# Validation of Modelled Ice Dynamics of the Greenland Ice Sheet using Historical Forcing

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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

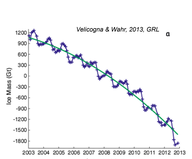
Calculate metrics to quantify model performance (e.g., to gauge improvement as new dynamics, physics, boundary conditions, higher-resolution are added).

## Validation Observations

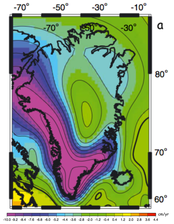
### GRACE

*Gravity Recovery and Climate Experiment*

Measures changes in mass 2002-present (ongoing)




Fine temporal resolution (~monthly mass anomalies)

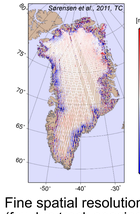



Coarse spatial resolution (~1/4-1° spherical harmonics)

### ICESat

*Ice, Cloud,and land Elevation Satellite*

Measures surface elevation 2003-2009




Fine spatial resolution (few km track spacing, 170 m along-track spacing)

| Start Date | End Date | Days in Operation | Laser Identifier |
|---|---|---|---|
| 2003-02-20 | 2003-03-29 | 38 | 1A8 |
| 2003-09-25 | 2003-11-19 | 55 | 2A |
| 2004-02-17 | 2004-03-21 | 34 | 2B |
| 2004-05-18 | 2004-06-21 | 35 | 2C |
| 2004-10-03 | 2004-11-08 | 37 | 3A |
| 2005-02-17 | 2005-03-24 | 36 | 3B |
| 2005-05-20 | 2005-06-23 | 35 | 3C |
| 2005-10-21 | 2005-11-24 | 35 | 3D |
| 2006-02-22 | 2006-03-28 | 34 | 3E |
| 2006-05-24 | 2006-06-26 | 33 | 3F |
| 2006-10-25 | 2006-11-27 | 34 | 3G |
| 2007-03-12 | 2007-04-14 | 34 | 3H |
| 2007-10-02 | 2007-11-05 | 35 | 3I |
| 2008-02-17 | 2008-03-21 | 34 | 3J |
| 2008-10-04 | 2008-10-19 | 16 | 3K |
| 2008-11-25 | 2008-12-17 | 23 | 2D |
| 2009-03-05 | 2009-04-11 | 34 | 2E |
| 2009-09-30 | 2009-10-11 | 12 | 2F |

Coarse temporal resolution (91 day exact repeat but campaigns 2-3x per year)

**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 of elevation for ICESat --> NASA GSFC for processing
* Text files of thickness for GRACE -->Univ. of S. Florida for processing

**ICESat 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

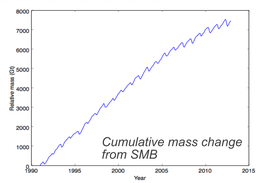
**GRACE Processing**
* Model lat., lon. ice thickness binned at ½ x ½ degree
* Thickness in each bin converted to cm water equiv.
* Binned data transformed to 60x60 spherical harmonics
* Result is model "seen" at equiv. resolution to GRACE
* Harmonics mapped back to ½ x ½ degree bins for plotting
* No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

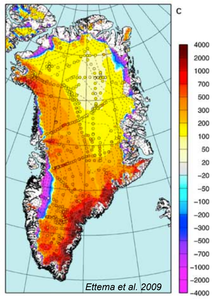
## Forcing Observations

### Surface Mass Balance - RACMO2

*van Angelen et al., Surv. Geophys., 2014*

* 11 km grid, interpolated to ice sheet model grid
* monthly temporal resolution
* applied as anomalies



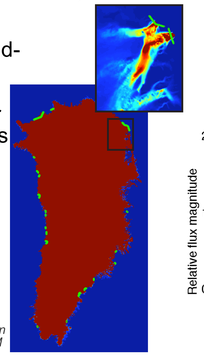




*Mean SMB calculated by RACMO compared to observations (circles)*

### Outlet Glacier Flux - InSAR, Ice-Penetrating Radar

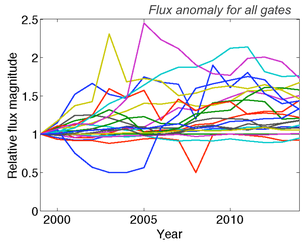
*Enderlin et al., GRL, 2014*

* mean-annual flux at grounding line
  * velocity from InSAR
  * ice thickness from radar
* 22 of largest outlet glaciers
* 1 km grid resolution
* annual resolution
* applied as anomalies



*Map of flux gate locations*

*Inset: flux gates for Zachariae and Nioghalvfjerdsfjorden shown over ice flux calculated by CISM*

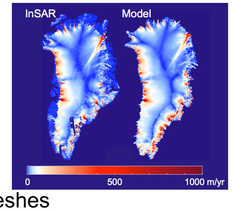



## Models

*http://oceans11.lanl.gov/cism/*

CISM 2.0.5:
- combination of finite-difference, finite-volume, and finite-element methods
- parallel, multiple momentum balance approximations
  - SIA, SSA, L1L2, DIVA, 3d Blatter-Pattyn
- 100 ka thermal spin-up with fixed geometry *[Morlighem et al., Nature Geo., 2014]*
- Formal optimization of basal friction parameter *[Perego et al.. JGR, 2014]*

FELIX-FO: *Tezaur et al., GMD, 2015*
- parallel, 3d, first-order Stokes approximation
- FEM of variable order on var. res. hex. and tet. meshes
- here, coupled to CISM 2.0 as external dycore




## Simulation Configurations

Initial condition: equilibium* with climatological SMB at 1990.

** Flux correction applied to maintain equilibrium*

All simulations are run from 1990-2014.

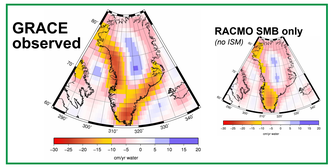
Thickness and temperature freely evolve; basal friction parameter held steady.
* SMB-Only: time-varying SMB
* SMB+Flux: time-varying SMB and outlet glacier flux forcing

Simulations are run at two grid resolutions: **4 km, 1km**

## Results

### GRACE Comparison

*2003-2011 mass trend maps*



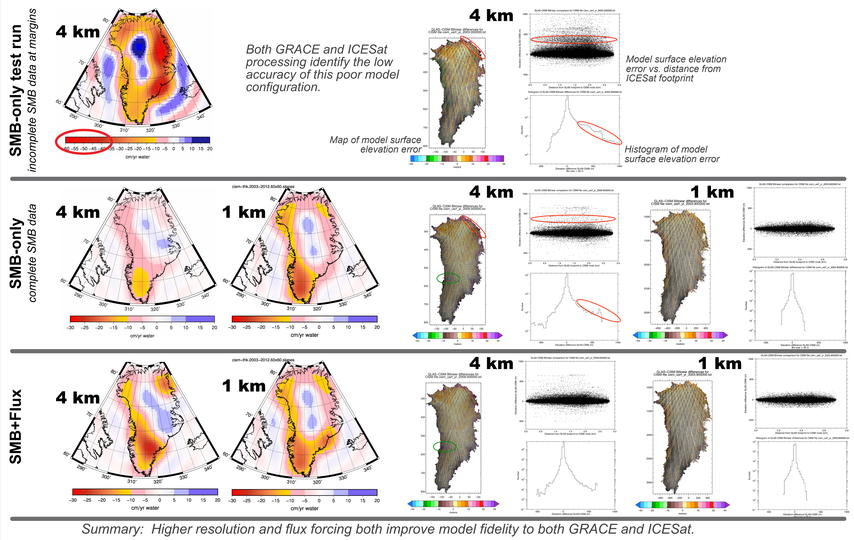

### ICESat Comparison

Compare modeled surface elevation to surface elevation measured by ICESat in each year. Examples from 2003 shown below.

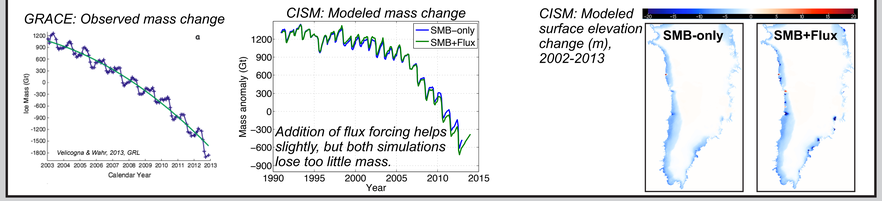
*Example metrics*

Elevation Difference (m): ICESat (2003) – Model

| Date | mean (stndv) | Mean Abs (stndv) | 5th percentile | 95 percentile | comment |
|---|---|---|---|---|---|
| 2003 | 6.14 (36.21) | 10.74 (35.12) | -13.17 | 26.48 | Poor SMB |
| 2003 | 3.81 (27.80) | 9.16 (26.52) | -15.00 | 22.30 | Improved SMB |
| N/A | 3.91 (27.66) | 9.21 (26.37) | -15.01 | 21.47 | Initial Cond. *** |




*Summary: Higher resolution and flux forcing both improve model fidelity to both GRACE and ICESat.*




## Future Work

* clean up / generalize 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
* use appropriate model optimization to avoid anomaly forcing constraints
* simulations using additional models, unstructured meshes

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