02 INFORMATION ABOUT PRINCIPAL INVESTIGATORS/PROJECT DIRECTORS(PI/PD) and co-PRINCIPAL INVESTIGATORS/co-PROJECT DIRECTORS

Submit only ONE copy of this form **for each PI/PD and co-PI/PD** identified on the proposal. The form(s) should be attached to the original proposal as specified in GPG Section II.B. Submission of this information is voluntary and is not a precondition of award. This information will not be disclosed to external peer reviewers. ***DO NOT INCLUDE THIS FORM WITH ANY OF THE OTHER COPIES OF YOUR PROPOSAL AS THIS MAY COMPROMISE THE CONFIDENTIALITY OF THE INFORMATION.***

PI/PD Name: Douglas R MacAyeal

Gender: ☒ Male ☐ Female

Ethnicity: (Choose one response) ☐ Hispanic or Latino ☒ Not Hispanic or Latino

Race:
(Select one or more)

- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Black or African American
- ☐ Native Hawaiian or Other Pacific Islander
- ☒ White

Disability Status:
(Select one or more)

- ☐ Hearing Impairment
- ☐ Visual Impairment
- ☐ Mobility/Orthopedic Impairment
- ☐ Other
- ☐ None

Citizenship: (Choose one) ☒ U.S. Citizen ☐ Permanent Resident ☐ Other non-U.S. Citizen

Check here if you do not wish to provide any or all of the above information (excluding PI/PD name): ☒

REQUIRED: Check here if you are currently serving (or have previously served) as a PI, co-PI or PD on any federally funded project ☒

Ethnicity Definition:
Hispanic or Latino. A person of Mexican, Puerto Rican, Cuban, South or Central American, or other Spanish culture or origin, regardless of race.
Race Definitions:
American Indian or Alaska Native. A person having origins in any of the original peoples of North and South America (including Central America), and who maintains tribal affiliation or community attachment.
Asian. A person having origins in any of the original peoples of the Far East, Southeast Asia, or the Indian subcontinent including, for example, Cambodia, China, India, Japan, Korea, Malaysia, Pakistan, the Philippine Islands, Thailand, and Vietnam.
Black or African American. A person having origins in any of the black racial groups of Africa.
Native Hawaiian or Other Pacific Islander. A person having origins in any of the original peoples of Hawaii, Guam, Samoa, or other Pacific Islands.
White. A person having origins in any of the original peoples of Europe, the Middle East, or North Africa.

WHY THIS INFORMATION IS BEING REQUESTED:

The Federal Government has a continuing commitment to monitor the operation of its review and award processes to identify and address any inequities based on gender, race, ethnicity, or disability of its proposed PIs/PDs. To gather information needed for this important task, the proposer should submit a single copy of this form for each identified PI/PD with each proposal. Submission of the requested information is voluntary and will not affect the organization's eligibility for an award. However, information not submitted will seriously undermine the statistical validity, and therefore the usefulness, of information recieved from others. Any individual not wishing to submit some or all the information should check the box provided for this purpose. (The exceptions are the PI/PD name and the information about prior Federal support, the last question above.)

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PI/PD Name: Jeremy N Bassis

Gender: ☒ Male ☐ Female

Ethnicity: (Choose one response) ☐ Hispanic or Latino ☐ Not Hispanic or Latino

Race:
(Select one or more)
☐ American Indian or Alaska Native
☐ Asian
☐ Black or African American
☐ Native Hawaiian or Other Pacific Islander
☐ White

Disability Status:
(Select one or more)
☐ Hearing Impairment
☐ Visual Impairment
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☐ Other
☐ None

Citizenship: (Choose one) ☒ U.S. Citizen ☐ Permanent Resident ☐ Other non-U.S. Citizen

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REQUIRED: Check here if you are currently serving (or have previously served) as a PI, co-PI or PD on any federally funded project ☐

Ethnicity Definition:
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Black or African American. A person having origins in any of the black racial groups of Africa.
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List of Suggested Reviewers or Reviewers Not To Include (optional)

SUGGESTED REVIEWERS:

Sarah B. Das
Thomas A. Neumann
Leigh A. Stearns
Ian M. Howat
Mark A. Fahnestock
Richard B. Alley
Gordon Hamilton
James L. Fastook
Ginny Catania
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Jay Zwally
Atsumu Ohmura
Roger Braithwaite
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COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 08-1 **NSF 08-597** **11/18/08**	**FOR NSF USE ONLY** **NSF PROPOSAL NUMBER**
FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.) **ARC - ARCTIC RESEARCH AND EDUCATION**	

DATE RECEIVED	NUMBER OF COPIES	DIVISION ASSIGNED	FUND CODE	DUNS# (Data Universal Numbering System)	FILE LOCATION
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AWARDEE ORGANIZATION CODE (IF KNOWN) **0017749000**	
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IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions) ☐ SMALL BUSINESS ☐ FOR-PROFIT ORGANIZATION ☐ MINORITY BUSINESS ☐ WOMAN-OWNED BUSINESS ☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **Model Studies of Surface Meltwater Lakes of the Greenland Ice Sheet**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ **370,309**	**36** months	**06/01/09**	

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

- ☐ BEGINNING INVESTIGATOR (GPG I.G.2)
- ☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C)
- ☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.D, II.C.1.d)
- ☐ HISTORIC PLACES (GPG II.C.2.j)
- ☐ SMALL GRANT FOR EXPLOR. RESEARCH (SGER) (GPG II.D.1)
- ☐ VERTEBRATE ANIMALS (GPG II.D.5) IACUC App. Date ________
  PHS Animal Welfare Assurance Number ________
- ☐ HUMAN SUBJECTS (GPG II.D.6) Human Subjects Assurance Number ________
  Exemption Subsection ________ or IRB App. Date ________
- ☐ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.2.j)
  ____
- ☐ HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.G.1)

PI/PD DEPARTMENT **Department of Geophysical Sciences**	PI/PD POSTAL ADDRESS **5734 S. Ellis Ave** **Chicago, IL 60637** **United States**
PI/PD FAX NUMBER **773-702-8198**	

NAMES (TYPED)	High Degree	Yr of Degree	Telephone Number	Electronic Mail Address
PI/PD NAME **Douglas R MacAyeal**	**Ph.D.**	**1983**	**773-702-8027**	**drm7@midway.uchicago.edu**
CO-PI/PD **Jeremy N Bassis**	**PhD**	**2007**	**312-738-0535**	**jbassis@uchicago.edu**
CO-PI/PD				
CO-PI/PD				
CO-PI/PD				

CERTIFICATION PAGE

Certification for Authorized Organizational Representative or Individual Applicant:

By signing and submitting this proposal, the Authorized Organizational Representative or Individual Applicant is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding debarment and suspension, drug-free workplace, and lobbying activities (see below), nondiscrimination, and flood hazard insurance (when applicable) as set forth in the NSF Proposal & Award Policies & Procedures Guide, Part I: the Grant Proposal Guide (GPG) (NSF 08-1). Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U. S. Code, Title 18, Section 1001).

Conflict of Interest Certification

In addition, if the applicant institution employs more than fifty persons, by electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative of the applicant institution is certifying that the institution has implemented a written and enforced conflict of interest policy that is consistent with the provisions of the NSF Proposal & Award Policies & Procedures Guide, Part II, Award & Administration Guide (AAG) Chapter IV.A; that to the best of his/her knowledge, all financial disclosures required by that conflict of interest policy have been made; and that all identified conflicts of interest will have been satisfactorily managed, reduced or eliminated prior to the institution's expenditure of any funds under the award, in accordance with the institution's conflict of interest policy. Conflicts which cannot be satisfactorily managed, reduced or eliminated must be dislosed to NSF.

Drug Free Work Place Certification

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Drug Free Work Place Certification contained in Exhibit II-3 of the Grant Proposal Guide.

Debarment and Suspension Certification

(If answer "yes", please provide explanation.)

Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency? Yes ☐ No ☒

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Debarment and Suspension Certification contained in Exhibit II-4 of the Grant Proposal Guide.

Certification Regarding Lobbying

The following certification is required for an award of a Federal contract, grant, or cooperative agreement exceeding $100,000 and for an award of a Federal loan or a commitment providing for the United States to insure or guarantee a loan exceeding $150,000.

Certification for Contracts, Grants, Loans and Cooperative Agreements

The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with this Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, ''Disclosure of Lobbying Activities,'' in accordance with its instructions.

(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

Certification Regarding Nondiscrimination

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative is providing the Certification Regarding Nondiscrimination contained in Exhibit II-6 of the Grant Proposal Guide.

Certification Regarding Flood Hazard Insurance

Two sections of the National Flood Insurance Act of 1968 (42 USC §4012a and §4106) bar Federal agencies from giving financial assistance for acquisition or construction purposes in any area identified by the Federal Emergency Management Agency (FEMA) as having special flood hazards unless the:

(1) community in which that area is located participates in the national flood insurance program; and
(2) building (and any related equipment) is covered by adequate flood insurance.

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(1) for NSF grants for the construction of a building or facility, regardless of the dollar amount of the grant; and
(2) for other NSF Grants when more than $25,000 has been budgeted in the proposal for repair, alteration or improvement (construction) of a building or facility.

AUTHORIZED ORGANIZATIONAL REPRESENTATIVE	SIGNATURE	DATE
NAME		

TELEPHONE NUMBER	ELECTRONIC MAIL ADDRESS	FAX NUMBER

*SUBMISSION OF SOCIAL SECURITY NUMBERS IS VOLUNTARY AND WILL NOT AFFECT THE ORGANIZATION'S ELIGIBILITY FOR AN AWARD. HOWEVER, THEY ARE AN INTEGRAL PART OF THE INFORMATION SYSTEM AND ASSIST IN PROCESSING THE PROPOSAL. SSN SOLICITED UNDER NSF ACT OF 1950, AS AMENDED.

Project Summary

Intellectual Merit: We seek a better understanding of the processes and consequences of surface meltwater production on the Greenland ice sheet, particularly the development of surface lakes and their subsequent drainage to the subglacial bed. Field study shows that Greenland meltwater production is linked to changes in ice-sheet flow, i.e., speed-up due to meltwater drainage to the subglacial bed, and this process has been invoked to explain (in part) increased iceberg calving rates observed over the recent decade. To realistically assess Greenland's contribution to sea-level rise over the coming century, it is necessary to improve representation of surface meltwater processes in ice-sheet and climate models. Our proposed research seeks to improve current understanding with the aid of numerical models designed to simulate the evolution of meltwater lakes on the Greenland Ice Sheet. The work effort will focus on: (a) establishing a self-consistent thermodynamic treatment that explicitly treats radiative forcing using a surface energy balance model, and (b) investigating new approaches to the dynamics of englacial water conduits that cause lake drainage to the subglacial bed. The surface energy balance formulation will specify the downward radiation from sun, clouds and clear sky in all the important wavelength bands (e.g., shortwave and longwave), use bulk transfer formulations to parameterize sensible- and latent-heat fluxes, and explicitly model heat transfer processes below the surface. The new approaches to englacial water conduit dynamics proposed here will involve stochastic processes involved in activation of pre-existing crack systems assumed to have spatial density and orientations described by probability density functions.

Two products will be created from the model development and experimentation. First will be a series of numerical simulations designed to address basic questions concerning the formation of surface lakes on the Greenland Ice Sheet and their drainage to the ice-sheet bed. These questions form the basic nucleus of how feedbacks between surface meltwater production and ultimate glacial discharge into the ocean will evolve, as more of Greenland's surface becomes an ablation zone. Second, we plan to develop a framework of diverse model approaches and apply them to the sub-grid-scale parameterization of large-scale ice-sheet models, thereby coupling them to climate models. This framework will be embodied by a website that encourages model intercomparison and future model enhancement.

Broader Impacts: The proposed work relates directly to the socio-environmental topics of climate change and sea-level rise, and will contribute to the important goal of advising public policy. ***Integration of research and education*** will be fostered through (1) the mentorship of a summer-intern/collegiate scholar associated with the Summer Research-Early Identification Program (SR-EIP) of the Leadership Alliance (University of Chicago is a project host site), (2) the training and education of a graduate student (Mac Cathles) and the mentoring of a postdoctoral scholar (Dr. Jeremy Bassis), and (3) participation in a summer science enrichment program for high-school teachers organized by colleagues at the University of Chicago.

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Biographical Sketches (Not to exceed 2 pages each)	4	
Budget (Plus up to 3 pages of budget justification)	6	
Current and Pending Support	2	
Facilities, Equipment and Other Resources	1	
Special Information/Supplementary Documentation	0	
Appendix (List below.) **(Include only if allowed by a specific program announcement/ solicitation or if approved in advance by the appropriate NSF Assistant Director or designee)**		

Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

Project Description

1. Results from Prior NSF Support

NSF OPP 0229546 ***"Collaborative Research of Earth's largest Icebergs"***, 07/01/2003 to 06/30/2008, $483,865.

This project was designed to investigate (a) the drift, evolution and ultimate break-up and melting of iceberg B15, and (b) the origin of iceberg tremor (a seismic signal picked up on various islands in the South Pacific).

Iceberg Harmonic Tremor (IHT) emanating from tabular icebergs in the Southern Ocean and along calving margins of the Antarctic Ice Sheet is a complex, evolving signal at frequencies above approximately 0.5 Hz. IHT has been observed as *T*-phases on islands in the equatorial Pacific, as hydro-acoustic signals in the Indian Ocean, and by local and regional Antarctic seismic networks. To identify the IHT source mechanism and to understand its relevance to iceberg calving, evolution, and break-up, we deployed seismometers on a giant (25 km by 50 km) tabular iceberg called C16 in the Ross Sea, Antarctica, during a uniquely accessible period (austral summer, 2003/4) when it was aground against the northern shore of Ross Island. During the deployment period, C16 was in sporadic contact with another giant tabular iceberg, B15A, which was moving under the influence of local ocean currents. This study reveals that the C16-associated IHT was a manifestation of extended episodes of discrete, repeating stick-slip icequakes (typically thousands of individual sub-events per hour) produced when the cliff-like edges of the tabular icebergs underwent glancing, strike-slip collisions. The IHT signal that we observed is thus not a phenomenon associated with iceberg elastic or fluid resonance modes, but is instead the consequence of long sequences of very regularly-spaced and similar pulses of seismic radiation from these constituent stick-slip sub-events. IHT represents a newly identified glaciogenic seismicity that can be used to improve our understanding of iceberg dynamics and possibly of ice-shelf disintegration processes.

Iceberg Firn Temperature Observation. Automatic weather stations (AWS) with thermistor strings deployed in the upper 16 meters of firn were deployed on Iceberg C16 (now adrift in the Southern Ocean off East Antarctica) and on the Nascent Iceberg (part of the Ross Ice Shelf expected to become an iceberg in the near future). Analysis of the firn temperature/depth profiles at these two sites is an ongoing process (and will continue as long as the stations survive and can transmit data via the ARGOS satellite system).

Contributions to Human Resources: Three PhD and two MS degrees were awarded as a result of research performed on this project. Of these, two PhD and one MS degrees were awarded to women.

Broader Impacts: The PI and graduate students participated in public lectures in the Chicago Area, interaction with media (e.g., an interview with NPR's *All Things Considered*) and participated in the making of Werner Herzog's film *Encounters at the End of the World* when Herzog was an artist in residence at McMurdo Station.

Publications: Project participants published twenty-two papers in refereed journals. Publications that provide an overview of project results are:

MacAyeal, D. R., E. A. Okal, R. C. Aster and J. N. Bassis (2008). Seismic and hydroacoustic tremor generated by colliding icebergs. *Journal of Geophysical Research*, 113, F03011, doi: 10.1029/2008JF001005.

MacAyeal, D. R., M. H. Okal, J. E. Thom, K. M. Brunt, Y.-J. Kim and A. K. Bliss (2008). Tabular iceberg collisions within the coastal regime. *Journal of Glaciology*, 54(118), 371-386.

Publications that are related to the proposed research include:

Sergienko, O. V., D. R. MacAyeal and J. E. Thom (2007). Reconstruction of snow/firn thermal properties from observed temperature variation: Application to iceberg C16 (Ross Sea, Antarctica), 2004-2007. *Annals of Glaciology*, 49, 91-95.

Sergienko, O. and D. R. MacAyeal, 2005. Surface melting on Larsen Ice Shelf, Antarctica. *Annals of Glaciology*, 40: 215-218.

Data Archive and Availability: Metadata is described in the Global Change Master Directory: http://gcmd.gsfc.nasa.gov/getdif.htm?macayeal_0229546; Actual data is archived and freely available at the NSIDC: e.g., http://nsidc.org/data/nsidc-0347.html.

2. Overview

Surface melting plays a well-known and direct role in the mass balance of the Greenland Ice Sheet, accounting for approximately 50% of the net mass lost [Box et al., 2004; Hanna et al., 2005; Rignot et al., 2008; Howat et al., 2008]. With the Greenland Ice Sheet mass balance becoming increasingly negative [Velicogna and Wahr, 2005], and with about half this change being attributed to the direct effect of increased surface melting [Krabill et al., 2004], the study of surface melting and runoff [e.g., Bougamont et al., 2005] has become increasingly important as a means to predict the influence of Greenland on future sea level rise.

One of the emerging discoveries in the study of surface melting and overall mass balance is the realization that meltwater can accumulate in surface lakes and, when certain enabling conditions are met, drain englacially through more than a kilometer of sub-freezing ice to reach the ice sheet bed [Lüthje et al., 2006a; Das et al., 2008, Catania et al., 2008]. This previously unrecognized process allows surface processes (surface meltwater production) to carry the signal of climate change rapidly to the subglacial bed which is normally insulated by >1000 m of overlying ice and thus otherwise slow to respond to climate change [Alley et al., 2005]. Some observations report the surprising result that meltwater drainage to the bed increases ice flow toward iceberg-calving margins [Zwally et al., 2002; van de Wal et al., 2008; Joughin et al., 2008], where surface lowering and increased outlet glacier discharge is already being observed [Howat et al., 2008].

This potential feedback between two ablation mechanisms is worrisome, and means that understanding the mechanisms by which surface meltwater reaches the bed must become a high-priority subject of glaciological research. An example of where this feedback would be most worrisome is provided by Fig. (1), which shows that a large area of the southern lobe where basal conditions are currently frozen is subject to increasingly large area of surface melting. It is possible that surface lakes developing in this area (e.g., the red zone in Fig. 1) could enhance basal lubrication and lead to greater outlet glacier discharge into the North Atlantic [e.g., Howat et al., 2007; 2008]. To foster improved predictions of these processes, it is imperative to develop multiple research approaches that can serve as the grist for deliberation by scientific and public policy advisory panels (e.g., the IPCC) that must assess Greenland's impending contribution to sea level rise.

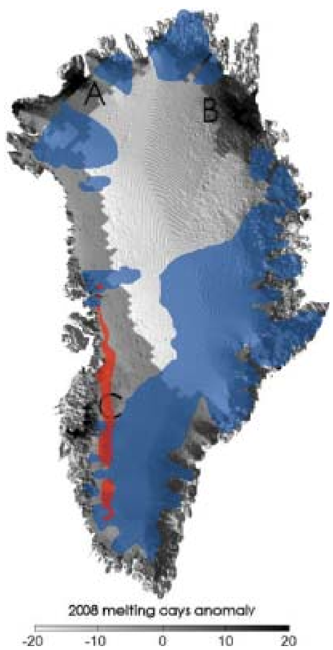

Figure 1 - *Greenland surface and basal conditions are displayed on top of a digital elevation model (DEM) of Greenland. Surface melting day anomalies (i.e., areas where summer melting has recently amplified) are shown in dark gray for 2008 [Tedesco, 2008]. Overlain on top are blue regions where basal temperatures are predominantly below freezing [Greve, 2005] and red regions where surface meltwater lakes are currently observed via MODIS imagery. The southern lobe of Greenland experiencing new melting in 2008 (i.e., the large area in blue that overlaps the area in dark gray) raises the possibility that surface lakes will soon form in this region.*

2.1 Primary Objectives

A vital issue in the effort to predict and understand the Greenland Ice Sheet's evolution in a warming climate is the need to incorporate the effects of surface meltwater lake (pond) formation and drainage in the current generation of ice-sheet flow models [e.g., as begun by Parizek and Alley, 2004]. Without resolving this issue, the ability to predict the effect of climate change is limited. Because surface meltwater lake formation and drainage is a complicated, highly non-linear process—involving a large number of contingencies and variables—we propose that the best approach to incorporating the effects of surface lakes in large-scale ice-sheet models is to first develop rational (based on asymptotic approximations) and verifiable (through comparison with observation) models of the micro- and meso-scale (snow grain scale to englacial conduit scale) processes that govern surface lake evolution. We propose to develop such models and explore their behavior in response to a variety of climatic forcing conditions (including those which are estimated from empirical projections and numerical forecasts of climate change). With this in mind, we state our 5 primary research objectives:

- Develop models that predict the evolution of the temperature and surface characteristics of ice, firn and snow surface layers in 1 and 2 spatial dimensions. These models will predict the production of surface meltwater in terms of the atmospheric environment (i.e., wind speed, radiative forcing, etc.) and will determine the co-evolution of the small-scale topography of the ice sheet surface as a means of predicting where surface lakes can (and cannot) form along with topographic and erosional feedbacks.
- Develop "cryo-limnological" models of surface lake evolution that predict the response of lake bodies to the seasonal cycle of atmospheric forcing. These models will explicitly treat the effects of: radiative transfer, thermal and wind-driven convection, and the range of conditions that permits persistent lakes that survive the winter by forming "lake ice".
- Develop models of alternative processes by which surface lakes drain englacially through thick, cold ice (as well as through ice that is temperate). One particularly promising approach will be to investigate the reactivation of pre-existing englacial crack/tunnel systems having spatial patterns described by probability density functions. This approach will be contrasted against the traditional lake-drainage model based on hydrostatically supported fracture propagation.
- Develop models of across-ice-surface flow (runoff) of meltwater into rivulets and lakes based on analogue treatments of channel incision in eroding terrestrial river systems. These models will be used to predict the evolution of small-scale ice-sheet surface roughness that promotes surface meltwater accumulation in closed basins, i.e., lake formation, as well as limits in the proportion of ice sheet surface area that permits surface melt lakes.
- Develop a rational (based on traditional asymptotic analysis) treatment of "far field" (full thickness) ice-sheet temperature which influences conditions at the bottom of surface meltwater lakes, conditions within englacial water conduits, and conditions at the subglacial bed into which surface lakes may drain.

Specific scientific questions we seek to address include:

1. Under what conditions do surface meltwater lakes form as perennial features each summer?
2. Under what climate conditions (if any) can surface meltwater lakes grow to be large and deep enough to avoid freezing over during the winter and will surface lakes on the Greenland ice sheet suffer the same sensitivity to conditions that promote an "ice-free Arctic Ocean" scenario, i.e., where lakes on the ice sheet will persist year round?
3. How do the size, shape and aerial extent of lakes vary as a function of surface morphology of the ice sheet (i.e., surface roughness and surface slope of the ice sheet)?
4. How do the size, depth and shape of lakes affect the probability of intersecting with an englacial drainage feature?
5. How does the geometry of pre-existing, but inactive, englacial fractures promote or inhibit englacial drainage? How likely is it that englacial conduits reactivate?

2.2 What We Can Contribute

To meet these objectives, we shall build upon the extensive and richly informative work on surface meltwater processes that has preceded our engagement with this important problem (i.e., as exemplified by the extensive literature on the subject). We believe we can add to this venerable work in the following ways:

- The subject of Greenland surface melting will be a primary topic of science and public policy advisory panels charged with the responsibility of assessing future sea level rise (and other effects of ice sheet melting). A key paradigm in the success of these panels, most notably exemplified by the recent IPCC report, is the realization of consensus opinion. Our proposed involvement in Greenland ice-sheet surface melting research will add to the depth and diversity of research results leading to a broader consensus.
- We plan to investigate/model some processes for the first time (i.e., channel incision models of surface runoff and roughness evolution), and to propose alternative models of other processes (i.e., a "crack reactivation process" based on probability rather than hydrostatically supported "one-time-only" fracture propagation). In an emerging field such as surface ice sheet hydrology, the investigation of more than one modeling approach to ice-sheet surface melting and lake evolution is desirable.
- Our effort is focused on micro and meso-scale processes (centimeter to kilometer scale) where as the majority of previous modeling efforts have been geared toward macroscopic (tens to hundreds of kilometer scale) processes that affect the large-scale mass balance of the Greenland Ice Sheet. Improved understanding of the sub-grid scale processes may allow a parameterized version of the processes to be incorporated into numerical ice sheet models.
- Finally, we are experienced ice-sheet modelers who also have extensive experience in field observation of ice-sheet surface environment, thermal evolution of firn, and surface melting of icebergs and ice shelves (i.e., see results of previous NSF-supported research). Our experience includes helping develop models for the Greenland Ice Sheet's North East Ice Stream [Joughin et al., 2001] and working within the context of the EISMINT model intercomparison experiments directed towards improvement of large-scale Greenland Ice Sheet models [Huybrechts, 1996].

2.3 Broader Impacts

The proposed work will involve three activities that ***integrate research and education***.

Training and Mentoring. The proposed project will also provide support for the PI to mentor Dr. Jeremy Bassis, who is a current postdoctoral scholar at the University of Chicago. Dr. Bassis already has achieved success in proposal writing and publication; thus, the mentoring plan will build upon these successes by: (1) helping him network in search for a faculty position, (2) exposing him to teaching and course development for undergraduate education, (3) giving him experience interacting with the public and with popular press and media, and above all, (4) fostering continued intellectual development.

The PI and Dr. Bassis will co-mentor a graduate student (L. M. Cathles) on the project. Mac Cathles is a promising young scientist who has participated in four field campaigns in both Greenland (with Dr. Mary Albert) and Antarctica (with Dr. Ted Scambos, and with the PI), and has published several first-authored papers in major journals on problems relating to ice-sheet surface temperature and iceberg calving (his short bio is included as a supplemental document). Cathles's professional development will continue with plans for him to: (1) complete a dissertation on the subject of the research described in this proposal, (2) become familiar with scientific discourse via his attendance at meetings, conferences and symposia, and (3) learn to teach and interact with public via participation in our outreach activities (see below). The PI will meet regularly with Dr. Bassis and Mac Cathles to discuss progress toward goals.

Broad dissemination to enhance scientific understanding. Project resources will be used to produce a series of lessons, lectures and demonstrations to be offered to Chicago's high-school science teachers as part of a summer professional development program organized by Prof. Noboru Nakamura (of our Department) and other colleagues in the Division of Physical Sciences at the University of Chicago. Mac Cathles, the graduate student involved in this proposal was a workshop helper during the 2008 event, and plans to participate more formally in future years by developing demonstrations that capture the intrinsic curiosity of young people and teachers, such as how the cryosphere influences every-day life. We shall also approach the Science and Technology Mentoring and Outreach Program of the University of Chicago to see if our demonstration materials can be used in one of their six outreach and mentoring activity channels (e.g., Science Teacher for a Day).

Fostering diversity. The University of Chicago participates in the Summer Research Early Identification Program (SR-EIP, http://leadershipalliance.uchicago.edu/). The PI will set up a Research Experience Program Site at the University of Chicago to host a summer collegiate scholar to perform satellite image analysis of Greenland surface lakes. This program offers many advantages for small research teams to participate in the encouragement of undergraduate students from underrepresented and underserved groups to become involved in scientific activities and careers. The SR-EIP vets the collegiate scholars who apply and provides stipends for collegiate scholars to attend program sites. We shall ask for funds to support the workstation and data storage needs of the summer intern we hope to attract from the SR-EIP program. The summer intern will be co-mentored by the PI and by Dr. Bassis. Funds are not needed for the summer intern's stipend or travel, as they are provided by SR-EIP.

Dissemination to enhance scientific understanding. We shall attempt to create standardized experiments and model result benchmarks to contribute to other groups working on the same or similar problems for the purpose of model inter-comparison. Many grass-roots efforts are underway presently to develop community standards for ice-sheet model development and inter-comparison (e.g., Jeremy Bassis is currently involved in an effort to predict sea-level rise contributions from Antarctica in a multi-investigator effort organized by Bob Bindschadler). We intend to proactively establish model-performance benchmarks and inter-comparison tests for further use by the glaciological and climate communities. We anticipate that these materials will lead to the establishment of a model inter-comparison website.

3. Research Description

To construct models of surface melting, surface lake evolution, and englacial surface lake drainage we must contend with a large number of interacting processes that exist on a variety of spatial and temporal scales, most of which are below the spatial and time resolution of common ice-sheet and climate models. To simplify the effort, we propose to focus our modeling effort on 4 process “clusters”: A. Surface energy balance; B. Surface water flow; C. lake energy balance and evolution; and D. Englacial drainage.

3.1 Process Cluster A – Firn Surface and Ice Surface Energy Balance

Historically, ice sheet models have relied on highly-empirical formulations of surface ablation based either on the adjustment of present-day ablation rates using environmental histories derived from ice cores [e.g., Kapsner et al., 1995] or on the positive-degree-day (PDD) empirical relationship between melting and surface temperature observed in the present climate regime [e.g., Ohmura, 2001]. These formulations have been extremely useful in initial efforts to examine sea-level contributions from large-scale (tens of kilometers) and long time-scale (hundreds of thousands of years) models of the Greenland Ice Sheet [e.g., Huybrechts, 2002] or to study future warming scenarios [e.g., Greve, 2000]. What these methods offer are simple relationships between ablation, temperature, elevation and paleoclimate ice-core record variables that avoid the need to specify the myriad of (often unknown) radiative parameters needed to explicitly treat the surface energy budget.

This easy approach, however, is insufficient for investigating specific, small-scale phenomena such as surface meltwater lake formation. For this, we must rely on the more complex alternative to these highly-empirical formulations known as the surface energy balance method [e.g., Gallée and Duynkerke, 1997; Bougamont et al., 2005; Sergienko, 2005; Sergienko and MacAyeal, 2005]. We drive our surface energy balance model using the formulation of radiative transfer developed by John Frederick at the University of Chicago [Frederick and Erlick, 1995; Frederick and Lubin, 1988]. This formulation will specify the downward radiation from sun, clouds and clear sky in all the important wavelength bands (e.g., short-wave and long-wave). We shall use bulk transfer formulations to parameterize these fluxes in terms of the temperature of the air above the surface (at a standard height of 10 m), the velocity of the wind blowing across the surface (assuming a standard vertical wind profile), and the relative humidity above the surface (again using a standard vertical profile). These inputs (downward radiation, surface air temperature, surface wind and humidity) can be estimated from climate models. However, the resolution of these models (typically hundreds of kilometers at best), is too coarse to obtain detailed radiative and surface meteorology at the kilometer scale we are considering in this study. Therefore, our intention is to use output from climate models and automatic weather stations as a guide to set reasonable baselines for each of the many parameters. A key aspect of our proposed study is bounding the range of behavior possible by fully exploring the parameter space.

The surface radiation balance seeks equilibrium between the incoming radiation, both short-wave radiation from the sun and sky, and long-wave radiation from the near surface atmosphere and clouds, with the outgoing long-wave radiation emitted from the surface. We write the radiation balance as

$$F_{rad} = (1-\alpha)S + \sigma e_a e_g T_{sa}^4 - \sigma e_g T_g^4, \qquad (1)$$

where S is the incoming insolation, α is the surface albedo, σ is the Stephan Boltzmann constant, e_a is the emisivity of the atmosphere, e_g is the emisivity of the surface, T_{sa} is the temperature of the surface air, and T_g is the temperature of the ground. The first term of Eqn. (1) is the incoming solar radiation incident on the surface of the ice sheet. The second and third terms account for the grey body radiation of the atmosphere just above the surface of the ice and radiation from the surface itself. The surface energy balance accounts for all the fluxes of energy that redistribute incoming radiation. These fluxes include a heat flux into the ground (F_{cond}) and turbulent heat fluxes which can be separated into a latent heat flux (F_L) and a sensible heat flux (F_{sens}). We follow Bougamont et al. [2005] and include an energy flux from precipitation, and Mölg and Hardy [2004] by also including a melting term that accounts for the latent heat of melting only if the ground temperature T_g reaches the freezing temperature of water. The surface energy balance can be written as

$$0 = F_{rad} - F_{sens} - F_L - F_{cond} + F_{precip} - F_{melt}. \qquad (2)$$

In formulating the turbulent heat flux, we follow Pierrehumbert [2008] and assume that the typical vertical velocity scale is proportional to the horizontal wind at the surface. Thus a generic flux is $F_c = aU\Delta C$, where a is a coefficient describing the strength of the flux. We write the sensible and latent heat flux as

$$F_{sens} = c_p \rho_s C_D U (T_{sa} - T_g) \qquad (3)$$

and

$$F_L = \frac{L}{r_w T_{sa}} C_D U (p_{sat}(T_g) - h_{sa} \cdot p_{sat}(T_{sa})). \qquad (4)$$

Where c_p is the heat capacity of air, ρ_s is the density of the air, U is the surface wind velocity, L is the latent heat of sublimation, p_{sat} is the saturation pressure of water vapor above ice or water (as needed), determined by thermodynamics in the form of the Clausius-Clapeyron relation, h_{sa} is the relative humidity of the surface air, r_w is the water vapor mixing ratio, and C_D is the coefficient of drag. By incorporating buoyancy effects into C_D we account for how the near-surface air temperature profile influences the turbulent heat transport. This can be accomplished by incorporating a Richardson number dependence within the coefficient using the Monin-Obukhav similarity theory [Garratt, 1992]. The conductive heat flux from the surface into the ground is given by Fourier's law, and the flux from precipitation includes both the temperature of the precipitation and the latent heat associated with rain (and condensation) falling on a cold surface.

If the surface temperature approaches the melting temperature of water, we must account for the latent heat of melting. We begin by requiring that that T_g cannot be greater than 0°C. This is reasonable even if the surface is covered in water because the thermal density inversion of liquid water will quickly transmit any heat to the ice water interface. Imposing a maximum surface temperature leads to an imbalance in the energy budget;

any surplus of energy in the system (which would have gone to increasing the surface temperature above freezing) goes into the latent heat of melting (F_{melt}).

Previous studies treat the surface energy balance and subsequent thermal diffusion problem separately. The novelty of our approach is that thermal diffusion is treated simultaneously and consistently as a part of the surface energy balance, i.e., the temperature profile of the near surface ice is determined as part of our solution rather than as a consequence of the surface temperature. We also allow the shortwave insolation to penetrate into the snow, as a distributed flux using Byerlee's law [Sergienko, 2005; Sergienko and MacAyeal, 2005]. This is important not only in calculating the thermal flux, as it affects the thermal profile, but also in incorporating the more complicated radiation distribution when the surface energy balance of a surface meltwater lake, which may include seasonal lake ice.

The intensity distribution below the ice sheet surface, *I(z)*, quickly becomes complicated. For a simple system with a layer of meltwater at the surface, the simplest vertical variation of the intensity is:

$$\begin{aligned} I(0 > z > D) &= (1-\alpha_1) I_0 e^{-\tau_w z} + \alpha_2 (1-\alpha_1) \cdot I_0 e^{-\tau_w (2D - z)} \\ I(z < D) &= (1-\alpha_2) \cdot (1-\alpha_1) \cdot I_0 e^{-\tau_w D} e^{-\tau_i z} \end{aligned} \tag{5}$$

where I_0 is the intensity of the incident radiation (combined short-wave and long-wave), D is the depth of the lake, α_1 and α_2 are the albedos of the air/water and water/ice interfaces; and τ_w and τ_i are the extinction coefficients for water and ice respectively. More complicated forms are possible when multiple reflections are included. When melt water is present at the ice sheet surface, we allow water to percolate through the firn according to Darcy's law [see, e.g., Sergienko, 2005].

To express thermal evolution, we solve the thermal diffusion equation with a radiative heating term through a domain extending into the ice sheet below the ice sheet surface:

$$\frac{\partial T}{\partial t} + \frac{1}{\rho_i c_p} \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) + \frac{1}{\rho_i c_p} \frac{\partial I(z,t)}{\partial z} = 0 \tag{6}$$

where c_p is the heat capacity of ice, and ρ_i is the density of the ice. This equation will be subject to the appropriate boundary condition deep in the ice and, most of concern, to an energy-flux condition at the surface.

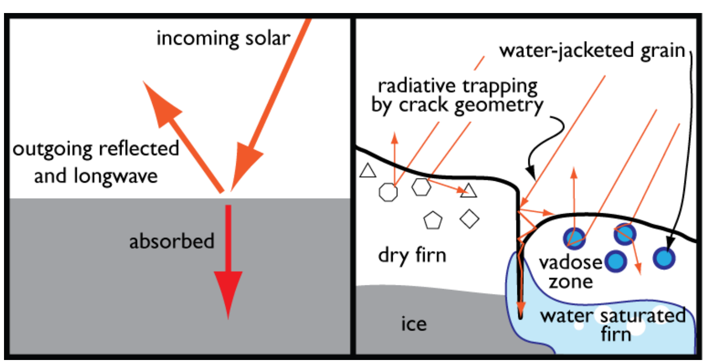

***Figure 2** – Ice and firn surface energy balance. Left panel, the traditional approach; right panel, a more complex picture of interactions between surface layers of various types and incoming radiation.*

The simple traditional approach described by Eqns. (1)-(6) above is represented by the icon in the left panel of Fig. (2). This approach will be augmented and possibly replaced by a more detailed approach designed to home in on the small-scale environment of the actual ice-sheet surface, as represented by the icons of the right panel of Fig. (2). We describe the additional processes of the new approach (right panel of Fig. 2) as follows.

- The white colored zone containing blue circles represents wet firn. The colors and circular geometry of the symbols represent water-jacketed ice grains within a vadose zone of warm firn. Within this zone, radiative transfer and melt production will be treated following the work of Sergienko [2005], Pfeffer et al. [1990], Jordan [1991], and Bozinsky and Shourova [1987].
- Below the vadose zone described in the previous bullet, radiative, convective and conductive heat transfer, and latent heat conversions will be treated following the methods of Illangasekare et al. [1990], and water movement will be treated via standard D'Arcian mechanics, e.g., following Pfeffer et al. [1990].
- In the center of the sketch is a surface roughness feature (crevasse, abandoned meltwater channel, abandoned lake shore) with a sufficient vertical profile to create "critical" reflection that geometrically traps incoming solar and outgoing long-wave radiation. This will be treated following the methodology of MacClune et al. [2003] and Pfeffer and Bretherton [1987]. Surface roughness features and their radiative trapping effects are considered unimportant for the over-all surface melting rate of the Greenland Ice Sheet, however, their small-scale focus may be essential to the determination of how surface roughness features evolve into incised meltwater channels and lakes.

3.2 Process Cluster B – Surface Meltwater Flow, Channel Incision and Basin Development.

Fig. (3) depicts process cluster D: the evolution of micro- and meso-scale (meters to tens of meters) over-surface water flow that modifies ice-sheet surface roughness, excavates lake basins, makes and breaks lake-basin connections, and delivers water to lakes (or drains lakes via surficial water conduits). In the left panel of Fig. (3), a lake with a localized circular meltwater catchment area is depicted. Models developed based on a probabilistic description of catchment area sizes and locations relative to meso- and large-scale surface topography will produce essentially static lake distributions based on whether catchment areas link into closed basin attractors. (Meso-scale denotes roughness on the scale of 100's to 1000's of meters; large-scale denotes the background slope of the ice-sheet surface that produces the large-scale driving stress that drives ice-sheet flow.)

The right panel of Fig. (3) depicts an alternative, explicitly modeled arborescent system of tributaries, distributaries and lake clusters. While the initial catchment geometry necessary to initiate such an arborescent system of surface water movement may be probabilistic, the subsequent evolution of the channel geometry and connectivity can be modeled explicitly using a combination of surface energy balance considerations and simple landscape evolution techniques adapted from non-cryospheric applications [e.g., channel/hillslope integrated landscape development models by Gasparini et al., 2008].

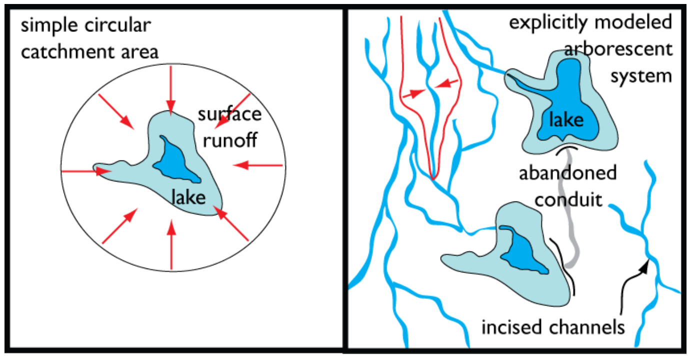

Figure 3 *– Landscape evolution in response to surface meltwater movement. Left panel, traditional approach assuming simple lake catchment area geometry; right panel, explicitly modeled arborescent system involving channels which incise the ice-sheet surface.*

In an effort to explicitly simulate changing channel geometry and channel incision, fluvial incision by local energy absorption enhancement and turbulent kinetic energy dissipation will be balanced against the general ablation of the surrounding surface using an equation of the form

$$\frac{\partial z}{\partial t} = -I(x,y,t) - k_a \nabla^2 z(x,y,t) \tag{7}$$

where *z(x,y,t)* is the local height of the surface relative to a large-scale reference surface (e.g., the "parabolic" shape of the Greenland Ice Sheet provides a reference surface about which micro- and meso-scale icescape topography is situated), *I* is the fluvial incision rate, and the second term on the right-hand side represents the general ablation of the surface by runoff processes (e.g., assumed to obey a Laplacian operator). The incision rate is postulated to be a function of the form [e.g., adapting from Gasparini et al., 2008]

$$I(x,y,t) = k_i \mathcal{F}(Q) A^\alpha S^\beta \tag{8}$$

where *A* is catchment area, *S* is surface slope, *F(Q)* is an incision efficiency factor that is determined by the rate of channel bottom melting by enhanced solar absorption and by turbulent dissipation associated with a channel water flux of *Q*. Coefficients k_a, k_i, α, and β are likely to be difficult to determine from first principle; however, the focus of model development and experimentation in this process cluster will be to examine the general bounds to arborescent surface water flow geometry and are possible with such a model approach.

3.3 Process Cluster C – Surface Lake Energy Balance and Evolution.

Fig. (4) depicting process cluster C showing our approach to modeling the energy balance of surface lakes. The simplified view (left panel) depicts an ephemeral lake that develops, expands, and drains in one summer season, with no effects passed through the winter period into the next summer season, and with no effects inherited from previous seasons. Satellite images from Catania et al. [2008; see also Lüthje et al., 2006a] depict persistent lakes on the surface of the Greenland Ice Sheet that are covered with surface lake ice. This suggests that an energy balance model approach to modeling the seasonal cycle of lakes (focusing on thermal stratification effects, convective effects, surface ice and snow cover and basal melting), both with and without englacial drainage events, is necessary to fully examine the complexity of surface lake geometry, surface area and volume needed to address process clusters A, B and D. We intend to develop a radiative/convective model of lake energy balance capable of simulating the seasonal cycle using standard limnological approaches used to study both lakes on Greenland and on Arctic sea ice [Lüthje et al., 2006a; Lüthje et al., 2006b]. In particular, we plan to investigate the effects of surface lake ice (and snow) via the methodologies developed for the study of Alaskan land lake systems [Jeffries et al., 2005]. Besides relying on the methodologies and approaches set out in previous literature, we shall rely on our experiences with modeling process cluster A (surface energy balance of "dry" surfaces) to guide our approach to dealing with lakes.

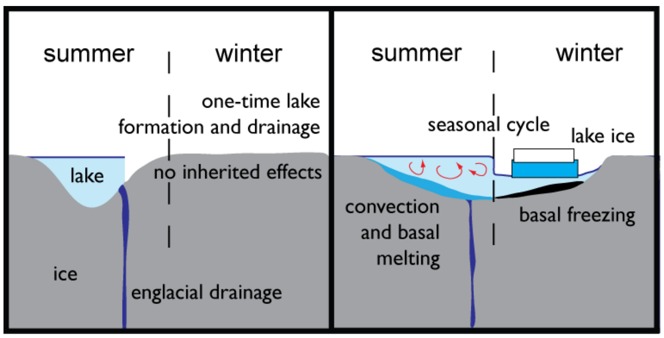

***Figure 4** – Lake evolution. Left panel, lakes are treated as ephemeral, one-time occurrences that do not pass effects from one melt season to the next. Right panel, detailed limnology and ice/lake interactions are treated to determine seasonal lake evolution.*

3.4 Process Cluster D – Englacial Meltwater Drainage.

Fig. (5) depicting process cluster D and shows our possible approaches to modeling the emergence of englacial drainage conduits responsible for delivering surface lake water to the bed. The left panel depicts what many previous studies have focused on: meltwater-driven (hydrostatically supported) elastic fracture of the ice, usually from within the context of linear elastic fracture mechanics [Weertman, 1979; Van der Veen, 1998; Rist and Sammonds, 2002]. These studies have been extended more recently to include thermodynamic processes, such as the time it takes for a water-filled crack to freeze [Alley et al., 2005]. Regardless of complexity, all of these studies, qualitatively at least, end up with the same basic result: if a small "starter-crack" is filled with water, it will penetrate all the way to the bed. If this theory is correct then the limiting factor in determining if a lake will drain is the probability that the lake intersects with a pre-existing fracture that is large enough to serve as a starter-crack that penetrates all the way to the bed.

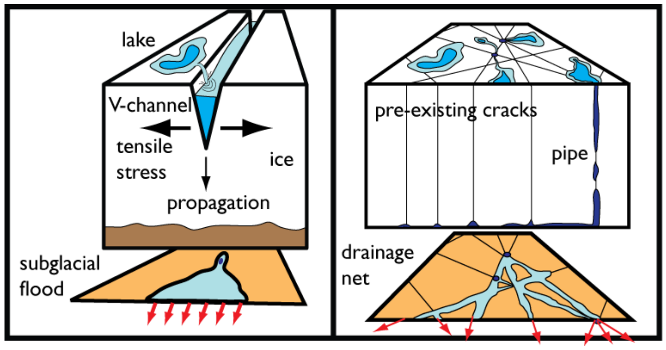

Figure 5 *– Englacial meltwater drainage concepts. Left panel depicts the traditional view of a V-shaped crack initiating an englacial conduit by hydrostatic support in a tensile stress regime. Right panel depicts an alternative approach consisting of re-activation of pre-existing cracks that intersect in pipes.*

For our proposed alternative approach depicted in the right panel of Fig. (5), we assume that pre-existing fractures are distributed within the ice sheet according to a Weibull distribution. (The Weibull distribution is commonly used to model the distribution of flaws within materials.) There are two important feedbacks that emerge: (1) the larger a surface lake is, the greater the probability that the lake will intersect one or more pre-existing fractures from which an englacial drainage conduit can initiate, and (2) the deeper the lake, and the greater its initial volume, the greater the excess pressure will be within the starter-crack to support downward propagation. For a given probability distribution of starter-crack size, we can compute the size-frequency distribution of supra-glacial lakes and compare against observed surface meltwater lake size-frequency distributions. (We expect a decreasing number of very large lakes because they have a very high probability of intersecting with a pre-existing starter crack.)

In the alternative approach, we depict a hypothesis that englacial drainage conduits develop where pre-existing fractures intersect. The point-like intersection provides a starter geometry for a "pipe" that has finite extent in the horizontal dimensions [e.g., as depicted in the radar study by Catania et al., 2008]. Pipes may develop in response to the effects of being submerged at the bottom of surface lakes (e.g., as depicted in the right most lake of the right panel of Fig. 5), or may develop in response to surface meltwater run-off preferring to occupy the surface topographic expressions where these pre-existing fractures intersect the ice-sheet surface (e.g., as depicted by the two lakes that share a single englacial drainage conduit in the middle of the sketch).

No matter which of the two (or more) approaches taken to address englacial conduit formation, the proposed research will embrace all of the thermomechanical aspects of englacial conduit activation described in previous literature [e.g., Alley et al., 2005; Delescluse et al., 2008]. We intend to use a finite-element package called COMSOL to simulate the process of fracture opening and subsequent maintenance against re-closure by creep and freezing.

4. Model Experimentation Tactics and Strategies – Work Plan

The previous discussion has highlighted the four principal areas of model development we believe will contribute to understanding how Greenland Ice Sheet surface melting might influence the evolution of the ice sheet and its contribution to sea level rise. Here, we describe several of the model-development and experimentation exercises we intend to carry out.

4.1 Strategic Work Plan

We intend to organize our work in four stages of model development/experimentation. Some stages (e.g., the first) will naturally evolve most quickly, and precede other stages.

Stage 1 – Model verification and quality control. The first stage of model experimentation is that which translates the "iconic image" of the process of concern into equations and then finite-element and other numerical fluid dynamics and radiative transfer codes. Experimentation at this stage will be mostly focused on establishing that the models are free of conceptual and coding errors, and that they run efficiently and make good use of computer resources.

Stage 2 – Parameter exploration and range of model behavior. The second stage of model experimentation (that blends seamlessly with the first) involves examining the range of model output behavior that results from reasonable control-parameter regimes. A common criticism of energy balance modeling approaches in glaciology is that many of the parameters and forcing fields are largely unknown or poorly constrained by observation. We do not dispute this; however, we do posit that progress in understanding ice-sheet evolution in response to climate change demands continued effort in this arena. Judicious use of inverse methods, e.g., control methods developed in the context of ice-stream flow simulations in the presence of unknown basal parameters, may help to define parameter ranges that are otherwise difficult to observe. Perhaps more importantly, however, is the need to define the full range of accessible states that are reachable by reasonable ranges of parameters. Sensitivity tests will be conducted to map-out the parameter spaces and tie aspects of surface meltwater lake behavior to specific ranges of controlling variables.

Stage 3 – Prediction experiments under simplified, idealized climate forcing scenarios. As part of the culmination of model-development and experimentation, efforts will be made to fully outline and predict likely consequences to surface conditions on the Greenland Ice Sheet in response to simple, idealized scenarios of climate change. These experiments will yield results that are useful to scientific and public policy advisory panels that are tasked with estimating Greenland's contribution to future sea-level rise.

Stage 4 – Coupled prediction experiments. In the final stages of our project we shall seek partners from other groups and institutions that do large-scale ice-sheet climate forecast modeling. Our models will be configured as both Fortran and Matlab subroutines, for use as estimator elements in an asymmetric up-scaling/down-scaling (in both space and time) scheme needed for prognostic simulations of the Greenland Ice Sheet. Ultimately, our models will be set up on-line as a resource for other glaciologists and climatologists to refer to and use.

4.2 Specific Modeling Approach

The strategic approach is described in the previous section, here we describe numerical experiments planned to address the specific scientific questions posed in Section 2.1.

Energy balance model – 1D. The physics included in the one dimensional energy balance model that we intend to create is described in Section 3.1. The focus of our treatment of the 1D problem will initially target efficiently and accurately modeling the freezing/melting phase boundaries in the multi-layer problem. For instance, it is well known that a melt lake can form on the surface of an ice sheet. We are also interested in how the lake freezes. We anticipate that the lake will freeze over from both the top and bottom, forming a layer of "lake ice" at the surface while simultaneously accreting ice onto the bottom. A key question we seek to address is whether melt lakes can persist over the winter. Another key aspect of our 1D modeling efforts will be to explore the parameter space under which lakes form. For instance, do larger wind speeds promote or hinder melt lake formation? More generally, what combination of radiative and meteorological parameters promotes or hinders melt lake development? How sensitive are these processes to firn permeability. We anticipate that this effort will occupy most of Year 1.

Extension to 2D - surface transport of water. After completing the 1D energy balance model, our next step is to extend the energy balance model to include both horizontal directions. An important test of the model at this stage is whether we can predict the satellite-derived profile of melt lake depths [e.g., Sneed and Hamilton, 2007]. Once we are satisfied that model performance is adequate we will surface water transport in our model. We anticipate that the key parameters in determining whether meltwater is able to form ponds or flows off the ice in streams are the mean surface slope and roughness of the ice. Surface slope can be easily obtained, e.g., from ICESat profiles and we shall experiment with a range of surface slopes. For roughness, we shall perform ensemble studies assuming the roughness is described by (i) a random Gaussian process and (ii) a random power-law process. An important feedback to explore is that the formation of melt lakes and rivers alters the roughness of the ice and may make the surface more hospitable to melt lakes. We anticipate focusing on these experiments during Year 2.

Englacial drainage of melt lakes. Our approach to melt lake drainage differs from the standard hydro-fracturing based on linear elastic fracture mechanics interspersed throughout the literature. We borrow from material science and treat this problem using a stochastic model where there is an assumed distribution of flaws within the ice sheet governed by a Weibull distribution. As a first guess, we shall assume that the probability that a lake drains is independent of the depth of the lake and the stress field surrounding the lake. Drainage is therefore controlled by the probability that a lake intersects with a flaw. Larger lakes will be more likely to intersect with a flaw while smaller lakes will be less likely. A prediction of the model is the size-frequency distribution of lakes. This can be compared with satellite imagery derived inventories of lake numbers and sizes for a range of parameters in the Weibull distribution (the Weibull distribution only has two parameters). Although we propose using the two parameters in the Weibull distribution as "tuning" parameters, if we can match the size-frequency distribution of lakes with our model, the "tuning" parameters enable us to statistically characterize the distribution of pipes/starter cracks/flaws within the ice that can be tested by independent field observations.

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van der Veen, C. J., Fracture mechanics approach to penetration of surface crevasses on glaciers, *Cold Regions Science and Technology*, *27*(1), 31–47, 1998.

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Biographical Sketch
Douglas R. MacAyeal

a. Professional Preparation.

Brown University, Physics, Sc.B., 1976
University of Maine, Physics, M.S., 1979
Princeton University, GFD, Phd., 1983

b. Appointments.

Professor, Department of Geophysical Sciences, U. of Chicago, 1993-present. (At same institution: Assoc. Prof., 1987-1993; Assist. Prof., 1983-1987.)

c. Publications.

(i) up to 5 most closely related to the proposed project.

Sergienko, O. V., **D. R. MacAyeal** and J. E. Thom (2007). Reconstruction of snow/firn thermal properties from observed temperature variation: Application to iceberg C16 (Ross Sea, Antarctica), 2004-2007. *Annals of Glaciology*, 49, 91-95.

Sergienko, O. and **D. R. MacAyeal**, 2005. Surface melting on Larsen Ice Shelf, Antarctica. *Annals of Glaciology*, 40: 215-218.

Leonard, K. C., L.-Bruno Tremblay, **D. R. MacAyeal**, and S. S. Jacobs (2008), Interactions of wind-transported snow with a rift in the Ross Ice Shelf, Antarctica, *Geophysical Research Letters*, 35, L05501, doi:10.1029/2007GL033005.

Scambos, T., O. Sergienko, A. Sargent, **D. R. MacAyeal** and J. Fastook, 2005. ICESat profiles of tabular iceberg margins and iceberg breakup at low latitudes. *Geophysical Research Letters*, 32: L23S09.

MacClune, K. L., A. G. Fountain, J. S. Kargel and **D. R. MacAyeal**, 2003. Glaciers of the McMurdo dry valleys: Terrestrial analog for Martian polar sublimation. *Journal of Geophysical Research-Planets*, 108(E4): 5031.

(ii) up to 5 other significant publications.

MacAyeal, D. R., E. A. Okal, R. C. Aster and J. N. Bassis (2008). Seismic and hydroacoustic tremor generated by colliding icebergs. J*ournal of Geophysical Research*, 113, F03011, doi: 10.1029/2008JF001005.

MacAyeal, D. R., M. H. Okal, J. E. Thom, K. M. Brunt, Y.-J. Kim and A. K. Bliss (2008). Tabular iceberg collisions within the coastal regime. *Journal of Glaciology*, 54(118), 371-386.

MacAyeal, D. R., E. A. Okal, R. C. Aster, et al., 2006. Transoceanic wave propagation links iceberg calving margins of Antarctica with storms in tropics and Northern Hemisphere. *Geophysical Research Letters*, 33(17): L17502

Joughin, I., M. Fahnestock, **D. R. MacAyeal**, J. L. Bamber and P. Gogineni, 2001. Observation and analysis of ice flow in the largest Greenland ice stream. *Journal of Geophysical Research*, 106(D24), 34021-342001.

Parizek, B.R., R.B. Alley, and **D.R. MacAyeal**, 2004. The PSU/UofC finite-element thermomechanical flowline model of ice-sheet evolution. *Cold Regions Science and Technology*, 42, 265-278.

d. Synergistic Activities.

1. During 2004, I served as the Chief Editor of the Annals of Glaciology, Vol. 40, and assisted in the development of a prototype on-line editing system for the journals of the International Glaciological Society.

2. I received the *Quantrell Award* of the University of Chicago for excellence in undergraduate teaching in 2002 (see, http://www.uchicago.edu/about/accolades/quantrell.shtml), and the *Provost's Teaching Award* for undergraduate teaching in 2006. In previous years I received the *Macelwane Medal* of the AGU, the *Richardson Medal* of the IGS, and have been elected a *Fellow of the AGU*.

3. I participated in various media outreach efforts, including interviews for news programs and documentaries and an interview in Werner Herzog's film, *Encounters at the End of the World*.

e. Collaborators and Other Affiliations.

(i) collaborators and co-editors
- Okal, E., Northwestern University
- Bassis, J., U. Chicago
- Aster, R., New Mexico Tech.
- Co-editors: none

(ii) graduate and postdoctoral advisors
- Thomas, R., University of Maine, Retired
- Bryan, K., Princeton University, NOAA/GFDL, Retired

(iii) thesis advisor and postgraduate scholar advisor
- Turnbull, I., phd., University of Chcago; Jeremy Bassis, phd., U. Chicago
- Brunt, K., phd., Scripps Institution of Oceanography
- Sergienko, O., phd., Portland State University
- Hulbe, C. L., phd., Portland State University
- Jackson, C., phd., Univ. of Texas at Austin
- Grumbine, R., phd, NOAA/NWS
- Lindstrom, D., phd, secondary school teacher in Minnesota.

Biographical Sketch
Jeremy N. Bassis

Professional Preparation

Postdoctoral Scholar	The Department of the Geophysical Sciences, The University of Chicago, Chicago, IL *Advisor: D.R. MacAyeal*	2007-present
Ph.D	Geophysics (Earth Sciences), Scripps Institution of Oceanography, University of California, San Diego *Advisors: J.B. Minster and H.A. Fricke*r	2000-2007
B.S., with distinction	Major *Physics* with a Minor in *Mathematics*, Pennsylvania State University, University Park, PA	1996-2000

Appointments

2007-2008	University of Chicago, Department of the Geosciences	Postdoctoral Researcher
2007-2008	Scripps Institution of Oceanography, University of California, San Diego	Postdoctoral Researcher
2000-2007	Scripps Institution of Oceanography, University of California, San Diego	Graduate Researcher
1997-2000	Department of Meteorology, Pennsylvania State University	Undergraduate Researcher

Publications

(i) 5 most closely related to this project.

Bassis, J.N., The Physics of Ice Sheets, (2008), in special International Polar Year edition of *Physics Education,* 43(4).

MacAyeal, D.R., E. Okal, R. Aster, **J.N. Bassis**, (2008), Seismic and Hydro-Acoustic Tremor Generated by Colliding Icebergs, *Journal of Geophysical Research,* 113, doi:10.1029/2008JF001005

Bassis, J.N., H.A. Fricker. R. Coleman, Y. Bock, J. Behrens, D. Darnell, M. Okal, J.B Minster, (2008), An Investigation Into the Forces that Drive Ice Shelf Rift Propagation, *Journal of Glaciology.* 184(54), 17-27.

Bassis, J.N., H.A. Fricker, J.B, (2007), Seismicity and Deformation Associated with Ice Shelf Rift Propagation, , *Journal of Glaciology*, 183(53), 523-536.

MacAyeal, D., E. Okal, **J.N. Bassis**, et al., (2006), Transoceanic wave propagation links iceberg calving margins of Antarctica with storms in Tropics and Northern Hemisphere, *Geophysical Research Letters* 33, doi:10.1029/2006GL027235

(i) up to 5 other significant publications.

Fricker, H.A., N. W. Young, R. Coleman, **J. N. Bassis**, J.B. Minster (2005), Multi-year monitoring of rift propagation on the Amery Ice Shelf, East Antarctica, *Geophysical Research Letters*., 32, L02502, doi: 10.1029/2004GL021036.

Bassis, J. N., R. Coleman, H. A. Fricker, J. B. Minster (2005), Episodic propagation of a rift on the Amery Ice Shelf, East Antarctica, *Geophysical Research Letters*, 32, L06502, doi: 10.1029/2004GL022048.

Fricker H. A., **J.N. Bassis**, J.B. Minster, D. R. MacAyeal (2005), ICESat's new perspective on ice shelf rifts: The vertical dimension, *Geophysical Reseach Letters*, 32, L23S08, doi:10.1029/2005GL025070.

Martinez, M., H. Harder, T.A. Kovacs, J.B. Simpas, **J.N. Bassis**, et al., (2003) OH and HO2 concentrations, sources, and loss rates during the Southern Oxidants Study in Nashville, Tennessee, summer 1999, *Journal of Geophysical Research*, 108 (D19), 4617, doi:10.1029/2003JD003551.

Jansen, V., Coleman, R., **J.N. Bassis**, *in press*, GPS-derived Strain Rates on an Active Ice Shelf Rift, *Survey Review*

Synergistic Activities

Dissertation examination committee for Kelly Brunt (thesis advisor: Douglas MacAyeal, University of Chicago), 2008
Member of the Community Ice Sheet Model (CISM) IPCC assessment committee
Contributing author for the Scientific Committee on Ice Sheet Research (SCAR) Ice Shelf Modeling Report
Member of the West Antarctic Ice Sheet (WAIS) education and outreach committee (2007-2008)
Contributing author for special International Polar Year (IPY) issue of *Physics Education* (2008)

Collaborators and Other Affiliations

H.A. Fricker (dissertation advisor, UCSD), J.B. Minster (dissertation advisor, UCSD), D.R. MacAyeal (postdoctoral advisor, UC), Richard Alley (PSU), Richard Coleman (UTas), Douglas MacAyeal (UC), Emile Okal (NWU), Richard Aster (NMT), Marianne Okal (PASSCAL), James Behrens, Mac Cathles UC), Shad O'Neel (USGS), Kelly Brunt (UCSD).

SUMMARY PROPOSAL BUDGET

YEAR 1

ORGANIZATION	FOR NSF USE ONLY		
University of Chicago	PROPOSAL NO.	DURATION (months)	
		Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR	AWARD NO.		
Douglas R MacAyeal			

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Douglas R MacAyeal - Prof.	0.00	0.00	0.25	$ 3,445	$
2. Jeremy N Bassis - Post-doc	2.00	0.00	0.00	9,338	
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (2) TOTAL SENIOR PERSONNEL (1 - 6)	2.00	0.00	0.25	12,783	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (1) GRADUATE STUDENTS				27,456	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				40,239	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				2,556	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				42,795	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				5,200	
2. FOREIGN				4,095	
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $ 0					
2. TRAVEL 0					
3. SUBSISTENCE 0					
4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				9,414	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				4,000	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				13,728	
TOTAL OTHER DIRECT COSTS				27,142	
H. TOTAL DIRECT COSTS (A THROUGH G)				79,232	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) Total direct minus G6 (tuition) (Rate: 56.0000, Base: 65542)					
TOTAL INDIRECT COSTS (F&A)				36,704	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				115,936	
K. RESIDUAL FUNDS				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 115,936	$
M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $				

PI/PD NAME	FOR NSF USE ONLY		
Douglas R MacAyeal	INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

SUMMARY PROPOSAL BUDGET

YEAR 2

ORGANIZATION **University of Chicago**				FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Douglas R MacAyeal**				AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Douglas R MacAyeal - Prof.**	0.00	0.00	0.25	$ **3,548**	$
2. **Jeremy N Bassis - Post-doc**	2.00	0.00	0.00	**9,618**	
3.					
4.					
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	**0**	
7. (**2**) TOTAL SENIOR PERSONNEL (1 - 6)	2.00	0.00	0.25	**13,166**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**0**) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	**0**	
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	**0**	
3. (**1**) GRADUATE STUDENTS				**28,280**	
4. (**0**) UNDERGRADUATE STUDENTS				**0**	
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				**0**	
6. (**0**) OTHER				**0**	
TOTAL SALARIES AND WAGES (A + B)				**41,446**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**2,633**	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				**44,079**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				**0**	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				**9,167**	
2. FOREIGN				**3,188**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **0**					
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS				**0**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**1,527**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**4,120**	
3. CONSULTANT SERVICES				**0**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**14,140**	
TOTAL OTHER DIRECT COSTS				**19,787**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**76,221**	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **H. - G6 (Rate: 56.0000, Base: 62081)**					
TOTAL INDIRECT COSTS (F&A)				**34,765**	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**110,986**	
K. RESIDUAL FUNDS				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ **110,986**	$

M. COST SHARING PROPOSED LEVEL $ **0**	AGREED LEVEL IF DIFFERENT $		
PI/PD NAME **Douglas R MacAyeal**	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

SUMMARY PROPOSAL BUDGET

YEAR 3

ORGANIZATION: University of Chicago				FOR NSF USE ONLY	
				PROPOSAL NO.	DURATION (months) Proposed / Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: Douglas R MacAyeal				AWARD NO.	

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Douglas R MacAyeal - Prof.	0.00	0.00	0.25	$ 3,654	$
2. Jeremy N Bassis - Post-doc	6.00	0.00	0.00	29,720	
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (2) TOTAL SENIOR PERSONNEL (1 - 6)	6.00	0.00	0.25	33,374	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (1) GRADUATE STUDENTS				29,128	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				62,502	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				6,675	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				69,177	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				7,585	
2. FOREIGN				0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				1,573	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				4,244	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				14,564	
TOTAL OTHER DIRECT COSTS				20,381	
H. TOTAL DIRECT COSTS (A THROUGH G)				97,143	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) H-G6 (Rate: 56.0000, Base: 82579)					
TOTAL INDIRECT COSTS (F&A)				46,244	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				143,387	
K. RESIDUAL FUNDS				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 143,387	$

M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $	
PI/PD NAME: Douglas R MacAyeal	FOR NSF USE ONLY — INDIRECT COST RATE VERIFICATION	
ORG. REP. NAME*	Date Checked / Date Of Rate Sheet	Initials - ORG

 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

SUMMARY PROPOSAL BUDGET Cumulative

ORGANIZATION **University of Chicago**			FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Douglas R MacAyeal**			AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Douglas R MacAyeal - Prof.**	0.00	0.00	0.75	$ **10,647**	$
2. **Jeremy N Bassis - Post-doc**	10.00	0.00	0.00	**48,676**	
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	**0**	
7. (**2**) TOTAL SENIOR PERSONNEL (1 - 6)	10.00	0.00	0.75	**59,323**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**0**) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	**0**	
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	**0**	
3. (**3**) GRADUATE STUDENTS				**84,864**	
4. (**0**) UNDERGRADUATE STUDENTS				**0**	
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				**0**	
6. (**0**) OTHER				**0**	
TOTAL SALARIES AND WAGES (A + B)				**144,187**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**11,864**	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				**156,051**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				**0**	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				**21,952**	
2. FOREIGN				**7,283**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **0**					
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS				**0**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**12,514**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**12,364**	
3. CONSULTANT SERVICES				**0**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**42,432**	
TOTAL OTHER DIRECT COSTS				**67,310**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**252,596**	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS (F&A)				**117,713**	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**370,309**	
K. RESIDUAL FUNDS				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ **370,309**	$
M. COST SHARING PROPOSED LEVEL $ **0**	AGREED LEVEL IF DIFFERENT $				

PI/PD NAME **Douglas R MacAyeal**	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

C ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

BUDGET JUSTIFICATION

Line A1. Senior Personnel/Co-PI: We request two months salary for the Co-PI/post-doc in Year 1 and Year 2, and six months salary in Year 3. He will work with the requested graduate student and conduct research.

Line A2. Senior Personnel/PI: Per annum, we request: ¼ of a month of summer salary for the PI. The requested ¼ summer month for the PI will allow him to conduct the research, advise and mentor the graduate student and postdoctoral scholar, and to coordinate scientific contributions of the overall project.

Line B3. Graduate Student: Per annum, we request 12 months salary for 1 graduate student, Lawrence Cathles. He will work on numerical model development and experimentation, and outreach activities.

Lines A1-B5. Other Comments: The budget assumes a 3% rate of inflation for all salary.

Fringe Benefits: The fringe benefits for the Principal Investigator and Co-PI will be charged at the current DHHS, dated September 2, 2008, at the agreed rate of 20.0%.

Section E: Travel:

E1. Domestic Travel: The PI, Postdoctoral Scholar, graduate student and summer intern will participate in the following scientific meetings (as part of the project's dissemination, education and mentoring effort):

- AGU Autumn Meeting in San Francisco, 4 participants each year.
- Midwest Glaciology Meeting (MGM) at location to be determined, 3 participants each year (not including the summer intern).
- PARCA meeting at location to be determined, 3 participants each year (not including the summer intern).
- International Glaciological Society symposium on Disappearing Ice, 13-17 Sept. 2010, Columbus, Ohio, 3 participants (not including summer intern).
- International Glaciological Society symposium on Ice Sheet and Ocean Interaction, 5 – 10 June, 2011, La Jolla, CA, 3 participants (not including summer intern).

E2. Foreign Travel . The PI, Postdoctoral Scholar and graduate student will participate in the following scientific meetings (as part of the project's dissemination, education and mentoring effort):

- EGU Spring Meeting in Vienna, 3 participants each year.
- International Glaciological Society symposium on the International Polar Year, 27-31 July, 2009, Newcastle, UK, 3 participants.
- MOCA-IAPSO Meeting in Montréal, Canada, 19-24 July, 2009, 1 participant.
- International Glaciological Society symposium on Sea Ice, 31 May – 4 June, 2010, Tromsø, Norway, 3 participants, (sea-ice surface melting and surface ponds are an analogue to meltwater lakes on the Greenland Ice Sheet, thus support is requested to attend this meeting).

Section G: Other Direct Costs:

Line G1. Materials and Supplies: Funds are requested for the purchase of a Macintosh Workstation to process satellite imagery of the Greenland Ice Sheet in Year 1. Also, funds will be used in Year 1 for the purchase of necessary software, including Matlab and Adobe Creative Suite. Maintenance for the Matlab Simulink will be required in Year 2 and Year 3. Currently, there is no available workstation and Matlab license for the SR-EIP collegiate scholar.

Line G2. Publication Costs: For publication in open, peer-reviewed journals, graphics, and reprints.

Line G8. Other Direct Costs/Tuition Remission: Partial tuition support for the graduate research assistant is requested. In accordance with the policy of the Physical Sciences Division at The University of Chicago, tuition is charged at 50% of graduate student's salary. This amount will partially cover for the actual university graduate student tuition.

Line I. Indirect Costs: The indirect cost rate is 56% Modified Total Direct Costs (MTDC), Total Direct Costs (TDC) less tuition remission support (G8).

Current and Pending Support

(See GPG Section II.C.2.h for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Douglas MacAyeal

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: An Investigation into the Initiation and Propagation of Ice Shelf Rifts

Source of Support: NASA

Total Award Amount: $ 355,261 Total Award Period Covered: 09/01/08 - 08/31/11

Location of Project: Chicago, IL

Person-Months Per Year Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 1.00

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Model Studies of Surface Meltwater Lakes of the Greenland Ice Sheet

Source of Support: NSF

Total Award Amount: $ 370,309 Total Award Period Covered: 06/01/09 - 05/31/12

Location of Project: Chicago, IL

Person-Months Per Year Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 0.25

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

 USE ADDITIONAL SHEETS AS NECESSARY

Current and Pending Support

(See GPG Section II.C.2.h for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Jeremy Bassis

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: An Investigation into the Initiation and Propagation of Ice Shelf Rifts

Source of Support: NASA

Total Award Amount: $ 355,261 Total Award Period Covered: 09/01/08 - 08/31/11

Location of Project: Chicago, IL

Person-Months Per Year Committed to the Project. Cal:10.00 Acad: 0.00 Sumr: 0.00

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Model Studies of Surface Meltwater Lakes of the Greenland Ice Sheet

Source of Support: NSF

Total Award Amount: $ 370,309 Total Award Period Covered: 06/01/09 - 05/31/12

Location of Project: Chicago, IL

Person-Months Per Year Committed to the Project. Cal:2.00 Acad: 0.00 Sumr: 0.00

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

---

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

 USE ADDITIONAL SHEETS AS NECESSARY

FACILITIES, EQUIPMENT & OTHER RESOURCES

FACILITIES: Identify the facilities to be used at each performance site listed and, as appropriate, indicate their capacities, pertinent capabilities, relative proximity, and extent of availability to the project. Use "Other" to describe the facilities at any other performance sites listed and at sites for field studies. USE additional pages as necessary.

Laboratory: No significant laboratory facilities are required for the project.

Clinical: n/a

Animal: n/a

Computer: The PI, the graduate student and postdoctoral scholar currently have Windows and Macintosh workstations equipped with Matlab software (the preferred environment for model development).

Office: Office space is available within the group area for the summer intern/collegiate scholar to be recruited using the Summer Research - Early Identification Program.

Other:

MAJOR EQUIPMENT: List the most important items available for this project and, as appropriate identifying the location and pertinent capabilities of each.

n/a

OTHER RESOURCES: Provide any information describing the other resources available for the project. Identify support services such as consultant, secretarial, machine shop, and electronics shop, and the extent to which they will be available for the project. Include an explanation of any consortium/contractual arrangements with other organizations.

THE UNIVERSITY OF CHICAGO
DEPARTMENT OF THE GEOPHYSICAL SCIENCES
5734 SOUTH ELLIS AVENUE
CHICAGO, ILLINOIS 60637

Noboru Nakamura

11/3/2008

Dear Doug,

I provide you with this letter indicating that the participation of you and your students is most welcome as participants in the teaching workshops I plan to run over the coming years as part of an NSF-sponsored project I have developed for the enrichment of secondary school teaching in subjects pertaining to fluid dynamics, weather and climate. I would particularly appreciate your contribution to aspects of the workshop that address the impacts of weather and climate on earth surfaces in the polar regions, as this is a subject of considerable public interest.

I wish you the best of luck in the success of your proposal.

Best wishes,

Noboru Nakamura

Associate Professor
Department of Geophysical Sciences
University of Chicago
5734 S. Ellis Avenue
Chicago, IL 60637
U.S.A.

nnn@uchicago.edu

Biographical Sketch
Lawrence M. Cathles

a. Professional Preparation.

Colby College, Waterville, Maine, BA, 2003

b. Appointments.

Graduate Student, University of Chicago, 2005 – Present.

Research Assistant, Cornell University, 2004 – 2005. (Learned basic modeling techniques and worked out a method to correct errors in low temperature thermocouple measurements, the outcome of which was a paper by Cathles, Cathles and Albert, 2007.)

Field Assistant, ***Antarctic Megadunes Project***, 2003/04 Austral field season. (Firn core collection, snow pack characterization across dunes.)

Science Technician, ***Veco Polar Resources, Summit, Greenland***, 2003. (Collected data, maintained and repaired scientific equipment)

Field Assistant, ***Summit Snow Photochemistry Experiment, Greenland***, 2002 and 2003 Arctic field season and spring 2004. (Ran experiments to collect data on physical properties of snow and firn.)

Student temporary employment program, CRREL, Hanover, NH, 2001-2003. (Drs. Mary Albert and Lewis Hunter were my advisors)

Research Assistant, Cornell University, 2000. (Assisted with agricultural experiments investigating tillage and nitrification methods for Dr. Harold Van Es.)

c. Publications

MacAyeal, D. R., E. A. Okal, R. C. Aster, J. N. Bassis, K. M. Brunt, **L. M. Cathles**, R. Drucker, H. A. Fricker, Y.-J. Kim, S. Martin, M. H. Okal, O. V. Sergienko, M. P. Sponsler, and J. E. Thom, (2006), Transoceanic wave propagation links iceberg calving margins of Antarctica with storms in tropics and Northern Hemisphere, *Geophys. Res. Lett.,* **33**, L17502.

Cathles IV, L. M., L.M. Cathles III, M.R. Albert, (2007). A physically based method for correcting temperature profile measurements made using thermocouples, *J. Glaciol.*, **53** (181), 298-304.

Courville, Z.R, M. Albert, M. Fahnestock, **L. M. Cathles**, (2007). Impact of accumulation hiatus on the physical properties of firn at a low accumulation site. *J. Geophys. Res.*, **112**, F02030.

Cathles IV, L. M., D. R. MacAyeal, & E. Okal, (2008). Sea-Swell observations at the front of the Ross Ice Shelf, Antarctica. *J. Geophys. Res.*, *in press*.

d. Synergistic Activities.

A teaching assistant for a series of introductory to physical sciences courses at the University of Chicago.

Gave a poster, which was placed in the top 5 of the session, on “Far Field Atmospheric Storms Shake Ice Shelves: Two years of observations.” At the *Marine Polar Science Gordon Conference*, 2007

Gave a talk on “Titanic Icebergs in Antarctica” at the *Saturday Science Fun Lecture Series* in Park Forest, Illinois. The Lecture series’ goal is to decrease the gap between middle class students and children of poverty by expanding students’ perspective of scientific knowledge as well as career opportunities. About 150 students from Chicago school district 163 attended the lecture.

THE UNIVERSITY OF CHICAGO . THE COLLEGE

BIOLOGICAL SCIENCES COLLEGIATE DIVISION

924 EAST 57TH STREET • CHICAGO • ILLINOIS 60637-5415

Douglas R. MacAyeal
Professor
Department of Geophysical Sciences
University of Chicago
5734 S. Ellis Ave.
Chicago, IL 60637

11/6/08

Dear Doug,

I understand that you are submitting a proposal to the NSF to study surface melt features on the Greenland Ice Sheet, and that you wish to involve a summer research student associated with the Summer Research - Early Identification Program (SR-EIP) of the Leadership Alliance (http://www.theleadershipalliance.org). As the University of Chicago's SR-EIP Research Coordinator, I write to assure you that the University of Chicago is indeed a participant in this program, and is identified as a program site to which summer students can apply. Our summer program is under the institutional direction of Kenneth Warren, Deputy Provost for Research and Minority Issues, and additional program details can be found at the following site: http://leadershipalliance.uchicago.edu/

In the event that your proposal is successful and that you are able to contemplate hosting a summer student, I stand ready to help you with the process of setting up a "research experience" to which applicants to the SR-EIP can apply.

With best wishes,

Megan McNulty

Megan McNulty, Ph.D.
Lecturer/Senior Adviser, Biological Sciences Collegiate Division
Summer Research Program Coordinator, Leadership Alliance SR-EIP

508.647.7000
info@mathworks.com

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3 Apple Hill Drive
Natick, MA 01760-2098 USA
www.mathworks.com

The MathWorks

11/10/2008

Prof. Douglas MacAyeal
University of Chicago
5735 S Ellis Ave
Geophysical Sciences
Chicago, IL 60637

Phone: (773)702-8027
Fax: (773)702-9505
Email: drm7@midway.uchicago.edu

RE: Quote 2187609

Dear Douglas,

I am writing to provide you with a quote for the following MathWorks products. This quote is valid until 12/31/08. Please reference your quote number on your purchase order.
In order to comply with state and local tax laws, we must have in our files a properly executed exemption certificate given to us in good faith from all our customers who claim sales tax exemption.
If I may be of any further assistance, please do not hesitate to contact me.

Sincerely,

Tim Mathieu

Tim Mathieu
Other
Phone:(508)647-7016
Fax: (508)652-6903
tim.mathieu@mathworks.com

508.647.7000
info@mathworks.com

The MathWorks, Inc.
3 Apple Hill Drive
Natick, MA 01760-2098 USA
www.mathworks.com

The MathWorks

Prof. Douglas MacAyeal
University of Chicago
5735 S Ellis Ave
Geophysical Sciences
Chicago, IL 60637

MathWorks Contact Info
Tim Mathieu
Phone: (508)647-7016
Fax: (508)652-6903

tim.mathieu@mathworks.com

Quote Number: 2187609
This quote is valid until 12/31/2008

License Number New 1 Individual ALL Douglas MacAyeal Academic Perpetual

SOFTWARE:

Qty	Product	Part #	Unit List Price	Ext. Price
1	MATLAB	MLALL	$500.00	$500.00
1	Simulink	SLALL	$500.00	$500.00
1	Bioinformatics Toolbox	BIALL	$200.00	$200.00
1	Curve Fitting Toolbox	CFALL	$200.00	$200.00
1	Image Processing Toolbox	IPALL	$200.00	$200.00
1	Optimization Toolbox	OPALL	$200.00	$200.00
1	Partial Differential Equation Toolbox	PDALL	$200.00	$200.00
1	Fixed-Point Toolbox	POALL	$200.00	$200.00
1	Signal Processing Toolbox	SGALL	$200.00	$200.00
1	Spline Toolbox	SPALL	$200.00	$200.00
1	Statistics Toolbox	STALL	$200.00	$200.00
1	Wavelet Toolbox	WAALL	$200.00	$200.00
1	First Year MathWorks Software Maintenance Service †		$0.00	$0.00
			Sub Total:	**$3,000.00**

Sub Total:	$3,000.00
***Tax:**	$0.00
Shipping:	$14.00
Grand Total:	$3,014.00

***Tax and shipping are subject to change.**
Product and pricing subject to change and availability

Our shipping terms are NET 30 FCA Origin.

Based on your shipping address, The MathWorks is required to collect sales tax. In order to comply with state and local tax laws, we must have in our files a properly executed exemption certificate given to us in good faith from all our customers who claim sales tax exemption. If we do not have this certificate, we are obligated to collect the tax for the state in which the property is delivered and where we are authorized to do so. If you are entitled to sales tax exemption, please complete a tax exemption certificate and include it with your order.

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Note: This quote may include reinstatement fees for applicable products which will appear on a separate line entitled "Reinstatement". Licenses that are subject to reinstatement fees will maintain their original end maintenance date.

For more information on Software Maintenance Service, go to www.mathworks.com/services/maintenance .

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Designated Computer. The products are installed on a single, designated computer, provided the computer is not a terminal server and the products are operated from the computer's console, i.e., not remotely.

Group License The Group license offers the Designated Computer activation type. Group licenses are intended for locations where an administrator installs and administers a group of Individual designated computer licenses

Concurrent License. Concurrent licensing allows products to be licensed per concurrent user on computers that are connected to a server running a single FLEXnet license manager. The product is not restricted to designated users; instead, it allows a specified number of concurrent users to run the products on any computer in a local area network.

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The Individual, Group and Concurrent license options are licensed on a PERPETUAL basis, providing the right to use the software indefinitely. The initial purchase price of a Perpetual license includes software maintenance service for the first 12 months. After the initial 12 month period, an annual software maintenance fee is required to renew your software maintenance service. Software maintenance service provides product updates and technical support.

Customer Training. The MathWorks offers introductory and advanced classes to teach you the latest technical computing techniques and to enhance your overall understanding of our products. We offer the flexibility to attend classes at our facilities around the world, at your own site, or via the Web. For more information about MathWorks Training Services visit www.mathworks.com/training .

Software Maintenance Service (SMS). The first year of service is included with new product licenses. You can continue uninterrupted service in subsequent years by renewing your MathWorks SMS subscription. The annual SMS subscription fee is calculated based on the products installed on your configuration and the license option acquired. Shipping and handling fees for product updates are included in the Software Maintenance renewal fee.

Software Maintenance Service (SMS) provides:

- **Access to New Features** New product features delivered in general releases twice each year.
- **Direct Technical Support** Resolve technical issues through telephone, e−mail, and Web assistance.
- **Online License Management** View license details, manage user permissions, activate software and obtain order status.
- **Ability to Add New Products** Access to the latest release will ensure compatibility with new versions of MathWorks products
- **Bug Fixes** Correct technical issues quickly with bug fixes delivered twice a year in the regular release cycle

For more information on Software Maintenance Service, go to www.mathworks.com/services/maintenance .

ORDERING INFORMATION

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