CESM/ISSM Coupling.

Eric Larour[1], Brian Kauffman[2], Nicole Schlegel[1], Bill Sacks[2], Mariana Vertenstein[2]

Land-Ice Working Group Meeting, NCAR 2018

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Background

- NASA Modeling and Analysis Program: 2008 -> 2012. Build-up of ice-sheet modeling capability (ISSM, PISM). Synchronized effort at NSF and DOE.
- NASA Modeling and Analysis Program: 2013-2017. Logical follow-up was funding for coupling ISMs and Climate Models. Grant for ISSM, Goddard GMAO GEOS-5 and CESM coupling.
  - 2013-> 2015-16: coupling with GEOS-5 based on ESMF compliance. Adaptation of ISSM to match ESMF modular based approach.
  - 2016->2017: start of the CESM/ISSM coupling effort. Using legacy developments for GEOS-5. Adaptation to the specifics of the CESM framework.
- Team:
  - ISSM side: Eric Larour and Nicole Schlegel.
  - CESM side: Bill Sacks, Brian Kauffman, Mariana Vertenstein.
  - Approach: integrate ISSM into CESM as a full fledged GLC component.

Technical Approach

- CESM:
  - modifications to CESM case setup scripts that allow CESM to recognize ISSM as a valid GLC component choice. In standard CESM fashion, one can create the run scripts required for running a configuration using ISSM as the glc component (eg. build, input-data positioning, & run scripts).
  - creation of input data required by the coupled system other than ISSM itself (e.g. the coupler). These are netCDF files that describe the grid that ISSM runs on and the mapping (regridding) files necessary to map to/from the native ISSM grid from/to the grid of other CESM components (atmosphere & land).
  - a detailed API for connecting a compiled ISSM library to the rest of the CESM software
- ISSM:
  - library mode of compilation to be included in any type of GCM framework.
  - constructor, iterator, destructors: major rewrite of ISSM to comply with these three main steps, a constant of any GCM model.
  - Modularization of each physical core in ISSM to be used by any driving framework: be it a GCM like CESM, or a Monte-Carlo sampler like Dakota, or an AD compliant framework such as ADOLC.
- What remains to be done:
  - Coding of CESM API calls into ISSM (similar to what was already implemented for GEOS-5).
  - Compiling/linking of ISSM library mode into CESM.
  - Validation/Verification of the coupled capability.

ISSM Capabilities

Capability Support

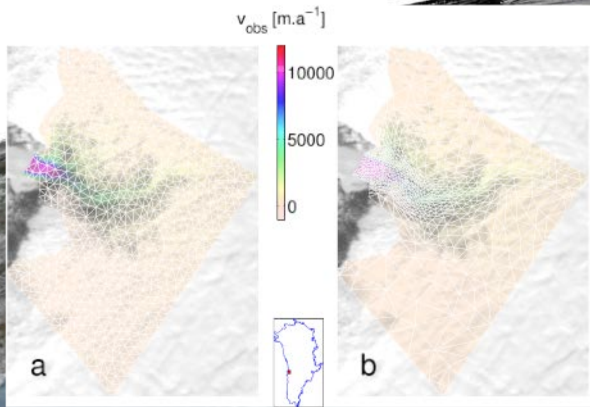
Capability	Support	Contacts
Stress balance		ISSM Team
Thermal (cold ice)		Seroussi
Thermal (enthalpy)		Bondzio & Seroussi
Mass transport		ISSM team
Transient		ISSM team
Static inversions (friction, B)		ISSM Team
Mesh generation		Bamg: Morlighem
Grounding line (hydrostatic)		Seroussi
Python Interface		Borstad & De Fleurian
GIA		Adhikari
UQ (dakota)		Schlegel
Balance velocities		Morlighem
Calving		Morlighem & Bondzio
Damage		Borstad
Rifts		Larour
Hydrology		De Fleurian
Grounding line (FS, contact)		Seroussi
Mass Conservation		Morlighem
MITgcm coupling		Seroussi
Automatic Differentiation		Larour
Sea level		Larour & Adhikari

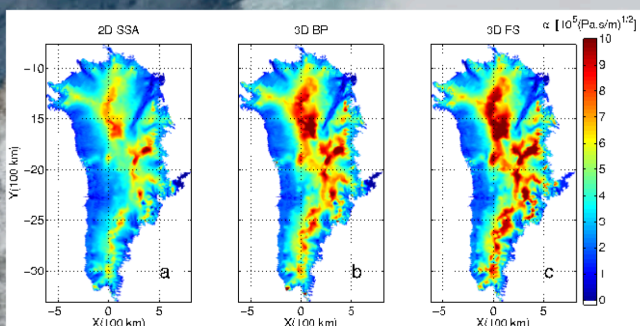
Legend:

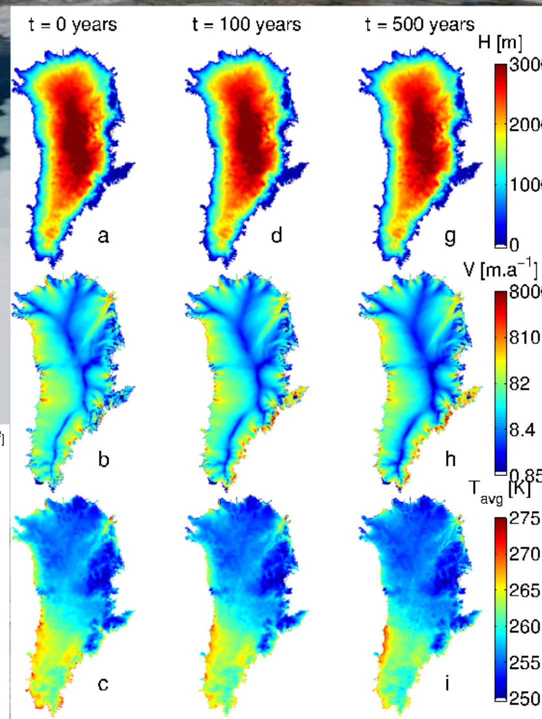
- Production (fully Supported)
- Development (not fully supported)
- Experimental (not supported)

ISSM: a quick history. Continental scale, high order, high spatial resolution, ice sheet modeling.

Larour, E., H. Seroussi, M. Morighem, E. Rignot







Upper left: anisotropic meshing in the region of Jakobshavn Isbrae. The optimized mesh (b) captures surface deformation more efficiently than the regular mesh (a). Lower left: inverted basal friction for the Greenland Ice Sheet using increasingly complex models (a: 2D Shelfy-Stream, b: 3D Blatter/Pattyn and c: 3D full-Stokes). Right: 500 year SeaRISE run using a 3D higher-order model. a, d, g: ice thickness. b, e, h: surface velocity. c, f, i: depth-averaged temperature.

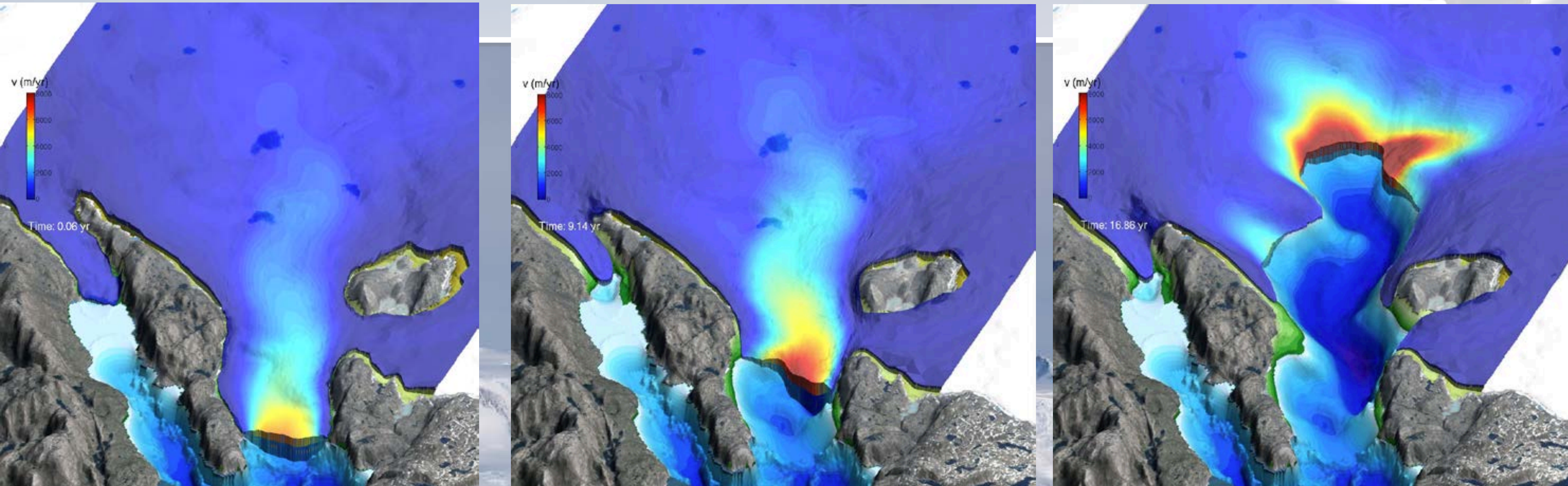
- Ice Sheet System Model: a JPL/UCI collaboration to develop an ice flow model capable of modeling the evolution of continental ice sheets in the next 100 years.
- Large scale capable: runs on NASA Ames Pleaides cluster. Full Antarctica model at 1.5 km resolution, Greenland model at 500 m resolution. 20 vertical layers.
- Higher-order capable: wide range of physics implemented, ranging from 2D Shelfy-Stream to 3D Blatter/Pattyn and 3D full-Stokes.
- Adjoint-based inversions at the continental scale. Using InSAR surface velocities, it is possible to invert for the basal friction at the ice/bed interface, or depth-averaged ice rigidity of ice-shelves.
- Project ice flow into the next 500 years, using model inversion and satellite data to spin-up.

Reference:

Larour, E., H. Seroussi, M. Morlighem, and E. Rignot, Continen- tal scale, high order, high spatial resolution, ice sheet modeling using the Ice Sheet System Model (ISSM), J. Geophys. Res., 117, F01022, 1–20, 2012.

Modeling of Store Gletscher's calving dynamics, West Greenland, in response to ocean thermal forcing

Morlighem, M., J. Bondzio, H. Seroussi, E. Rignot, E. Larour, A. Humbert and S. Rebuffi



30-year modeled evolution of Store with ocean induced melting of 12 m/day in the Summer. Fjord bathymetry is shown on a blue-green color scheme (depths below sea level are shown in blue). The color scheme of the ice shows the ice velocity.

Main points:

•Warmer ocean currents around Greenland trigger dramatic changes on its marine-terminating glaciers. We use numerical modeling to assess the vulnerability of Store Gletscher.

•We developed a methodology that can be applied to other Greenland glaciers to quantify the impact of ice-ocean interactions on glacier flow.

•We find that the bed topography is a key control on the stability of ice fronts and we determine that ocean-induced melt needs to quadruple to dislodge the glacier from its stabilizing sill.

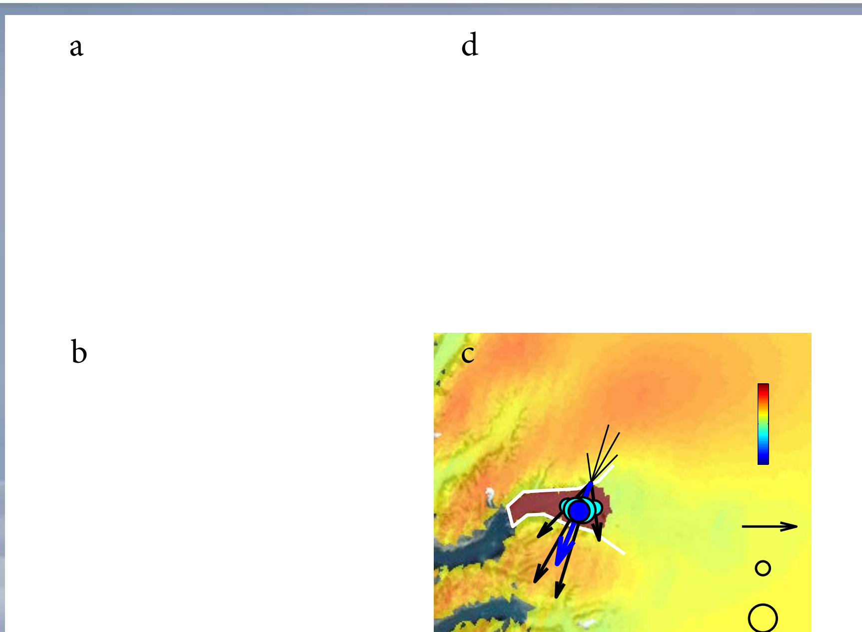
• NASA resources:
  - Grant: NNX15AD55G
  - Ice Sheet System Model (ISSM)
  - Pleiades cluster (NASA Advanced Supercomputing)

• NASA data:
  - BedMachine Greenland
  - InSAR-Based Greenland Ice Velocity Map

Morlighem, M., J. Bondzio, H. Seroussi, E. Rignot, E. Larour, A. Humbert, and S. Rebuffi, *Modeling of Store Gletscher's calving dynamics, West Greenland, in response to ocean thermal forcing*, Geophys. Res. Lett., 43, doi:10.1002/2016GL067695.

Discovery of solitary waves of ice loss

Surendra Adhikari, Erik R. Ivins, Eric Larour



Mass transport waves detected in solid Earth deformation. (a) Measurements of horizontal crustal motion by a single GNSS station, located on bedrock next to the Rink Glacier. Notice anomalous signal in 2012. (b) Horizontal crustal displacement vectors (arrows) and inferred mass anomalies (circles) traveling through the Rink Glacier trunk (white boundary) during July-Sept 2012. Background map shows mean monthly surface mass balance (SMB). (c) Same as (b), but during Oct 2012 – Jan 2013. (d) Summary of (b) & (c), revealing seasonal wave of mass transport.

Adhikari, S., Ivins, E.R., Larour, E. 2017: Mass transport waves amplified by intense Greenland melt and detected in solid Earth deformation, *Geophysical Research Letters*, 44, 4965-4975.

See Surendra's Invited Talk on Wednesday at 8:30 in #222 [G31E-03]

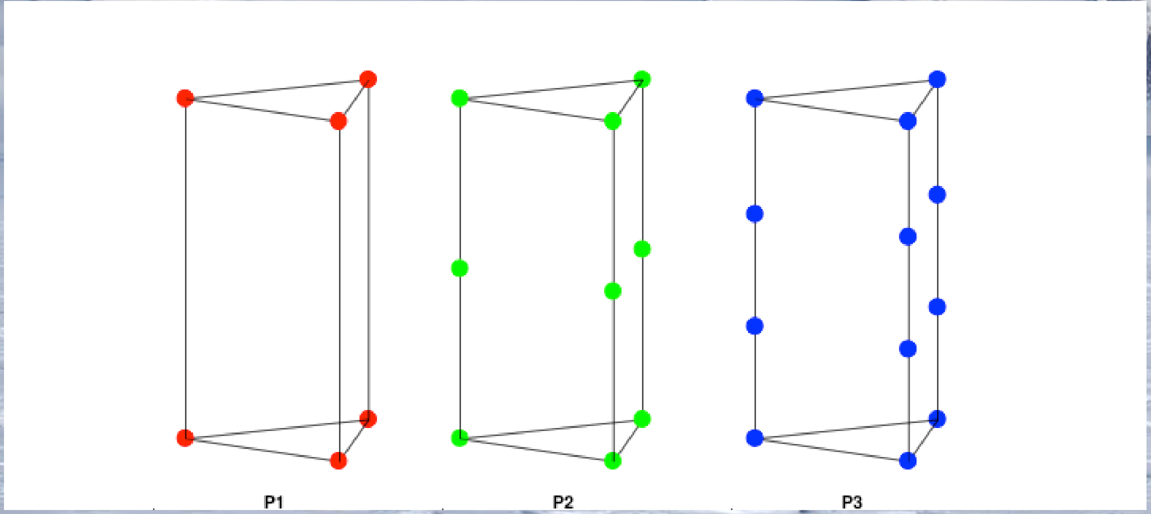
Science Question: Can horizontal crustal displacements adjacent to Greenland fast moving outlet glaciers reveal loading associated with ice dynamics? Might we anticipate this during expect intense Greenland melt years (2012 & 2010)? A bedrock GNSS station, located 2 km from the Rink Glacier, recorded systematic horizontal crustal motions (Fig. a). We then aimed at answering: What were the causal mechanisms for this?

Data & Results: We combined satellite geodetic observations (GRACE, CryoSat-2), climate reanalysis (SMB), & measurements of glacier velocity and calving front positions to conclude that solitary waves carrying substantial ice traveled down the Rink Glacier during two of Greenland's intense melt years. During June-Sept 2012, the wave speed was about 7 km/month, ultimately dumping a total of 6.7 Gt of ice/water into the oceans.

Significance: 1st quantitative measurement of solitary mass transport waves on any glacier in Greenland or Antarctica. This "new mode" of rapid pulse of ice loss in the form of waves may strengthen the sustained ice loss from Greenland, with important implications for the future sea-level rise.

Implementation of higher order finite elements for paleoclimate simulations

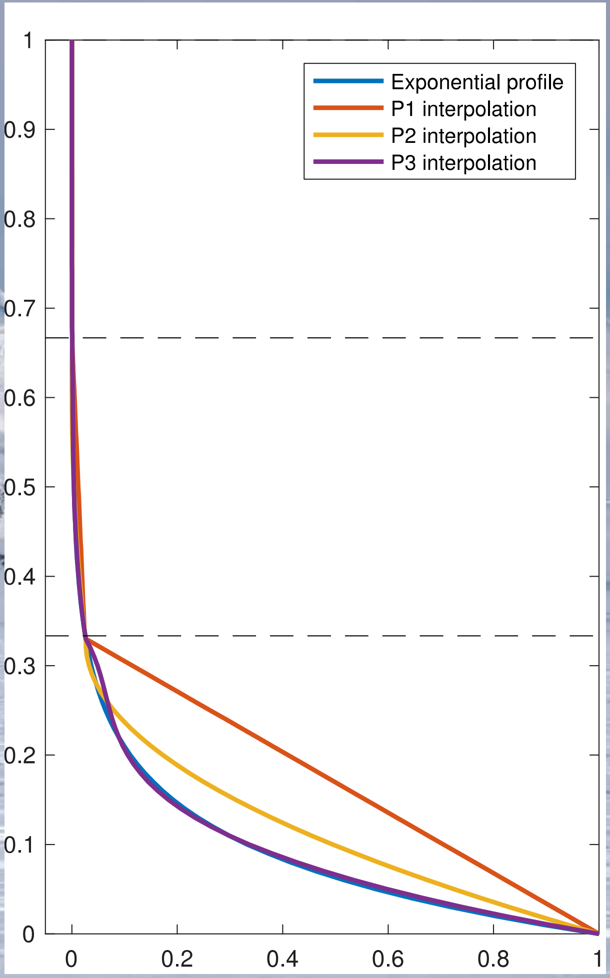
- ISSM typically uses a 25 layer model with P1 vertical elements.
- We find that using 5 vertical layers using P1xP2 finite elements yields the same accuracy as our traditional approach (25 L P1) .
- 57x faster than traditional linear interpolation.



Linear interpolation

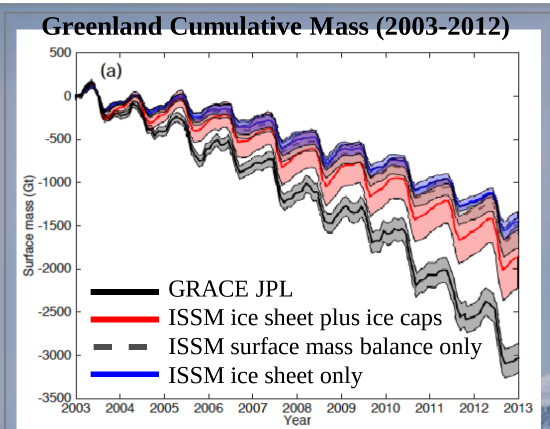
Quadratic interpolation

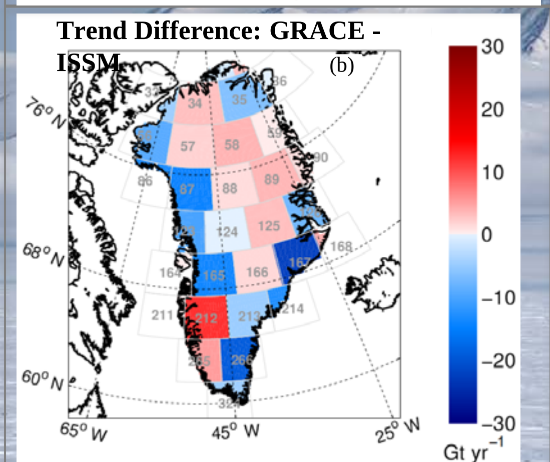
Cubic interpolation



In prep

Utility of GRACE in assessing model estimates of Greenland mass change (Nicole-Jeanne Schlegel)





Ice Sheet System Model (ISSM) simulations of Greenland mass and JPL's GRACE mascon solution, compared (above) as time series and (below) spatially by mascon.

Problem: Model estimates of Greenland ice mass change differ from observed. In order to improve these estimates, it is crucial to characterize model uncertainty.

Finding: In the Southwest and Northeast, model uncertainty is dominated by errors in surface climate, particularly during the summer. In the Northwest and Southeast, GRACE observes consistent mass loss due to short-term increases in ice loss during the spring. These events are not modeled, therefore ISSM underestimates mass loss.

Sources of Ice Model Uncertainty	*% Uncertainty*	*Sea Level (mm/yr)*
SURFACE CLIMATE	10	.08
UN-MODELED MASS LOSS	35	.28

Significance: Uncertainties impact model estimates of Greenland's sea level contribution by 45%. In order to reduce uncertainties, it is necessary to observe ice sheet processes that occur on monthly timescale (such as melt events, basal hydrology, and ice-ocean interaction) and to physically represent these processes in the models.

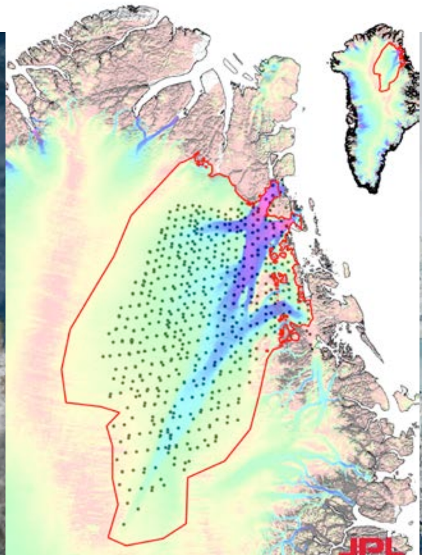
Schlegel, N.-J., Wiese, D. N., Larour, E. Y., Watkins, M. M., Box, J. E., Fettweis, X., and van den Broeke, M. R.: Application of GRACE to the assessment of model-based estimates of monthly Greenland Ice Sheet mass balance (2003–2012), The Cryosphere, 10, 1965-1989, doi:10.5194/tc-10-1965-2016, 2016.

Supported by NASA's Cryosphere (T. Wagner) and GRACE (L. Tsaoussi) programs

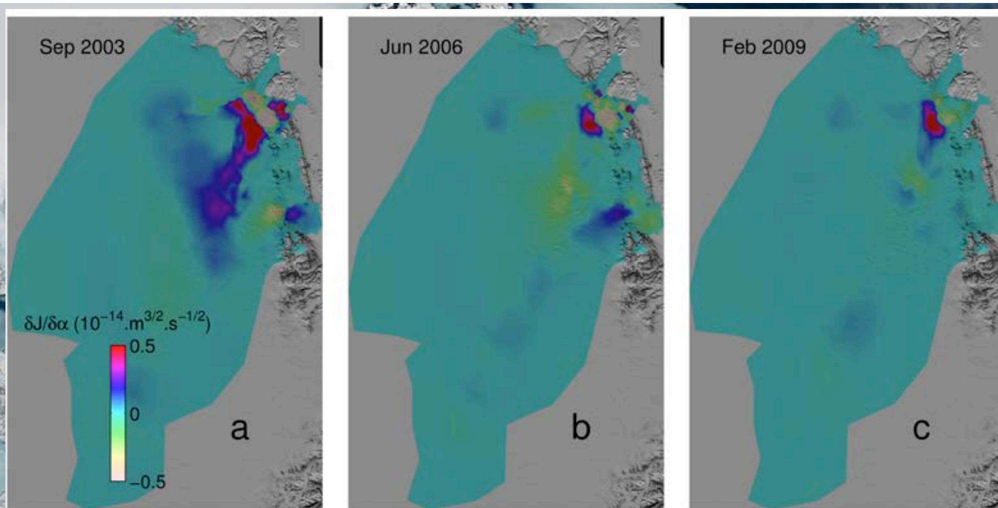
Data assimilation of ICESat data into ice flow model of North-East Greenland

E. Larour, J. Utke, B. Csatho, A. Schenk, H. Seroussi, M. Morlighem, E. Rignot, N. Schlegel, and A. Khazendar

- First-time assimilation of ICESat altimetry data into an ice flow model (Ice Sheet System Model, ISSM)
- We reconstruct time series of basal friction and surface mass balance to best-fit the altimetry data.
- The time series show high annual and intra-annual variability, which is not currently captured by forward models.
- Paves the way for integration of GRACE, NiSAR, Operation IceBridge and ICESat (1-2) data.
- Will yield improved understanding of processes that cannot be observed directly, and therefore improved projections of SLR.



ICESat time series (black dots) 2003-2016 on North-East Greenland Glacier



Temporal gradient of model best-fit to observations with respect to basal friction. Allows for inversion of basal friction (idem for surface mass balance) to best match altimetry observations.

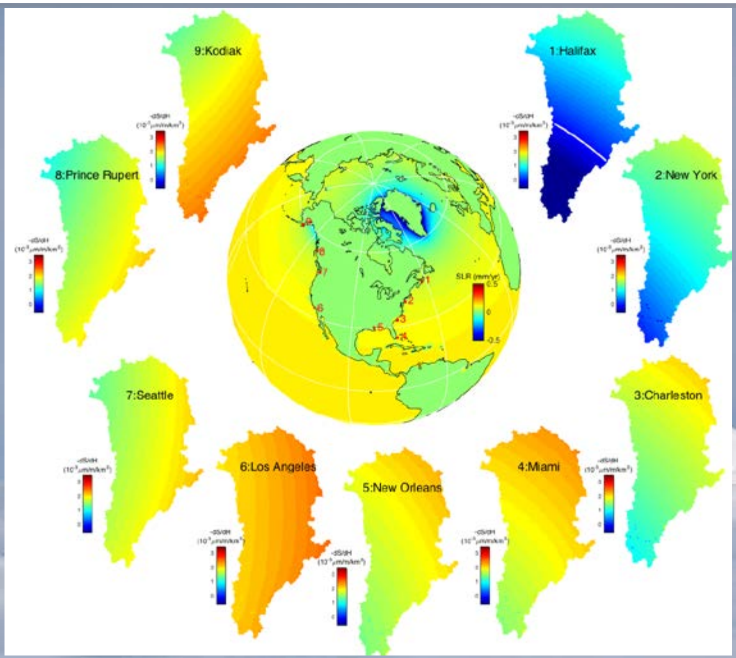
Funding sources: NASA Cryospheric Sciences Program and NAS Modeling, Analysis and Prediction Program.

Reference: E. Larour, J. Utke, B. Csatho, A. Schenk, H. Seroussi, M. Morlighem, E. Rignot, N. Schlegel, and A. Khazendar, Inferred basal friction and surface mass balance of the Northeast Greenland Ice Stream using data assimilation of ICESat (Ice Cloud and land Elevation Satellite) surface altimetry and ISSM (Ice Sheet System Model), The Cryosphere, 8, 2335-2351, doi:10.5194/tc-8-2335-2014

Should coastal planners worry about where the ice is melting?

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Eric Larour, Erik Ivins and Surendra Adhikari



Gradient fingerprint dS/dH of local sea-level rise (S) in 9 cities along the US coastline, to changes in ice thickness (H) in Greenland. The forward sea-level fingerprint used to compute the gradient is shown in the middle frame (in mm/yr), calibrated using thickness changes from GRACE from 2003-2015. For example, glaciers in SW Greenland do not effect sea-level rise in NY or Halifax (dS/dH~0) while all of Greenland significantly affects Los Angeles. The fingerprints capture perturbations to the gravity field, bedrock rebound, and rotational feedback caused by ice melt.

Larour, E., Adhikari, S., Ivins, 2017: Should coastal planners have concern over where land ice is melting?, *Science Advances*, 3 (11), doi: 10.1126/sciadv.170537.

This work was funded through the NASA Cryosphere, MAP, ESI and N-SLCT programs.

Science Question: what is the sensitivity of local sea level rise in coastal cities to changes in ice mass transport in every single glaciated area of the world. Are cities vulnerable to specific glaciers/ice streams across the Cryosphere? To answer the question, we implemented a breakthrough adjoint model of our ISSM-SESAW sea-level rise solver, and reverse computed the desired sensitivities (dS/dH for every city, see Fig 1) also called "Gradient Fingerprints".

Data & Results: We relied on GRACE data to compute forward sea-level fingerprints and their gradient (reverse direction) for 293 locations around the world. The gradient fingerprints revealed strong spatial variations in the sensitivity of sea-level rise in coastal cities of Northern Europe, Artic and North-America to thickness changes in Greenland. Similarly, ice melt in specific areas of Antarctica causes significant sea level change in South-America, South of Africa and Australia. The results are hosted on the vesl.jpl.nasa.gov website and the NASA Sea-level Change Science Team portal.

Significance and Impact: First time a high resolution gradient fingerprint has been computed for a comprehensive number of coastal cities. Can be used directly by coastal planners to understand and quantify the risk posed by far-away glaciated areas to their specific coastal city, even as our understanding of the cryosphere evolves. The portal has seen a traffic of **~100,000** users in 4 days. The study has generated articles from 41 news outlets.

ISSM Web/Outreach capabilities.
VESL and NASA SLCT integration.

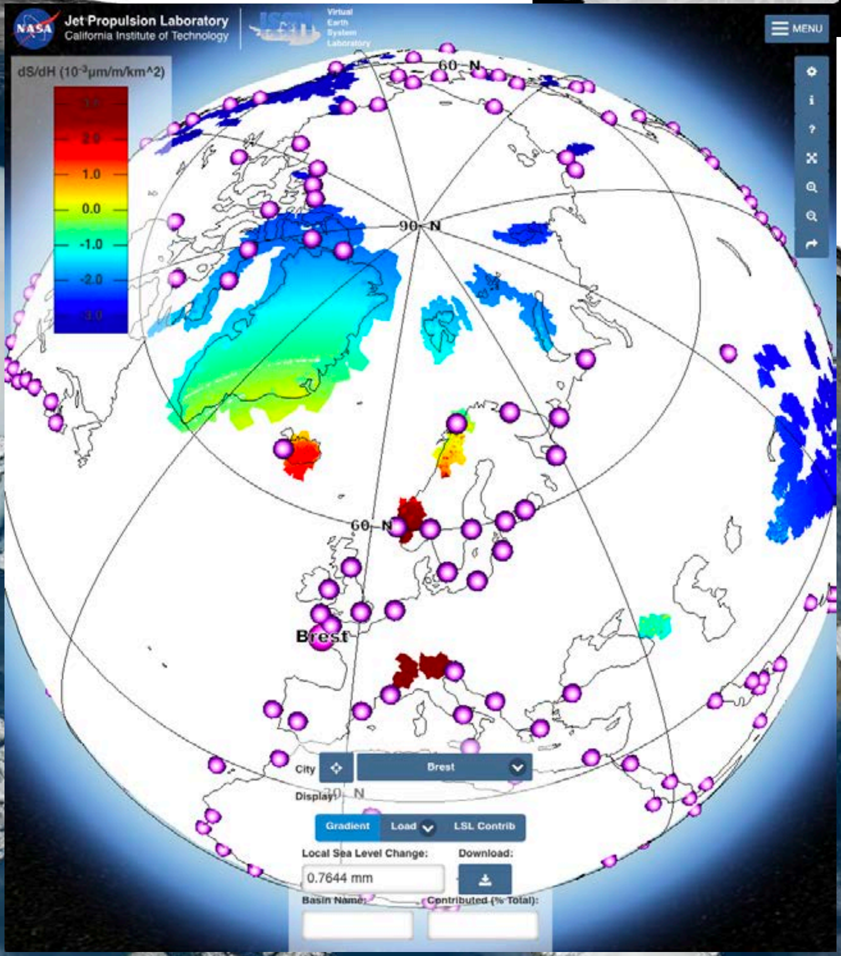
Main points:

•NASA/JPL's Ice Sheet System Model (ISSM) now capable of running inside a WebSite using a new JavaScript API (similar to running in Matlab or Python!).

•This allows for delivery of powerful ISSM capabilities directly to web users, without actual expertise running ISSM itself.

•Integration of these capabilities already realized to support simulations on the NASA N-SLCT portal (see figure).

•Integration of a wide range of simulations on the ISSM VESL (Virtual Earth System Laboratory) website (vesl.jpl.nasa.gov) with emphasis on outreach and education.



Sea-level rise simulation (Gradient Fingerprint Mapping) on the VESL/N-SLCT website using ISSM JavaScript capabilities. User controls a simple interface (choice of city, type of loading from NASA GRACE datasets) and back-end computations using ISSM are carried out on the Amazon EC2 cloud and returned almost instantly to be visualized and/or downloaded.

Larour, E. et al, A JavaScript API for the Ice Sheet System Model (ISSM) 4.11: towards an online interactive model for the Cryosphere Community , Geoscientific Model Development. 2017.

What next?

- Finish first prototype and run V&V tests.
- Leverage existing programs from JPL and NCAR (JPL R&TD, NSF, NASA) to fund further Validation/Production runs using the new coupled capability.
- Looking for potential users that are enthusiastic about synergizing existing CESM capabilities and new capabilities from ISSM.
- Examples:
  - Paleo-simulations using new fast thermal solvers, friction scalings.
  - Fully coupled, fully geodetic compliant sea-level reconstructions/projections
  - Data assimilation to improve spin-up of coupled reconstructions/projections?

Contact

- Website: http://issm.jpl.nasa.gov
- Skype channels: eric.larour@jpl.nasa.gov, nicole.schlegel@jpl.nasa.gov
- ISSM forum: https://issm.ess.uci.edu/forum/index.php (google)
- Workshops: check on website. Next one in Hawaii, after AOGS 2018.

Thanks !

This work was performed at the California Institute of Technology's Jet Propulsion Laboratory under a contract with the National Aeronautics and Space Administration's Cryosphere Science Program.