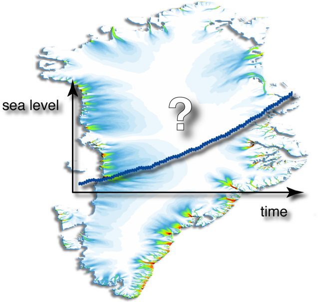
The need for hindcasting in ice sheet modeling

or why we can get the right answer for the wrong reason

Andy Aschwanden

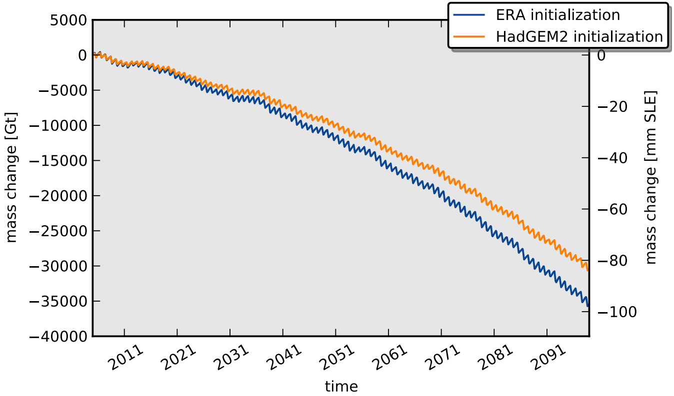


Outline

Hindcasting

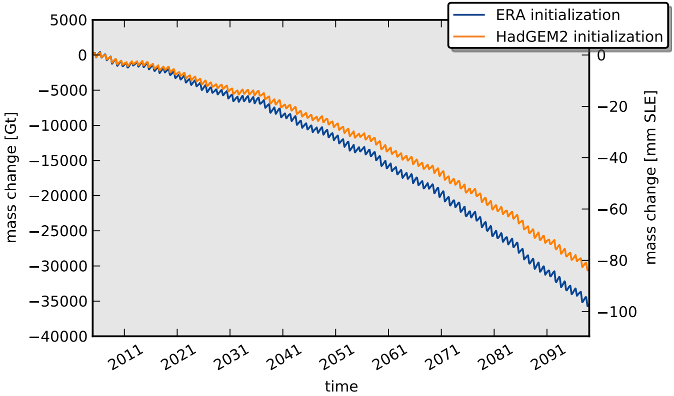
Internal variability of glaciers and ice sheets

Greenland's future contribution the global sea-level



- produced with the Parallel Ice Sheet Model PISM
- climate forcing from RACMO2/GR using RCP4.5 emission scenario
- what is the difference between the two simulations?
- do you trust these simulations?

Greenland's future contribution the global sea-level



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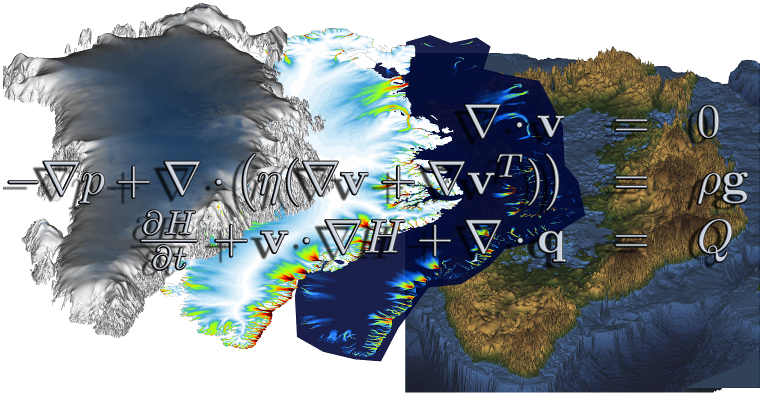
Ice sheet (system) model



- ice dynamics
- thermodynamics
- surface processes
- boundary conditions
- hydrology
- ice-ocean interaction (e.g. calving)

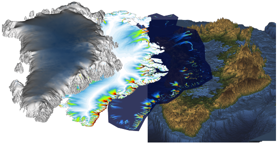
Verification

"Are we solving the equations right?"

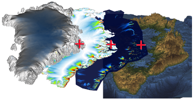
- The comparison of results from a numerical approximation to exact solutions of the same continuum model equations.

Verification
is only possible for

- a few subsystems
- a simple coupled system



Ice sheet model validation



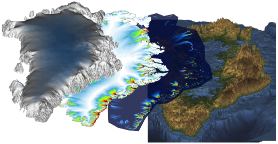
“Are we solving the right equations?”

- comparing model results to a set of observations adequate to falsify a model

Direct validation

of substantial sub-systems such as

- basal hydrology
- thermodynamics
- ice dynamics

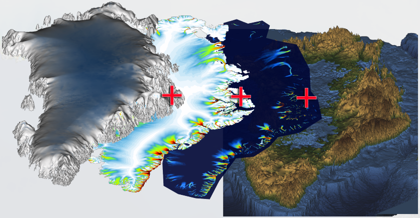


is difficult or impossible

as most or all observations available for validation are not linked to a single process, but are the consequence of a complex interplay between sub-systems.

View as part of an earth system model

- we evaluate how the *system* responds to a given forcing
- "How successful is a state-of-the art ice sheet system model (i.e. the combination of physical models, their numerical approximations and implementations, and particular choices of boundary forcing and initial states) in reproducing observations of quantities such as ice thickness, and their temporal changes?"



The system model approach

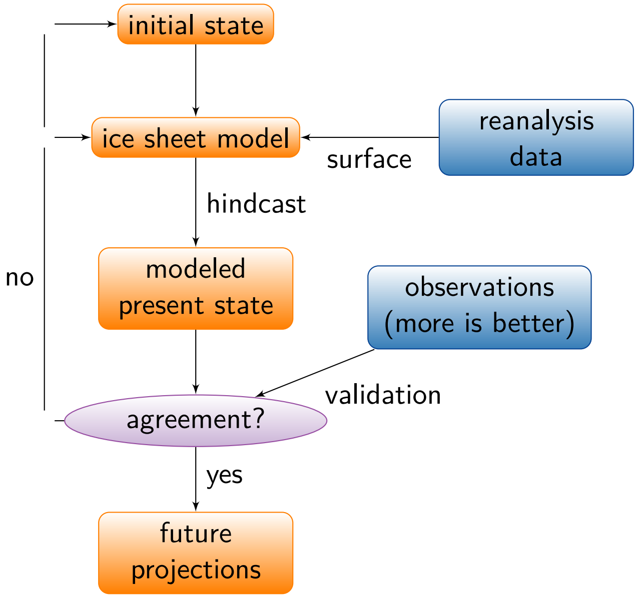
- new Boeing 787 “Dreamliner” airplanes were grounded from January to April 2013
- because a battery overheated and started a fire in an empty 787
- batteries had passed all independent tests
- flaws in battery design only revealed in assembled airplane
- cause remains unclear

⇒ testing the system as a whole is indispensable

Hindcasting

- A hindcast is a way of testing a mathematical model.
- Known or closely estimated inputs for past events are entered into the model to see how well the output matches the known results.
- established concept from global climate and ocean circulation modeling

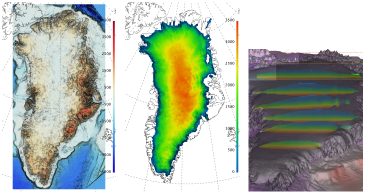
How to test your ice sheet model



Initialization

initialization → hindcast → forecast

- ice sheet model simulations require an initialized ice sheet



distribution of

- mass (ice thickness)
- momentum (basal friction)
- energy (temperature)

within the ice sheet

Problem

- full set of initial conditions not readily available through observations alone

Solution

- use of assimilation techniques
  - inverse methods
  - past climate initialization ("spin-up")

Initialization

Two general types of methods

Inverse methods

- assimilate present-day data
- obtain missing data using inverse theory

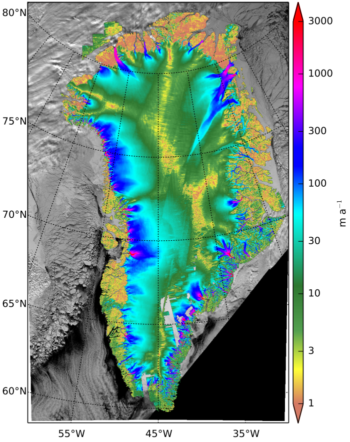
Past climate initialization

- start simulation far back in the past with initial guess
- forward simulation using information about past climate

Inverse methods

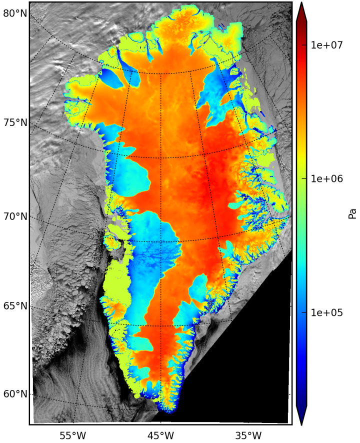
Some ice sheet models like ISSM, Elmer, and VarGlaS have built-in data assimilation using adjont methods

surface velocities



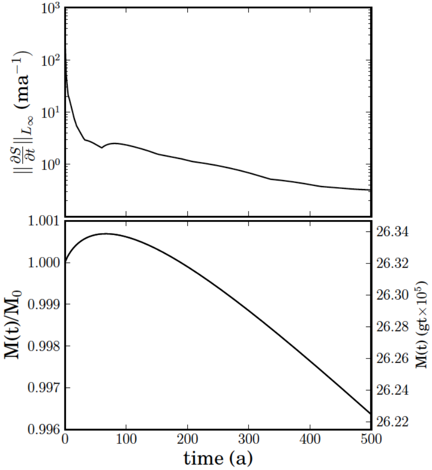
$\Rightarrow$

basal yield stress



Example: VarGlaS

a next-generation ice sheet model



Brinkerhoff and Johnson (2013)

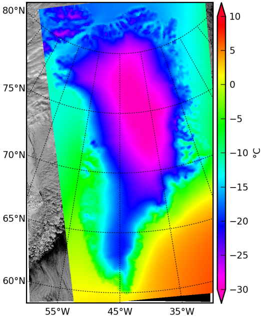
- data assimilation using observations of
  - surface velocities
  - surface temperature
  - ice thickness
- 500 a forward simulation shows initial mass gain (instead of loss, as observed)
- large transient signals propagate through the system at the beginning of the run
- ELMER/Ice and ISSM show similar issues

Initialization

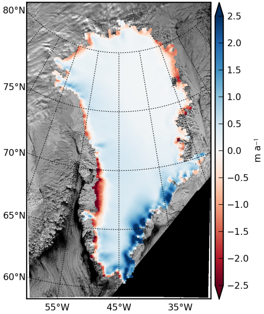
initialization → hindcast → forecast

- RACMO2/GR driven by
  - ERA-reanalysis from 1961-2004
  - HadGEM2 from 1971-2004
- PISM driven by mean values of:

2 m air temperature



climatic mass balance

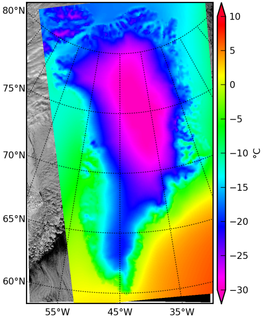


Hindcast

initialization → hindcast → forecast

- RACMO2/GR driven by
  - ERA-reanalysis from 1961-2004
  - HadGEM2 from 1971-2004
- PISM driven by monthly time-series of:

2 m air temperature



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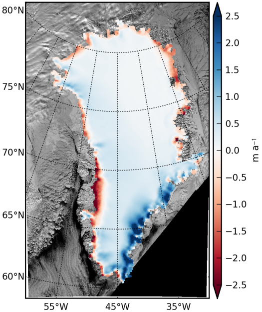
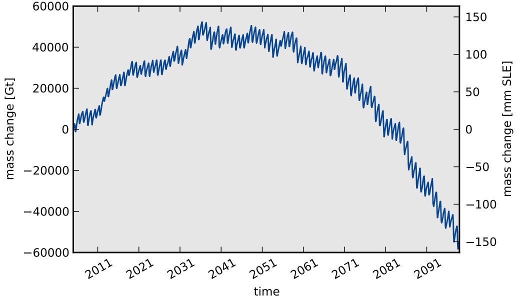


Forecast

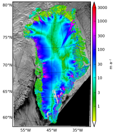
initialization → hindcast → forecast

- RACMO2/GR driven by HadGEM2 RCP 4.5 forcing
- PISM driven by RACMO climate:
  - RACMO - HadGEM2 directly
  - RACMO - ERA/HadGEM2 anomalies

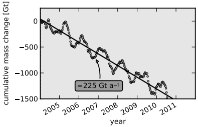


Comparison with observations

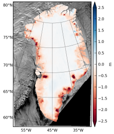
Hindcasts cover an era where we have a variety of in-situ and remotely-sensed observations such as:



- mean flow speed from 2000,2006–2008 (SAR) from *Joughin et al.* (2010)

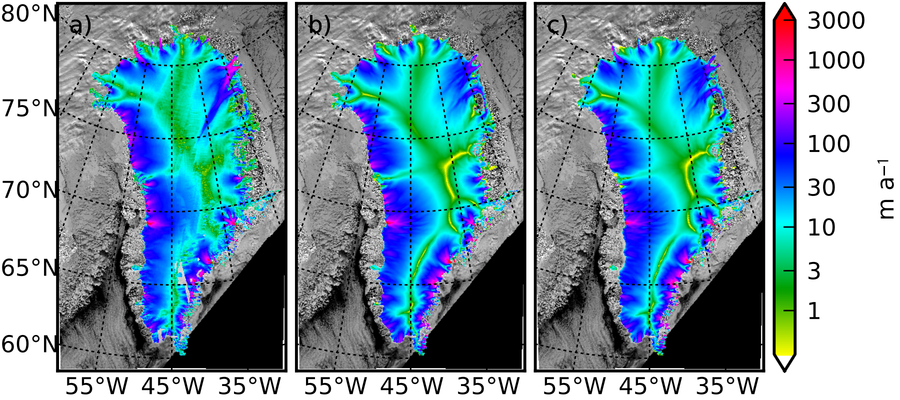


- cumulative mass change from 2003–2011 (GRACE) from *Luthcke et al.* (2013)



- elevation change from 2003–2009 (ICESat) from *Sørensen et al.* (2011)

Flow speed



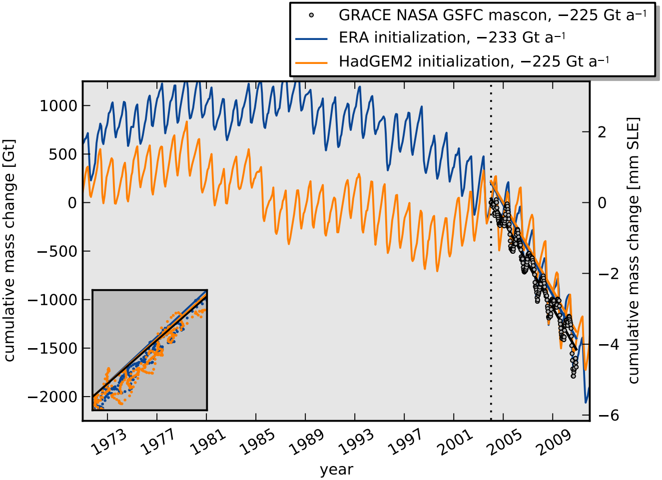
(a) SAR
(Joughin et al, 2010)

(b) ERA init.

(c) HadGEM2 init.

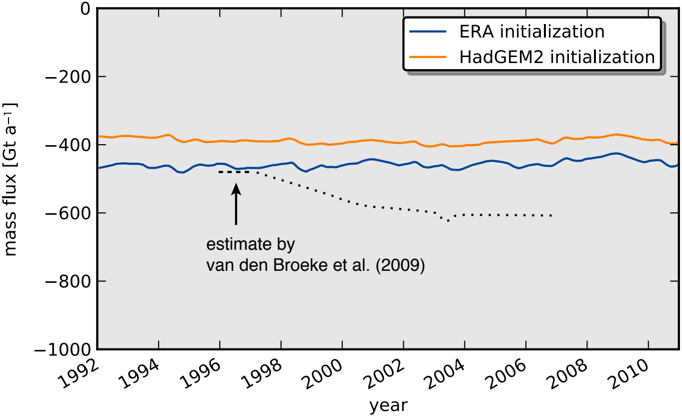
- reasonable agreement with observations

Mass changes



- wow, we're getting the trend right!
- an almost perfect fit (?)

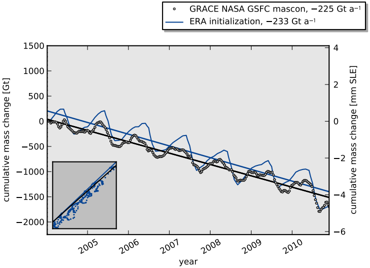
Ice discharge at ice/ocean interface



- simulated ice discharge remains nearly constant
- observed increase not simulated

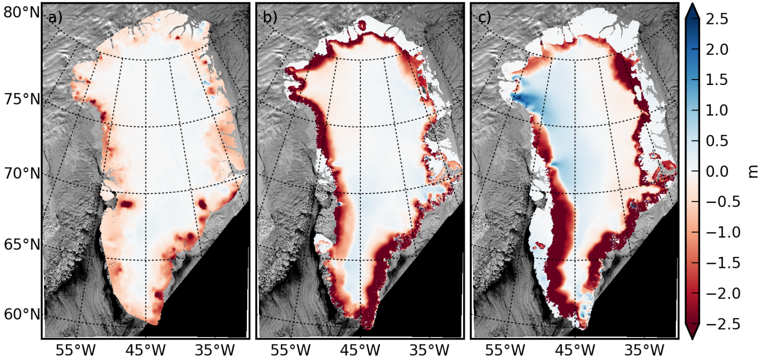
Wait a minute. . .

- 2000–2008 mass changes equally split between changes in surface mass balance and ice discharge (van den Broeke et al, 2009)
- but simulated ice discharge is nearly constant
- why do we get such a good agreement with observed mass loss?



We can get "the right result" for the "wrong reason"

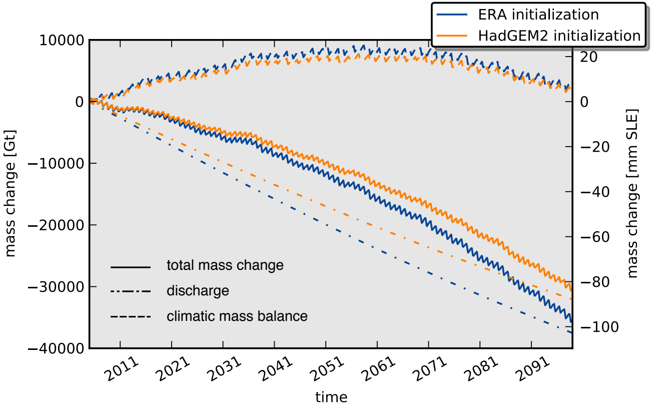
Surface elevation changes 2003–2009



(a) ICESat (Sørensen et al, 2011) **(b)** ERA init. **(c)** HadGEM2 init.

spatially-rich time-series are needed!

Some conclusions



- despite ERA and HadGEM2 initializations showing very similar mass loss trends between 2004 and 2010, they differ by 2 cm SLE by 2100
- as a result of having different initial states

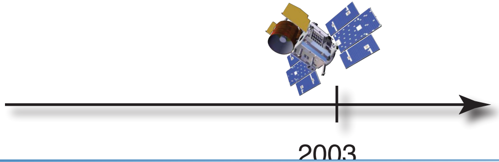
Limitations of hindcasting

Theoretical

- The appropriate time-scale for hindcasting is unknown
- Hindcasts are short (decades) compared to the time-scale associated with changes in energy (thousands of years)
- Even a hindcast showing good agreement with all available observations may not capture the system's true behavior
- Are we living inside a simulation? We can't tell for sure.

Practical

- Duration of hindcasts is limited by the length of observational records



Outline

Hindcasting

Internal variability of glaciers and ice sheets

Out of curiosity

Work in progress. . .

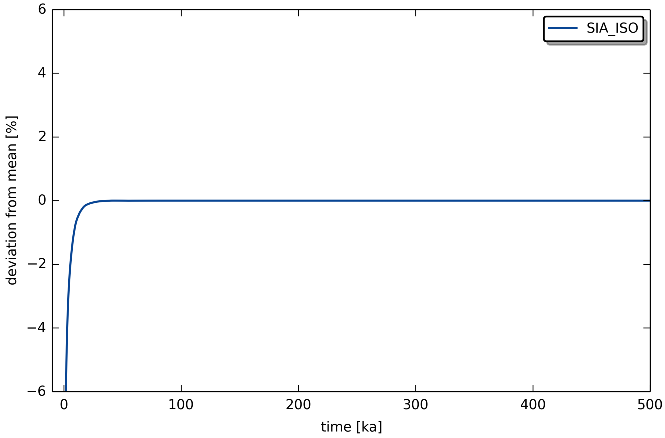
How to get a constant-climate initial state?

- run for a fixed length (e.g. 125 or 250 ka) years
- run until a steady-state is reached

What is a steady-state?

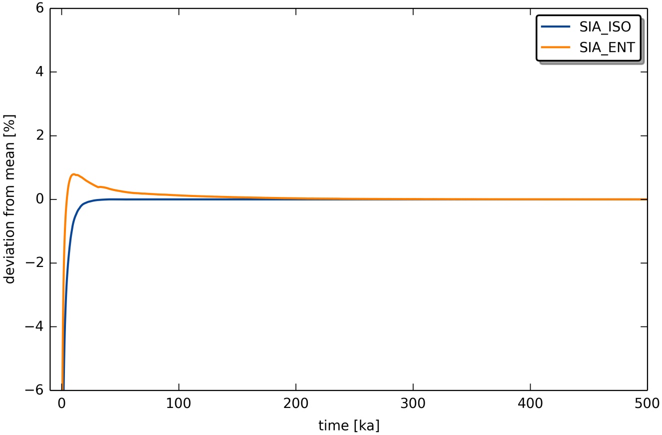
- for a sufficiently complex system, a steady-state in the mathematical sense ($\partial/\partial t = 0$) may not exist
- relaxed definition: e.g. mass change $< 0.01\,\%$ in 10,000 years (EISMINT)

Internal variability



relative deviation from mean mass, $(m - \bar{m})/\bar{m}$, where $\bar{m}$ is the mean

Internal variability



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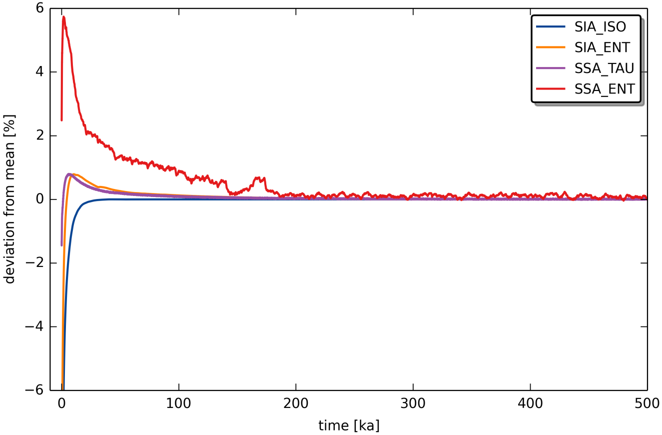
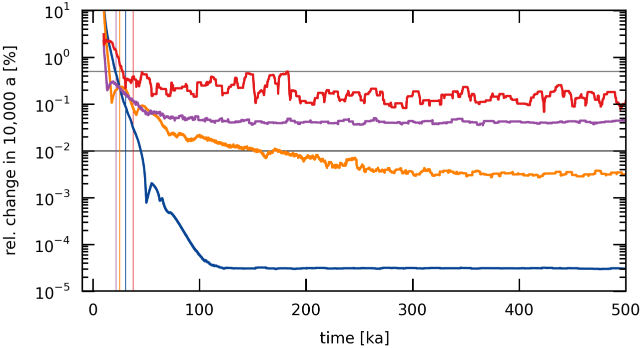
Internal variability



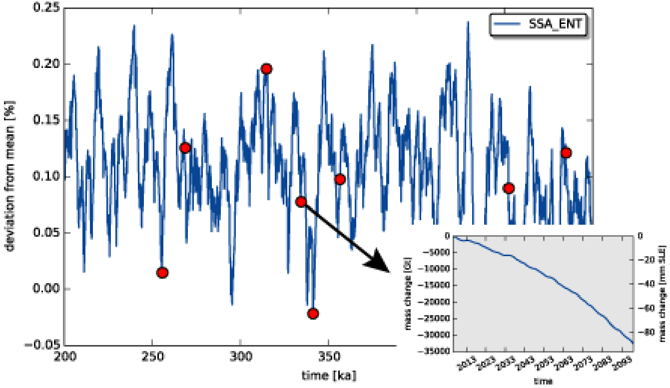
relative deviation from mean mass, $(m - \bar{m})/\bar{m}$, where $\bar{m}$ is the mean

Internal variability



- only less-complex simulations fullfill EISMINT steady-state criterion

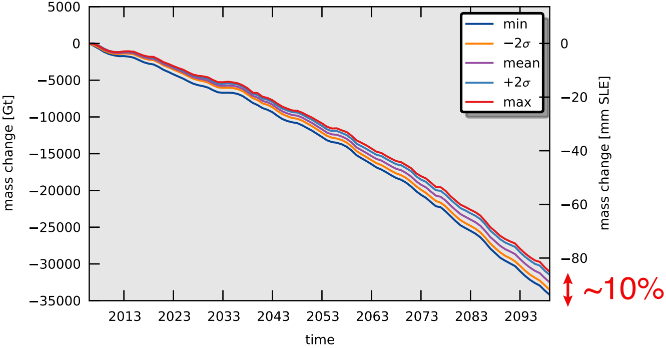
Sensitivty to initial state



1000 initial states randomly chosen between 250 and 500 ka

- make forecasts (2005-2098) from 1000 randomly chosen initial states

Forecast: ensemble



- projected mass loss ranges from 82–91 mm sea-level equivalent, a spread of about 10 % of the total mass change
- maximum uncertainty of 10 % from the initial state, all other things being equal

Food for thoughts

- is this variability real or a numerical artifact?
- all simulations are relatively simple
- variability increases with model complexity
- even very complex model are likely to undersample real variability
- could internal variability explain on/off behavior of ice streams?
- numerical simulations are challenging because of the mass of data produced (efficient data writing and analysis needed)