

University of New Hampshire
University of New Hampshire Scholars' Repository

Center for Coastal and Ocean Mapping

Center for Coastal and Ocean Mapping

2003

The Grounding of an Ice Shelf in the Central Arctic Ocean: A Modeling Experiment

Martin Jakobsson

University of New Hampshire, Durham


M Siegert

University of Bristol, England

Mark Paton

Interactive Visualization Systems

Follow this and additional works at: <https://scholars.unh.edu/ccom>

 Part of the [Computer Sciences Commons](#), and the [Oceanography and Atmospheric Sciences and Meteorology Commons](#)

Recommended Citation

Jakobsson, Martin; Siegert, M; and Paton, Mark, "The Grounding of an Ice Shelf in the Central Arctic Ocean: A Modeling Experiment" (2003). *International Conference on Arctic Margins*. 286.

<https://scholars.unh.edu/ccom/286>

This Conference Proceeding is brought to you for free and open access by the Center for Coastal and Ocean Mapping at University of New Hampshire Scholars' Repository. It has been accepted for inclusion in Center for Coastal and Ocean Mapping by an authorized administrator of University of New Hampshire Scholars' Repository. For more information, please contact nicole.hentz@unh.edu.

IS GROUNDING OF AN ICE SHELF POSSIBLE IN THE CENTRAL ARCTIC OCEAN? A MODELING EXPERIMENT

Martin Jakobsson*, Department of Geology and Geochemistry, Stockholm University, Sweden

Martin.jakobsson@geo.su.se

Martin J. Siegert, Bristol Glaciology Centre, School of Geographical Sciences, University of Bristol, UK

Mark Paton, Interactive Visualization Systems (IVS), New Brunswick, Canada

*previous affiliation: Center for Coastal and Ocean Mapping/Joint Hydrographic Center, University of New Hampshire, USA

ABSTRACT

A numerical ice sheet model was used in a first test towards evaluating the hypothesis that, during a period of large-scale glaciation, an ice shelf emanating from the Barents/Kara Seas grounded across parts of the Lomonosov Ridge to a depth of around 1000 m below present sea level (Jakobsson, 1999; Polyak et al., 2001). Despite that we not include complex ice shelf physics or grounding line mechanics in our model and treat the process of marine melting in a simple manner, our experiments are the necessary first steps toward providing a comprehensive reconstruction of the former ice-sheet/ice-shelf system in the Arctic Ocean. A series of model runs was performed where ice shelf mass balance and ice shelf strain per unit time (strain rate) were adjusted. The mass balance and shelf ice strain rate are the key model parameters that govern the flux of ice into the Arctic Ocean. Grounding on the Lomonosov Ridge was not modeled when the ice shelf strain rate was 0.005 year^{-1} (i.e. a free flowing ice shelf). Even with low rates ($<10 \text{ cm/year}$) of basal melting, the ice shelf thickness was always less than 100 m over the central part of the ridge. Our experiment suggests that grounding on the Lomonosov Ridge by a free-flowing ice shelf is not possible. When the strain rate in the shelf ice was reduced to zero, however, the shelf thickness increased substantially. Such conditions are likely only to have occurred during periods of large-scale glaciation if substantial stagnant and thickened sea ice was present in the ocean, buttressing the ice shelf flowing from the Barents Sea. A comprehensive study using a coupled ice-sheet/shelf/sea-ice model would build on these preliminary results and have the potential to further constrain the history of circum-Arctic Ocean ice sheets.

INTRODUCTION

The extent of Pleistocene glaciations in the high Arctic and Arctic Ocean is a widely discussed and unresolved problem. The notion of a former huge Arctic Ocean

floating ice shelf was first developed by Mercer (1970), who pointed out the similarity in physiographic setting between the present-day Arctic and West Antarctica. However, for the late Weichselian the hypothesis of a huge pan Arctic ice sheet has been disproved through recent field investigations within the European Science Foundation program QUEEN (QUaternary Environments of the Eurasian North) (Svendsen *et al.*, 1999; 2004). Such a glacial scenario remains, nevertheless, at least possible for pre-Weichselian marine glaciations, and marine geophysical mapping during recent years has indeed revealed glacial features at substantial water depths in the Arctic Ocean.

Survey of the Lomonosov Ridge crest in the central Arctic Ocean was carried out by deploying a chirp sonar subbottom profiler from the Swedish icebreaker *Oden* (Jakobsson, 1999). The high-resolution subbottom stratigraphic images reveal large-scale erosion down to a depth of the ridge crest of 1000 m below present sea level (Figs. 1 and 2). Ice grounding was proposed as one possible explanation for this erosion but the data were not conclusive. The hypothesis for ice-grounding on the Lomonosov Ridge was, however, later supported by side-scan sonar and additional chirp sonar data collected in 1999 during the SCICEX expedition onboard USS *Hawbill* (Polyak et al., 2001). These data revealed glacial fluting at the deepest eroded areas down to about 1000 m water depth and subparallel scours from 950 m depth to the shallowest parts of the ridge crest. The directions of the mapped glacial features and the re-deposition of eroded material on the Amerasian side of the ridge indicate ice flow from the Eurasian Basin across the ridge (Polyak et al., 2001) (Fig. 2). This interpretation is supported by sea-floor sediment cores, which show that the source of the material derives from the Barents-Kara Sea region (Spielhagen et al., 1997; 2004). In addition, sediment core studies reveal that this erosion took place during Marine Isotope Stage (MIS) 6 (Jakobsson et al., 2001).

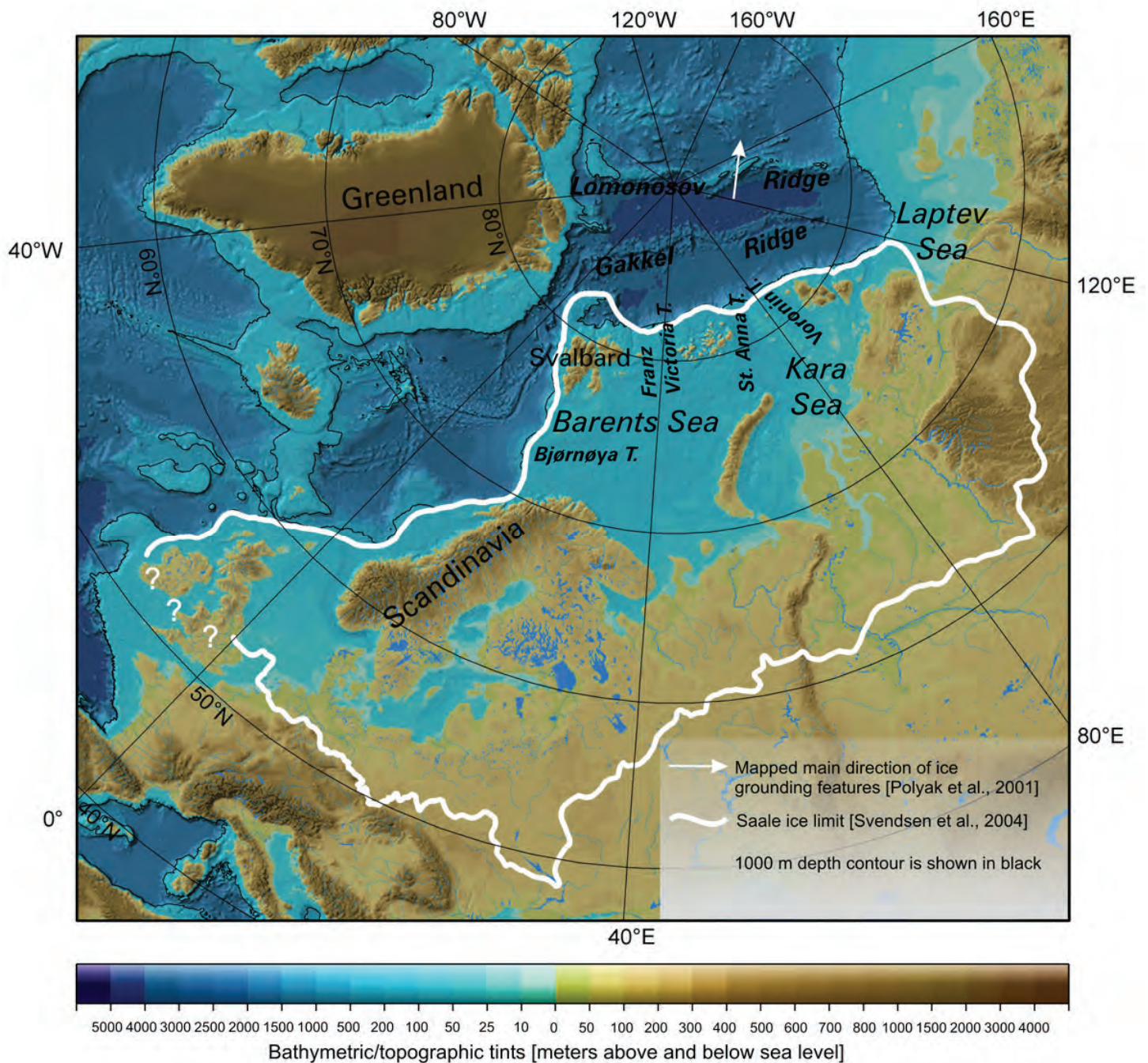


Figure 1. Map showing the bathymetry of the Arctic Ocean, the maximum extent of the Saale ice sheet (Svendsen et al., 2004), and the main direction of ice scour features on the Lomonosov Ridge (Polyak et al., 2001).

Glacial geological evidence strongly suggests that the Late Saalian (MIS 6) ice sheet margin reached the shelf break of the Barents-Kara Sea (Mangerud et al., 1998; Knies et al., 2001). This glacial scenario leads to two hypotheses about the causes of ice erosional features on the Lomonosov Ridge. One is the grounding of a floating ice shelf and the other is the scouring from large deep icebergs. The former could either imply a huge continuous floating ice shelf covering the entire Arctic Ocean, analogous to the

hypothesis of Mercer (1970), or an ice shelf emanating from the Barents/Kara Seas. The latter explanation requires the Late Saalian Barents-Kara Ice Sheet to produce huge deep icebergs that drifted within the permanent Arctic sea ice toward the Lomonosov Ridge crest, perhaps clustered together in an armada of icebergs as proposed by Kristoffersen et al. (2004). The St Anna Trough is the most prominent glacial trough on the Barents-Kara Sea margin and a likely source for the large iceberg during Pleistocene glaciations. Support

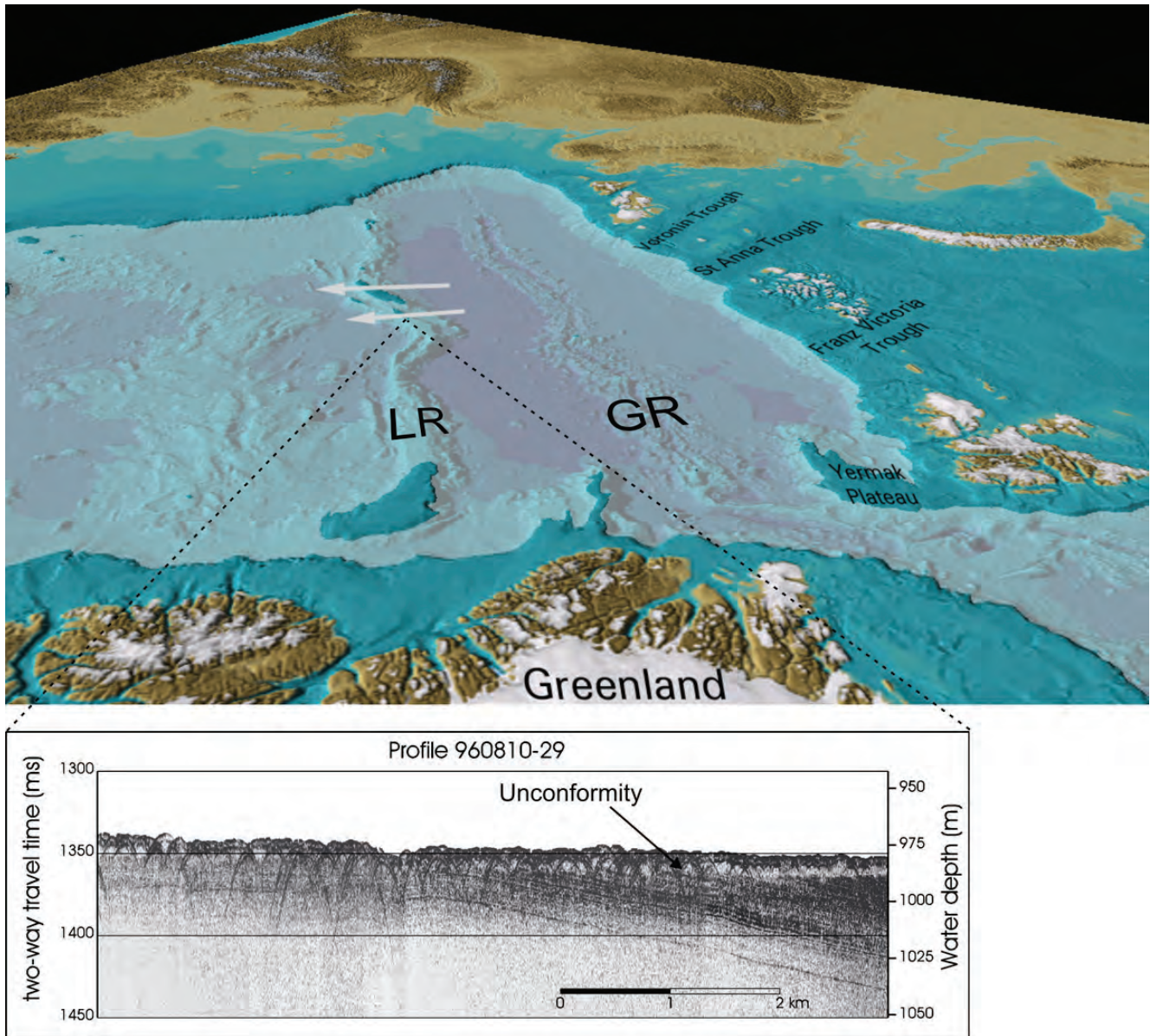


Figure 2. Major erosion of the Lomonosov Ridge crest above 1000 m present water depth is clearly revealed by a prominent unconformity in Profile 960810-29 acquired using chirp sonar during the Arctic Ocean 96 expedition with icebreaker Oden (Jakobsson, 1999). The white arrows indicate the directions of mapped ice scours from the SCICEX data (Polyak et al., 2001). A white semitransparent plane has been inserted at 1000 m below present sea level to emphasize the areas of the Lomonosov Ridge that are shallower than 1000 m. LR=Lomonosov Ridge, GR=Gakkel Ridge.

for the iceberg hypothesis may be the discovery of deep iceberg ploughmarks on the Yermak Plateau that are mapped to more than 850 m below the present sea level (Vogt et al., 1994).

One conclusion of the QUEEN project was that the Saalian ice sheet was far larger than those of the Weichselian (Svendsen et al., 2004) (Fig. 1). The grounded margin of this ice mass would have reached the continental shelf break of the Barents/Kara Seas, within bathymetric troughs (i.e. Voronin, St Anna,

Franz Victoria, and Bjørnøya Troughs), at depths of several hundred meters below sea level.

Although the idea of a thick Arctic Ocean ice shelf has been discussed by several authors (e.g. Hughes et al., 1977; Grosswald, 1980; Grosswald and Hughes, 1999), the conditions that permit ice grounding of the Lomonosov Ridge have not been quantified. In this paper we model the growth of an ice shelf within the Arctic Ocean, emanating from the Eurasian ice sheet during a phase of large-scale glaciation. In doing so we

provide an assessment of the gross conditions needed to ground ice in the central Arctic Ocean by an ice shelf fed from the Barents-Kara Seas. This experiment constitutes a first step in a more comprehensive evaluation of the former ice-sheet/ice-shelf system in the Arctic Ocean. We take a simple approach where the complex ice shelf dynamics and grounding line mechanics not are included. Such an approach allows us to undertake a sensitivity analysis of the problem, in a way not possible with a complex coupled model. In this way we are able to explore a full range of possible situations, the result of which will guide future modeling investigations over the next few years.

ICE SHEET MODEL

Numerical ice sheet modeling is a well-established tool for constraining the large-scale flow and form of ice sheets with well-understood empirical laws. We use a numerical model that has been used previously to model the Eurasian ice sheet during the last glaciation (Siegert and Dowdeswell, 1995; Siegert et al., 1999). Brief details of the model are qualitatively outlined below and we refer to Siegert and Dowdeswell (1995) and Siegert et al. (1999) for a more detailed description of the numerical model.

The growth of glacier ice is modeled over a regular grid of bathymetry and topography. This base data set was prepared from the International Bathymetric Chart of the Arctic Ocean (IBCAO) (Jakobsson et al., 2000, version 1.0) and the Global Seafloor Topography from satellite altimetry and ship soundings (Smith and Sandwell, 1997, version 8.2). The latter data set was used in the areas included in the model below 64°N, which is south of the IBCAO coverage. Both these data sets have derived the land topography of the Eurasian continent from GTOP030 (U.S. Geological Survey, 1997). A grid with 20 × 20 km cell spacing was prepared on a Lambert equal area projection (Projection center 90°N, central meridian 44°E) by sub-sampling the original re-projected data points from the input databases using a nearest neighbor algorithm.

The numerical ice-sheet model is based upon the continuity equation for ice (Mahaffy, 1976), where the time-dependent change in the ice thickness of a model grid cell is associated with the specific net ice mass budget of that particular cell. The net flux of ice from a given model grid cell is function of ice thickness and ice velocity in that cell and its neighbouring cells. The ice mass balance is controlling the ice thickness. Mass balance of an ice sheet is defined as the difference between the mass gained by snow accumulation and that lost by ice ablation and calving of icebergs. In order to make an ice shelf grow out into the Arctic

Ocean we removed the model iceberg calving function and instead allowed the ice to flow out off the shelf edge and into the ocean.

The ice shelf model is simple. The velocity of floating ice is determined by:

$$u_f = u_{f0} + \Delta x \cdot \varepsilon_s, \quad (1)$$

where u_f is the velocity of floating ice, u_{f0} is the velocity of ice coming into the cell of floating ice, Δx is the grid cell spacing (20 km) and ε_s is the strain rate of the ice shelf, which is varied between 0.005 and 0.000 year⁻¹ (Table 1). The strain rate is the rate at which deformation of the ice shelf occurs. The ice shelf model can be understood by considering that a freely flowing ice shelf is likely to have a strain rate around 0.005 year⁻¹ (Payne et al., 1989). Thus, we model both a freely flowing ice shelf, and one in which no acceleration can take place (when the strain rate is zero). The rationale for the latter experiment is that

Table 1. Numerical ice sheet modeling strategy and boundary conditions.

Model experiment #	Rate of marine melting (cm/year)	Ice surface accumulation over shelf	Strain Rate (year ⁻¹)	Grounded ice in the Arctic Ocean?
1	10	N	0.005	N
2	30	N	0.005	N
3	50	N	0.005	N
4	50	Y	0.005	N
5	80	Y	0.005	N
6	50	N	0.0	Yermak (10 kyr), Gakkel (17.4 kyr)
7	50	Y	0.0	Yermak (6 kyr), Gakkel (11 kyr), Morris Jessup Rise (12.2 kyr), Lomonosov W (12.8 kyr), Lomonosov E (15.2 kyr)
8	80	Y	0.0	Yermak (10 kyr), Gakkel (18.8 kyr)
9	100	Y	0.0	Yermak Plateau only (14.2 kyr)

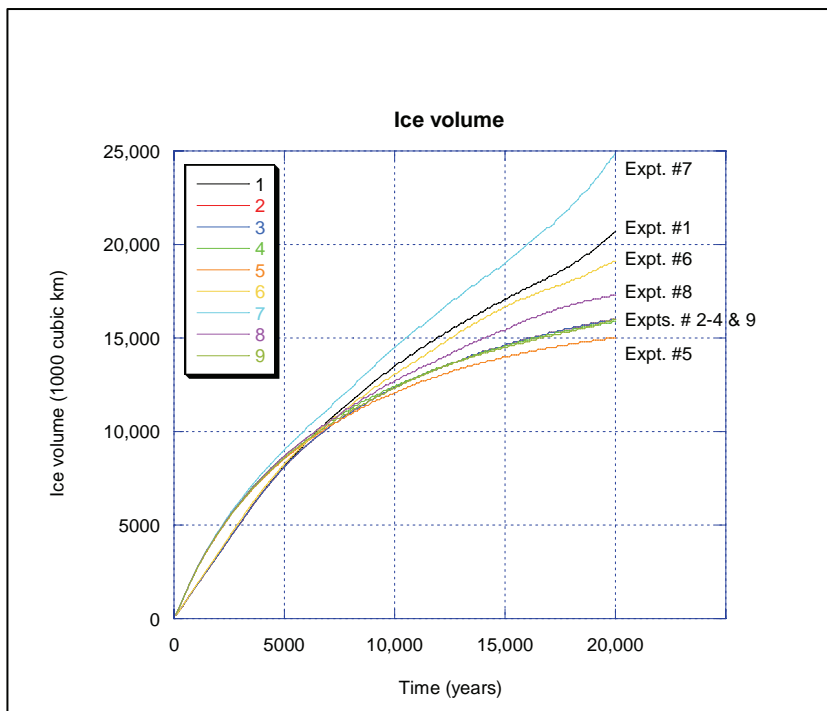


Figure 3. Ice sheet volume with time for experiments 1-9 (Table 1). Note that in experiments # 1, 6 and 7, the rate of change of ice volume increases with time at 20,000 years, due to the unstable form of the ice sheet modeled at this time.

increased flow rates are curtailed by a counter force, which could come from thick sea-ice acting against the terminus of the ice shelf.

It should be noted that the model contains no grounding line physics. It simply switches between grounded ice and ice shelf flow between cells of grounded and floating ice. Although this model is simple it is adequate for the purpose of this investigation, to assess the gross-conditions required for a thick ice shelf to form within the Arctic Ocean.

Iceberg calving is modeled using a depth-related function, which can describe the rate of icebergs calved from grounded margins (Pelto and Warren, 1991). This treatment is applied only to the western margin of the ice sheet. In all experiments iceberg calving was not allowed within the Arctic Ocean.

The included ice shelf model has a very simple marine melting function, which is an over simplification of the ocean/ice conditions expected in a complex oceanographic environment such as the Arctic Ocean. However, full quantification of the problem involves the use of coupled ocean/ice sheet models and this is far beyond the scope of our first test, but will be in further experiments, as mentioned above. The degree of ice shelf basal melting is difficult to assess for glacial periods in the Arctic Ocean due to the poorly

known oceanographic conditions. In this paper we force the basal melting of the ice shelf floating into the Arctic Ocean at a constant value. This value is varied within our sensitivity tests (Table 1). The surface accumulation of ice was included following the ice-sheet/AGCM model inter-comparison work of Siegert and Marsiat (2001). This accumulation distribution is that required to form a Late Weichselian style ice sheet across the Eurasian Arctic.

We experiment with two modes of ice shelf surface accumulation: one in which no accumulation takes place (so that the effects of ice flow and basal melting can be assessed) and one in which accumulation is retained in the model, following Siegert and Marsiat (2001).

EXPERIMENTAL DESIGN

In order to establish the likelihood of an Arctic Ocean ice shelf supplied exclusively from the Eurasian ice sheet, numerical model experiments were undertaken with a variety of oceanographic and climate boundary conditions. The model was run for a maximum of 20,000 years (starting at zero with no ice) assuming constant environmental forcing. Table 1 shows the parameters used for each of the model runs discussed in Section 6.

RESULTS

Of the many experiments undertaken we have chosen to discuss nine (Table 1). These examples display the full range of results that were produced in our investigation. For each of the nine experiments the ice sheet volume through time is provided in Figure 3.

Experiment #1. 10 cm/year melting, zero ice shelf accumulation. (Figs. 4 a, b, c, d): 1800, 2800, 3800 and 4200 years

The first thing to note about this experiment is that the velocity field starts to become ‘unstable’ (that is, the Arctic Ocean basin fills with ice, which results in the model miscalculating the ice shelf velocity) after about 4200 years. Prior to this, however, the model produced some interesting results (Fig. 4). An ice shelf readily formed within the Arctic Ocean as ice growth took place in the Barents Sea. Major outlet drainage pathways within the St. Anna and Franz Victoria Troughs were the main suppliers of ice to this ice shelf.

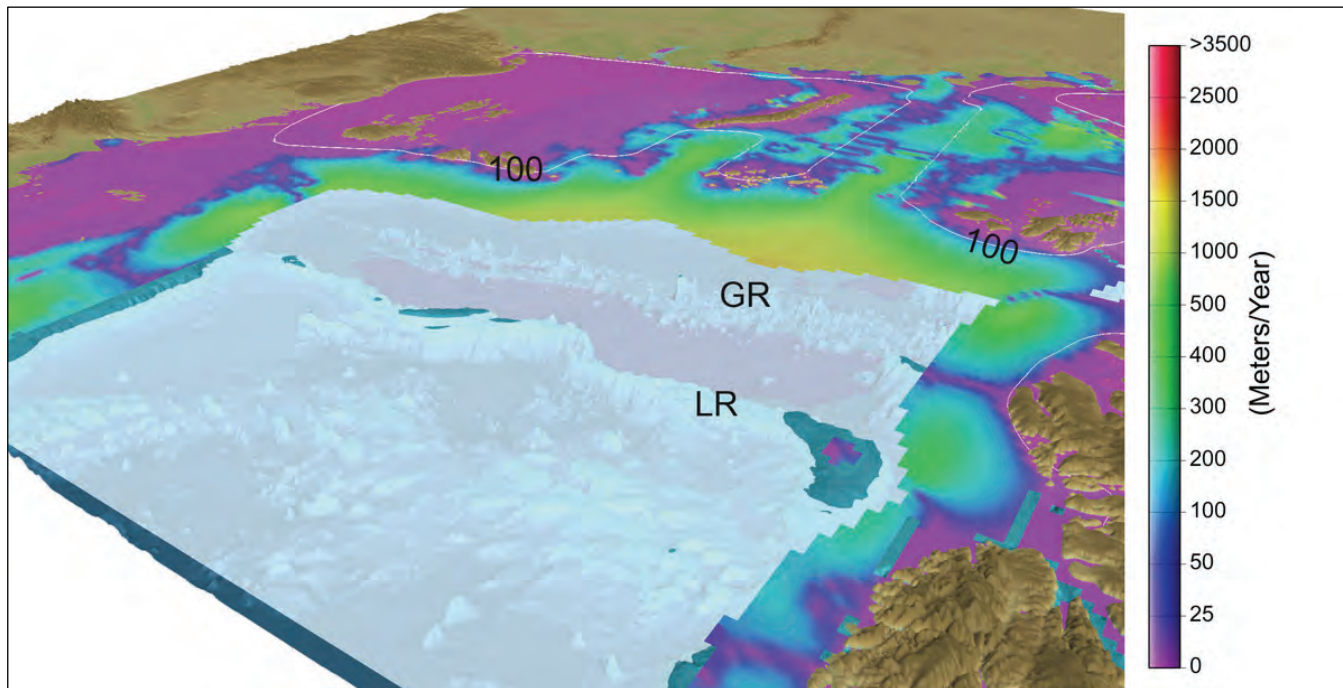


Figure 4a. 1800 year time snapshot from experiment #1, 10 cm/year marine melting, zero ice shelf accumulation. The modeled ice is shown with a color table representing ice velocity in meters/year. The white contours are ice thickness in meters. As in figure 2, a white semitransparent plane has been inserted at 1000 m below present sea level to emphasize the areas of the Lomonosov Ridge that are shallower than 1000 m. LR=Lomonosov Ridge, GK=Gakkel Ridge.

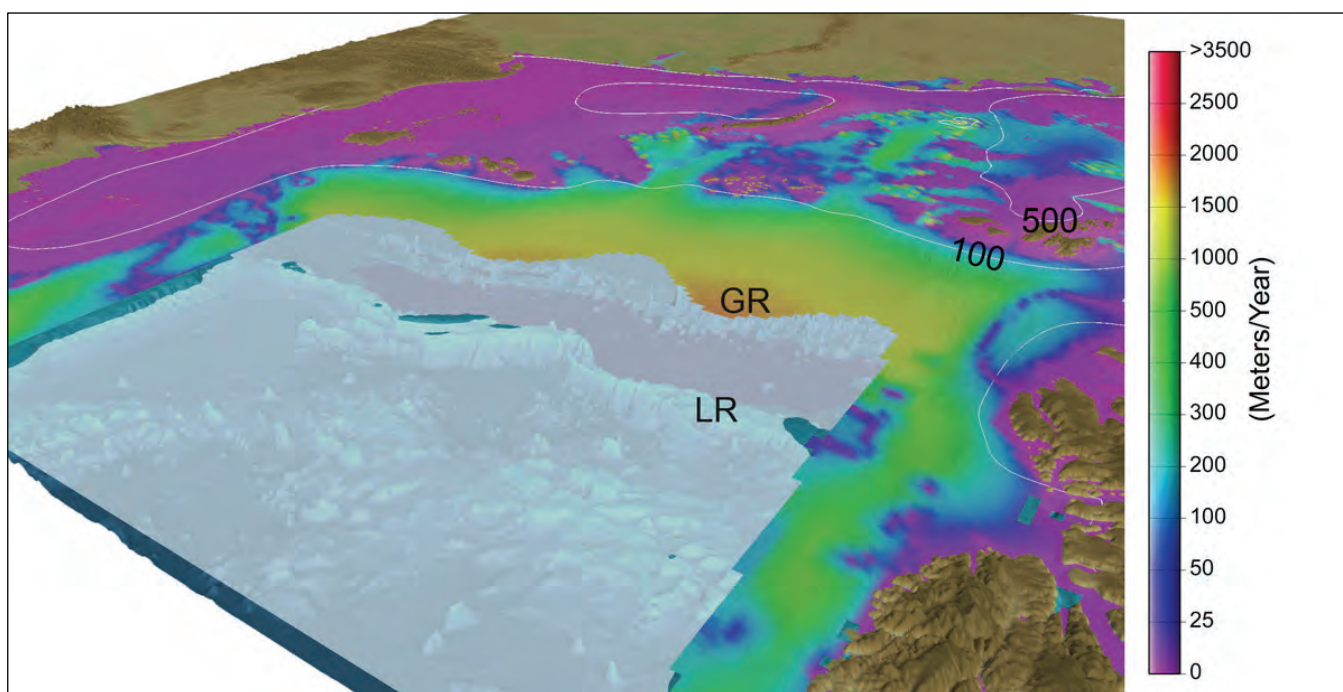


Figure 4b. 2800 year time snapshot from experiment #1, 10 cm/year marine melting, zero ice shelf accumulation.

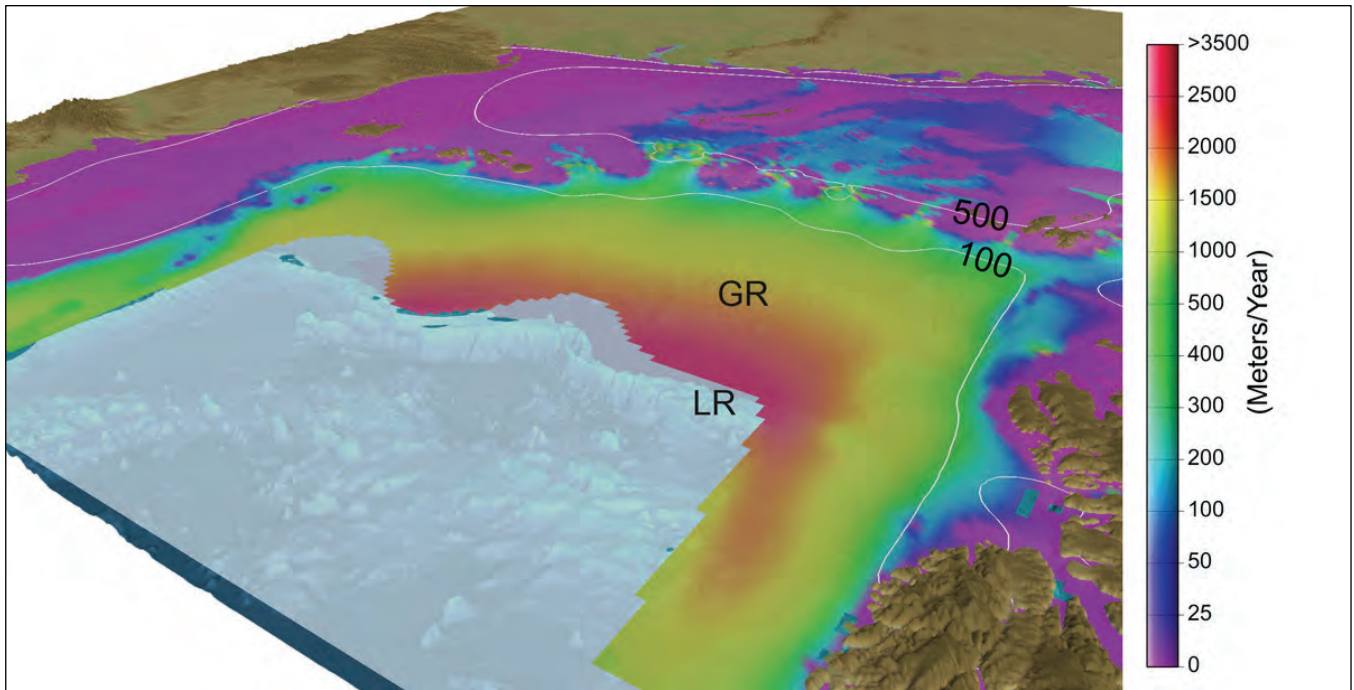


Figure 4c. 3800 year time snapshot from experiment #1, 10 cm/year marine melting, zero ice shelf accumulation.

Between 3800 and 4200 years the ice shelf covers the region of the Lomonosov Ridge where ice was once grounded, but the thickness at this time was very small (Figs. 4d and e). At 4200 years, the ice shelf in front of the Franz Victoria Trough over the Lomonosov Ridge was less than 15 m thick. This experiment showed that it was possible to grow a thick ice shelf rapidly within the Arctic Ocean provided that the marine melting rate was low. However, the thickness required for grounding was never reached. The general form of the ice shelf at 4200 years is as one might expect from an Antarctic point of view; the grounding zone is thick (around 700 m) and the ice shelf thins to around 100 m some 500 km from the grounding zone. At no time did ice ground across any part of the Lomonosov Ridge. The results from this experiment were similar to those when marine melting is increased to 20 cm/year.

Experiment #2, 30 cm/year marine melting, zero ice shelf accumulation (Fig. 5): 9000 years

By increasing the rate of marine melting to 30 cm/year the ice shelf within the Arctic Ocean fails to fill the whole basin. Instead, lobes of floating ice are established in front of the St. Anna and Franz Victoria ice streams. The St. Anna floating ice shelf covers the region where ice was grounded, but the thickness of the ice shelf in this position is never greater than 80 m. The velocity field in this experiment becomes unstable at about 10,000 years.

Experiment #3, 50 cm/year marine melting, zero ice shelf accumulation (Fig. 6 a, b): 6000 & 9000 years

By increasing the rate of marine melting to 50 cm/year, the model gave similar results to experiment 2. The ice shelf grew from the St. Anna Trough across the region of grounded ice, but the ice shelf thickness in this run was never greater than 50 m.

Experiment #4, 50 cm/year marine melting, ice accumulation included (Fig. 7): 6000 years

When ice accumulation was included in the model with 50 cm/year of marine melting, the ice shelf became unstable after 6000 years. This is because the accumulation (which is greatest toward the west) offset the amount of ice loss due to melting and encouraged ice shelf growth to occur across the entire Arctic Ocean. This experiment is a benchmark for our tests, because it suggests that marine-melting conditions where ice loss rates are less than 50 cm/year would cause complete ice shelf coverage of the Arctic Ocean under the precipitation conditions that occur across the Barents Sea. Notably, prior to the model becoming unstable at 6000 years, the ice shelf in front of the Franz Victoria Trough had a thickness of more than 100 m over the Lomonosov Ridge close to the continental margin of northern Greenland. The thickness fails to get much greater than this value. Only when the flow field is unstable does the ice shelf

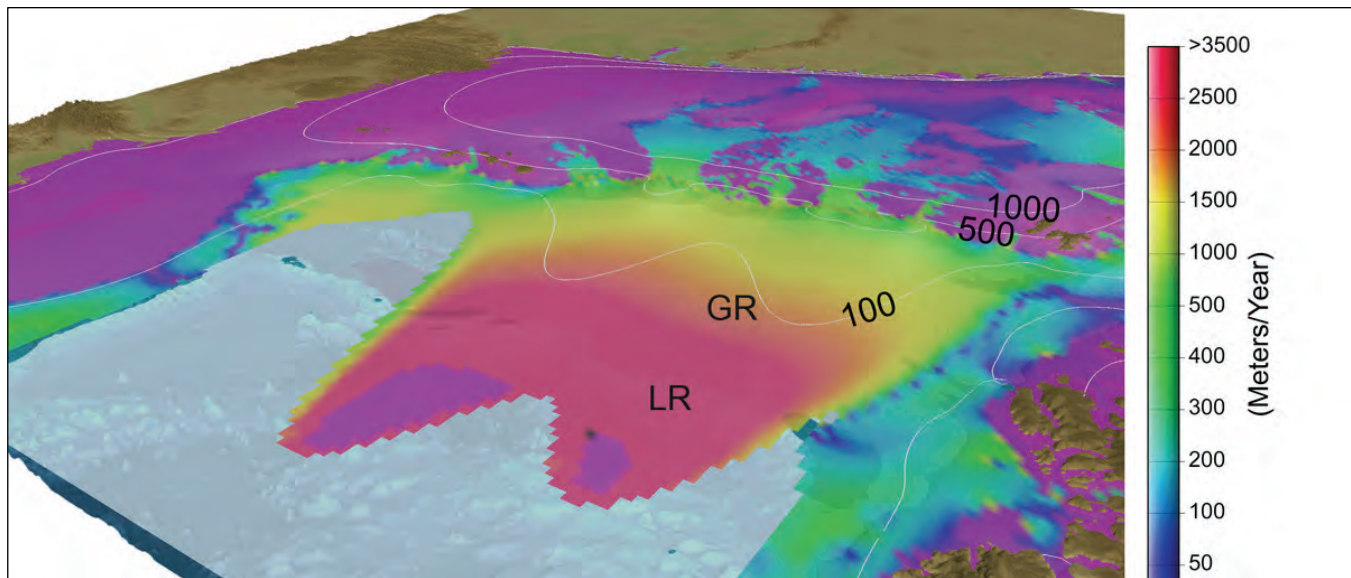


Figure 5. 9000 year time snapshot from experiment #2, 30 cm/year marine melting, zero ice shelf accumulation. The modeled ice is shown with a color table representing ice velocity in meters/year. The white contours are ice thickness in meters. As in figure 2, a white semitransparent plane has been inserted at 1000 m below present sea level to emphasize the areas of the Lomonosov Ridge that are shallower than 1000 m. LR=Lomonosov Ridge, GK=Gakkel Ridge.

thicken to more than 500 m over the Lomonosov Ridge.

The ice shelves immediately in front of the Franz Victoria and St. Anna Troughs have a thickness of over 700 m. In this experiment, as in others, the thickness reduces to no more than 80 m by the time the ice gets to the Lomonosov Ridge.

Experiment #5, 80 cm/year marine melting, ice accumulation included (Fig. 8): 10,000 years

In this experiment small stable ice shelves existed across the mouths of the St. Anna and Franz Victoria Troughs. However, these ice shelves failed to cover the Lomonosov Ridge. Under these environmental conditions it is unlikely that a substantial ice shelf could have existed within the Arctic Ocean.

Experiment #6, 50 cm/year marine melting, zero ice shelf accumulation, strain rate=0 (Fig. 9 a, b): 10,000 & 20,000 years

In experiments 1-5 grounding of ice across the Lomonosov Ridge was never achieved. Despite low basal melt rates, the ice shelf spread and thinned from the Barents/Kara margin such that it was less than 100 m thick across the ridge. One way to stop the ice shelf thinning is to reduce the strain rate. As there appears to be no way to ground an ice shelf with a strain rate of 0.005 year^{-1} , the strain rate was reduced in a further set of tests.

By reducing the strain rate of ice to zero, the velocity of the ice shelf was modified significantly. Whereas in experiment #3 ice less than 50 m thick flowed out across the Lomonosov Ridge from the Kara Sea, now the ice is thick enough to ground across the continental margin.

In the model, ice that is grounded well below sea level may be treated as if it were in an ice stream (as in the Bjørnøya Trough ice stream, north of Norway). In this experiment, such anomalous grounded ice velocities can be seen across the northern continental slopes (e.g. the Yermak Plateau) (Fig. 9a, b). This rather unusual velocity profile is unlikely to be realistic (longitudinal stresses, neglected in the model, would in reality act to smooth the velocity in these regions). However, as the grounded velocities in such places are surrounded by slow-flowing floating ice, the ice sheet profile is not adversely affected (in other words the model is not unstable). Thus, we are able to detect the places where grounding occurs by observing those locations where unusually high ice velocities are calculated.

In this experiment, ice was grounded across the Arctic Ocean in two places. First, after 10,000 model years, the Yermak Plateau was covered by grounded ice. Second, after 17,400 years, grounded ice covered the shallowest region of the Gakkel Ridge where a pinnacle in the ridge known as the Langseth Ridge reaches above 1000 m water depth according to the

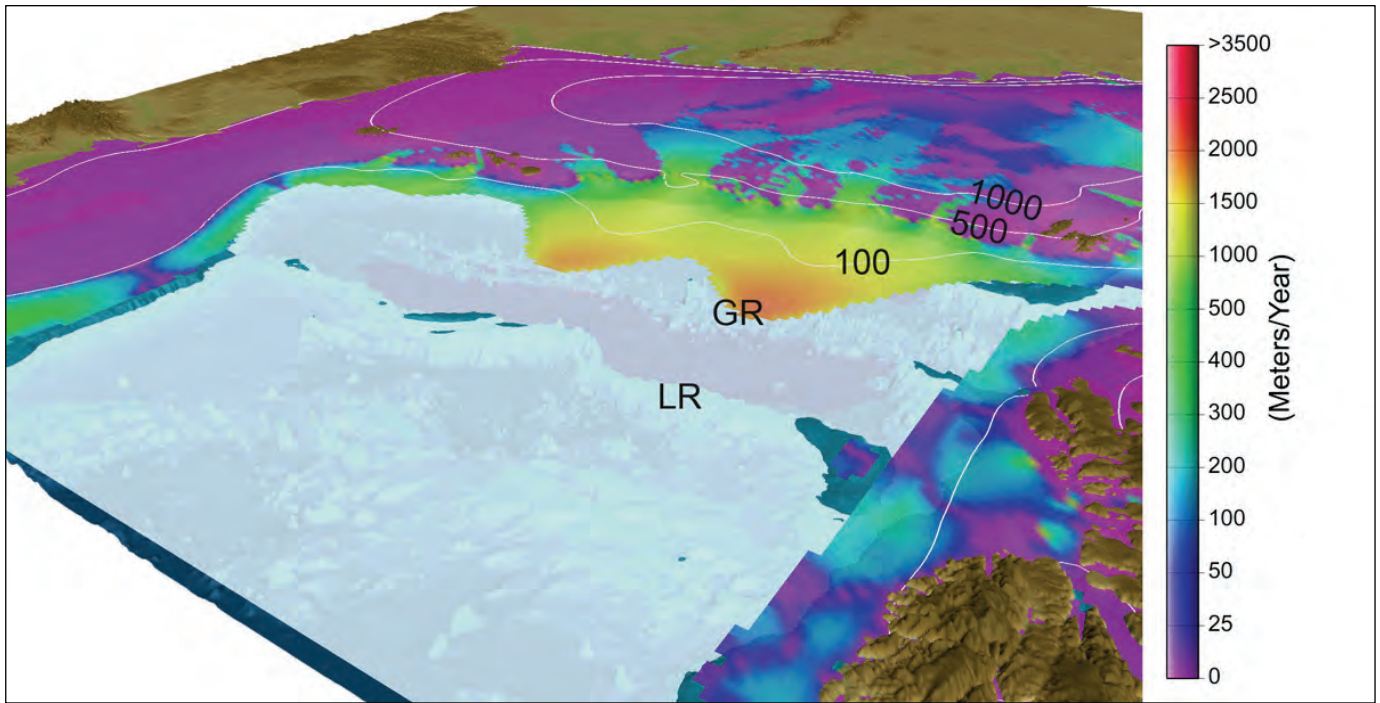


Figure 6a. 6000 year time snapshot from experiment #3, 50 cm/year marine melting, zero ice shelf accumulation. The modeled ice is shown with a color table representing ice velocity in meters/year. The white contours are ice thickness in meters. As in figure 2, a white semitransparent plane has been inserted at 1000 m below present sea level to emphasize the areas of the Lomonosov Ridge that are shallower than 1000 m. LR=Lomonosov Ridge, GK=Gakkel Ridge.

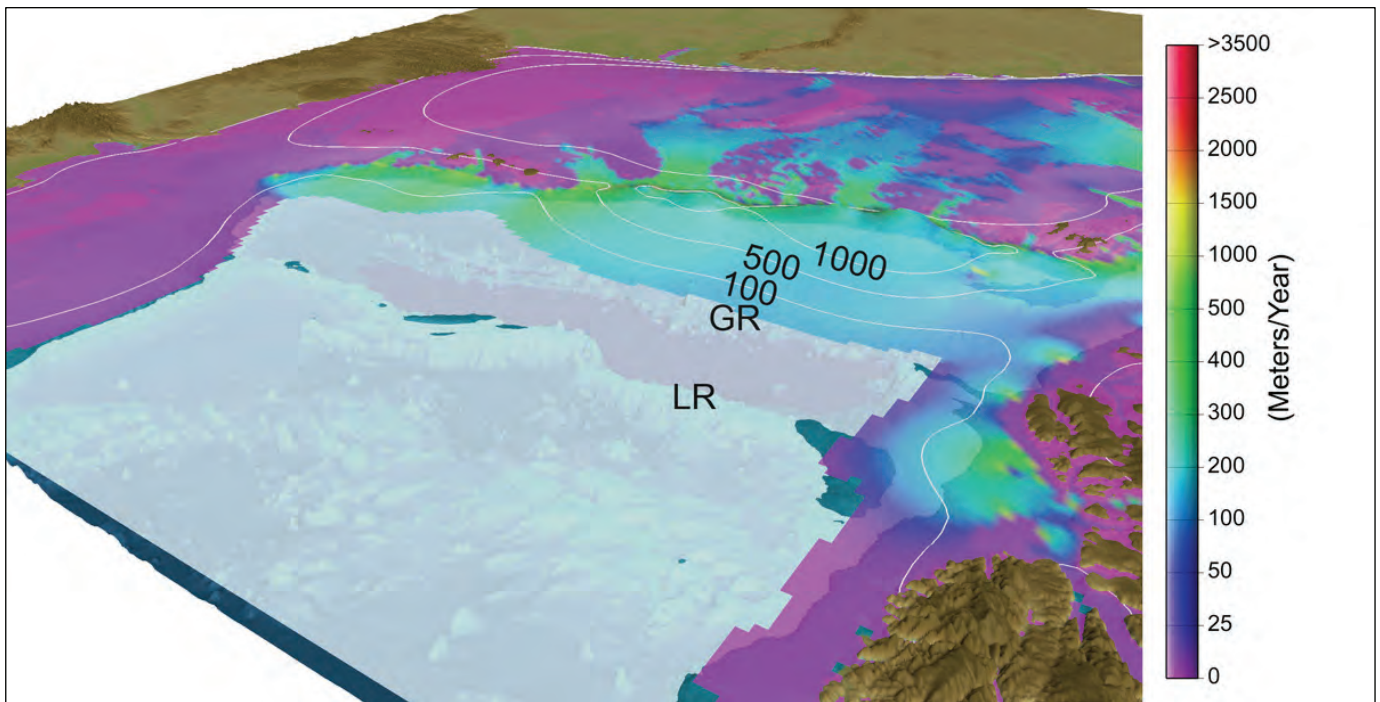


Figure 6b. 9000 year time snapshot from experiment #3, 50 cm/year marine melting, zero ice shelf accumulation.

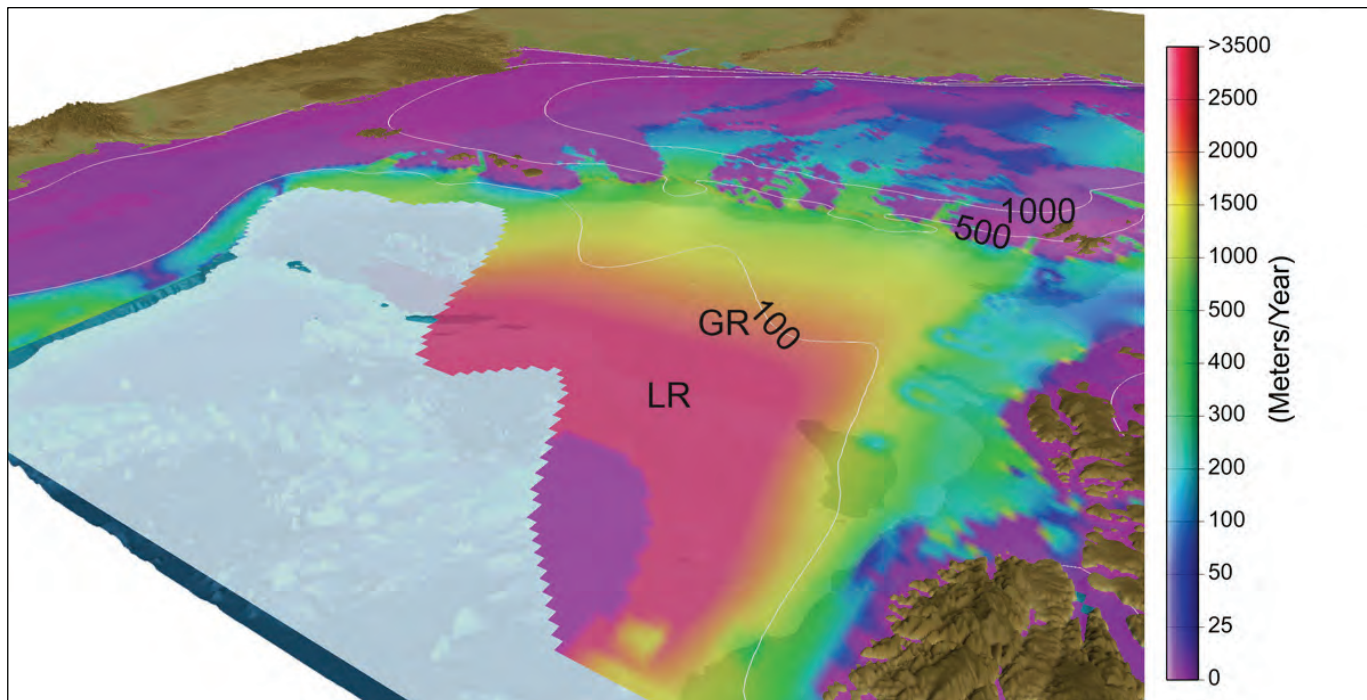


Figure 7. 6000 year time snapshot from experiment #4, 50 cm/year marine melting, ice accumulation included. The modeled ice is shown with a color table representing ice velocity in meters/year. The white contours are ice thickness in meters. As in figure 2, a white semitransparent plane has been inserted at 1000 m below present sea level to emphasize the areas of the Lomonosov Ridge that are shallower than 1000 m. LR=Lomonosov Ridge, GK=Gakkel Ridge.

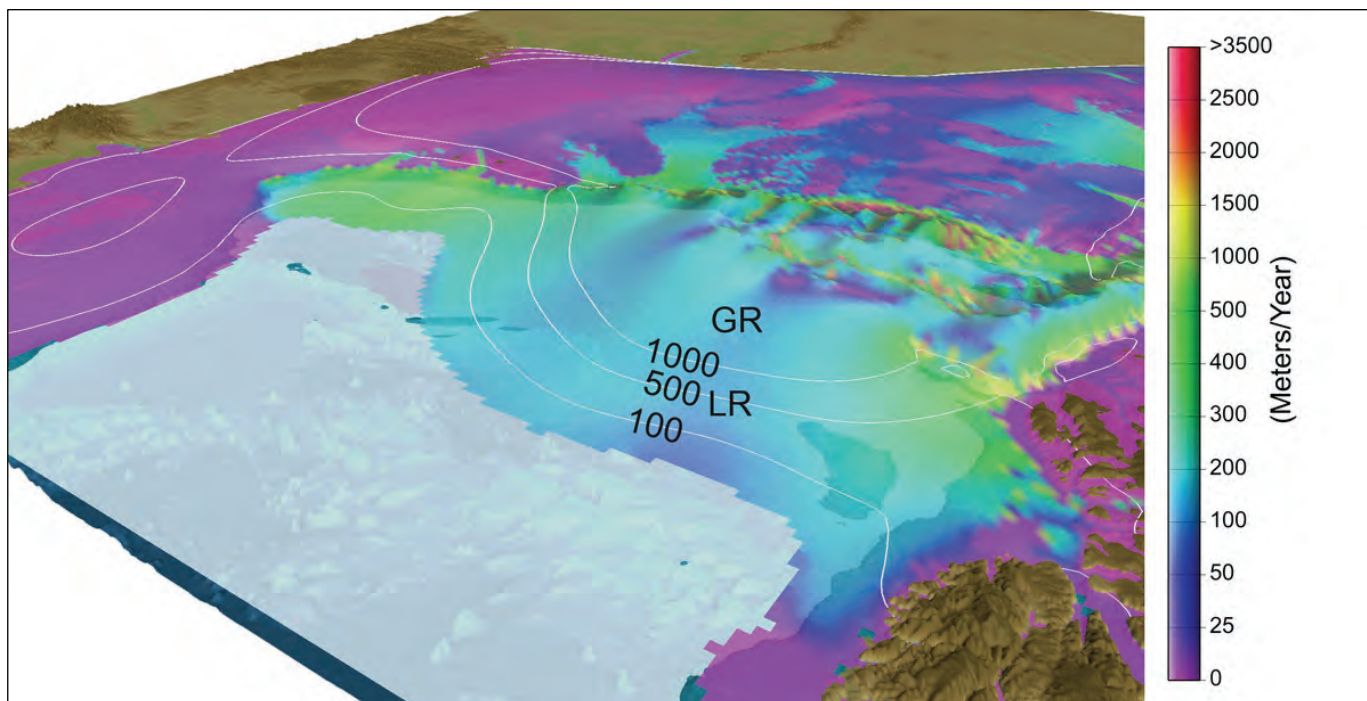


Figure 8. 10,000 year time snapshot from experiment #5, 80 cm/year marine melting, ice accumulation included. The modeled ice is shown with a color table representing ice velocity in meters/year. The white contours are ice thickness in meters. As in figure 2, a white semitransparent plane has been inserted at 1000 m below present sea level to emphasize the areas of the Lomonosov Ridge that are shallower than 1000 m. LR=Lomonosov Ridge, GK=Gakkel Ridge.

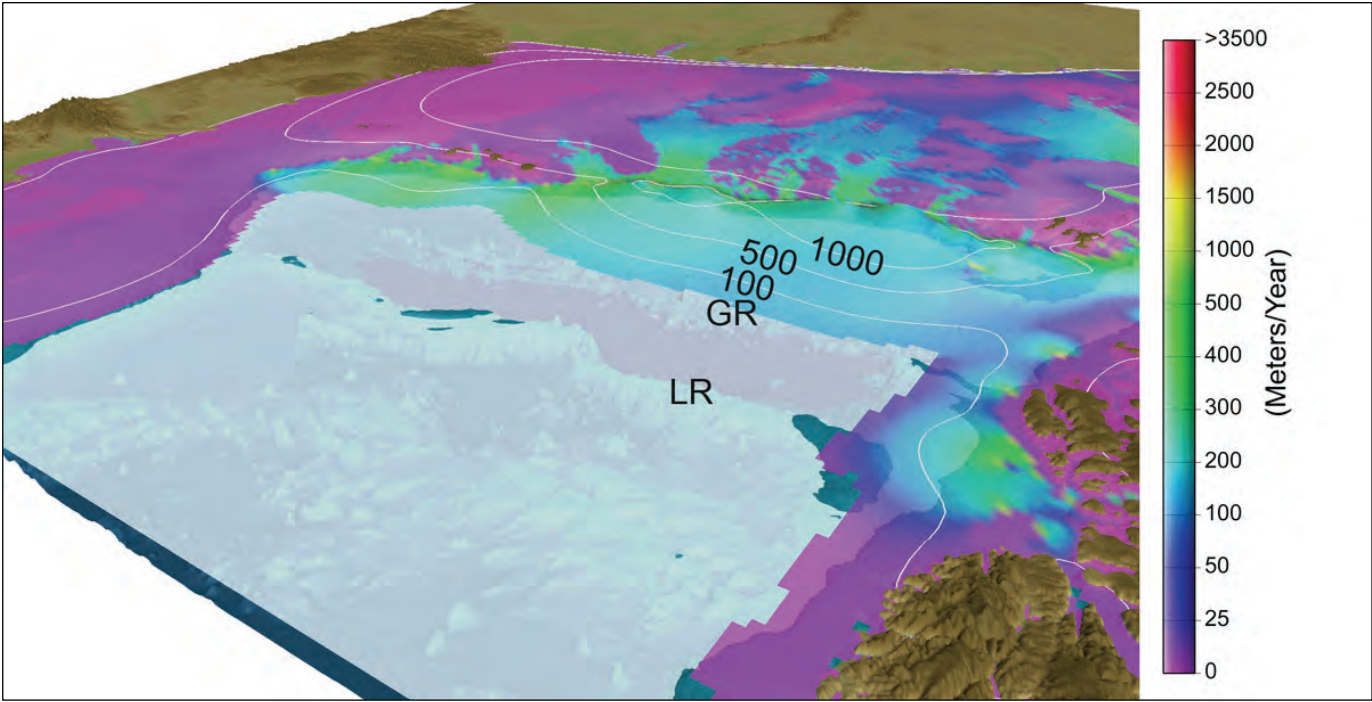


Figure 9a. 10,000 year time snapshot from experiment #6, 50 cm/year marine melting, zero ice accumulation, strain rate=0. The modeled ice is shown with a color table representing ice velocity in meters/year. The white contours are ice thickness in meters. As in figure 2, a white semitransparent plane has been inserted at 1000 m below present sea level to emphasize the areas of the Lomonosov Ridge that are shallower than 1000 m. LR=Lomonosov Ridge, GK=Gakkel Ridge.

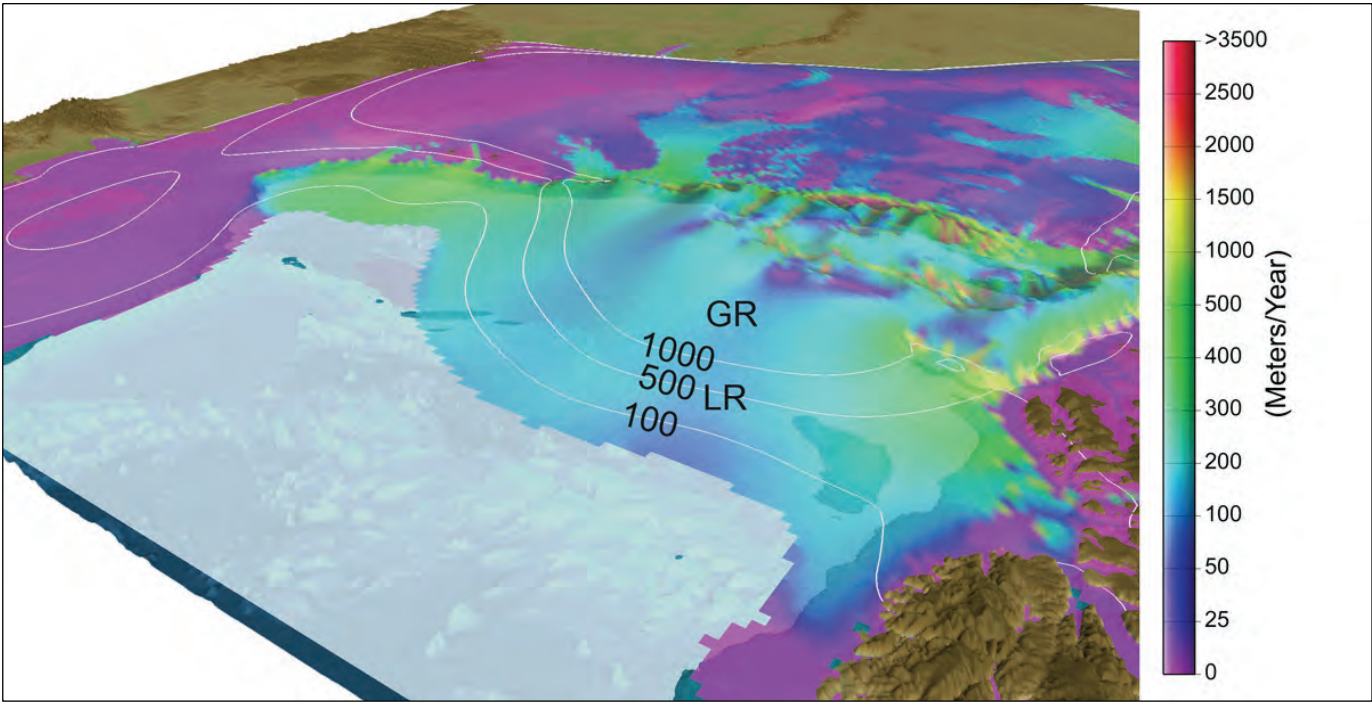


Figure 9b. 20,000 year time snapshot from experiment #6, 50 cm/year marine melting, zero ice accumulation, strain rate=0.

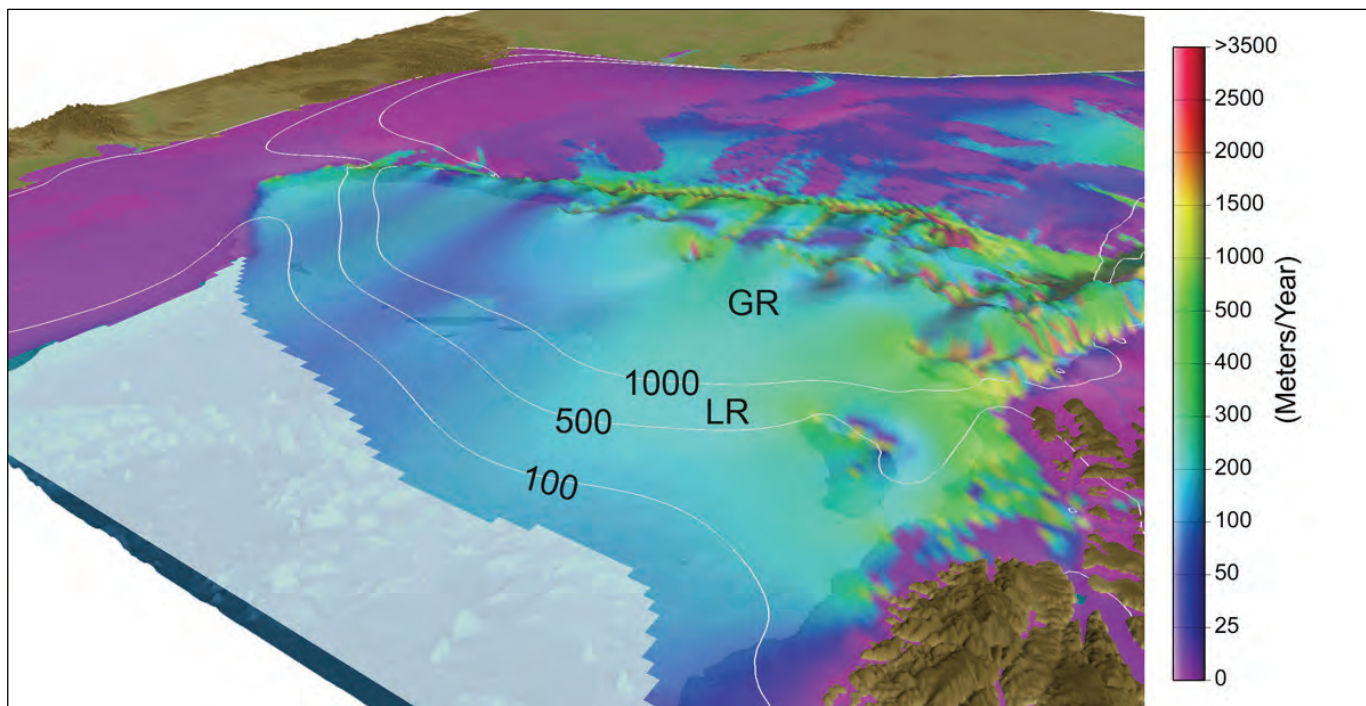


Figure 10a. 15,200 year time snapshot from experiment #7, 50 cm/year marine melting, ice accumulation included, strain rate=0. The modeled ice is shown with a color table representing ice velocity in meters/year. The white contours are ice thickness in meters. As in figure 2, a white semitransparent plane has been inserted at 1000 m below present sea level to emphasize the areas of the Lomonosov Ridge that are shallower than 1000 m. LR=Lomonosov Ridge, GK=Gakkel Ridge.

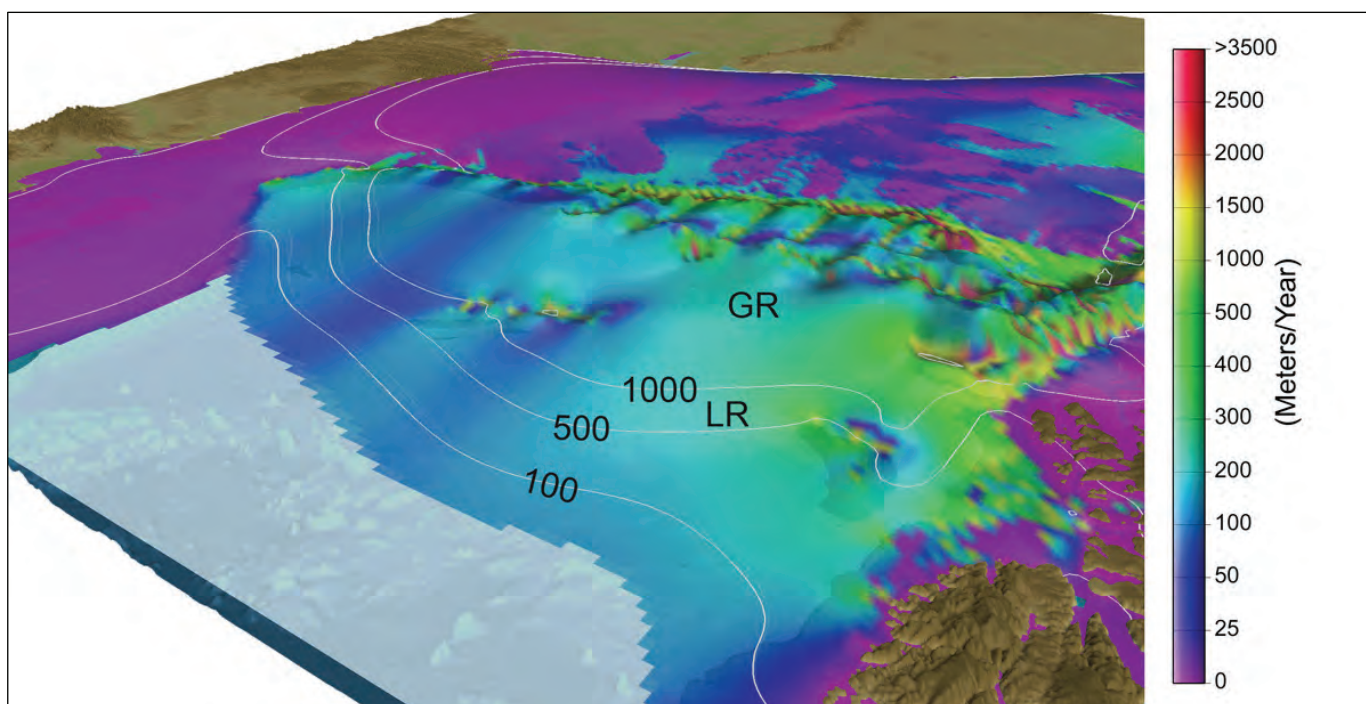


Figure 10b. 15,600 year time snapshot from experiment #7, 50 cm/year marine melting, ice accumulation included, strain rate=0.

IBCAO map. No other regions of the Arctic Ocean floor were affected by grounded ice.

Experiment #7, 50 cm/year marine melting, ice accumulation included, strain rate=0 (Fig. 10 a, b): 15,200 & 15,600 years

When ice accumulation is accounted for, the ice sheet grounds across much of the Arctic Ocean. Such a situation is highly unrealistic, but it makes the point that significant ice thickness can be produced within the Arctic Ocean by a stagnant ice shelf whose surface balance exceeds its basal melting.

After 6000 years of model time, the Yermak Plateau was covered with grounded ice; 4000 years earlier than in experiment #6. Later, at 12,200 model years, the Gakkel Ridge experienced grounded ice. By 15,200 years, the Lomonosov Ridge was covered by grounded ice in the region where there is evidence for ice grounding.

Experiment #8, 80 cm/year marine melting, ice accumulation included, strain rate=0

By increasing the rate of subglacial melting to 80 cm/year, the ice shelf extent was reduced significantly from that in experiment #7 (to something closer to experiment #6). In this case only the Yermak Plateau and the Gakkel Ridge, again at the Langseth Ridge area, were affected by grounded ice.

Experiment #9, 100 cm/year marine melting, ice accumulation included, strain rate=0

Increasing the rate of melting to 100 cm produced an ice shelf that was restricted to the Barents-Kara margin. Only the Yermak Plateau was covered by grounded ice.

DISCUSSION

The results of our model are not conclusive evidence for former ice shelf grounding. We do not model ice shelf physics very well, nor do we include grounding line mechanics. Further, we treat the process of marine melting within the Arctic Ocean by applying the same rates of melting at all places. This oversimplification is required in the absence of highly complex coupled ice-sheet/shelf/sea modeling. Our study focuses solely on defining the gross mass balance requirements of an ice shelf within the ocean fed by ice from the Barents and Kara Seas. The results of this experiment must be viewed with the above limitations in mind.

Modeling experiments 1-5 fail to produce floating shelf ice lobes emanating from the Barents and Kara

Seas that are thick enough to ground on the Lomonosov Ridge. The modeled ice sheet behaves like what is seen in Antarctica today where the shelf ice thins fairly rapidly from beyond the grounding line where it starts to float. Measurements of ice thickness along calving lines on the Antarctic shelf generally yield a thickness on the order of 200-300 m, although a thickness of more than 500 m has been observed at the margin of the Filchner Ice Shelf (Drewry, 1983) and recent plowmarks are reported from Antarctic waters from depths as deep as 600 m (Orheim and Elverhøi, 1981). Tabular icebergs may increase their draft by 50% if capsized (Lewis and Bennett, 1984) and this may explain some of the deepest plowmarks found on the Antarctic continental shelf as well as in the Arctic Ocean. Capsized deep icebergs are, however, less likely to have caused the spatially extensive and directionally consistent flutes and large size scours mapped over large areas of the Lomonosov Ridge and the Chukchi Borderland (Polyak et al., 2001). In experiments with ice shelf basal melting included, the model produces a shelf which resembles a series of 'lobes' originating from the fast flowing grounded outlets. In reality the growth of such lobes may be restricted by lateral flow of ice, not accounted for well in our ice shelf model. Without this lateral spreading, however, we give the ice shelf the maximum possible chance of extending out to the Arctic Ocean.

We reach a thickness of about 700 m immediately in front of the Franz Victoria and St. Anna Troughs in experiment #4 when ice accumulation was included in the model with 50 cm of marine basal melting. If we assume a sea level as much as 150 m below present during a large glaciation this scenario has the potential of producing very deep icebergs, although a keel depth of about 850 m is required to ground on the deepest areas of the Lomonosov Ridge crest where glacial bedforms have been mapped (Jakobsson, 1999; Polyak et al., 2001). By adopting the idea that capsized tabular icebergs could have produced some of the deepest scours mapped in the Arctic Ocean the pre capsized tabular icebergs would have to have drafts less than 570 m in order to reach 850 m while capsized. Polyak et al. (1997) reported that ice filled the St Anna Trough down to 630 m below present sea level during the last glaciation and this may be a potential source for some of the deep ice scours found, although not the deepest on the Lomonosov Ridge, which in addition to being deeper predates the last glaciation (Jakobsson et al., 2001).

The key parameter that prevents the ice lobes from the Franz Victoria and St. Anna Troughs from grounding on the Lomonosov Ridge is the ice shelf

strain rate. In experiments # 1-5, the strain rate was set at 0.005 year^{-1} , which is a generalization for free-flowing ice in water (Payne et al., 1989). Therefore, these experiments are intended to describe how a free-flowing ice shelf would behave within the Arctic Ocean. The strain rate, multiplied by the distance over which the strain operates, amounts to an increase in ice velocity as the ice flows under its own weight. This increase in velocity causes the ice shelf to thin with distance from the grounding zone. By lowering the strain rate to zero a completely different scenario emerges. In experiment #7, which accounts for accumulation and a basal melting of 50 cm/year, the ice sheet grounds after 15,200 model years on the western Lomonosov Ridge and after 15,600 years in the areas of the ridge where grounding has been mapped (Figs. 10a, b). This leads to the question regarding the type of conditions that could lead to an extraordinary low ice strain rate. We can speculate that such conditions could have prevailed during periods of large-scale glaciation with a substantially thickened and stagnant sea ice present in the ocean. This could have a buttressing effect on the ice flowing from the Barents Sea and, thus, preventing the ice from rapidly thinning while flowing out into the Arctic Ocean.

Today the deep Arctic Ocean sea ice cover is generally not thicker than 5 m (for discussion about sea ice thickness distribution in the Arctic Ocean see Wadhams, 1997). While discussing the hypothesis of a floating ice shelf in Arctic Ocean Broecker (1975) pointed out that sea ice reaches its equilibrium thickness when winter growth just matches summer ablation and, therefore, different climatic conditions would produce different steady-state thicknesses. It was proposed by Crary (1960), and later discussed by Mercer (1970), that if the heat from the inflowing warm Atlantic water were reduced to below one third of its present value almost unlimited thickening of the sea ice would occur. Mercer (1970) suggested that this could be an important mechanism for growing an ice shelf during glacial conditions. Thus, the existence of such an ice shelf is compatible with the model's requirement for grounding that the sub ice shelf melt rates are less than 50 cm/year.

The experiments testify to the importance of the ice shelf's net mass balance of the location of grounded ice in the Arctic Ocean (under zero ice shelf strain rates). In the model, grounding is only possible over the Lomonosov Ridge when surface ice accumulation is included and basal melt rates are low (50 cm/year). As the melt rates are increased, so the maximum distance from grounded ice in the Arctic Ocean to the Barents margin is reduced. Thus, when the melt rate is 100 cm/year, grounding is only possible over the Yermak

Plateau (experiment #9). The model treats basal melting in the oceans as being the same rate in all places. It would probably be more realistic to assume that rates of basal melting would be spatially variable. For instance, one could argue that melt rates closer to the Fram Strait would be greater than those further into the Arctic Ocean (due to influx of warm Atlantic Water). Such a situation would not affect the grounding of ice across the Yermak Plateau, as it is covered by grounded ice in all the experiments #6-9. However, the large-scale grounding of the Gakkel Ridge may be curtailed under a geographically-modified melt regime. Furthermore, as the area of the Lomonosov Ridge that is known to have been affected by ice grounding is far from the Fram Strait, we would expect lower rates of melting here compared with regions farther to the west.

CONCLUSIONS

A numerical ice sheet model was used to test the hypothesis that an ice shelf once grounded across the Lomonosov Ridge to a depth of around 1000 m below present sea level. We undertook nine tests with a variety of mass balance (basal melting and surface accumulation) conditions and ice shelf strain rates. In all experiments iceberg calving is not allowed (as this process would dismantle the ice shelf). The following conclusions could be drawn from the model experiments:

- When the ice shelf strain rate was 0.005 year^{-1} , under relatively low rates of basal melting (less than 80 cm/year), an ice shelf flowed from the Barents/Kara Seas across the Lomonosov Ridge. However, the ice shelf was never thicker than 100 m across the ridge. Reducing the rate of subglacial melting to zero caused the ice shelf to thicken, but only by a few tens of meters. A free-flowing ice shelf from the Barents Sea is therefore unlikely to have been responsible for the grounding observed across the ridge.
- When the ice shelf strain rate was reduced to zero floating ice velocities could not increase from the grounding zone. This allowed the ice shelf to become much thicker than in previous experiments and, in some experiments where the subglacial melting was less than 80 cm/year, grounding of ice across the Lomonosov Ridge was modeled.
- An ice shelf flowing with a low strain rate could not be considered to be 'free flowing'. Instead, the ice shelf must be supported or 'buttressed' by a counter force. For the case of the Arctic Ocean, such buttressing could come

from the action of ultra thick sea ice held fast within the Arctic Ocean basin.

- Thus, grounding of ice across the Lomonosov Ridge, emanating from the Barents Sea, is possible but only if the ice shelf velocities and basal melt rates are kept low.

ACKNOWLEDGEMENTS

Martin Jakobsson was supported by NOAA Grant NA97OG0241 and Martin Siegert by NERC Grant NER/A/S/2000/01256. We would also like to thank Larry Mayer and John K. Hall for their helpful suggestions to improve the manuscript. James V Gardner and Bernhard Coakley provided valuable and insightful reviews. The interactive visualization software *Fledermaus* was used to analyze and present the modeling results.

REFERENCES

- Alley, R.B., 1989. Multiple steady states in ice-water-till systems. *Annals of Glaciology*, 14, 1-5, 1990.
- Alley, R.B., Water-pressure coupling of sliding and bed deformation: II. Velocity-depth Profiles. *Journal of Glaciology*, 35, 119-129.
- Boulton, G.S., and Hindmarsh, R.C.A., 1987. Sediment deformation beneath glaciers: rheology and geological consequences. *Journal of Geophysical Research*, 92, 9059-9082.
- Broecker, W.S., 1975. Floating Glacial Ice Caps in the Arctic Ocean, *Science*, 188, 1116-1118.
- Crary, A.P., 1960. Arctic ice island and ice shelf studies, 2, *Arctic*, 13(1), 32-50.
- Drewry, D.J., 1983. Antarctic glaciological and geophysical folio, Cambridge, England, Scott Polar Research Institute, 8 sheets.
- Grosswald, M. G., 1980. Late Weichselian ice sheets of northern Eurasia, *Quaternary Research*, 13, 1-32.
- Grosswald, M.G. and Hughes, T.J., 1999. The case for an ice shelf in the Pleistocene Arctic Ocean, *Polar Geography*, 23, 23-54.
- Hughes, T. J., Denton, G. H., and Grosswald, M. G., 1977. Was there a late Würm ice sheet? *Nature*, 266, 596-602.
- Jakobsson, M., Løvlie, R., Arnold, E. M., Backman, J., Polyak, L., Knutsen, JO., and Musatov, E., 2001. Pleistocene stratigraphy and paleoenvironmental variation from Lomonosov Ridge sediments, central Arctic Ocean, *Global and Planetary Change*, 31(1-4), 1-21.
- Jakobsson, M., N. Cherkis, J. Woodward, B. Coakley, and R. Macnab, 2000. A new grid of Arctic bathymetry: A significant resource for scientists and mapmakers, *EOS Transactions, AGU*, 81, no. 9, pp. 89, 93, 96.
- Jakobsson, M., 1999. First high-resolution chirp sonar profiles from the central Arctic Ocean reveal erosion of Lomonosov Ridge sediments, *Marine Geology*, 158, 111-123.
- Knies, J., Kleiber, H.-P., Matthiessen, J., Müller, C., Niessen, F., Stein, R., Weiel, D., 2001. Marine records indicate maximum extent of Saalian and Weichselian ice-sheets along the northern Eurasian margin, *Global and Planetary Change*, 31, 45-64.
- Kristoffersen, Y., Coakley, B., Jokat, W., Edwards, M., Brekke, H., and Gjengedal, J., 2004. Seabed erosion on the Lomonosov Ridge, central Arctic Ocean: A tale of deep draft icebergs in the Eurasia Basin and the influence of Atlantic water inflow on iceberg motion? *Paleoceanography*, 19(3), PA3006.
- Lewis, J.C., and Bennett, G., 1984. Monte Carlo calculations of ice berg draft changes caused by roll, *Cold Regions Science and Technology*, 10, 1-10.
- Mahaffy, M.W., 1976. A Three Dimensional Numerical Model of Ice Sheets: Tests on the Barnes Ice Cap, Northwest Territories. *Journal of Geophysical Research*, 81, 1059-1066.
- Mangerud, J., Dokken, T., Hebbeln, D., Heggen, B., Ingólfsson, O., Landvik, J.Y., Mejdahl, V., Svendsen, J.I., Vorren, T.O., 1998. Fluctuations of the Svalbard-Barents Sea Ice Sheet during the last 150 000 years. *Quaternary Science Reviews*, 17, 11-22.
- Mercer, J.H., 1970. A former ice sheet in the Arctic Ocean? *Palaeogeogr., Palaeoclimatol., Palaeoecol.* 8, 19-27.
- Orheim, O. and Elverhøi, A., 1981. Model for submarine glacial deposition, *Annals of Glaciology*, 2, 123-128.
- Payne, A.J., Sugden, D.E. and Clapperton, C.M., 1989. Modeling the growth and decay of the Antarctic Peninsula Ice Sheet. *Quaternary Research*, 31, 119-134.
- Pelto, M.S., and Warren, C.R., 1991. Relationship between tidewater glacier calving velocity and water depth at the calving front, *Annals of Glaciology*, 15, 115-118.
- Polyak, L., Edwards, M. H., Coakley, B. J. and Jakobsson, M., 2001. Ice shelves in the Pleistocene Arctic Ocean inferred from glaciogenic deep-sea bedforms, *Nature*, 410, 453-457.
- Polyak, L., Forman, S.L., Herlihy, F.A., Ivanov, G., Kritnitksy, P., 1997. Late Weichselian deglacial

- history of the Svyataya (Saint) Anna trough, northern Kara Sea, Arctic Russia, *Marine Geology*, 143, 169-188.
- Siegert, M.J. and Dowdeswell, J.A., 1995. Numerical modeling of the Late Weichselian Svalbard-Barents Sea Ice Sheet. *Quaternary Research*, 43, 1-13.
- Siegert, M.J., Dowdeswell, J.A. and Melles, M., 1999. Late Weichselian glaciation of the Eurasian High Arctic. *Quaternary Research*, 52, 273-285.
- Siegert, M.J. and Marsiat, I., 2001. Numerical reconstructions of LGM climate across the Eurasian High Arctic. *Quaternary Science Reviews*, 20 (15), 1595-1605.
- Smith, H.F.W., and D. T. Sandwell, 1997. Global Seafloor Topography from Satellite Altimetry and Ship Depth Soundings, *Science*, 277, 1956-1962.
- Spielhagen, R.F., Baumann, K-H., Erlenkeuser, H., Nowaczyk, N.R., Norgaard-Pedersen, N., Vogt, C., and Weiel, D., 2004. Arctic Ocean deep-sea record of northern Eurasian ice sheet history, *Quaternary Science Reviews*, 23, 1455-1483.
- Spielhagen R. F., Bonani, G., Eisenhauer, A., Frank, M., Frederichs, T., Kassens, H., Kubik, P.W., Mangini A., Norgaard-Pedersen, N., Nowaczyk, N.R., Schper, S., Stein, R., Thiede, J., Tiedemann, R., and Wahsner, M., 1997. Arctic Ocean evidence for late Quaternary initiation of northern Eurasian ice sheets, *Geology*, 25, 783-786.
- Svendsen, J.I., Alexanderson, H., Astakhov, V.I., Demidov, I., Dowdeswell, J.A., Henriksen, M., Hjort, C., Houmark-Nielsen, M., Hubberten, H.W., Ingólfson, O., Jakobsson, M., Kjær, K., Larsen, E., Lokrantz, H., Lunkka, J.P., Lyså, A., Mangerud, J., Maslenikova, O., Matioushkov, A., Murray, A., Möller, P., Niessen, F., Saarnisto, M., Siegert, C., Stein, R., Siegert, M.J., Spielhagen, R., 2004. Late Quaternary ice sheet history of Northern Eurasia, *Quaternary Science Reviews*, 23, 1229-1271.
- Svendsen J. I., V. Astakhov, D. Y. Bolshiyarov, I. Demidov, J. A. Dowdeswell, V. Gataullin, C. Hjort, H. W. Hubberten, E. Larsen, J. Mangerud, M. Melles, P. Möller, M. Saarnisto, M. J. Siegert, 1999. Maximum extent of the Eurasian ice sheets in the Barents and Kara sea region during the Weichselian, *Boreas*, 28. 234-242.
- U.S. Geological Survey, ed., 1997. GTOPO30 Digital Elevation Model. U.S. Geological Survey, EROS Data Center, Sioux Falls, South Dakota.
- Vogt, P.R., Crane, K., and Sundvor, E., 1994. Deep Pleistocene iceberg plowmarks on the Yermak Plateau: sidescan and 3.5 kHz evidence for thick calving ice fronts and a possible marine ice sheet in the Arctic Ocean, *Geology*, 22(5), 403-406.
- Wadhams, P., 1997. Ice thickness in the Arctic Ocean: The statistical reliability of experimental data, *Journal of Geophysical Research*, 102(C13), 27951-27959.