Towards A Historical-Forcing Ice Sheet Model Validation Framework for Greenland

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Model simulations conducted on Hopper and Titan at NERSC and OLCF

U.S. DEPARTMENT OF ENERGY Office of Science

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SciDAC Scientific Discovery through Advanced Computing

Motivation / Concept

Tools

Results

Summary & Future Work

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Motivation

There are currently ~2 decades of large-scale satellite observations of Greenland ice sheet geometry change:

ICESat1:	2003 – 2009
GRACE:	2002 – 201? (ongoing)

Future missions will extend these observational time series:

ICESat2:	2017 – 20??
GRACE “follow-on”:	2017 – 20??
GRACE2	2020’s - ?

These data can be used for ice sheet model *validation***, but no framework currently exists for doing so.

** *validation:* How well do our models represent the real ice sheet?

Concept

Run ice sheet model over some specified time period for which ICESat and / or GRACE observations exist

Process model output for comparison to these observations

Process observations for comparison to model output

Evaluate model performance relative to observations:

ICESat : ice sheet surface elevation

GRACE : mass trends

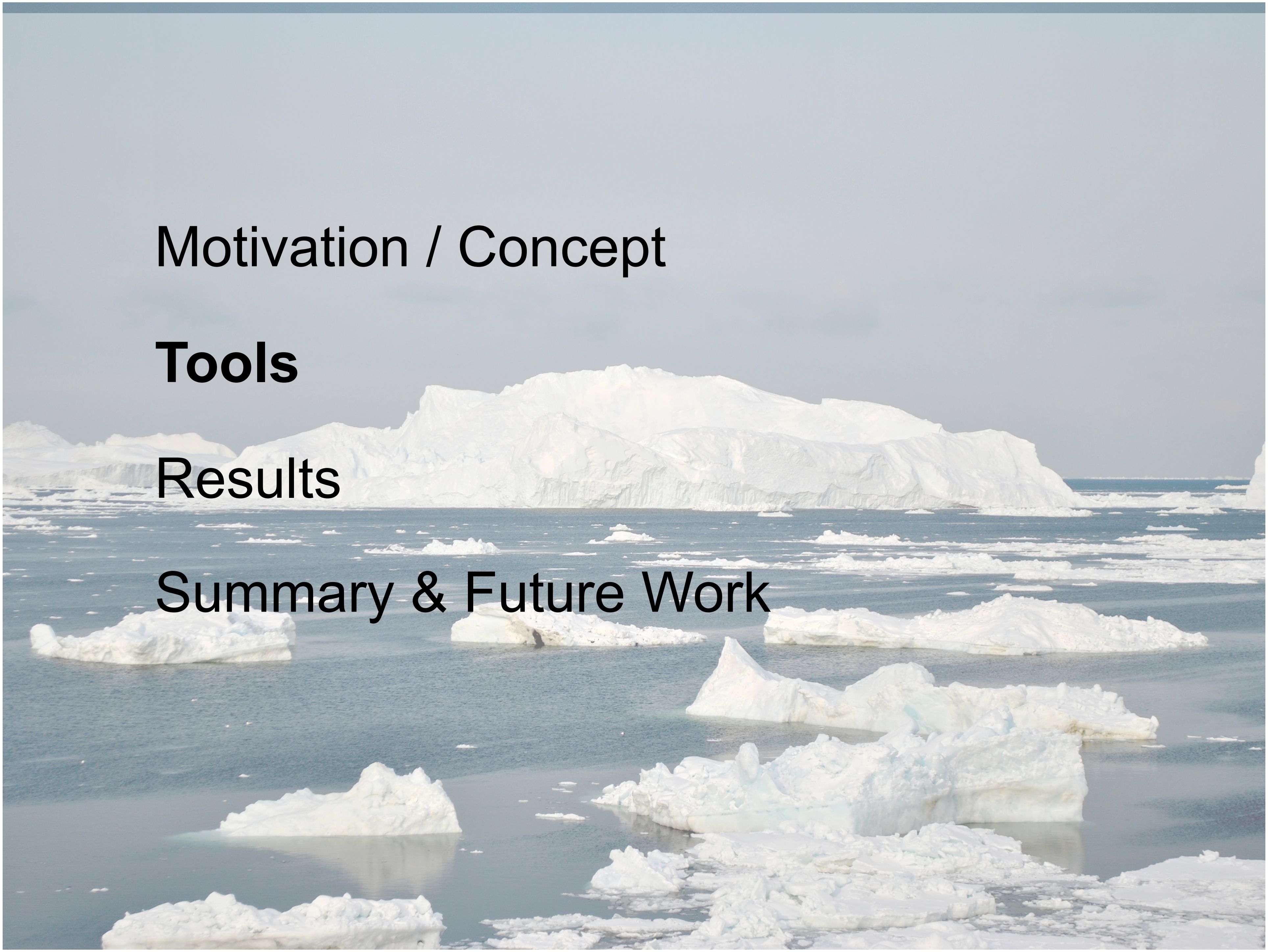
Calculate *metrics* to quantify model performance (e.g., to gauge improvement as new dynamics, physics, boundary conditions, higher-resolution are added)

Questions

1. Are the models currently mature enough that this makes sense to pursue?

2. Is the observational time series currently (or in ~10 yrs) long enough that this makes sense to pursue?

3. Does the concept of trying to constrain the model forcing (SMB, outlet glacier flux) in order to define a standard “test case” make sense?



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Tools: Observations

Validation

ICESat: 2003 – 2009;

GRACE: 2003 – 2011 (CSR Release-05)

Model Forcing

RACMO2[1]: mean-annual SMB (applied as anomalies)

Outlet Glacier Flux[2]: mean-annual flux at grounding line

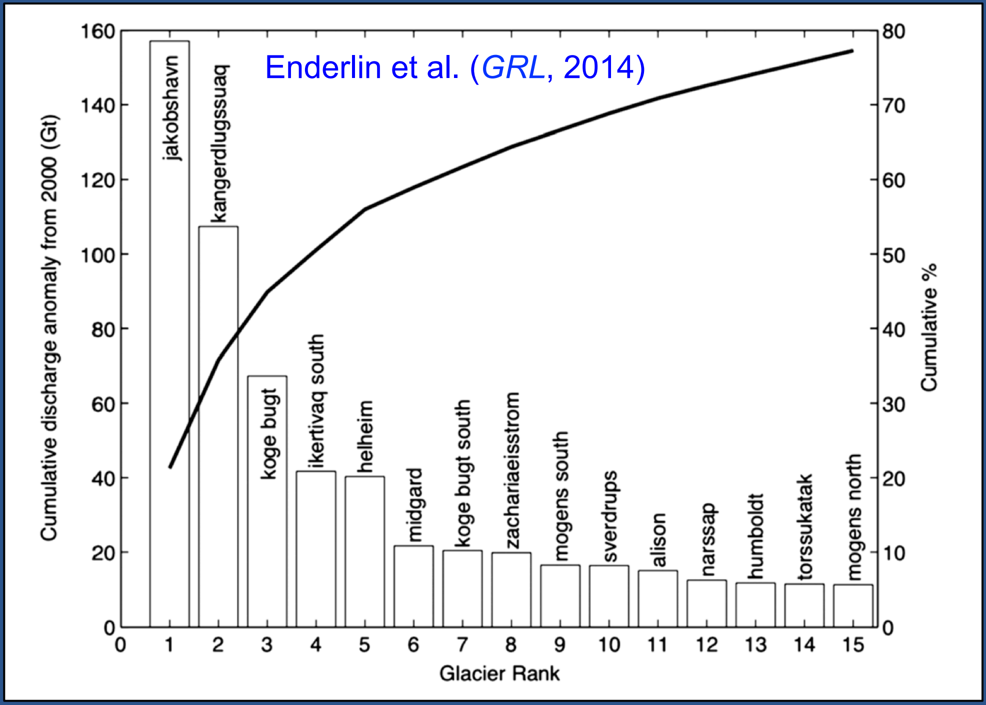
[1] van Angelen et al. (*Surv. Geophys.*, 2014)   [2] Enderlin et al. (*GRL*, 2014)

Tools: Model Forcing

RACMO[1] SMB over time period of interest is well validated over Greenland

Dynamic thinning over same time is well captured by the flux time series from ~15 outlet glaciers[2]

Taking these datasets as the "truth", can we use them as model forcing and design a standard test bed for use in Greenland ice sheet model validation?



[1] van Angelen et al. (*Surv. Geophys.*, 2014)
[2] Enderlin et al. (*GRL*, 2014)

Tools: Models

CISM 2.0[1] : Used to generate 4 km res. initial condition:

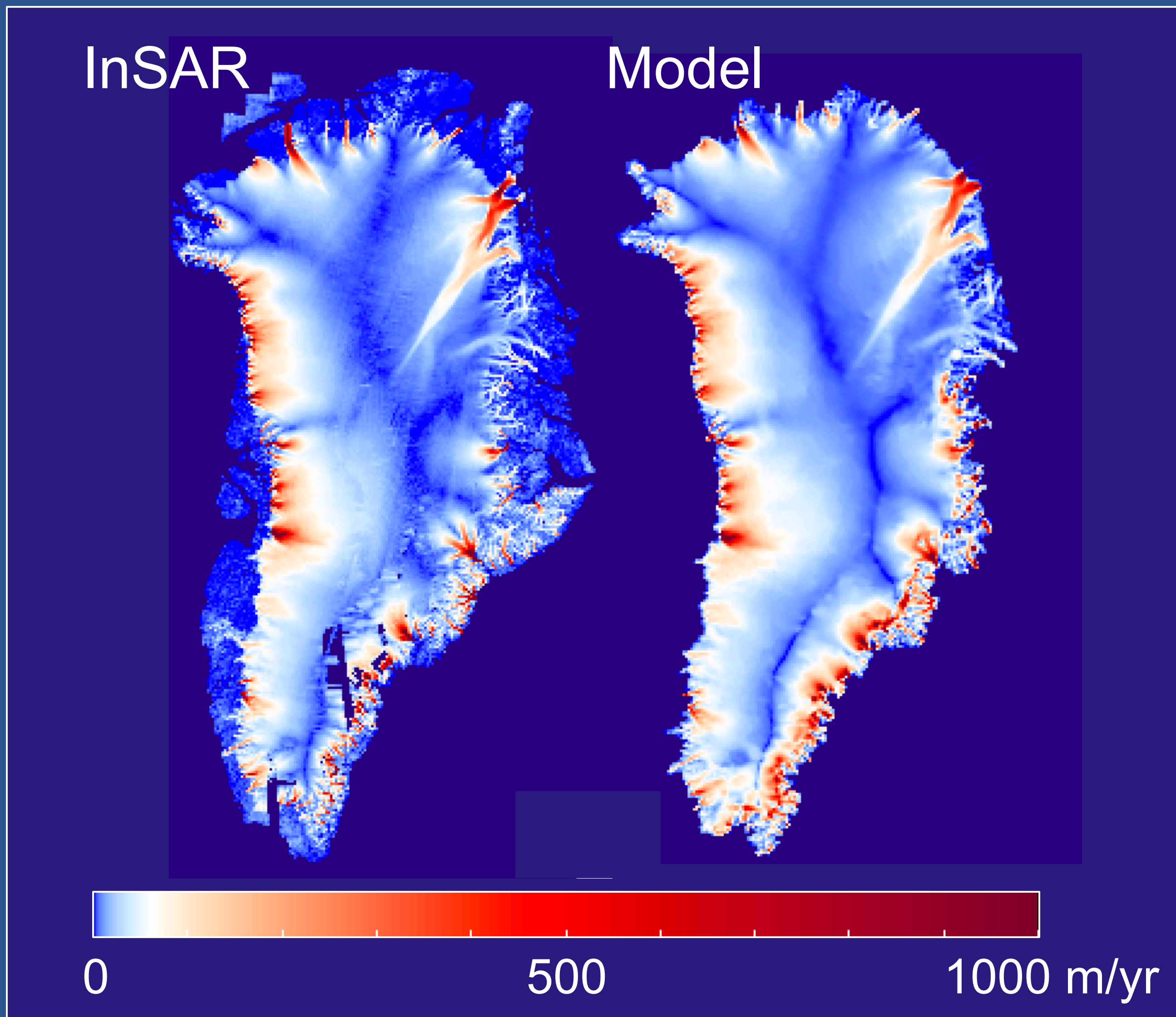
- parallel, 3d, first-order Stokes approximation
- 10 ka thermal spin-up with fixed geometry[2]
- Iterative, *ad hoc* optimization of basal sliding coefficient[3]

FELIX-FO[4] : Using for hi-res forward model simulations:

- parallel, 3d, first-order Stokes approximation
- FEM of variable order on hex. and tet. (var. res.) meshes
- here, coupled to CISM 2.0 as external dycore (hex. mesh)

[1] http://github.com/CISM/cism/ [2] Bamber et al. (*TC*, 2013) [3] Price et al. (*PNAS*, 2011)
[3] Kalashnikova et al. (*GMDD*, 2014)

4 km res. initial condition: surface speed



Tools: Model Post Processing

- Convert model coords. from polar stereo. to lat., lon.
- Shift vertical datum from EIGEN-GL04C (Bamber DEM) to WGS-84
- Write annual model output to text file of lat., lon. and elev. (ICESat) or thickness (GRACE) at each grid point
- Text files for ICESat --> NASA GSFC for processing
- Text files for GRACE -->Univ. of S. Florida for processing

Tools: ICESat Post Processing

- GIMP 90-m DEM mask used to filter GLAS rel. 64 data. GLAS points excluded …
  - if not within GIMP mask
  - if reflectivity < 0.0375
  - if waveform stndev > 0.0375 volts
  - if | GIMP – GLAS | > 200 m
- Annual model output compared to elevations from fall ICESat campaign of same year
- Model grid points interpolated to nearest GLAS footprint

Tools: GRACE Post Processing

- Model lat., lon. ice thickness binned at ½ x ½ degree
- Thickness in each bin converted to cm water equiv.
- Binned data transformed to 60x60 spherical harmonics
- Result is model “seen” at equiv. resolution to GRACE
- Harmonics mapped back to ½ x ½ degree bins for plotting
- No smoothing or other GRACE post-processing applied

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Model runs conducted:

1. Model forced from 1991-2012 by RACMO SMB only
2. Model forced " … " plus perturbed basal sliding param.
3. Model forced " … " plus outlet glacier flux time series

Compare yearly (winter) model output to fall ICESat obs. and annually averaged GRACE obs.

Only simulations 1 & 2 are discussed here, but adequate for demonstrating the proposed testing framework and its use in gauging model improvement (here, sim. 2 is a rough proxy for dynamic response expected from sim. 3)

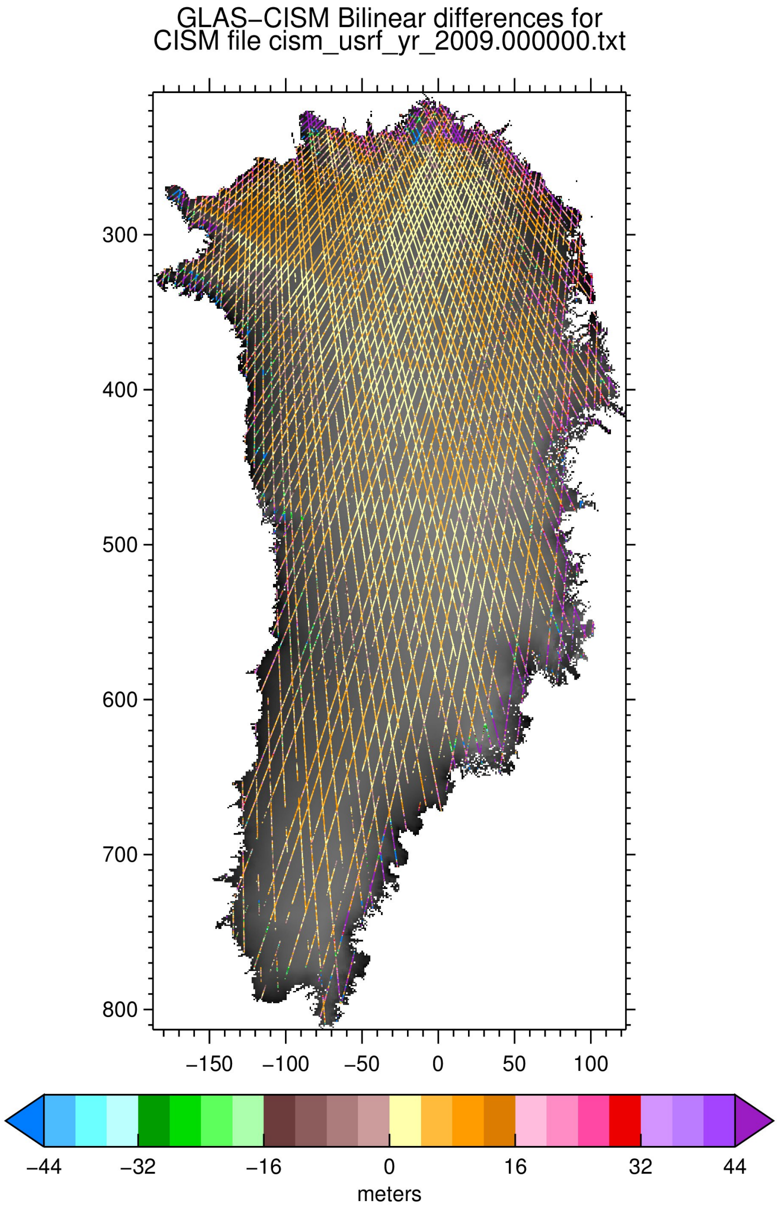
Results: ICESat

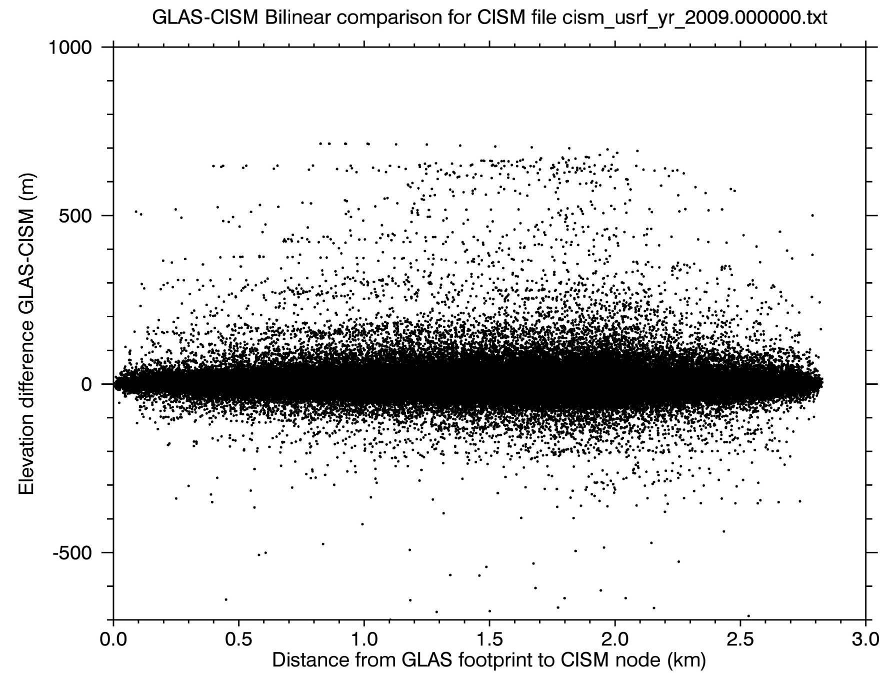
Shown and discussed are surface elevation differences for 2003 (other years through 2009 similar) for …

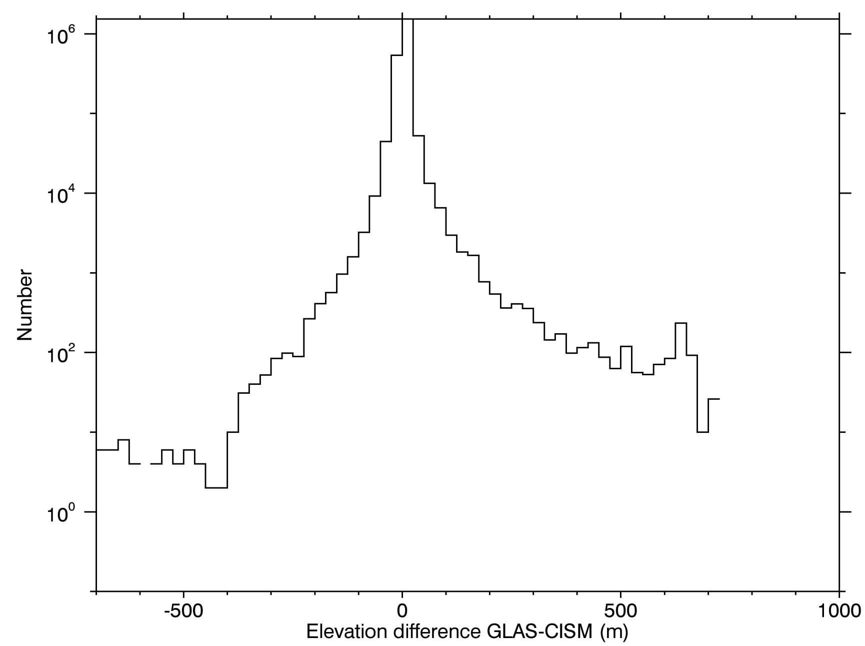
- Maps of ICESat minus model elevations
- Scatter-plots of ICESat minus model elevations
- Histograms of ICESat minus model elevations

Also shown are a few proposed metrics for quantifying the comparison of models and GRACE observations.

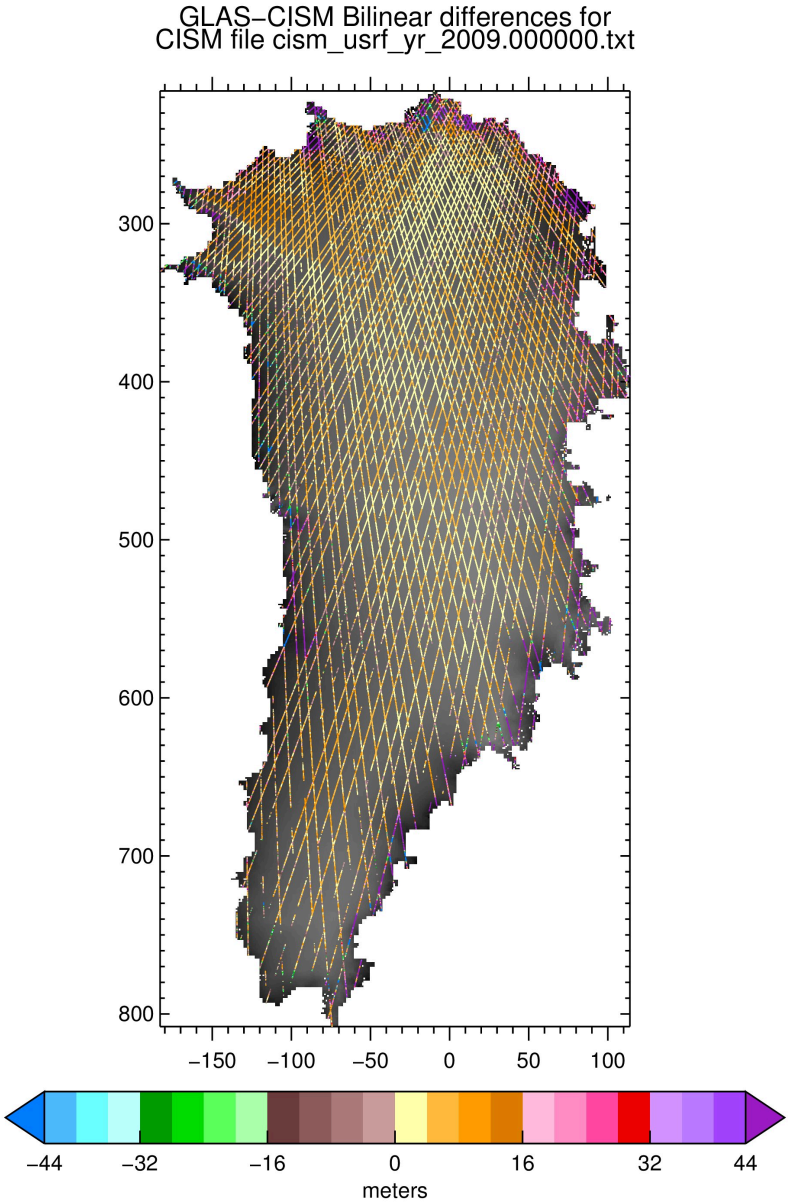
SMB forcing only

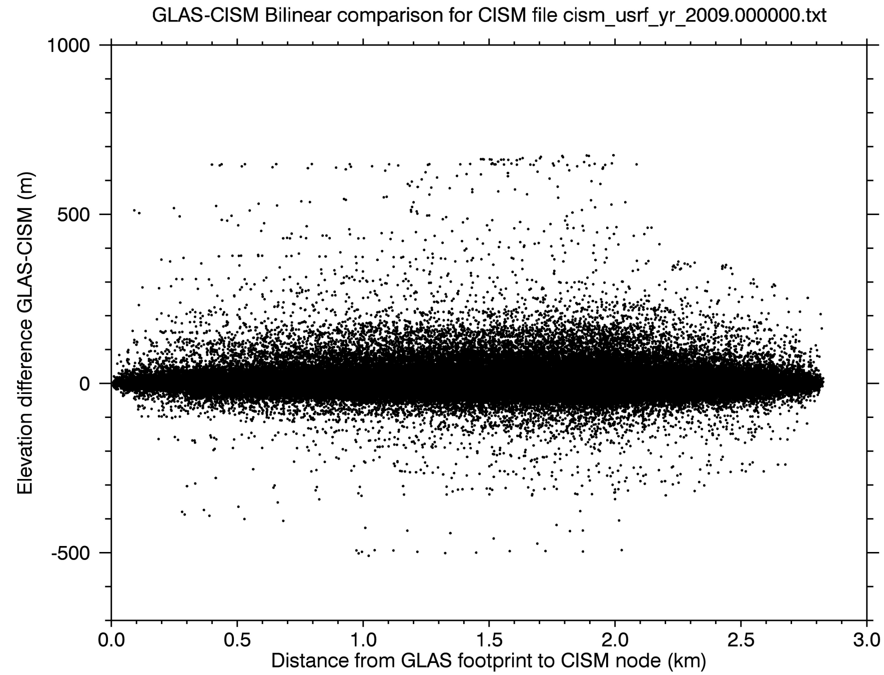


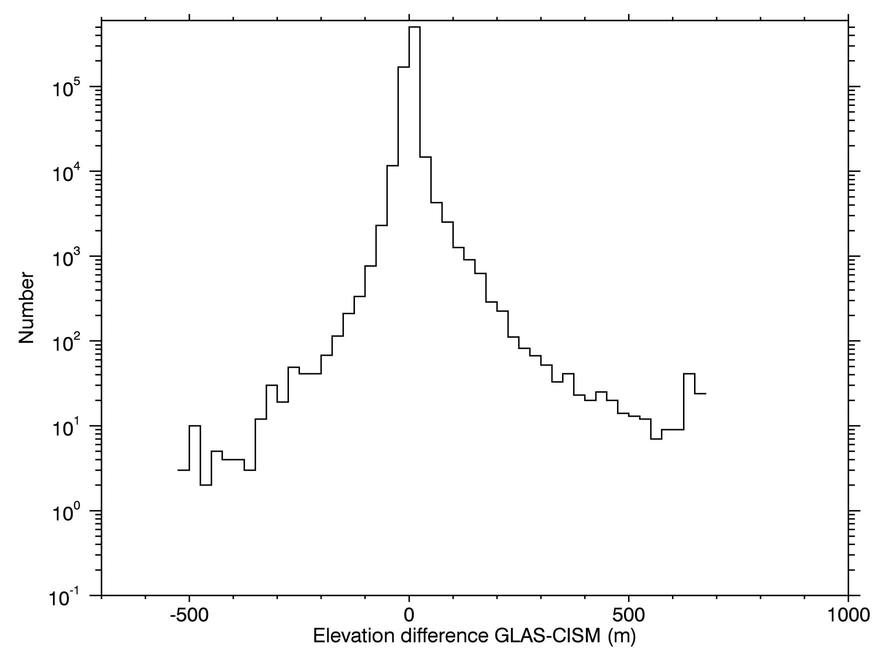




SMB + sliding perturb.







Results: ICESat Metrics

Elevation Difference (m): ICESat – Model

Date	mean (stndv)	Mean Abs (stndv)	5th percentile	95 percentile	comment
2009	2.91 (21.89)	8.56 (20.36)	-16.10	19.70	SMB only
2009	3.24 (20.56)	8.18 (19.14)	-13.95	18.70	SMB + …

Results: ICESat – "Persistence"?

The model was initialized using the recent Bamber DEM, which uses ICESat data from the time span of our model run:

> *" … derived from data collected between 2000 and 2009…Validation against ICESat data, indicated vertical errors of ±5 m on the ice sheet and ±7 m for the unglaciated margins."* [1]

It is possible / likely that we are looking at a comparison to the initial condition and that the model isn't adding any value (akin to "red noise" null hypothesis in spectral analysis).

[1] Bamber et al. (*TC*, 2013)

Results: ICESat Metrics

Elevation Difference (m): ICESat – Model

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2009	3.24 (20.56)	8.18 (19.14)	-13.95	18.70	SMB + …
N/A	3.91 (27.66)	9.21 (26.37)	-15.01	21.47	Initial Cond. **

Persistence? Possibly (GRACE will help answer)

** Bamber et al. (*The Cryosphere*, 7, 2013)

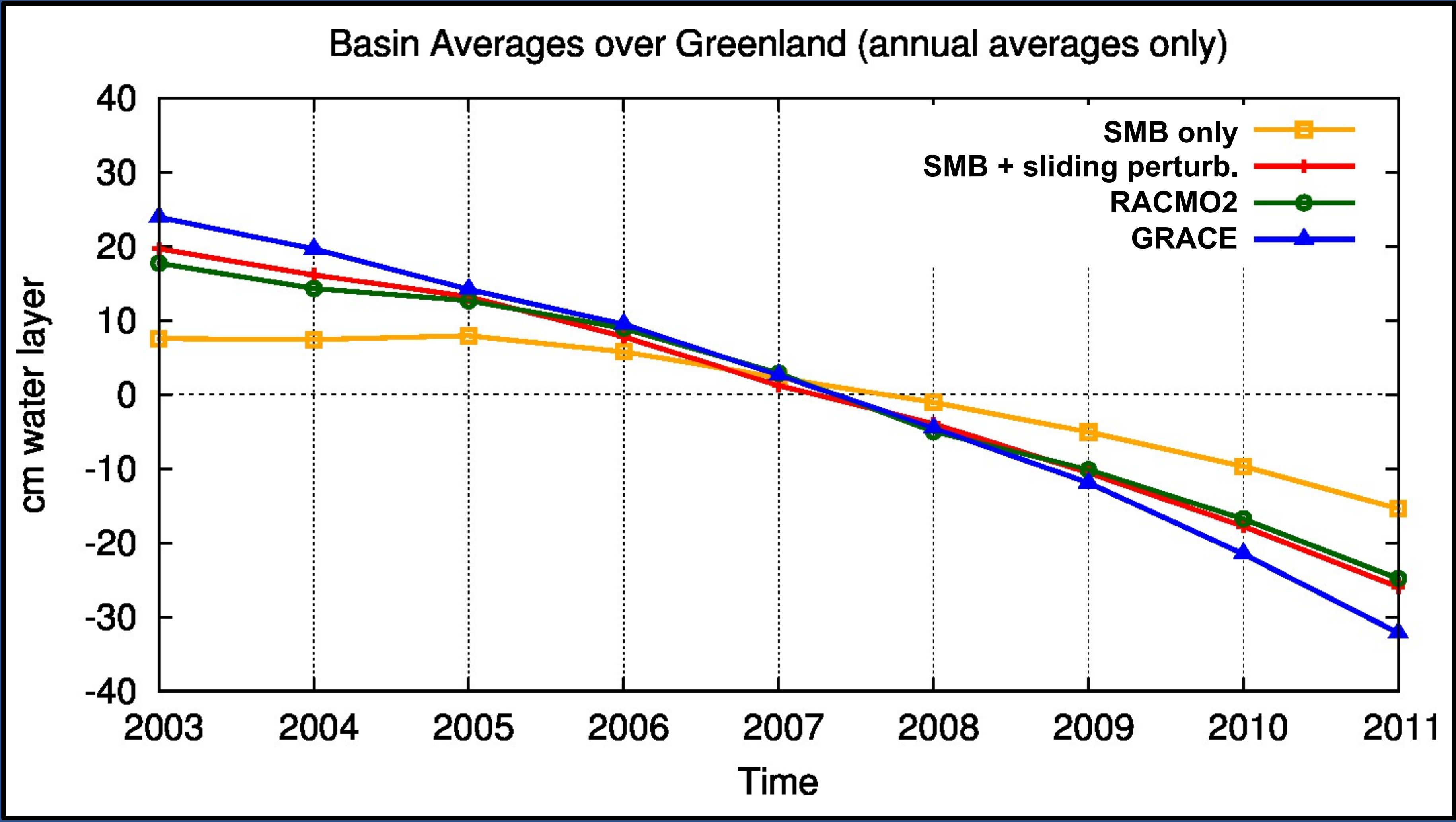
Results: GRACE

Shown and discussed are 2003-2011 mass trend maps (relative to the 2003-2011 mean) for …

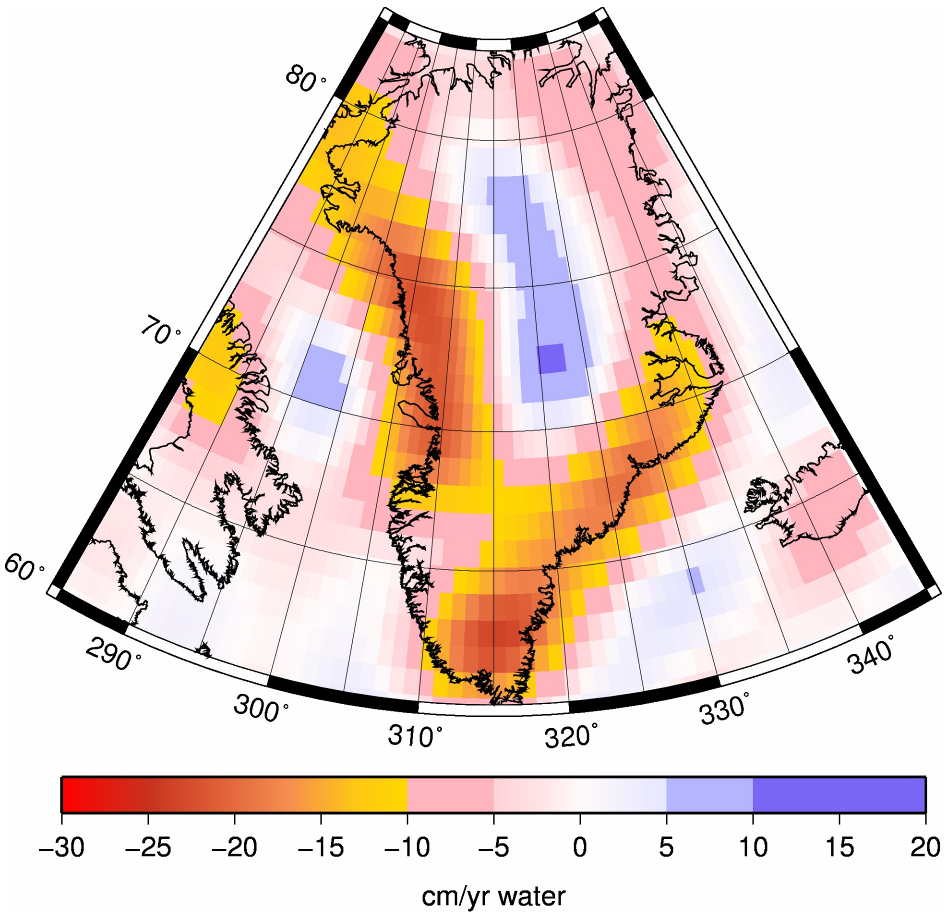
- SMB-only forced simulation as seen by GRACE
- SMB + basal sliding perturb. as seen by GRACE
- RACMO2 SMB time series as seen by GRACE
- Actual GRACE trends

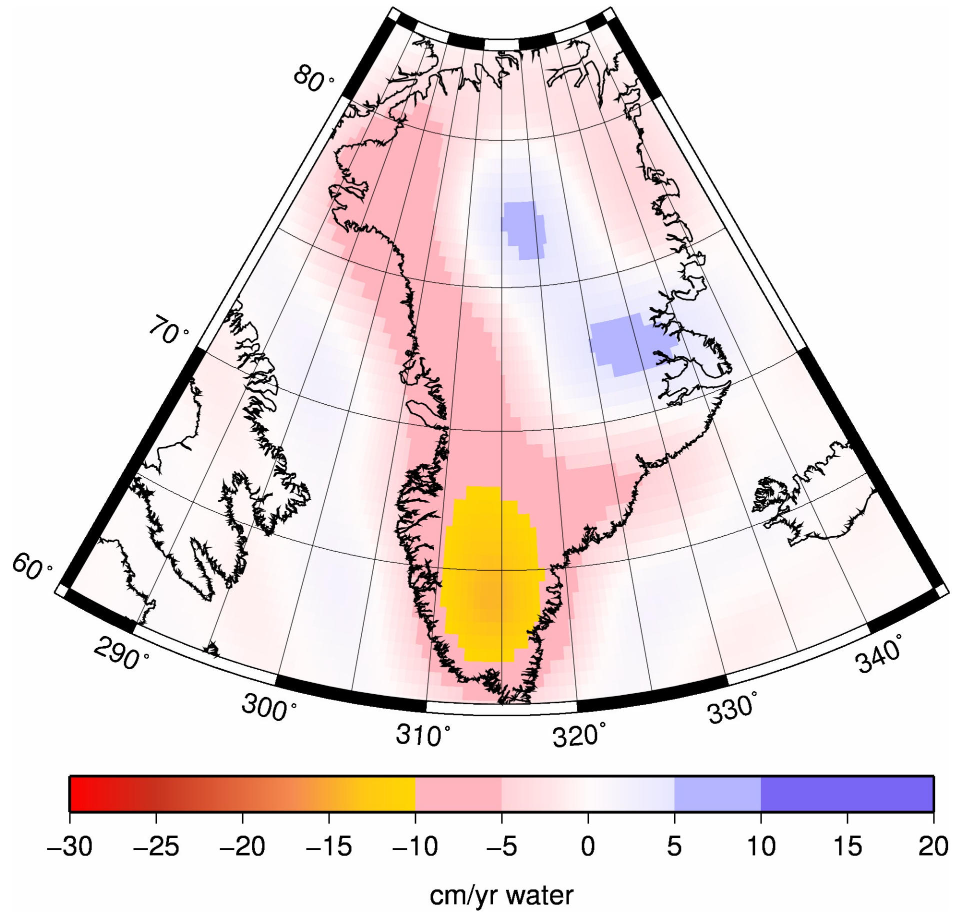
Also shown are a few yearly snapshots and some proposed metrics for quantifying the comparison of models and GRACE observations.

Results: GRACE



SMB forcing only

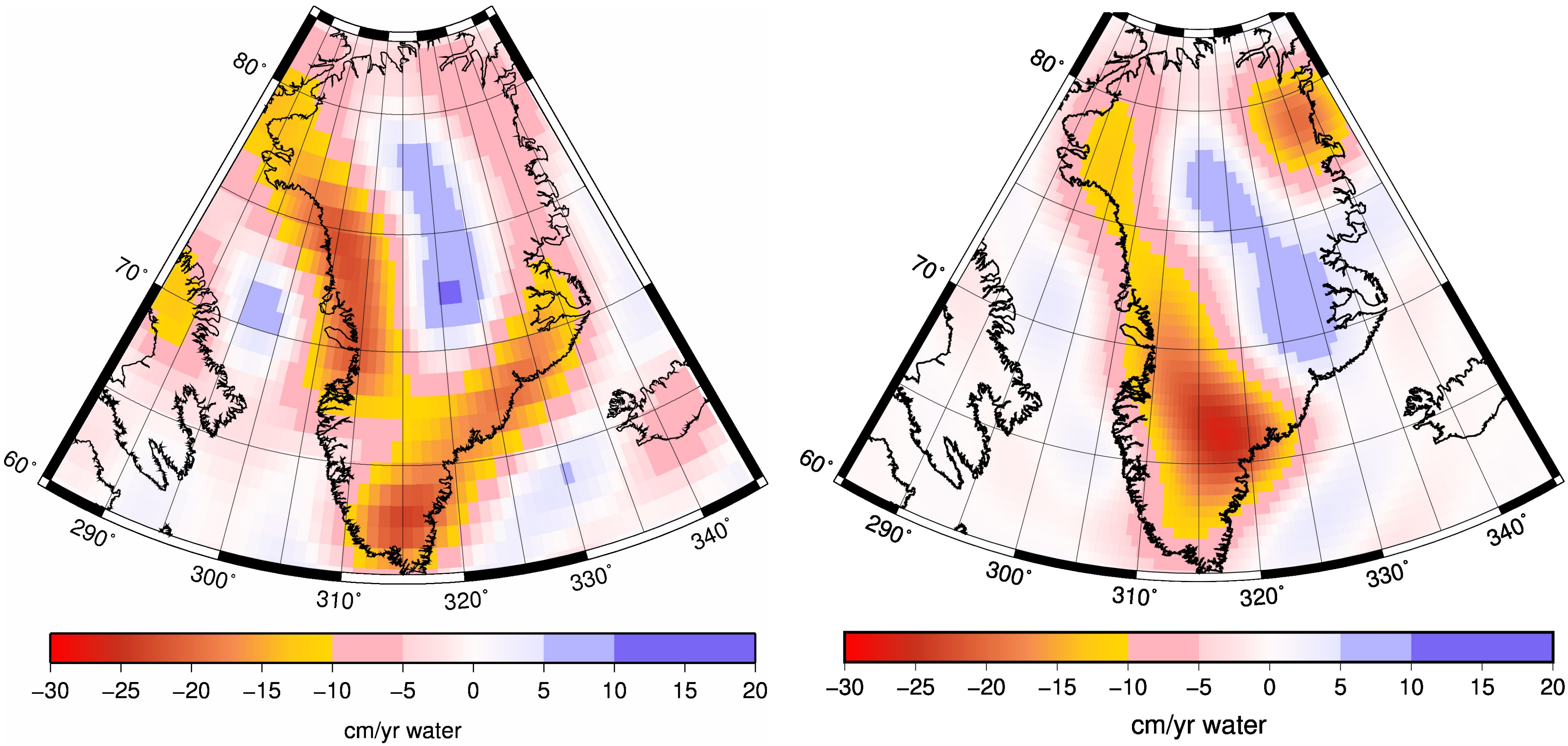




GRACE

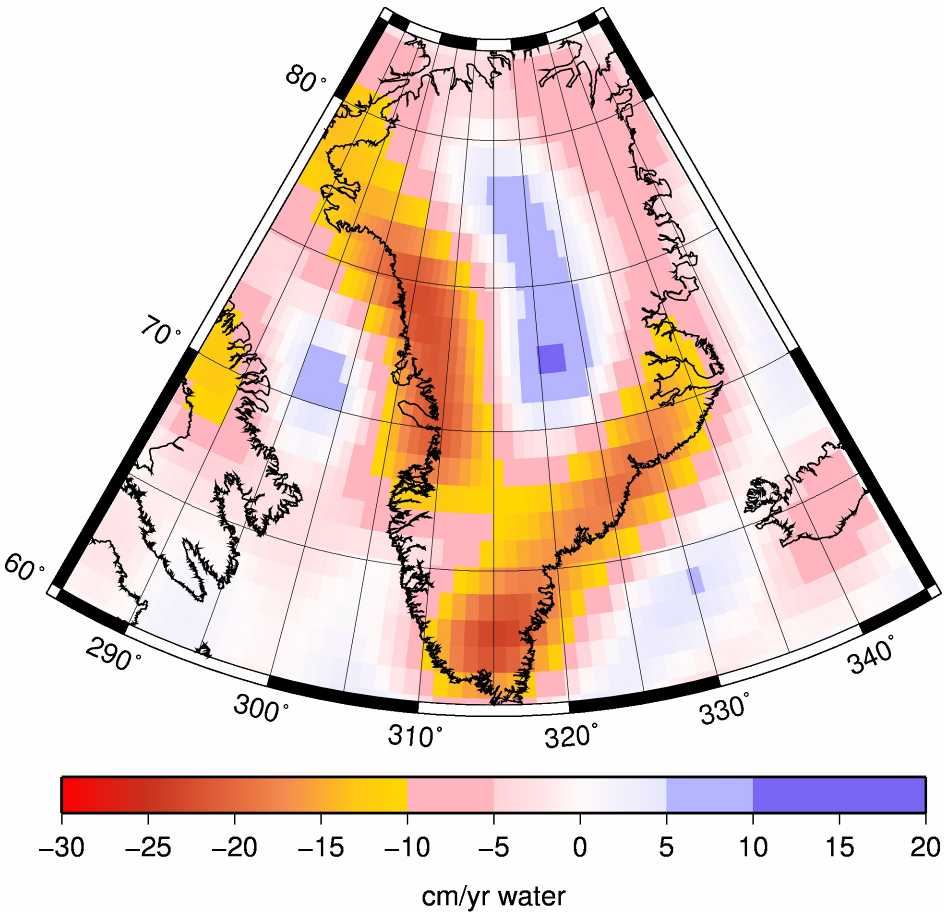
Model

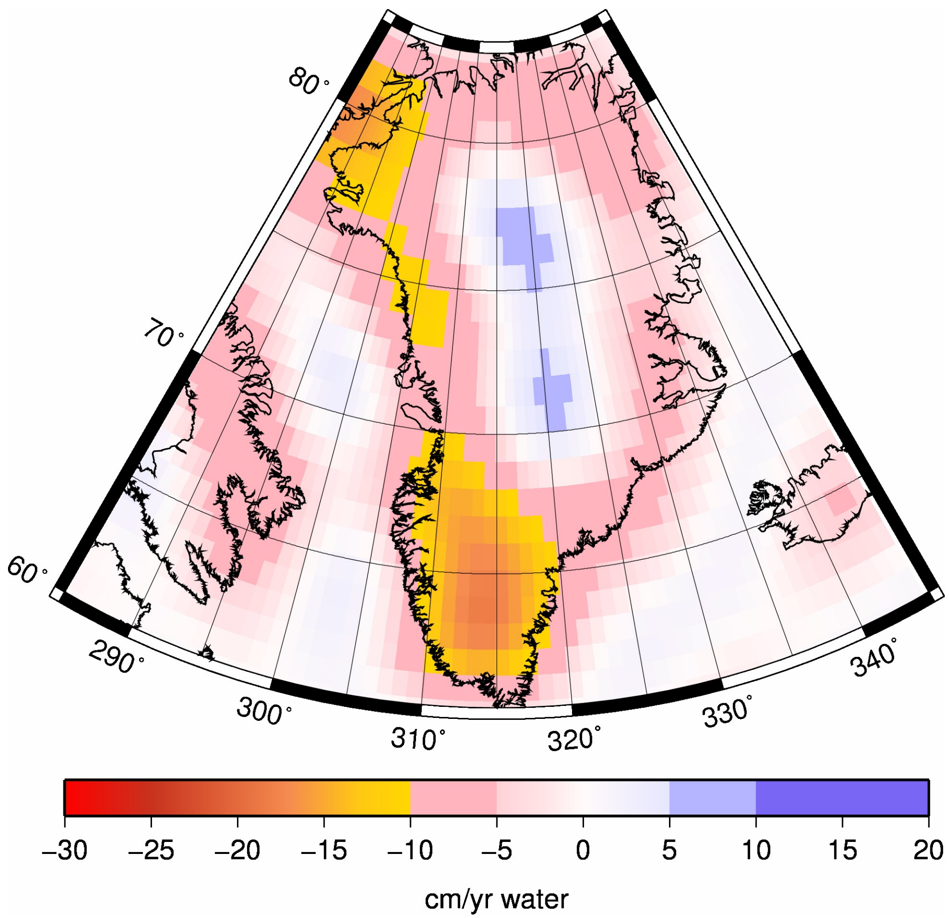
SMB + sliding perturb.



GRACE **Model**

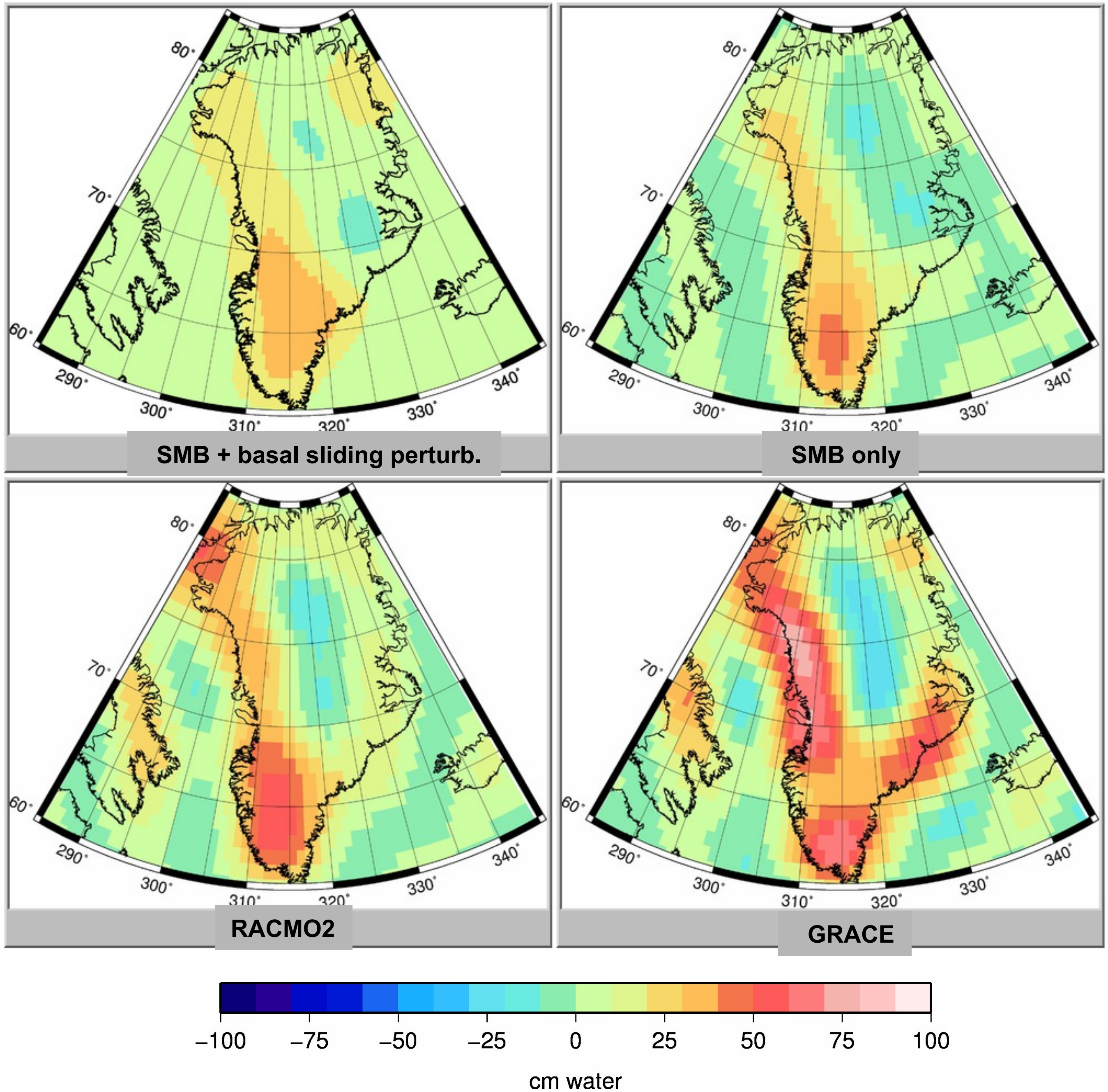
RACMO2 only (no ice sheet model)



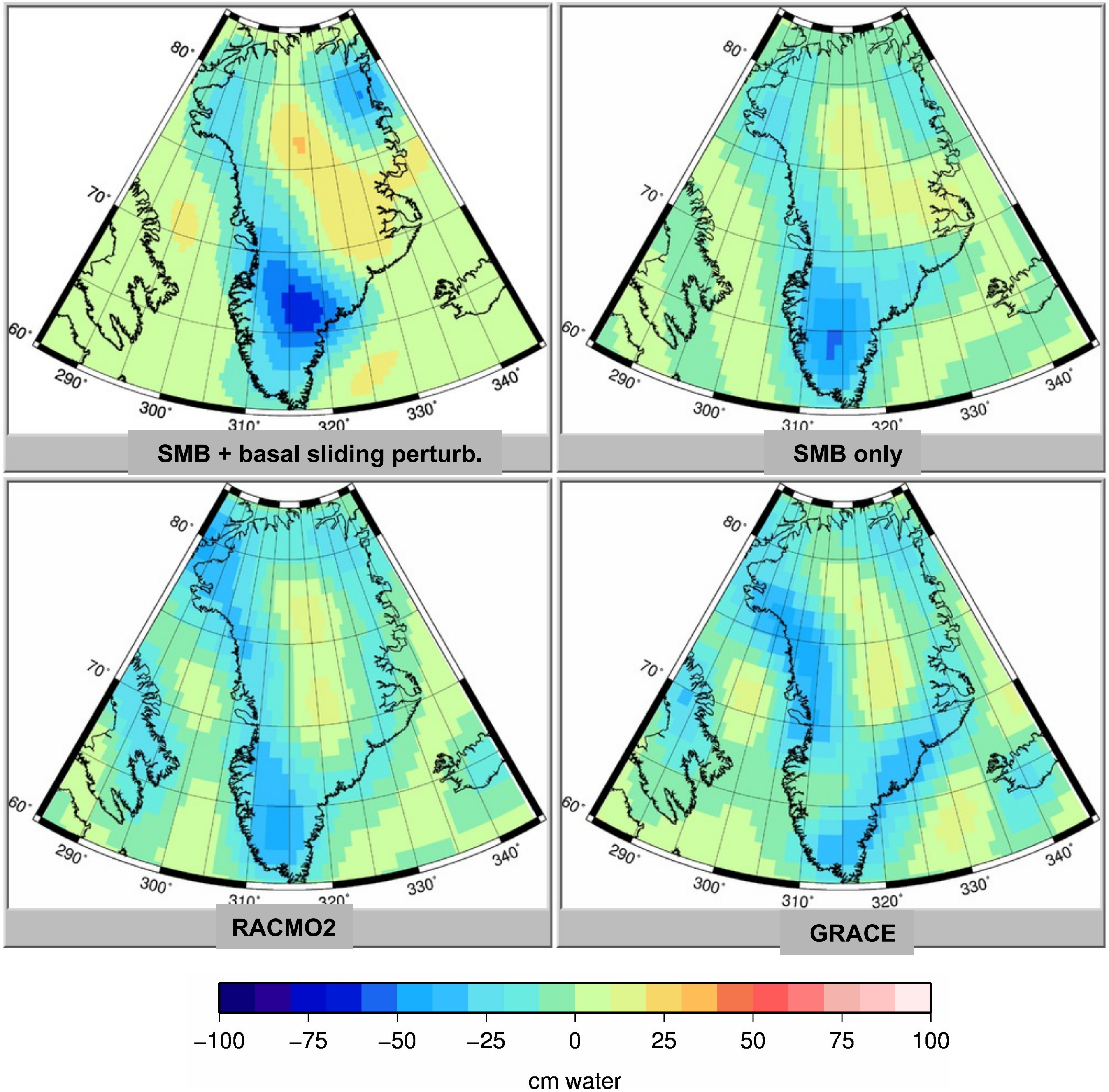


GRACE **RACMO**

GRACE, RACMO, & Model: year-on-year mass changes: **2005**



GRACE, RACMO, & Model: year-on-year mass changes: **2010**



Results: GRACE Metrics

Example scalar metric, *M*, for use in evaluating model performance relative to GRACE observations:

$$M(x,y) = \frac{\sigma_{GRACE} - [\sigma_{GRACE} - \sigma_{model}]}{\sigma_{GRACE}}$$

- SMB forcing only: M_{bar} = 35%
- SMB + basal sliding perturb: M_{bar} = 32%
- RACMO2 only: M_{bar} = 54%

M: Average percent GRACE variance explained by model

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Summary

Using some initial (and admittedly crude) model simulations, we have demonstrated that we can:

- post-process model output for comparison to obs. from ICESat and GRACE
- post-process ICESat and GRACE obs. for comparison to models (processing will be grid-independent)
- analyze differences, using visual output and metrics, to discriminate between relatively better / worse model performance

Future Work

Observations

- clean up existing processing software
- decide on / support output of standard metrics
- automate processing (internet based service)
- support other datasets (NASA ATM, OIB, ERS)
- account for seasonal and longer-term firn effects

Future Work

Modeling

- clean up / generalize post-processing software
- implement outlet-glacier flux forcing successfully (and assess if practical for long-term test bed use)
- test for improvement (if any) when using "mass conserving bed"-based model geometry
- use appropriate model optimization[1] to avoid anomaly forcing constraints
- simulations using higher resolution, unstruc. meshes

Flux Forcing