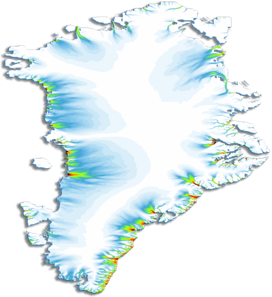
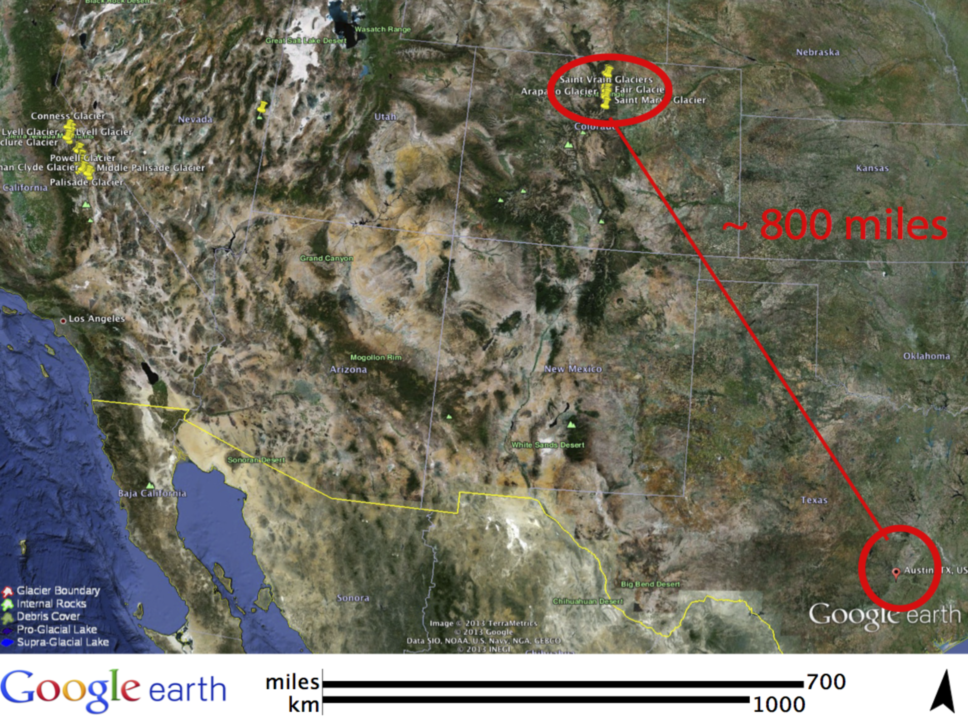
Why we model ice sheets

Andy Aschwanden



Outline

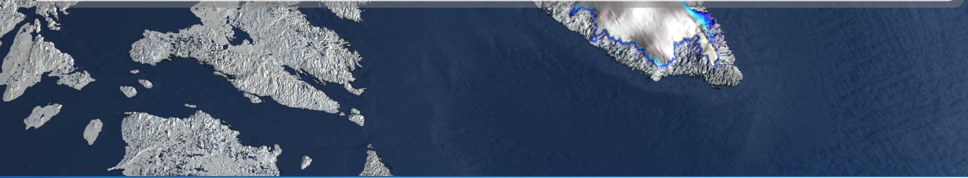


Saint Vrain Glaciers
Arapaho Glacier
Fair Glacier
Saint Mary Glacier
~ 800 miles
Nebraska
Kansas
Oklahoma
Texas
Austin TX, US
Colorado
Utah
Nevada
New Mexico
Arizona
California
Wasatch Range
Great Salt Lake Desert
Conness Glacier
Lyell Glacier
Powell Glacier
Middle Palisade Glacier
Palisade Glacier
Grand Canyon
Los Angeles
Mogollon Rim
White Sands Desert
Sonoran Desert
Baja California
Sonora
Big Bend Desert
Chihuahuan Desert
Glacier Boundary
Internal Rocks
Debris Cover
Pro-Glacial Lake
Supra-Glacial Lake
Image © 2013 TerraMetrics
© 2013 Google
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2013 INEGI
Google earth
miles
700
km
1000

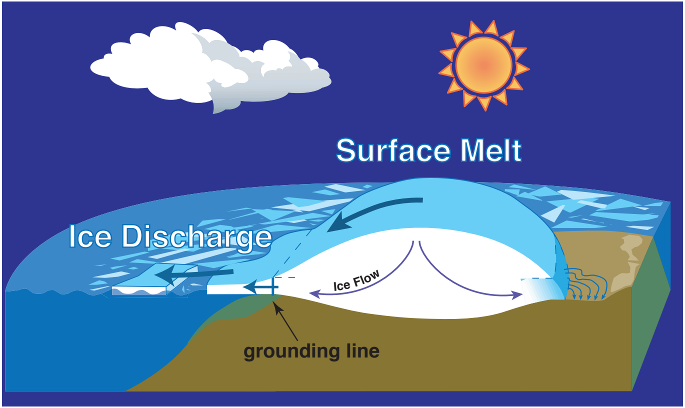
Why we care about ice sheets

- knowledge of changes in Greenland and Antarctica is critical for understanding present and future sea level rise
- holds a great potential to raise sea level substantially
- observations over the past decades show
  - rapid acceleration of several outlet glaciers
  - increased mass loss
  - thinning around the margin
  - loss of ice shelves

$\Rightarrow$ we all have heard these arguments before



How does an ice sheet lose mass?

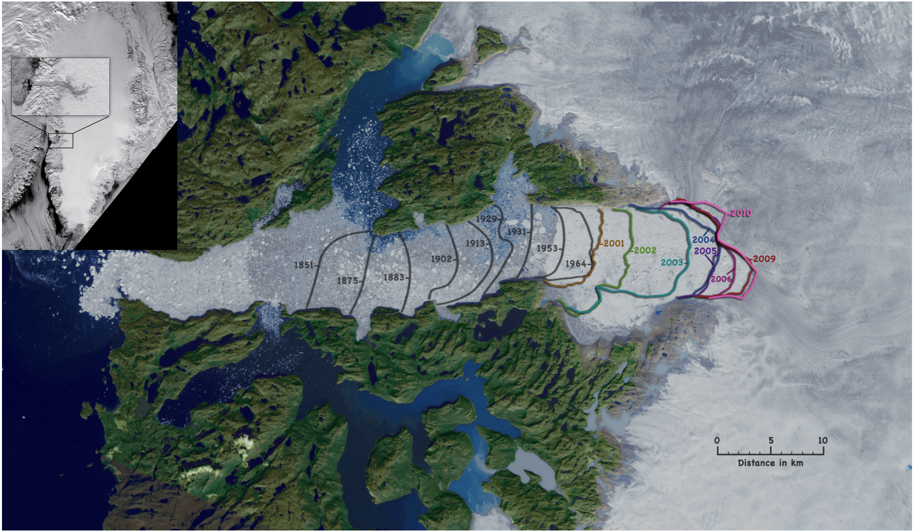


modified from ICESat brochure

before the mid-90s mass loss was dominated by surface mass balance

ice discharge = ice thickness $\times$ vertically-averaged horizontal velocity

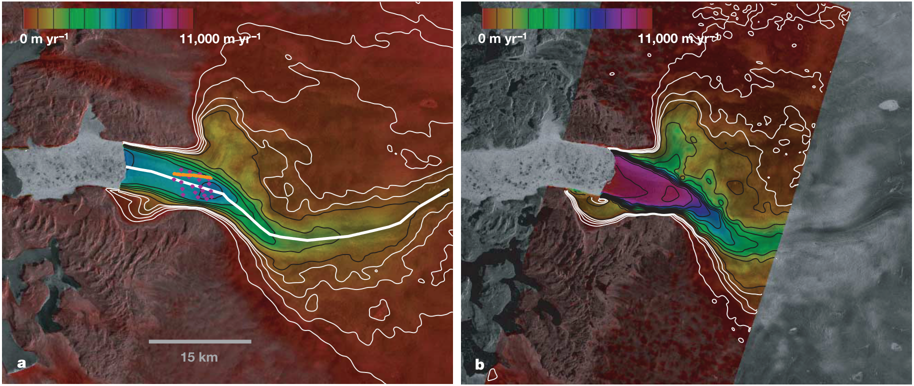
Jakobshavn Isbræ, west Greenland



credit: NASA SVS and M. Fahnestock

Speed-up of Jakobshavn Isbræ 1992-2000

- almost doubled its flow speed between the 1992 and 2000

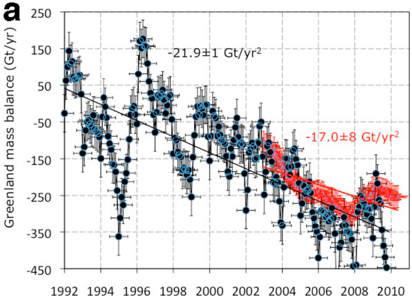


Joughin et al. (2004)

What has the future in stock?

Since 2000 the mass balance has been persistently negative with

- a decrease in surface mass balance
- an increase in ice discharge



Rignot et al, 2011

"Realistic projections of ice sheet response to a changing climate should be based on a physical understanding of the processes involved, rather than trend extrapolation of historical observations" (Arthern & Hindmarsh, 2006)

Sea Level Response to Ice Sheet Evolution

- "SeaRISE" led by Bob Bindschadler
- national and international unfunded participants

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Ice-sheet model sensitivities to environmental forcing and their use in projecting future sea level (the SeaRISE project)

Robert A. BINDSCHADLER,[1] Sophie NOWICKI,[1] Ayako Abe-OUCHI,[2] Andy ASCHWANDEN,[3] Hyeungu CHOI,[4] Jim FASTOOK,[5] Glen GRANZOW,[6] Ralf GREVE,[7] Gail GUTOWSKI,[8] Ute HERZFELD,[9] Charles JACKSON,[8] Jesse JOHNSON,[6] Constantine KHROULEV,[3] Anders LEVERMANN,[10] William H. LIPSCOMB,[11] Maria A. MARTIN,[12] Mathieu MORLIGHEM,[13] Byron R. PARIZEK,[14] David POLLARD,[15] Stephen F. PRICE,[11] Diandong REN,[16] Fuyuki SAITO,[17] Tatsuru SATO,[7] Hakime SEDDIK,[7] Helene SEROUSSI,[18] Kunio TAKAHASHI,[17] Ryan WALKER,[19] Wei Li WANG[1]

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[14]*Mathematics and Geoscience, Penn State DuBois, DuBois, PA, USA*
[15]*Earth and Environmental Systems Institute, The Pennsylvania State University, University Park, PA, USA*
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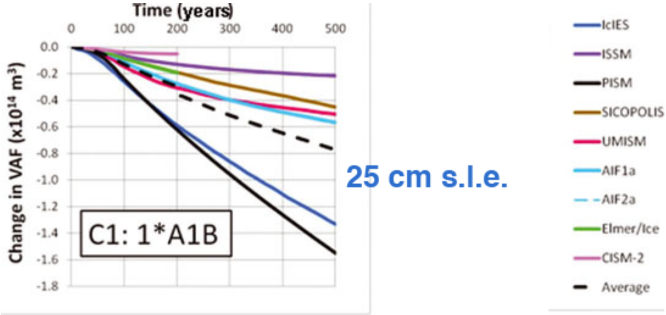
[17]*Japan Agency for Marine–Earth Science and Technology, Research Institute for Global Change, Showamachi, Kanazawa, Yokohama, Kanagawa, Japan*
[18]*Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA*
[19]*Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA*

"SeaRISE"



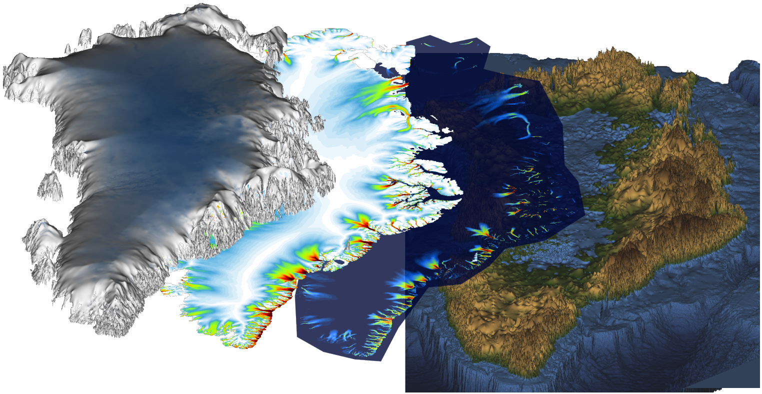
Bindschadler et al. (2013), mod.

Would you rather trust

- a particular model
- the ensemble average
- none

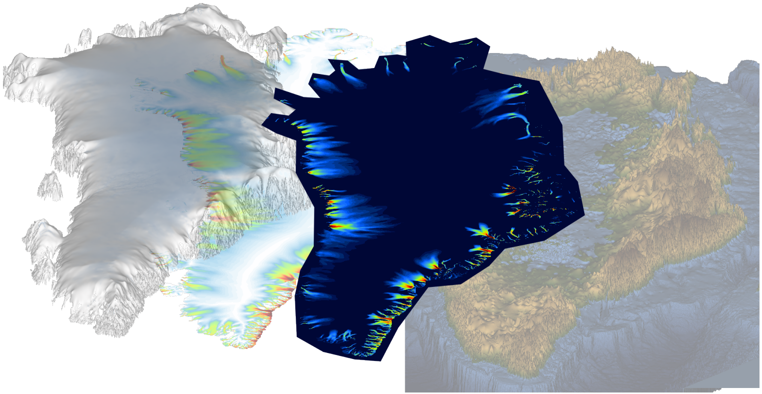
$\Rightarrow$ let's look behind the scenes

Ice sheet system



- ice dynamics
- thermodynamics
- surface processes
- boundary conditions
- hydrology
- ice-ocean interaction (e.g. calving)

Ice sheet system



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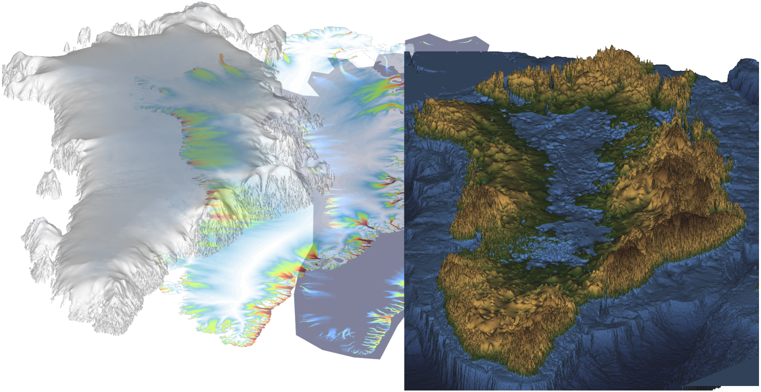

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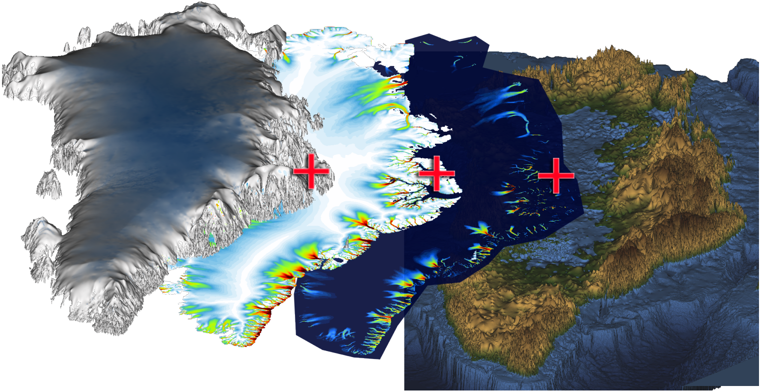
Ice sheet system



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- thermodynamics
- surface processes
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Parallel Ice Sheet Model

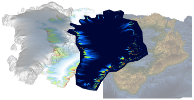
Documentation: `www.pism-docs.org`
Source code: `https://github.com/pism/pism`

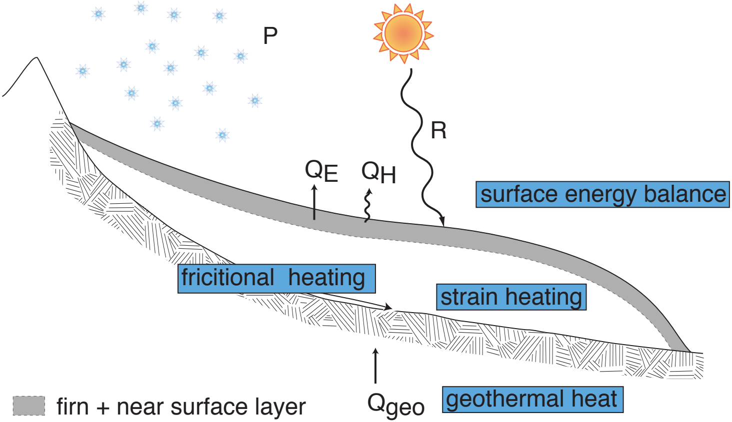
- open-source
- parallel
- high-resolution

- led by PI Ed Bueler, UAF
- jointly developed by UAF and Potsdam Institute for Climate Impact Research
- main software engineer: Constantine Khroulev, UAF
- $>$ 20 contributors and users worldwide
- funded by

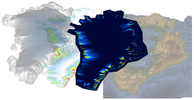
Outline

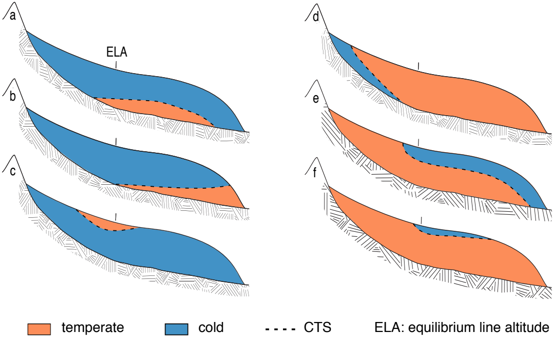
Heat sources





Polythermal glaciers





Cold ice

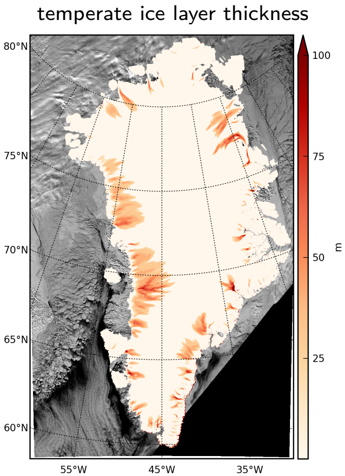
- below pressure melting point

Temperate ice

- at pressure melting point

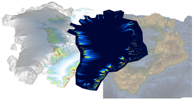
Temperate ice in Greenland

- ≈ 35 % of the base is temperate (by area)
- ≈ 0.5 % of ice is temperate (by volume)
- but temperate where strain rates are already high



Aschwanden et al. (2012, modified)

Thermodynamics



Cold ice

- below pressure melting point
- solid phase only
- no liquid water content

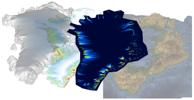
Temperate ice

- at pressure melting point
- binary mixture of solid and liquid phase
- up to 5 % liquid water within the ice matrix

Viscosity of ice depends on

- temperature
- liquid water fraction
- effective strain rate
- crystal orientation, impurities, etc.

Enthalpy equation



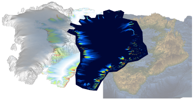
- Conventional firn and glacier models are not energy conserving
- We replace the advection-diffusion-production equation for temperature with a similar equation for enthalpy (i.e. inner energy)

$$\rho \frac{\partial \cancelto{H}{T}}{\partial t} + \mathbf{v} \cdot \nabla \cancelto{H}{T} = -\nabla \cdot \mathbf{q} + Q$$

- Same PDE $\Rightarrow$ relatively easy to implement

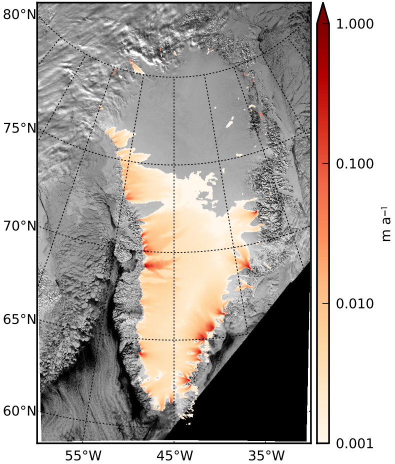
Aschwanden and Blatter (2009), Aschwanden et al. (2012)

Basal melt rates



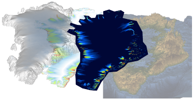
- conservation of energy
- more realistic basal melt rates
- more realistic ice streams

temperature equation



Aschwanden et al. (2012, modified)

Basal melt rates



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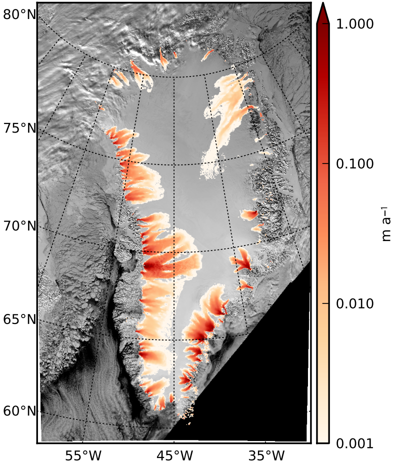
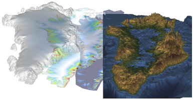
enthalpy equation

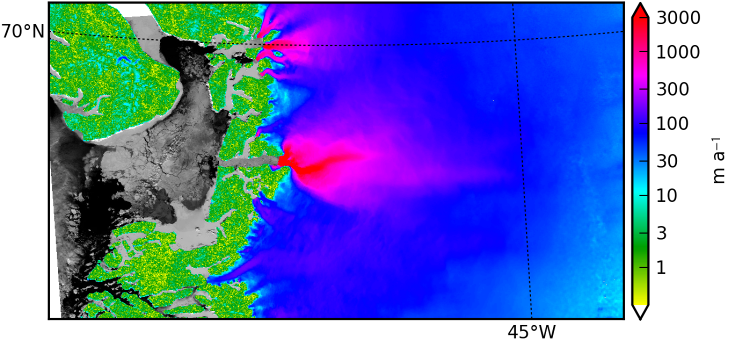


Aschwanden et al. (2012, modified)

Outline

Jakobshavn flows fast



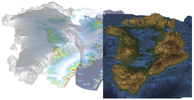


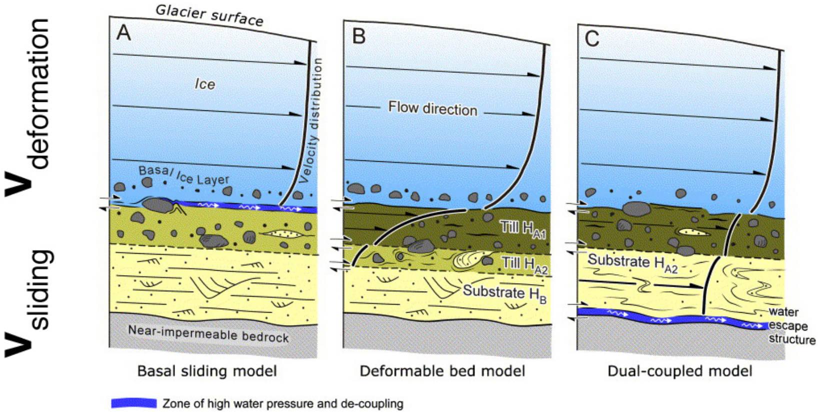
- Why does Jakobshavn flow so fast?
- boring from above

Jakobshavn flows fast

- Why does Jakobshavn flow so fast?
- boring from above

Ice flow

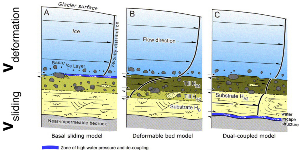




Kjær et al., (2006, modified)

$$\mathbf{v} = \mathbf{v}_{\text{deformation}} + \mathbf{v}_{\text{sliding}}, \qquad \mathbf{v} : \text{velocity}$$

Ice flow



scaling arguments tell us:

$$\mathbf{v}_{\text{deformation}} \sim (\sin\alpha)^3\,(H)^4$$

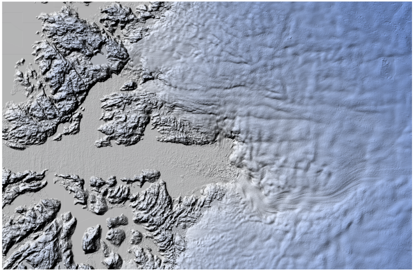
H: ice thickness
α: surface slope

Example

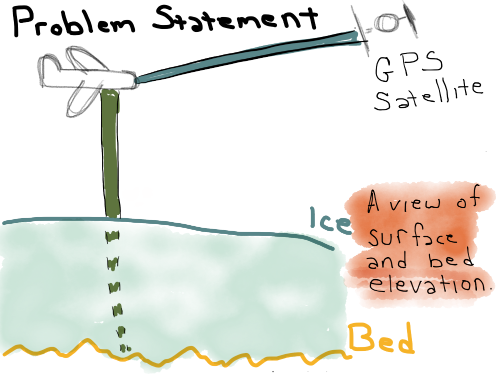
$$\frac{\delta H = 100\,\text{m}}{H = 1000\,\text{m}} = 10\,\% \quad \Rightarrow \quad \frac{\delta \mathbf{v}}{\mathbf{v}} = 40\,\%$$

Surface slope & ice thickness

surface elevation (slope)

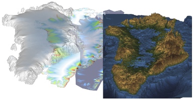


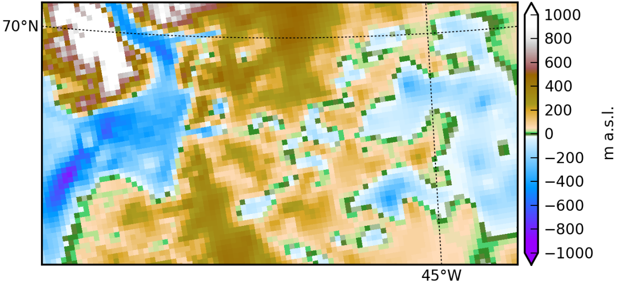
GIMP DEM (Howat et al.)



credit: Jesse Johnson

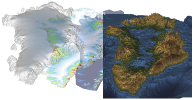
Basal topography





Bamber et al. (2001)

- Operation Ice Bridge Mission since 2009
- Center for Remote Sensing (CReSIS) radar
- huge progress between 2001 and 2012



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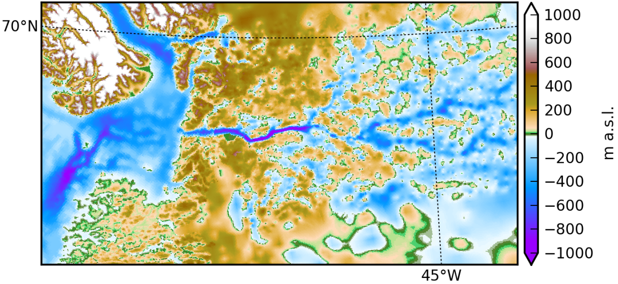
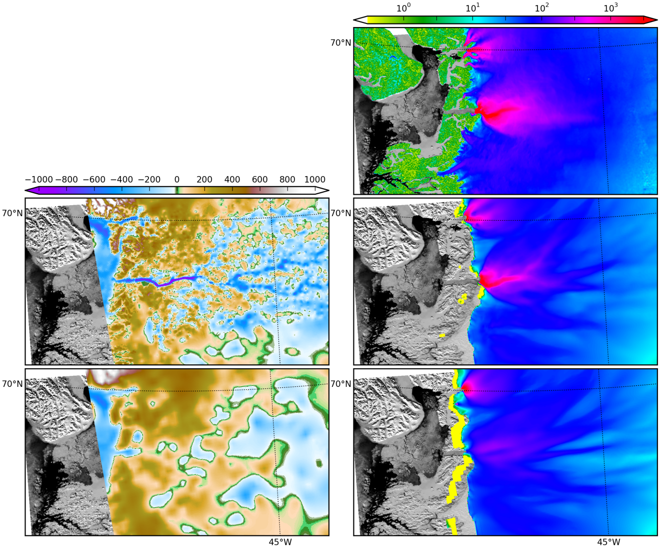


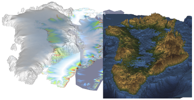
Griggs et al. (2012)

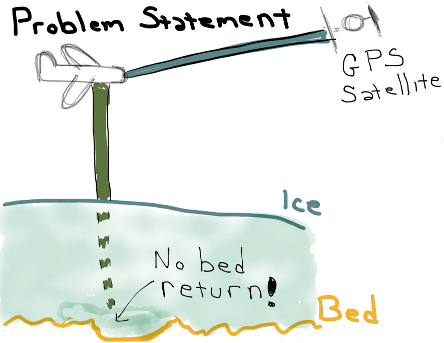
- Operation Ice Bridge Mission since 2009
- Center for Remote Sensing (CReSIS) radar
- huge progress between 2001 and 2012

It makes a difference

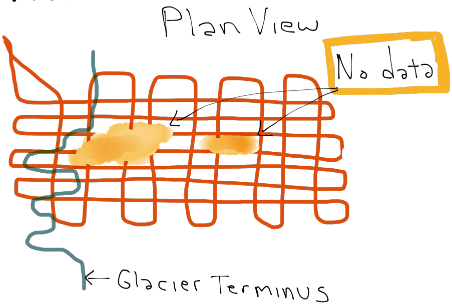


Ice thickness



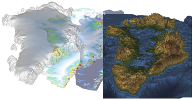


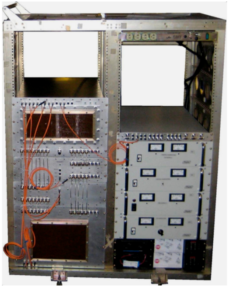
credit: Jesse Johnson

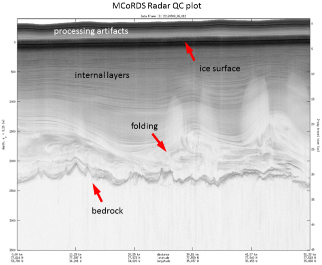


credit: Jesse Johnson

A new depth sounder





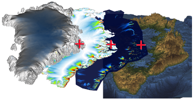


MRI

Development of a high power, large-antenna array for a Basler for sounding and imaging of fast-flowing glaciers and ultra wideband radars to map near-surface internal layers. PI: Rick Hale, University of Kansas. NSF. Current support 2012–2014.

Outline

Ice sheet model validation



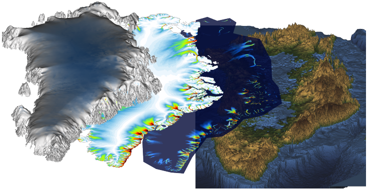
- comparing model results to a set of observations adequate to falsify a model

Direct validation

of substantial sub-systems such as

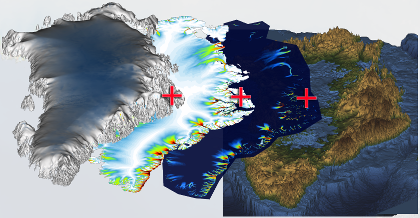
- basal hydrology
- thermodynamics
- ice dynamics

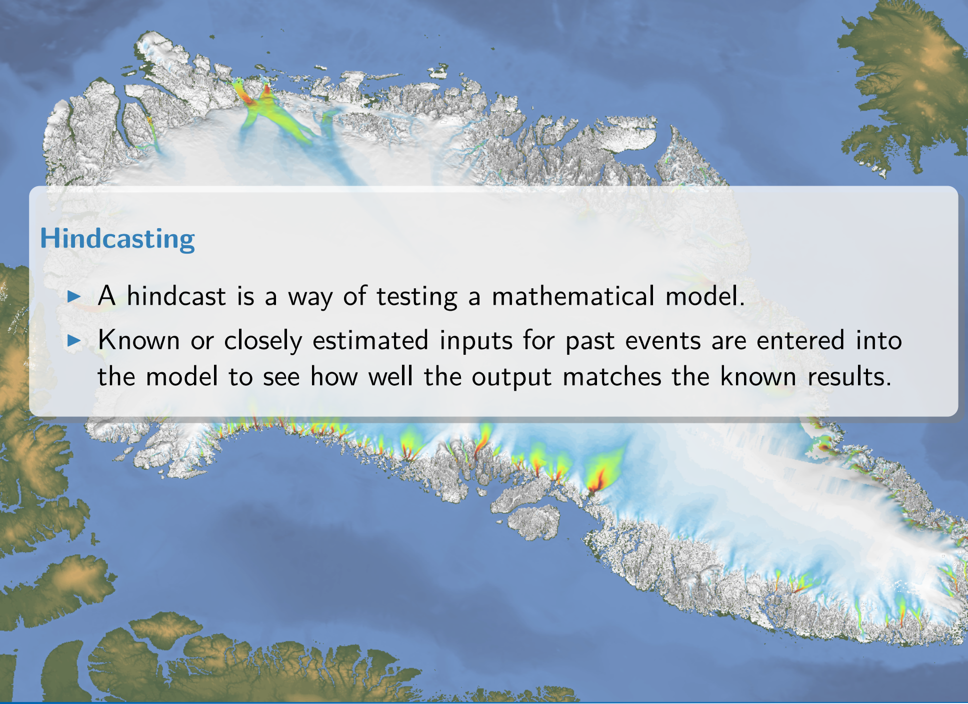
is difficult or impossible



View as part of an earth system model

- we evaluate how the *system* responds to a given forcing
- "How successful is a state-of-the art ice sheet system model (i.e. the combination of physical models, their numerical approximations and implementations, and particular choices of boundary forcing and initial states) in reproducing observations of quantities such as ice thickness, and their temporal changes?"

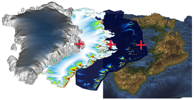




Hindcasting

- A hindcast is a way of testing a mathematical model.
- Known or closely estimated inputs for past events are entered into the model to see how well the output matches the known results.

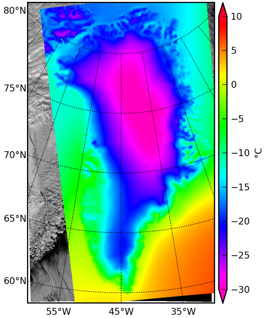
Initialization



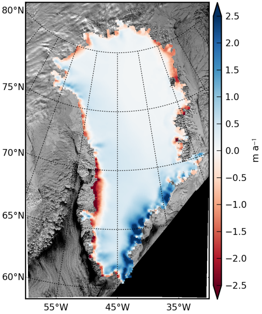
initialization → hindcast → forecast

- RACMO2/GR driven by ERA-reanalysis from 1961-2004
- PISM driven by mean values of:

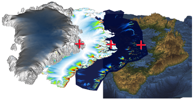
2 m air temperature



climatic mass balance



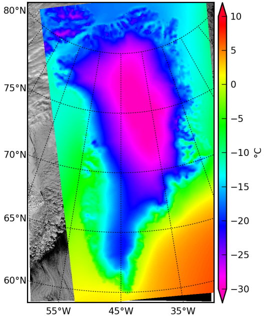
Hindcast



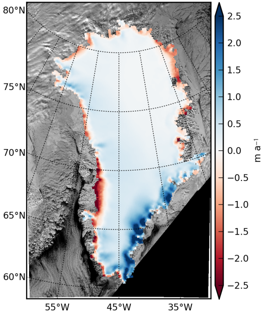
initialization → hindcast → forecast

- RACMO2/GR driven by ERA-reanalysis from 1961-2004
- PISM driven by monthly time-series of:

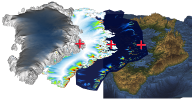
2 m air temperature



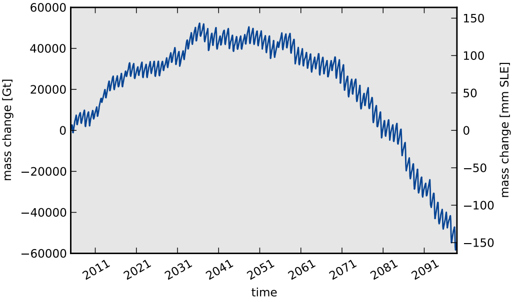
climatic mass balance



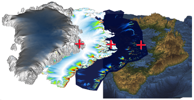
Forecast



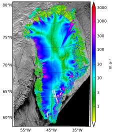
- Not the topic of this talk



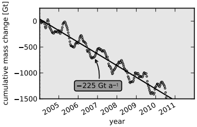
Comparison with observations



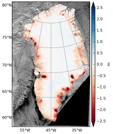
Hindcasts cover an era where we have a variety of in-situ and remotely-sensed observations such as:



- mean flow speed from 2000,2006–2008 (SAR) from *Joughin et al.* (2010)

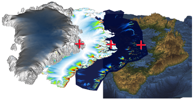


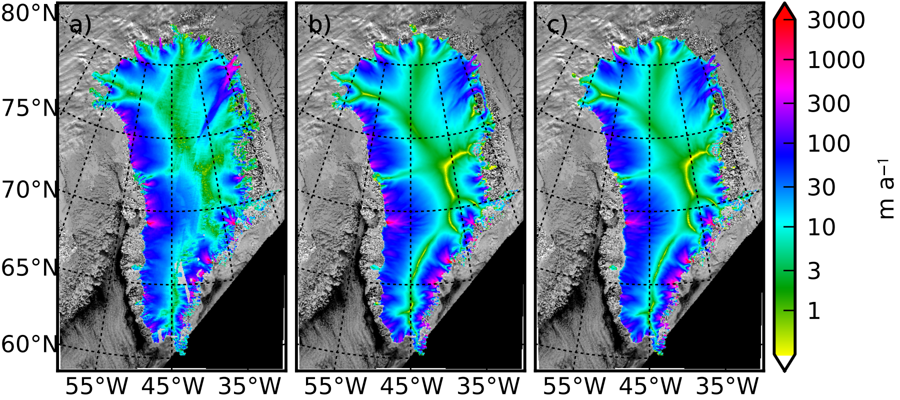
- cumulative mass change from 2003–2011 (GRACE) from *Luthcke et al.* (under review)



- elevation change from 2003–2009 (ICESat) from *Sørensen et al.* (2011)

Flow speed





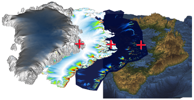
(a) SAR
(Joughin et al, 2010)

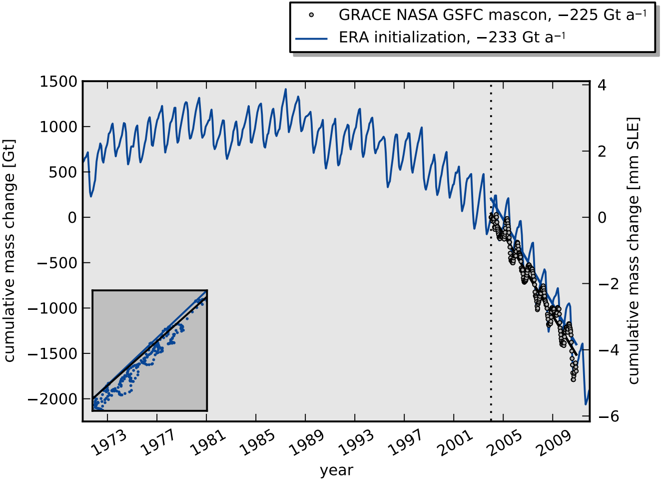
(b) ERA init.

(c) HadGEM2 init.

- reasonable agreement with observations

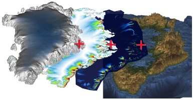
Mass changes

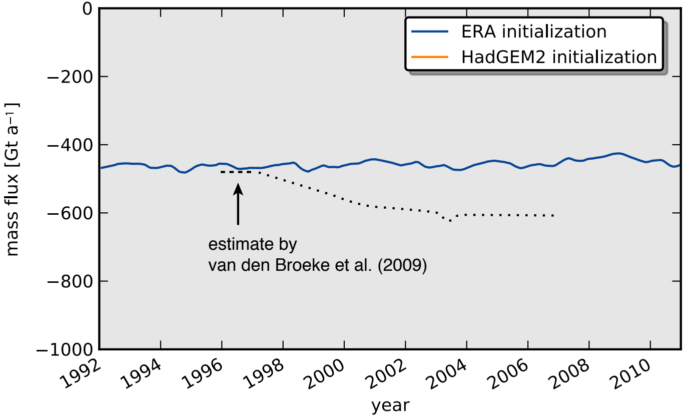




- an almost perfect fit (?)

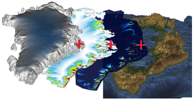
Ice discharge at ice/ocean interface



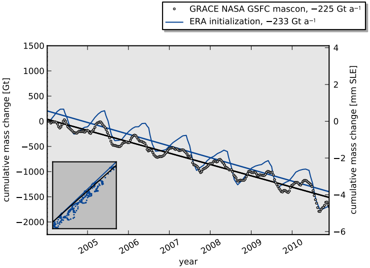


- simulated ice discharge remains nearly constant
- observed increase not simulated

Wait a minute. . .

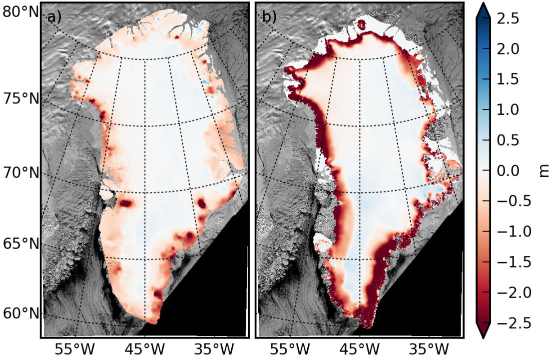


- 2000–2008 mass changes equally split between changes in surface mass balance and ice discharge (van den Broeke et al, 2009)
- but simulated ice discharge is nearly constant
- why do we get such a good agreement with observed mass loss?



We can get "the right result" for the "wrong reason"

Surface elevation changes 2003–2009

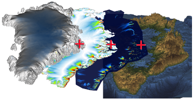


(a) ICESat
(Sørensen et al, 2011)

(b) ERA init.

spatially-rich time-series are needed!

Limitations of hindcasting

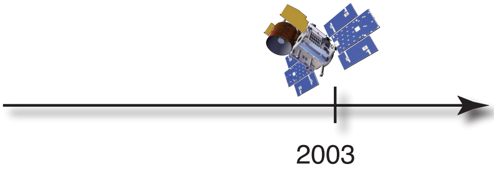


Theoretical

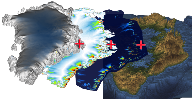
- The appropriate time-scale for hindcasting is unknown
- Hindcasts are short (decades) compared to the time-scale associated with changes in energy (thousands of years)
- Even a hindcast showing good agreement with all available observations may not capture the system's true behavior

Practical

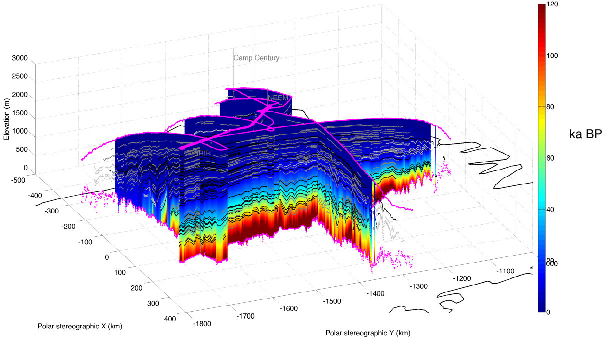
- Duration of hindcasts is limited by the length of observational records



Outlook: Isochrones

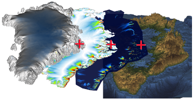


- distribution of energy within an ice sheet cannot be measured directly
- age field has similar time-scales



credit: J. MacGregor

Outlook: Isochrones



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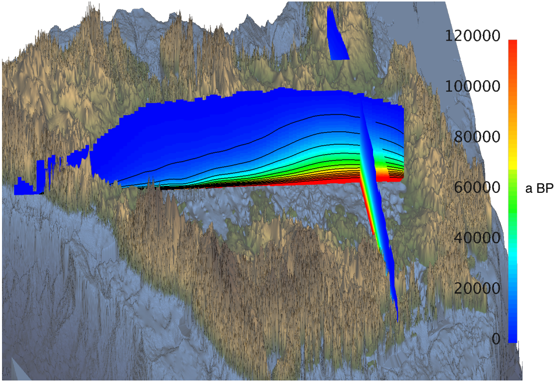

Outlook: statistical frameworks

- hindcasting may be integrated into comprehensive statistical frameworks to quantify uncertainties in ice sheet evolution due to different sources of model and observation uncertainty

NASA ROSES Cryosphere

Challenging the Parallel Ice Sheet Model with reproducing the present-day mass loss signal from the Jakobshavn basin, Greenland. PI A. Aschwanden, 2013–2016.