FINAL REPORT DOE/ER/61689--T1

GLACIER CALVING, DYNAMICS, AND SEA-LEVEL RISE
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RATIONALE

Calving of icebergs from large glaciers and ice sheets constitutes a major component of the global flux of ice from land to the ocean. Iceberg calving accounts for roughly half of the ablation from Greenland and most of that from Antarctica. Despite the importance of calving in the global glacier mass balance, little is understood about the nature of the calving processor the role of calving in glacier dynamics. The present-day calving flux from Greenland and Antarctica is poorly known, and this accounts for a significant portion of the uncertainty in the current mass balance of these ice sheets. Similarly, the lack of knowledge about the role of calving in glacier dynamics constitutes a major uncertainty in predicting the response of glaciers and ice sheets to changes in climate and thus sea level. Another fundamental problem has to do with our incomplete knowledge of glacier areas and volumes, needed for analyses of sea-level change due to changing climate.

PROPOSED APPROACH

We proposed to develop an improved ability to predict the future contributions of glaciers to sea level by combining work from four research areas: remote sensing observations of calving activity and iceberg flux, numerical modeling of glacier dynamics, theoretical analysis of the calving process, and numerical techniques for modeling flow with large deformations and fracture. These four areas have never been combined into a single research effort on this subject; in particular, calving dynamics have never before been included explicitly in a model of glacier dynamics. A crucial issue that we proposed to address was the general question of how calving dynamics and glacier flow dynamics interact.

RESULTS

General statement

Most of the objectives listed above were accomplished, although the final results deviated slightly from the original proposal to take advantage of some new opportunities for advancing knowledge on the glacier - sea level relation. Funding constraints made it necessary to delete the proposed field work to control some of the remote observations, and to curtail travel for discussions with Danish colleagues. Some of the new numerical techniques we proposed to explore for modeling large-scale fracture proved to be difficult to develop in unexpected ways and are not yet implemented in models, but we developed

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and validated a useful model that combined calving and flow dynamics. An unanticipated result was the development of a tool (scaling) which permitted a new and better estimate of the sizes and properties of glaciers of the world, which could be used to refine predictions of sea level rise due to glacier wastage under different climatic scenarios; this was incorporated in the IPCC 1995 Scientific Assessment.

In addition to these scientific contributions, this grant funded two graduate theses, and helped to fund the work of two post-docs and one senior research associate. Formal presentations on this work were made attire international and nine national meetings. A total of fourteen scientific papers have been published as well as thirteen abstracts. Some publications are still in process, and the code developed for the glacier dynamics/calving model is being documented and will be made available on our web site.

Glacier dynamics model development

A numerical model was developed which allowed us to simulate the advance of a glacier terminus into ocean water and investigate the interaction between the calving terminus with the ocean and with upstream dynamics in the glacier channel. The model was based on a finite element model originally made by James Fastook at the University of Maine, and was modified by us to include buoyancy forces in water, stress interaction along flowlines (longitudinal coupling), and loss of ice at floating glacier margins through fracture and calving of icebergs. The principle application of the model during the lifetime of this project has been in simulations of a geologically-inferred advance of ice from Labrador in northern Quebec across Hudson Strait onto Baffin Island at the time of the Younger Dryas. This advance is now well documented in the geological record and thus provides a well-constrained test case for a simulation of a large glacial advance into deep water. Additionally, the advance may have been involved in the major re-organization of north Atlantic thermohaline circulation at this time; for this reason estimates of meltwater and/or ice input to the north Atlantic have been made from oceanographic data sources, and these estimates provide additional constraints on calving fluxes produced by the model. Results obtained in this application are presented in one publication (Pfeffer, et al, Paleoceanography, 1997), one book chapter (Pfeffer, In Press), and one report (Pfeffer, et al, 1996). This work also resulted in one MS Thesis (B. Raup, Geological Sciences, 1995).

The model has proven to be a useful tool in further investigations of ice/ocean interactions and in iceberg calving. Among these are model investigations being performed by a current CU Geological Sciences graduate student on other Baffin Island advances (Kaplan, 1997 AGU abstract; and paper In Review in Canadian Journal of Earth Sciences), and a modeling test of theoretical analysis of glacier response times (Pfeffer, et al, JGR 1998, and Bahr et al, JGR 1998). The model is presently in regular use, and is going to made available to the scientific community through some internet-based access in the near future, following some cleaning of the code.

Ice fracture modeling studies

One of the significant challenges in the original project was to develop algorithms for iceberg calving based on physical principles (e.g. fracture mechanics), and to implement those algorithms in a numerical model at length scales suitable for simulation of large glaciers. The model of calving implemented in the glacier dynamics model described above is based on finite element modeling of crack propagation, but is still relatively simplistic and gives results which appear to us to underestimate calving flux (see Pfeffer et al, JGR, 1997). The model performs satisfactorily at present, and predicted calving fluxes can be interpreted by the user in light of our knowledge of the conservative character of calving.

A second research track of this project, parallel to the development of the glacier dynamics model, was basic analysis and development of numerical models which allow fracture initiation and propagation, and block interaction, in a non-linear viscoelastic medium. Accomplishments in this track include adaptations of engineering techniques developed for linear elastic media to non-linear fluid media (Dwyer et al, International Journal of Solids Structures, 1997; Pan et al, Computational Mechanics, 1997), basic analysis of glacier mechanics and crevassing (Sassolas et al, Cold Regions Science and Technology, 1996), and extension of the DDA (Discontinuous Deformation Analysis) method to allow for floatation and fluid pressure (Lin, Ph.D. Thesis, 1995). To date we are still working on full integration of fracture mechanics and discrete-block analyses into a non-linear fluid flow model. One of our original objectives was to adapt the DDA method to non-linear viscoelastic media. Completion of this goal eluded us during the lifetime of this project, but the research done during the project laid much the necessary groundwork for completion of this task. Many of the personnel on this project (particularly B. Amadei and E. Pan) are still engaged in the DDA research under new NSF funding, and a non-linear viscoelastic DDA glacier prototype model appears to be nearly in hand, thanks in large part to the work done during this project.

Remote observations of calving and studies of a calving law

Newer data from Columbia Glacier together with observations from Greenland, Alaska, and glaciers calving into fresh-water lakes have been analyzed. The purpose of this work was to see if a calving relation of general applicability could be found. New techniques such as the use of percolation theory were tried to see if the difficult physics involved in the calving process could be circumvented; the result of this were partially successful. The following conclusions have come from the remote observational studies:

(a) The important role of sliding due to basal water in the dynamics of tidewater, calving glaciers was established.

(b) The newer data from the rapidly-retreating Columbia Glacier are consistent with the linear "water-depth" calving relation previously obtained when this glacier was nearly stable, and with data from other Alaskan glaciers. A "terminus-thickness" relation also fits the empirical data from Alaskan glaciers.

(c) The water-depth relation fits well for glaciers calving into fresh water but the calving speed is only one-fifteenth as large.

(d) The terminus-thickness relation works very well with Greenland glaciers having floating termini. However, their calving speeds are slower, for a given ice thickness, than for Alaskan glaciers.

(e) Iceberg calving and ice flow have to be considered as interacting processes with significant positive and negative feedbacks. These feedbacks have been defined but they add an additional layer of complexity to modeling efforts.

Ice and sea level

A major new opportunity developed during the course of this research, triggered in part by Dr. Meier's appointment as a Lead Author for the sea level chapter of the forthcoming (1995) Intergovernmental Panel on Climate Change (IPCC) Scientific Assessment. This work required a deeper understanding and prediction of the impact of glacier wastage on rising sea levels. As such it was directly relevant to the objective of the grant. New developments in stochastic scaling and methods for obtaining global averages of glacier mass balance results were used in the IPCC report to better estimate the impact of glaciers on sea level during the past century, and to project this component of sea-level rise to the year 2100.This study also produced the first rational estimates of the distributions of glacier numbers, areas, and volumes for the world. It also opened up anew field for estimating the distribution of other glacier properties from data on easily-obtained area observations.

EDUCATIONAL ACCOMPLISHMENTS

One M.S. (Raup) and one Ph.D. (Lin) Thesis (see 'Theses' below), 2 additional graduate students supported (Kaplan, Sassolas), 2 Post-Doctoral Research Associates (Dwyer, Pan) supported. Research work was incorporated into graduate and undergraduate curricula (Meier, GEOL 4640/5640, University of Colorado; Pfeffer, GEOL 1060/1070, University of Colorado) and presented in various non-scientific public forums.

ARTICLES, PRESENTATIONS, AND ABSTRACTS

Refereed Publications:

Pending and In Press:

Pfeffer, W.T., Ice dynamics modeling of the Hudson Strait region at late Glacial time, Book Chapter In Press for Geological Survey of Canada Hudson Strait Report, (Brian McLean, Ed.)

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Bahr, D.B., W.T. Pfeffer, C. Sassolas, and M.F. Meier, Response time of glaciers as a function of size and mass balance: I. Theory, Journal of Geophysical Research ,Vol. 103(B5), 9777-9782, 1998.

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Meier, M. F. Ice, climate, and sea level; do we know what is happening? In, W. R. Peltier (Ed), Ice in the Climate System. NATO ASI Series, Vol. I 12,Springer-Verlag - Berlin Heidelberg. p. 141-160.

THESES:

Raup, B. H., Incorporation of Longitudinal Stress Coupling into a Map-Plane Finite Element Glacier Flow Model. MS Thesis, Department of Geological Sciences, University of Colorado, 1995.

Lin, C.T., Extensions to the Discontinuous Deformation Analysis for Jointed Rock Masses and Other Blocky Systems. Ph.D. Thesis, Department of Civil, Environmental, and Architectural Engineering, University of Colorado, 1995.

REPORTS:

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ABSTRACTS

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Pfeffer, W.T., Dynamic and kinematic interactions of calving and glacier flow, AGU 1994 Fall Meeting, EOS Supplement Nov. 1, 1994, p. 223.