Insights on Ice-Dynamic Modeling from Observations of Fast Glacier Movement

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- NASA Cryospheric Sciences
- University of Colorado Undergraduate Research Opportunity Program
Two types of fast glacier movement and acceleration

Jakobshavn Isbræ, Western Greenland —

- Spatial acceleration caused by existence of a deep trough in the subglacial topography
- Continuously fast-flowing

Bering Glacier System, Alaska

- Acceleration (in time) caused by internal dynamics of the glacier – surge cycle
- Quasi-cyclic oscillation between phases of slow and fast movement
Complications

Jakobshavn Isbræ, Western Greenland —

- Rapid retreat and acceleration since 1997, accompanied by surface lowering
- The main cause of fast flow is still the trough
- Reversible IF fjord-glacier cycle
- Probably irreversible if warming at front (ice-ocean interaction)

Bering Glacier System, Alaska

- Surge cycles are underlain by a trend of glacial retreat

This talk is not about the complications!
Insights on Ice-Dynamic Modeling from Observations of Fast Glacier Movement
Flight Tracks of Bering – Bagley System Observations 2011-2012

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Surge Reinitiation in 2012

New Drawdown (South) - 2012 (October 1)

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Insights on Ice-Dynamic Modeling from Observations of Fast Glacier Movement
New Drawdown (South) - 2012 (October 1)
New surge-type crevassing in eastern Bagley Ice Field, 24 Aug 2013
8-2013: Surge continues to expand further up Bagley Ice Field

En-échelon crevassing, Bagley Ice Field, 24 Aug 2013

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Insights on Ice-Dynamic Modeling from Observations of Fast Glacier Movement
8-2013: Surge continues to expand further up Bagley Ice Field

New surge-type crevassing in eastern Bagley Ice Field, 24 Aug 2013
New Drawdown (North) - 2012 (October 1)
What is a glacier surge?

(1) Surges occur repeatedly.
(2) Quiescent phase is fairly constant (10-100 yrs).
(3) Surge phase is short (1-several years).
(4) Surge phase: ice speed 10-100 times the normal speed, ice displaced rapidly from upglacier reservoir to downglacier receiving area, large elevation changes in ice surface (10-100m).
(5) Quiescent phase: low ice speed, ice builds up in reservoir area.
Bering Glacier 1993–1995 Surge

(a) Beginning surge stage: Early summer 1993, few crevasse fields
(b) Mature surge stage: after surge reached terminus in 1993, and summer 1994
(c) Late surge stage: after onset of water outburst during August 1994, and continuing through August 1995

Note: Bagley Ice Field surges as well, mostly the eastern Bagley. Surge extended 15km into western Bagley. Steller Glacier pulses.

Project Objectives: BERING Glacier Surge RAPID (NSF)

Background

▶ The cryosphere changes at an alarming rate.
▶ Most changes in glaciers and ice sheets are driven by glacial acceleration.
▶ Surges are one of three only three forms of acceleration and the least studied one (surges are relatively rare but important).
▶ The Bering-Bagley Glacier System is a large, complex glacier system (largest glacier outside of Greenland and Antarctic Ice Sheets); but most glaciologic knowledge on surges is based on small glaciers.

Objectives

▶ Observation: Systematic collection of airborne videographic, photographic, GPS and laser altimeter data
▶ Analysis: Elevation change, crevassing, hydrologic changes, surge progression
▶ Parameterization: Derivation of parameters that can be used in ice-dynamic modeling of a surge
▶ Transfer: Prototype of a surge in large, complex glacier system
Laser Altimetry

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Insights on Ice-Dynamic Modeling from Observations of Fast Glacier Movement
Integrated Observation System 2012 (Laser Altimeter, Video, GPS, Computer for Data Registration)
Rift Location

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+Rift

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Insights on Ice-Dynamic Modeling from Observations of Fast Glacier Movement

- Maximum Crevasse Depth
- Average Crevasse Depth
Insights on Ice-Dynamic Modeling from Observations of Fast Glacier Movement

Average Crevasse Spacing

Average Curvature of Crevasse Edges
What is spatial surface roughness?

- a derivative of (micro)topography
  → characterization of spatial behavior

Why do we need spatial surface roughness?

- sub-scale information for satellite measurements
- indicator variable for other, harder to observe processes
- parameterization of sub-scale features or processes
Definition of Vario Functions

\[ V = \{(x, z) \text{ with } x = (x_1, x_2) \in \mathcal{D} \text{ and } z = z(x)\} \subseteq \mathbb{R}^3 \]

discrete-surface case or

\[ V = \{(x, z) \text{ with } x \in \mathcal{D} \text{ and } z = z(x)\} \subseteq \mathbb{R}^2 \]

discrete-profile case

Define the first-order vario function \( v_1 \)

\[ v_1(h) = \frac{1}{2n} \sum_{i=1}^{n} [z(x_i) - z(x_i + h)]^2 \]

with \((x_i, z(x_i)), (x_i + h, z(x_i + h)) \in \mathcal{D}\) and \(n\) the number of pairs separated by \(h\).
Higher-Order Vario Functions

The first-order vario-function set is

\[ V_1 = \{(h, v_1(h))\} = \varphi(V_0) \]

Then: get \( V_2 \) from \( V_1 \) in the same way you get \( V_1 \) from \( V_0 \). The second-order vario function is also called varvar function.

Recursively, the vario function set of order \( i + 1 \) is defined by

\[ V_{i+1} = \varphi(V_i) \]

for \( i \in \mathbb{N}_0 \).
Geostatistical Classification Parameters

significance parameters:

slope parameter:

\[ p_1 = \frac{\gamma_{\text{max}_1} - \gamma_{\text{min}_1}}{h_{\text{min}_1} - h_{\text{max}_1}} \]

relative significance parameter:

\[ p_2 = \frac{\gamma_{\text{max}_1} - \gamma_{\text{min}_1}}{\gamma_{\text{max}_1}} \]

pond – maximum vario value

mindist – distance to first min after first max

\[ \text{avgspac} = \frac{1}{n} \sum_{i=1}^{n} \frac{1}{i} h_{\text{min}_i} \]

typically for \( n = 3 \) or \( n = 4 \)
Directional variograms of laser-altimeter profiles of Bering Glacier crevasses

Figure 1: Eyak:/home/mcdonabw/Work/Bering2011/vario/plots/7500.1 data.png
Figure 2: Eyak:/home/mcdonabw/Work/Bering2011/vario/plots/7500.1 2 1 201 m2m3.png
Figure 3: Eyak:/home/mcdonabw/Work/Bering2011/vario/plots/7500.1 1 201 m2m3.png
Figure 4: Eyak:/home/mcdonabw/Work/Bering2011/vario/plots/7500.1 0.5 401 m2m3.png

Laser Altimetry

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Insights on Ice-Dynamic Modeling from Observations of Fast Glaciers
Geostatistical classification parameters calculated from laser altimeter data for the region of the rift.

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Elevation-change determination

- Elevation change -40 to -70 m in reservoir area, +20-40 m in Tashalich Arm (receiving area)
- Sudden mass transfer typical of a surge

Elevation change determined from laser altimeter data collected by C. Larsen, University Alaska Fairbanks, 2010, under NASA Operation IceBridge, and by U.C Herzfeld, Sept. 2011, as part of NSF project. (Herzfeld et al., Annals Glaciol 2013a)
Automated Image Analysis to Derive Deformation Types

Crevasse types - Sept 2011

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Insights on Ice-Dynamic Modeling from Observations of Fast Glaciers
Analysis:
Connectionist – Geostatistical Classification and Parameterization

Neural net design for 9 output classes and 42 input parameters
Capability: Association 95% correct

(Herzfeld and Zahner, Computers & Geosciences, v. 27, no 5, p. 499–512, 2001)
### Nine Class

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>undisturbed surface, moraines, rocks</td>
</tr>
<tr>
<td>1</td>
<td>chaos</td>
</tr>
<tr>
<td>2</td>
<td>parallel crevasses</td>
</tr>
<tr>
<td>3</td>
<td>parallel crevasses filled with snow</td>
</tr>
<tr>
<td>4</td>
<td>acute angle bidirectional crevasses</td>
</tr>
<tr>
<td>5</td>
<td>bidirectional with one dominant direction</td>
</tr>
<tr>
<td>6</td>
<td>square-top blocky pattern</td>
</tr>
<tr>
<td>7</td>
<td>rhombic pattern</td>
</tr>
<tr>
<td>8</td>
<td>en-échelon crevasses</td>
</tr>
</tbody>
</table>

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*Insights on Ice-Dynamic Modeling from Observations of Fast Glacier Movement*
Crevasse Classes Bering Glacier Surge 2011

Crevasse Classes 2011 used in Connectionist-Geostatistical Classification

(Herzfeld, McDonald, Weltman, Annals Glaciol, 2013b)
NN Classification for Bering Glacier Surge 2012

Class 01

Class 02

Class 03

Class 04

Class 05

Class 06

Class 07

Class 08

Class 09

Class10

Class11

Class12

**Crevasse Classes:** Undisturbed Snow, Chaos, Parallel, Acute Bi-directional, Multi-direction and Multi-deformed, Bi-directional with one dominant direction, Waves, Square topped, Rhombic, EnEchelon, Sastrugi EnEchelon, Big EnEchelon. – Griffin Hale

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Confusion Matrix for 2012 NN

Confusion Matrix

Result: 12-class association 85 percent correct for 2012 image data
by Griffin Hale

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Semi-Automated Training of a Crevasse Classification Neural Net

A separate algorithm automatically sorts a larger image data set into selected classes. The user then manually revises the NN's decisions.

User manually sorts images into classes.

Algorithm takes the location of the main directory and creates a structure of the sorted images and the associated classifications.

Algorithm creates patterns using combinations of three-directional variograms, compiles an input matrix, and an associated target matrix using the classification structure.

Algorithm sorts out training, test, and validation patterns from target and input matrices and creates an untrained NN.

If the NN does not meet the accuracy criteria, then the NN is reconstructed with a different set of training, test and validation patterns. This iterative process continues, until a cutoff value is reached.

If the desired accuracy is not met with the selected number of iterations, a partially trained NN is obtained.

Trained Network

No

Meets Accuracy

No

Untrained Neural Network with training, testing, and validation patterns

Algorithm Trains Network

Target and Input Matrices

Classification Structure

Partial Trained Network

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Insights on Ice-Dynamic Modeling from Observations of Fast Glacier Movement
Applications:

- Segmentation of Bering–Bagley System into deformation provinces
- Understanding of surge phenomenon
- Parameterization of fracturing in glaciers
  - subgrid modeling
- Parameterization of deformation processes
  - modeling glacial dynamics
- Transfer of dynamic processes to understand acceleration and dynamic thinning in other glaciers, e.g. Greenland outlet glaciers
Towards Modeling Surges in Complex Glacier Systems

Questions:

- What makes a glacier a surge-type glacier?
- What causes and controls surges?
- What initiates a surge?
- Environmental setting or special physics?
- Can the surge phenomenon be explained by standard physics (Glen’s flow law and using full Stokes)?

The following experiments use Glen’s flow law and full Stokes and employ Elmer Ice. (Model experiments by Tom Trantow).

Then compare modeled variables and observations: What can the model explain? What can it not explain?
Surface Elevation of Bering Glacier from CryoSat-2 Data

(a) Summer 2011
(b) Winter 2011/2012
(c) Summer 2012
(d) Winter 2012/2013

From Trantow and Herzfeld (2013 subm.)

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Insights on Ice-Dynamic Modeling from Observations of Fast Glacier Movement
Elevation Change of Bering Glacier from CryoSat-2 Data

Winter 2011/2012 - Summer 2011

Summer 2012 - Winter 2011/2012

Winter 2012/2013 - Summer 2012

Summer 2012 - Summer 2011

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Elevation Change of Bering Glacier from CryoSat-2 Data

Winter 2012/2013 - Winter 2011/2012

Winter 2012/2013 - Summer 2011
Figure 9. Nugget values, noise levels and error values. (a)(b)(c) Summer 2011, (d)(e)(f) winter 2011/2012, (g)(h)(i) summer 2012, and (j)(k)(l) winter 2012/2013. Nugget values are in the left column (a,d,g,j), noise values in the middle column (b,e,h,k) and errors in the right column (c,f,i,l). Color scale is chosen to show variability in nugget, noise and error values. Values in very few points exceed the maximum of the color scales and are given in Table 1.
Bering Glacier and Bagley Icefield Bed Topography

Subglacial topography data analysis - in progress

Interim results:

Bering Glacier Bed
Bagley Icefield Bed

Data from Howard Conway, Univ. Washington, Bruce Molnia, USGS, Eric Rignot and Jeremy Mouginot, JPL

– need to apply trough-bed algorithm
Building a Greenland Bed for Modeling (at 5 km)

(1) Greenland bed with Jak trough (SeaRISE dev1.2, 2010)
(2) JakHelKanPetBed (avail on SeaRISE wiki/Greenland data sets, 2011)
(3) new bed (2013)

- (1), (2) use Bamber, Layberry, Gogineni 2001 5km DEM as base grid
- (3) starts from scratch: from CreSIS thickness data
(4) use trough-system algorithm
Helheim Glacier

(a) CReSIS data, gridded  (b) trough detection  (c) trough over hi-res grid

(d) orig bed (Bamber et al. 2001)  (e) interpolated w new data  (f) final bed w trough integration

(from Herzfeld et al., Annals Glaciol., 2013, ms)  Insights on Ice-Dynamic Modeling from Observations of Fast Glaciers
UMISM [James Fastook]: Jakobshavn Isbræ

30000 year Spin-up to present

[a] = Old Bed v093 (Bamber et al. 2001), [b] = New Bed JHKP

(Herzfeld, Greve, Fastook, ... AnnalsGlaciol 2012)
BBGS Model Output

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Figure 2. Bering-Bagley Glacier System: Modeled elevation change. The results of an experimental simulation of Bering Glacier using the MultiPhysics and F.E.M. software Elmer/Ice. Surface and bed elevation maps (DEMS) are used as inputs (Boundary Conditions) and were derived from satellite and airborne altimeter data. Time steps are 2.4333 days, elevation gain is in meters (experiment #60). – By Thomas Trantow.
Indicative of blocked englacial hydrological system during surge; near Bering-Bagley Junction, 24 Aug 2013
Basal Hydropotential

Summer 2012

Winter 2012/2013

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Insights on Ice-Dynamic Modeling from Observations of Fast Glaciers
Questions?