Ice Sheet Modelling
State of the Art & Implications for Simulation of Glacial Sedimentation

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Outline

1. Basis of ice sheet modelling
2. Current state of the art – strengths
3. Current state of the art – weaknesses, aka. the current research frontier:
   - → Issues re: iceberg calving
   - → Issues re: basal hydrology
   - → Issues re: basal flow & ice streams
4. Implications for modelling sediment entrainment, transport, and deposition
5. Scale issues: Ice sheets vs. glaciers

1. Basis of Ice Sheet Modelling

- Continuum-mechanical models of ice deformation under gravity
- Several 3D models in the world; resolve 3D velocity, temperature, stress fields as well as ice sheet thickness (t)

ICE SHEET DYNAMICS

- Conservation of Mass

$$\frac{\partial H}{\partial t} = -\frac{\partial}{\partial x}(uH) - \frac{\partial}{\partial y}(vH) + b$$

Ice Flux Divergence

Mass Balance

ICE SHEET DYNAMICS

Conservation of Momentum

$$\frac{\partial \boldsymbol{\sigma}}{\partial \boldsymbol{x}_j} = -\rho \boldsymbol{g}$$

Glen's Flow Law

$$\dot{\varepsilon}_{ij} = B(T)\left[\Sigma_2'\right]^{\frac{(n-1)}{2}} \sigma_{ij}'$$

ICE SHEET THERMODYNAMICS

- Conservation of Energy

Diffusion

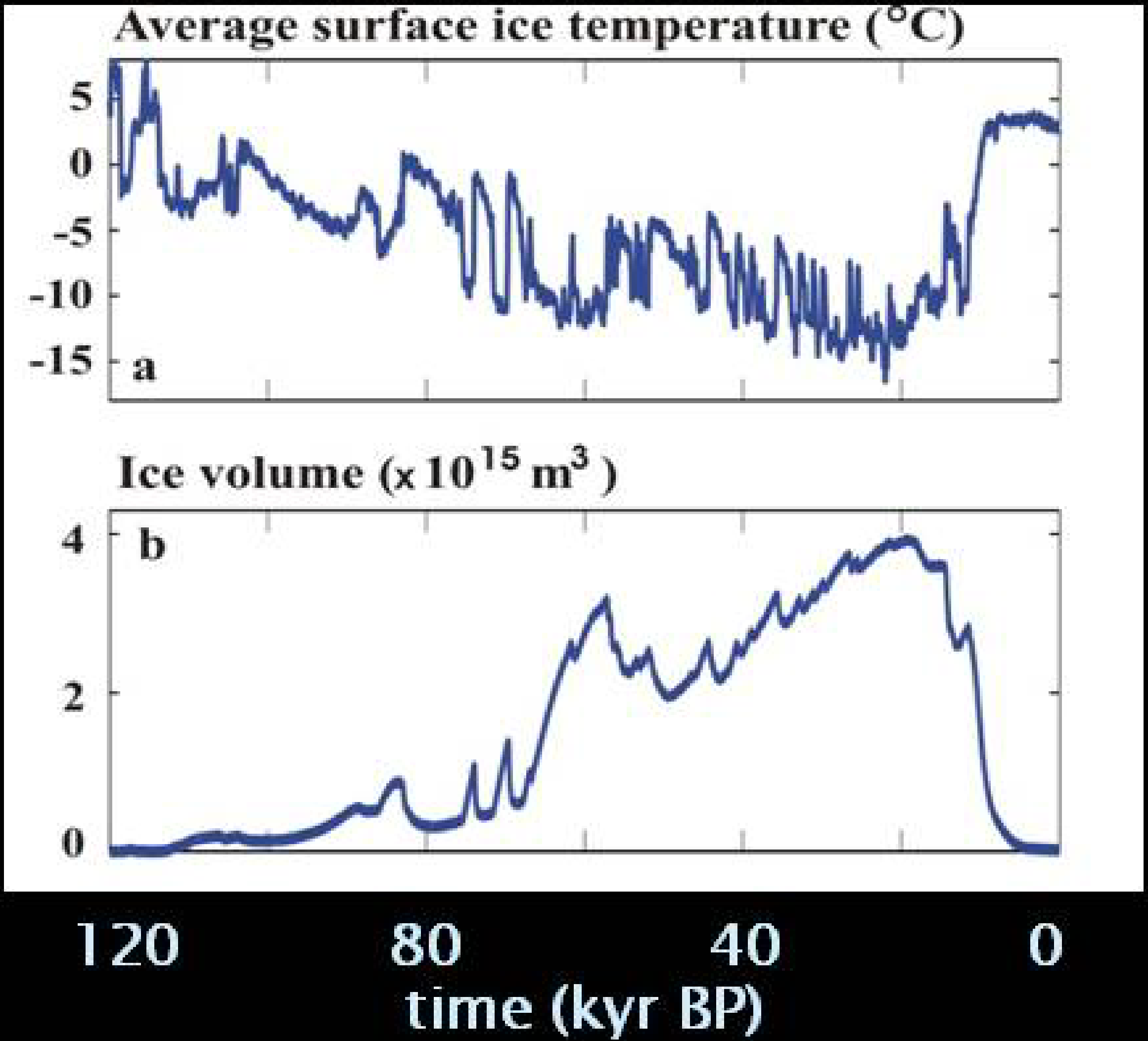
$$\frac{\partial T}{\partial t} = -v_k \frac{\partial T}{\partial x_k} + \kappa \frac{\partial^2 T}{\partial x_k^2} + \frac{\Phi}{\rho c}$$

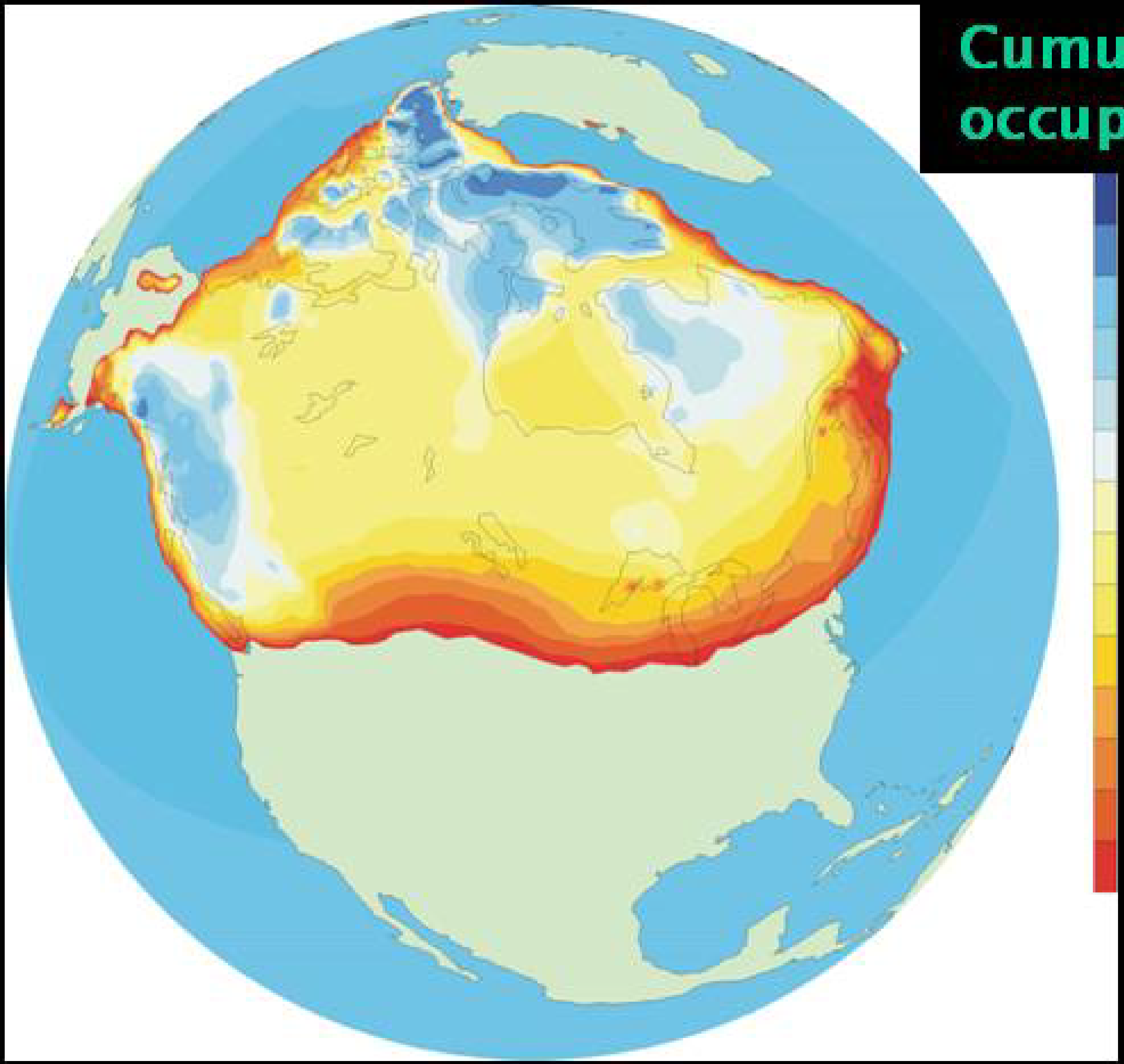
Advection

Strain Heating

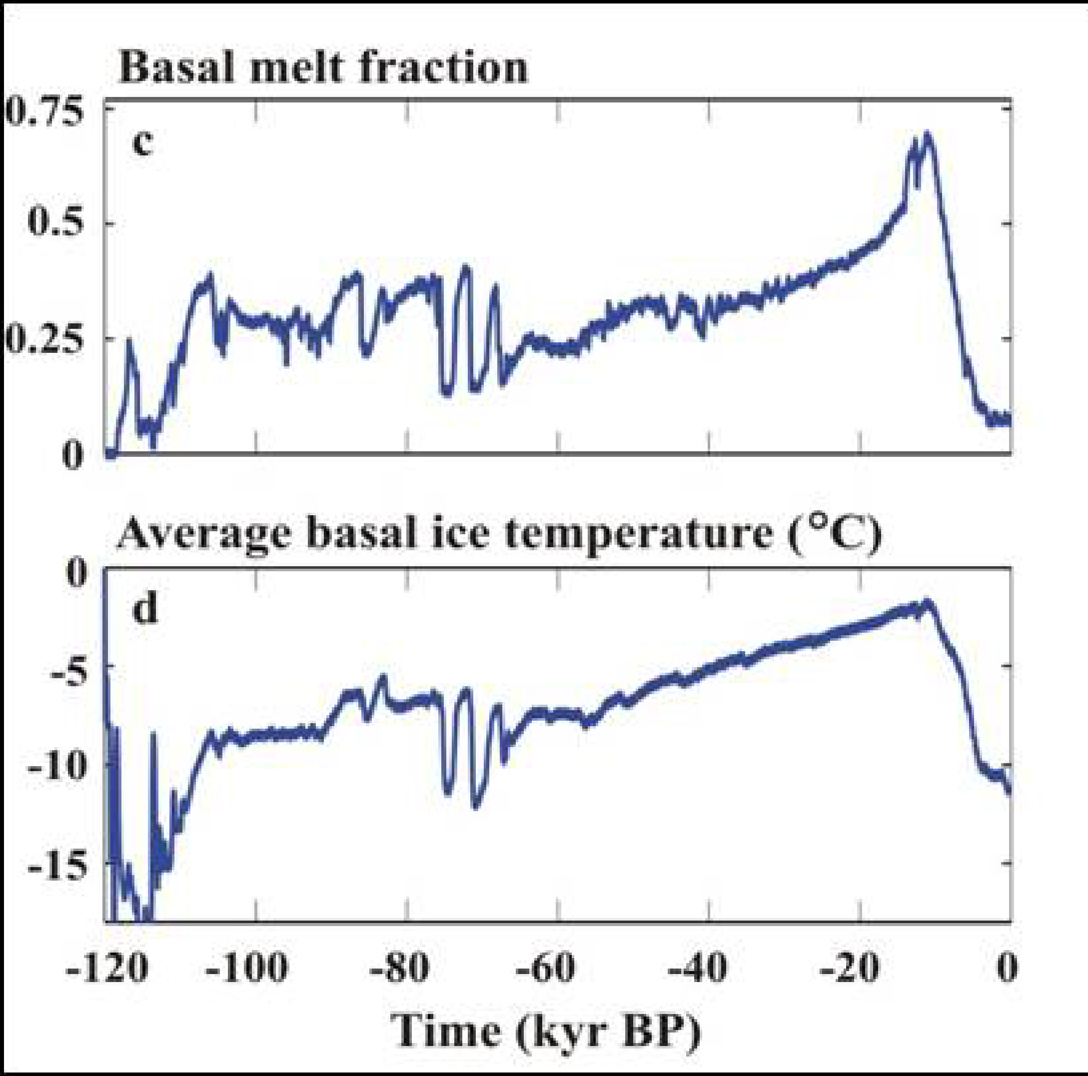
$$\Phi = \dot{\varepsilon}_{ij} \sigma'_{ij}$$

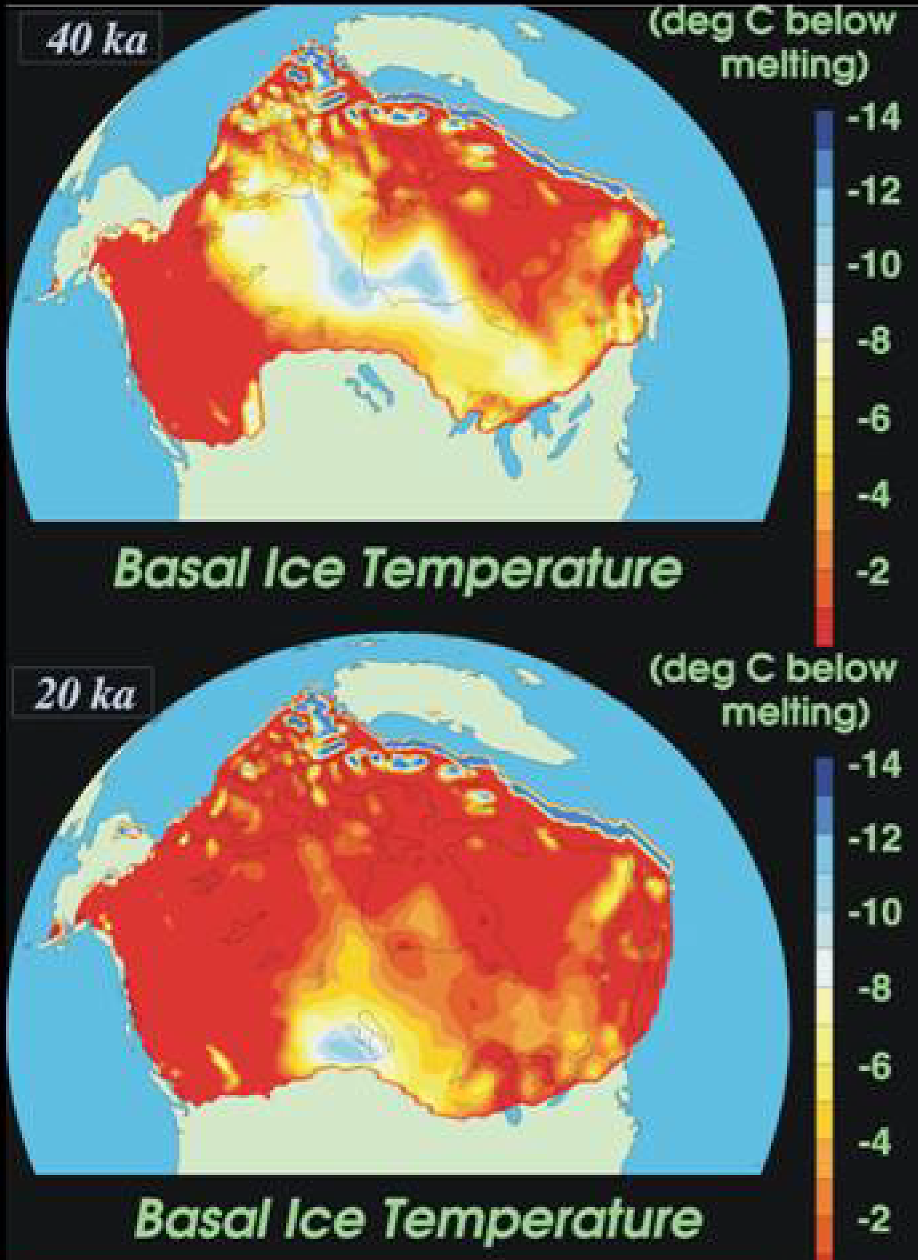
The Last Glacial Cycle in North America




Cumulative ice occupation (kyr)
100
80
60
40
20
0

The Last Glacial Cycle in North America





Ice Temperature Evolution

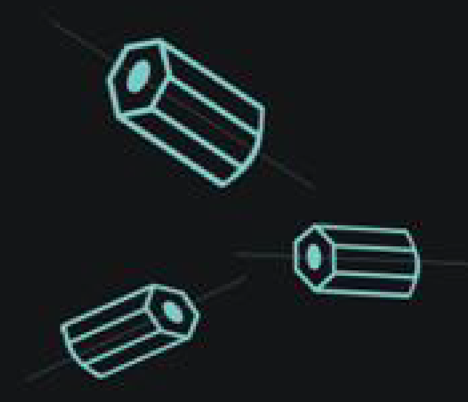
Uncertainties: Ice Rheology

Glen's "Enhanced" Flow Law

$$\varepsilon_{ij} = E B_0 \exp\left(\frac{-Q}{RT}\right) \Sigma_2'^{\,(n\text{-}1)} \sigma'_{ij}$$

Complications:

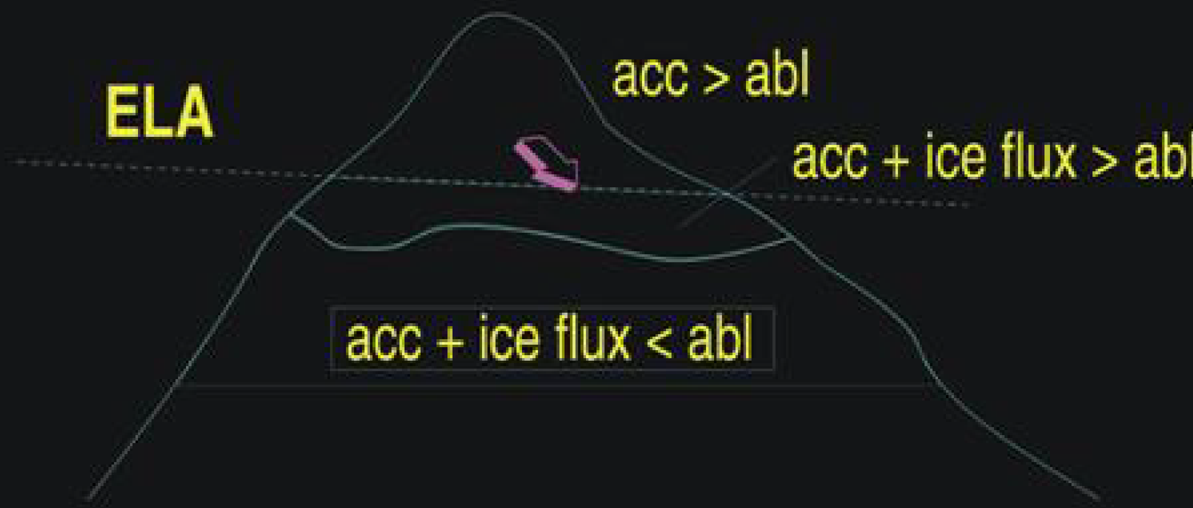
- Anisotropy
- Impurities
- Water content



Uncertainties: Mass Balance

Importance:

Ice sheet or glacier nutrition and health



Concerns:

Skill of climate model

Model resolution

Ablation parameterizations: capturing the physics?

3. Current State of the Art – Weaknesses

Current research frontiers:

→ Issues re: glacial hydrology
→ Issues re: iceberg calving
→ Issues re: basal flow & ice streams

→ Only just getting to geologic outputs:
e.g. landforms, permafrost, striations, isotopic labelling of groundwater and runoff, erosion, dispersal trains, marine sedimentation...

Glacial Hydrology

Expect large advances:
Has finally caught the interest of many in the ice sheet modelling world

Involves surface, englacial, subglacial, and groundwater routing. Definite challenges in both scale and process understanding

*** The relevant physical fields are relatively well-modelled or available as inputs**

❄ Subglacial Melt/Refreeze

When T_b is at the pressure melting point:

$$\rho L \frac{\partial H}{\partial t} = \rho L \dot{m}_b = \sum Q_b$$

Basal melt or refreezing rate

Basal heat fluxes

❄ Subglacial Energy Balance

Same physics in both 3D and 1D models:

$$\frac{\partial T_b}{\partial t} = -v_{bk}\frac{\partial T_b}{\partial x_k} + \frac{k_I}{\rho c}\frac{\partial T_b}{\partial z} - \frac{1}{\rho c}\left[k_W \frac{\partial T_W}{\partial z} \,\middle|\, k_B \frac{\partial T_B}{\partial z}\right] + \frac{(\Phi_b + \gamma_b)}{\rho c}$$

Basal heat flux

So for basal hydrology:

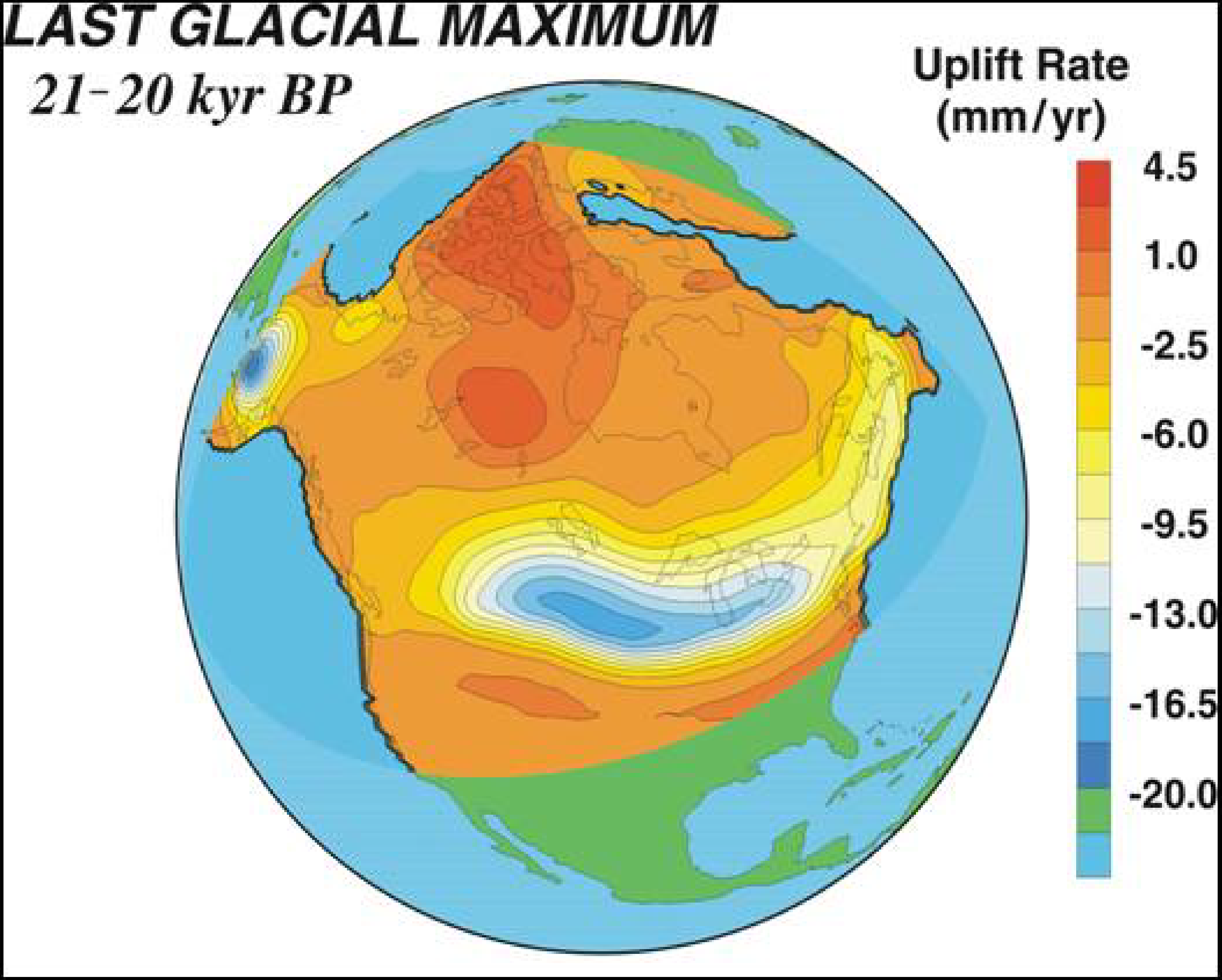
- OK for calculating sources
- Modelling subglacial drainage is another question. But progress here → Alley, Arnold, Flowers, Fastook and Johnson

  * need storage & routing considerations

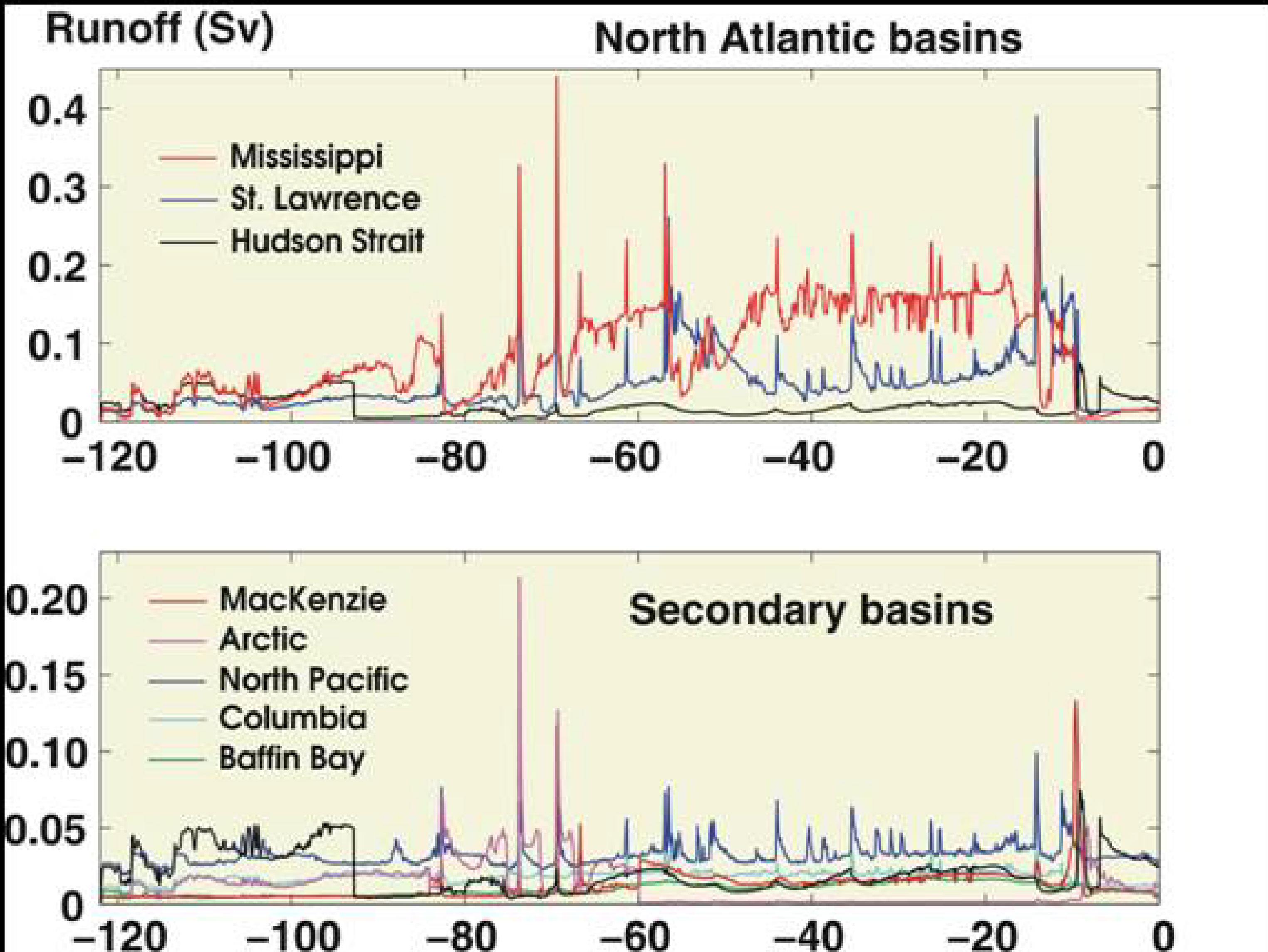
Surface hydrology and runoff:

- Actually easier
- Possible to quantify time-evolving “river” flow in a coarse sense → scale issues for more detail

Modelled Isostatic Uplift, LGM

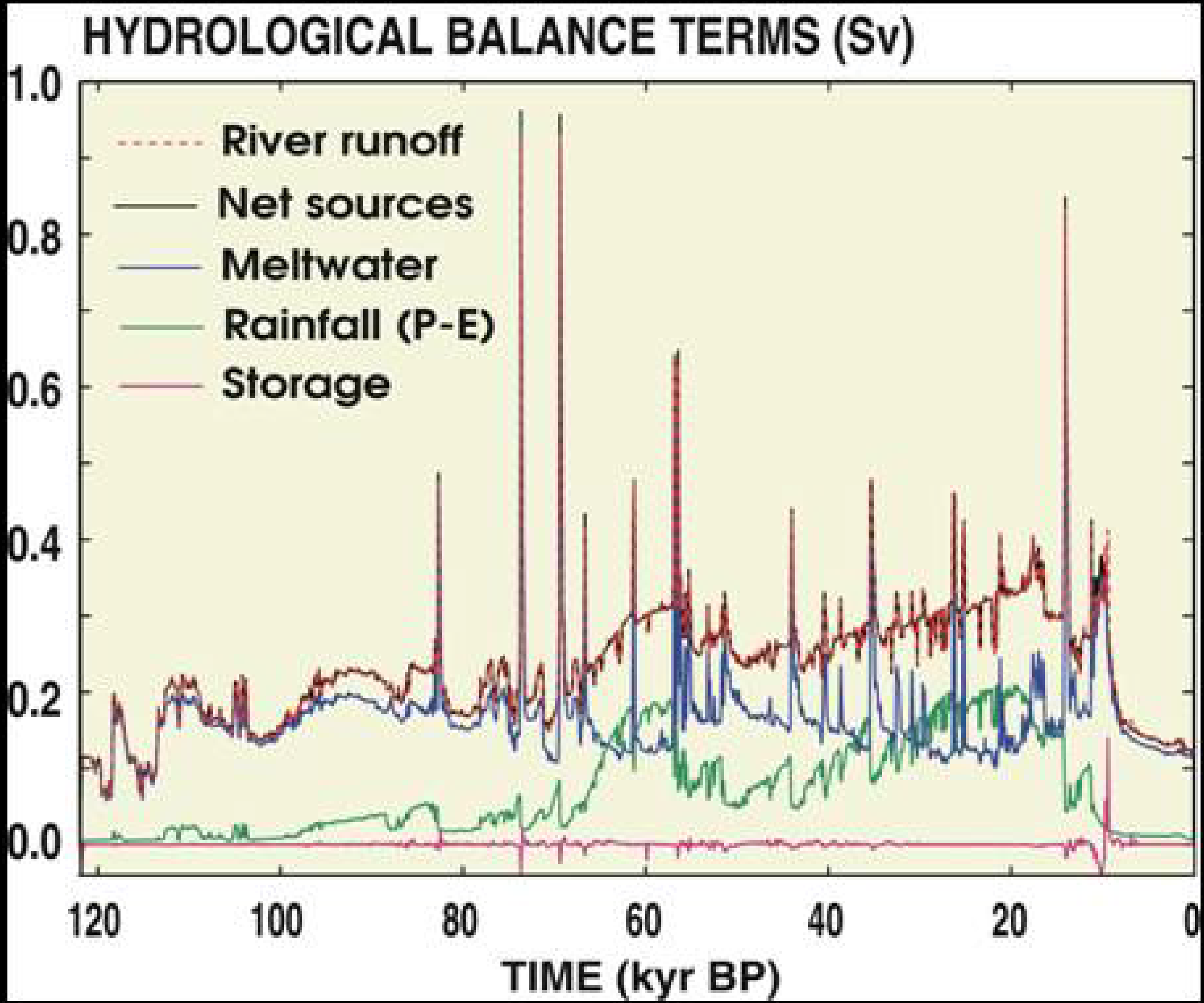


North American River Runoff, Last Glacial Cycle

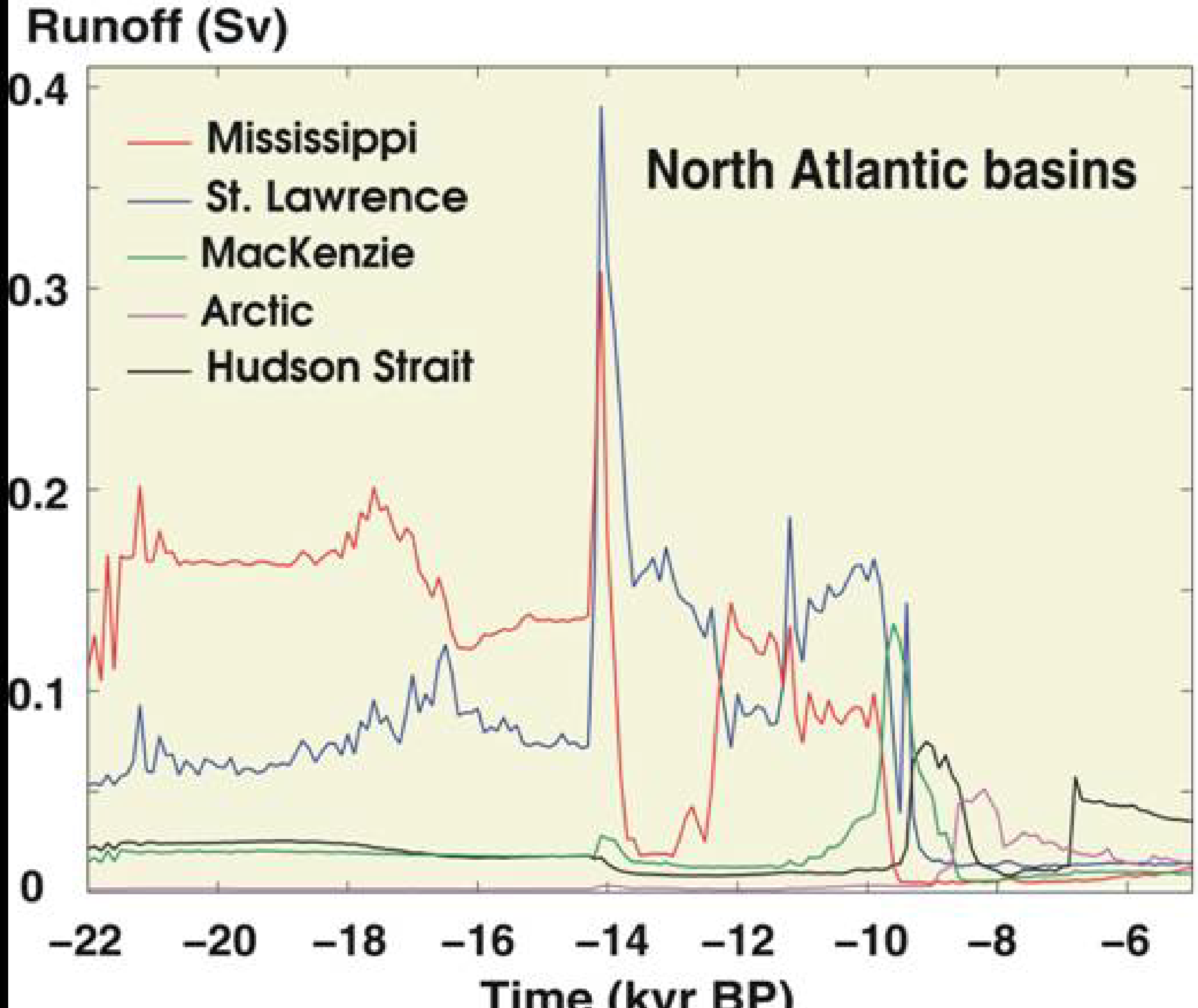


Time (kyr BP)

NORTH AMERICAN HYDROLOGICAL BALANCE, LAST GLACIAL CYCLE

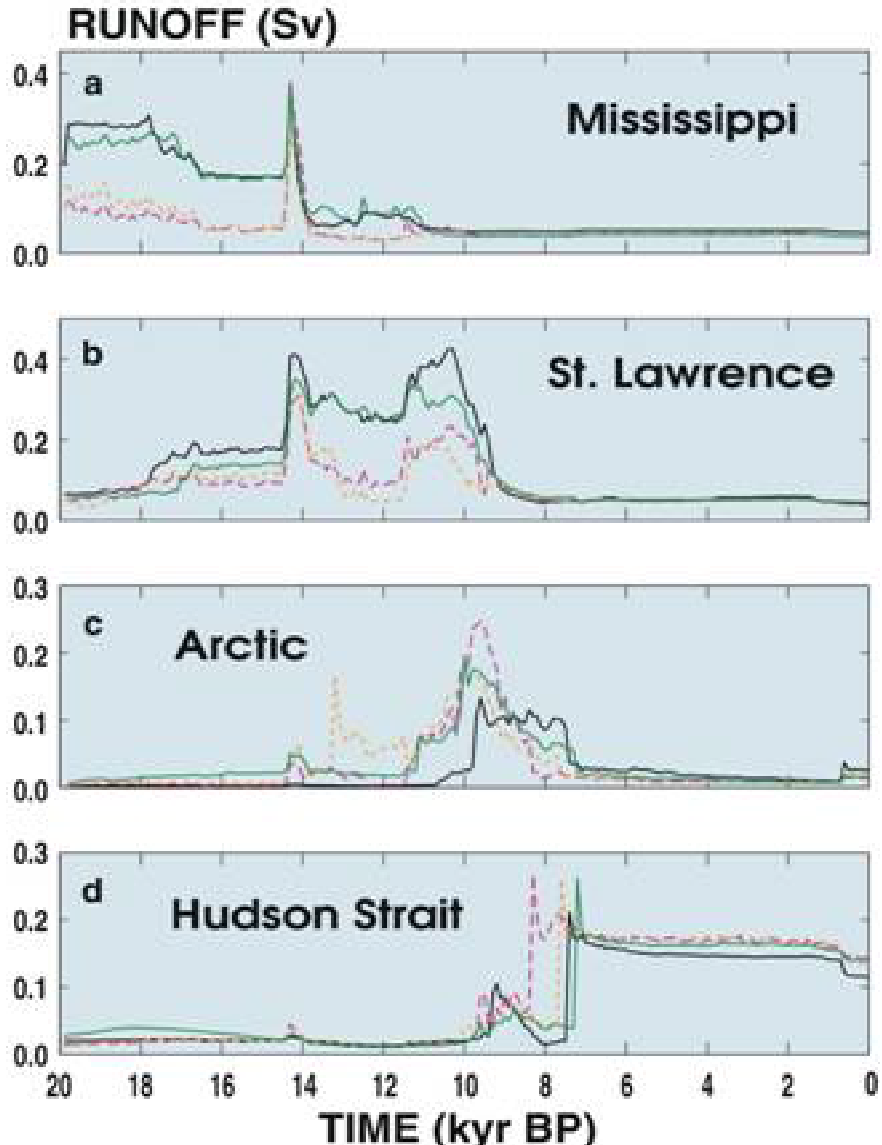


Deglacial Meltwater Pulses



Staged Runoff Sequence

Sensitivity tests, deglaciation



Iceberg Calving: Model Issues

Importance:

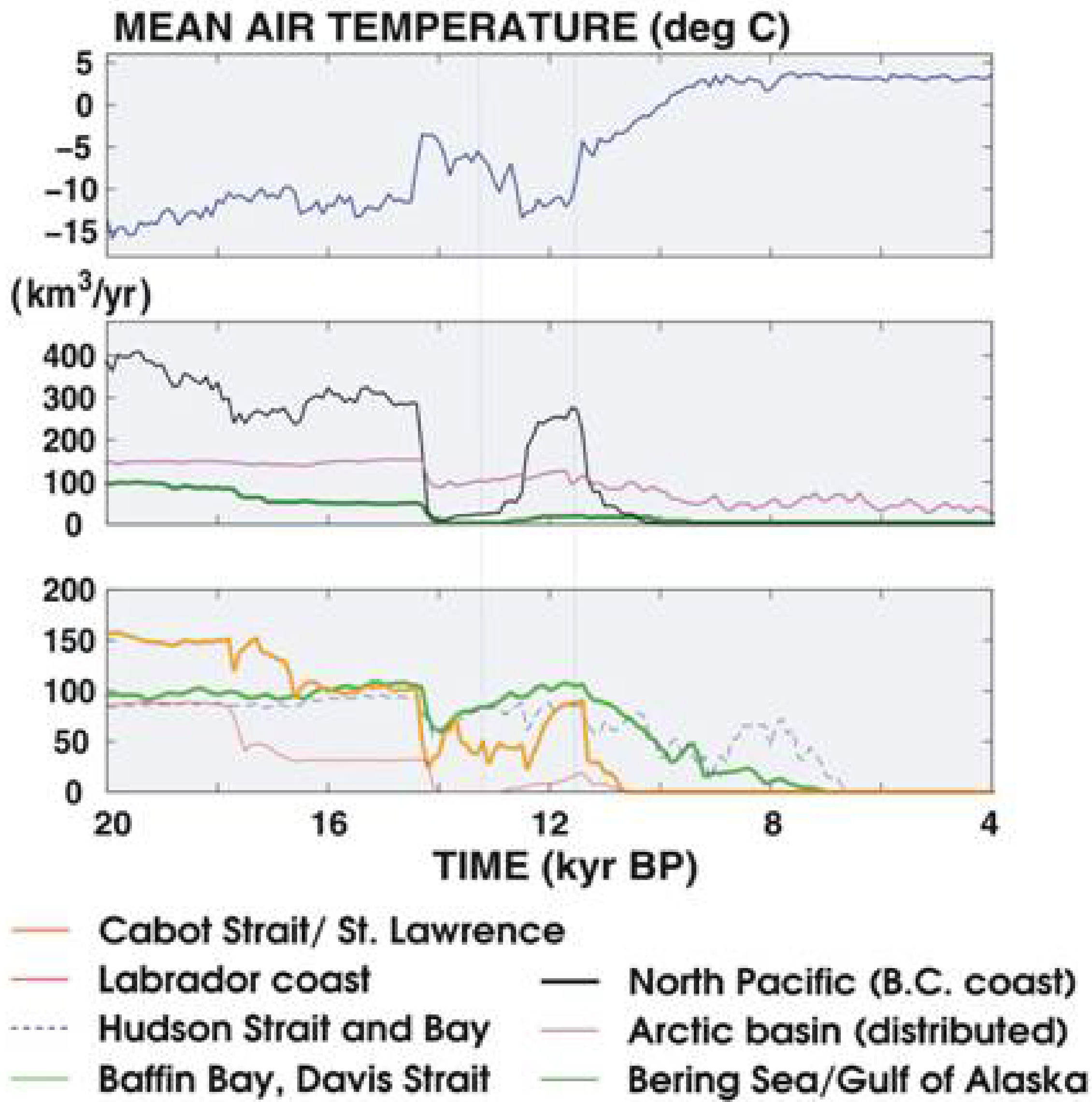
- Dominant mass loss term in Antarctica
- Rapid response to climate change?

Process Physics:

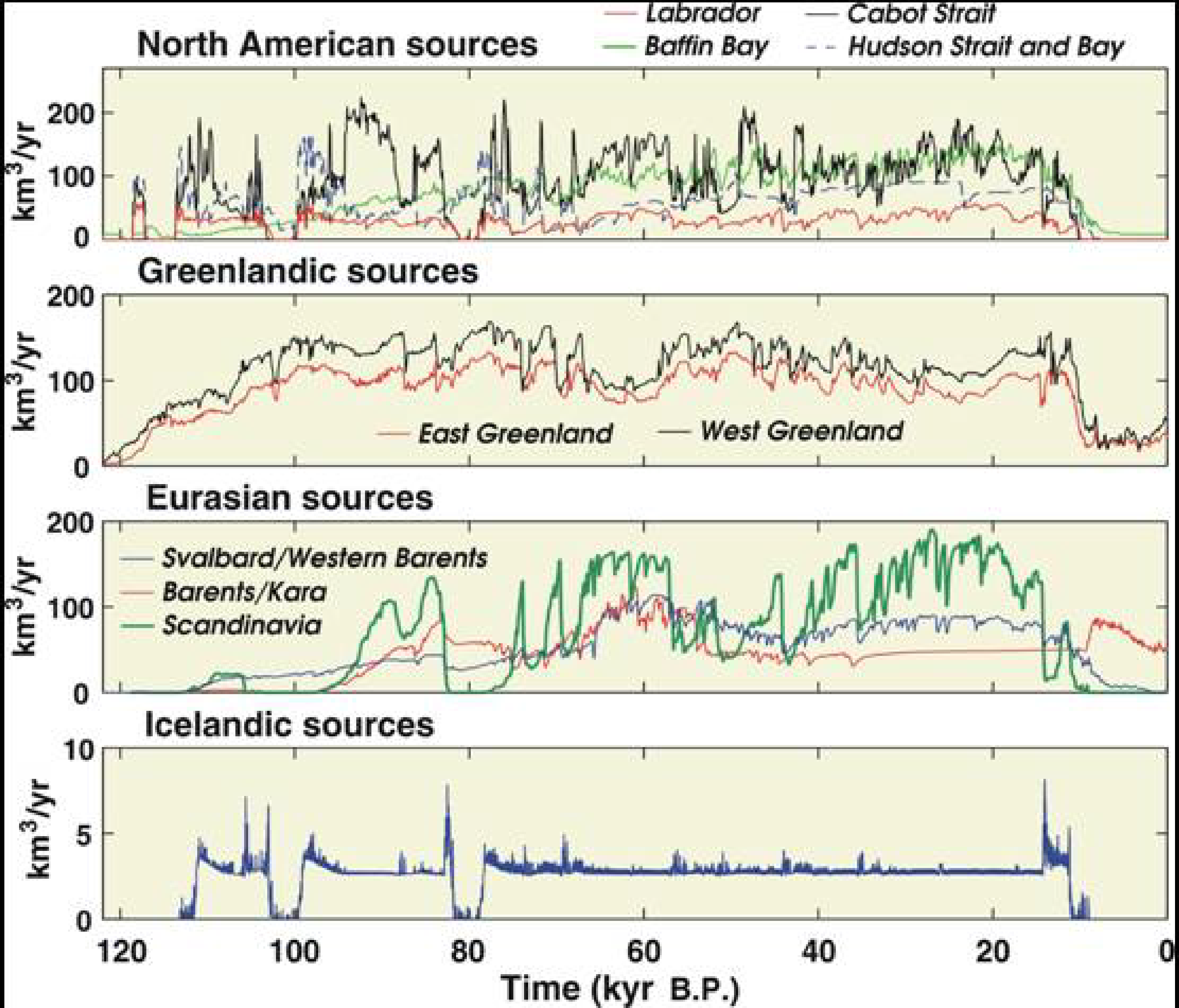
- Not yet quantified, possibly non-deterministic
- Involves 3D stress and temperature fields, fracture mechanics, water depth, open water season, and possibly water temperature, tidal amplitude

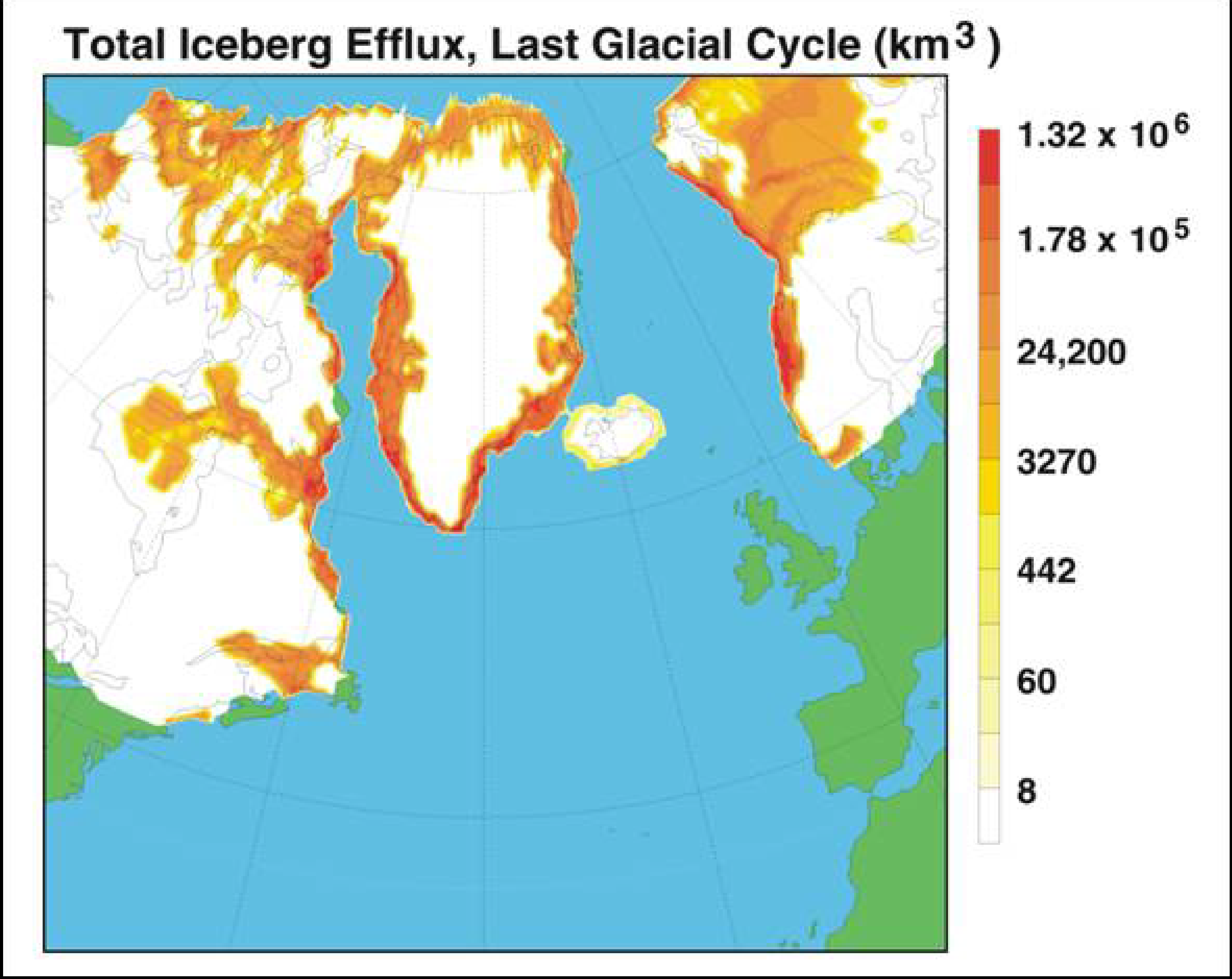
Modelled Iceberg Flux: Time Lag with Climate Forcing

Deglaciation, t = 20-4 ka



North Atlantic Iceberg Flux, Last Glacial Cycle



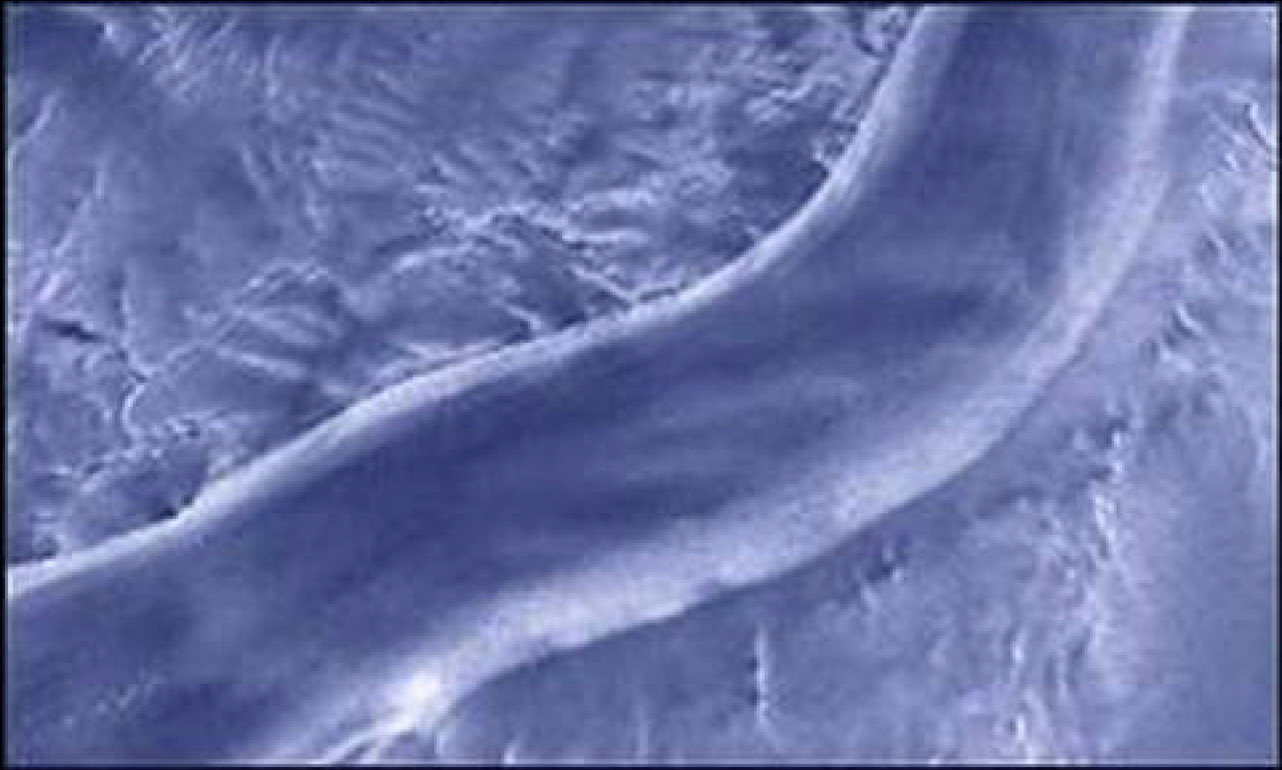


Total Iceberg Efflux, Last Glacial Cycle (km^3)
1.32 x 10^6
1.78 x 10^5
24,200
3270
442
60
8

Basal Flow and Ice Streams

Also on the map now

Definite challenges in both scale and process understanding



❄ Uncertainties: Basal Flow

Importance:

Ice streams are the main arteries of an ice sheet

Paleo-fast flow evidence abounds

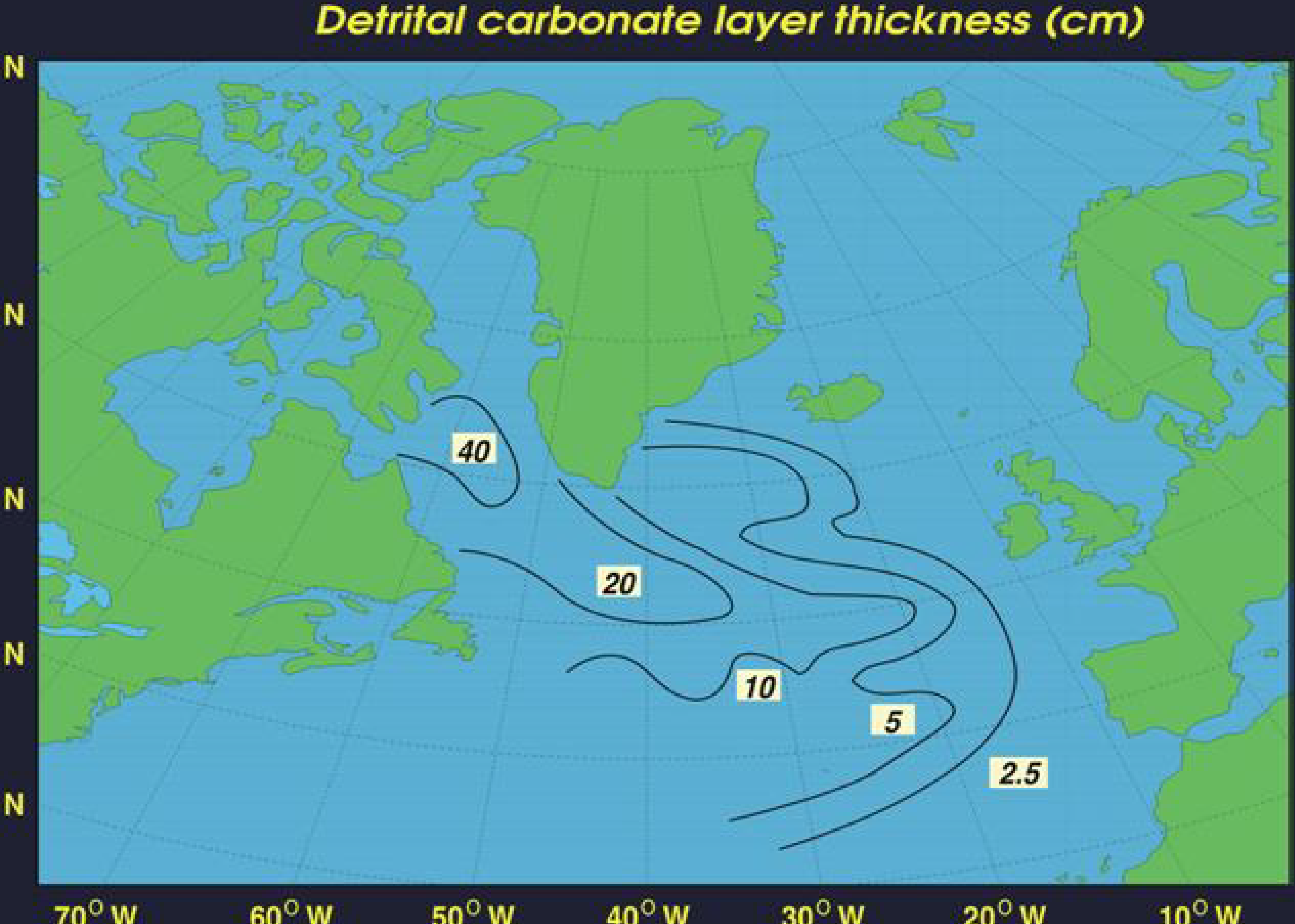
Main short-term influence on sea level, ocean freshwater balance

Process Physics:

Not yet quantified, probably non-deterministic

Involves ice and bed mechanics, basal temperature regime, subglacial hydrology, bed topography and geology

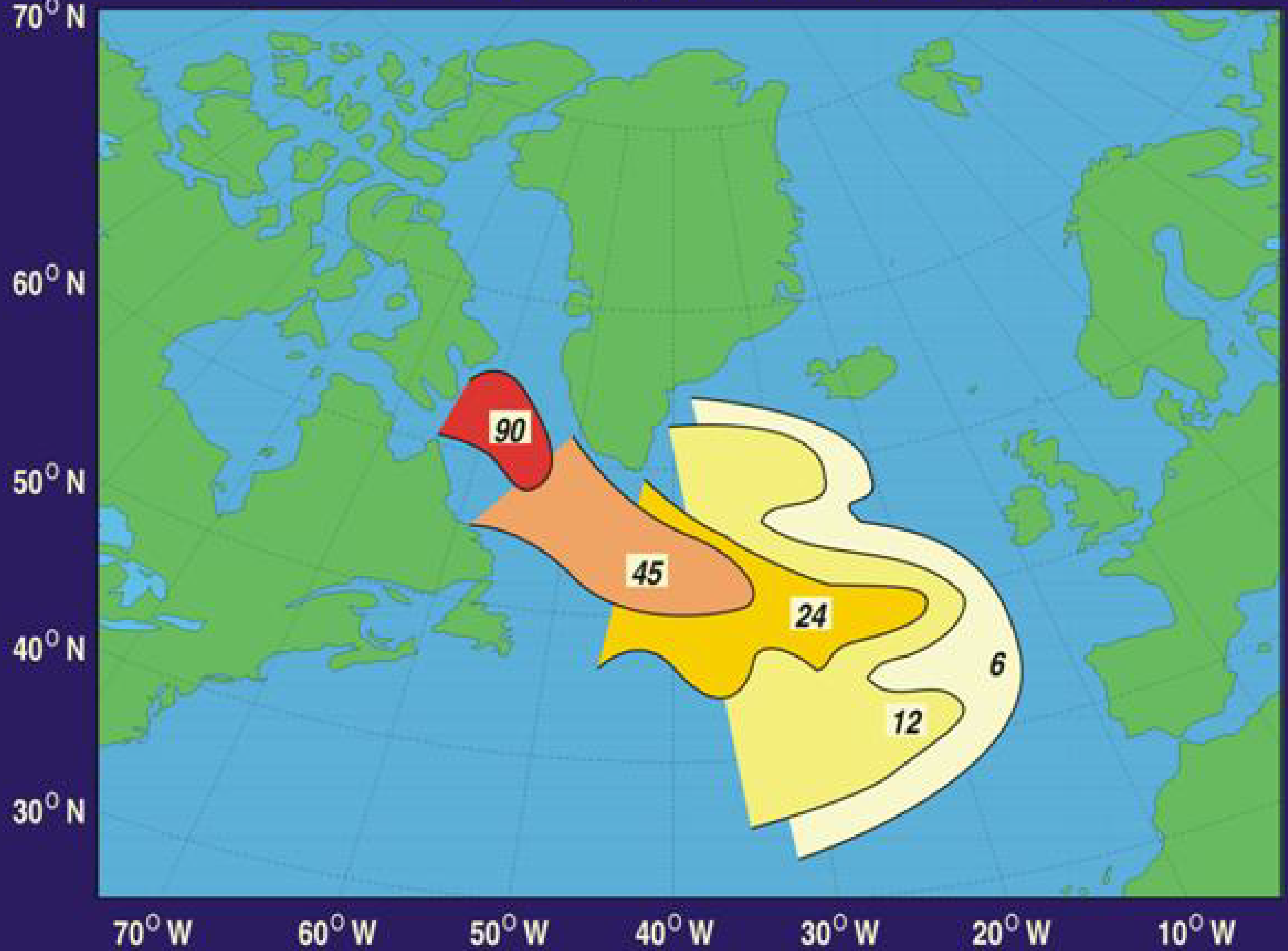
ICEBERG RAFTED DEBRIS IN A HEINRICH EVENT



After Dowdeswell et al. (1995)

ICEBERG FLUX IN A HEINRICH EVENT

Freshwater-equivalent melt rates (cm/yr)



Maximum surge scenario, Marshall and Clarke (1997)

4. Modelling sediment entrainment, transport, and deposition

Again, a lot of the relevant physical fields are currently modelled: basal stress regime, water pressure, temperature, basal flow

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Again, a lot of the relevant physical fields are currently modelled: basal stress regime, water pressure, temperature, basal flow

However, a relatively untouched field:

→ geological substrate must be characterized
→ process scale << model scale
→ process physics challenging
→ process physics involve some glaciological fields that are not well-characterized, e.g. water pressure fluctuations

Simple approaches still insightful:

e.g. erosion modelling,

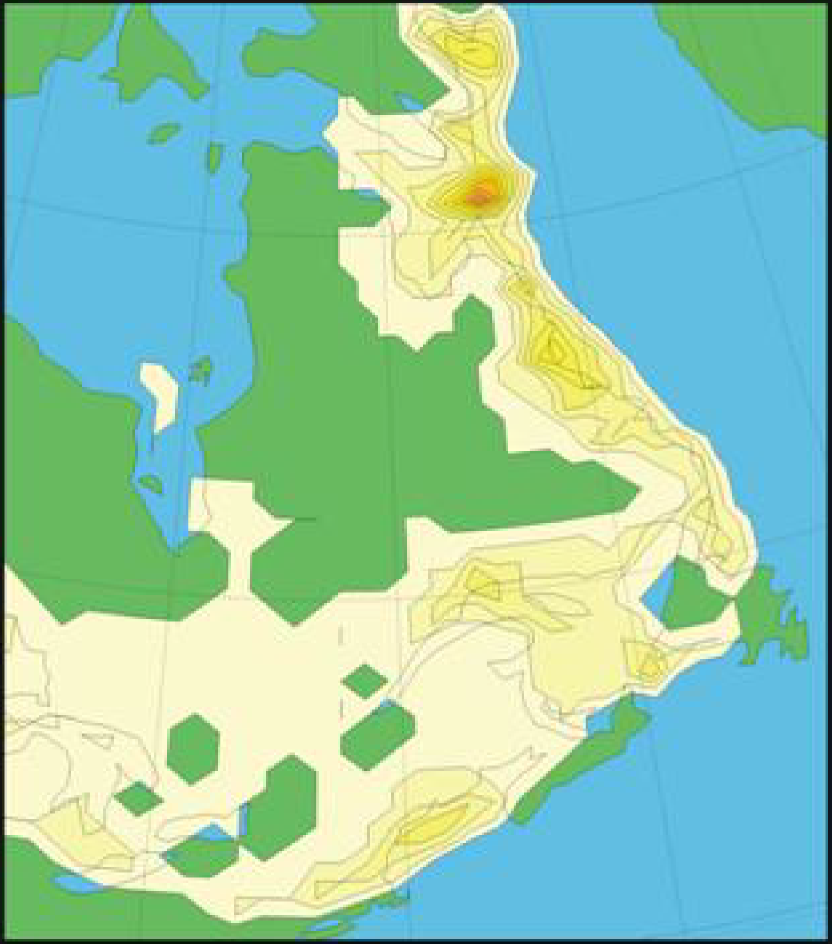
$$E(\lambda,\theta,t) \propto E_0(\lambda,\theta)\int f\left[v_{bj}(\lambda,\theta,t),\tau_{bj}(\lambda,\theta,t)\right] dt$$

One can experiment with erosion models $f\left[v_{bj}(\lambda,\theta,t),\tau_{bj}(\lambda,\theta,t)\right]$ and consider freeze-on & regelation (T,P) entrainment processes, etc.

→ Advect with the ice or the subglacial drainage

Last Glacial Cycle in Quebec/Labrador

Potential Erosion



Easterly Striations

Last Glacial Cycle in Quebec/Labrador

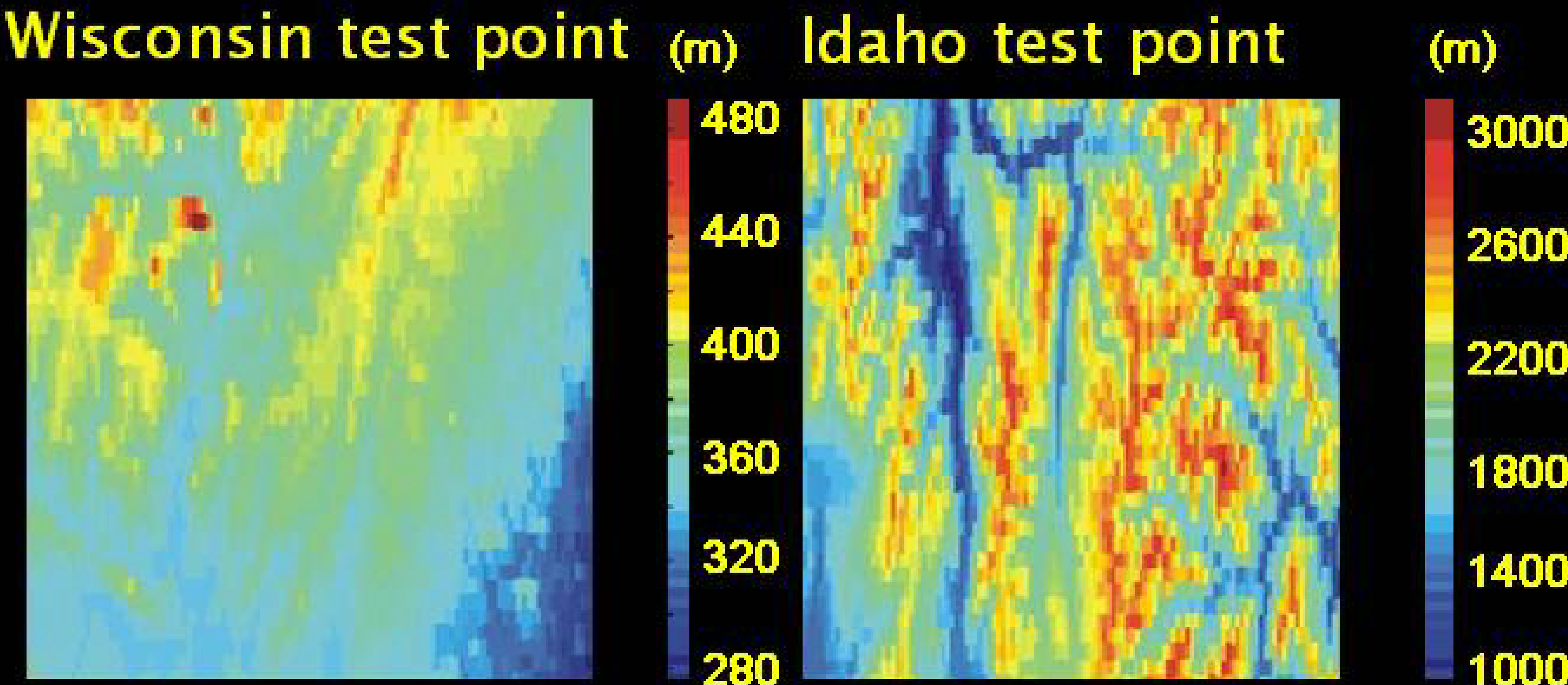
Southerly Striations

Westerly Striations

5. Scale Issues: Ice Sheets vs. Glaciers

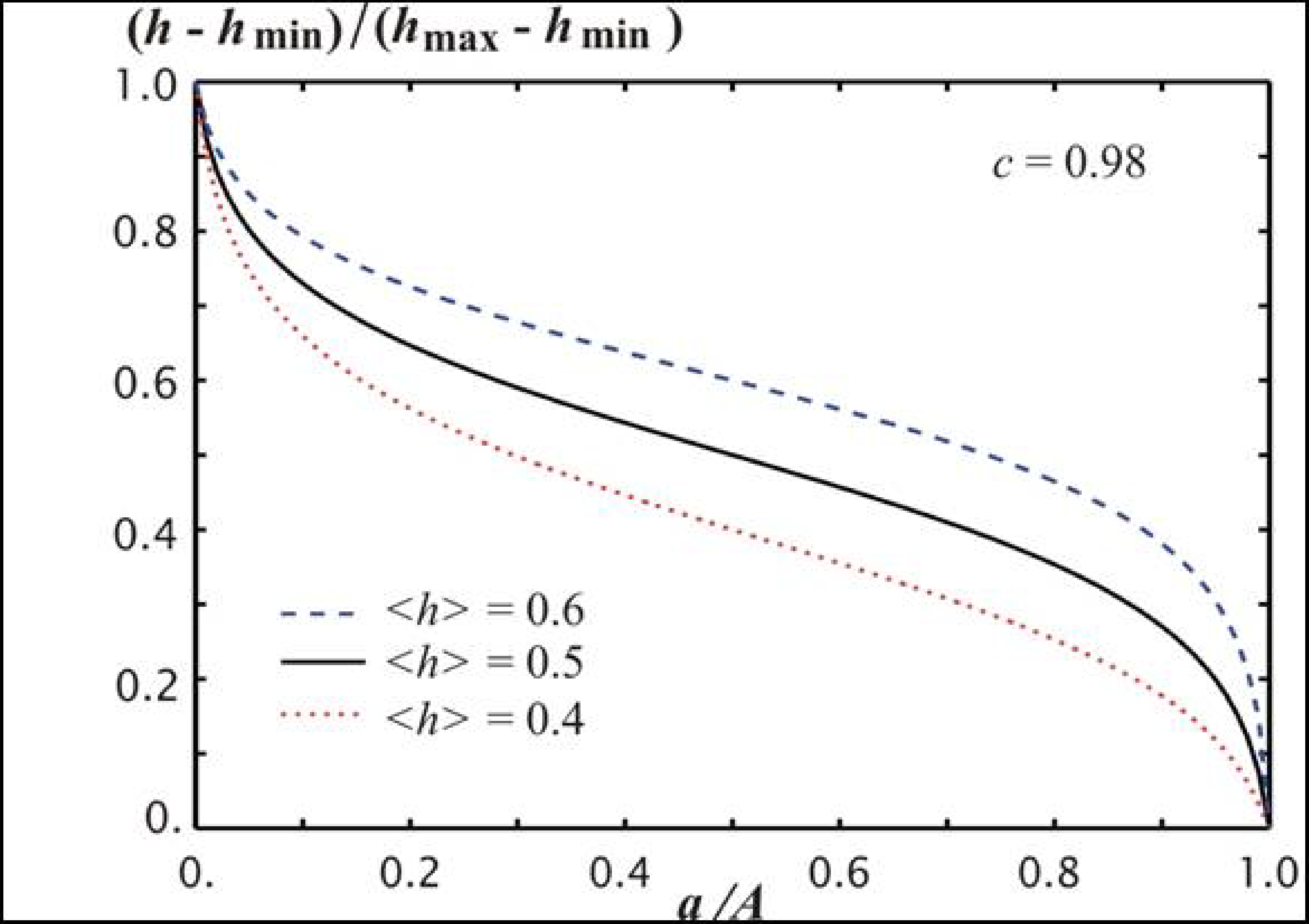
- Limitations to application of large-scale ice sheet models: $\Delta x > \sim 3H$
- Higher-order dynamical models have been developed, esp. for 1d modelling; so we're OK on the scale of individual glaciers.
- Harder: 2d and 3d simulation in complex terrain. Will get there though.

Topographic Demeanor

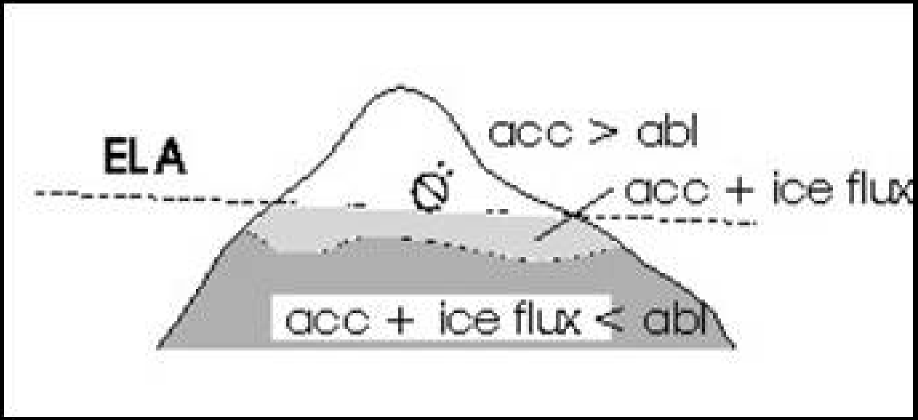


1-Degree Cells

Synthetic Hypsometry Function

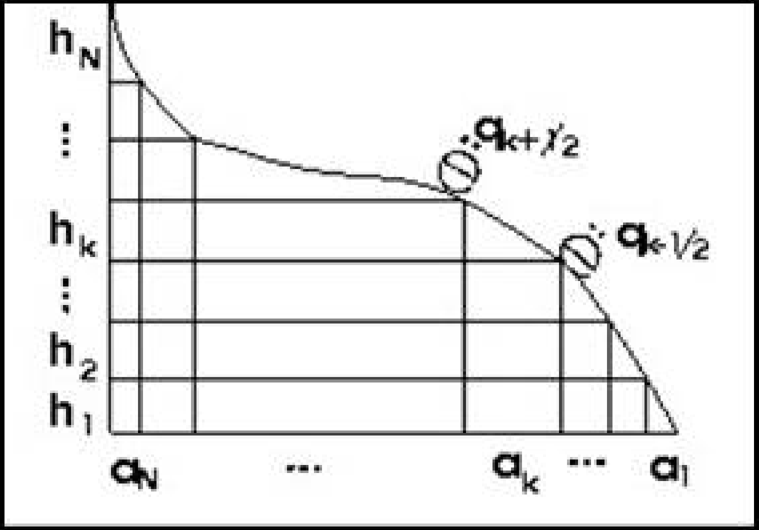


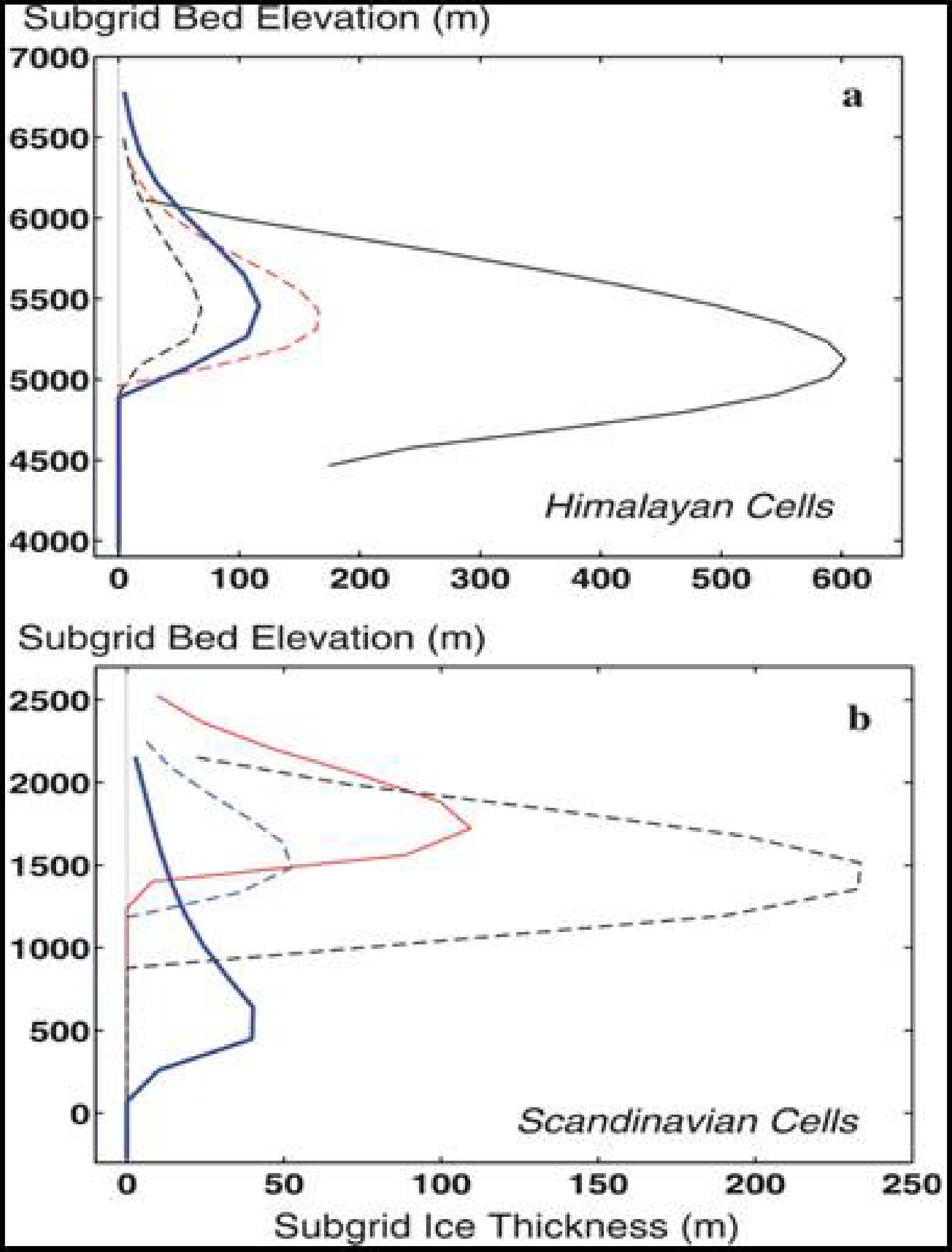
Subgrid Scheme



Downslope grid transport in subgrid bins

$$q_k = (H_k + \int b_k \, dt) / \tau$$
$$[\, 1 - \exp(-(\Delta h_{sk}/L_k)^3) \,]$$





Subgrid Ice Distribution

Sample Synoptic Grid Cells

Summary

- Good timing to incorporate glacial process models into the CSM strategic plan
  - → the relevant process considerations and large-scale outputs are on the glacial modellers' module list
- As ice sheet models GCMize, there is a new need for top-down co-ordination in the glacial modelling world
- Glaciologists need help with this
  - → data to constrain, process understanding

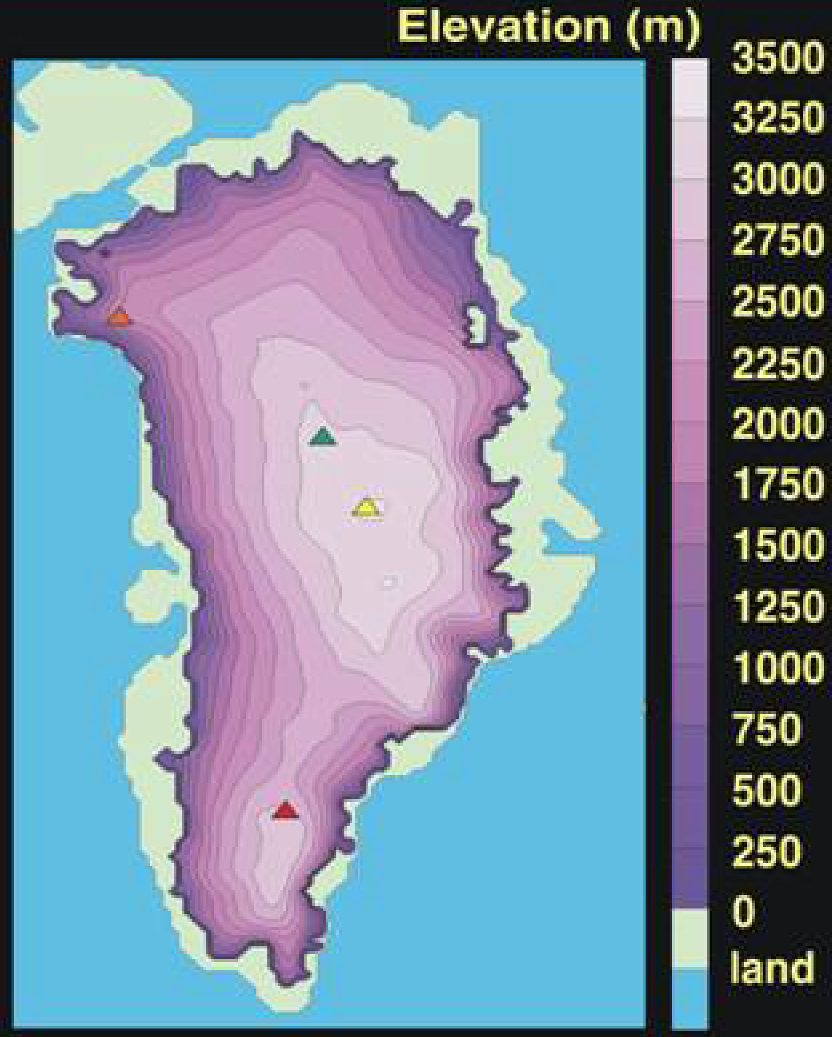
1. Basis of Ice Sheet Modelling

- Continuum-mechanical models of ice deformation under gravity
- Several 3D models in the world; resolve 3D velocity, temperature, stress fields as well as ice sheet thickness (t)
- Typically FD or FE, 5-100 km resolution
- Other approaches: flowline or planform models that permit higher resolution and in some cases, higher-order dynamics

2. *Current State of the Art – Strengths*

- General success with large-scale ice area and volume (Greenland, Antarctica).
- Good on time evolution, e.g. glacial cycle simulations. Possible to run for *O* (Ma).
- Well-integrated with climate and isostatic models.
- Considerable experience; intercomparisons and benchmarks established.

Greenland Deep Ice Cores



Summit (GRIP, GISP2)
Camp Century
NGRIP
Dye 3