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Collaborative Research: Did the Laurentine Ice Sheet Control Abrupt Climate Change?

Terence J. Hughes
Principal Investigator; University of Maine, Orono, terry.hughes@maine.edu

James L. Fastook
Co-Principal Investigator; University of Maine, fastook@maine.edu

David Bromwich
Co-Project Director; Ohio State University

E. Richard Toracinta
Co-Principal Investigator; Ohio State University

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Principal Investigator: Hughes, Terence J. **Award ID:** 9900477

Organization: University of Maine

Title:

Collaborative Research: Did the Laurentine Ice Sheet Control Abrupt Climate Change?

Project Participants

Senior Personnel

Name: Hughes, Terence
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Fastook, James
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Bromwich, David
Worked for more than 160 Hours: Yes
Contribution to Project:
Co-Project Director

Name: Toracinta, Richard
Worked for more than 160 Hours: Yes
Contribution to Project:
He is replacing John Cassano as a co-PI from The Ohio State University.

Post-doc

Graduate Student

Undergraduate Student

Technician, Programmer

Other Participant

Name: Wu, Patrick
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Oglesby, Robert
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Kleman, Johan
Worked for more than 160 Hours: Yes
Contribution to Project:
Collaborated in specifying terrestrial glacial geological constraints on the Laurentide Ice Sheet

Name: Polyak, Leonid

Worked for more than 160 Hours: No

Contribution to Project:

Consulted on Arctic marine glacial geology.

Research Experience for Undergraduates

Organizational Partners

University of Calgary

Patrick Wu, Subcontractor

Ohio State University

Principal Investigator/Project Directors: David Bromwich
Co-Principal Investigator: Richard Toracinta

Purdue University

Consultant: Robert J. Oglesby

Other Collaborators or Contacts

Unpaid Collaborator: Johan Kleman, Stockholm University (Sweden)
Unpaid Collaborator: Leonid Polyak, The Ohio State University

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

Findings:

See activities section. Activities and findings have been intergrated into one section.

Training and Development:

First-year work included training two graduate students at the doctoral level, Jesse Johnson and James Kenneally. Johnson worked on modeling subglacial hydrology for sheet flow and stream flow. Ph.D. awarded in 2002. Kenneally worked on modeling calving along maring and lacustrine ice-sheet margins. Ph.D. awarded in 2003.

Outreach Activities:

The materials have been placed on The Ohio State University Meteorology Group's web site, which is http://www-bprc.mps.ohio-state.edu/PolarMet/paleonwp.html

A mailing list is being created for collaborators to communicate with. There is an ftp site for collaborators to share large data files.

Journal Publications

Books or Other One-time Publications

Web/Internet Site

Other Specific Products

Contributions

Contributions within Discipline:

Contributions to Other Disciplines:

Contributions to Human Resource Development:

Contributions to Resources for Research and Education:

Contributions Beyond Science and Engineering:

Categories for which nothing is reported:

Any Journal
Any Book
Any Web/Internet Site
Any Product
Contributions: To Any within Discipline
Contributions: To Any Other Disciplines
Contributions: To Any Human Resource Development
Contributions: To Any Resources for Research and Education
Contributions: To Any Beyond Science and Engineering

Final Technical Report to NSF (30 April 2003)

Project Title
Collaborative Research: Did the Laurentide Ice Sheet Control Abrupt Climate Change?

This project was a collaborative effort between the University of Maine and The Ohio State University aimed at determining by numerical modeling techniques if changes in the size and shape of the former Laurentide Ice Sheet were large enough and fast enough to trigger abrupt changes in regional and global climate. Ice sheet modeling was conducted at the University of Maine by Drs. James Fastook and Terence Hughes, with Fastook responsible for ice sheet modeling and Hughes responsible for modeling calving of ice from ice sheets. Climate modeling was conducted at The Ohio State University, under the direction of Dr. David Bromwich, with Dr. Rick Toracinta having primary responsibility for running the regional climate model for North America and surrounding oceans. Subcontracts were awarded from the University of Maine to Dr. Patrick Wu at the University of Calgary for modeling glacial isostasy associated with ice sheet modeling, and from The Ohio State University to Dr. Robert Oglesby (then) at Purdue University for assistance in nesting the regional climate model in the latest version of the NCAR Community Climate Model for global atmospheric circulation. In addition, Dr. Johan Kleman of Stockholm University was enlisted to provide control for the ice sheet model, using his diagnostic glacial geological inversion model to interpret time-transgressive glacial geology. Dr. Kleman had separate funding for applications of his model, first to the glacial geological record of the Scandinavian Ice Sheet and then of the Laurentide Ice Sheet. Dr. Leonid Polyak of The Ohio State University was an unpaid consultant on Arctic marine glacial geology, which served to distinguish between permanent sea ice and a floating ice shelf as boundary conditions for reconstructed ice sheets. As Project Director, Dr. Hughes was responsible for coordinating all modeling activities. Coordination was accomplished at annual workshops for each year of the three-year project.

As originally envisioned, collaborative research was aimed at simulating the full cycle of the last Quaternary glaciation, with modeling focused on four times of known rapid climate change that have been associated with massive outbursts of Laurentide ice into the North Atlantic, at 25, 21, 15, and 11 ka (thousand years before present). Climate modeling was directed at producing "snapshots" of climate at these times. First-year modeling activities revealed the need for extensive development of both the Laurentide Ice Sheet model and the regional climate model before these experiments could be conducted. By year's end, it was clear that both ice sheet and climate modeling should be directed at obtaining the best interaction between the ice sheet and climate for the Last Glacial Maximum (LGM) before simulations of abrupt change were attempted. In addition, it became clear that the ice sheet model needed to have nested within it a high resolution capability similar to the high resolution of the regional climate model. High resolution was needed to capture the dynamics of ice streams that discharged ice rapidly, and therefore were the conduits for linking ice sheet dynamics to times of rapid climate change. Calving dynamics, both from ice streams ending in water and from floating ice shelves, provided the mechanism for rapidly cooling the North Atlantic by way of outbursts of Laurentide icebergs.

At the end of a four-year study period, which included an additional fourth year of unfunded work, both ice sheet and climate modeling had arrived at the threshold for conducting the investigation of abrupt changes that was originally envisioned. Two breakthroughs by graduate students employed on the project made this possible. First, Jesse Johnson developed a model for subglacial hydrology that could be coupled to the Fastook ice sheet model. Second, James Kenneally developed a model for initiating crevassing in floating ice that led to production of icebergs of various sizes. Both received doctorates for their work. However, it had become clear that the ice sheet model needed to base the dynamics of ice streams on gravitational forcing that included ice-bed uncoupling caused by increasing basal buoyancy as ice streams became afloat in deep water, and that the climate model needed to be coupled with a model of ocean circulation to transport icebergs across the North Atlantic and to transport moisture from the oceans to the ice sheet. This understanding of further model development resulted in a proposal being submitted requesting an additional three years of funding in order to reliably simulate rapid discharge and transport of Laurentide ice at times of known rapid climate change, as originally envisioned.

Results of Laurentide modeling for this project, including results from both the climate and ice sheet models, including their interactions, are published on the following website:
http://www-bprc.mps.ohio-state.edu/PolarMet/paleonwp.html

A full description of the ice sheet model and selected modeling results are published on the following website:
http://tulip.umcs.maine.edu/~shamis/umism/umism.html

Results from the subglacial hydrology model that is linked to the ice sheet model are published on the following website:
www.cs.umt.edu/u/johnson/research/phd_html/node7.html

Published and submitted results from the four years of work completed at the University of Maine included applications to present-day ice sheets and former ice sheets other than the Laurentide Ice Sheet, where sensitivity studies of the ice sheet and ice calving models could be conducted. These results are the following:

Denton, G.H. and Hughes, T.J., 2000. Reconstruction of the Ross ice drainage system, Antarctica, at the last glacial maximum. *Geografiska Annaler*, **82A**(2–3): 143–166.

Denton, G.H. and Hughes, T.J., 2002. Reconstructing the Antarctic Ice Sheet at the Last Glacial Maximum. *Quaternary Sciences Reviews*, **21**:193–202.

Grosswald, M.G. and Hughes, T.J., 2002. The Russian component of an Arctic Ice Sheet during the Last Glacial Maximum. *Quaternary Science Reviews*, **21**(1): 121–146.

Hughes, T., 2002. Calving Bays. *Quaternary Science Reviews*, **21**(1): 267–282.

Hughes, T.J. and Wilch, E., 2000. Calculating basal thermal zones beneath the Antarctic Ice Sheet. *Journal of Glaciology*, **46**(100): 297-310.

Johnson, J., 2002. *A Basal Water Model for Ice Sheets*. Ph.D. thesis, Department of Physics, University of Maine.

Johnson, J. and Fastook, J.L., 2002. Northern Hemisphere glaciation and its sensitivity to basal melt water. *Quaternary International*, **95–96**: 65–74.

Kenneally, J.P., 2003. *Crevassing and Calving of Glacial Ice*. Ph.D. thesis, Department of Physics, University of Maine.

Kenneally, J.P., 2003. Comments on "Buoyancy-driven lacustrine calving, Glaciar Nef, Chilean Patagonia," by Charles Warren, Doug Benn, Vanessa Winchester, and Stephan Harrison. *Journal of Glaciology*, **In press**.

Kenneally, J.P. and Hughes, T.J., 2002. The Calving Constraints on Inception of Quaternary Ice Sheets. *Quaternary International*, **95**(1): 43–53.

Kleman, J., Fastook, J.L. and Stroeven, A.P., 2002. Geologically and geomorphically constrained numerical model of Lauurentide ice Sheet inception and build-up. *Quaternary International*, **95–96**: 87–98.

Näslund, J.-O., Fastook, J.L. and Holmund, P., 2000. Numerical modelling of the ice sheet in western Dronning Maud Land, East Antarctica: impacts of present, past, and future climates. *Journal of Glaciology*, **46**(152): 54–66.

Näslund, J.-O., Rodhe, L., Fastook, J.L. and Holmlund, P., 2003. New ways of studying ice sheet flow directions and glacial erosion by computer modelling; examples from Fennoscandia. *Quaternary Science Reviews*, **22**(2–4): 245–258.

Payne, A.J., Huybrechts, P., Abe-Ouchi, A., Calov, R., Fastook, J.L., Greve, R., Marshall, S.J., Marsiat, I., Ritz, C. and Tarasov, L., 2000. Results from the EISMINT phase 2 simplified geometry experiments: The effects of thermomechanical coupling. *Journal of Glaciology*, **46**(153): 227–238.

Prescott, P.R., Kenneally, J.P. and Hughes, T.J., 2003. Relating crevassing to nonlinear strain in the floating part of Jakobshavns Isbrae. *Annals of Glaciology*, **In press**.

Steig, E.J., Fastook, J.L., Zweck, C., Goodwin, I.D., Licht, K.J., White, J.W.C. and Ackert Jr., R.P., 2001. West Antarctic Ice Sheet Elevation Changes. *The West Antarctic Ice Sheet: Behavior and Environment*. Alley, R.B. and Bindschadler, R.A., Editors. Washington, DC, American Geophysical Union (Antarctic Research Series). **77**, 75–90.

SUBMITTED

P.R. Prescott and T. Hughes. Relating crevassing to apparent ice stiffness variations in the floating part of Jakobshavns Isbrae. Submitted to the Journal of Glaciology

J. Johnson and J.L. Fastook. Lakes beneath Antarctica. Submitted to the Journal of Glaciology.

J.L. Fastook and T. Hughes. Marine embayment “white holes” yield alternative ice sheet initiation scenarios. Submitted to the Canadian Journal of Earth Science.

T. Hughes. Is the “Jakobshavns Effect” in effect in Greenland? Submitted to the Canadian Journal of Earth Science.

T. Hughes. Why the West Antarctic Ice Sheet is collapsing. Submitted to the Journal of Geophysical Research

T. Hughes. The geometrical force balance in glaciology. Submitted to the Journal of Geophysical Research

D. Reusch and T. Hughes. Surface “waves” on Byrd Glacier, Antarctica. Submitted to Antarctic Science

Collaborative research: Did the Laurentide Ice Sheet cause abrupt climate change?

A report on the second annual workshop, Stockholm University, 15-17 June 2001.

The second annual workshop of this NSF-funded project was hosted by the Department of Physical and Quarternary Geology at Stockholm University, upon the invitation of Department Chair, Professor Johan Kleman. The workshop was followed, on 17-20 June 2001, by a workshop organized by Kleman on Mechanisms, Patterns, and Timing of Ice Sheet Inception (Inceptions) at Idre, Sweden. Dr. Jane Dionne, Program Manager for Arctic Natural Sciences in the Office of Polar Programs of the US National Science Foundation (NSF) attended both workshops, along with all of those attending the Laurentide workshop, all but one of whom gave presentations. Papers presented at the Inceptions workshop will be published in the journal, *Quaternary International,* in 2002. The reason for holding the Laurentide and Inceptions workshops back-to-back was because during the first Laurentide workshop, held at the University of Maine in June of 2000, the question arose as to whether the manner in which the Laurentide Ice Sheet formed would determine its size and shape at the last glacial maximum and during early stages of deglaciation. The question was whether thick sea ice or floating ice shelves formed in Hudson Bay, in Foxe Basin, and in the straits and interisland channels of Arctic Canada during inception and, if so, how did that affect the subsequent development of the ice sheet? Specifically, did it affect the capacity of the ice sheet for abrupt changes that may trigger abrupt climate changes?

The second Laurentide workshop followed the same format adopted by the first workshop. Presentations were made by all of the investigators assigned to various components of the overall project, with no time limits on presentations, and allowing full discussions during and following each presentation. This provided a thorough exchange of views and problems related to each component, and among components.

The first day was devoted to presentations by the modelers who provide boundary conditions for the ice-sheet modelers. This included (1) modeling the isostatic response of North America and surrounding oceans to the changing load of Laurentide ice during the time from 25 to 11 ka BP (thousand years before present) when abrupt changes are known to have occurred, (2) reports by climate modelers on the regional climate of North America generated by a high-resolution climate model and a global atmospheric circulation model to which the regional model would be coupled, (3) results on determining the basal thermal conditions and flow patterns of the Laurentide Ice Sheet during this timespan, as deduced from interpretations of landforms observed in aerial photos and space images, and (4) the evidence for a thick ice shelf floating in the Arctic Ocean during Pleistocene glaciations, possibly including the last glacation, that would affect the dynamics of both the climate and ice-sheet models.

The second day was devoted to presentations by the ice-sheet modelers. This included (1) simulation of the last (Wisconsin) glaciation cycle of the Laurentide Ice Sheet controlled by the climate record from the GRIP corehole at the summit of the Greenland Ice Sheet, including simulations of stream flow and changing flow patterns that provided a close fit to known ice-sheet margins from 25 to 11 ka BP, (2) simulations of the subglacial hydrology that produced stream flow within the ice sheet, and how the amount and distribution of basal water changed through time to provide a mechanism for fast advance and subsequent stagnation of Laurentide ice, (3) results from physically-based calving models for both slab and tabular calving of ice along marine and lacustrine ice-sheet margins to provide a mechanism for fast retreat of Laurentide ice during stagnation of stream flow (the calving results were presented more fully at the Inceptions workshop).

The third day was devoted to planning and coordinating work for the third and final year of our Laurentide study. Owing to registration and a noon departure of the bus to Idre for the Inceptions workshop, these tasks were for the most part postponed until the last day of the Inceptions workshop. This allowed us to incorporate results by speakers at the Inceptions workshop into our Laurentide planning, notably the major conclusions arising from the Inceptions workshop that would affect our third-year Laurentide work.

Individual presentations at the Laurentide workshop, including discussions during and following the presentations, are summarized below. Presentations by Bromwich and Hughes were also presented at the workshop on Environmental Processes of the Ice Age: Land, Oceans, Glaciers (EPILOG) in November of 2000, and will be published in the first 2002 issue of *Quaternary Science Reviews.*

Pat Wu presented his results for modeling the isostatic response beneath and beyond the Laurentide Ice Sheet based on non-linear rheology in Earth's mantle similar to the known creep deformation in ice, rocks, and other crystalline materials. The crustal forebulge beyond the ice-sheet margin was higher, narrower, and collapsed in place, instead of migrating inward, as creep moved from the viscous to the plastic end of the viscoplastic creep spectrum. A question arose as to whether both a viscosity and a yield stress that were viscoplastic in nature should be used in the model. A related question concerned whether the crustal forebulge would occur within the ice-sheet margin where the thin concave profiles of ice streams discharged floating tongues and grounded lobes of ice, and whether the small ice load was below a viscoplastic yield stress for Earth's crust and mantle. How would this affect the depth and extent of proglacial lakes along landward ice-sheet margins? Another question was whether marine ice-sheet margins ending at the transition between continental and oceanic crust would produce a glacial isostatic response in the crust different from the one at ice-sheet margins ending within the North American continent.

Bob Oglesby presented results from version 3 of the NCAR Community Climate Model (CCM3) for simulating global atmospheric circulation. His results provide initial conditions and boundary conditions to constrain the regional climate model for North America and surrounding oceans. These results were presented as global maps of atmospheric pressure at the surface and aloft (500 millibars), winds at these levels, surface temperature and precipitation rates as rain or snow, and cloud cover, both seasonally and as annual averages over the world for present-day conditions of insolation and vegetation. The model output was then compared with output at the last glacial maximum for insolation and vegetation conditions at that time, but with no ice sheets other than present-day ice sheets. These experiments were conducted to investigate perturbations in model output that would guide our thinking as to the locations and extent of ice-sheet and mountain glaciation for generating the ice-sheet models of Northern Hemisphere glaciation that provide the elevated ice-sheet topography and lowered sea level for the "snapshots" of global climate at 25, 21, 17, 15, 13, and 11 ka BP when abrupt changes occurred. Questions arose as to whether seasonal or annual output was a better guide, especially the combination of warm, dry winters and cool, wet summers, compared to annual simulations that captured important conditions in the spring and fall.

Dave Bromwich and Rick Toracinta presented results from the global climate model (NCAR Community Climate Model version 3—CCM3) using present-day conditions of vegetation, insolation, topography, sea level, and using climatological sea surface temperatures (SST). These results served as the control and were compared with CCM3 results using conditions at the last glacial maximum (LGM). The modified boundary conditions for the LGM included (1) implementation of the Laurentide and Fennoscandian ice sheets from glaciological simulations by Jim Fastook, (2) lowered sea level by 120 meters, (3) used 20 ka BP orbital parameters for insolation, (4) set atmospheric carbon dioxide at 200 ppm, (5) reduced CLIMAP SST by 4 degrees Celsius from 30 N to 30 S, used a linear blend to CLIMAP values in the latitude band from 30 to 40 degrees, and used the CLIMAP values from 40 degrees to the Poles, and (6) retained the CLIMAP sea ice distribution except for modifications in the North Atlantic sector, based on results from sediment cores from Quebec University.

Results from the present-day control and the LGM simulations were averaged annually and seasonally (DJF, JJA) over ten years of the model run. The results show a strong global atmospheric response to the LGM boundary conditions. Global average surface temperature is nearly 10 degrees cooler at the LGM than at present with the strongest cooling just east of Greenland and over Antarctica. A redistribution of atmospheric mass is evident in the LGM simulations with a significant weakening of both the Icelandic low and the Antarctic circumpolar trough, with corresponding deepening of the Aleutian low. As a result, precipitation patterns show a relative increase during the LGM across the North Pacific and along the southern margin of the Laurentide Ice Sheet. The Atlantic storm track has a more zonal orientation and extends to western Europe at the LGM, indicative of the (near) absence of the North Atlantic drift. There is substantial weakening (drying) of the Asian monsoon. In the Southern Hemisphere, the South Pacific Convergence Zone (SPCZ) is enhanced during the LGM, with distinct precipitation maxima extending from New Guinea to near the southern Chilean coast.

Bromwich and Toracinta noted that the model atmosphere appears to be very sensitive to the SST distribution. Refinements to the LGM SST distribution were discussed and will be implemented prior to a final LGM run with the CCM3. Coupling the global CCM3 model to the regional climate model (NCAR Mesoscale Model version 5—MM5) for detailed mass balance information over the Laurentide Ice Sheet is anticipated by early fall of 2001. The plan for these simulations was presented in the Annual Report for Award #9905381 to The Ohio State University, written by Bromwich and submitted to NSF.

Johan Kleman presented his analysis of aerial photos and space images over Canada that provided a record of the regions beneath the Laurentide Ice Sheet where the bed was frozen and thawed, and a record of the changing flow regime of ice during the last glaciation cycle. In particular, the analysis identified four major Laurentide ice streams that flowed north at the last glacial maximum, one down the Mackenzie river valley, one into Amundsen Gulf, one into McClintock Channel, and one into the Gulf of Boothia. The overall flow pattern and these ice streams required that the Laurentide Ice Sheet and the Cordilleran Ice Sheet had merged across western Canada from the American border almost to the Arctic Ocean at the last glacial maximum. This is a significant alteration of the prevailing view that this merger was only temporary and confined to east-central British Columbia. This solid merger had been generated by the Fastook ice-sheet model, and could be suppressed only by prescribing unusual ablation rates along the ice-sheet margins in this region. Now we know that those high ablation rates did not exist. Kleman's ground-truth results provide a reliable constraint on output from our ice-sheet model.

Leonid Polyak presented results of his study with Margo Edwards of the submarine seismic and bathymetric profiling of Lomonosov Ridge and the Chuckchi Borderland in the Arctic Ocean. These results demonstrated that elevations shallower than 1000 m had been planed flat on Lomonosov Ridge by an ice shelf moving from the Barents and Kara Seas into the Amerasian Basin during at least some Pleistocene glaciations cycles, and that an ice shelf less thick and supplied by the Laurentide ice streams mapped by Kleman had moved westward across the Chukchi Borderland toward the central Arctic Ocean. In addition, a set of glacigenic lineations south of Chukchi Borderland required an ice dome on the continental shelf of the East Siberian Sea and/or the Chukchi Sea. These features are undated, but their mere existence calls into question the prevailing view that Eurasian glaciation was confined to Scandinavia and the Barents Sea at the last several glacial maxima. When the CCM3 model is run for the "snapshot" climate experiments, an ice-shelf albedo should be prescribed for the Arctic Ocean, and all ocean-atmosphere heat exchange in that region should be suppressed. In addition, north-flowing ice streams from the Laurentide Ice Sheet should be buttressed by the ice shelf in the Arctic Ocean at glacial maxima, but unbuttressed as the ice shelf disintegrates during early stages of deglaciation. Unbuttressing should facilitate irreversible gravitational collapse of the ice sheet, terminating the glaciation cycle.

Jim Fastook presented results of his finite-element model simulation of the last glaciation cycle. He compared glaciation histories for the Laurentide and Eurasian ice sheets for two initial conditions, a "black hole" scenario in which all highland ice calved upon reaching the sea and was therefore lost to the ice-sheet system, and a "white hole" scenario in which thick sea ice or ice shelves retained all calved ice within the system. Both scenarios led to identical conditions at the last glacial maximum for the Laurentide Ice Sheet, but the "white hole" scenario produced more extensive Eurasian glaciation at the last glacial maximum, especially in the Kara Sea and on the Russian mainland. This would be compatible with flow directions deduced by Polyak for an ice shelf in the Arctic Ocean. The model also generated fast stream flow at the places where Kleman had located ice streams at the last glacial maximum, but it generated sheet flow with high surface and basal melting rates along the southern Laurentide margin, where ice lobes believed to be termini of ice streams have been mapped. The model prescribes a "pole of glaciation" in Greenland in order to attain the southern limit of Laurentide ice. Alternatively, the pole of glaciation may be closer to the North Pole, and the southern limit of advance may be produced by surging ice streams that behave almost like linear ice shelves. The physics for this alternative scenario does not yet exist in Fastook's model (or in any other ice-sheet model). This possibility must be addressed.

Jesse Johnson presented results of his subglacial hydrology model, in which basal meltwater produced by Fastook's ice-sheet model flows primarily down the ice thickness gradient, where the meltwater then refreezes, seeps into a subglacial aquifer, or is discharged along the ice-sheet margin. Fast stream flow in the ice sheet is produced where subglacial meltwater drainage is concentrated. Meltwater production and discharge, controlled ultimately by the climate record from the GRIP corehole through the Greenland Ice Sheet, shuts on and off in a way that might be matched to the Heinrich events of icebergs discharged from the Laurentide Ice Sheet. The ice-sheet elevation lowers up to 1000 m during these episodes of rapid discharge. If the gravitational driving force for sheet flow and shelf flow can be combined to produce a more physically-based stream flow, in which ice streams have concave surface profiles, then the thick basal water layer produced by the hydrology model should become concentrated along ice streams, enhancing their rapid advance and, when the meltwater is discharged along their termini, hasten their stagnation. This possibility must be addressed.

Terry Hughes and Jim Kenneally presented models for calving along marine and lacustrine ice-sheet margins. The Hughes model for slab calving above water and block calving below water is based on a detailed study of slab calving from an ice wall produced by the August 1970 volcanic eruption on Deception Island, which lies just north of the Antarctic Peninsula. The model calculates rates of slab and block calving that encompass the envelope of observed calving rates from Alaskan tidewater glaciers and Greenland ice streams. The calving rate increases with the longitudinal strain rate on these glaciers and ice streams, as a faster strain rate decreases the spacing of crevasses along which slabs calve. The Kenneally model for calving tabular icebergs from floating ice streams and ice shelves employs dislocation-based fracture mechanics and crack propagation through elastic materials to calculate the vertical rate of crack propagation. Dividing the ice thickness by this rate gives the time for fracture, and dividing the distance from the fracture to the ice front by this time gives the calving rate of tabular icebergs. These calving mechanisms allow rapid retreat of the Laurentide Ice Sheet along marine and lacustrine margins after ice-stream surges have extended these margins and the margins have stagnated when the surges are spent.

Planning for the third and final year of the Laurentide modeling study consisted of (1) incorporating the Wu glacial isostasy model and the Hughes-Kenneally calving models into the Fastook ice-sheet model and the Johnson hydrology model, (2) developing an ice-stream model that is physically based and linked to the ice sheet and subglacial hydrology models, with an on-off capability for stream flow, (3) coupling the high-resolution North American regional climate model to the NCAR global climate model, and using the ice-sheet model to generate high ice-sheet elevations and low sea levels for the "snapshot" climate simulations, (4) conducting the snapshot simulations at 25, 21, 17, 15, 13, and 11 ka BP to provide input to the time-dependent simulations by the full ice-sheet/hydrology/isostasy/calving model of abrupt changes in the size and shape of the Laurentide Ice Sheet through this timespan, (5) running the full ice-sheet model through the last glaciation cycle to simulate abrupt changes that coincide with known abrupt changes, especially with Heinrich discharges of icebergs into the North Atlantic, and with the ice flow regime and basal thermal regime mapped by Kleman, and (6) using these abrupt changes in the Laurentide Ice Sheet as boundary conditions for the regional and global climate models to see if the Laurentide changes cause abrupt climate changes.

The planning meeting included a discussion of extending the Laurentide study to all ice sheets in the timespan from 25 to 11 ka BP, with the goal of determining whether the other ice sheets also produce abrupt changes that affect global climate, and whether these changes are synchronous or nearly synchronous. An important element of this future study would be to determine the extent of Eurasian glaciation at and near the last glacial maximum. That glaciation should lie somewhere between the limits of "black hole" and "white hole" glaciation. Determining the extent of ice shelves in the Arctic Ocean just before, at, and just after the last glacial maximum will provide an essential boundary condition in controlling these simulations.

Terence J. Hughes
6 July 2001