Greenland Observations and a Multi-Model-Data Comparison Approach for ISMIP-6: MAPCOMP, ICESat-2 Outlook and Greenland Bed Topography

Ute C. Herzfeld[1,2,3],
Thomas Trantow[1], Gavin Medley[1,3], Mattia Astarita[1,4],
Mason Markle[1,4] and Reed Anderson[1,5]

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(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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Talk Topics

(I) MAPCOMP: A Synthesis Tool for ISMIP6/CMIP6:
A Multivariate Map-Comparison Method for Model Evaluation and Spatial Model-Data Comparison

(II) Outlook to ICESat-2: Ice-Surface Height Data

(1) Algorithm Development for Ice-Surface Determination for NASA's Future ICESat-2 Mission

(2) Airborne Simulator Instrument (SIMPL) Data over Giesecke Bræer, NW Greenland

(3) MABEL data over Bering Rift

(III) Greenland Subglacial Topography

(1) Data Analysis Philosophy

(2) Trough System Algorithm

(3) Results: Greenland Bed DEMs

(I) MAPCOMP

ISMIP6: Need for analysis of multi-variate multi-model spatial experiment results and multiple spatial data sets

Existing methods for analysis comparison of many models/ model results/ experiments/model-data/maps:

- line plots of summarizing parameters
- difference maps
- one map of a summarizing parameter

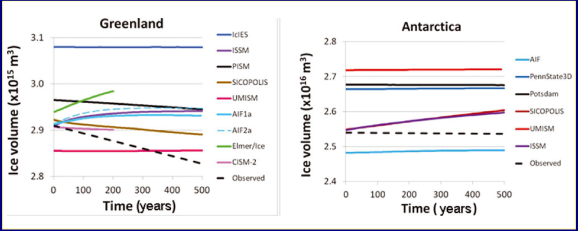


Figure 1. Change in ice-sheet volume (grounded ice plus ice shelves) for control runs of the Greenland and Antarctic ice sheets for different models. Models are identified and described in Table 2 and Appendix A. Black dashed lines begin with the current volume of each ice sheet at 0 years and apply a recently published rate of ice-sheet mass
change (Shepherd and others, 2012). Fig. 1 from Bindschadler et al. 2013.

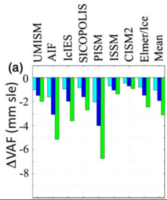


Figure 2. The change (experiment-control) in volume above flotation for the basins of the Greenland ice sheet after 100 simulated years. Atmospheric forcings for N Basin C1, C2, and C3 (light blue, blue, and green). Figure 4a from Nowicki et al. 2013.

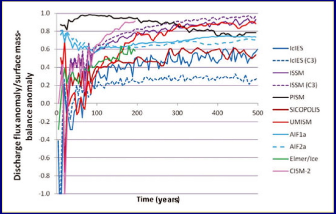


Figure 3. Ratio of discharge flux anomaly to surface mass-balance anomaly for the C1 (1 × A1B) climate experiment of the Greenland ice sheet. Anomalies are calculated by differencing discharge flux and surface mass-balance values from the respective control experiments. For comparison, the equivalent ratios for the C3 (2 × A1B) experiment for the IciIES and ISSM models are also shown as short-dashed lines. Fig. 4 from Bindschadler et al. 2013.

MAPCOMP Idea

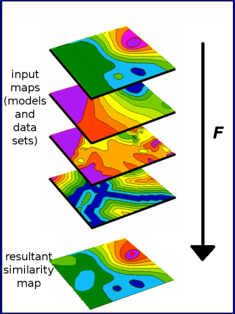


Figure 4. Schematic illustration of the map-comparison method. F denotes the MAPCOMP operator.

MAPCOMP Math

- Assume there are n maps/ model results/ experiment results/ data sets to be compared (n input maps).
- The MAPCOMP operator calculates an algebraic semi-norm in a space of $\frac{n(n-1)}{2}$, the number of comparisons possible.
- Uses a matrix functional at each grid node.
- The result is a single similarity map (or comparison map), with values in [0,1]. Close to zero - good similarity; close to one - high dissimilarity. $\rightarrow$ Indicates regions and processes that may need improvement.
- Weighting options
- Options for missing-data handling
- Several methods for pre-analysis standardization to compare the same or different variables/ units
- Use netcdf and other modeling standards
- MAPOPT - Optimization of parameters or testing of simple functional relationships

MAPCOMP – Application Example

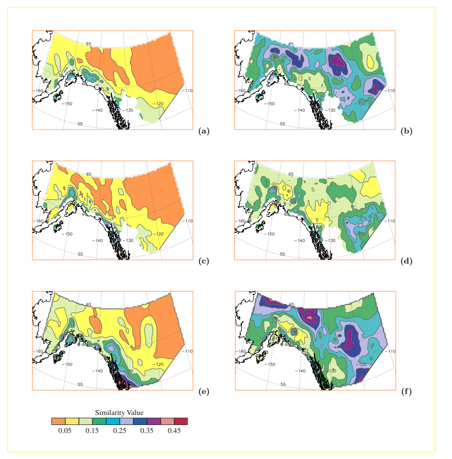


Figure 5. Example of application of the map-comparison method for the Western Arctic Linkage Experiment (WALE) for model validation, based on 18 input maps. Model validation for MM5 precipitation prediction using algebraic similarity mapping with 18 input maps. (a) Similarity map ERA-40 vs MM5, January 1992-2000; (b) similarity map ERA-40 vs MM5, July 1992-2000; (c) similarity map UDEL(MW) vs MM5, January 1992-2000; (d) similarity map UDEL(MW) vs MM5, July 1992-2000; (e) similarity map NCEP1 (=NCAR) vs MM5, January 1992-2000; and (f) similarity map NCEP1 (=NCAR) vs MM5, July 1992-2000. (from Herzfeld et al. (2007) Earth Interactions).

The figures shows that regional differences in model performance exist and that models match the data sets used in the evaluation to different degrees, indicating a dependence on topographic relief, continentality and seasonality.

Plans for ISMIP6:

- Create MAPCOMP/MAPOPT for Greenland, Antarctica and regional studies and ISMIP6 standards
- Apply MAPCOMP to analyze results from all experiments and models
- Apply MAPCOMP in model-data comparison, especially using ice-surface elevation, but also any other output parameter.
- Identify regions of agreement and disagreement among models and models/data

For first examples of MAPCOMP applied to Greenland and Alaska, see

Poster by Mattia Astarita, Mason Markle, Tom Trantow, Ute Herzfeld

(II) Recent Altimeter Data Sets

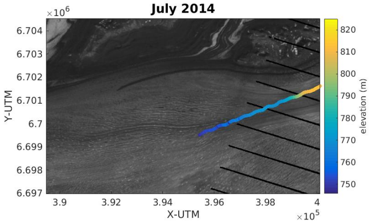
(A) Satellite Altimetry

- GEOSAT Radar Altimeter Data (12 March 1985 - 30 Sept 1986 (GM), then ERM to 1990)
- ERS-1 Satellite Radar Altimeter Data (17 July 1991 - 1995; mission ended 10 March 2000) - ESA
- ERS-2 Satellite Radar Altimeter Data (21 April 1995 - 2011) - ESA
- ENVISAT Satellite Radar Altimeter Data (March 2002 - 8 April 2012) - ESA
- ICESat Geoscience Laser Altimeter System (GLAS) (Jan 13 2003 - Aug 14 2010) - NASA
- CryoSat-2 SIRAL Data (8 April 2010 - present) - ESA
- ICESat-2 ATLAS: micro-pulse multi-beam photon-counting laser(launch planned late 2017/early 2018)

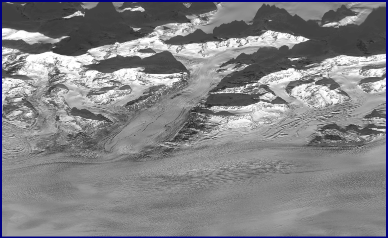
(B) Airborne Altimetry

- Operation IceBridge - NASA
- ICESat-2 predecessor instruments: MABEL, SIMPL
- PI-led airborne campaigns

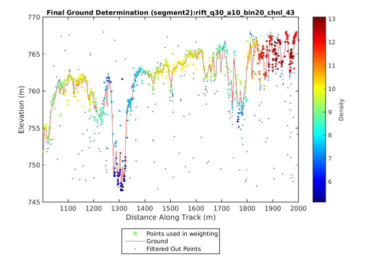
MABEL Data 2014: The Rift in Bering Glacier



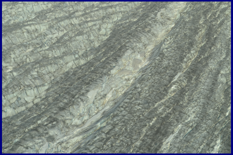
Geolocated MABEL track (2014-07-31)
on LANDSAT7 (2014-07) crosses and straddles the rift
(channel 43 elevations, 1064 nm).



Rift on 2012-10-28. WorldView2, DigitalGlobe

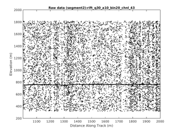


Ice-surface heights determined with the DDA show the rift
near 1300 and 1800 (channel 43, 1064 nm).

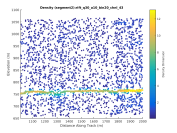


2013-08-23:
Rift-center close-up.
N Wall is higher.

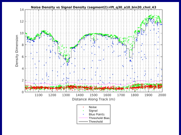
Density-Dimension Algorithm for ICESat-2 Type Data: multi-beam micro-pulse photon-counting lidar altimeter



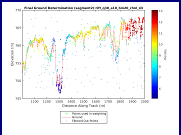
Raw MABEL photon data



Density



Threshold determination



Ice surface across rift

(1) Data aggregation using a Gaussian radial basis function, to calculate density for each recorded photon

$$f_d(c) = \sum_{x \epsilon \mathcal{D}_c} W_c(x) \quad (1)$$

$$W(c, x) = W_c(x) = \Phi(\|x - c\|_a) \quad (2)$$

with

$$\Phi(r) = e^{-\left(\frac{r}{\sqrt{2}s}\right)^2} \quad (3)$$

(2) Anisotropic kernel

(3) Auto-adaptive signal-vs-noise threshold determination to match variations in ground reflectance, atmospheric conditions, night-time/day-time data, without user intervention during ICESat-2 operational phase (density becomes a third dimension, hence the name)

(4) Here: Piece-wise linear density-weighted ground follower using signal-class photons

(5) Option to run density twice to distinguish reflector types

Results

- for MABEL and the Bering-Bagley Surge

(1) MABEL can detect the rift and smaller crevasses and measure surface height.

(2) The rift grew longer throughout the surge, while decreasing in depth: The depth of the rift was 60 m in 2011 ULS measurements, 30 m in 2012 and 18 m in 2014.

- for ICESat-2

(3) ICESat-2 can be expected to measure surface heights over crevassed regions.

(4) Using the Density-Dimension Algorithm, surface heights can be determined and compared to heights from GLAS, OIB, and other satellite and airborne campaigns.

SIMPL Data 2015: Heights of Crevassed Glaciers in Greenland

SIMPL tracks across Giesecke Brær (73 39 18N/55 34W to 73 26N/54 57W). Southern Glacier: Kakiffaat Sermiat, Northern Glacier: Qeqertarsuup Sermia.

SIMPL. The airborne Slope Imaging Multi-polarization Photon-counting Lidar (SIMPL) is a four-beam, two-color, polarimetric lidar that provides information about surface properties as well as topography. Each beam has 4 channels:

channel 1(mod 4): 1064 nm $\vdash$

channel 2(mod 4): 1064 nm $||$

channel 3(mod 4): 532 nm $\vdash$

channel 0(mod 4): 532 nm $||$

$\vdash$ (perpendicular) and $||$‘ (parallel)

indicate the polarization state relative

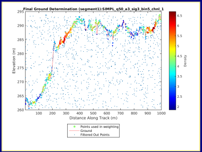
to the plane-polarized transmit beam.

Greenland 2015 flight altitudes were

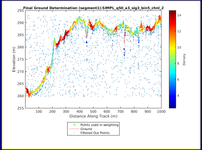
2-3 km above ground.

SIMPL Data 2015: Heights of Crevassed Glaciers in Greenland

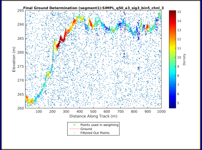
Comparison of frequencies and polarization modes



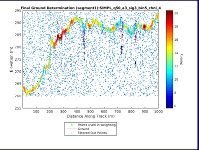
Channel1: 1064 nm ⊢



Channel2: 1064 nm ||

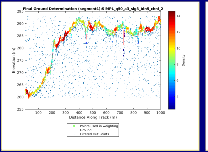


Channel3: 532 nm ⊢

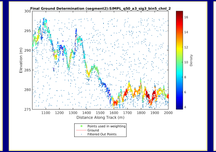


Channel4: 532 nm ||

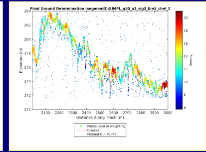
Crossing of Giesecke Bræ



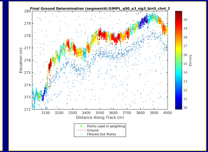
Channel2: segment1



Channel2: segment2



Channel2: segment3



Channel2: segment4

Results. (1) SIMPL is well suited to measure the relief of crevasses because it has cm-level vertical precision and a high density of geolocated single-photon returns.
(2) Surface height in crevassed terrain can be determined using the DDA.
(3) The ICESat-2 ATLAS instrument can be expected to measure rough ice surfaces as well.
(4) Using ICESat-2 data, we will be able to study the spatial variability in accelerating glaciers!

Herzfeld and Trantow (2016 subm., IEEE TGRS)

Plans for ISMIP6:

- Provide gridded surface topography and surface roughness information from ICESat-2 for model-data comparison
- Include elevation and bed topography in the analysis input stack of maps, along with model experiment results

MICROTOP'97-'99: Measurement of Ice Surface Roughness with the Glacier Roughness Sensor (GRS) in the Jakobshavn IsbræDrainage Basin:

Energy available for melting depends with a factor of 2.7 on surface roughness.

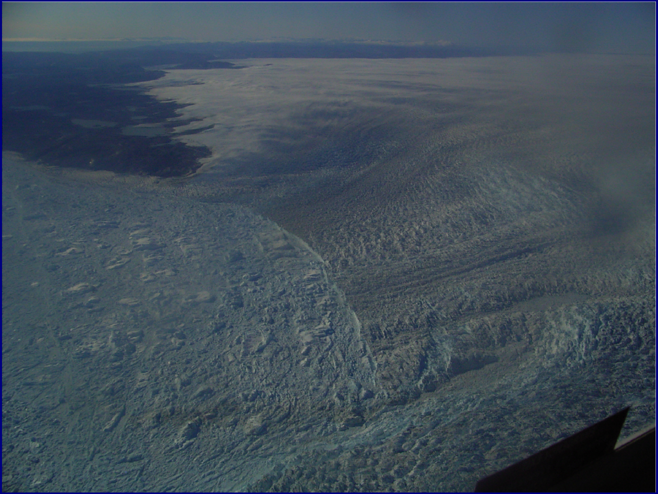
Herzfeld et al., ZGG, 2001

(III) Subglacial Topography

Plans for ISMIP-6

- Derive new Greenland bed topography from CReSIS MCoRDS data (once revised by CReSIS)
- Resolution 1 km or 2 km or variable/ meshes [Preferences?]
- Provide to ISMIP-6 as input for sensitivity study on the influence of bed topography on model results

Contribution to sea-level change through mass loss from the Greenland Ice Sheet is to a large part through fast-moving outlet glaciers



Jakobshavns Isbræ, retreat of calving front: July 2005

Skagt Glacier, Sermilik region, East Greenland. July 2005. Photograph by Helmut Mayer and Ute Herzfeld.

Problems

- The width of subglacial troughs is often near or below the resolution of ice-sheet models (at least for model comparisons)
- Radar signals do not always reach the bottoms of narrow troughs.
- Generalization of high-resolution data to lower resolution grid needed

- Some fast-moving glaciers follow troughs in subglacial bedrock, others do not.
- Subglacial troughs cause acceleration.
- Estimation of sea-level rise is performed by dynamic ice-sheet models.
- Subglacial topography is an important constraint in dynamic ice-sheet models
- .... and hence subglacial topography is a important ingredient in assessments of sea-level rise.

Building a Greenland Bed for Modeling

Goals

(1) create bed DEMs such that the physics of a modeled variable are unaltered

(2) obtain better results with current modeling techniques

(3) proper generalization of sub-grid scale features

Principles

(1) use all MCoRDS radar data collected to present

(2) derive bed DEM using mathematical analysis methods

(3) do not use auxiliary data sets

(4) do not use physical assumptions to create the bed, leave those for model validation

Herzfeld, U., P. Chen, B. Wallin, B. McDonald, H. Mayer, J. Paden and K. Leuschen (2014) The trough-system algorithm and its application to spatial modeling of Greenland subglacial topography, Annals of Glaciology, v. 55 (67), pp. 115-126, doi:10.3189/2014AoG67A001

Herzfeld, U., B. Wallin, J. Paden, C. Leuschen(2011) An Algorithm for Adjusting Topography to Grids while Preserving Sub-Scale Morphologic Characteristics — Creating A Glacier Bed DEM for Jakobshavns Trough as Low-Resolution Input for Dynamic Ice Sheet Models, Computers&Geosciences, vol. 37, pp. 1793-1801, DOI: 10.1016/j.cageo.2011.02.021

Greenland Subglacial Topography

Data Analysis Philosophy

- Use an algorithm that does not require modeling assumption ("mass-conserving" algorithms also make assumptions about linearity in downward continuation of velocity and about constant velocity in time)
- Use only radar data, mathematical morphology and interpolation/extrapolation methods (not ancillary data, e.g. velocity)

Algorithm steps for new Greenland bed DEM

(1) aggregation of all MCORDS thickness data (to 2016) from CReSIS (100m grid)

(2) sort out [most] bad tracks (automatically)

(3) Variography and Kriging of base DEM (thickness)

(4) calculate better DEM for outlet glacier regions (thickness)

(5) integrate outlet-glacier regions in thickness DEM

(6) use a surface DEM to derive bed DEM

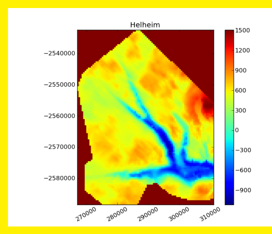
alternatively:

(4a) use a surface DEM: bed(x) = surface(x) - thickness(x)

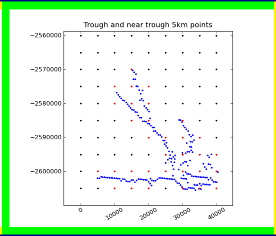
(5a) calculate better DEM for outlet glacier regions (bed)

(6a) integrate outlet-glacier regions in bed DEM

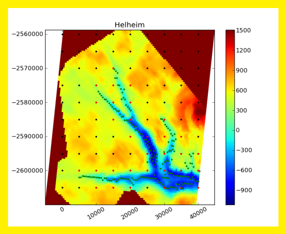
Helheim Glacier



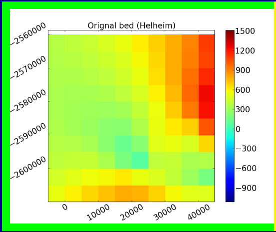
(a) CReSIS data, gridded



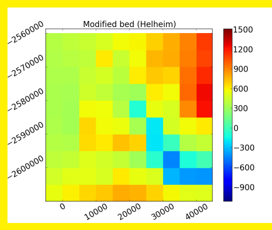
(b) trough detection



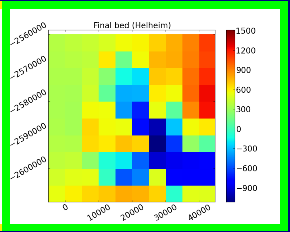
(c) trough over hi-res grid



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



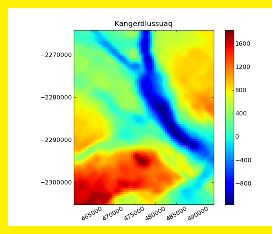
(e) interpolated w new data



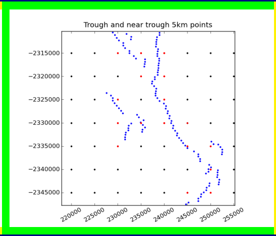
(f) final bed w trough integration

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

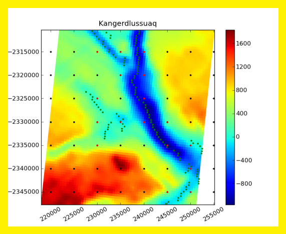
Kangerdlussuaq Glacier



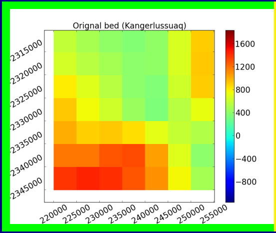
(a) CReSIS data, gridded



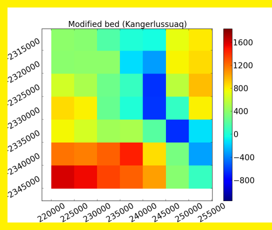
(b) trough detection



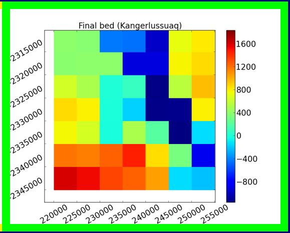
(c) trough over hi-res grid



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



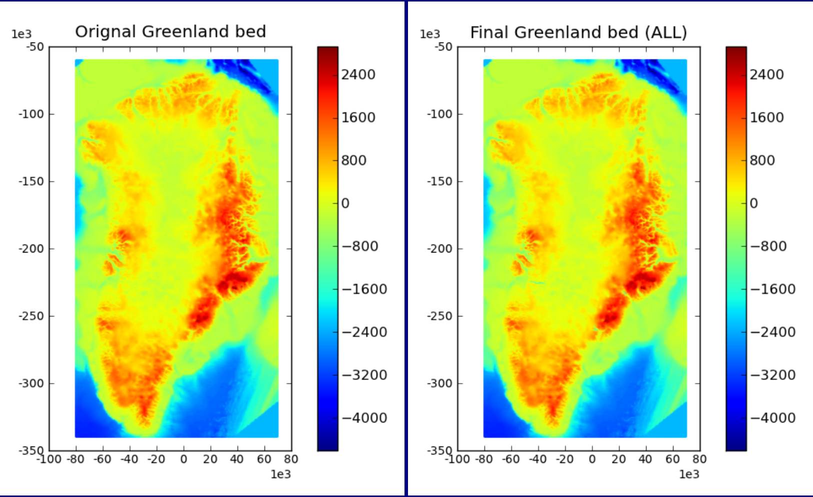
(e) interpolated w new data



(f) final bed w trough integration

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

Greenland 5km subglacial topography



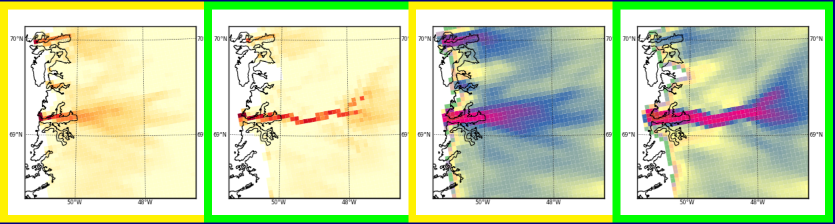
(a) orig bed (Bamber et al. 2001)

(b) JakHelKanPet Bed DEM

Sensitivity Studies

Influence of Subglacial Topography on Results from Dynamic Ice Sheet Models

UMISM [James Fastook]: Jakobshavn Isbræ



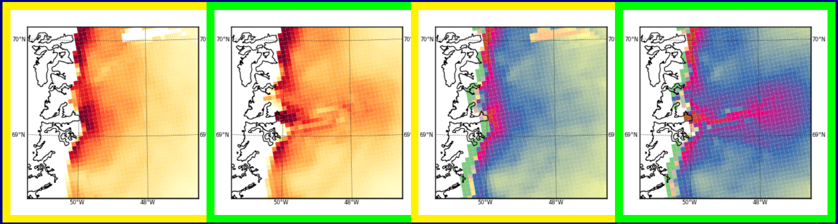
(a) Bed w Water [a] (b) Bed w Water [b] (c) Ice Velocity [a] (d) Ice Velocity [b]

30000 year Spin-up to present

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

(Herzfeld, Greve, Fastook, ... AnnalsGlaciol 2012)

SICOPOLIS [Ralf Greve]: Jakobshavn Isbræ



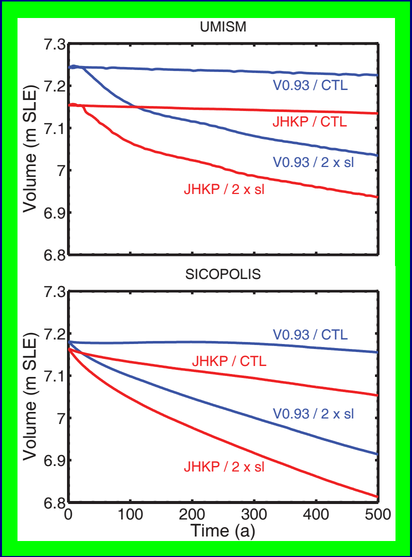
(a) Bed w Water [a] (b) Bed w Water [b] (c) Ice Velocity [a] (d) Ice Velocity [b]

30000 year Spin-up to present

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

(Herzfeld, Greve, Fastook, ... AnnalsGlaciol 2012)

Results of Sensitivity Experiments



CTL- control run, 2x sl - 2x sliding

Sea-Level-Rise: The effect of including only 4 outlet-glacier troughs in the bed DEM is on the same order of magnitude as the effect of hypothetically assuming doubled sliding of all glaciers and the ice sheet in Greenland.
(Herzfeld, Greve, Fastook, ... AnnalsGlaciol 2012)

Questions?

Sheridan Glacier