Validation of modeled ice dynamics of the Greenland Ice Sheet using historical forcing

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Model simulations conducted on Hopper and Titan at NERSC and OLCF
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?
GRACE measures changes in mass

Operational: 2003-present

GRACE resolves subannual variations

GRACE has coarse spatial resolution

Velicogna & Wahr, 2013, GRL
ICESat measures surface elevation

ICESat has fine spatial resolution but coarse temporal resolution (91 day exact repeat)

Elevation change requires processing

Ice thickness (or mass) change requires more processing
Forcing: SMB, 1991-2012

- RACMO2 \textit{van Angelen et al., Surv. Geophys., 2014}
- 11 km grid, interpolated to 1km ice sheet model grid (no downscaling)
- monthly temporal resolution
- applied as anomalies
Forcing: Outlet Glacier Flux, 1991-2012

- InSAR ice velocity + IceBridge ice thickness  \textit{Enderlin et al. GRL 2014}
- mean annual flux at grounding line
- 22 of largest outlet glaciers
- 1km grid resolution
- applied as anomalies
Models

**CISM 2.0**  [http://github.com/CISM/cism](http://github.com/CISM/cism)

Velocity solvers used:

- **DIVA**: parallel, FEM, 2d, first-order Stokes approximation (Goldberg JGlac 2011)
- **FELIX-FO**: parallel, FEM, 3d, first-order Stokes approximation (Tezaur et al. GMD 2014)
  - here, coupled to CISM 2.0 as external dycore

**Spin-up and initialization**

- 1km regular grid using BedMachine (Morlighem et al. Nat. Geo. 2014) geometry
- 350 ka thermal spin-up with fixed geometry using DIVA
- formal optimization of basal sliding coefficient using FELIX (Perego et al. JGR 2014)
- Flux correction applied to hold equilibrium with climatic SMB
1 km res. initial condition: surface speed
Results

Model runs conducted:
1. **SMB-only**: forced from 1991-2012 by RACMO SMB
2. **SMB+Flux**: forced “… “ plus outlet glacier flux time series, 2000-2012
   a. 4 km resolution
   b. 1 km resolution

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)
Model Post Processing

**LANL**
- **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

**NASA Goddard**
- **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 std dev > 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

**Univ. South Florida**
- **GRACE Processing**
  - Model lat., lon. ice thickness binned at \( \frac{1}{2} \times \frac{1}{2} \) 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 \( \frac{1}{2} \times \frac{1}{2} \) degree bins for plotting
  - No smoothing or other GRACE post-processing applied

**Goal:** automated web service for all steps
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
SMB-Only 4 km
SMB-Only 1 km
SMB+Flux 1 km

GLAS-CISM Bilinear differences for CISM file cism_usrf_yr_2003.800000.txt

Elevation difference GLAS-CISM (m)

Distance from GLAS footprint to CISM node (km)

Histogram of GLAS-CISM Bilinear differences for CISM file cism_usrf_yr_2003.800000.txt

Number

Elevation difference GLAS-CISM (m)
Results: GRACE

[Graph showing the water layer over time with different models: SMB-Only, SMB+Flux, RACMO, and GRACE. The graph illustrates a downward trend from 2003 to 2012.]
GRACE, RACMO, & Model: year-on-year mass changes: 2005

SMB+Flux

SMB-only

RACMO2

GRACE Obs.

cm water

-100  -75  -50  -25  0   25   50   75   100
Stndev of diffs. from time series mean
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
Sim. 3: Example of flux forcing (Jakobshavn Isbrae)

Zwally et al., 2011, JGlac
Thickness change rates

- measured
- reconstructed
- residual

ICESat/ATM  RACMO2

Csatho et al., 2014, PNAS