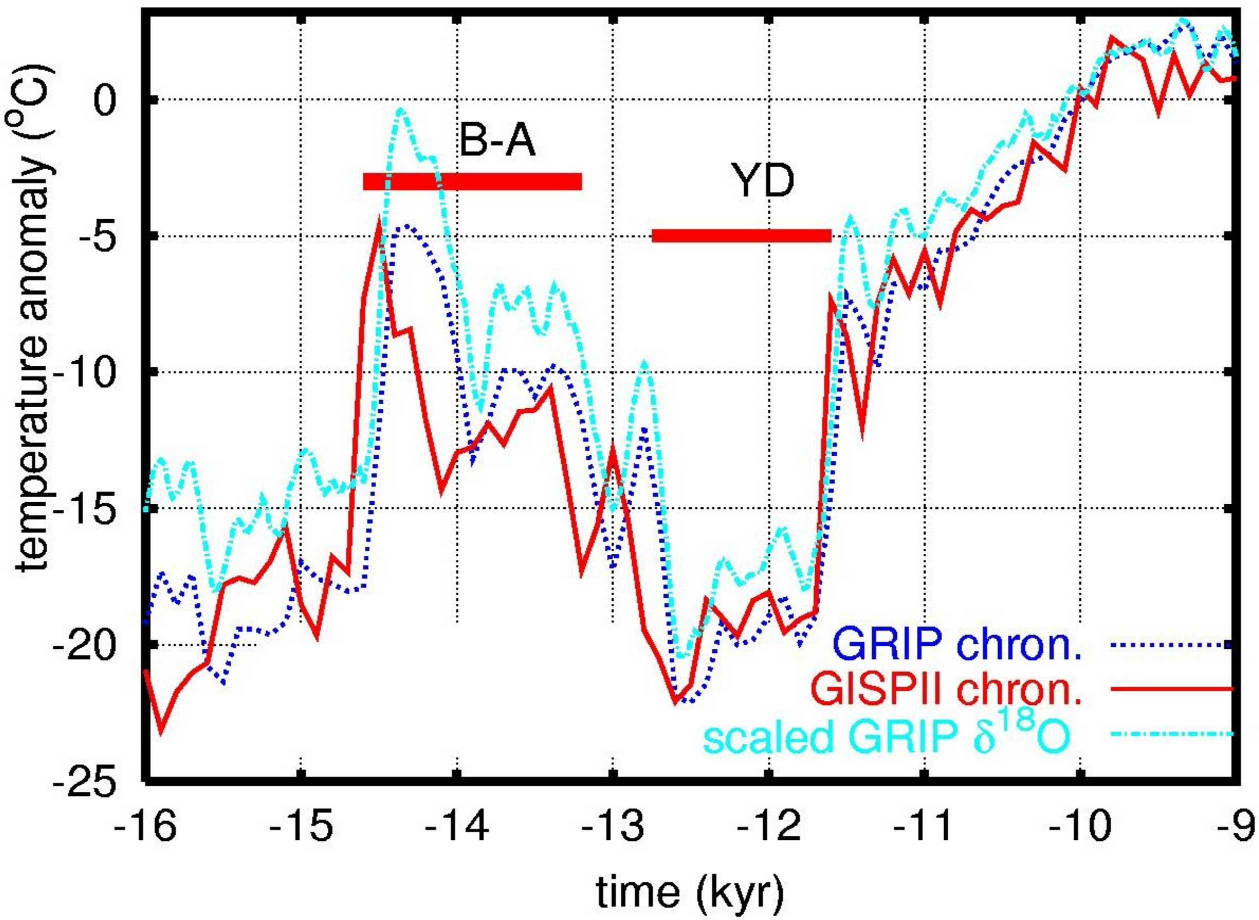
Bridging the data/model divide: calibration of a model of North American deglaciation in the context of understanding the Younger Dryas

Outline

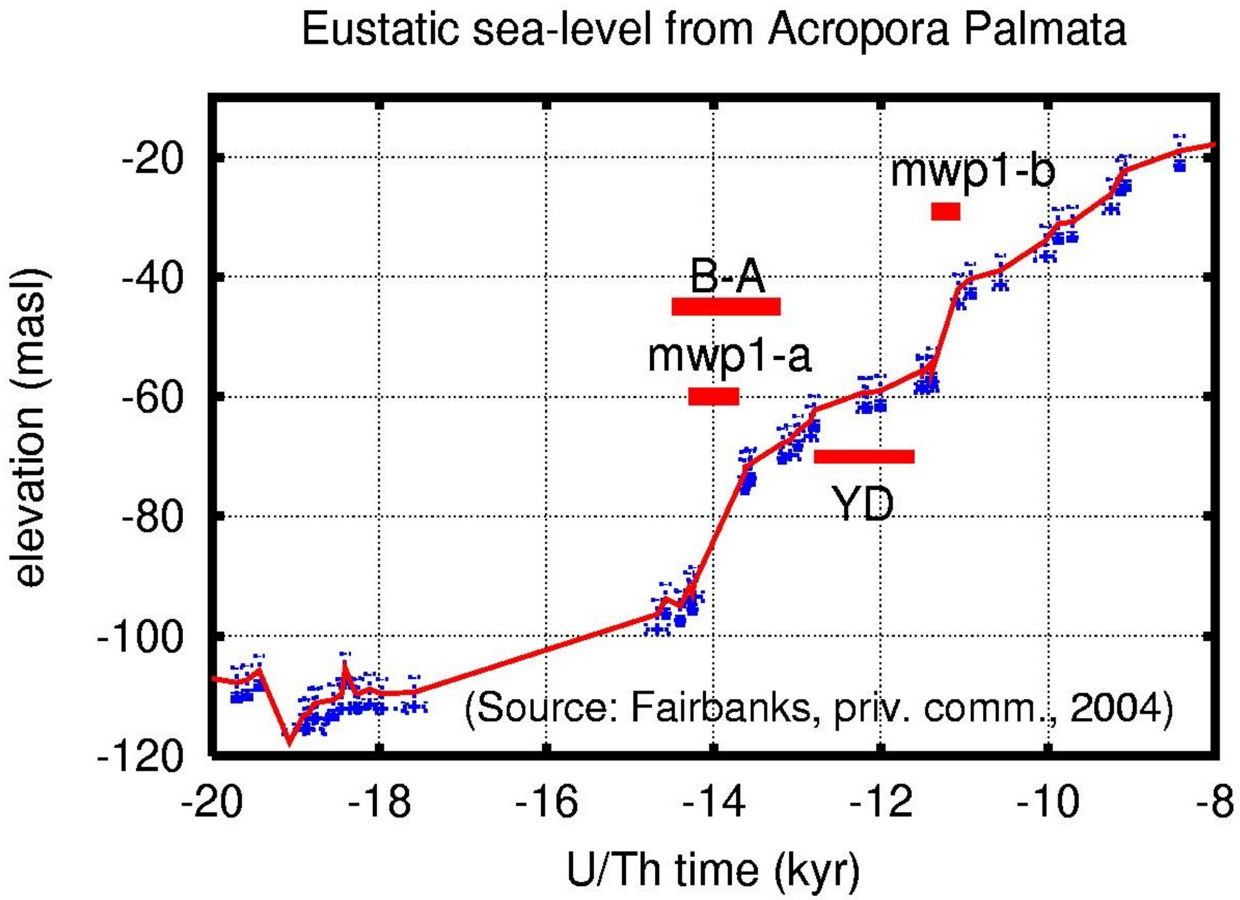
- motivation
- INSIGHT and VALIDATION: Glacial Systems Model (GSM) and model calibration
- ICE: A few general results
- THE CRITICAL LINK: Drainage results
- Implications for climate dynamics

Inferred Greenland temperature



(from Tarasov and Peltier, 2003)

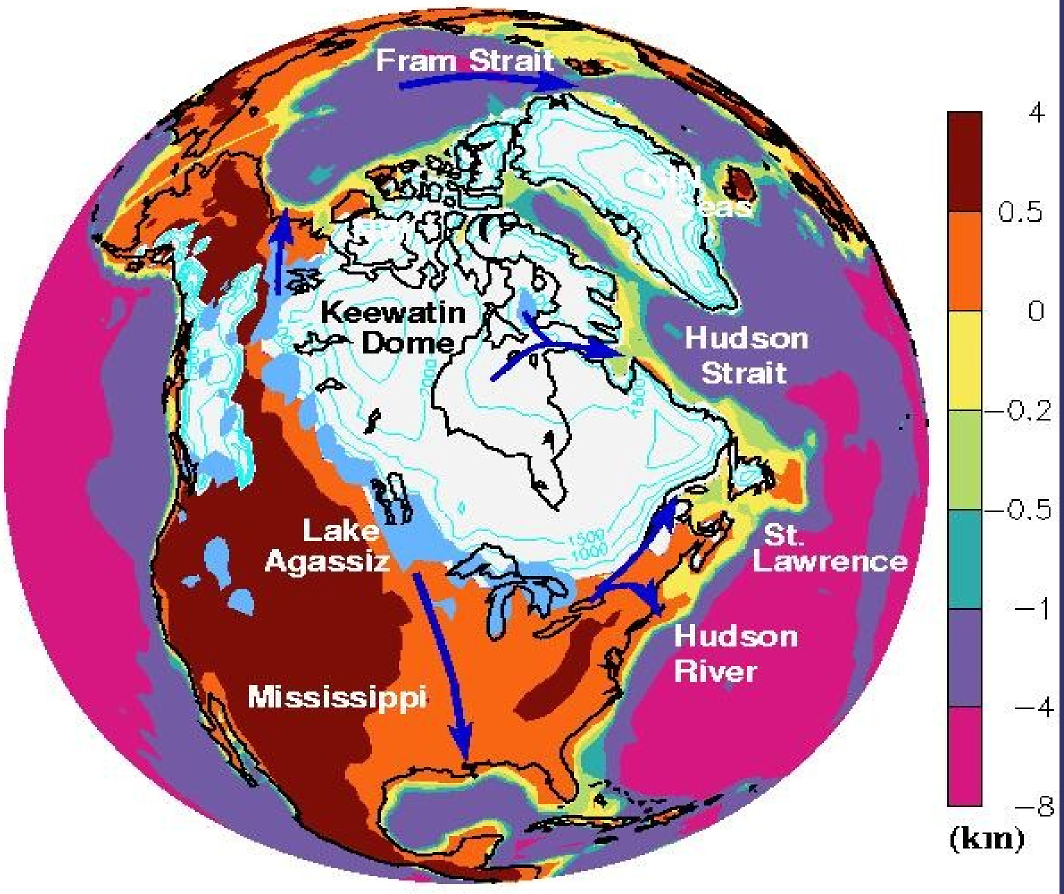
Barbados sea-level record



Some side issues: observations and physics

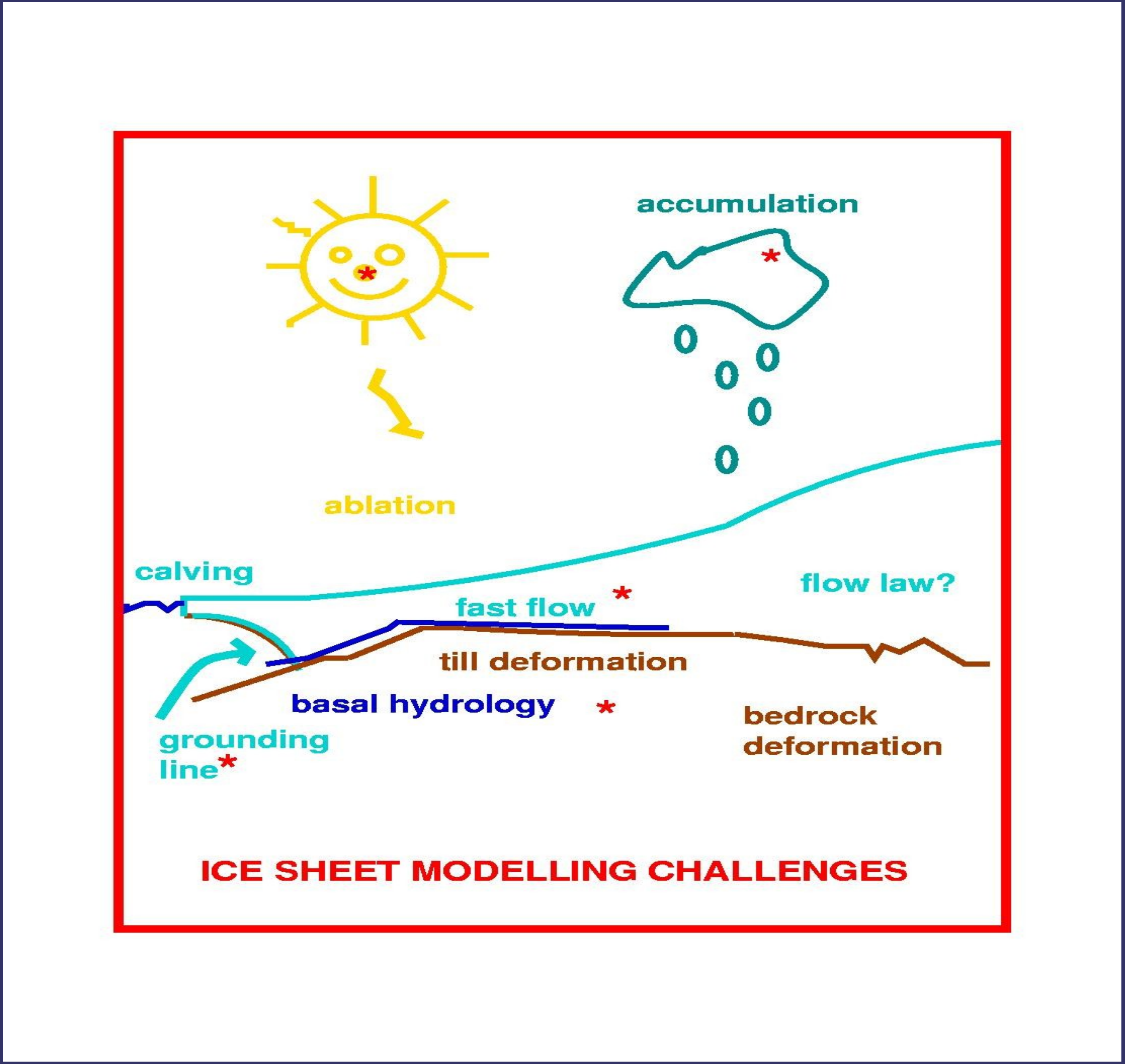
- High surface salinity for Gulf of St. Lawrence during YD (de Vernal et al., Nature,1996)
- Absence of floodway for eastern drainage of Lake Agassiz during YD onset (Lowell et al, EOS, 2005)
- Muddy water sinks: hyperpycnal plumes (Parsons et al., Sed., 2001; Aharon, EPSL, 2006)
- Baroclinic Gulf Stream

Deglacial drainage

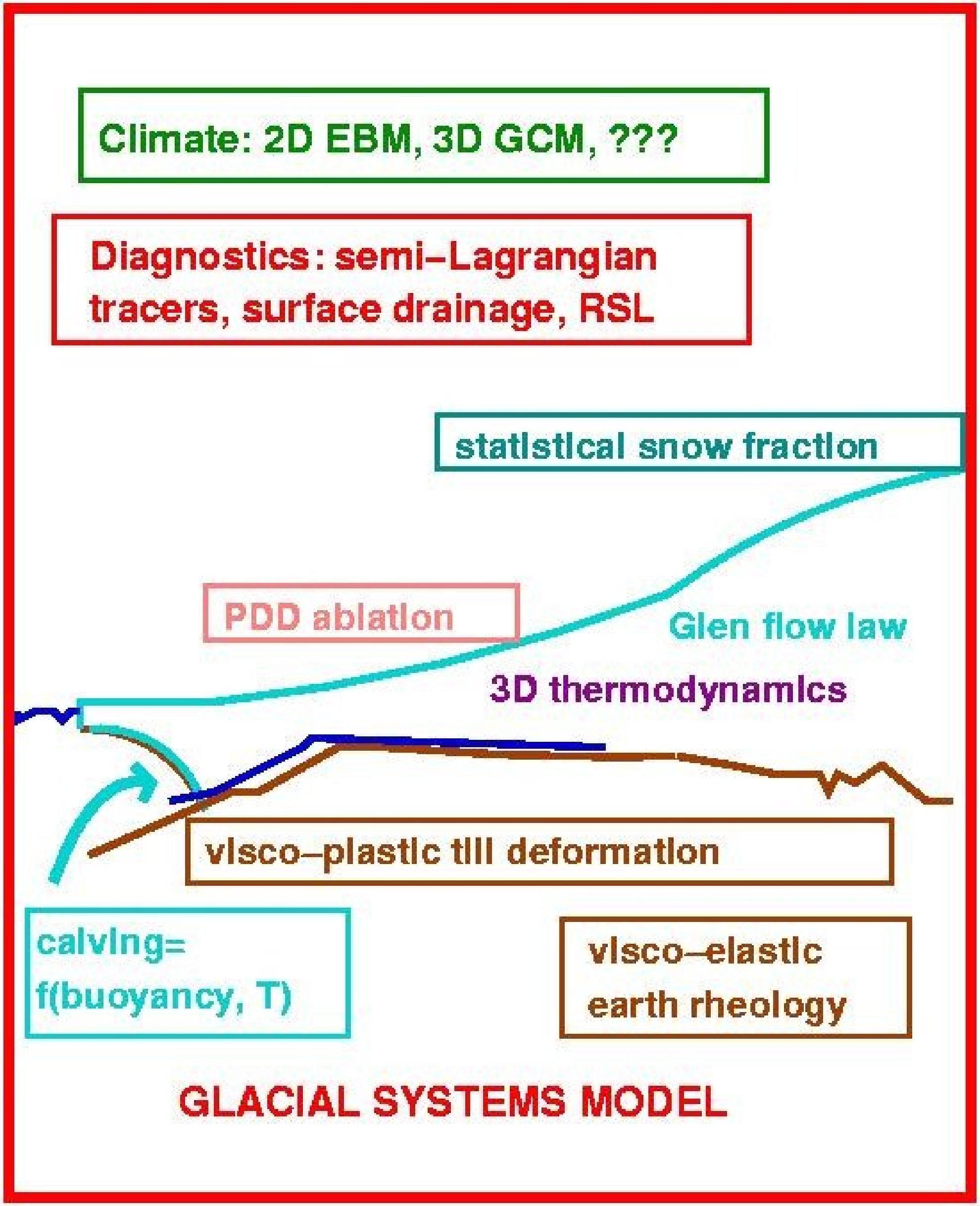


North American deglacial drainage

Glacial modelling challenges and issues



Glacial Systems Model (GSM)



Climate: 2D EBM, 3D GCM, ???

Diagnostics: semi–Lagrangian tracers, surface drainage, RSL

statistical snow fraction

PDD ablation

Glen flow law

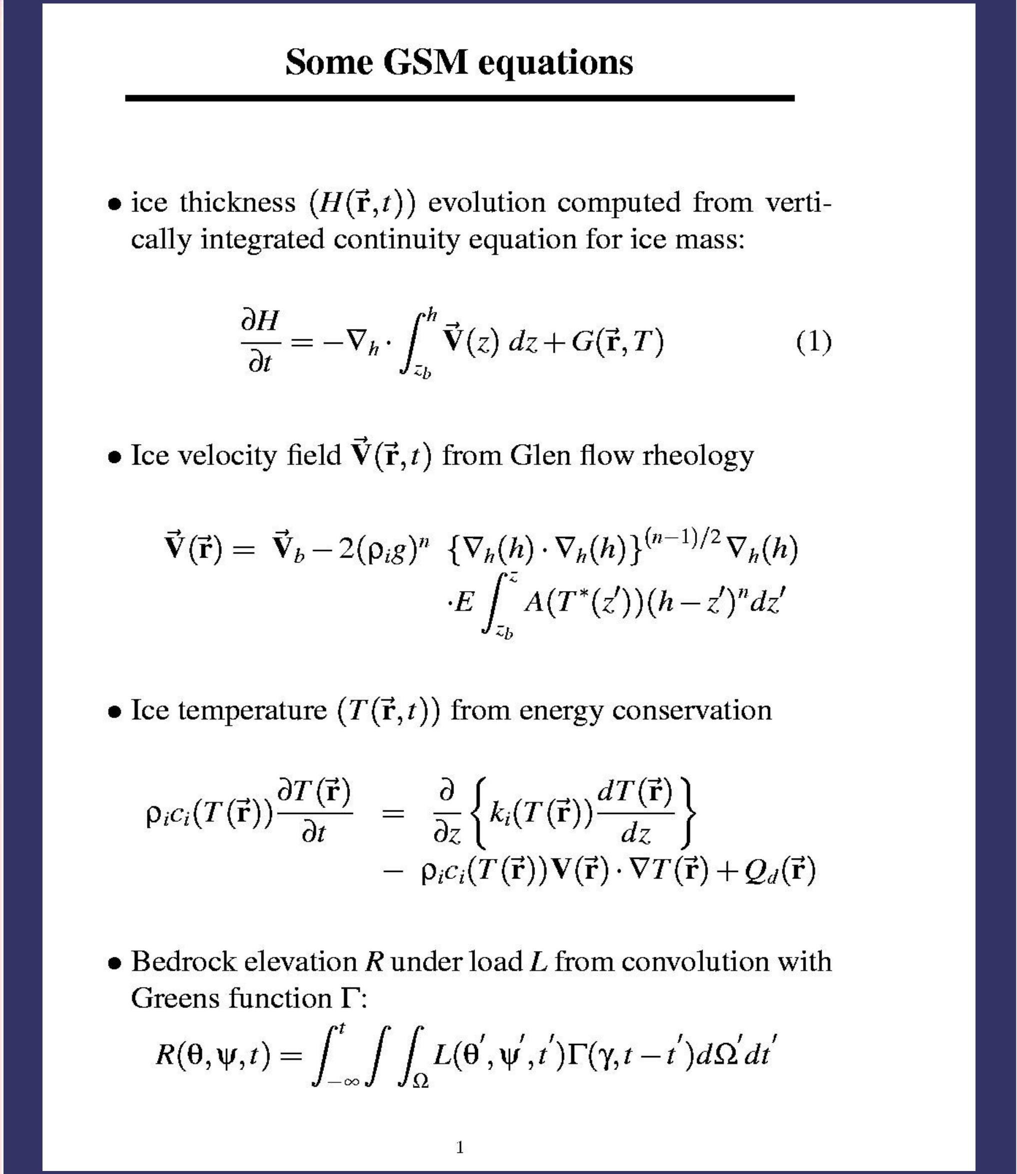
3D thermodynamics

visco–plastic till deformation

calving= f(buoyancy, T)

visco–elastic earth rheology

GLACIAL SYSTEMS MODEL



Some GSM equations

- ice thickness $(H(\vec{\mathbf{r}},t))$ evolution computed from vertically integrated continuity equation for ice mass:

$$\frac{\partial H}{\partial t} = -\nabla_h \cdot \int_{z_b}^{h} \vec{\mathbf{V}}(z)\, dz + G(\vec{\mathbf{r}},T) \qquad (1)$$

- Ice velocity field $\vec{\mathbf{V}}(\vec{\mathbf{r}},t)$ from Glen flow rheology

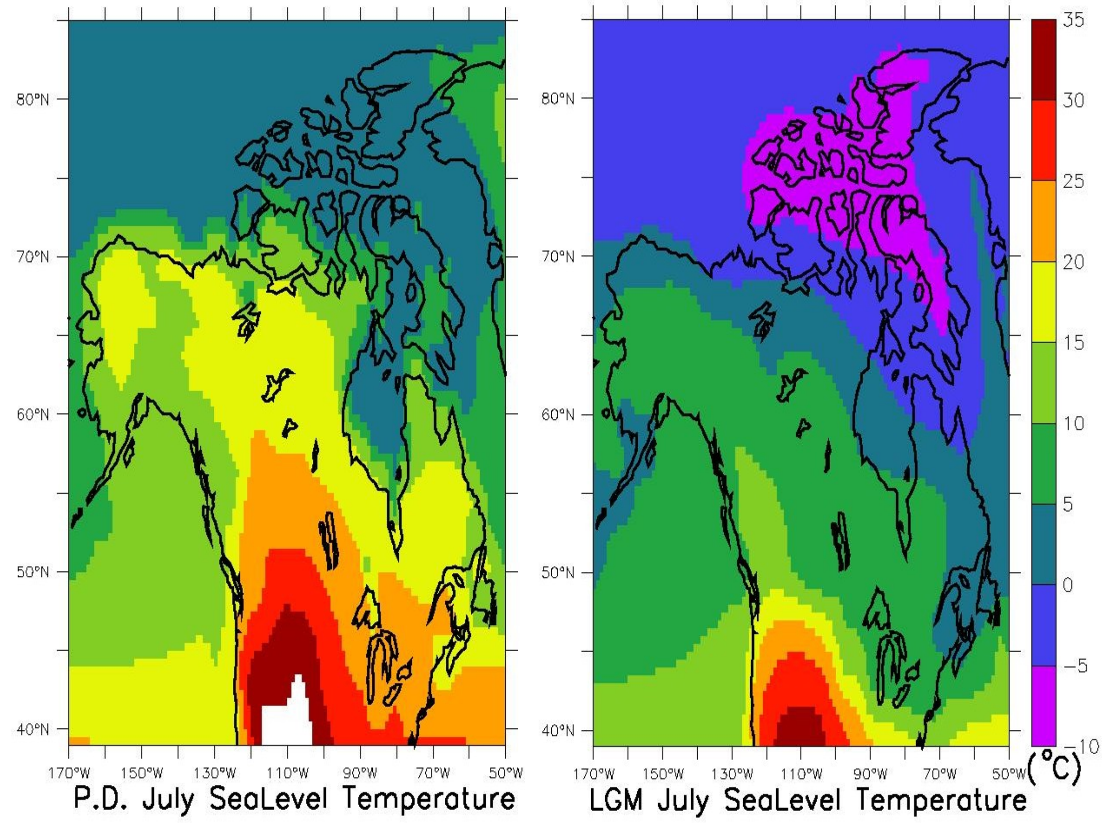
$$\begin{aligned}\vec{\mathbf{V}}(\vec{\mathbf{r}}) = {} & \vec{\mathbf{V}}_b - 2(\rho_i g)^n \ \{\nabla_h(h)\cdot\nabla_h(h)\}^{(n-1)/2}\nabla_h(h) \\ & \cdot E\int_{z_b}^{z} A(T^*(z'))(h-z')^n dz'\end{aligned}$$

- Ice temperature $(T(\vec{\mathbf{r}},t))$ from energy conservation

$$\begin{aligned}\rho_i c_i(T(\vec{\mathbf{r}}))\frac{\partial T(\vec{\mathbf{r}})}{\partial t} &= \frac{\partial}{\partial z}\left\{k_i(T(\vec{\mathbf{r}}))\frac{dT(\vec{\mathbf{r}})}{dz}\right\} \\ &- \rho_i c_i(T(\vec{\mathbf{r}}))\mathbf{V}(\vec{\mathbf{r}})\cdot\nabla T(\vec{\mathbf{r}}) + Q_d(\vec{\mathbf{r}})\end{aligned}$$

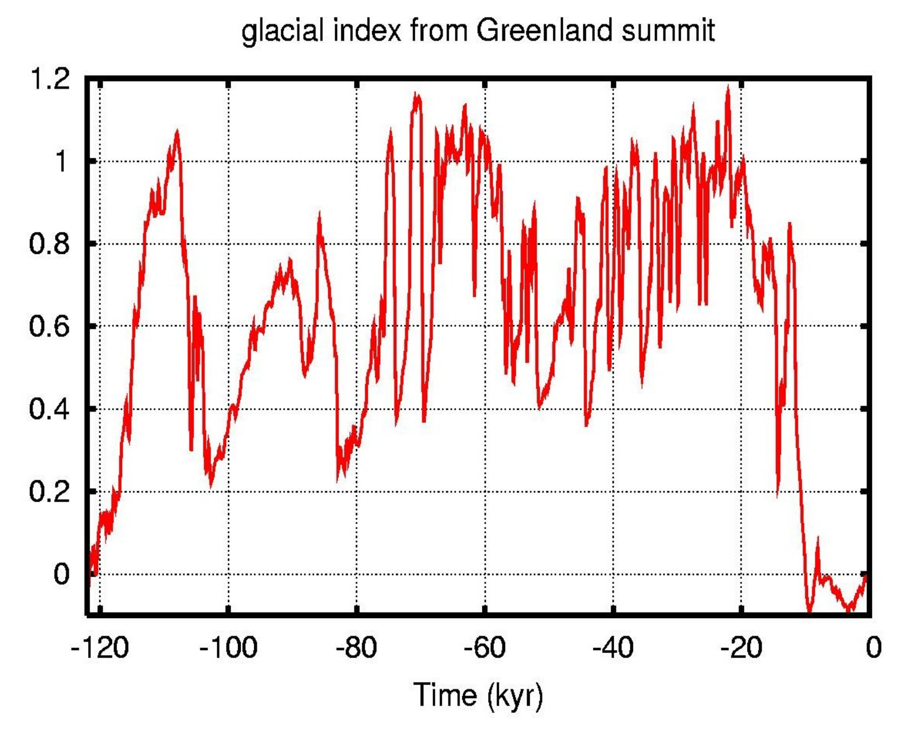
- Bedrock elevation R under load L from convolution with Greens function Γ:
$$R(\theta,\psi,t) = \int_{-\infty}^{t}\int\int_{\Omega} L(\theta',\psi',t')\Gamma(\gamma,t-t')d\Omega' dt'$$

Climate forcing



- Last Glacial Maximum (LGM) precipitation and temperature from 6 highest resolution Paleo Model Intercomparison Project GCM runs
  - Mean and EOF fields
- Present day observed fields

Climate forcing time-dependence



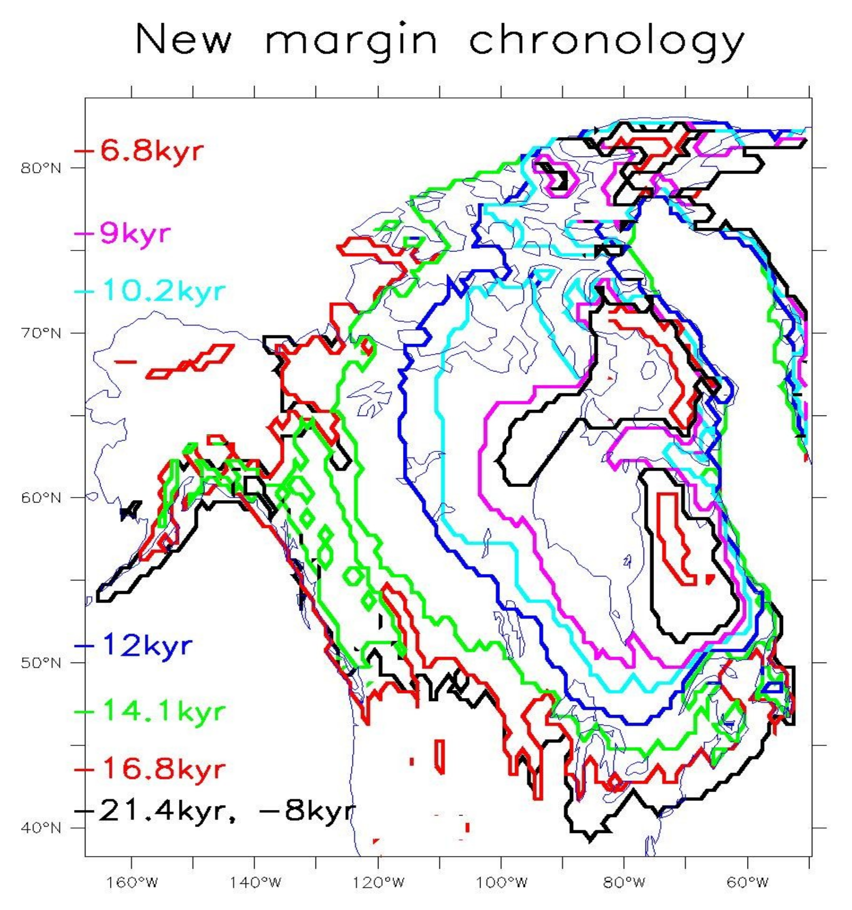
- glacial index weights interpolation between present-day climatology and LGM PMIP fields
- 4 ensemble parameters control temperature specification
- 16 ensemble parameters control precipitation

Lots of ensemble parameters

- 5 ice dynamical
- 16 regional precipitation
  - LGM precipitation EOFs most significant !
- 4 ice calving
- 4 temperature
- 2 ice margins
- = 31

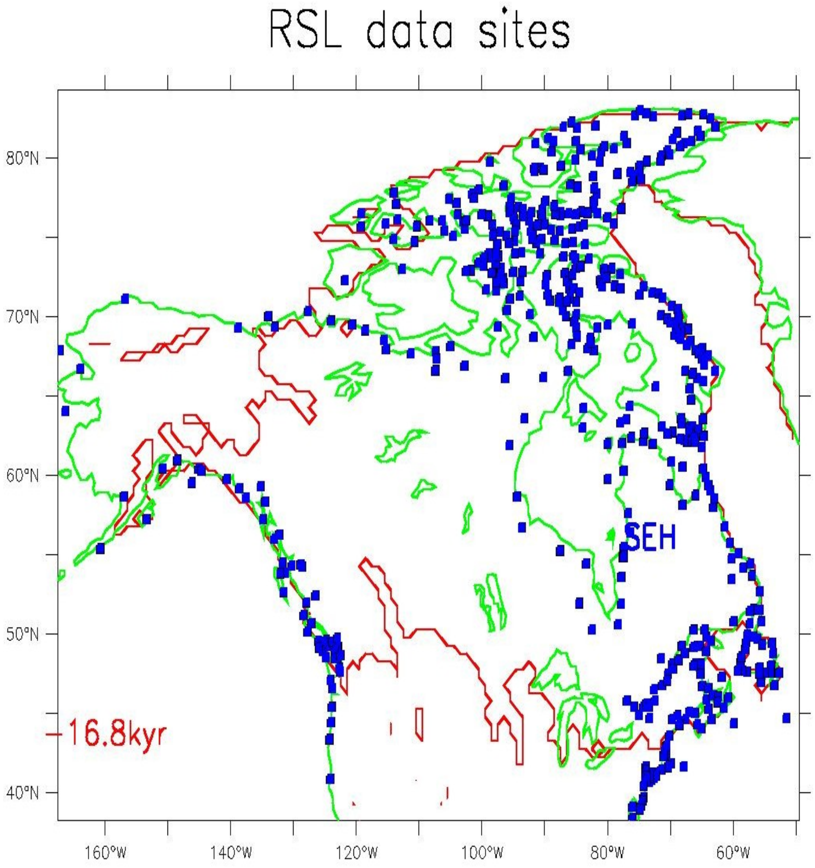
Need constraints -> DATA

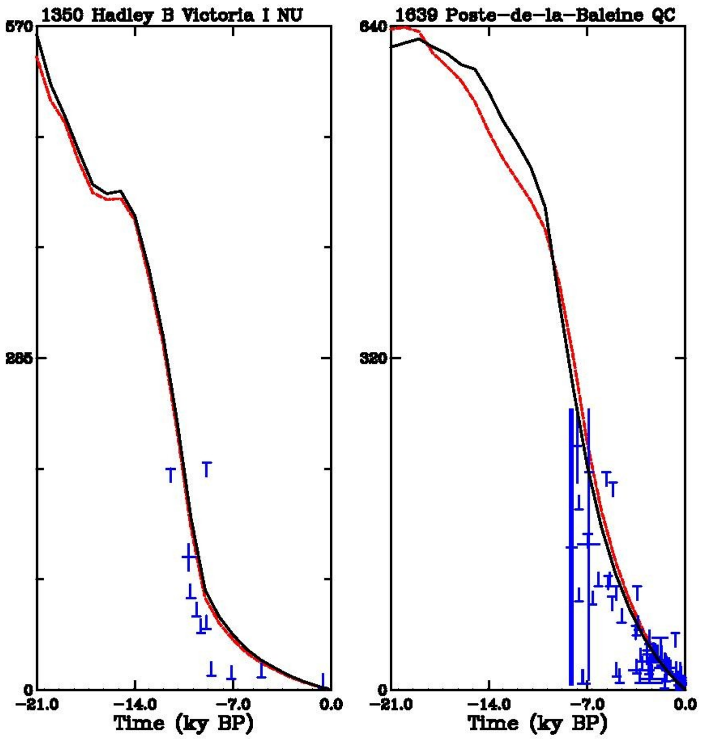
Deglacial margin chronology



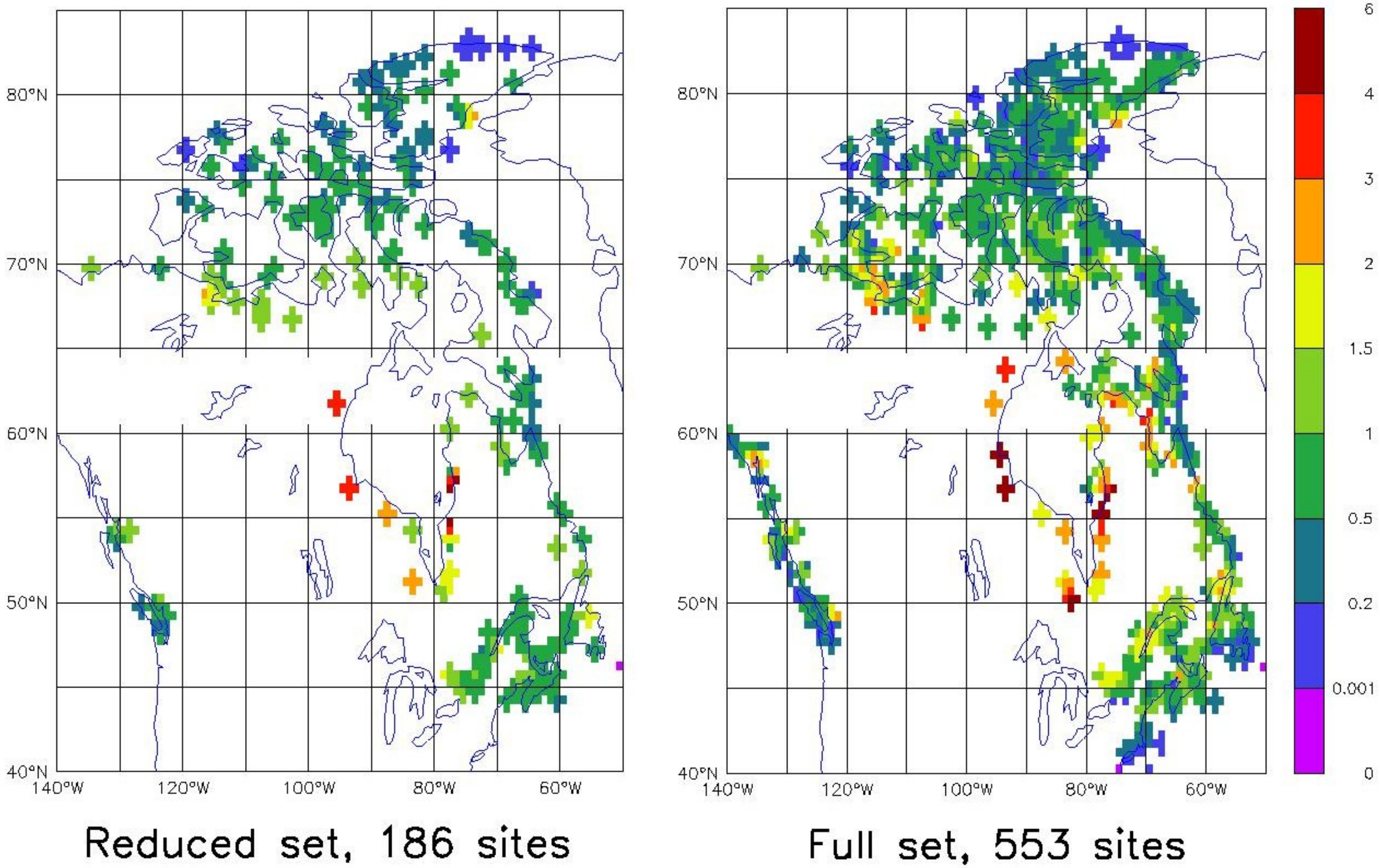
- (Dyke, 2003)
- 36 time-slices
- +/- 50 km uncertainty
- Margin buffer
- 2 ensemble parameters

Relative sea-level (RSL) data





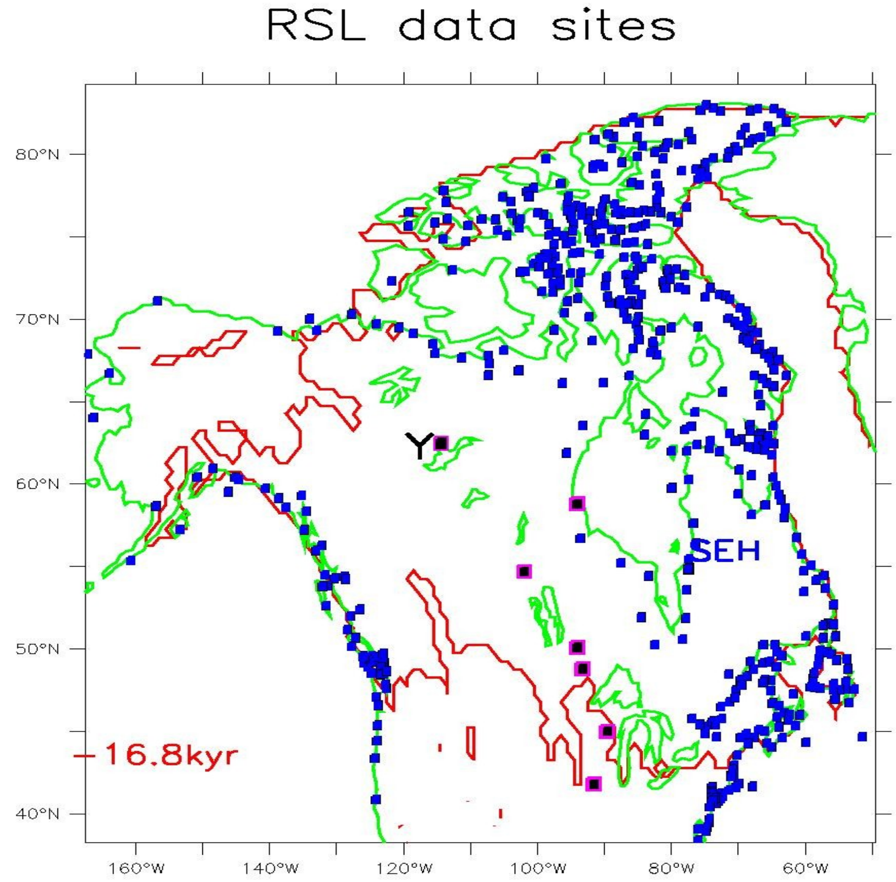
RSL site weighting

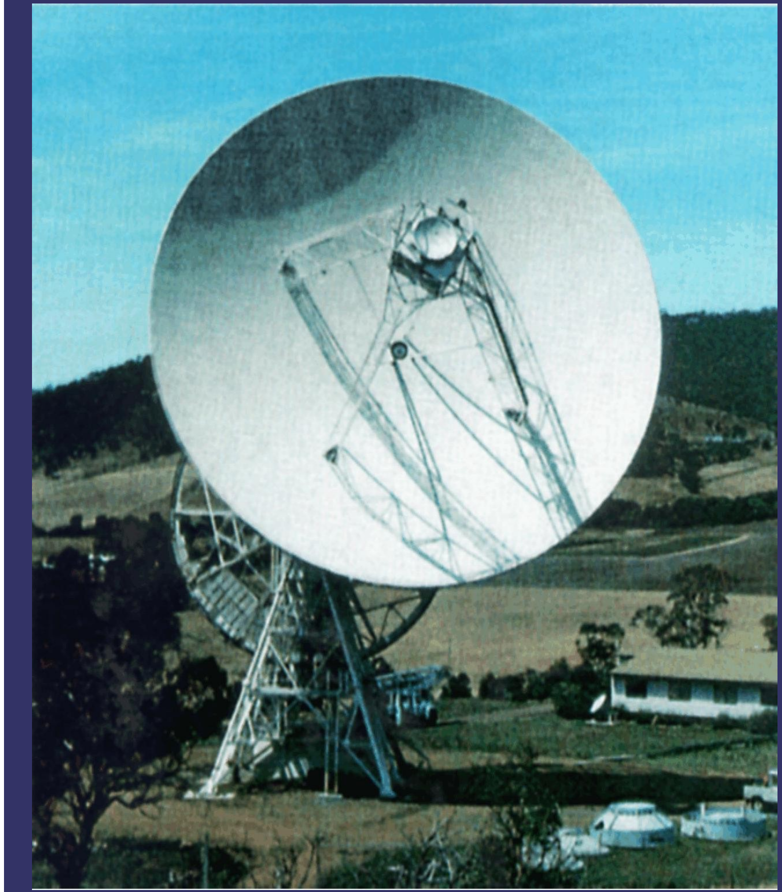


Reduced set, 186 sites

Full set, 553 sites

VLBI and absolute gravity data





Noisy data and non-linear system !!!!

Noisy data and non-linear system =>

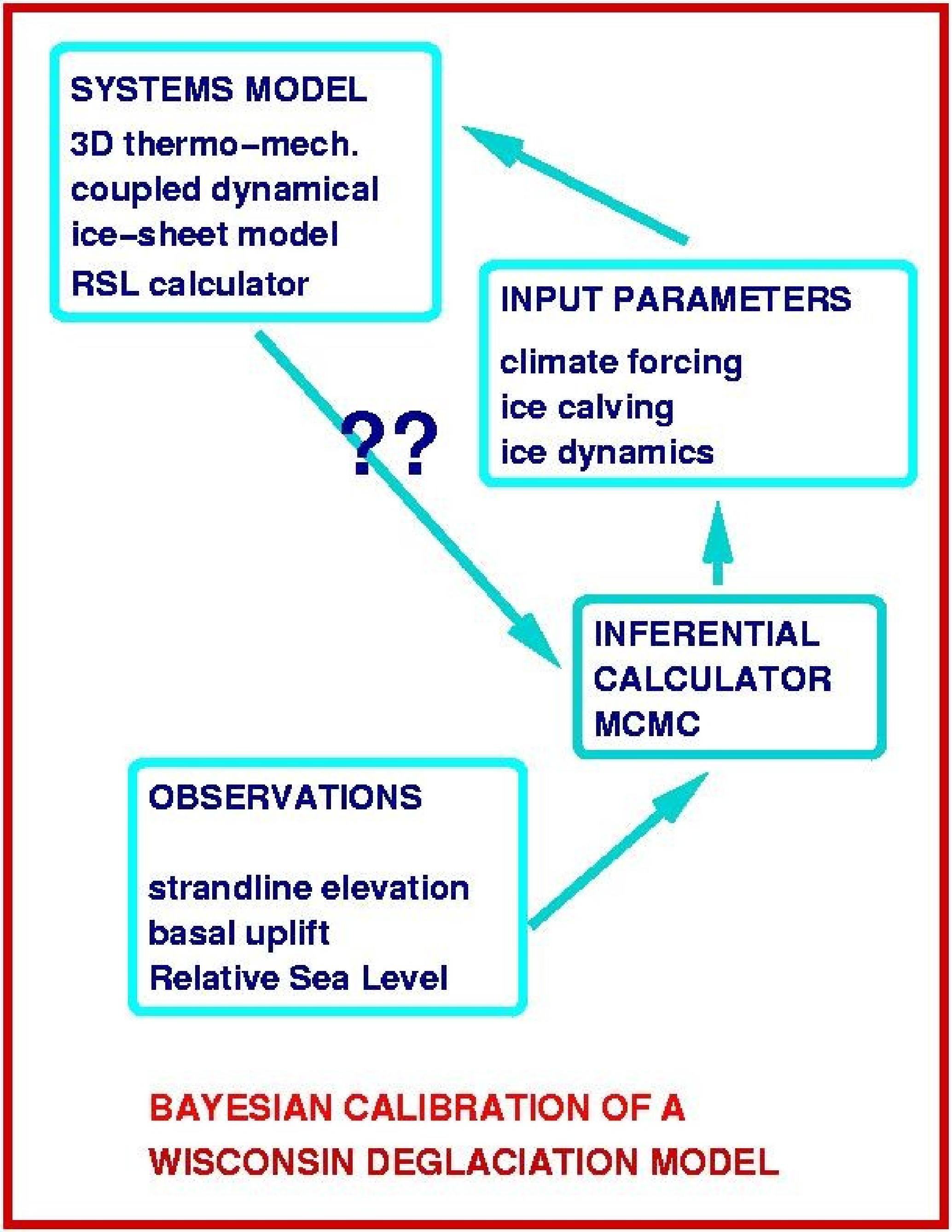
=> need calibration and error bars

Criteria for calibration methodology

- Complicated under-constrained non-linear system with threshold behavior
  - effectively large number of poorly constrained model parameters
- Large set of diverse noisy constraint data
- bumpy phase and likelihood spaces (shown below) further rule out gradient-based approaches such as adjoint (eg. 4D var) methods

- SUGGESTS : a stochastic methodology
- accurate propagation of data uncertainties -> Bayesian approach
- => Markov Chain Monte Carlo

Bayesian calibration



SYSTEMS MODEL

3D thermo–mech.
coupled dynamical
ice–sheet model
RSL calculator

??

INPUT PARAMETERS

climate forcing
ice calving
ice dynamics

INFERENTIAL
CALCULATOR
MCMC

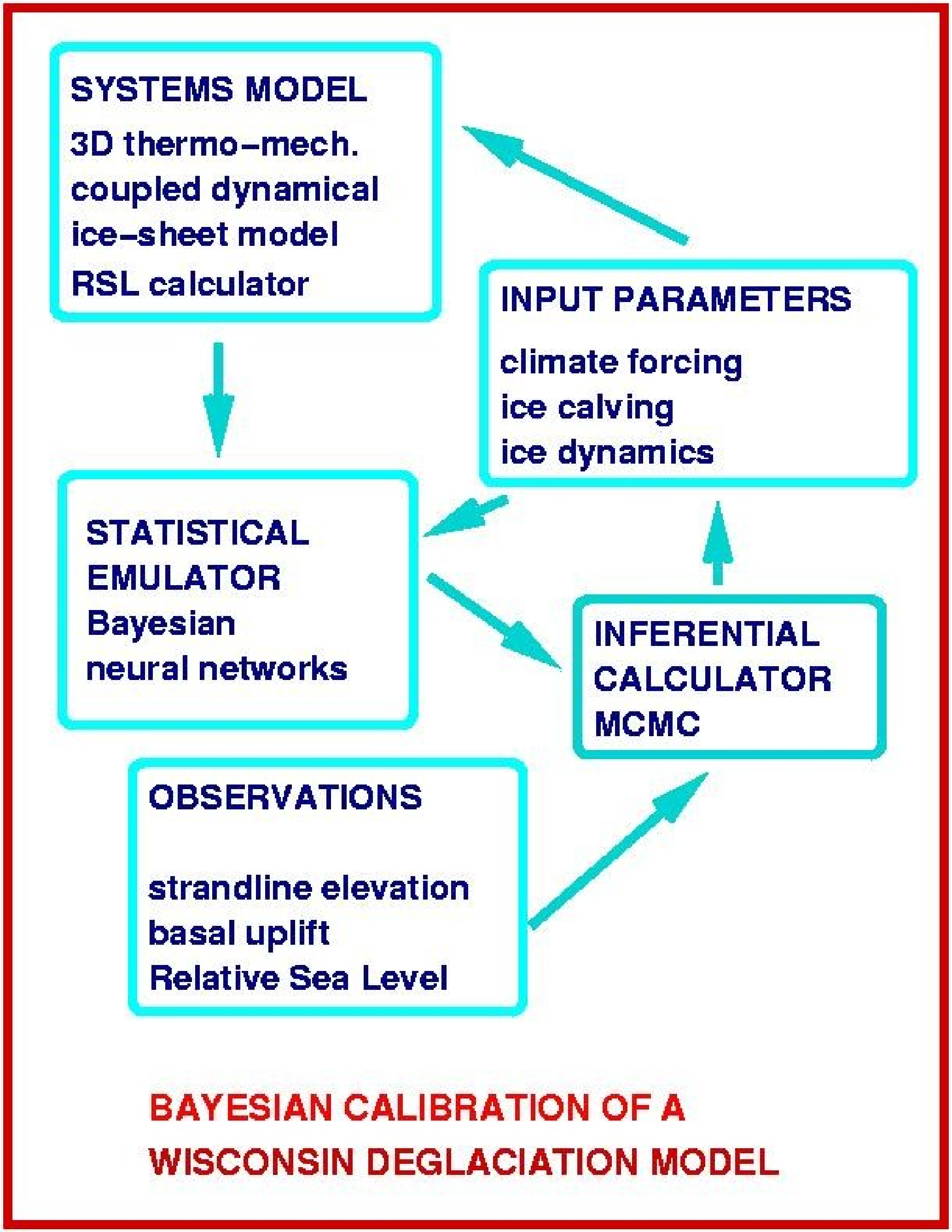
OBSERVATIONS

strandline elevation
basal uplift
Relative Sea Level

BAYESIAN CALIBRATION OF A
WISCONSIN DEGLACIATION MODEL

- Sample over posterior probability distribution for the ensemble parameters given fits to observational data using Markov Chain Monte Carlo (MCMC) methods
- Other constraints:
  - Minimal margin forcing at LGM
  - LGM/-30kyr/-49kyr ice volume bounds
  - mwp1-a magnitude
  - Hudson Bay glaciated at -25kyr

Large ensemble Bayesian calibration



SYSTEMS MODEL
3D thermo–mech.
coupled dynamical
ice–sheet model
RSL calculator

INPUT PARAMETERS
climate forcing
ice calving
ice dynamics

STATISTICAL
EMULATOR
Bayesian
neural networks

INFERENTIAL
CALCULATOR
MCMC

OBSERVATIONS
strandline elevation
basal uplift
Relative Sea Level

BAYESIAN CALIBRATION OF A
WISCONSIN DEGLACIATION MODEL

- Bayesian neural network integrates over weight space
  - Self-regularized
  - Can handle local minima

Calibration details

- The expectation of the posterior distribution of possible models (GSM) given constraint data set D is given by:

$$
\begin{aligned}
< GSM|D > &= \int GSM(y)P(y|D)dy \\
&= \int GSM(y)P(D|y)Z^{-1}P(y)dy \quad ,
\end{aligned}
$$

  where $P(y)$ is the prior probability distribution for the ensemble parameter vector y. The normalization constant Z is a function only of D and is therefore ignored.

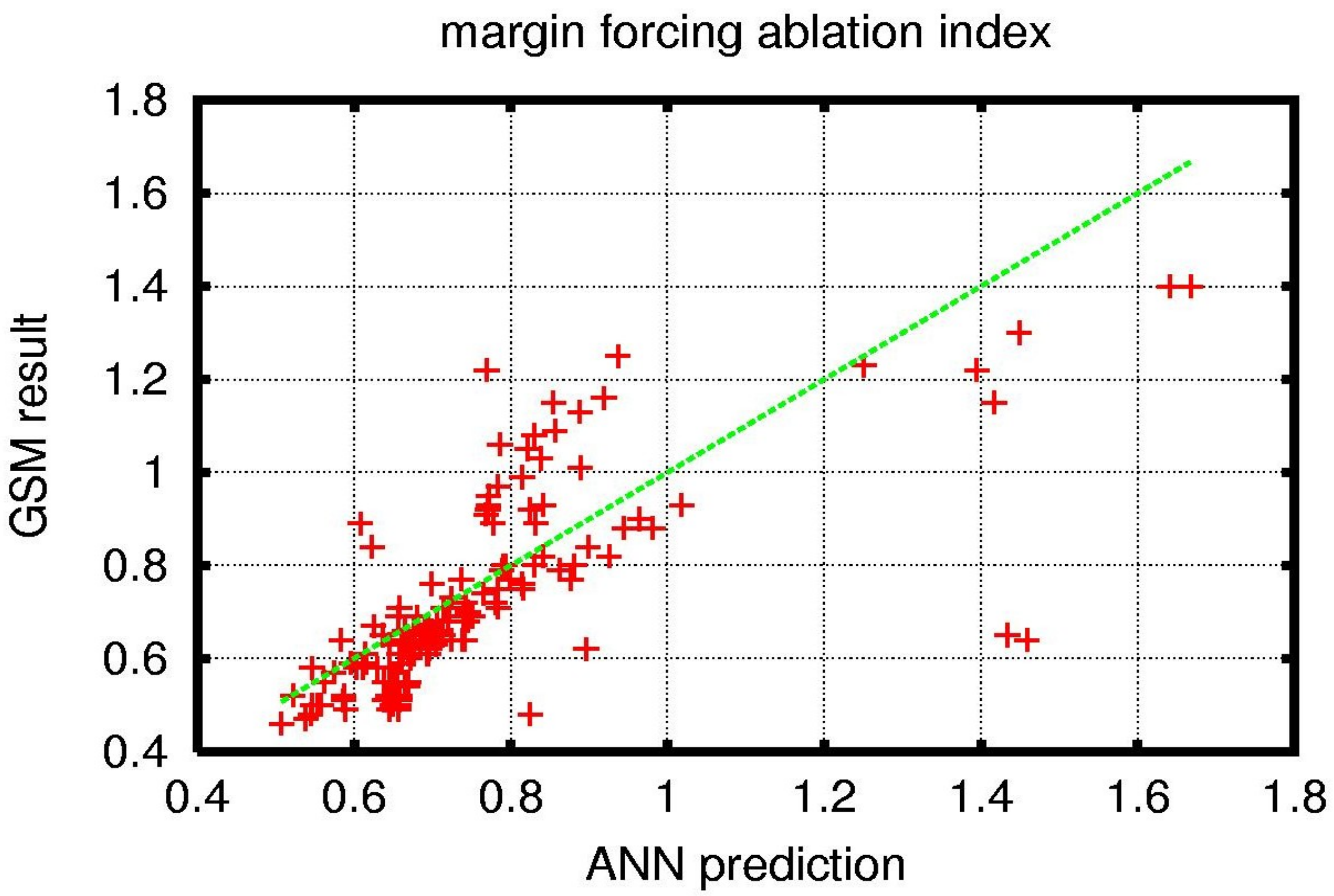
- In MCMC sampling, this becomes

$$
< GSM|D > \simeq N^{-1} \sum_{MCMC(P(y),P(D|y))} GSM(y) \quad ,
$$

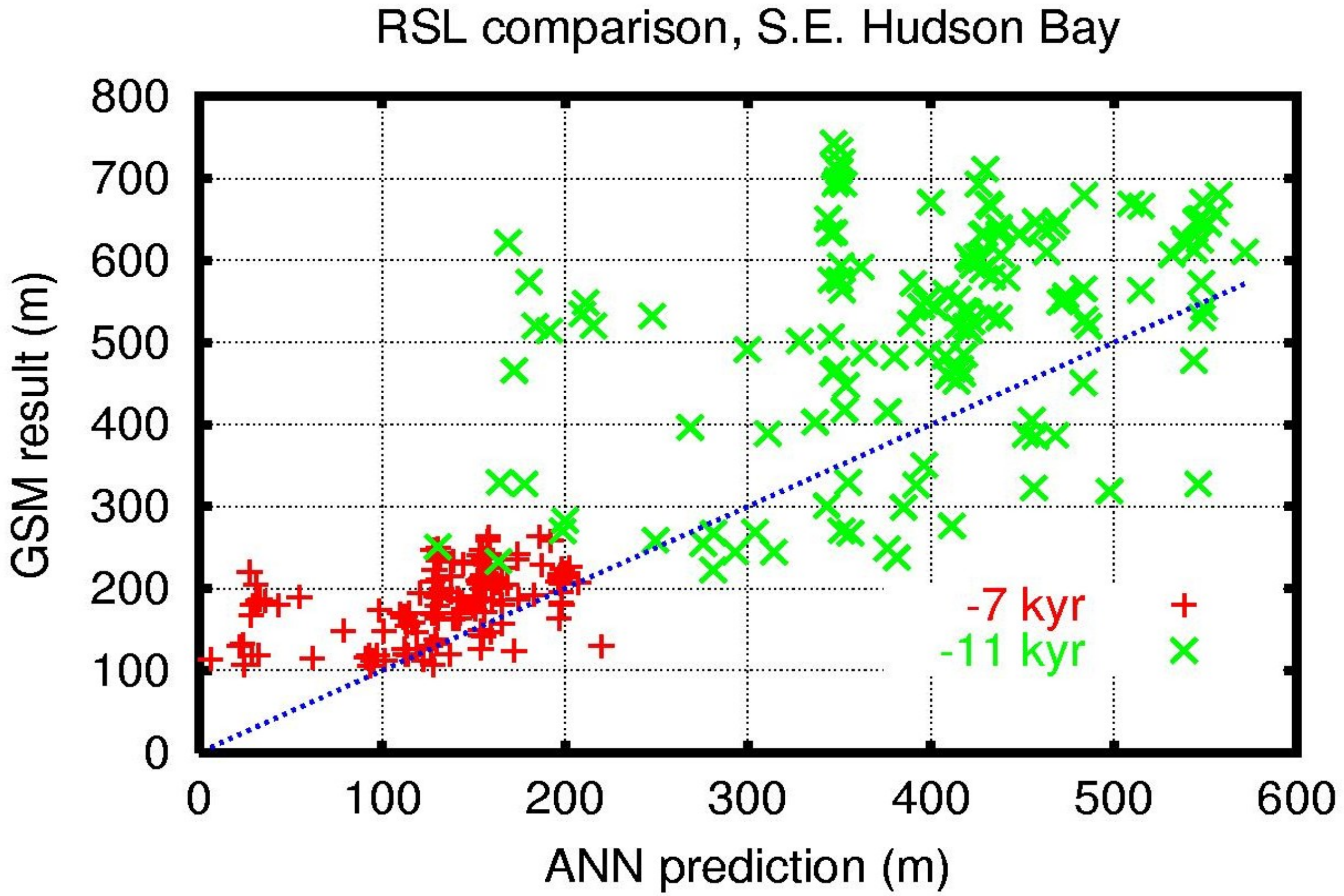
  for N samples. However, given that $P(D|y)_{\text{networks}}$ employed in the MCMC sampling is not entirely accurate, and given that further observations (DML) are used to score the final results, use:

$$
\begin{aligned}
< GSM|D > \simeq N^{-1} \sum_{y(MCMC)} \{ & GSM(y) \\
& \cdot \; P(DML|y)_{\text{GSM}} P(D|y)_{\text{GSM}} / P(D|y)_{\text{networks}} \}
\end{aligned}
$$

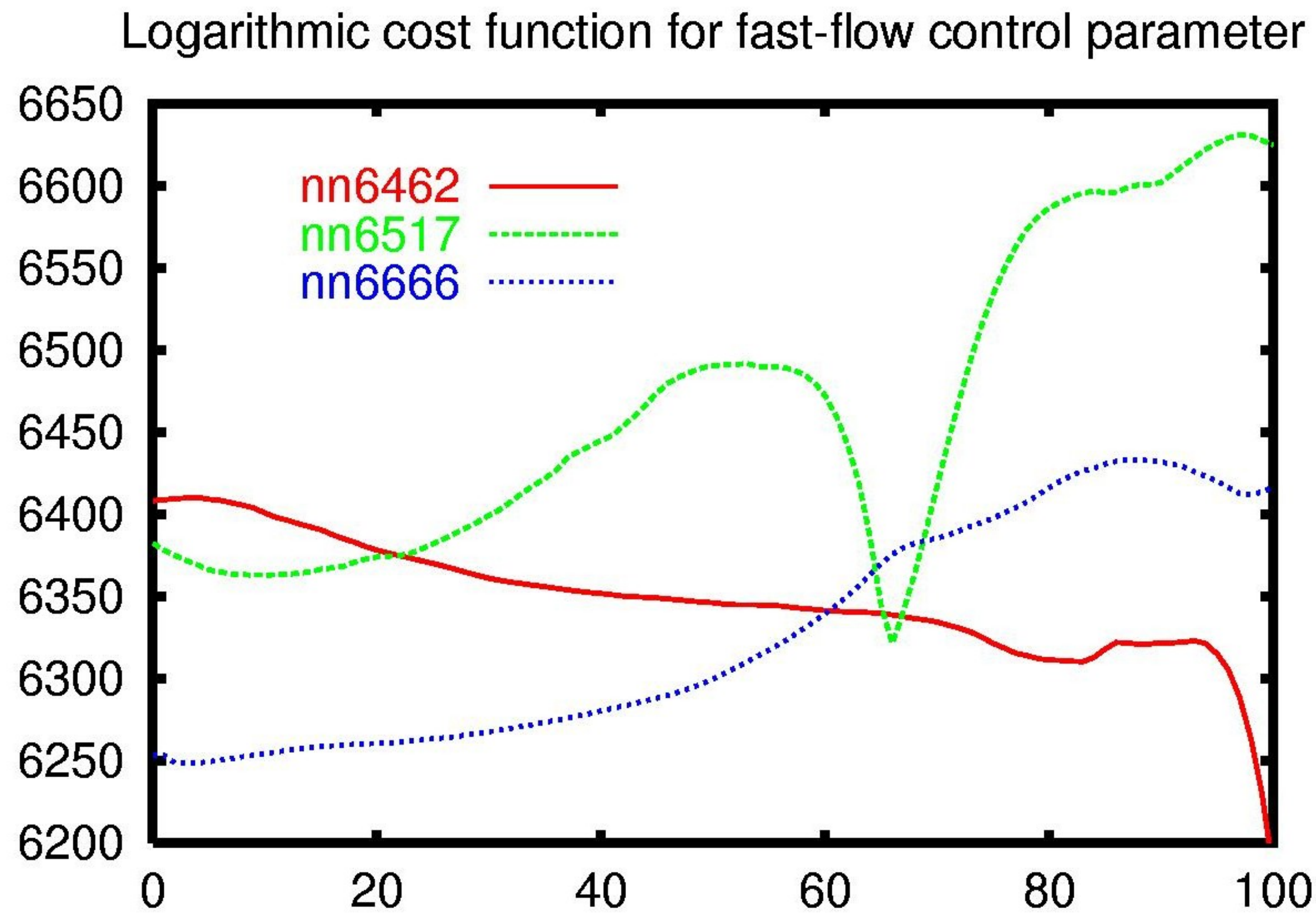
ANN versus GSM : forcing index



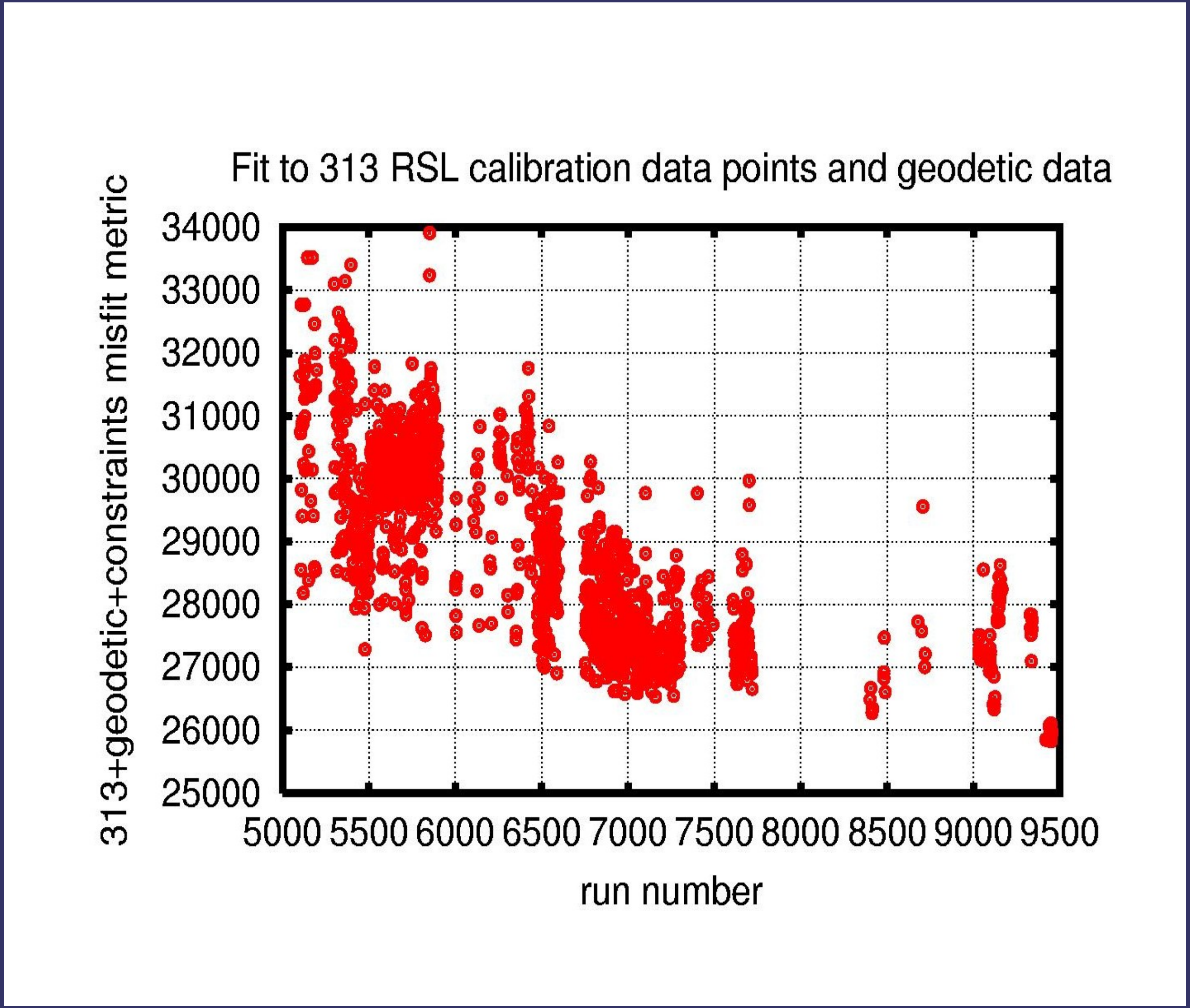
ANN versus GSM : RSL



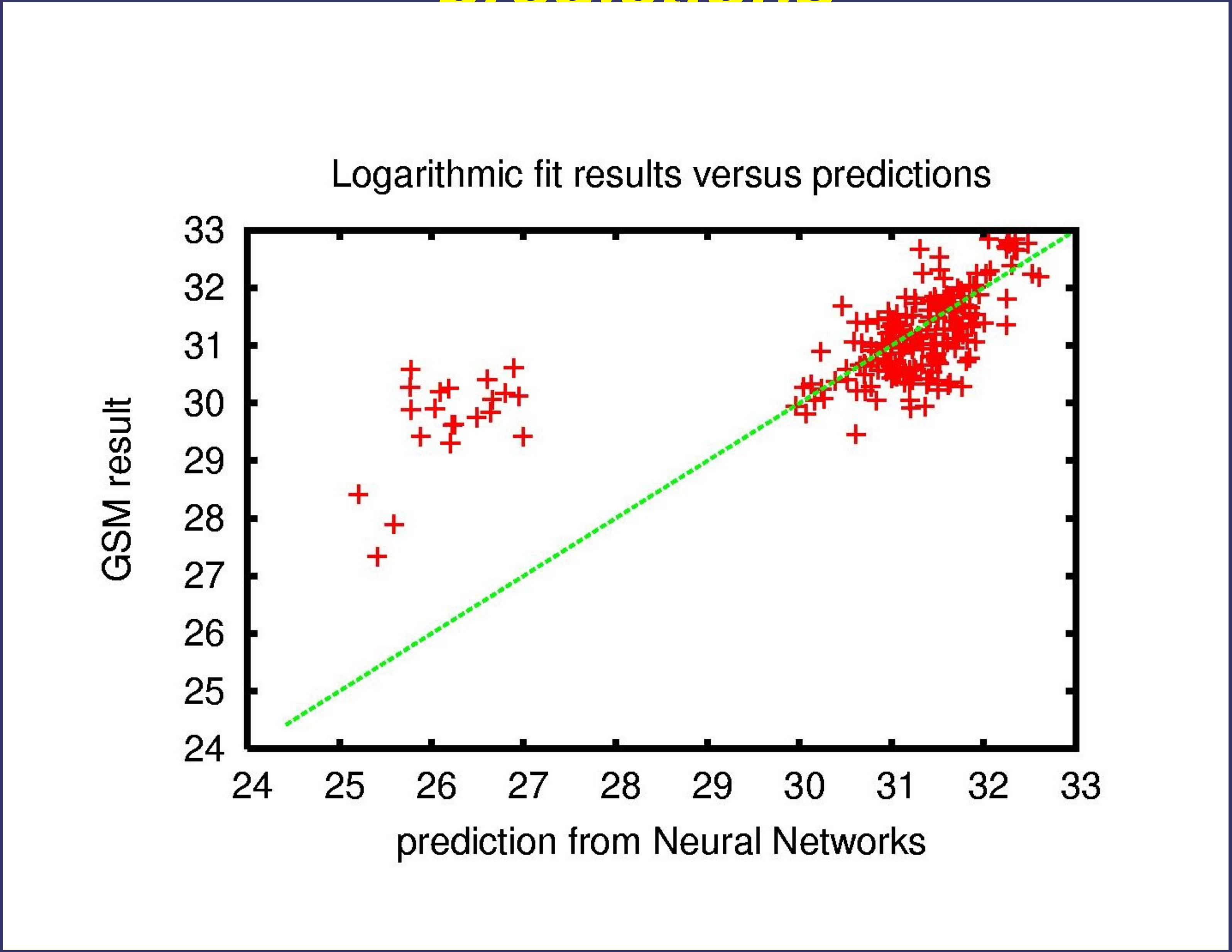
Complexity of parameter space



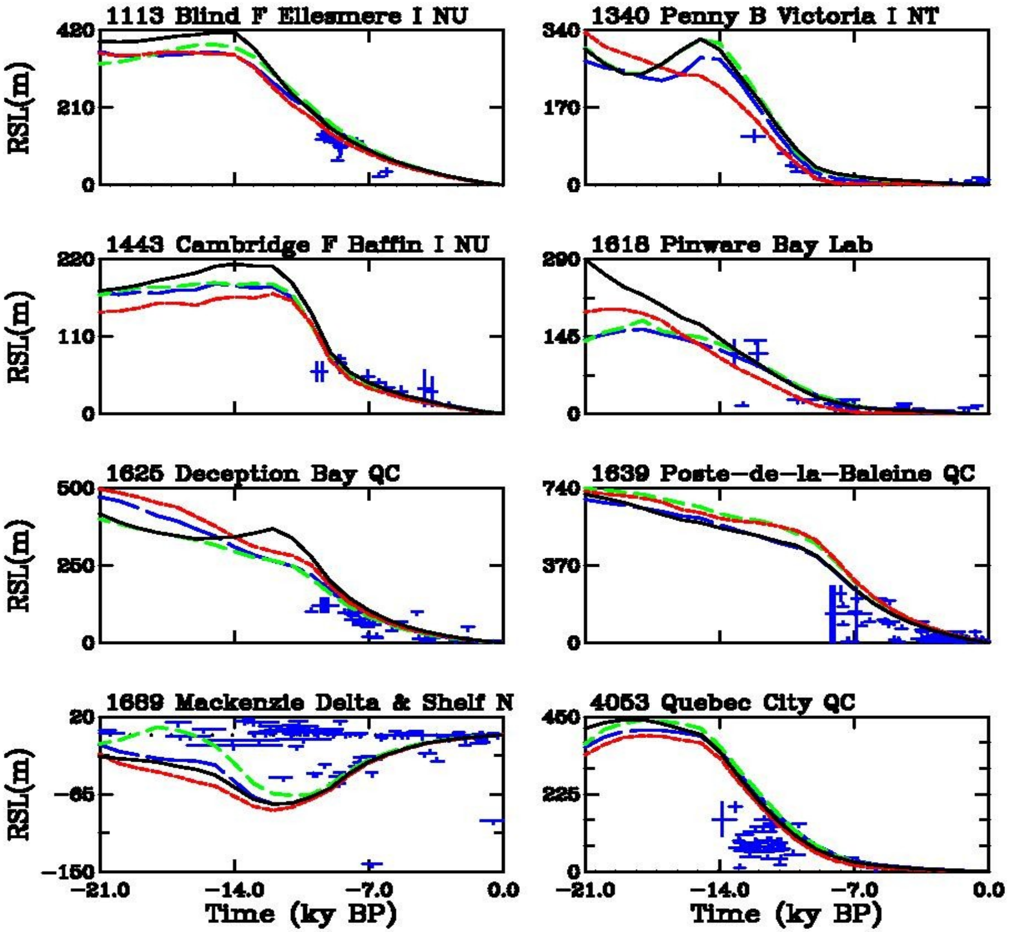
It works!


Fit to 313 RSL calibration data points and geodetic data
313+geodetic+constraints misfit metric
34000
33000
32000
31000
30000
29000
28000
27000
26000
25000
5000
5500
6000
6500
7000
7500
8000
8500
9000
9500
run number

GSM versus neural network fit predictions



RSL results, some best fit models

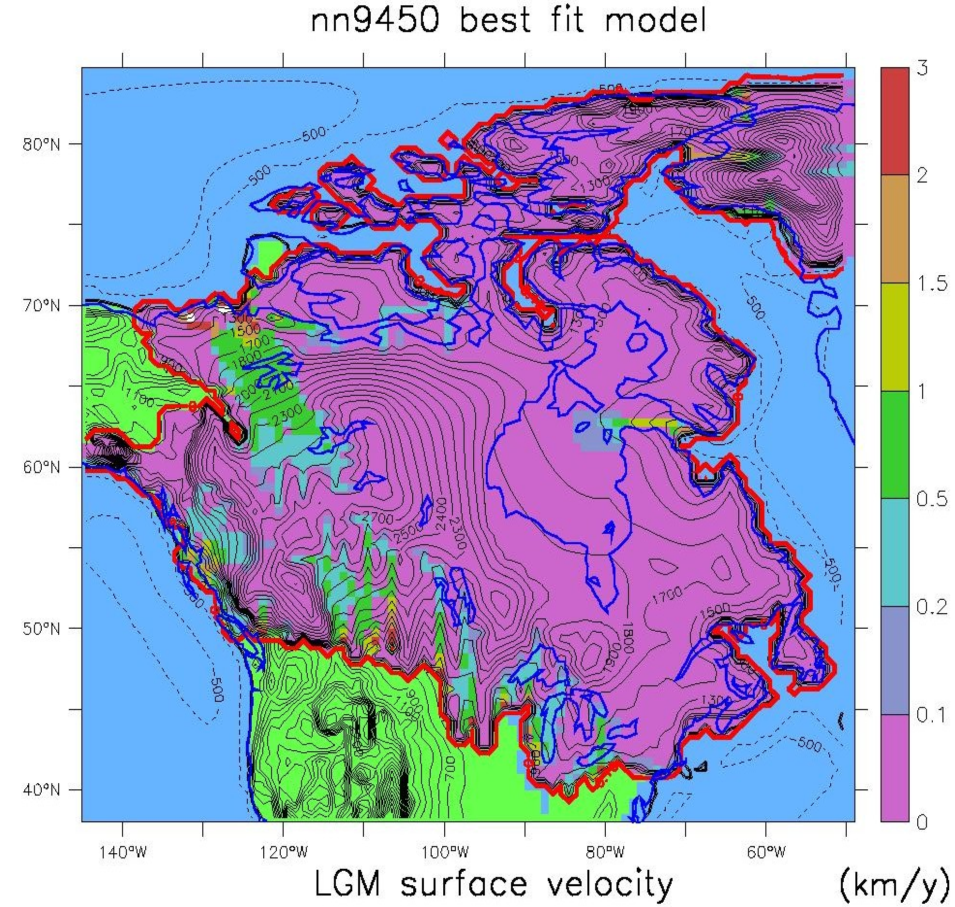


Issues and challenges

- Choice of ensemble parameters
  - Parameter set ended up being extended with time as troublesome regions were identified
  - Challenge of identifying appropriate priors for each parameter
- Error model for RSL data
  - Noisy and likely site biased
  - Heavy-tailed error model to limit influence of outliers
- Neural network
  - Non-trivial to find appropriate configuration
  - Neural network for RSL was most complex: multi-layered and separate clusters for site location and time
  - Training takes a long time, predictions can be weak for distant regions -> move to spatially sectored RSL networks
- MCMC sampling
  - Can get stuck in local minima
  - “Unphysical” solutions cropped up => added constraints

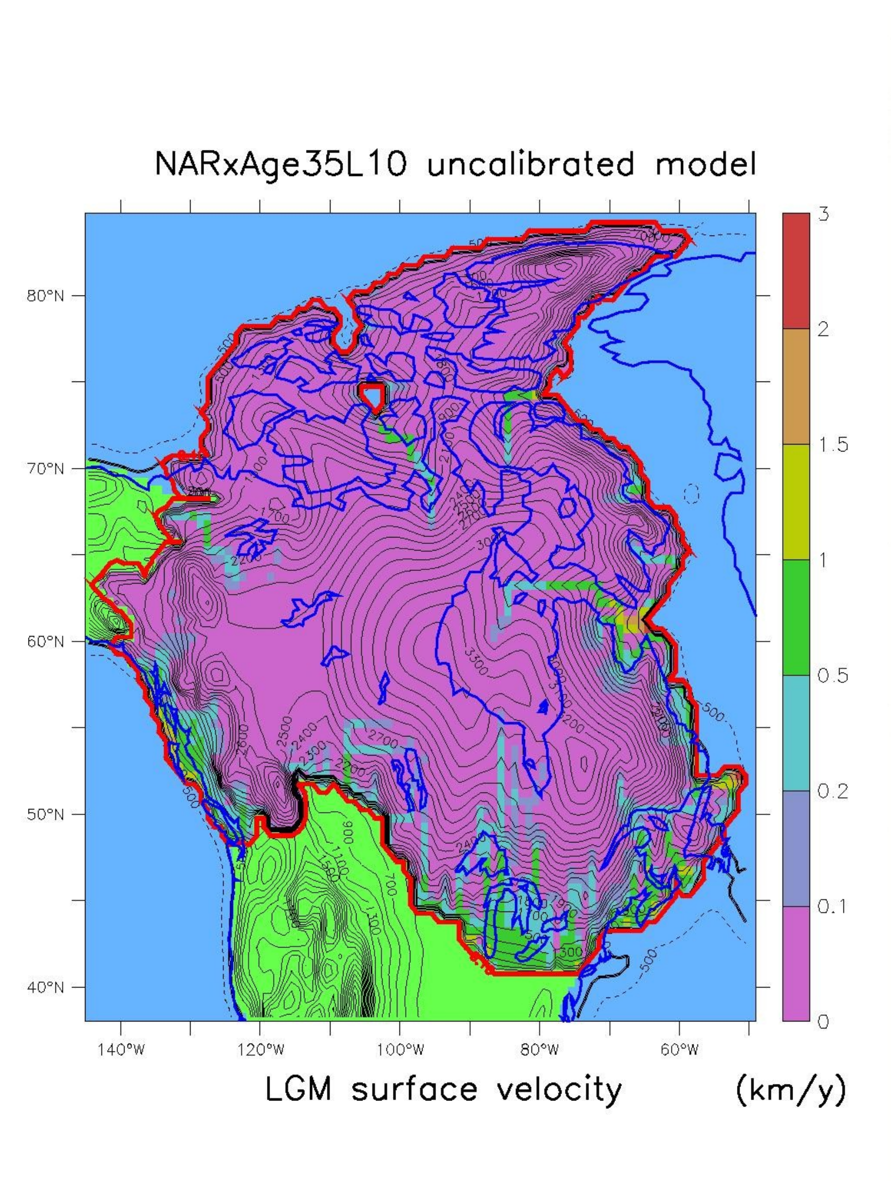
Some general ice results

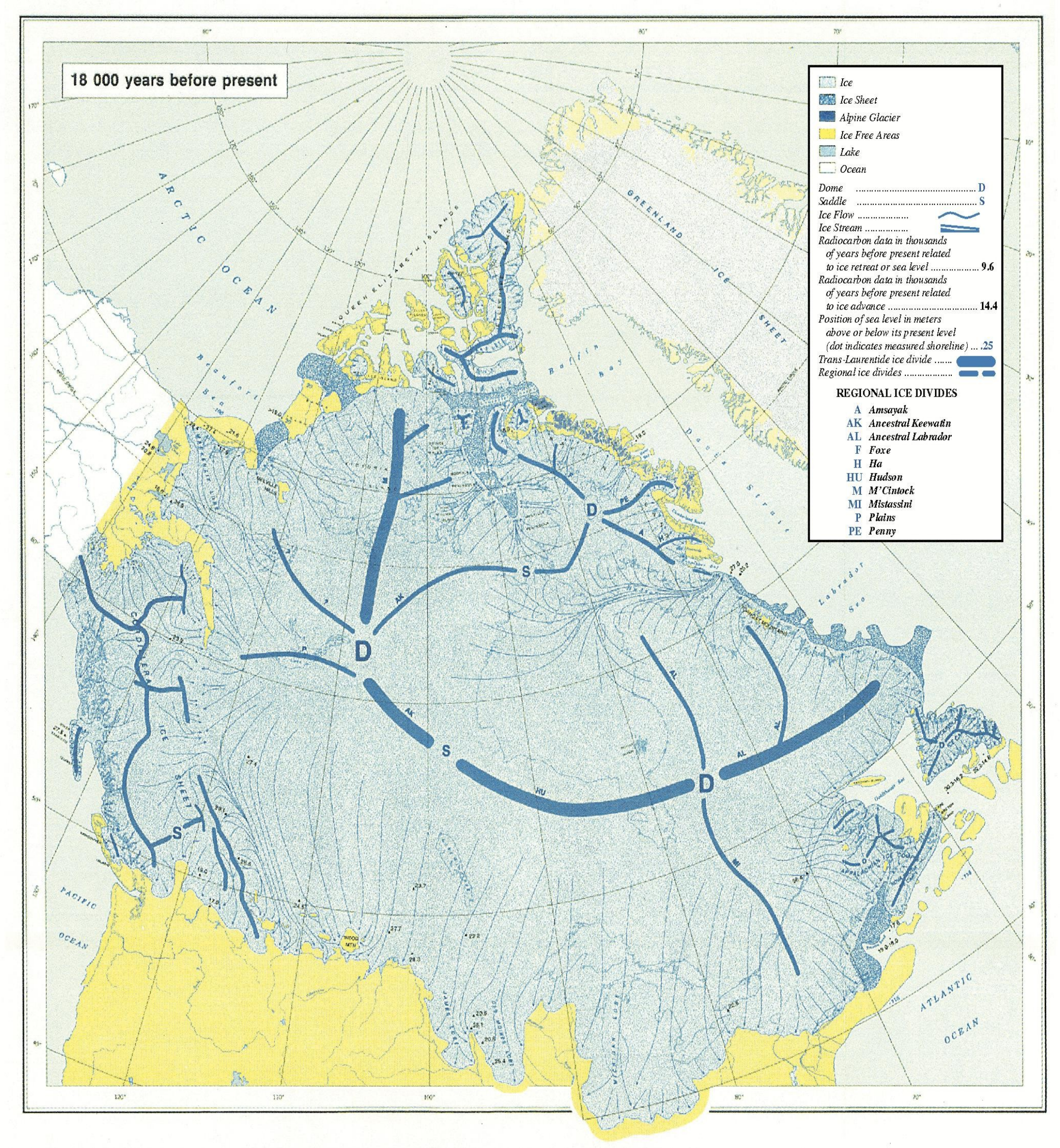
old version LGM characteristics



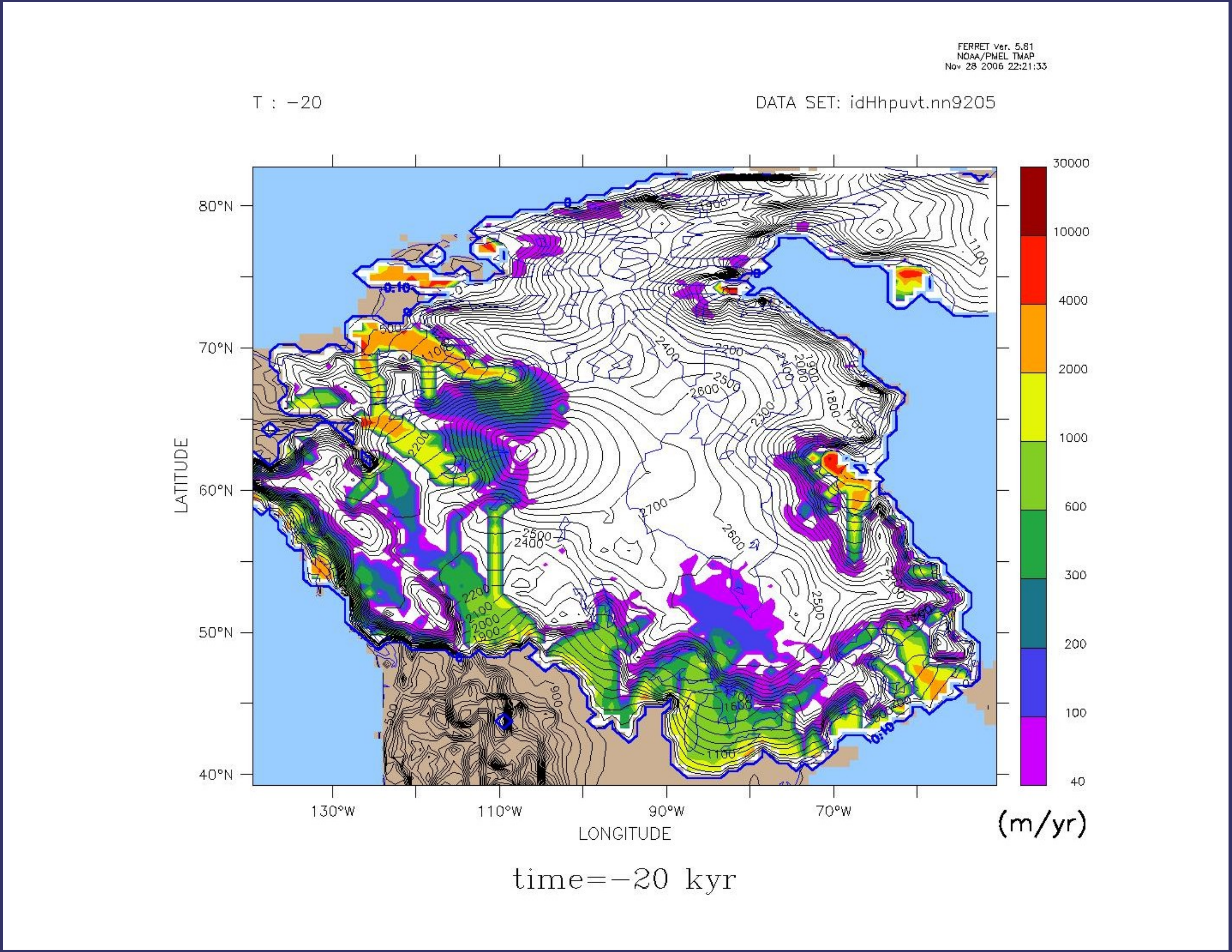
LGM comparisons

(Dyke and Prest,1987)

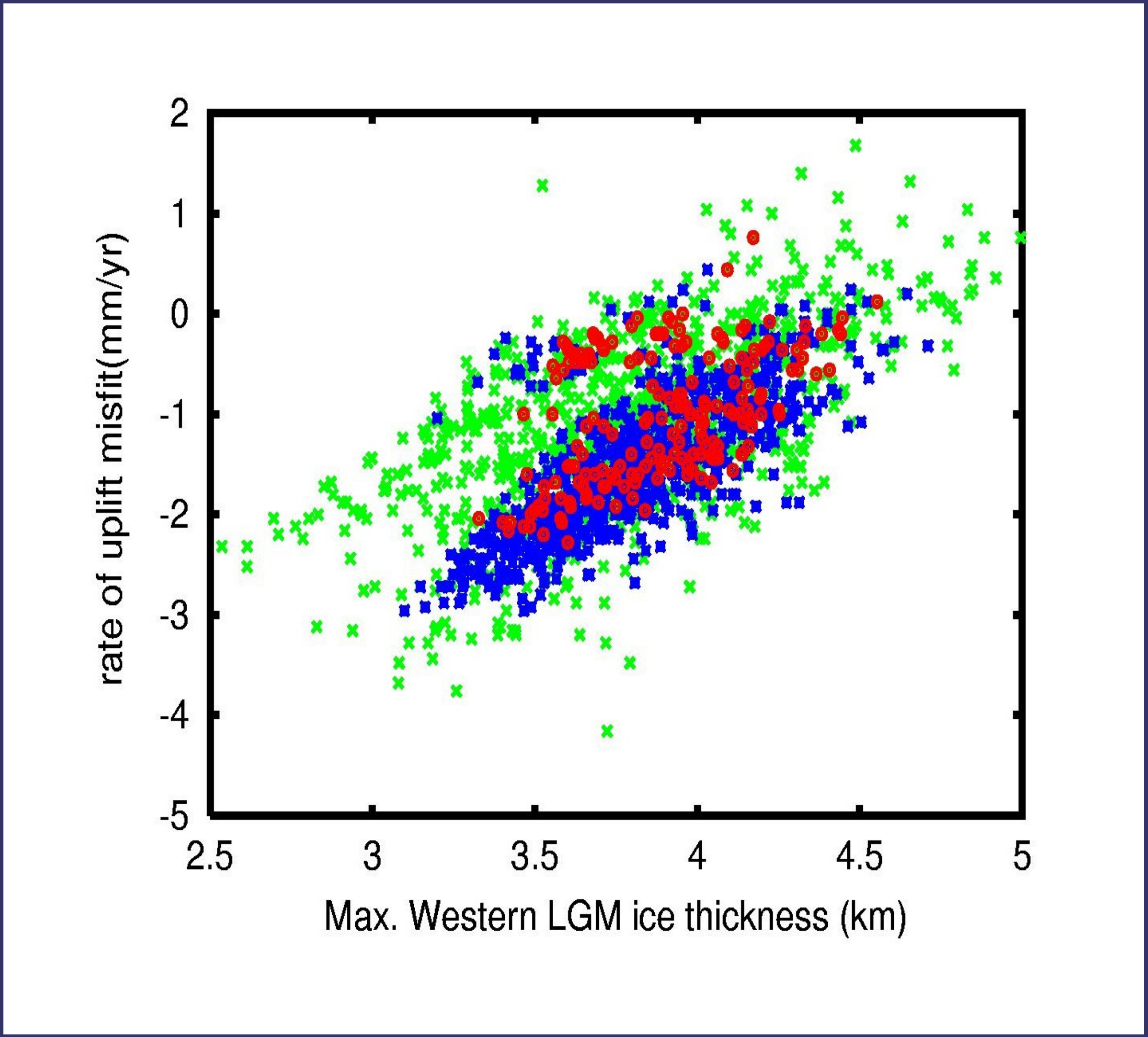




A recent example result for LGM



Maximum NW ice thickness

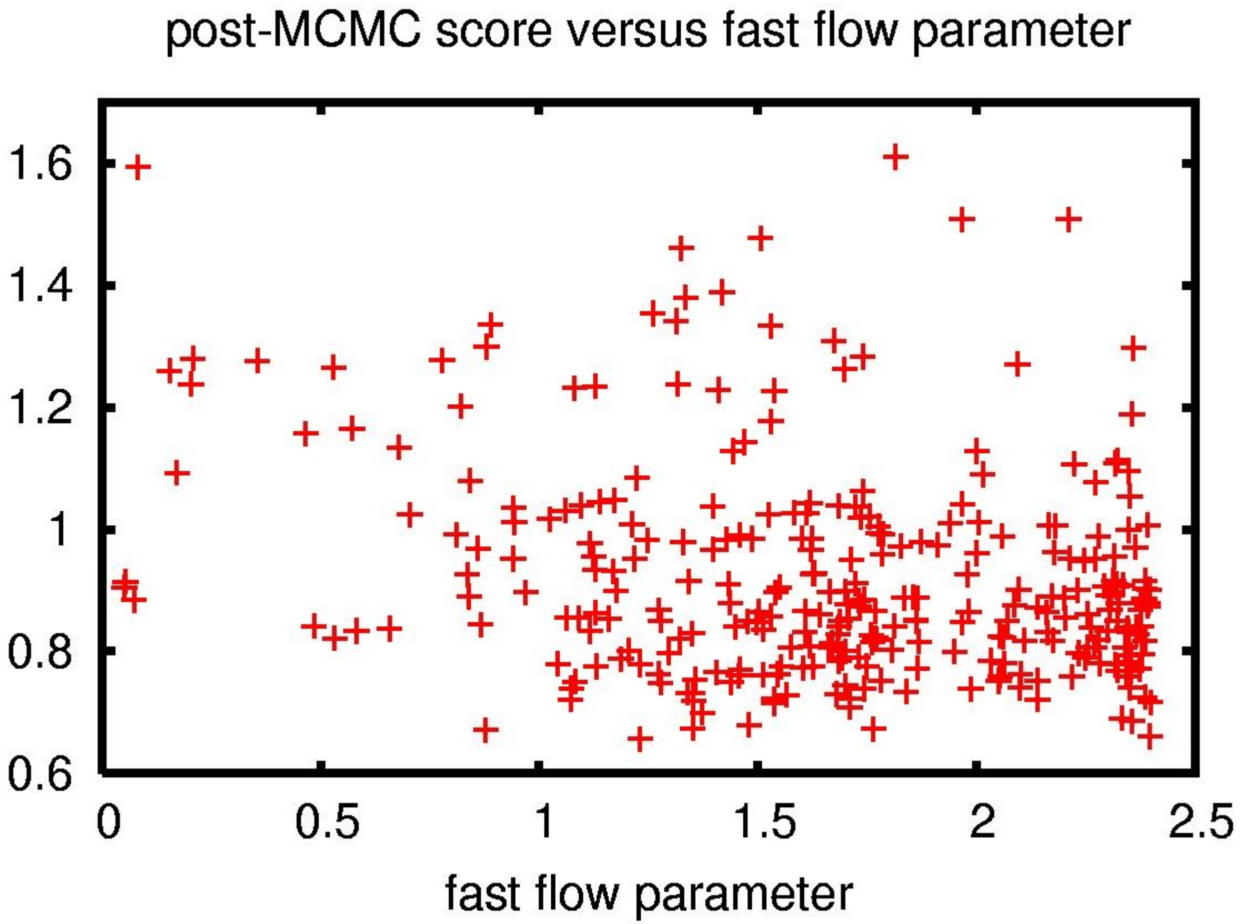


Green runs fail constraints

Blue runs pass constraints

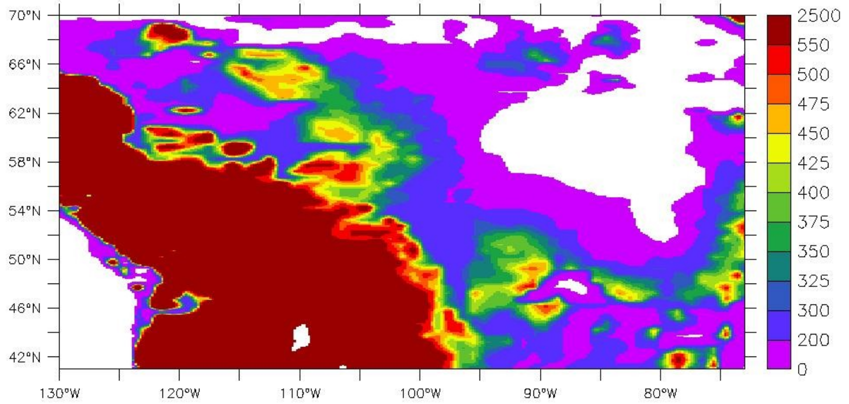
Red runs are top 20% of blue runs

Calibration favours fast flow

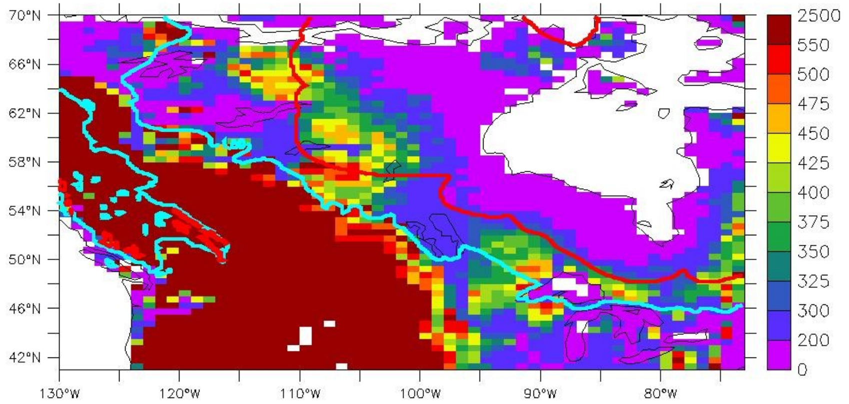


Deglacial Drainage

Drainage topography



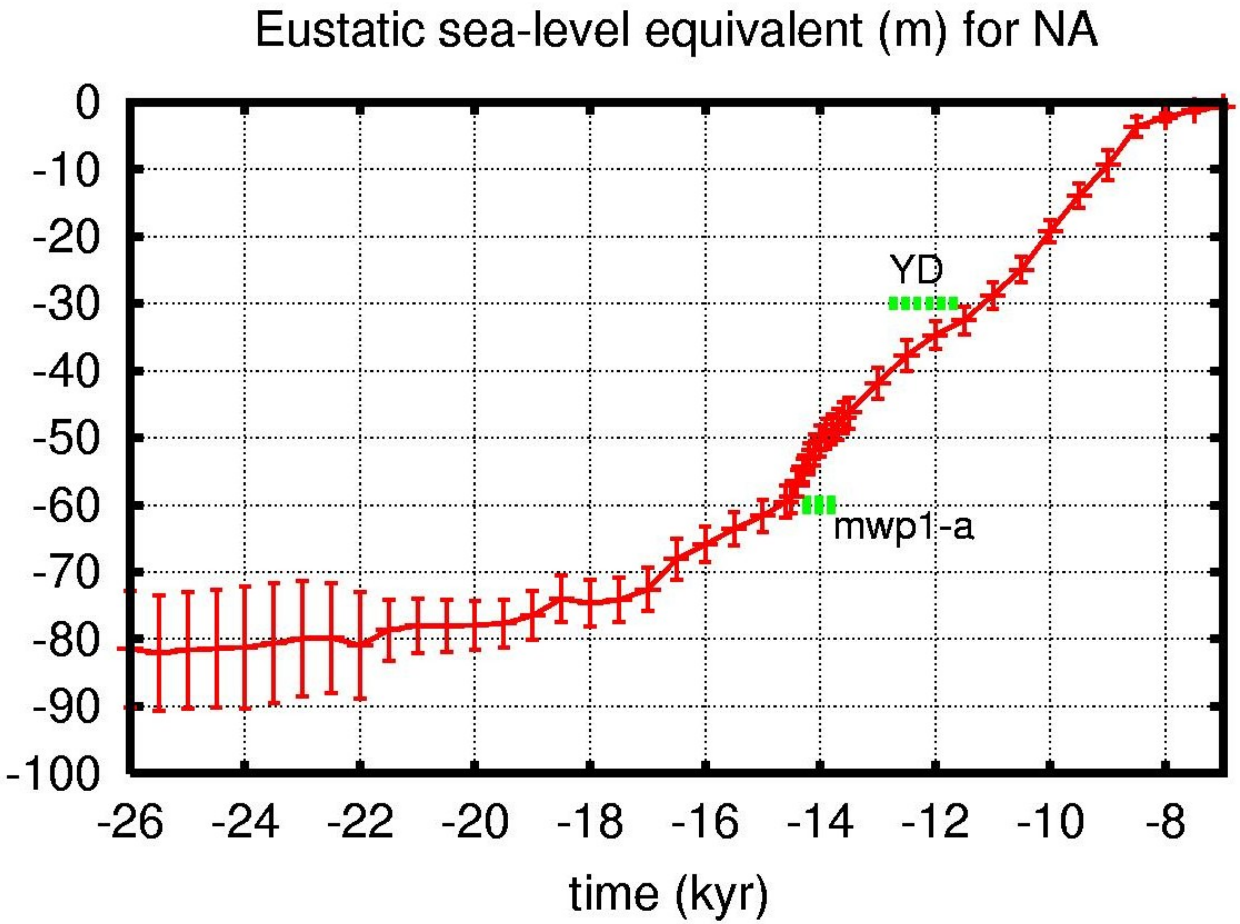
0.2 * 0.1 resolution drainage topography



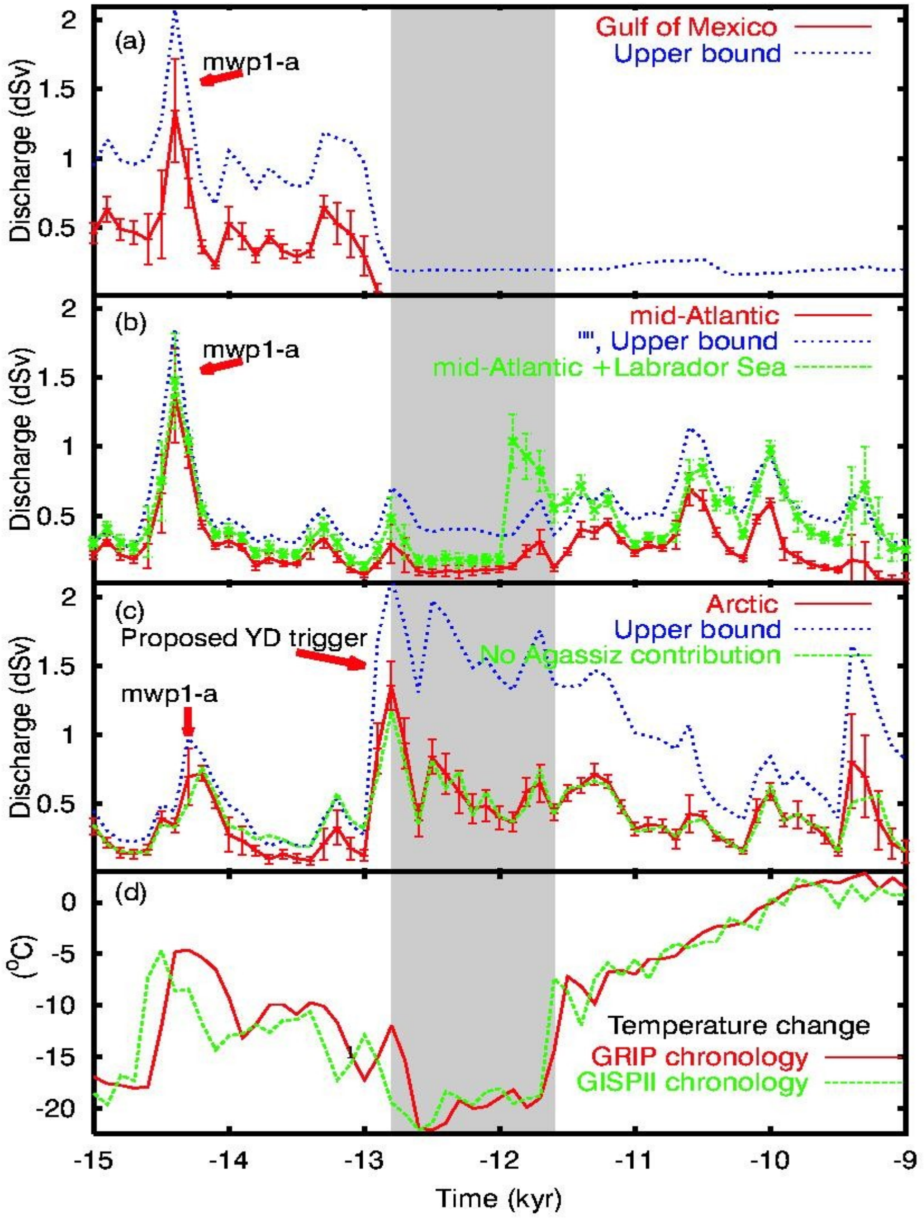
1 * 0.5 resolution drainage topography

- Diagnostic down-slope surface drainage and water storage solver
  - 100 year time-steps
- Challenge of accurate coarse resolution drainage calculation
  - Solver and drainage topography validated for present day against drainage basins of Hydro-1k data-set

Deglacial eustatic sea-level chronology

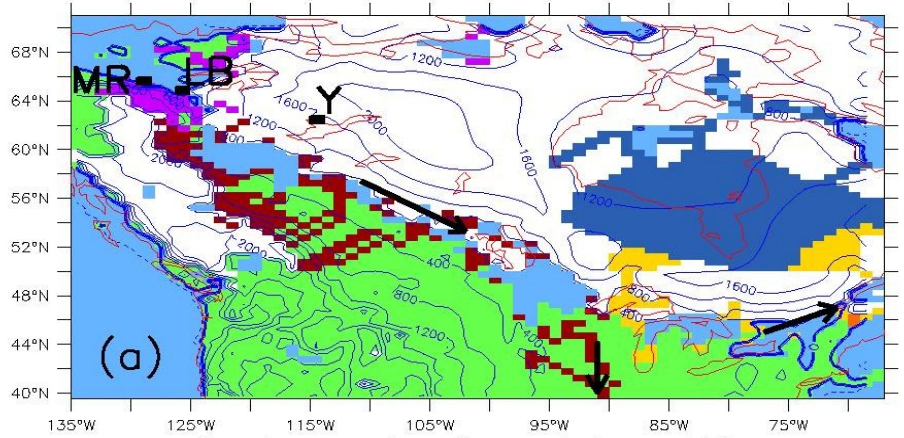


Climate and meltwater phasing

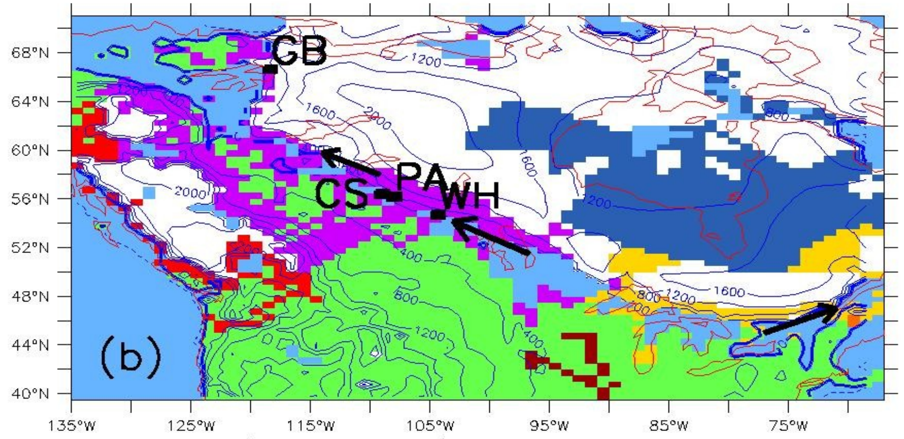


(Tarasov and Peltier, Nature 2005)

YD onset drainage basins



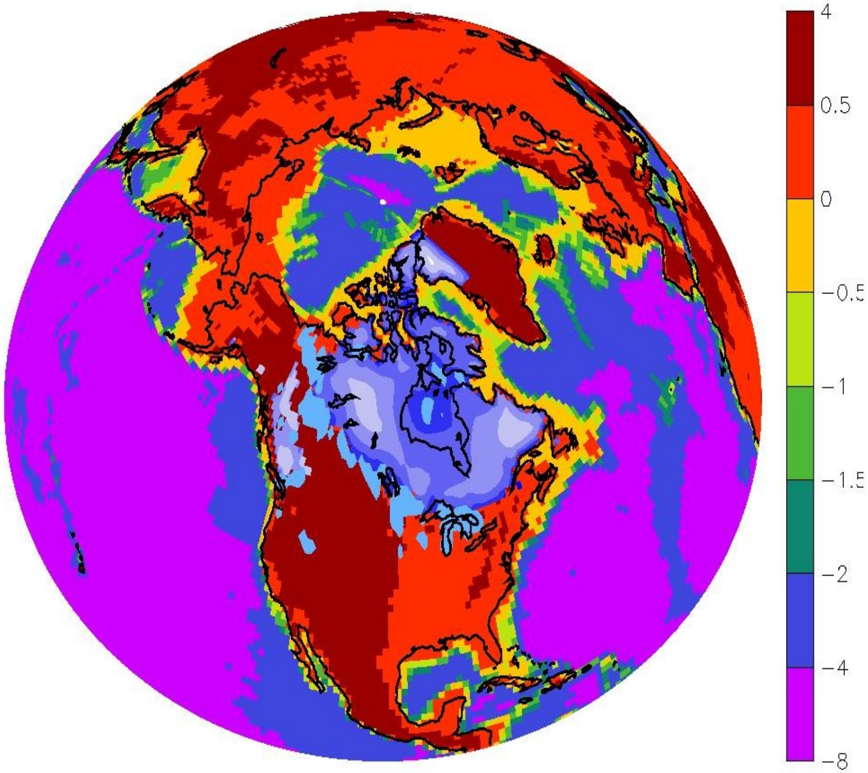
Drainage basins at t=−13kyr



Drainage basins at t=−12.8kyr

- Mississippi drainage
- NW Arctic drainage
- Labrador Sea drainage
- Gulf of St. Lawrence drainage
- Hudson River drainage
- Pacific drainage

Where does the meltwater go?



YD marine elevation (km)

- Bauch et al (2001): evidence of a low salinity event at or before YD onset in western Fram Strait
-
- 3 data-points from two other cores (PS2837, PS2887, Norgaard-Pedersen et al, Paleoc., 2003) -> freshening in Western Fram Strait between 10.5

Science Summary

- Yellowknife uplift data -> Large Keewatin ice-dome
- Largest (1.2 to 2.2 dSv one sigma range over 100 years) discharge into the NW Arctic Basin during YD onset
  - Most of NW discharge is due to the reduction of the Keewatin ice dome
  - Trigger for Younger Dryas?
- Ensemble NA contributions to mwp-1a range from 7.2 to 11.4 m eustatic
- Calibration favours strong fast flow: a dynamic ice-sheet

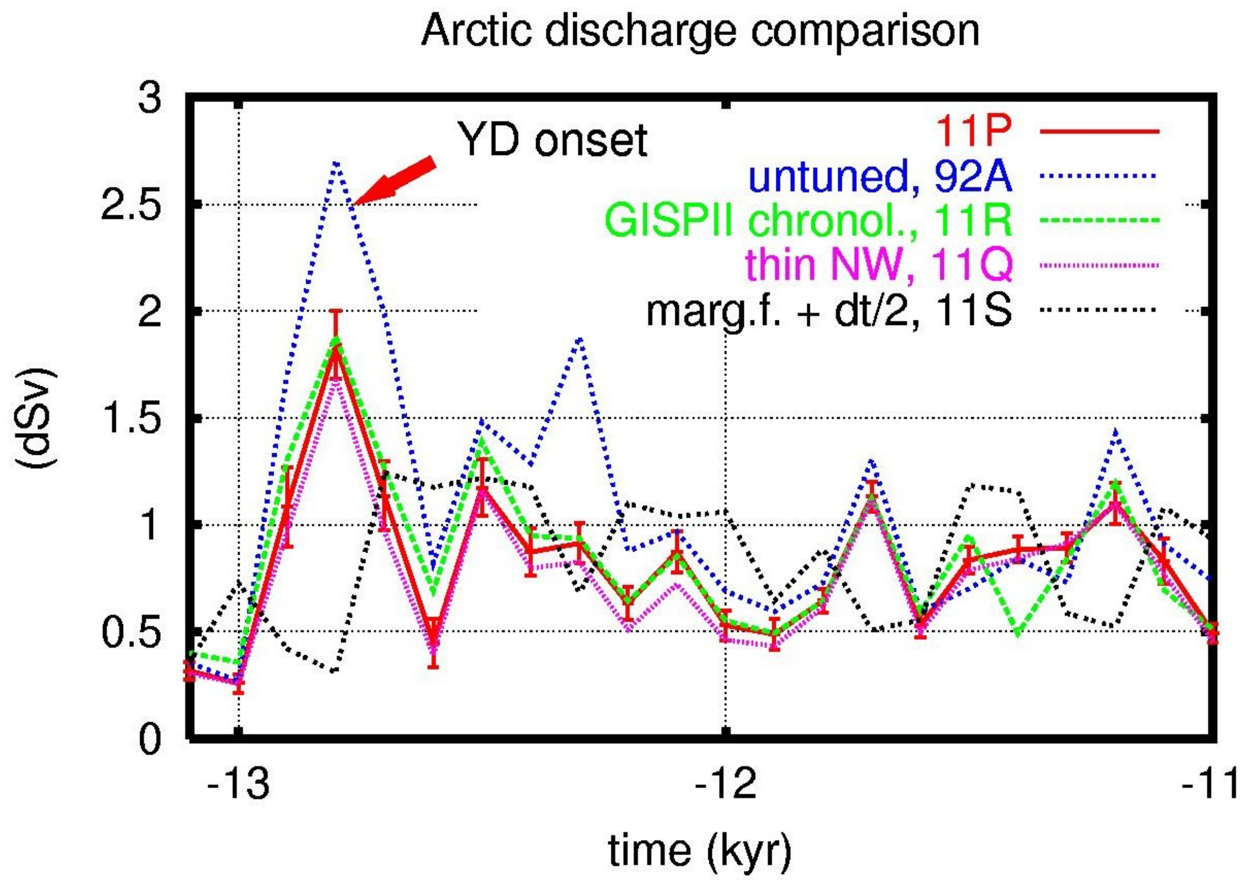
Key points to walk away with

- Results suggests Arctic hydrology played a critical role in millenial scale climate variations -> future?
- numerical model + calibration = data and physics integration

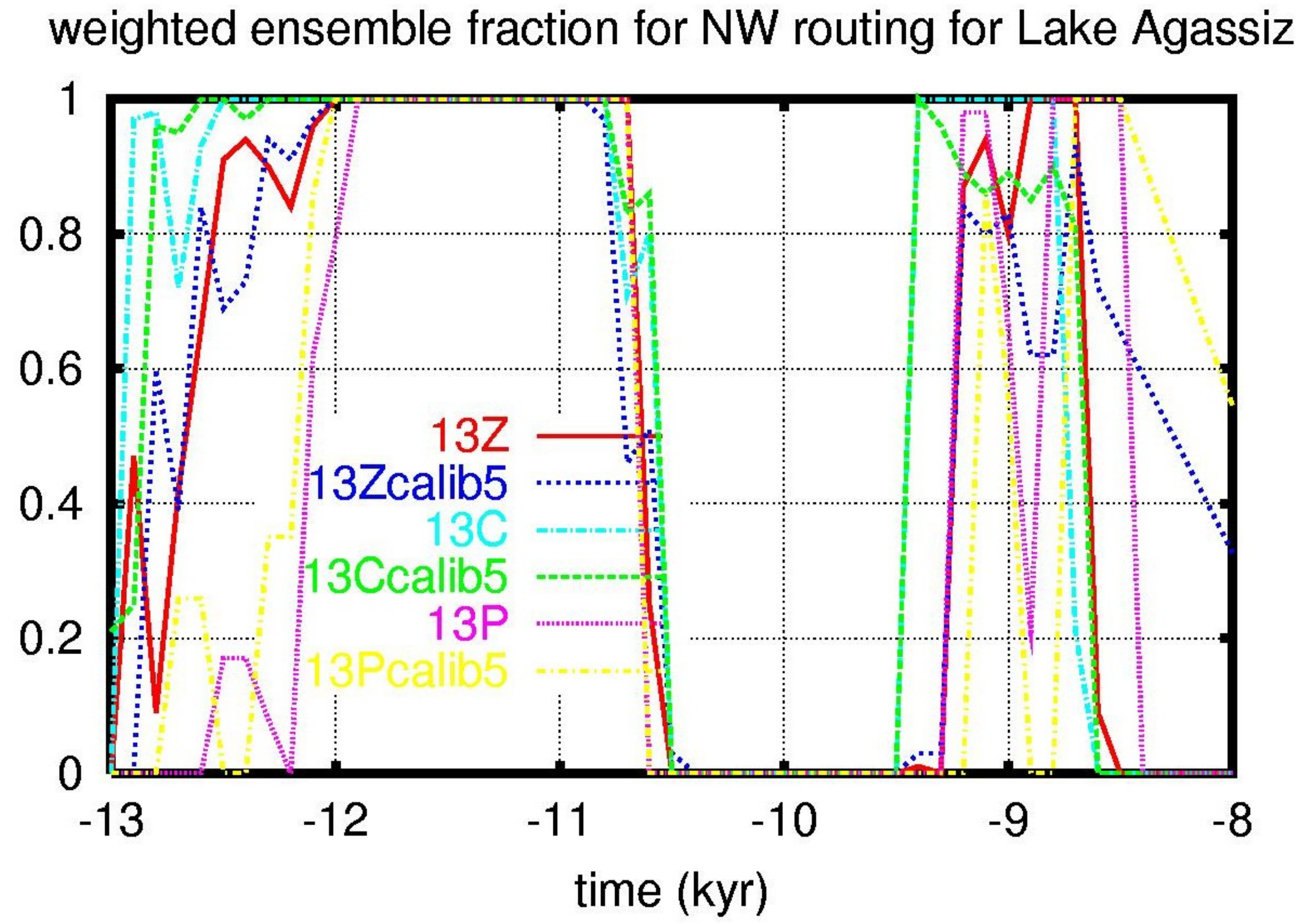
Issues: to do

- Meltwater chronology for other ice-sheets?
  - => repeat calibration process for other ice-sheets
- More proxy data,
  - Repeating calibration with expanded constraint set
- Self-consistency of climate forcing?
  - Snap-shot and asynchronous coupling with various EMICS and GCMs
  - Check against paleo-climate proxies
- Ocean response?
  - High-resolution local basin modelling of ocean circulation

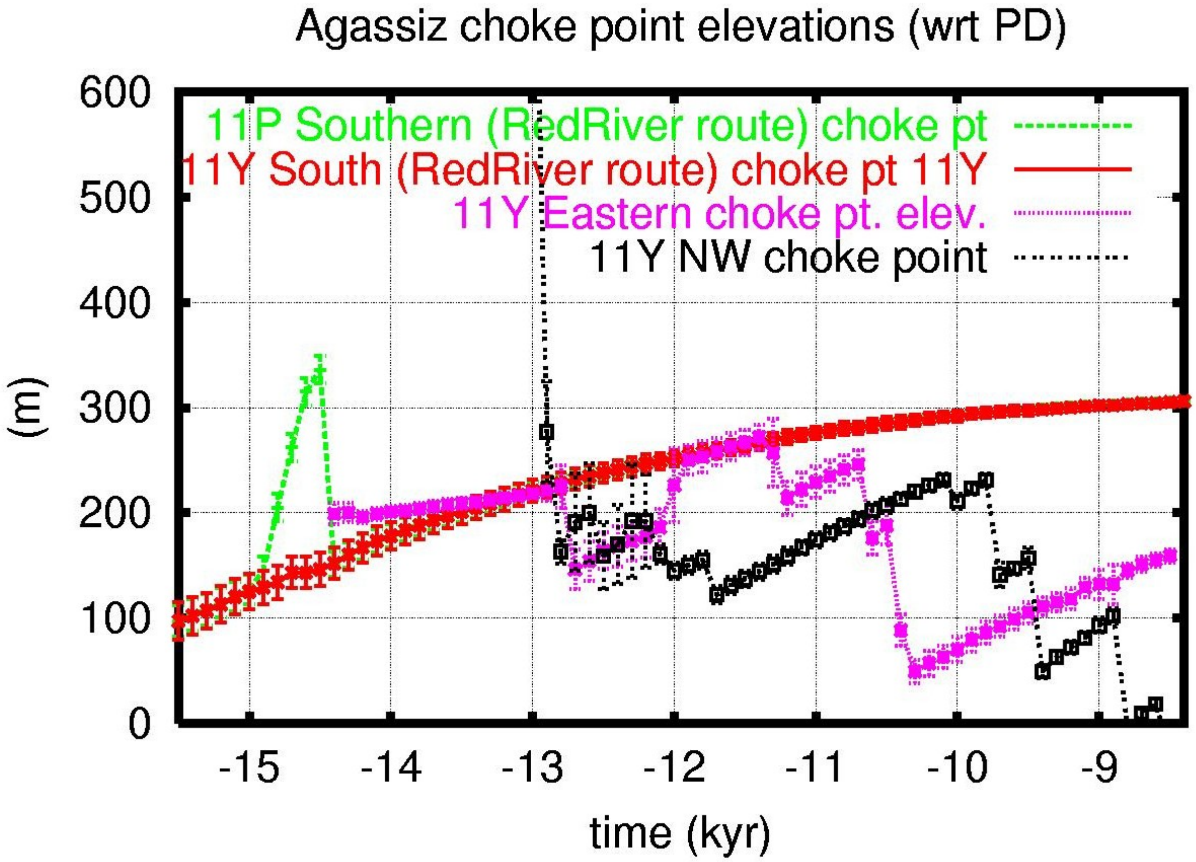
Arctic discharge robustness



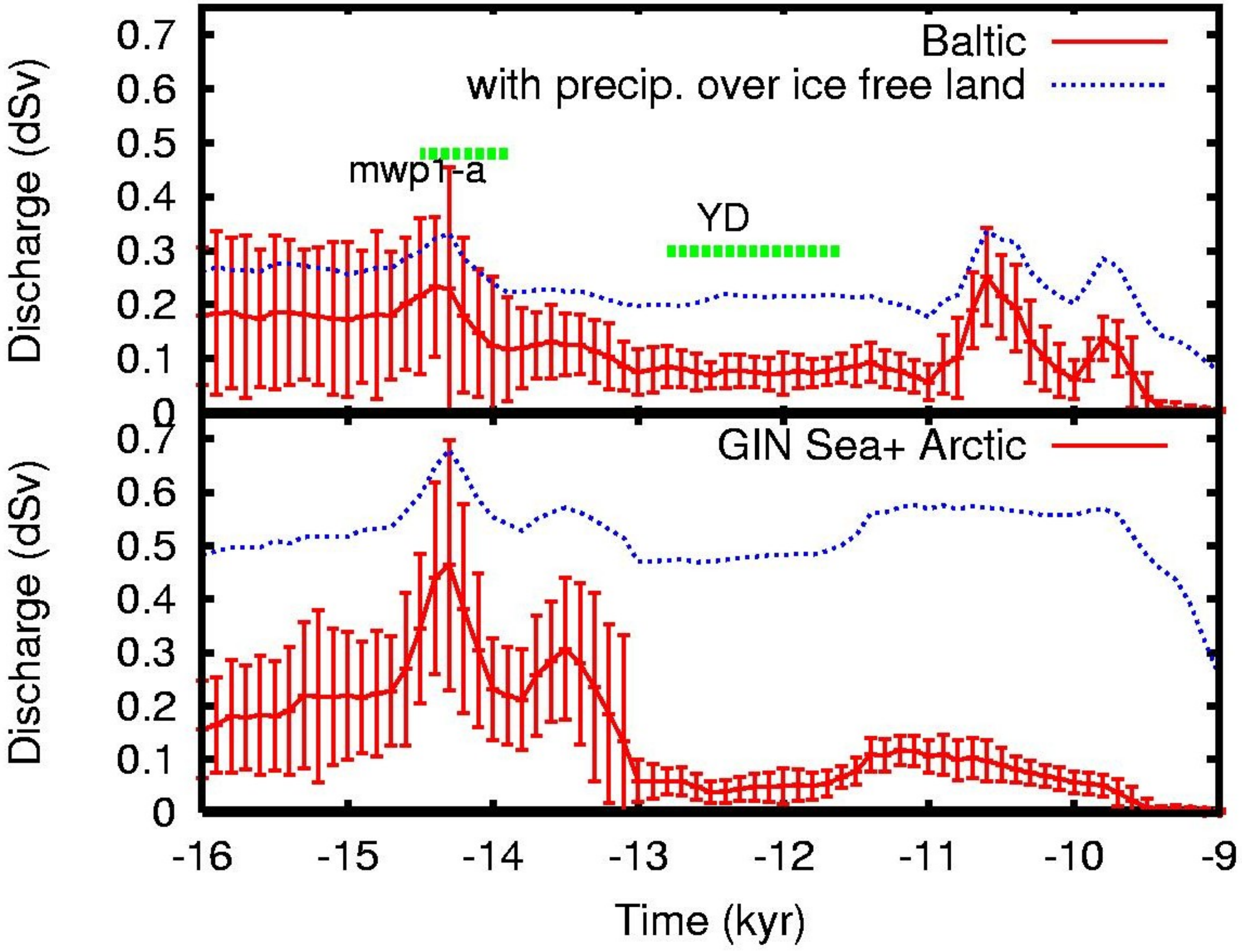
NW routing for Lake Agassiz



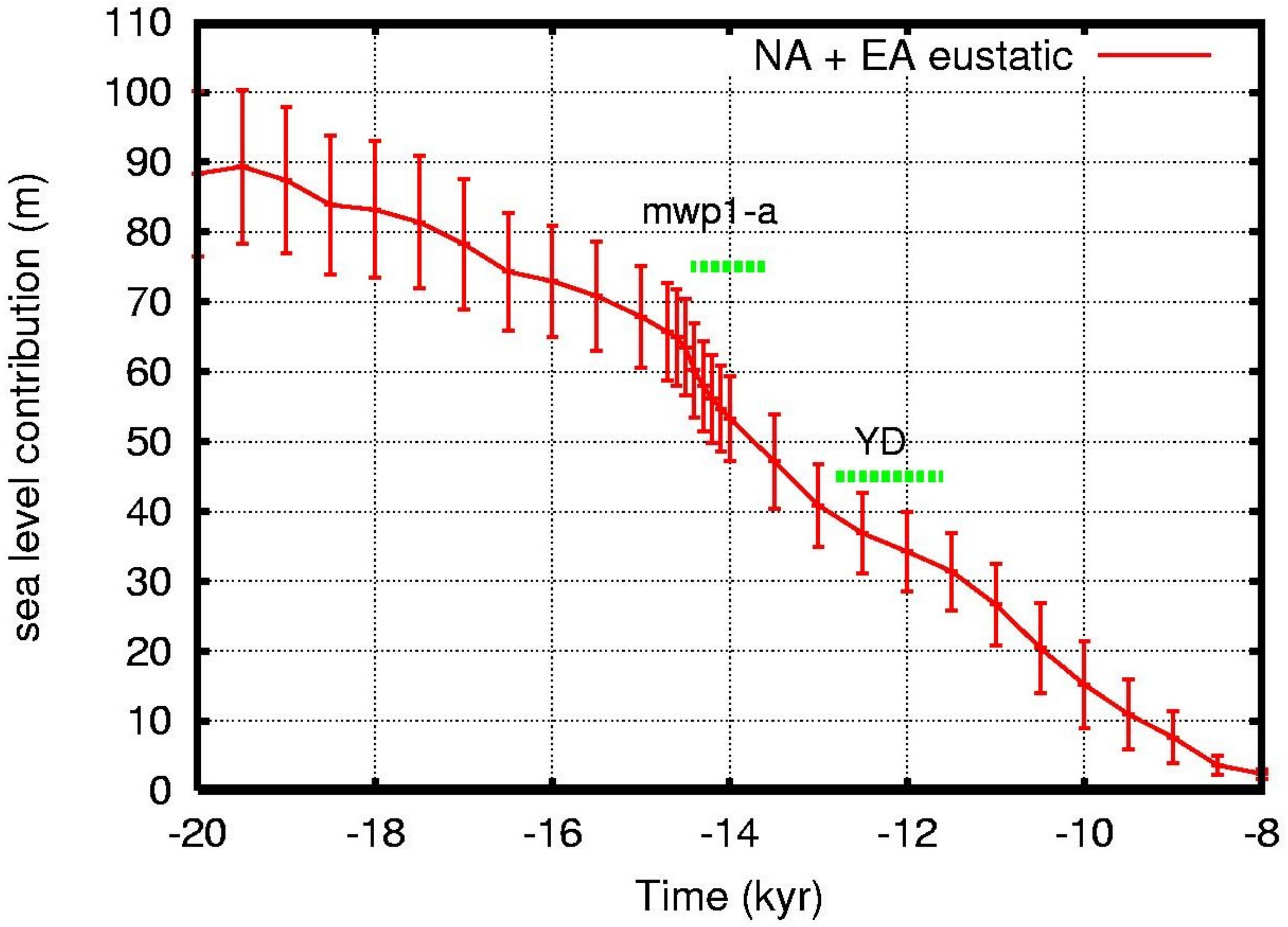
Lake Agassiz choke point elevations



European meltwater drainage



Deglacial eustatic sea-level chronology



Other and longer-term projects

- Further development and application of calibration methodology to other models
- Higher order ice-sheet/stream/shelf model
  - Get better constraints on Heinrich events
- Additions and improvement to components of GSM:
  - Field work : ice calving -> better model
  - Sub-grid mass-balance parameterizations
  - Sub-glacial hydrology
  - Sediment transport
- Climate system modelling to understand what drives the 100,000 year glacial cycle
- Isotopic tracking : ground-water and existing ice-caps
- Use calibrated models to constrain future evolution of present-day ice sheets