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

Ute C. Herzfeld[1,2,3]
Thomas Trantow[3,1], Brian McDonald[1], Griffin Hale[1,4], Alex Weltman[1,5], Maciej Stachura[4], Phil Chen[1,2]
(1) Department of Electrical, Computer and Energy Engineering
(2) Cooperative Institute for Research in Environmental Sciences
(3) Department of Applied Mathematics
(4) Department of Aerospace Engineering Sciences
(5) Department of Computer Sciences
University of Colorado Boulder

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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 —

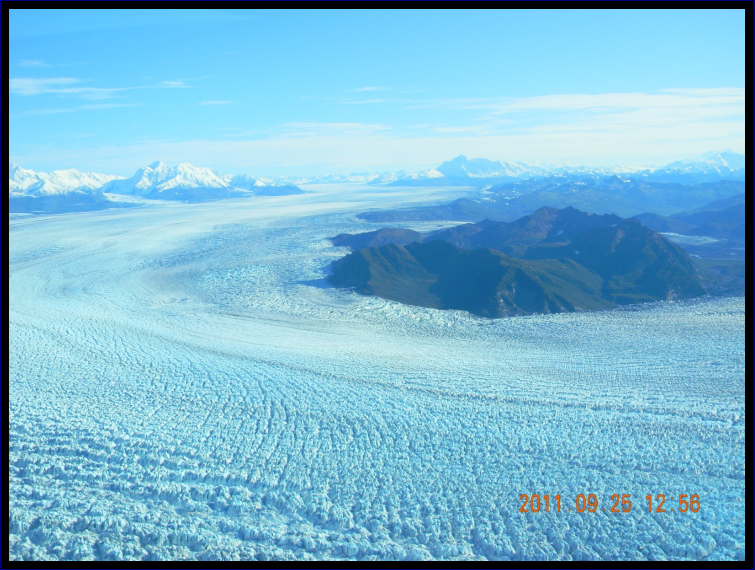
- Rapid retreat and acceleration since 1997, accompanied by surface lowering
- The main cause of fast flow is still the trough
- Reversible IF fjord-glacier cycle
- Probably irreversible if warming at front (ice-ocean interaction)

Bering Glacier System, Alaska

- Surge cycles are underlain by a trend of glacial retreat

This talk is not about the complications !

Bering Glacier Surge 2011 – 2012 – 2013 – ?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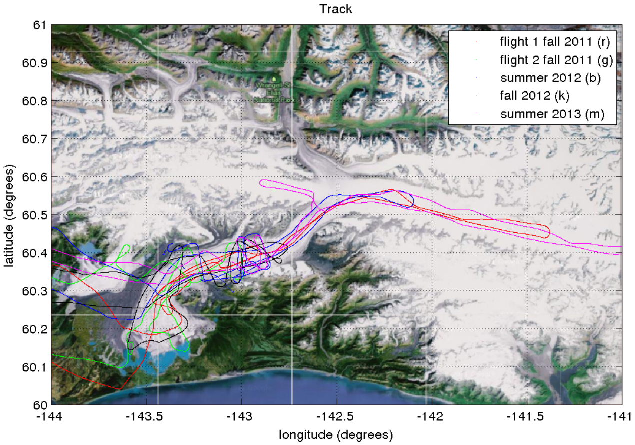
Chukchi Sea
Alaska
Yukon
Anchorage
Gulf of Alaska
Bering Sea
200 mi
500 km



Flight Tracks of Bering – Bagley System Observations 2011-2012


2011.09.26 17:31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2011.09.25 13:18


2011.09.25 13:44


2011.09.26 16:32

Surge Reinitiation in 2012

New Drawdown (South) - 2012 (October 1)

New Drawdown (South) - 2012 (October 1)

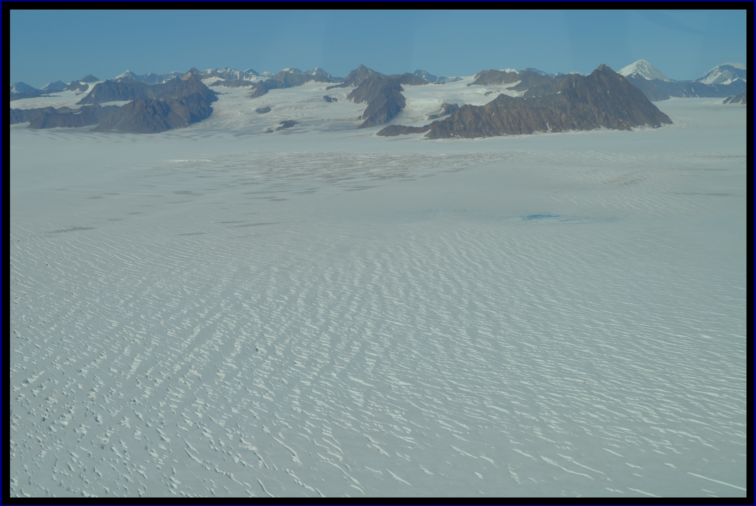
8-2013: Surge continues to expand further up Bagley Ice Field

New surge-type crevassing in eastern Bagley Ice Field, 24 Aug 2013

8-2013: Surge continues to expand further up Bagley Ice Field

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

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 uplacier 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.

References: Herzfeld 1998 (BeringBook), Herzfeld and Mayer J. Glaciol. 1997

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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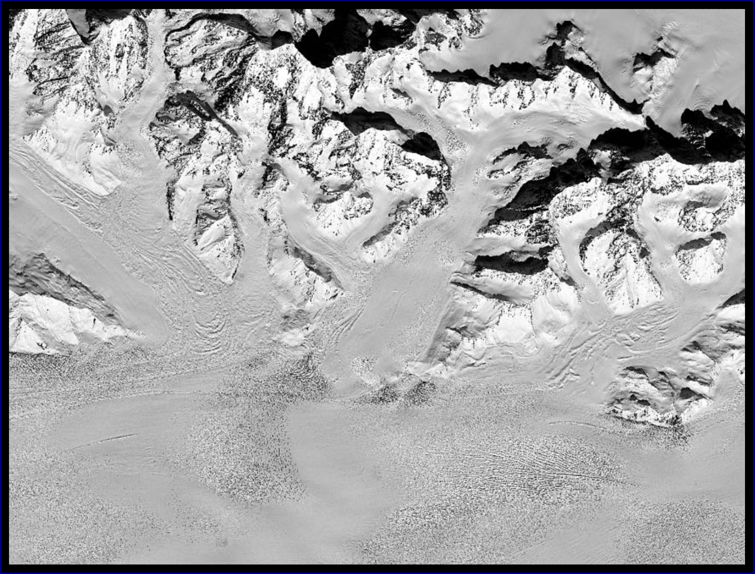
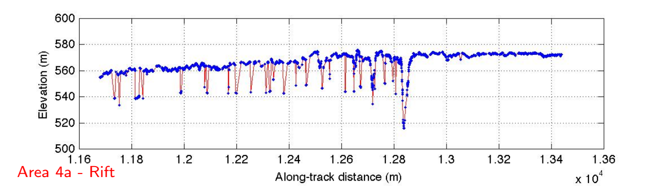
Laser Altimetry

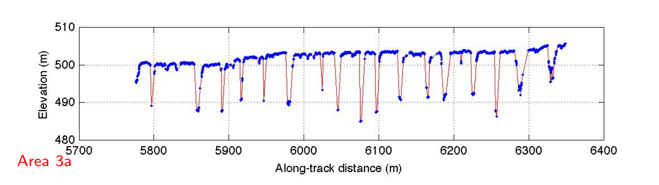
Integrated Observation System 2012 (Laser Altimeter, Video, GPS, Computer for Data Registration)

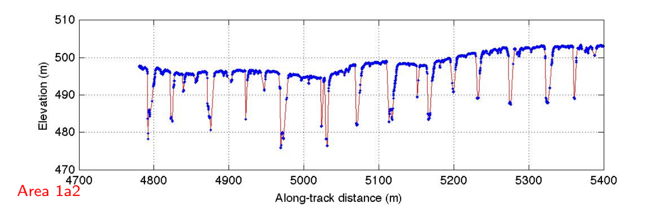


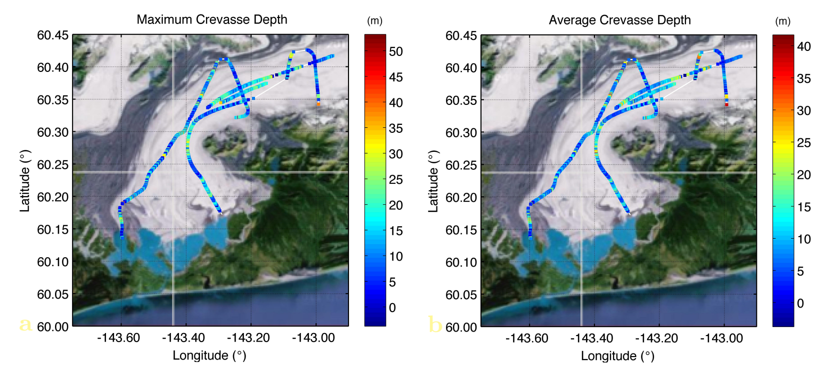
Rift Location

Rift

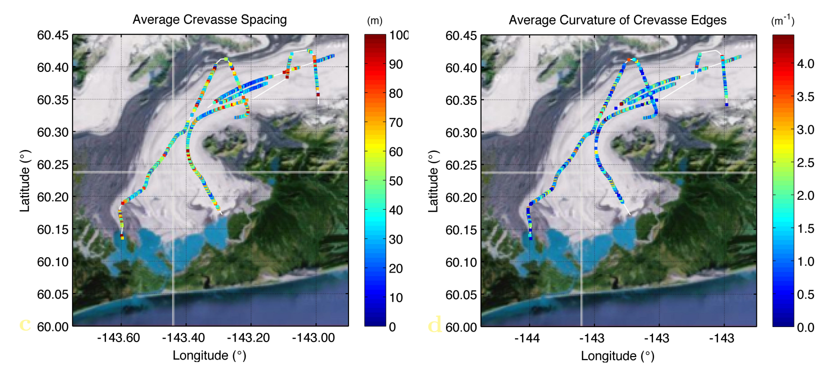

Elevation (m)
600
580
560
540
520
500
1.16
1.18
1.2
1.22
1.24
1.26
1.28
1.3
1.32
1.34
1.36
x 10^4
Along-track distance (m)
Area 4a - Rift


Elevation (m)
510
500
490
480
5700
5800
5900
6000
6100
6200
6300
6400
Along-track distance (m)
Area 3a


Elevation (m)
510
500
490
480
470
4700
4800
4900
5000
5100
5200
5300
5400
Along-track distance (m)
Area 1a2



Maximum Crevasse Depth
(m)
60.45
60.40
60.35
60.30
60.25
60.20
60.15
60.10
60.05
60.00
Latitude (°)
-143.60
-143.40
-143.20
-143.00
Longitude (°)
50
45
40
35
30
25
20
15
10
5
0
a
Average Crevasse Depth
(m)
40
35
30
25
20
15
10
5
0
b


Average Crevasse Spacing
(m)
60.45
60.40
60.35
60.30
60.25
60.20
60.15
60.10
60.05
60.00
Latitude (°)
c
-143.60
-143.40
-143.20
-143.00
Longitude (°)
100
90
80
70
60
50
40
30
20
10
0
Average Curvature of Crevasse Edges
(m^{-1})
d
-144
-143
-143
-143
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0

What is spatial surface roughness?

- a derivative of (micro)topography
  $\rightarrow$ 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

$$V = \{(x, z) \text{ with } x = (x_1, x_2)\epsilon\mathcal{D} \text{ and } z = z(x)\} \subseteq \mathcal{R}^3$$

discrete-surface case or

$$V = \{(x, z) \text{ with } x\epsilon\mathcal{D} \text{ and } z = z(x)\} \subseteq \mathcal{R}^2$$

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 $(x_i, z(x_i)), (x_i + h, z(x_i + h))\epsilon\mathcal{D}$ and n the number of pairs separated by h.

Higher-Order Vario Functions

The first-order vario-function set is

$$V_1 = \{(h, v_1(h))\} = \underline{v}(V_0)$$

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

$$V_{i+1} = \underline{v}(V_i)$$

for $i \epsilon \mathcal{N}_0$.

Geostatistical Classification Parameters

significance parameters:

slope parameter:

$$p1 = \frac{\gamma_{max_1} - \gamma_{min_1}}{h_{min_1} - h_{max_1}}$$

relative significance parameter:

$$p2 = \frac{\gamma_{max_1} - \gamma_{min_1}}{\gamma_{max_1}}$$

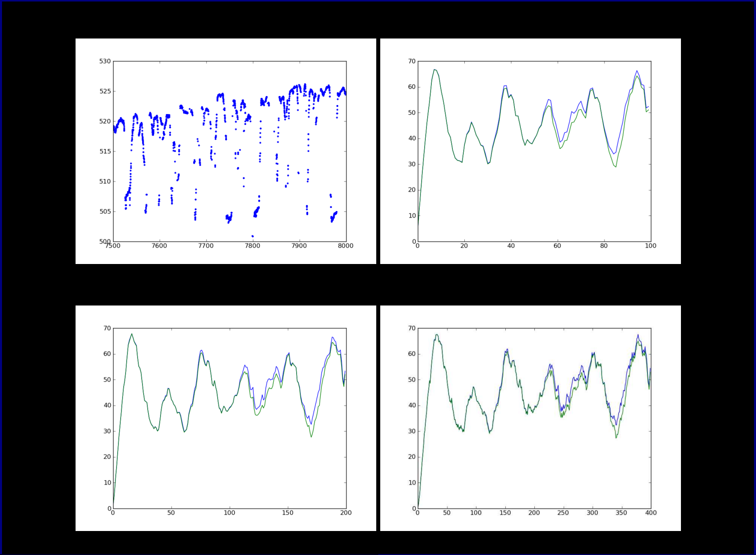
pond – maximum vario value

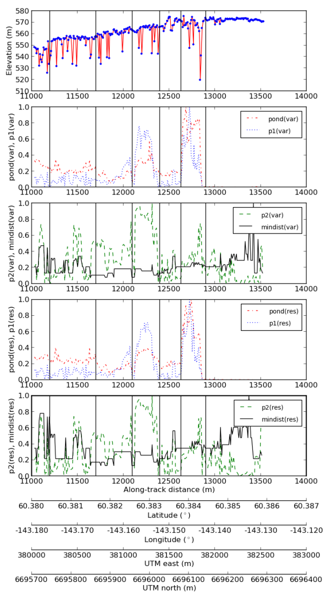
mindist – distance to first min after first max

$$avgspac = \frac{1}{n} \sum_{i=1}^{n} \frac{1}{i} \; h_{min_i}$$

typically for $n = 3$ or $n = 4$

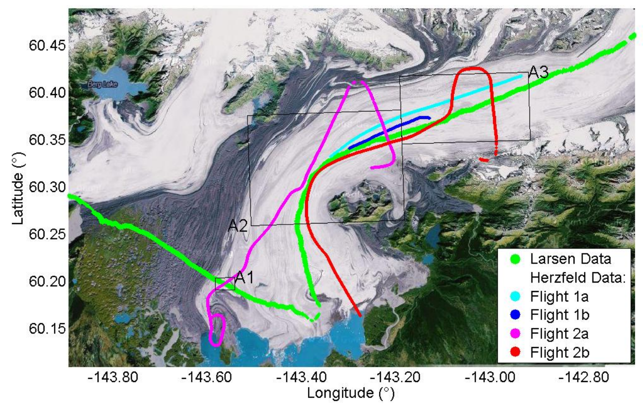
Directional variograms of laser-altimeter profiles of Bering Glacier crevasses





Geostatistical classification parameters calculated from laser altimeter data for the region of the rift.

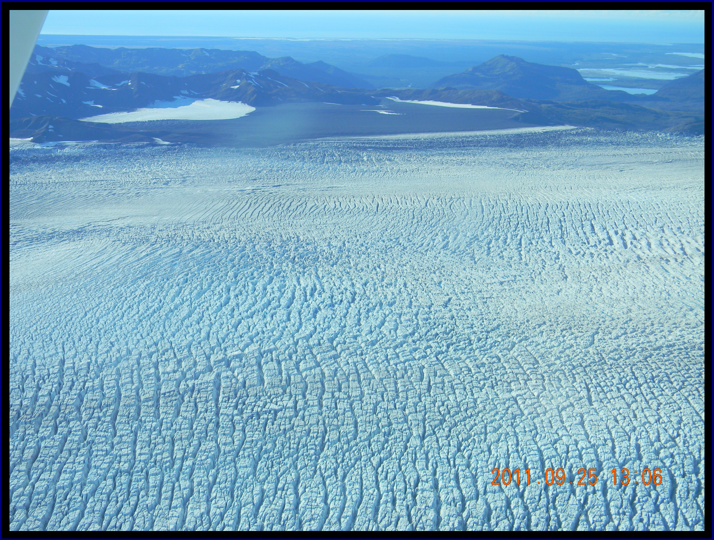
Elevation-change determination



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

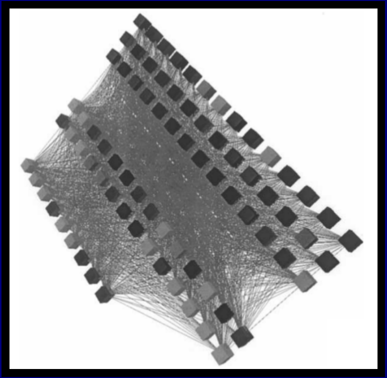
Elevation change determined from laser altimeter data collected by C. Larsen, University Alaska Fairbanks, 2010, under NASA Operation IceBridge, and by U.C Herzfeld, Sept. 2011, as part of NSF project. (Herzfeld et al.,

Automated Image Analysis to Derive Deformation Types



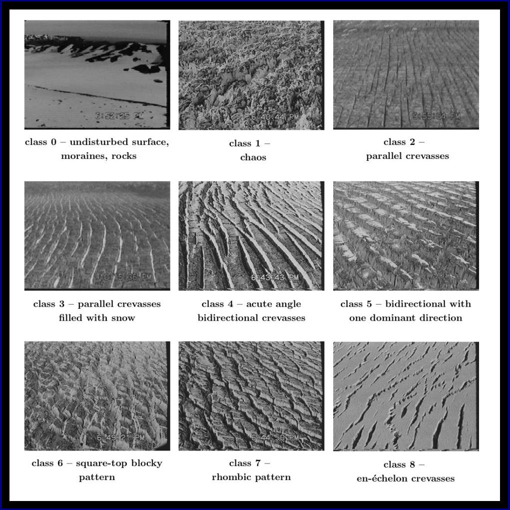
Crevasse types - Sept 2011

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)



class 0 – undisturbed surface, moraines, rocks

class 1 – chaos

class 2 – parallel crevasses

class 3 – parallel crevasses filled with snow

class 4 – acute angle bidirectional crevasses

class 5 – bidirectional with one dominant direction

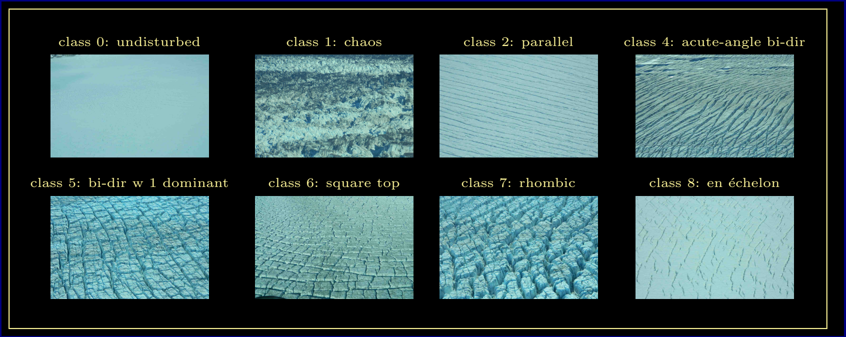
class 6 – square-top blocky pattern

class 7 – rhombic pattern

class 8 – en-échelon crevasses

Nine Class

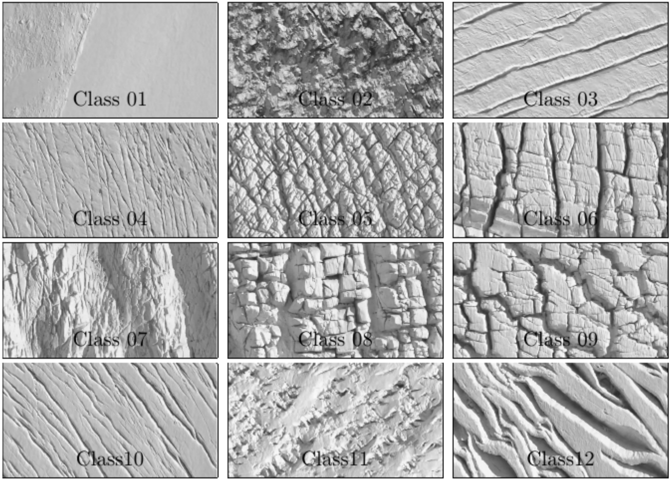
Crevasse Classes Bering Glacier Surge 2011



Crevasse Classes 2011 used in Connectionist-Geostatistical Classification

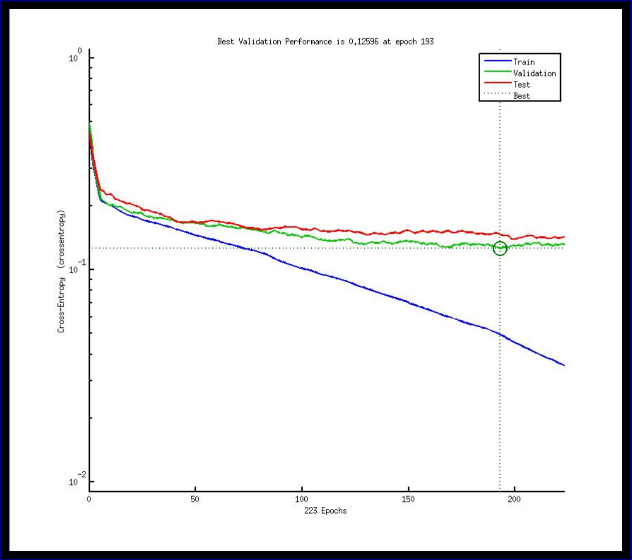
(Herzfeld, McDonald, Weltman, Annals Glaciol, 2013b)

NN Classification for Bering Glacier Surge 2012

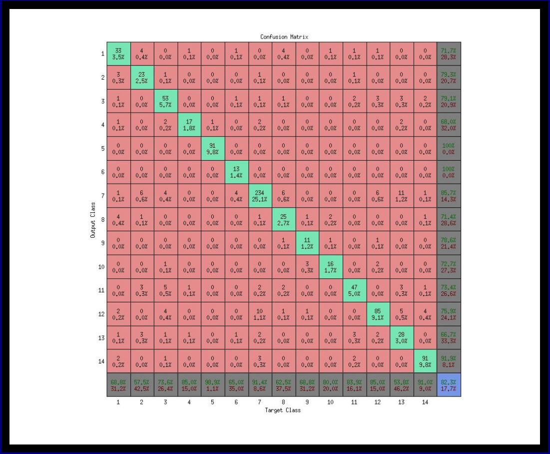


Crevasse Classes: Undisturbed Snow, Chaos, Parallel, Acute Bi-directional, Multi-direction and Multi-deformed, Bi-directional with one dominant direction, Waves, Square topped, Rhombic, EnEchelon, Sastrugi EnEchelon,Big EnEchelon. – Griffin Hale

NN Performance

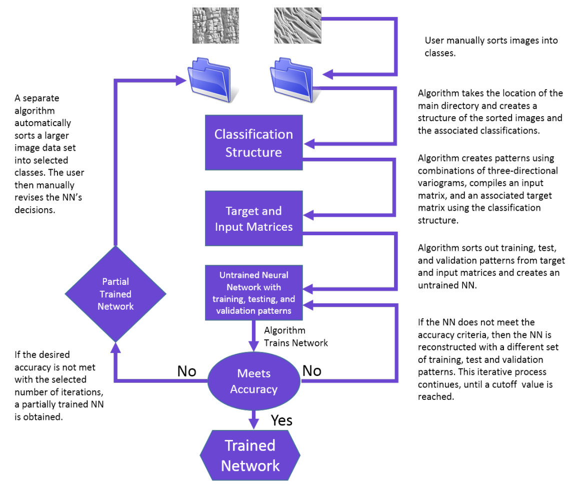


Confusion Matrix for 2012 NN



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

Semi-Automated Training of a Crevasse Classification Neural Net



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

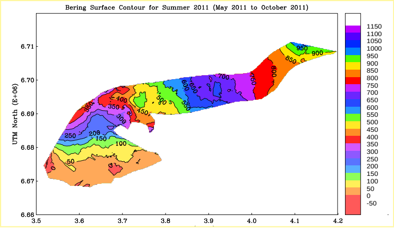
Questions:

- 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)?

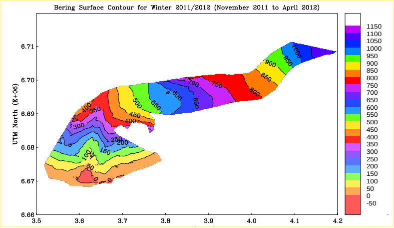
The following experiments use Glen's flow law and full Stokes and employ Elmer Ice. (Model experiments by Tom Trantow).

Then compare modeled variables and observations: What can the model explain? What can it not explain?

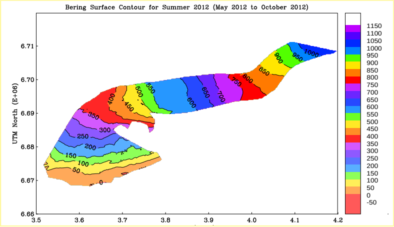
Surface Elevation of Bering Glacier from CryoSat-2 Data



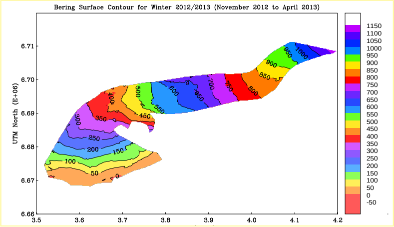
(a) Summer 2011



(b) Winter2011/2012



(c) Summer 2012

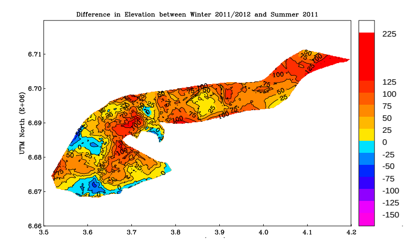


(d) Winter 2012/2013

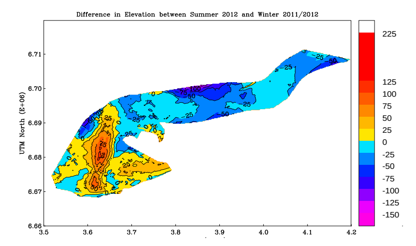
From Trantow and Herzfeld (2013 subm.)

Elevation Change of Bering Glacier from CryoSat-2 Data

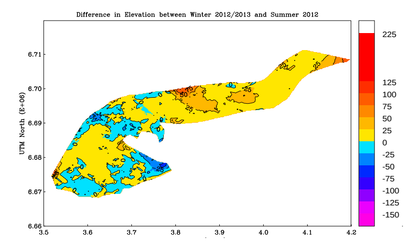
Winter 2011/2012 - Summer 2011



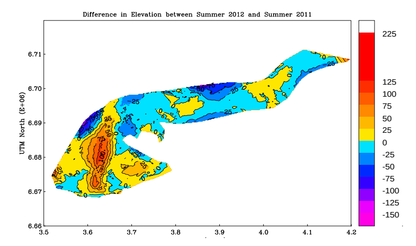
Summer 2012 - Winter 2011/2012



Winter 2012/2013 - Summer 2012

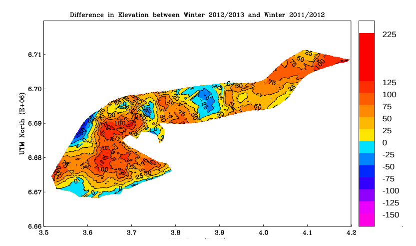


Summer 2012 - Summer 2011

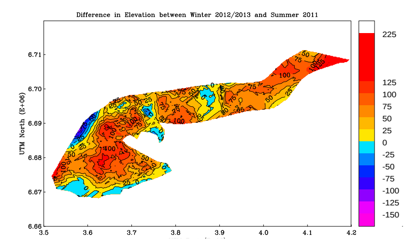


Elevation Change of Bering Glacier from CryoSat-2 Data

Winter 2012/2013 - Winter 2011/2012



Winter 2012/2013 - Summer 2011



CryoSat-2 Data Analysis – Error Analysis

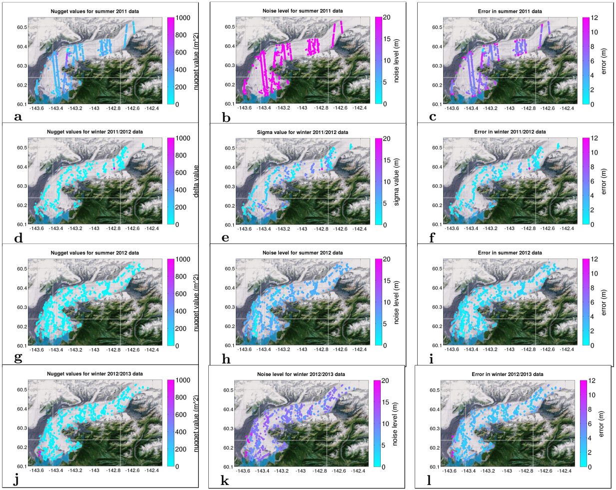
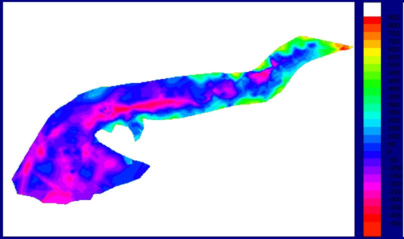


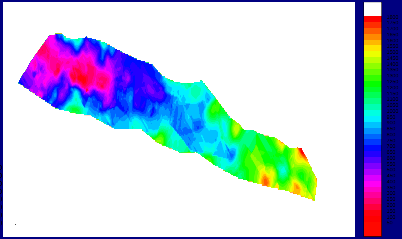
Figure 9. Nugget values, noise levels and error values. (a)(b)(c) Summer 2011, (d)(e)(f) winter 2011/2012, (g)(h)(i) summer 2012, and (j)(k)(l) winter 2012/2013. Nugget values are in the left column (a,d,g,j), noise values in the middle column (b,e,h,k) and errors in the right column (c,f,i,l). Color 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

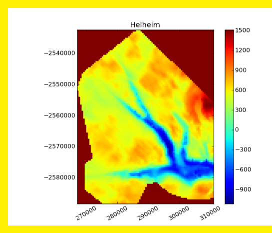
Building a Greenland Bed for Modeling (at 5 km)

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

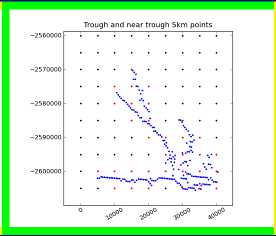
- (1), (2) use Bamber, Layberry, Gogineni 2001 5km DEM as base grid
- (3) starts from scratch: from CreSIS thickness data

(4) use trough-system algorithm

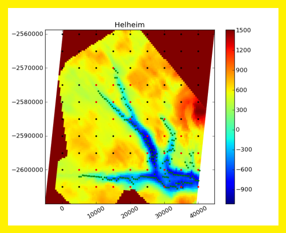
Helheim Glacier



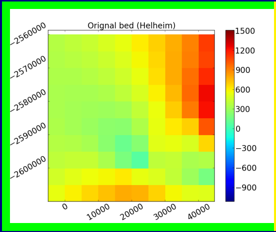
(a) CReSIS data, gridded



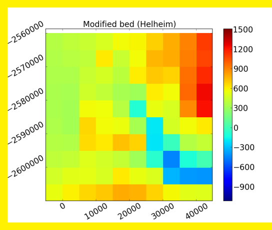
(b) trough detection



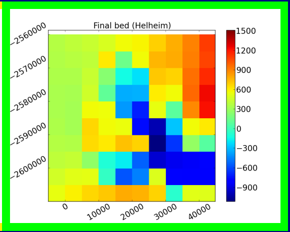
(c) trough over hi-res grid



(d) orig bed (Bamber et al. 2001)



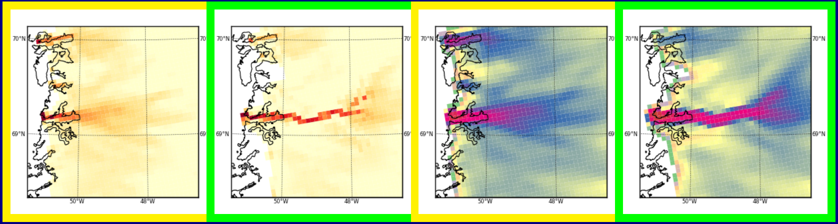
(e) interpolated w new data



(f) final bed w trough integration

(from Herzfeld et al., Annals Glaciol., 2013, ms)

UMISM [James Fastook]: Jakobshavn Isbræ



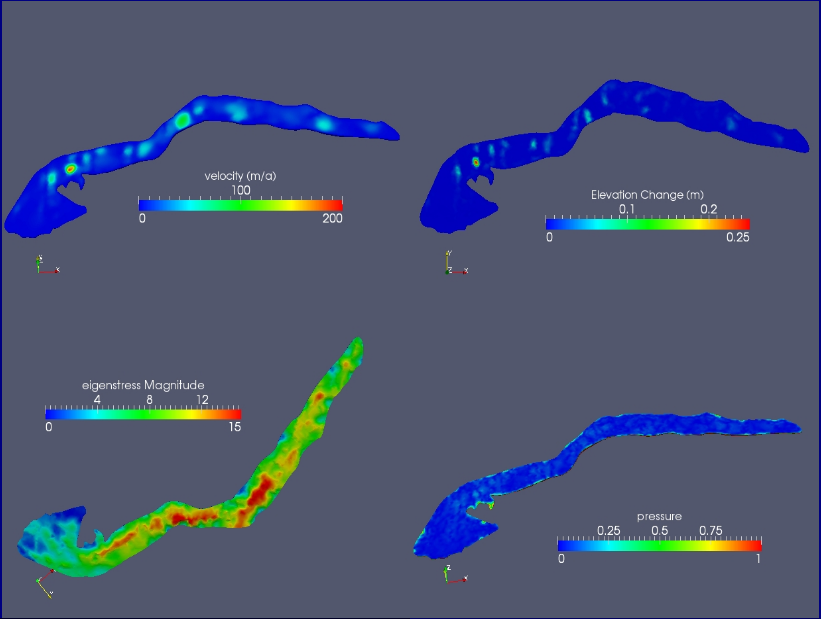
(a) Bed w Water [a]   (b) Bed w Water [b]   (c) Ice Velocity [a]   (d) Ice Velocity [b]

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



Bering Glacier: Numerical Modeling of Surge Progression

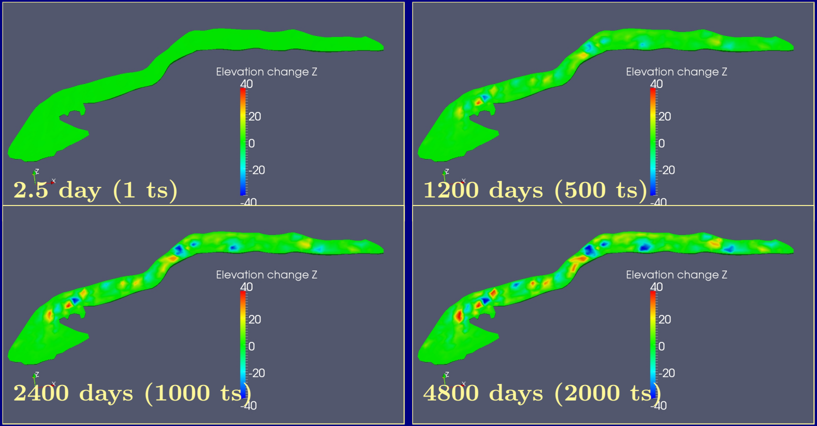
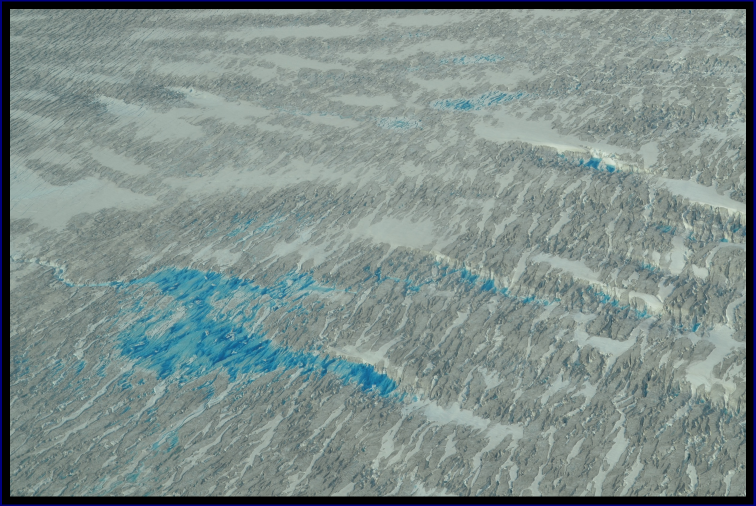


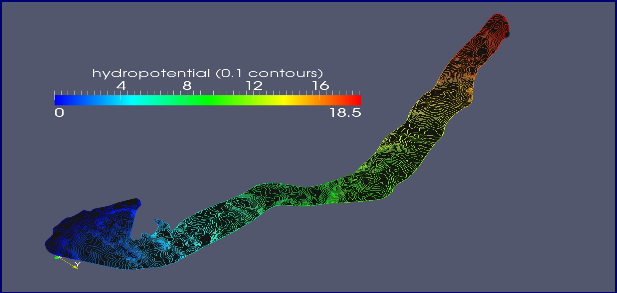
Figure 2. Bering-Bagley Glacier System: Modeled elevation change. The results of an experimental simulation of Bering Glacier using the MultiPhysics and F.E.M. software Elmer/Ice. Surface and bed elevation maps (DEMS) are used as inputs (Boundary Conditions) and were derived from satellite and airborne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

8-2013: Supraglacial Water, Bagley Ice Field

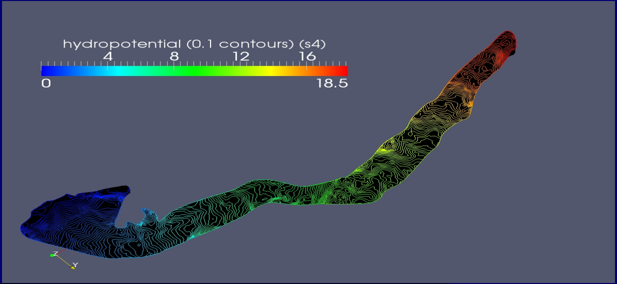


Indicative of blocked englacial hydrological system during surge; near Bering-Bagley Junction, 24 Aug 2013

Basal Hydropotential

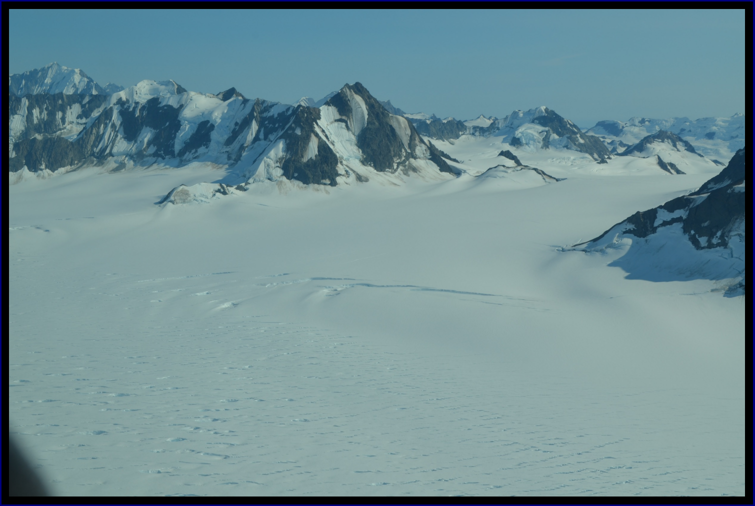


Summer 2012



Winter 2012/2013

Sheridan Glacier



Questions?