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Embedded Ice Sheet Model

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Principal Investigator: Fastook, James L. **Award ID:** 0337165

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Submitted By:

Fastook, James - Principal Investigator

Title:

An Embedded Ice Sheet Model

Project Participants

Senior Personnel

Name: Fastook, James

Worked for more than 160 Hours: Yes

Contribution to Project:

Post-doc

Graduate Student

Name: Sargent, Aitbala

Worked for more than 160 Hours: Yes

Contribution to Project:

Aitbala is working on her PhD in Computer Science, and she is primarily applying herself to the 'bette physics' aspect of the proposal. As such she has been coming up to speed with the Finte Element Method, our primary numerical tool. She has implemented the Morland equations for ice shelf flow, which can be adapted to ice streams ala MacAyeal and Hulbe, and she has begun work on a full-momentum equation solver. Of this she has completed and tested a 2D version, designed for easy conversion to 3D, our ultimate goal. Testing is much easier in 2D and several 'bugs' in the program were flushed out by this exercise.

Name: Kenneway, Debra

Worked for more than 160 Hours: Yes

Contribution to Project:

Debra is a Physics PhD candidate supported by the CreSiS grant with Terry Hughes, but her research topic uverlaps with work we are doing here with the embedded model, in particular, the better physics, higher-order model.

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

Other Collaborators or Contacts

I have collaborated with Jens Naslund of the University of Stockholm doing high-resolution models of the Scandinavian Ice Sheet using hi-res measured geothermal heat fluxes. This involved using the embedded model.

I have collaborated with Ted Scambos at the University of Colorado modeling iceberg profiles. This involved the solution of the full-momentum equation.

I have collaborated with David Bromwich and Rick Toracinta of the Ohio State University providing ice sheet reconstructions for input to the MM5 climate model. This involved using the embedded model to match resolution with the MM5, which itself is an embedded climate model.

I am also actively collaborating with Jesse Johnson, at University of Montana, who has recently received a grant to develop a community ice sheet model. He feels that the embedded feature, which is unique to the University of Maine Ice Sheet Model, should be included in the community model. I am not a Co-PI on his grant, but am involved as an advisor.

Activities and Findings

Research and Education Activities:

The major thrust has been in the area of 'better physics.' We are working on the full-momentum equation where no stress components are neglected. The shallow ice approximation, which is the standard ice sheet modeling paradigm and the basis of our map-plane model, only incorporates the basal drag. The Morland Equations, used to model ice shelves, only incorporates the longitudinal stresses. Some have tried to adapt the Morland Equations to ice streams by adding a basal drag term, but this addition violates the assumptions of the derivation of the Morland Equations, and hence is not self-consistent. The only way to truly model ice streams, where both basal drag and longitudinal stresses are important is to solve the full-momentum equation.

To do this we first started with a 2D version of the equations. The 2D arena is much easier to work with. Programs run faster, display of results is easier, and boundary conditions are easier to specify. We designed the 2D program to be easy to convert to 3D. All references to the dimension of the problem were defined in terms of a named parameter within the model, so that conversion will require only changing a constant from 2 to 3 in the model.

We have applied the 2D model to 2 situations: 1) bending of icebergs, and 2) flow across a subglacial lake such as Vostok.

The bending of icebergs involves only longitudinal stresses, whereas the flow across a lake involves transition from a region where basal drag dominates to a region where there is no basal drag. Both of these provide good tests for how the full-momentum solver works.

We have applied this to the Ross and Amundsen Sea sectors, focusing on the period from LGM to the present. A sequence of nested grids allows us to go from a continental view at low resolution, to a regional view at intermediate resolution, and finally to an ice-stream-specific view at the full resolution of the BEDMAP data set. Fast flow regions of wet bed, as predicted by the UMISM basal water component, are compared with known ice streams.

Embedded modeling successfully recreates high-resolution features such as ice streams in appropriate positions.

Additional mass loss beyond that provided by Weertman thinning is necessary to maintain Amundsen Sector at the current grounding line If the effective buttressing of ice shelves around Antarctica ever return to the values that were NECESSARY to produce retreat of the grounding line at rates in agreement with geological evidence, then MAJOR collapse of

West Antarctica would occur in less than 2000 years.

No major retreat of East Antarctica will occur with only Weertman thinning. An additional mechanism 10 times more effective would be necessary.

This work was reported at the 2005 WAIS meeting in Sterling, VA and at the Fall 2005 AGU in San Francisco.

Since then we have extended our use of the 2D solver described above (application to the tabular bergs, etc) with an application to Thwaites Glacier. This work was presented at the 2006 WAIS workshop in Seattle, WA. The following is excerpted from the abstract submitted to that conference:

Better physics using full momentum solver in 2D vertical slice domain, where does longitudinal stress really matter? Application to the Thwaites Glacier flowline

Debra Kenneway, Aitbala Sargent, James Fastook (University of Maine)

The commonly used shallow-ice approximation neglects all stresses except the basal drag, an assumption that is very good for inland ice but may be very poor for fast-flowing, low-surface slope ice streams, where longitudinal stresses may not only be important, but may in fact be the dominant stress [fastook04b]. A higher-order approach is to couple the mass- and momentum-conservation equations (the prognostic and diagnostic equations [macayeal97]) and solve with no neglected stresses. In the process of developing such a full-momentum solver in 3D, for embedded application within the map-plane University of Maine Ice Sheet Model (UMISM) [fastook93c], we are testing a 2D simplification which models a vertical slice through the ice sheet along a flowline. This allows us to do two things: 1) implement and test the complex boundary conditions that must be specified for a full-momentum solver, and 2) evaluate when and where longitudinal stresses are
important or even dominant.

Specification of the differential equation describing conservation of momentum (also referred to as the 'balance of forces') allows for two types of boundary conditions [thjhughes87]: 1) Dirichlet, where the state variable, in this case the velocity, is specified, and 2) Neumann, where the conserved flux, in this case the force applied on the boundary, is specified. Where the bed is frozen, Dirichlet boundary conditions are the obvious choice, as the velocity is zero and can be specified as such. Where the bed is not frozen, where sliding is occurring (for example, in ice streams, where our shallow-ice approximation breaks down), we cannot specify the velocity, but instead must specify the force exerted on the ice by the bed in resisting its forward motion. We know that this resistive force cannot exceed the driving stress (if it equals the driving stress, we have the shallow-ice solution). A temptation is to use some fraction of the driving stress, and indeed, this approach does produce the concave profile characteristic of an ice stream, but the fraction is hard to define (a model parameter). A better approach, and the one we have taken, is to use a boundary-layer. We can preserve our Dirichlet-type specification of zero velocity on the boundary, but allow greater deformation within the boundary layer to simulate sliding at the bed. This soft layer can be interpreted either as a deformable till or as a layer of water-saturated ice at the melting point (slush). In either case its thickness will be negligible compared with the ice thickness, and while the geometry and mechanical properties (how thick and how soft) are still difficult to define, at least they have a physical meaning, which is a good thing for a model parameter to have.

We apply this to a flowline along the Thwaites Glacier in the Amundsen Sea sector using excellent new data from the Airborne Geophysical survey of the Amundsen Sea

Embayment (AGASEA), by University of Texas [holt06] and British Antarctic Survey [vaughan06] teams.

[fastook93c] J.L. Fastook. The finite-element method for solving conservation equations in glaciology. Computational Science and Engineering, 1(1):55--67, 1993.

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[vaughan06] D.G. Vaughan, H.F.J. Corr, F. Ferraccioli, N. Frearson, A. O'Hare, D. Mach, J.W. Holt, D.D. Blankenship, D.L. Morse, and D.A. Young. New boundary conditions for the West Antarctic Ice Sheet: Subglacial topography beneath Pine Island Glacier. Geophys. Res. Lett., doi:10.1029/2005GL025588, 2006.

We have also re-run the experiment reported last year at 2005 Fall AGU, and at the 2005 WAIS Workshop with the new AGSEA/BBAS dataset developed for the Amundsen Sea Sector (Thwaites and Pine Island are the focus). This is a major application of the nested, embedded feature of the model, allowing much higher resolution than would be possible running in non-embedded mode. The following is the excerpted version of the abstract submitted. This work was presented at the Fall 2006 AGU, as well as at the 2006 WAIS workshop. Much of this material has also been submitted as a contributed chapter to the ACCE document (Turner, J., et al., in review, The Instrumental Period, In: Turner J, Convey P, di Prisco G, Mayewski PA, Hodgson DA, Fahrbach E, Bindschadler R (eds) Antarctic Climate Change and the Environment.)

Thanks SO Much for ALL the Data: The Amundsen Sea Sector Data Set: Applications with UMISM: Where and How Much WATER? What WILL happen in the future?

James L Fastook (University of Maine)

Recent extraordinary programs of the Airborne Geophysical survey of the Amundsen Sea Embayment (AGASEA), by University of Texas [holt06] and British Antarctic Survey [vaughan06] teams in the astral summers of 2004/2005, collected some 75,000 km of flight-line data measuring ice thickness with radar sounders and surface elevation with laser or radar altimeters. Recently these data have been made available as a 5-km gridded data set in a format convenient for modeling. We apply the University of Maine Ice Sheet Model (UMISM) in its embedded mode [fastook04b] to do high-resolution analysis of the velocity distribution within the Amundsen Catchment. We show that the model adequately captures velocity distributions measured by SAR radar [rignot04]. We show the distribution of basal water predicted by the model [fastook97, johnson99, johnson02b, johnson02]. We hope that, within the limitations of our grounding line parameterization, the model has predictive capabilities and will show some examples of possible future retreat.

The nest of embedded models begins with a 40 km grid of the entire ice sheet. Embedded in this is a 10 km grid that includes the entire AGASEA measurement area. Nested inside this medium-resolution grid are two 5 km grids encompassing Thwaites and Pine Island Glaciers. This procedure allows us to obtain the highest-resolution results with very reasonable runtimes. A cycle of growth to an LGM configuration followed by retreat to the present configuration is run for this nest of embedded grids. Advance and retreat is controlled by a 'thinning-at-the-grounding-line' parameter (the WEERTMAN) which is coupled to the Vostok Core temperature proxy. Full resolution 5-km results for thickness, velocity, and water distribution are shown for the two focused embedded grids.

We also present a plausible, but perhaps extreme, scenario of future retreat that might arise if conditions ever returned to the state that produced the large retreat from the LGM configuration. One of these scenarios produces complete collapse of the WAIS in a few thousand years, while the other demonstrates how the 'weak underbelly' might collapse [hughes81c].

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[vaughan06] D.G. Vaughan, H.F.J. Corr, F. Ferraccioli, N. Frearson, A. O'Hare, D. Mach, J.W. Holt, D.D. Blankenship, D.L. Morse, and D.A. Young. New boundary conditions for the West Antarctic Ice Sheet: Subglacial topography beneath Pine Island Glacier. Geophys. Res. Lett., doi:10.1029/2005GL025588, 2006.

At the 2007 WAIS meeting we presented work on progress with the full-momentum solver, specifically how we would have to deal with the difficult basal boundary conditions. Again, we present the abstract from that meeting.

Boundary conditions for a full-momentum solver: 1) The dilemma of sliding and 2) how do we do embedded models?

James L Fastook

The holy grail of ice sheet modeling is the full-momentum solver. In principle, conservation of momentum, coupled with a flow law, can provide a differential equation solvable for velocities at every point within the ice sheet volume. The shallow-ice approximation neglects all but the basal drag and is useful for slow-moving inland ice. The Morland-MacAyeal equations neglect all but the longitudinal stresses and are useful for ice shelves and perhaps, in limited circumstances, ice streams. Both of these approximations take advantage of the different scales of the horizontal versus the vertical dimensions of the ice sheet, and involve an integration and removal of the vertical coordinate. Both of these approximations have severe limitations, especially in the dynamically critical ice streams that drain most of the mass out of Antarctica. The key interaction of shelf and inland ice, though the ice stream, cannot be adequately captured with either of these 'end-member' approximations.

While very computationally intensive, a full-momentum solver that neglects no stresses and makes no assumptions or vertical integrations should give us the best and most accurate model for ice streams. Because of the computational requirements, such a model is not reasonable for a whole-ice sheet simulation, and hence we have pursued the embedded-grid approach, whereby a shallow-ice model is run for the whole ice sheet, and the full-momentum solver is applied only to a sub-region where ice stream dynamics are known to be important.

As such there are three different types of boundary conditions that must be specified, the top, the bottom, and the sides. The top is easy, a free-boundary is easily specified.

The sides and bottom are more difficult. On the sides we have a choice, either Dirichlet or Neumann boundary conditions. Dirichlet boundary conditions consist of specified boundary velocities (the unknowns, or degrees of freedom in the full-momentum solver), whereas Neumann boundary conditions are specified pressures or surface tractions (the source of momentum). From the shallow-ice model, we can provide both of these conditions, although the vertical variation in velocity is only of lower order. Pressures are not difficult to specify, however, conservation of angular momentum (net rotational torque should be zero), does require specification of some surface traction (the so-called ' dynamical stresses'), and this can be problematic.

The bottom is most difficult, mainly due to the poorly understood nature of sliding (hard rock, deformable sediments, polythermal ice, basal water, etc.). A frozen bed is again easy, a simple Dirichlet boundary condition with velocities specified at zero. A completely uncoupled bottom is also easy, with simply a free boundary condition in the two horizontal dimensions. Of course in both of these cases the vertical velocity is specified to be zero.

Instead with Neumann boundary conditions, we can specify the basal traction. If this is specified to be equal to the driving stress (rho*g*h*alpha), we basically obtain the same solution that we get when we specify no sliding. We have tried specifying a given fraction of the driving stress, but this leads to unrealistic oscillations in the ice sheet profile. A uniform stress works well, but there is no indication that this is a reasonable assumption, nor does that deal well with the transition from inland to streaming to shelf. Both of these also require 'yet-another-parameter,' and hence are undesirable. A third approach involves a ' deformable' basal layer, ie. a thin layer of elements, the order of meters thick, with much softer physical characteristics. With this approach, one can preserve the easy-to-implement Dirichlet boundary conditions of all basal velocities specified at zero, and yet obtain high sliding velocities, and plug-like flow, the dilemma being the requirement of a 'parameter' (how soft and how thick is this layer?). Tuning such a model (and remember, this is how the parameters in most sliding laws are obtained, by tuning) would involve comparison of measured and modeled velocity fields in well-documented areas such as the Siple Coast, and soon the Amundsen Sector.

At WAIS 2008, we had two presentations, one on A. Sargent's revisions on the Morland-MacAyeal Equations, and the other on the potential for accurate model predictions of sea-level rise in response to projected climate change. Again the abstracts are included here.

Modified Morland-MacAyeal model for ice-stream flow

Aitbala Sargent and James Fastook

Higher-order models have been a goal of ice sheet modelers as they have attempted to leave behind the limitations of the shallow-ice approximation. SIA is appropriate for the interior slow moving regions of the ice sheet, but due to the fact that all stresses except basal drag are neglected means that SIA fails in the transition zone in streams as the grounding line is approached. Many are approaching this with attempts at so-called 'full-momentum' solvers, ie. formulations that neglect no stresses. This approach, however, is computationally very expensive.

The SIA for interior ice, and the Morland Equations for the ice shelf flow [Morland, 1987] both reduce the scale of the problem by integrating out the vertical dimension, taking advantage of the fact that the vertical dimension is very different from the two horizontal dimensions. In the case of SIA, it is the fact that the stress distribution in the vertical can be approximated as varying linearly from zero at the ice surface to the driving stress at the bed, and a mass-conserving velocity profile obtained through the flow law. In the case of the Morland Equations, a uniform velocity with depth and the zero basal drag can be used to remove the vertical coordinate from the formulation. Doing so reduces the scale of the problem for a 100X100 km region modeled with 2 km resolution in x and y and 10 layers in the vertical from 300,000 degrees of freedom to 20,000.

The Morland Equations apply specifically to ice shelf physics, but they have been successfully applied to the transition zone in ice streams with a modification whereby a basal drag of arbitrary magnitude is added to the momentum-source term in the Morland formulation [MacAyeal, 1989; Hulbe, 1998]. While this approach does yield reasonable results, the fact that the addition of this stress after the fact, violates the assumptions that go into the original integration of the vertical dimension, and hence is not self-consistent.

We present a formulation for the diagnostic equation that follows the original Morland derivation closely [MacAyeal, 1997], but include at the outset an explicit term for the basal drag. This self-consistent formulation, coupled with a prognostic equation for mass conservation and solved using the Finite Element Method, is tested for a number of simplified geometries where longitudinal stresses are comparable to the basal drag. The ultimate goal is to include this as an 'embedded' higher-order component within an SIA model of the entire ice sheet [Fastook and Sargent, 2004; Fastook, 2007].

References:

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How to improve predictions of future WAIS behavior

James Fastook

Modeling ice sheets has proceeded from

1. the very simplest parabolic profiles of the perfectly plastic approximation, a 1-D, steady-state solution where the driving stress is exactly balanced by a uniform basal yield stress;

2. on to the elliptical profiles, where a uniform accumulation rate is assumed, again a 1-D steady-state solution, but now the basal stress varies along the flowline;

3. to the shallow-ice approximation, a 1-D flowline or 2-D map-plane, time-dependent models, where only the basal stress is included and is assumed to equal the driving stress;

4. to the 'shelfy-flow' models which are ad hoc adaptations of Morland's ice shelf equations, a 1-D or 2-D time-dependent solutions with only longitudinal stresses and an added basal resistance term;

5. to the current full-momentum solvers, true 3-D, time-dependent solutions where all stresses are presumably accounted for.

All of these treatments have in common the requirement that the modeler must specify some parameter that characterizes the coupling of the ice sheet with the bed. For the parabolic profiles it is the yield stress. For elliptical profiles and the shallow-ice approximation it is the ice hardness in the Flow Law and the lubrication factor in the Sliding Law. For shelfy flow it is again the ice hardness and also the basal resistance term For full-momentum it is the explicit basal boundary condition, either a Dirichlet-style specified velocity (zero for no sliding, non-zero for sliding) or a Neumann-style applied stress (the basal resistance, analogous to the term in the shelfy flow).

In modeling the interior of an ice sheet where sliding does not occur, parabolic, elliptical, and shallow-ice do a reasonable job of reproducing ice sheet behavior. Only shallow-ice is time-dependent, and since we are concerned with 'predictions,' this is a necessary capability. In all three of these, however, a 'fitting' process is required to 'tune' the model.

Early shallow-ice models specified the ice hardness in the Flow Law, but thermo-mechanical coupled models eliminated the need to specify ice hardness, as it could be calculated from the temperature field within the ice sheet. A new parameter, the flow-enhancement parameter, emerged to allow us to still 'tune' the model. This new parameter, while an improvement over the old ' specification' of ice hardness, is necessary to have the model adequately describe the present configuration. As with other parameters in the model, the flow enhancement factor accounts for something we don't understand (impurity content, etc.). We have mentioned the lubrication factor, a parameter within the Sliding Law that basically serves to turn on and off sliding and to determine its magnitude. We have a clear picture that this depends in some way on the presence and amount of water at the bed, but sliding's actual coupling with the water field is uncertain (as well as being complicated by different kinds of sliding, hard-bed vs. deformable sediment, etc.)

An additional factor to consider in our search for improved predictions, is that we need a good starting point from which to project into the future. We are not starting from a simple steady-state ice sheet, but instead from one that has undergone significant changes in the not too distant past. Most geological reconstructions of the ice sheet have the Ross Sea beneath the current ice shelf fully grounded, possibly out to the continental shelf, with the major retreat occurring relatively late. With such a recent major change in the ice sheet configuration, major features such as the internal temperature field and the distribution of water at the bed will have preserved in them transient features reflective of the retreat history. Both internal temperature and basal water have a strong impact on the ice sheet's dynamic behavior, and hence must be well characterized in order to have a good starting point for a predictive model. The easiest way to accommodate this is to run the model for a glacial cycle capturing the endpoint as initial conditions for the predictive run. One problem with this approach is that the known history of the ice sheet is relatively short, and not unambiguously understood. The expanded extent of the ice sheet, the timing at which it stood at that larger configuration, the increase in the volume, as well as the important timing of the recent collapse are all controversial questions. Another problem of course involves which climate 'proxy' to use to drive the ice sheet through it cycle, and how to couple that proxy to the controlling mechanisms.

The point here is that expecting higher-order models to solve all our problems is naive. We need a clearer understanding of the physical processes involved, or at least an adequate and versatile parameterization of said process that can be tuned to match the current configuration. Included in this of course is the recognition that we are dealing with a time-dependent creature, one whose current configuration (the starting point for our predictions) contains transients reflecting recent past behavior, which must be well characterized.

Findings:

ICESat profiles of tabular icebergs and the Ronne Ice Shelf edge have shapes indicative of two types of bending forces at their margins. Icebergs and shelf fronts in cold (sea-ice-covered) water show profiles with broad (~1000 m wide), rounded, ~1m high æbermsÆ, with outer edges that slope down several meters towards the water. Bergs in warmer water have 2 to 5 m æramparts Æ with ~1500 m-wide edge-parallel æmoatsÆ inboard of the edge. This latter pattern was initially observed in images from Space Station, showing edge-parallel surface meltwater ponds on one iceberg just prior to its disintegration. Our models indicate these patterns result from hydrostatic and lithostatic forces acting on the ice face. Near-vertical iceberg margins develop æbermÆ profiles resulting from differential ice and water pressure along the face. æRampart-moatÆ profiles result from waterline erosion that leaves a submerged bench of ice that lifts the ice edge. We use these models to discuss tabular iceberg breakup in low latitudes.

Past studies have investigated ice shelf edge structure [Reeh, 1968; Fastook, 1986], and the effect of a torque acting on the floating face of the berg or shelf (Figure 5); but the rampart-and-moat profile was not previously observed or modeled. Berm profiles arise from the difference in pressure gradient between water and ice along a vertical face of floating ice. Because this force is incurred at different rates along the face (water pressure increases faster than ice lithostatic pressure) there is a net torque in the direction of rotating the top edge of the floating ice outward and down toward the water. A second force we consider is the buoyancy of a submerged æbenchÆ of ice. We infer that waterline erosion of an iceberg leads to this shape [Hughes, 2002], and that it forms rapidly in warm water. We use two model approaches, and review the results of Reeh [1968] to investigate the cold, æbermÆ-type pattern (Figure attached, top). Model investigations are exploratory, and do not include ice density or temperature variations, or berg shapes other than nearly rectangular. An elastic plate-bending approach [Sergienko et al., 2004], using estimated ice thickness and a standard value for YoungÆs modulus (E, 8.88 Mpa @ -5?C), leads to berm amplitudes and wavelengths that are too large by a factor of 4 relative to the observed profiles. By adjusting e downward significantly (0.3 E), and reducing the thickness, we approach a profile similar to those observed (Figure attached); clearly plastic effects are important. In another model (modified from Fastook [1984]), two-dimensional stress balance equations, incorporating GlenÆs flow law and using ice strength parameters for a û12?C mean temperature, are solved using a finite element model. Reeh [1968] considers the viscous deformation of a floating ice plate over time. Using his derivations, the berm profiles are best modeled with a mean ice temperature of û12?C, a firn-corrected ice thickness value [Bamber and Bentley, 1994] of 300 to 350 meters, and a time factor (mean time since last calving) of ~1.5 years.

The warm-water model was investigated using the finite element model. We examined the effects of an ice bench of varying widths with an upper surface 5m below water level, for several ice thicknesses in the range of the observed icebergs. Benches of just a few meters width were sufficient to completely eliminate the æbermÆ shape and lift the berg margin higher than the mean freeboard. We find that benches of 20 to 40 meters width best match the observed warm-water berg profiles. Ice thickness estimates for model comparisons to the warm-climate icebergs assumes a modified firn density due to increased melt percolation.

Work with the 2D solver for Thwaites suggests the Longitudinal stress penetrates no more than 30 km inland from the grounding line. This is based on matching flow velocities.

Revised experiments with the embedded high-res UMISM shows that the older BEDMAP dataset was not too bad in its representation of the bed beneath West Antarctica, but with the new AGSEA/BBAS bed, we can be more confident of the model's predictions, which indicate a certain degree of retreat over several hundreds of years.

Recently the full momentum solver was used in modeing the Wilkins Ice Shelf breakup. This work has been submitted and accepted by Earth and Planetary Science Letters (Scambos et al. Ice Shelf Disintegration by Plate Bending and Hydro-fracture: Satellite Observations and Model Results of the 2008 Wilkins Ice Shelf Break-ups, Earth and Planetary Science Letters, accepted 2008). A portion of the abstract is included here:

Satellite remote sensing observations of three break-up events in 2008 for the northwest Wilkins Ice Shelf (28 February to 6 March, 27 May to 31 May, and 28 June to mid-July) provide unprecedented detail of ice shelf calving during rapid break-up. The observations reveal that the Wilkins break-ups occur through a distinctive type of shelf calving, which we term ædisintegrationÆ, as well as more typical rifting and calving. Here we focus on the disintegration process, which is characterized by multiple fractures which form quickly and create narrow ice-edge-parallel blocks, with subsequent block toppling and fragmentation forming an expanding iceberg and ice rubble mass. We use these data to develop and test a model of floating ice plate disintegration in which ice plate bending stresses at the ice front arising from buoyancy forces can lead to runaway calving when free (mobile) water is available. High-resolution satellite images and laser altimetry of the first break-up event provide details of fracture spacings, ice thicknesses, and plate bending profiles that agree well with our model predictions. We suggest that surface or near-surface meltwater is the main pre-condition for disintegration, and that hydro-fracture is the main mechanism. Brine layers from near-waterline brine infiltration can support a similar process, but is less effective unless regional ice stress patterns contribute to the net stress available at the crack tip for fracturing. A combination of brine-enhanced fracturing and changing internal net extensional stresses was the likely mechanism of the latter two Wilkins events.

Finally, work with the embedded model has not been limited to terrestrial ice sheets. After several years of attendance at the LPSC conference held annually in Houston, TX, a synthesis paper on tropical mountain glaciers on Mars was published in Icarus (Fastook et al., Tropical mountain glaciers on Mars: Altitude-dependence of ice accumulation, accumulation conditions, formation times, glacier dynamics, and implications for planetary spin-axis/orbital history, Icarus, 198, pp 305-317, 2008). A portion of that abstract is also included here:

Fan-shaped deposits up to 166,000 square km in area are found on the northwest flanks of the huge Tharsis Montes volcanoes in the tropics of Mars. Recent spacecraft data have confirmed earlier hypotheses that these lobate deposits are glacial in origin. Increased knowledge of polar-latitude terrestrial glacial analogs in the Antarctic Dry Valleys has been used to show that the lobate deposits are the remnants of cold-based glaciers that formed in the extremely cold, hyper-arid climate of Mars. Mars atmospheric general circulation models (GCM) show that these glaciers could form during periods of high obliquity when upwelling and adiabatic cooling of moist air favor deposition of snow on the northwest flanks of the Tharsis Montes. We present a simulation of the Tharsis Montes ice sheets produced by a static accumulation pattern based on the GCM results and compare this with the nature and extent of the geologic deposits. We use the fundamental differences between the atmospheric snow accumulation environments (mass balance) on Earth and Mars, geological observations and ice-sheet models to show that two equilibrium lines should characterize ice-sheet mass balance on Mars, and that glacial accumulation should be favored on the flanks of large volcanoes, not on their summits as seen on Earth. Predicted accumulation rates from such a parameterization, together with sample spin-axis obliquity histories, are used to show that obliquity in excess of 45 degress and multiple 120,000 year obliquity cycles are necessary to produce the observed deposits. Our results indicate that the formation of these deposits required multiple successive stages of advance and retreat before their full extent could be reached, and thus imply that spin-axis obliquity remained at these high values for millions of years during the Late Amazonian period of Mars history. Spin-axis obliquity is one of the main factors in the distribution and intensity of solar insolation, and thus in determining the climate history of Mars. Unfortunately, reconstruction of past climate history is inhibited by the fact that the chaotic nature of the solution makes the calculation of orbital histories unreliable prior to about 20 Ma ago. We show, however, that the geological record, combined with glacial modeling, can be used to provide insight into the nature of the spin-axis/orbital history of Mars in the Late Amazonian, and to begin to establish data points for the geologically based reconstruction of the climate and orbital history of Mars.

Training and Development:

The graduate student involved with the project, Aitbala Sargent, has become proficient with the Finite Element Method. She is now capable of writing her own programs. She has also taken Glaciology, with Terry Hughes, and has become familiar with the vocabulary of ice sheet modeling. She has completing a Master's Project and a drafdt of her PhD thesis is complete and she should graduate in May, 2009.

Debra Kenneway, PhD candidate in Physics, has koined the project with support from another grant. She too has been becoming proficient with the ice sheet model, and has contributed to development of the higher-order physics component. She is working on the 3D temperature solver and on formulating basal boundary conditions.

Outreach Activities:

Each year in COS415/515, the modeling and simulation class, a series of lectures are given on ice sheet modeling as a Computer Science problem. The different aspects of modeling (equation development, numerical solution, and graphical display of results) are discussed. A shorter version of this is also delivered at a number of open-house activities for both the Computer Science Dept, and for the Climate Change Institute. The latter reach high school students considering attending the University of Maine, as well as their parents.

I was interviewed by a reporter from the Antarctic Sun.

Journal Publications

Ted Scambos, Olga Sergienko, Aitbala Sargent, Douglas MacAyeal, and Jim Fastook, "ICESat Profiles of Tabular Iceberg Margins and Iceberg Break-up at Low Latitudes", Geophysical Research Letters, p. , vol. , ( ). in final preparation, will be submitted soon,

Bromwich, D.H., E.R. Toracinta, R.J. Oglesby, J.L. Fastook and T. Hughes, "LGM Summer Climate on the Southern Margin of the Laurentide Ice Sheet: Wet or Dry?", Journal of Climate, p. , vol. , (2005). Accepted,

Jens-Ove Näslund, Peter Jansson, James L. Fastook, Leif Andersson, and Jesse Johnson, "Using realistic geothermal heat flow data for ice sheet modelling of basal temperatures and melt water production", Annals of Glaciology, p. , vol. , ( ). Submitted,

*Bromwich, D.H., E.R. Toracinta, H. Wei, R.J. Oglesby, J.L. Fastook and T. Hughes, "Polar MM5 simulations of the winter climate of the Laurentide Ice Sheet at the LGM", Journal of Climate, p. 3415, vol. 17, (2004). Published,

Jane Staiger, John Gosse, Rick Toracinta, Bob Oglesby, James Fastook, Jesse V. Johnson , "Atmospheric scaling of cosmogenic nuclide production: the climate effect ", JGR- Solid Earth, p. , vol. , ( ). Accepted,

Jane Staiger, John Gosse, Rick Toracinta, Bob Oglesby, James Fastook, Jesse V. Johnson, "Atmospheric scaling of cosmogenic nuclide production: the climate effect", JOURNAL OF GEOPHYSICAL RESEARCH, p. B02205, vol. 112, (2007). Published, Shean, D. E., J. W. Head, III, J. L. Fastook, and D. R. Marchant, "Recent glaciation at high elevations on Arsia Mons, Mars: Implications for the formation", J. Geophys. Res., p. E03004, vol. 112, (2007). Published,

J. L. Fastook, J. W. Head, and D. R. Marchant, "Tharsis Montes Ice Sheet Models at High Obliquity Driven by GCM Results", Lunar and Planetary Science Conference, p. 0, vol. 38#1119, (2007). Published,

D. R. Marchant, W. M. Phillips, J. L. Fastook, J. W. Head, III, J. M. Schaefer, D. E. Shean, D. E. Kowalewski, "DATING THE WORLD?S OLDEST DEBRIS-COVERED GLACIER: IMPLICATIONS FOR INTERPRETING VISCOUS-FLOW FEATURES ON MARS", Lunar and Planetaru Science Conference, p. 0, vol. 38#1895, (2007). Published,

R. L. Hooke and J. L. Fastook, "Thermal conditions at the bed of the Laurentide ice sheet in Maine during deglaciation: implications for esker formation", Journal of Glaciology, p. 646, vol. 53, (2007). Published,

D. E. Shean, J. W. Head, J. L. Fastook, and D. R. Marchant, "Recent glaciations at high elevations on Asia Mons, Mars: Implications for the formation and evolution of large tropical mountain glaciers", J. Geophys. Res., p. EO3004, vol. 112, (2007). Published,

J.L. Fastook and A. Sargent, "Better physics in embedded models", West Antarctic Ice Sheet Initiative Workshop, p. , vol. , (2004). Published,

J L Fastook, "Embedded Models: Application to the Ross Sea and Amundsen Sea Sectors, Retreat from LGM", West Antarctic Ice Sheet Initiative Workshop, p. , vol. , (2005). Published,

J L Fastook, "Embedded Models: Application to the Ross Sea and Amundsen Sea Sectors, Retreat from LGM", Fall AGU, p. , vol. , (2005). Published,

A Sargent, T Scambos, J L Fastook, "Better Physics in Embedded Models: Iceberg arcing and Lake-surface profiles", West Antarctic Ice Sheet Initiative Workshop, p. , vol. , (2005). Published,

J L Fastook, "Thanks SO Much for ALL the Data: The Amundsen Sea Sector Data Set: Applications with UMISM: Where and How Much WATER? What WILL happen in the future?", West Antarctic Ice Sheet Initiative Workshop, p. , vol. , (2006). Published,

D Kenneway, A Sargent, J L Fastook, "Better physics using full momentum solver in 2D vertical slice domain, where do longitudinal stress really matter? Application to the Thwaites Glacier flowline", West Antarctic Ice Sheet Initiative Workshop, p. , vol. , (2006). Published,

J L Fastook, "The Amundsen Sea Sector Data Set: Applications with UMISM: Where and How Much WATER? What WILL happen in the future?", Fall AGU, p. , vol. , (2006). Published,

J. L. Fastook, "Boundary conditions for a full-momentum solver: 1) The dilemma of sliding and 2) how do we do embedded models?", West Antarctic Ice Sheet Initiative Workshop, p. , vol. , (2007). Published,

Aitbala Sargent and James Fastook, "Modified Morland-MacAyeal model for ice-stream flow", West Antarctic Ice Sheet Workshop, Sterling, VA, Sept 2008, p. , vol. , (2008). Published,

James Fastook, "How to improve predictions of future WAIS behavior", West Antrarctic Ice Sheet Workshop, Sterling, VA, Sept 2008, p. , vol. , (2008). Published,

James L. Fastook, James W. Head, David R. Marchant, Francois Forget, "Tropical mountain glaciers on Mars: Altitude-dependence of ice accumulation, accumulation conditions, formation times, glacier dynamics, and implications for planetary spin-axis/orbital history", Icarus, p. 305, vol. 198, (2008). Published,

J. L. Fastook and J. W. Head and D. R. Marchant, "Dichotomy Boundary Glaciation Models: Implications for Timing and Glacial Processes", Lunar and Planetary Science XXXIX #1109, p. , vol. , (2008). Published,

Books or Other One-time Publications

Aibala Sargent, "Modeling Ice Streams", (2008). Thesis, Submitted
Bibliography: University of Maine PhD thesis in Computer Science

Rodney A Jacobs, "DATA STRUCTURES AND ALGORITHMS FOR EFFICIENT SOLUTION OF SIMULTANEOUS LINEAR EQUATIONS FROM 3-D ICE SHEET MODELS", (2005). Thesis, Published
Bibliography: University of Maine Masters thesis in Computer Science

Web/Internet Site

URL(s):

http://tulip.umcs.maine.edu/~shamis/umism/umism.html

Description:

This is a document describing all the features of the UMISM ice sheet model in detail that is often not possible in actual publications. It includes background on ice-age and climate-related problems, as well as descriptions of many (not all, but we are always working on it) of the experiments we have done with the model. It also includes a user manual for UMISM. The monograph has been used as a textbook in short courses on ice sheet modeling presented at Brown University and to a visiting student from LSU.

Other Specific Products

Contributions

Contributions within Discipline:

UMISM is the only ice sheet model with embedded capabilities. Our involvement as advisor to Jesse Johnson's and Christina Hulbe's NSF-funded community ice sheet model will insure that at least some of this capability makes it into their ultimate product.

Contributions to Other Disciplines:

Work by Aitbala Sargent, a PhD candidate in Computer Science, has contributed to the field of CS. She has been doing work in the parallel computing arena and had a paper accepted for a CS conference summer 2008 in Las Vegas, NV (Sargent et al., Applying SuperLU Parallel Solver to a Glacier Ice Sheet Model, CCI Symposium, Las Vegas, NV, May 2008). The abstract is included here:

Application of SuperLU-DIST multiprocessor software package to solving large sparse systems of linear equations generated by University of Maine Ice Sheet Model (UMISM) will be presented. The UMISM is a mathematical model for the formation and disappearance of glacial ice sheets. It has been applied to the Antarctica, Greenland, Scandinavian, and Laurentide ice sheets.

The model uses conservation of mass, energy, and momentum, and constitutive relations to form partial differential equations describing ice sheet thickness, temperature, and velocity as functions of time and position. These equations are solved numerically using the finite element method. Early models were done on a 2-dimensional map plane. More recent models use better physics to describe ice velocities in regions where velocities vary significantly over short distances. These models generate systems of linear equations with sparse non diagonally dominant matrices. The iterative methods canÆt be used to solve these types of equations. Solving the systems with the direct methods, on the other hand, is time demanding.

The above reasons have motivated us to explore the possibility of using multiprocessors for solving these equations. We have chosen freely available solver for distributed memory parallel computers known as SuperLU-DIST. For dense matrices, the SuperLU-DIST algorithm has been shown to exhibit good scalability, that is, its efficiency (a measure of process utilization in a parallel program) can be approximately maintained as the number of processors increases. For sparse matrices, however, efficiency is much harder to predict since it depends on the sparsity pattern of the matrix.

In this work, we have explored the scalability of SuperLU-DIST applied to matrices generated by the UMISM and estimated the accuracy of the method.
Test results indicate that SuperLU-DIST is a reasonable package for applying to ice sheet problem; however, to improve the accuracy of the method careful consideration must be given to apriory matrix transformation using knowledge of the matrix structure.

She also participated in the ISMASS meeting in St. Petersburg, Russia summer 2008.

Contributions to Human Resource Development:

Contributions to Resources for Research and Education:

Contributions Beyond Science and Engineering:

Categories for which nothing is reported:

Organizational Partners
Any Product
Contributions: To Any Human Resource Development
Contributions: To Any Resources for Research and Education
Contributions: To Any Beyond Science and Engineering