the largest iceberg producing in the northern hemisphere today, with total annual production of 2.25 x 10¹⁴ kg [Robe, 1980]. Other estimates of Greenland iceberg production are roughly equivalent, but the estimates are not entirely reliable because only about 45% of the total estimated iceberg production is based on observed calving front ice velocities and thickness [Roch, 1985]. All icebergs in the model are nontabular (Table 1), which is the characteristic type produced by Greenland tidewater glaciers [Kollmeyer, 1978; Napier, 1979]. Following field observations and mass balance calculations by Robe [1980], I assign 80% of the total iceberg production to west Greenland and 20% to east Greenland (Figure 1). However, for computational efficiency, I neglect all icebergs that originate from the far northern part of west Greenland (around Melville Bugt along Baffin Bay), amount-

| Table 1. Nontabular iceberg Characteristics from Mountain [1980] |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Size            | Mass, 10⁶ kg   | Aₐ, m²          | Aₐ Per Depth Layer, m³ |
|                 |                | 0-20 m          | 20-50 m          | 50-100 m        | 100-120 m       |
| Small           | 75              | 230             | 780              | 820             | 0               | 0               |
| Medium          | 900             | 910             | 1800             | 1900            | 2700            | 0               |
| Large           | 5500            | 200             | 3500             | 3750            | 5300            | 1400            |

As defined in the notation section, Aₐ is the cross-sectional area of iceberg above water. Aₐ is the submerged cross-sectional area, divided into four (i) layers, as described in text.
Iceberg Drift Routine

Iceberg drift is modeled dynamically using the method suggested by Mountain [1980], whose model is in operational use by the International Ice Patrol (IIP) to forecast and warn iceberg locations each spring to ships navigating in the northwestern North Atlantic. During weather conditions unfavorable for sighting icebergs, IIP uses real-time ocean current and wind data to model the drift of individual icebergs every 12 hours [Murphy and Anderson, 1986]. The drift routine of the model presented here is modified to drift multiple icebergs simultaneously over wide regions and many years using monthly climatology wind data [Trenberth, 1989] and annually averaged ocean current data [Toth, 1994], both wind and current data are generated by GCMs simulating present-day conditions. I use annually averaged ocean flow fields because seasonal changes in ocean flow fields are not large and I am interested in average interglacial iceberg behavior, particularly since modeled IRD results are compared with the stage 5e IRD distribution pattern by Ruddiman [1977], which is time-averaged over 10,000 years. I use monthly averaged winds because winds, unlike the ocean currents, change seasonally over larger spatial range, for the obvious reason that winds do not have confining lateral boundaries.

The model expresses four main forces that act on icebergs in equations of motion and solves them numerically to yield iceberg position and velocity. The four forces are water drag, wind drag, Coriolis force, and the gravitational force due to sea surface slope (i.e., the dynamic topography). The equations of motion are (see notation section for symbols)

\[
\frac{dx}{dt} = u
\]

\[
\frac{dy}{dt} = v
\]

\[
\frac{du}{dt} = -fv - fV_y + \frac{\frac{1}{2} \rho_w D_w A_1 W^2 \sin(\theta)}{M} + \frac{\frac{1}{2} \rho_w D_w A_1 |U_i - u| S_i}{M}
\]

\[
\frac{dv}{dt} = -fu - fU_x + \frac{\frac{1}{2} \rho_w D_w A_1 W^2 \cos(\theta)}{M} + \frac{\frac{1}{2} \rho_w D_w A_1 |V_i - v| S_i}{M}
\]

where \(x\) and \(y\) are Cartesian coordinates representing the east-west and north-south components of iceberg position, respectively, and \(u\) and \(v\) arc the same components of iceberg velocity. In the acceleration formulae...
(3) and (4), the first term is the Coriolis acceleration due to iceberg motion. The second term is that due to sea surface slope expressed as the negative of the associated Coriolis force on the geostrophic current which balances this slope. The third term is wind drag related quadratically to wind speed. The last and most important term is water drag. Since water velocity varies with depth, water drag has to be integrated over the entire submerged portion of the iceberg to obtain the true water drag. Because water velocities at only discrete depths are known, the model approximates the integration by dividing the water column into four layers (Table 1). Water drag in each of the four layers is computed separately and summed to yield the total water drag.

In reality, there are other forces, such as those from tidal and wave actions, that act on icebergs, but these forces are oscillatory or smaller in magnitude and are excluded from dynamical considerations. However, these and other subgrid-scale processes are represented as random forcing and are necessary to achieve a “spread” in iceberg drift and position. Without such forcing, model results show that icebergs tightly drift along the streamlines of ocean currents just along the coastline, regardless of the magnitude of drag coefficients. The drift of modern icebergs, however, is not restricted to the waters immediately adjacent to the coastline [U.S. Naval Oceanographic Office, 1988]. Random forcing is thus applied to icebergs, in addition to the four dynamic forces, with just enough magnitude to achieve the observed spread in iceberg drift and position.

The four formulas (1)-(4) constitute a complete initial value problem by specifying iceberg sources and is solved by a fourth-order Runge-Kutta method with an adaptive time step. Adaptive time step maintains as large a time step as possible while limiting the finite-difference error to a preset bound, ensuring efficient solution [Press et al., 1989]. Given the initial position and velocity \( (x, y, u, \text{ and } v) \) of icebergs, all four acceleration terms in formulae (3) and (4) are computed and summed to yield total acceleration. The initial velocity and total acceleration are stepped forward in time (i.e., multiplied by time step) to predict new iceberg position and velocity.

Iceberg parameters such as drag coefficients and the area of aerial and submerged portions of icebergs, on which winds and currents act separately, are difficult to obtain by observation [e.g., Napoleon, 1979]. For example, a number of investigators [e.g., Hanke and Smith, 1974; Dempster, 1973] towed icebergs to obtain the nondimensional water drag coefficient; their estimates range from 0.6 to 2.0. Russell et al. [1978] point out that high values of water drag coefficient must be used to predict iceberg drift under steady state conditions such as in this study. Therefore, I use 2.0, which is still within IIP’s allowable values (D. Murphy, personal communication, 1995). As for air drag coefficient, I use a value of 1.5 following IIP. Although not presented here, model runs using various values of water and air drag coefficients show that model results are rather insensitive to changes in drag coefficients: icebergs largely drift along ocean currents with some meandering induced by random forcing. Scale analysis of the four forces reveals that forces due to sea surface slope and Coriolis effect act in opposite directions and are largely similar in magnitudes, thus canceling each other to a large extent. Of the two remaining forces, water drag is typically an order of magnitude greater than air drag, and hence changes in the value of drag coefficients within their allowable ranges do not affect the relative magnitude of the two drag forces. I use iceberg characteristics (e.g., mass and size) compiled by IIP [Mountain, 1980] from a large number of iceberg observations (Table 1).

### Iceberg Decay Routine

Iceberg decay by melting is based on an empirical relation (Figure 2) between iceberg life expectancy in the Labrador Sea and Grand Banks and the iceberg’s ambient environment (i.e., sea surface temperature, air temperature, wave period and height, and wind speed) [Venkatesh and El-Tahan, 1988]. As El-Tahan et al. [1987] describe, a number of mechanisms, such as surface melting by solar radiation, erosion by waves, and basal melting by buoyancy convection, are involved in iceberg deterioration. All these mechanisms and ambient environmental conditions are expressed by the empirical relation:

\[
L = a M^b
\]

where \( L \) is the iceberg life expectancy in hours and \( a \) and \( b \) are constants which vary by month in the Labrador Sea and Grand Banks. Given iceberg size, position, and the time of year, the model computes the amount of iceberg decay in a given time span. A small iceberg will completely melt in less than 3 days during July to November in the Grand Banks area, and medium and large icebergs will melt in an order of weeks in the Labrador Sea in the same summer months. Constants \( a \) and \( b \) are determined empirically in the Labrador Sea and Grand Banks where the majority of icebergs are found today [Venkatesh and El-Tahan, 1988]. For regions outside the two regions where environmental data coverage is sparse and where a small portion of the total model icebergs are affected, I extrapolate the values for \( a \) and \( b \). When the constants are made very small, the model decays icebergs quickly and the maximal extent of icebergs is limited to coastal regions. In contrast, the model drifts icebergs far from the coast when the constants are larger. I therefore choose constants \( a \) and \( b \) so that the modeled iceberg positions on a monthly basis are close to what is observed today [U.S. Naval
Figure 2. Schematic representation of equation (5) that relates iceberg life expectancy (hours) and the time of year adapted from Venkatesh and El-Tahan [1988]. Icebergs survive the longest in March and the shortest in September.

Oceanographic Office, 1968] as a means to “tune” the model. Without empirically determined \( a \) and \( b \), this is a reasonable first-order estimation of the constants. As a general rule, I decrease the values southward and eastward in the North Atlantic to reflect the shorter iceberg life expectancies in those directions due to higher sea surface temperatures.

Icebergs are known to run aground where water is shallow and remain there until they deteriorate sufficiently and are dislodged. The model has no water depth parameter in its ocean domain and flags icebergs as grounded when they touch the coastline. The model reduces the mass of grounded icebergs by 15% and “places” them 0.5° away from the coast for further drifting. The amount of iceberg mass reduction and shift in position do not affect the overall model results significantly because calculations show that over 85% of icebergs never run aground in the model regardless of grounding treatment. Of those that do run aground, about half (5%) run aground repeatedly under the prescribed grounding treatment above, showing that icebergs affected seriously by the treatment are small in proportion. The number of repeatedly grounding (i.e., the seriously affected) icebergs decreases as shift in position is increased from 0.5° because icebergs are likely to be placed out of the environment whose forces pushed the icebergs on to the coast. The appropriate amount of shift in position cannot be determined systematically, but 0.5° represents roughly 50 km (depending on latitude) and seems reasonable to a first approximation. Perhaps a more conservative shift (i.e., less than 50 km) may be more appropriate since 50 km represents roughly 10 days of iceberg drift distance in typical ocean current speeds, a long distance for icebergs. Whether the appropriate amount of shift in position is much larger, say, a couple degrees or smaller, the uncertainty that arises from it becomes insignificant in the end because one or two degrees is minuscule compared with model results that are (ocean) basin-wide in scale.

IRD Deposition Routine

As with dynamic iceberg deterioration, it is not possible to model IRD deposition directly from ambient environmental conditions for two reasons. First, the deposition mechanisms are complicated; they include iceberg basal melting by buoyancy convection and iceberg stability (i.e., the tendency for the icebergs to tip over). Second, it requires parameters that are unavailable, such as the debris distribution within the iceberg that is related to the dynamic and thermodynamic states of parent tidewater glaciers [Dowdeswell and Murray, 1990]. Although Dowdeswell and Murray [1990] have attempted to model IRD sedimentation rates as a function of ambient conditions, their model is inappropriate here because it considers iceberg drift in one dimension only, whereas the model presented in this paper is two dimensional. Admittedly, their model is suited for simple, fjord-type environments where icebergs move directly down fjord and away from the calving front, and thus are unsuited when icebergs display complex two-dimensional drift patterns as they often do in reality and in this model.

I model IRD deposition by relating the proportion of IRD held by an iceberg to the proportion of its mass, that is,

\[
\frac{ID(t)}{ID_0} = \left( \frac{M(t)}{M_0} \right)^\beta
\]

(6)

where \( M(t) \) and \( M_0 \) are the iceberg masses at times \( t \) and 0, respectively, and \( ID(t) \) and \( ID_0 \) are the iceberg debris at times \( t \) and 0, respectively. Iceberg debris distribution and release is prescribed by a free parameter \( \beta \). The value of \( \beta \) must be greater than 1 to realistically prescribe iceberg debris distribution and release.

In a linear relationship (i.e., \( \beta = 1 \)), icebergs lose the same proportion of IRD as their masses, which implies that icebergs will continue to carry IRD proportional to their mass until they are completely melted. This implication contradicts the general notion that substantially deteriorated icebergs are virtually debris free. The physical interpretation of a linear relationship is an iceberg with uniformly distributed debris, and this also contradicts the observation that debris is concentrated in an “outer shell” of the iceberg. Because glaciers en-
train debris at the subglacial bed [e.g., Boulton, 1970; Alley and MacAyeal, 1994], debris is contained at the bottom of freshly calved icebergs. The debris at the bottom will rotate to the top and the sides as icebergs overturn in water, hence an outer shell. A natural consequence of this outer shell is that icebergs release much of their IRD early in their decay history because they melt from the outside inward [Dowdeswell et al., 1995]. Prescribing an early release of IRD in the model requires the value of $\beta$ to be greater than 1 (Figure 3). With $\beta > 1$, IRD release per unit change in iceberg mass is greater when iceberg mass is larger. The appropriate value for $\beta$ would differ for individual icebergs depending on the nature of their outer shell and decay history. Some kind of average value for $\beta$ can be estimated by running the model with various values for $\beta$ and determining which modeled IRD deposition pattern seems "right" when compared with the observed. I estimate the right value to be around 5; however, since this crude estimation involves much uncertainty, I present modeled IRD results from simulations using more extreme $\beta$ values 3 and 7. The purpose is to give a feel for the uncertainty, but as I will demonstrate below, conclusions are unaffected because they are drawn from robust features of the model (i.e., features insensitive to the choice of value for $\beta$).

In formula (6), $ID(t)$ is the desired unknown and $ID_0$ is the original debris content, assumed to be 0.001% of the original iceberg volume, a typical value observed in Baffin Island tidewater glaciers [Dowdeswell, 1986]. This value may not represent all icebergs in the North Atlantic because as stated above, the actual debris content varies from iceberg to iceberg depending on the thermal regime of the parent glacier that influences debris entrainment at the glacier bed [Dowdeswell and Murray, 1990]. Using a different value of the original debris content in the model will proportionally change the IRD flux calculations.

**Iceberg Drift Paths**

The model consistently drifts icebergs along ocean currents despite monthly changing wind forcing (Figure 4), corroborating the rule of thumb that water drag is the dominant force on icebergs. Icebergs from east Greenland source drift along the coastline southward in the East Greenland Current. On reaching the southern tip of Greenland, most icebergs turn west and then north, entering the Labrador Sea. These icebergs then make a gradual turn counterclockwise toward Hudson Strait, where they join icebergs from west Greenland. Together they drift southwest mostly along the North American coastline in the Labrador Current. At around 50°N, they make a sharp turn and head eastward into the open ocean. Although icebergs from far northern west Greenland are neglected in computing meltwater and IRD fluxes, separate model runs show that their drift is westward toward Baffin Island. These modeled drift paths compare remarkably well with today's observed iceberg sightings [e.g., Rohe, 1980], providing confidence in the model.

**Iceberg Meltwater Flux**

Meltwater fluxes are computed from steady state conditions, when total annual iceberg production roughly equals total removal by melting. The model reaches steady state in approximately 2 years. The maximum iceberg survival duration of 2 years compares favorably with modern observations that some icebergs, in much colder conditions than those considered in the model, can survive for several years [Fenko Newfoundland Limited, 1982]. Nontabular icebergs enter the waters at their sources every month for the first 8 years, and the model runs approximately 2 more years for a total of about 10 years, until all icebergs melt. Since the first and the last 2 years are not in steady state, meltwater fluxes are computed for the period from years 3 to 8, when meltwater flux is in steady state. During steady state conditions, the model drifts between 400 and 700 icebergs at any one time, obviously more during the
winter months and fewer during the summer months. In total, 3456 icebergs are modeled in a 10-year period.

Monthly meltwater fluxes are computed for the entire North Atlantic and the Labrador Sea (Table 2). These values represent the present ambient iceberg meltwater fluxes. As explained above, meltwater flux to the North Atlantic includes that to the Labrador Sea but not farther north in Baffin Bay. Flux to the Labrador Sea is defined as any meltwater in the region bounded by latitudes 54°N and 64°N and longitudes 63°W and 41°W.

Meltwater flux to the North Atlantic is minimum in February at $9.8 \times 10^{-4}$ sverdrup ($Sv = 10^6 \text{m}^3\text{s}^{-1}$) and maximum in September at $9.59 \times 10^{-3}$ Sv, a difference of a factor of 10. As expected, the timing of maximum flux occurs when icebergs have the highest melting rate, or the shortest life expectancy, which is in September. Following the same argument, the timing for minimum flux is expected in March, but the model predicts it to be in February. With a higher melting rate in February than in March, it appears that meltwater flux in February ought to be larger. The model predicts the opposite because it properly accounts for the number and location of icebergs, which are important because icebergs in different regions decay by differently prescribed melting rates. There simply are fewer icebergs in the warmer midlatitude waters to melt during February than in March because the previous melting season melted away many of the icebergs in the warmer waters. This demonstrates that iceberg melting rate alone cannot be used to predict meltwater flux.

Seasonal variation of the meltwater flux to the Labrador Sea mimics that to the North Atlantic, with maximum of $4.67 \times 10^{-3}$ Sv in September and minimum of $4.5 \times 10^{-4}$ Sv in February, again a difference of a factor of 10. This difference is preserved in the smaller Labrador Sea domain because the relative proportion of flux to the Labrador Sea is nearly constant at 50% (Table 2).

The spatial limit of any meltwater contribution varies seasonally (Figure 5) and follows directly from seasonal variation in iceberg life expectancy. Meltwater limit is most expansive in March when icebergs have the highest life expectancy and thus live the longest and drift the farthest; minimum limit occurs in September when the life expectancy is the lowest. Meltwater extent for other months lies between that for March and September. Monthly iceberg positions inferred from modeled
Meltwater flux to the Labrador Sea is any iceberg melt in the region bounded by latitudes 54°N and 64°N and longitudes 41°W and 63°W. Percent Labrador is the Labrador fraction of the total meltwater flux to the North Atlantic.

\[\text{Sverdrup} = 10^9 \text{ m}^3 \text{ s}^{-1}\]

The necessary increases in the Greenland iceberg production to alter the present NADW formation, 7.2 being the smallest increase, seems too large to realize under steady state Greenland ice volume. Only a waning, nonsteady state ice sheet characterized by surging glaciers seems capable of significantly increasing its iceberg production.

**IRD Deposition**

IRD deposition to the North Atlantic is modeled in the same simulation conditions that generated the meltwater flux, with 3456 total icebergs over a 10-year run period. For direct comparison with the observed IRD deposition pattern, the modeled IRD deposition is given in sedimentation rate with units of mg cm\(^{-2}\) ka\(^{-1}\) [Ruddiman, 1977]. Extrapolating results from a 10-year run to 1000 years is justified because in steady state, the year-to-year variations in IRD deposition are minimal. This is clear from the fact that icebergs largely drift along ocean currents, and the model uses annually averaged currents of modern North Atlantic that are time independent.

As stated above, I present modeled IRD results using two different values of \(\beta\) in formula (6) to give a sense of uncertainty that arises from different choices of value for \(\beta\) (Figures 6 and 7). Higher values of \(\beta\) prescribe most IRD release early in iceberg decay history, while lower values allow icebergs to retain their debris for a
longer decay history. Figure 6 represents IRD deposition rate pattern with \( \beta = 3 \). All three contour lines (0, 100, 1000 mg cm\(^{-2}\) ka\(^{-1}\)) are extended and pushed far from iceberg sources, as expected, because icebergs carry more debris until later in their decay history. In contrast, IRD deposition rate pattern with \( \beta = 7 \) (Figure 7) is described by the three contour lines closer to iceberg sources. Compared with Figure 6, the 100 and 1000 mg cm\(^{-2}\) ka\(^{-1}\) contour lines in Figure 7 have a much more limited extension southward and the 0 mg cm\(^{-2}\) ka\(^{-1}\) contour line has a more limited extension eastward around Grand Banks. Despite the differences in the spread of IRD contour lines as a consequence of different choices of \( \beta \) value, three features are common to both figures. The two modeled IRD deposition rate patterns both reflect iceberg drift paths, display prominent eastward extending lobes, and have the lobe extension limited to no more than 30°W. Increasing the value of \( \beta \) to more than 7 and decreasing the value to lower than 3 positions the contour lines closer and farther from iceberg sources, respectively, but the changes in model results do not negate the three common features. What value of \( \beta \) best describes true iceberg debris release cannot be determined systematically; however, this point is irrelevant in this paper because I will discuss and draw conclusions from the three features so as to eliminate uncertainties from the choice of \( \beta \) value.

The modeled IRD deposition rate patterns largely reflect iceberg drift paths, and the rates generally decrease with distance from iceberg sources. Drift paths rather than distance from sources seem more important in determining the deposition rate pattern. For example, the east coast of Canada has higher rates exceeding 1000 mg cm\(^{-2}\) ka\(^{-1}\) than in the middle of Labrador Sea, which is much closer to Greenland but has a lower rate of about 100 mg cm\(^{-2}\) ka\(^{-1}\).

The modeled IRD patterns display a prominent lobe that extends eastward along latitudes between 45°N and 51°N from the coast of North America out to about 30°W. Ruddiman [1977] also observes an eastward lobe in his mapped IRD deposition pattern from the last interglacial between 125,000 to 115,000 years B.P. (marine isotopic stage 5e), which he describes as “basic interglacial mode” (Figure 8). There are other similarities in the basic structure of the contour lines, such as the way they wrap around southern Greenland and push up north into the Labrador Sea. These gross similarities suggest that the oceanographic conditions at the
Figure 6. Modeled interglacial IRD sedimentation rates (mg cm$^{-2}$ ka$^{-1}$) using $\beta = 3$ in formula (6).

Figure 7. Modeled interglacial IRD sedimentation rates (mg cm$^{-2}$ ka$^{-1}$) using $\beta = 7$ in formula (6). Compared with Figure 6 which uses $\beta = 3$, this figure has all three contour lines (0, 100, and 1000 mg cm$^{-2}$ ka$^{-1}$) closer to iceberg sources because most iceberg debris was released early in iceberg decay history. Three features are common to both figures: modeled IRD deposition rate patterns reflect iceberg drift paths, display prominent eastward extending lobes, and have the lobe extension limited to no more than 30°W.
surface at stage 5c were similar to the existing conditions. However, closer examination of the observed and the modeled patterns reveals differences in detail. The observed eastward lobe, in contrast to the modeled, is much narrower and extends at a higher latitude at about 53°N to as far east as 20°W. Iceberg sightings made regularly during the past 2 decades by IIP show that icebergs under existing oceanographic conditions do not survive to even 30°W, although U.S. Naval Oceanographic Office [1968] indicates some exceptional sightings east of 30°W. Also, the frequency of iceberg sightings and reports between 45°N and 50°N predicts high IRD deposition rates between those latitudes [Vieckman and Baumer, 1995] (D. Murphy, personal communication, 1995). These recent observations thus support the modeled results.

The differences in IRD deposition pattern between the observed and the modeled suggest one or both of two things. First, the observed pattern described as basic interglacial mode is not entirely interglacial because the time constraint used to map the observed may not be tight. The wide application of stable-isotope chronology because popular after this early work on IRD by Ruddiman [1977], who notes that the establishment of chronology required large time interpolation between control levels at 125,000 and 82,000 years B.P. with possible errors of a few thousand years. Furthermore, bioturbation easily allows contamination from adjacent time intervals, and only a small amount of IRD can give a false glacial-like appearance (W. Ruddiman, personal communication, 1996). Although the effect of bioturbation on the observed IRD pattern may be important, I do not couple deep-sea sedimentation processes to the iceberg model. The subject of bioturbation is rich and complex, and it ought to be addressed fully in separate studies. Second, accepting the observed IRD pattern as basically interglacial, the generally warm 10,000-year period had oceanographic conditions similar to today’s for the most part, as reported by McManus et al. [1994] but was punctuated by conditions that enabled icebergs to drift as far east as 20°W. The two conditions that would allow such long iceberg drifts are increased surface current speed and lower ocean surface temperatures. Of the two, faster surface current is improbable because although it would drift icebergs faster, it requires higher surface wind speeds. Higher surface wind speeds enhance iceberg disintegration due to increased wave erosion, which is the major iceberg deterioration mechanism [El-Tahan et al., 1987]. Therefore the two effects of higher wind speeds on long iceberg drifts are mutually canceling although the relative magnitude of the two effects cannot be quantified. The more plausible condition that allows long iceberg drifts is lower ocean surface temperatures that enhance iceberg sur-
vivability. Temperatures must be significantly lower, especially during the summer months, because icebergs need to survive at least three summers in the midlatitudes to reach 20°W with their typical speeds. A likely mechanism that lowers ocean surface temperatures is southerly migration of the polar front; however, there is no evidence for such a migration during the last interglacial from two eastern North Atlantic cores [McManus et al., 1994]. The spatial coverage of the study by McManus et al. [1994] seems limited though, and changing positions of the polar front during the last interglacial should not be discounted. In fact, recent evidence for "cold snaps" accompanied by ice-rafting events in the vicinity of Iceland during the Holocene [Bond, 1995] raises the possibility that similar cold snaps occurred during stage 5e and other warm periods. It is not possible to resolve in this paper whether the observed IRD pattern results from genuine differences between present and stage 5e ocean conditions (i.e., cold snaps during stage 5e) or inaccurate chronology. Both factors may well have contributed to the observed IRD pattern.

Another difference between the observed and the modeled IRD deposition pattern is the spatial gradient of deposition rates. The observed pattern is composed of widely spaced contour lines with values 50, 100, and 150 mg cm⁻² ka⁻¹, indicating a low gradient. In contrast, the modeled pattern has a much higher gradient, with contour lines from 0 to 1000 mg cm⁻² ka⁻¹ more tightly spaced. Although slightly lower gradients can be modeled by modifying β in formula (6) (i.e., iceberg debris distribution), they are not lowered nearly as much as the observed. Furthermore, it is not clear what lower gradients would signify physically. In contrast, a strong gradient in IRD deposition rates is a natural consequence of iceberg debris distribution and drift. By considering the debris distribution within icebergs and how icebergs melt, I arrived at the conclusion above that icebergs drop IRD early in their decay history (see Figure 3). Since icebergs release much of their debris early in their decay history (i.e., near their parent glaciers) and very little later (i.e., far from their parent glaciers after drifting large distances), a strong spatial gradient with distance from iceberg source is expected. Dowdeswell et al. [1995] report just such a case: a strong decay eastward of the thickness of Heinrich layers H1 and H2 mapped from more than 50 North Atlantic cores. Without a physically sensible explanation for the observed low gradient in IRD deposition rates, I again raise the possibility that the observed pattern is contaminated with IRD from adjacent time intervals.

Conclusion

Iceberg drift, melt, and IRD release were modeled using modern atmospheric and oceanic surface conditions in order to generate meltwater and IRD fluxes to the North Atlantic. Assuming that today’s conditions are similar to the last interglacial, results were compared with observations from both the present (in case of iceberg positions and drift paths) and the last interglacial (IRD deposition patterns), and inferences on the past climatic conditions are made as they relate to icebergs. Modern IRD distribution pattern would be better suited for comparison with the modeled IRD results, but a modern pattern has not been mapped.

The model involves a number of parameters poorly constrained by observations, so an attempt has been made to vary these parameters within the range of their possible variability or to study them by other means to assess the uncertainties in model results. Also, to diminish the influence of uncertainties caused by error in the choices of parameters, conclusions are drawn from robust features of the model.

Close similarities between the modeled iceberg drift paths and those observed today validate the drift routine of the model. Icebergs consistently drift along ocean currents even when the values of air and water drag coefficients were varied, confirming that water drag is the most important force on icebergs. Melting routine was "tuned" to present conditions by adjusting constants a and b in formula (5). The close correspondence of the modeled drift paths and the modeled IRD deposition pattern indicates that the IRD pattern seen in the geologic record primarily reflects drift paths. The distance from iceberg sources is reflected secondarily in the IRD deposition pattern.

Iceberg debris release routine of the model contains a free parameter β. Robust features from model runs with two very different values of β are compared with IRD deposition pattern observed from the last interglacial during stage 5e. The gross similarity between the modeled and observed IRD patterns indicates that the surface conditions during marine isotopic stage 5e were largely similar to the present. However, the observed IRD deposition as far east as 20°W suggests either that colder surface conditions punctuated the generally warm North Atlantic during stage 5e or that non-5e sediments were included in the "5e" data set owing to dating errors in the data set.

The modeled monthly meltwater fluxes to the North Atlantic exhibit large seasonal and spatial variations. The averaged monthly flux to the North Atlantic is $4.17 \times 10^{-3}$ Sv with variations of order 10 between the maximum in September and minimum in February. The Labrador Sea, a subregion of the North Atlantic, receives an averaged monthly flux of $2.09 \times 10^{-3}$ Sv, which is about half the flux to the North Atlantic. If iceberg meltwater is indeed the source of freshwater that shuts down the North Atlantic conveyor and triggers climate change as suggested by Broecker [1994], substantially more meltwater flux than that modeled for the present is necessary. In climate and ice conditions
similar to the modern, the necessary increase in iceberg meltwater flux can be achieved only under a rapidly warming Greenland ice sheet. A waning ice sheet may, of course, increase meltwater runoff directly instead of iceberg calving, thereby shutting down deepwater formation.

A natural extension of this work is to model the IRD and meltwater fluxes under glacial conditions. Since Heinrich and other ice-rafting events occurred during the last glaciation, it is important to understand the role and behavior of icebergs under glacial conditions. Modeling icebergs under glacial conditions requires glacial surface winds and ocean currents, which must inevitably come from GCM simulations. Glacial flow fields are obviously much less reliable than the modern flow fields used in this paper, but modeled results can be compared with mapped IRD distributions from glacial North Atlantic [e.g., Grousset et al., 1993; Dowdeswell et al., 1995] for validity.

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