Continental Hydrology, Rapid Climate Change, and the Intensity of the Atlantic MOC: Insights from Paleoclimatology

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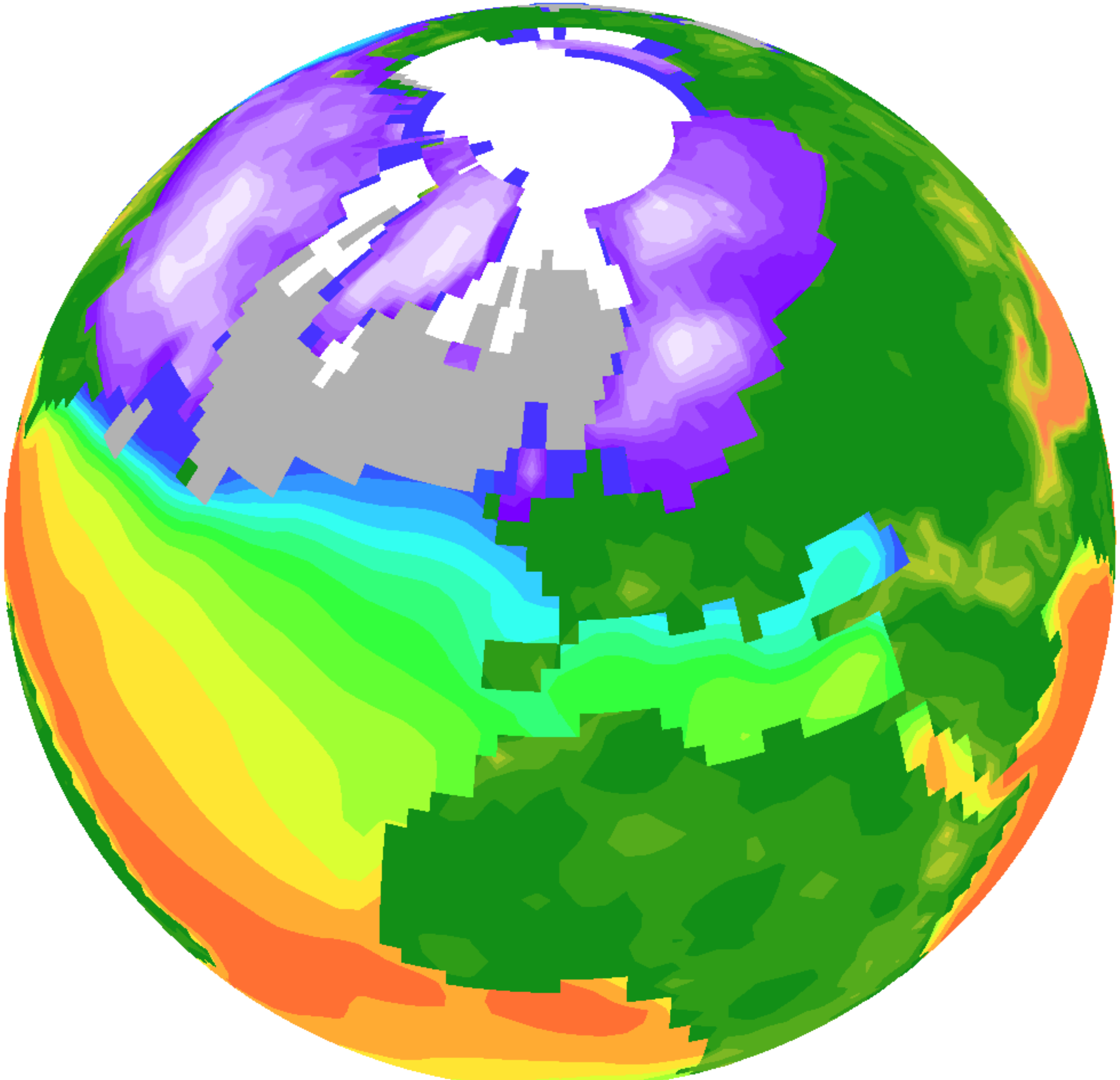
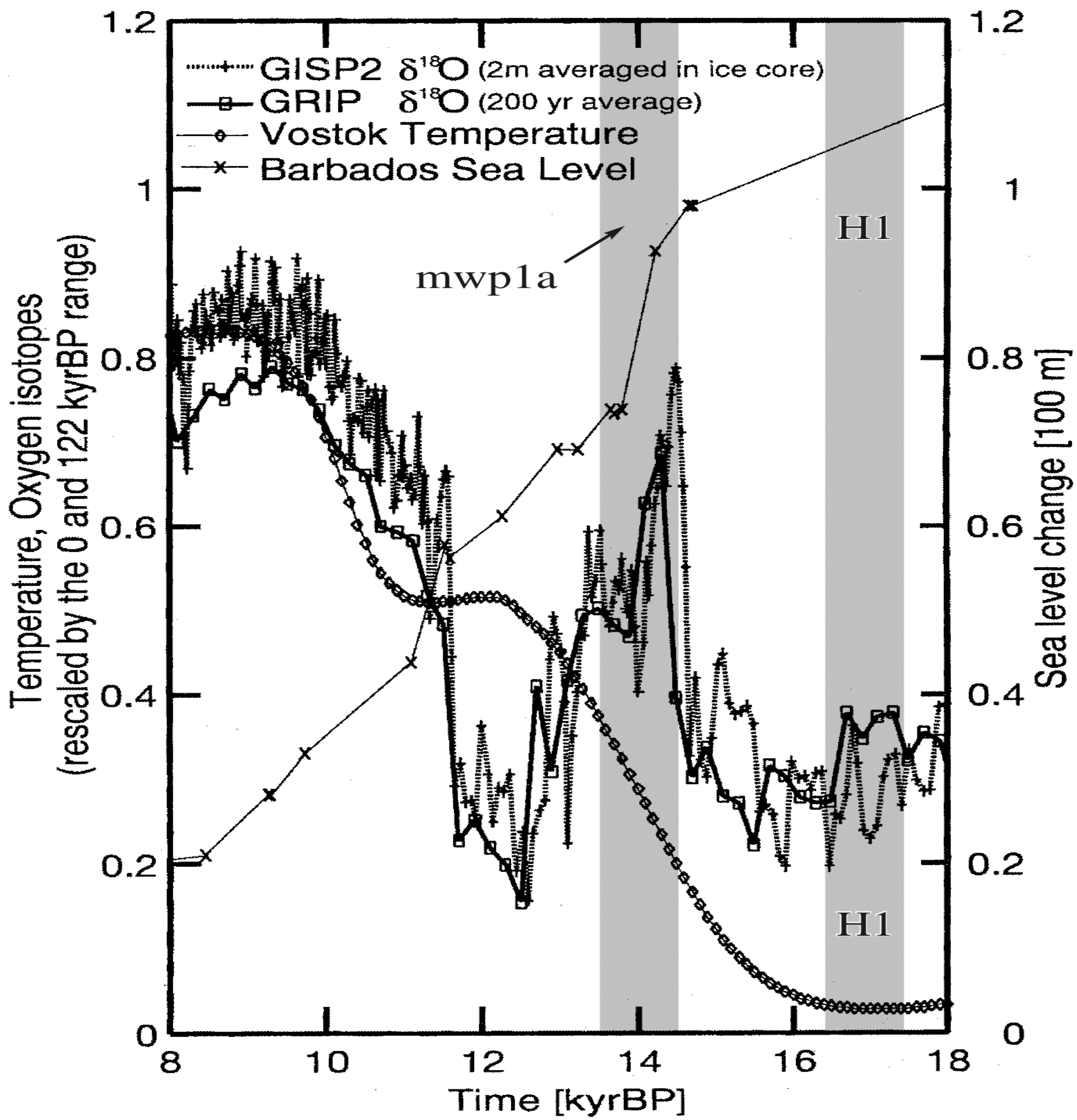
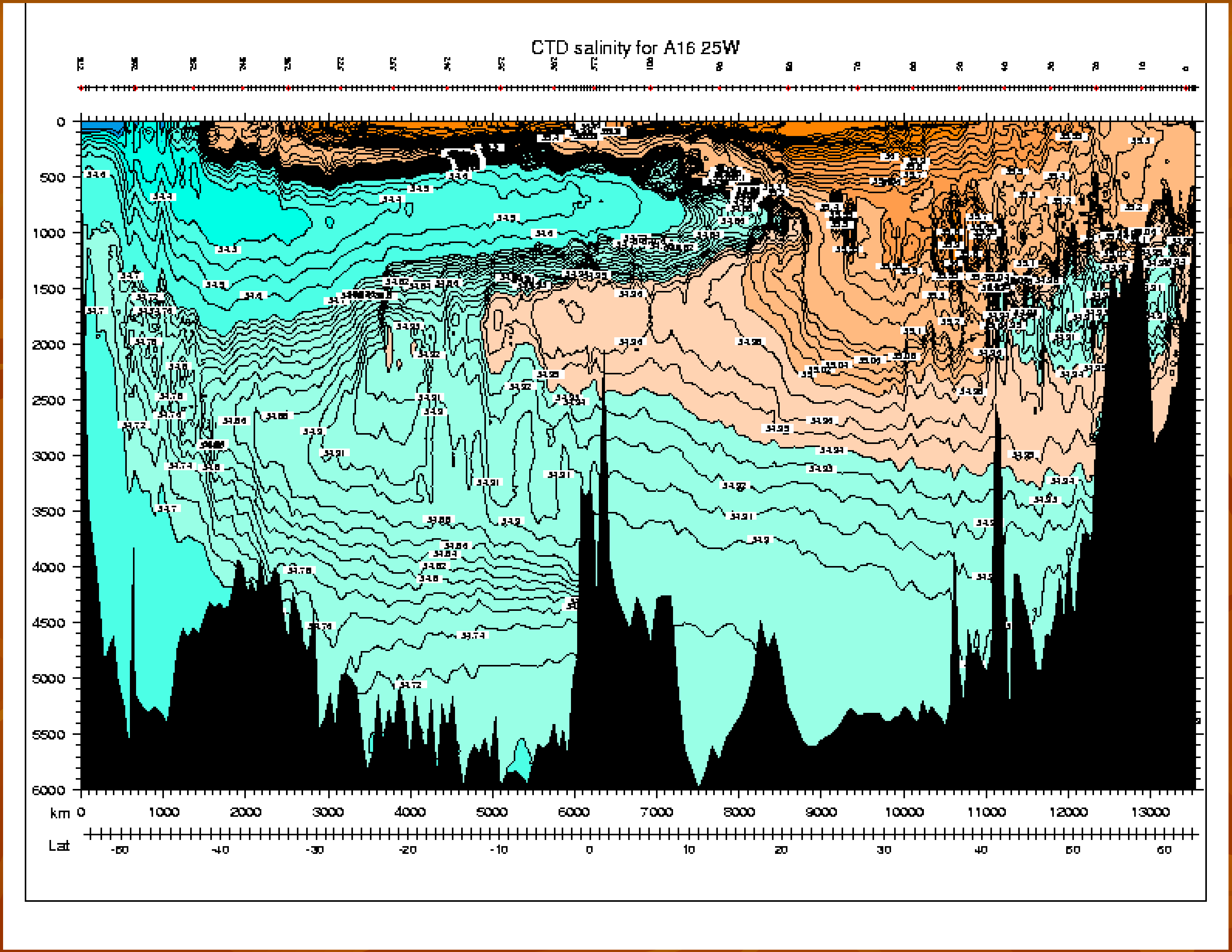
LGM Ice Extent and SST

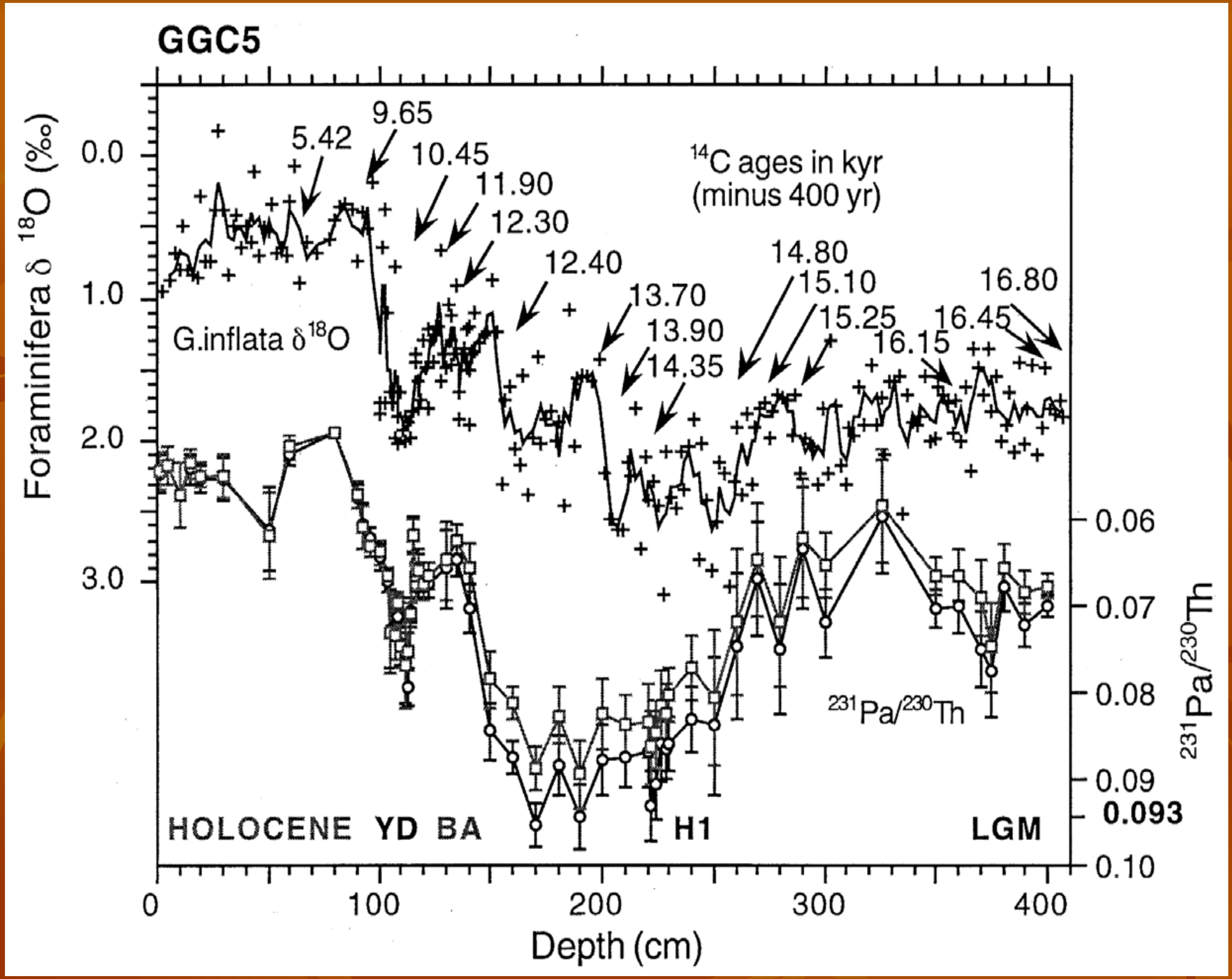




GISP2 $\delta^{18}O$ (2m averaged in ice core)
GRIP $\delta^{18}O$ (200 yr average)
Vostok Temperature
Barbados Sea Level
mwp1a
H1
H1
Temperature, Oxygen isotopes
(rescaled by the 0 and 122 kyrBP range)
Sea level change [100 m]
Time [kyrBP]
1.2
1
0.8
0.6
0.4
0.2
0
8
10
12
14
16
18

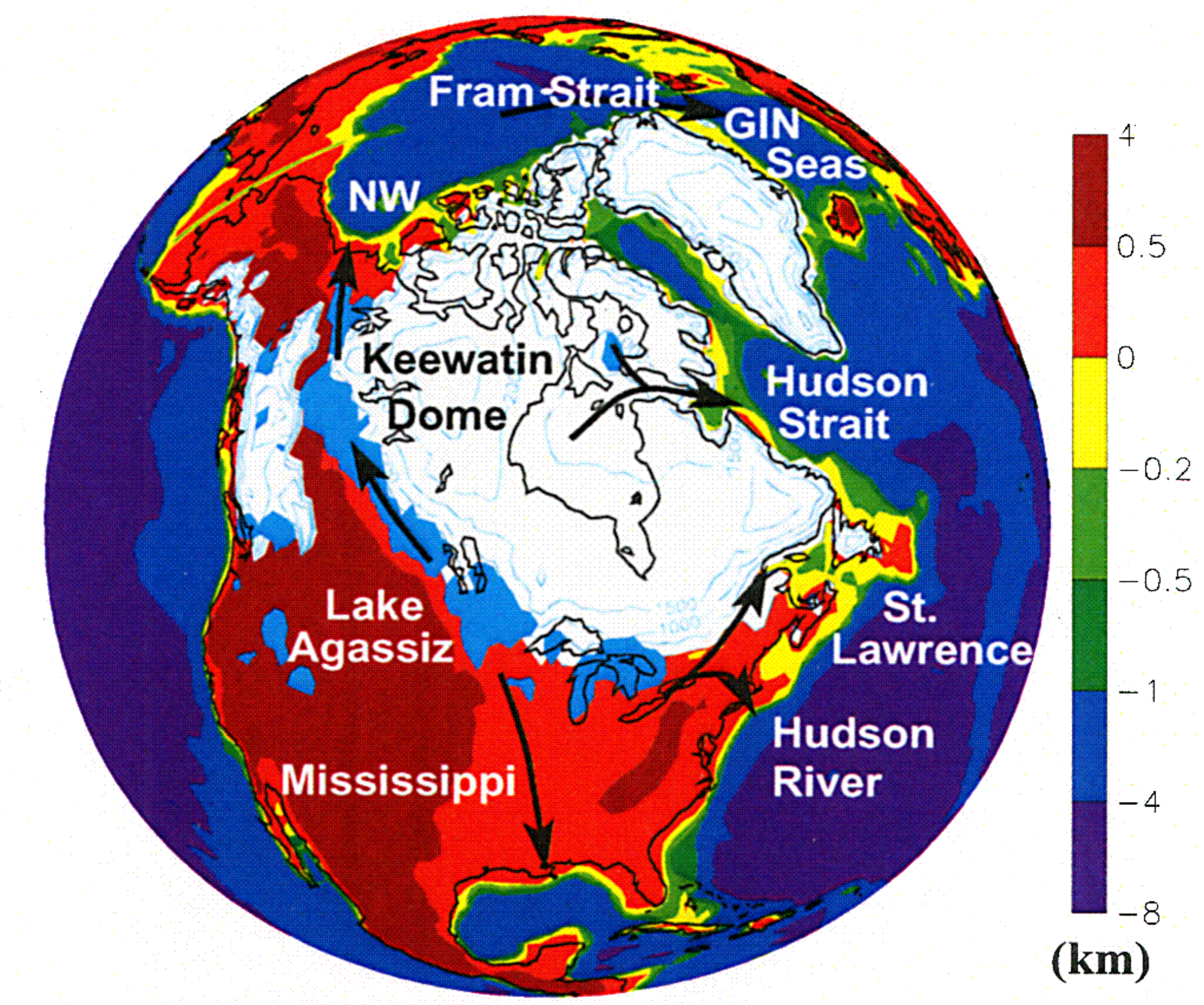


WOCE derived N-S salinity section through the Atlantic Ocean Basin



From McManus et al. (Nature, 2004)

North American ice cover and pro-glacial lakes just prior to the onset of the Younger-Dryas cold reversal



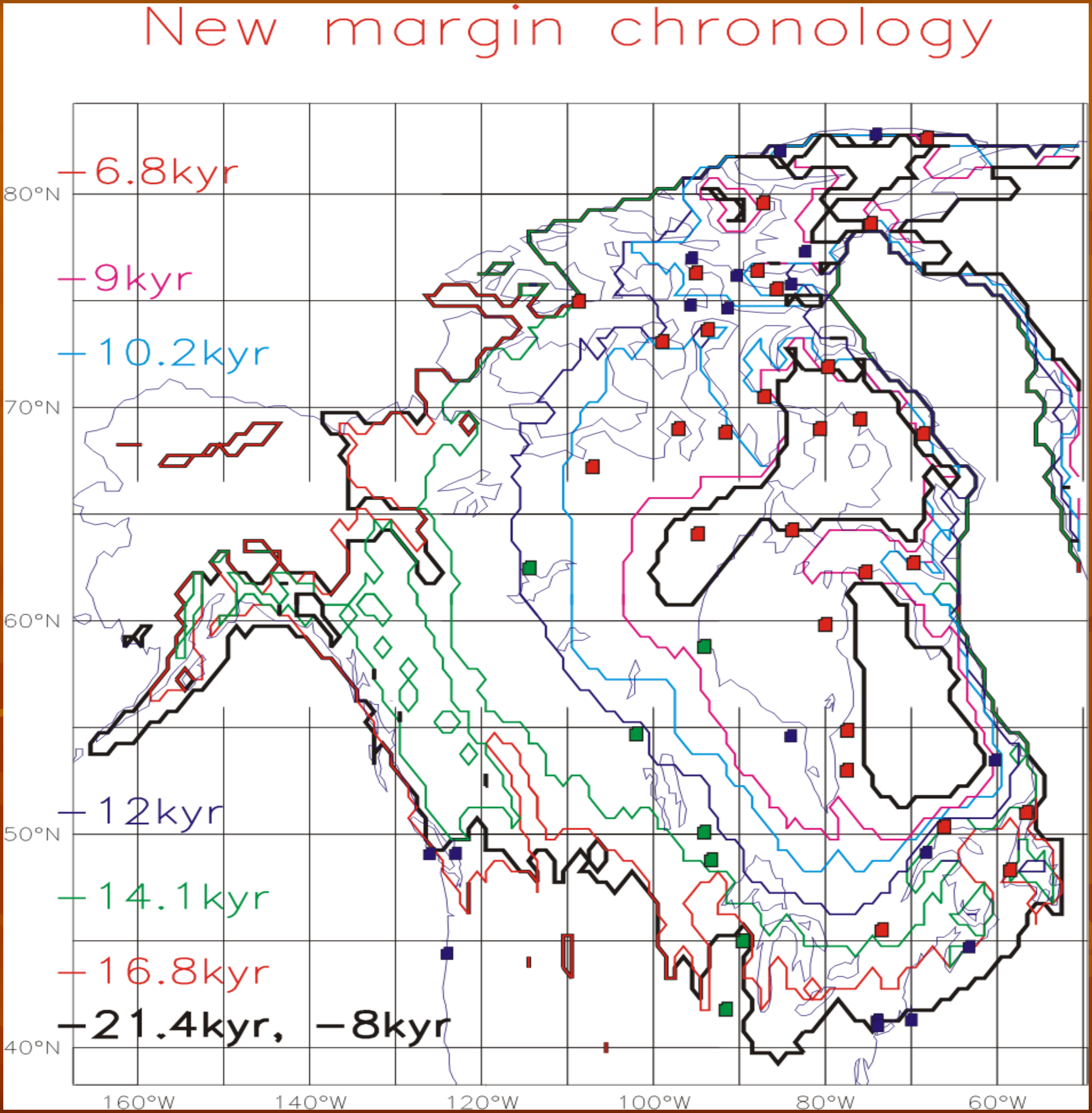
North American deglacial drainage

Outline

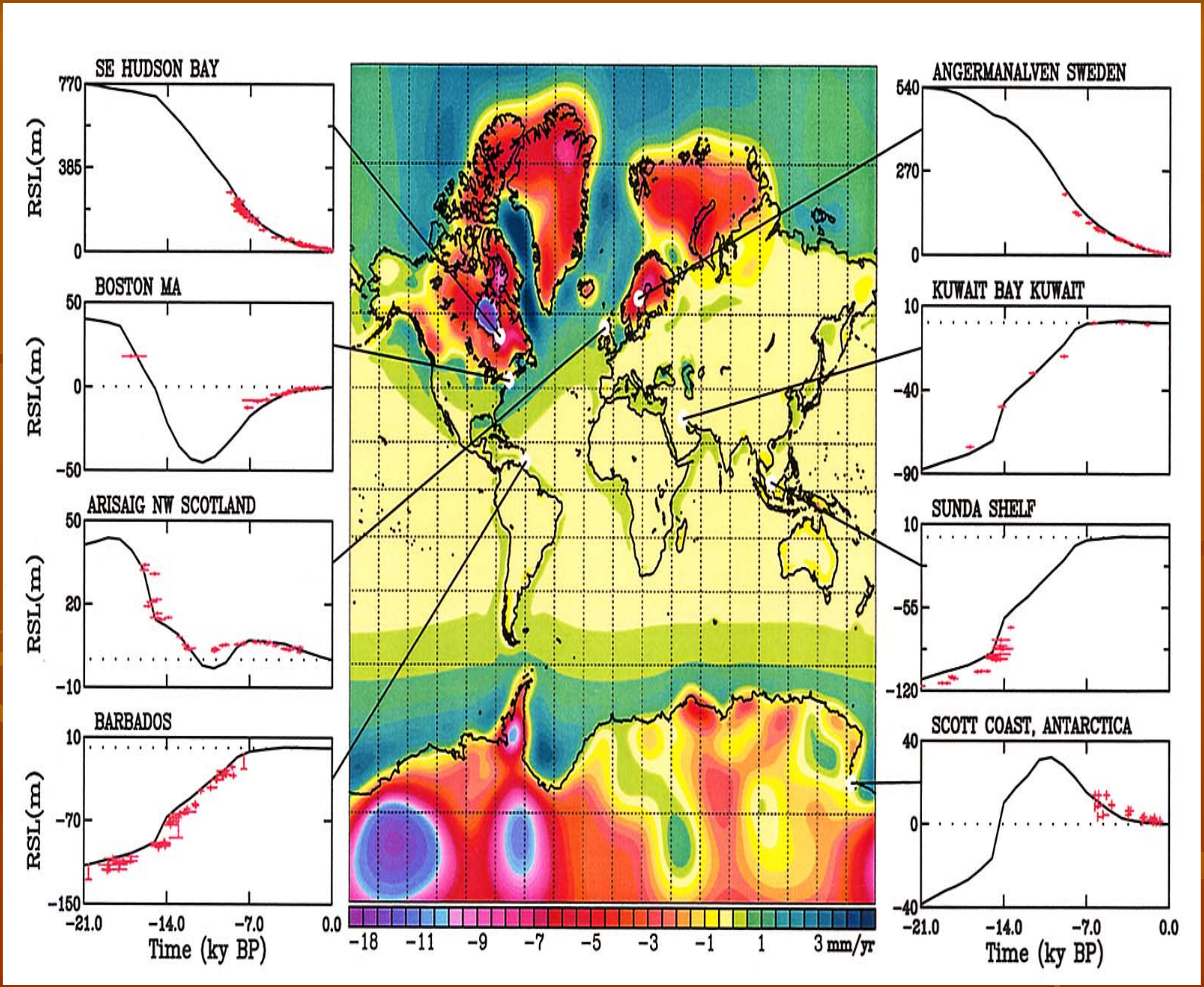
- Motivation: Although the origin of the Younger-Dryas cooling event is widely understood to have been due to a sharp reduction in the strength of the Atlantic MOC, there is no consensus as to the geographical routing of the runoff from the continents that was the ultimate cause.
- Constraining models of continental deglaciation: geological, geophysical and geodetic observations.
- Runoff routing during North American deglaciation: detailed ice mechanical reconstructions of ice sheet evolution—AN ARCTIC TRIGGER FOR THE Y-D.
- Arctic vs. Atlantic “hosing” and the shutdown of the MOC.
- Summary

Quantitative Constraints on Continental Scale Ice Sheet Reconstructions

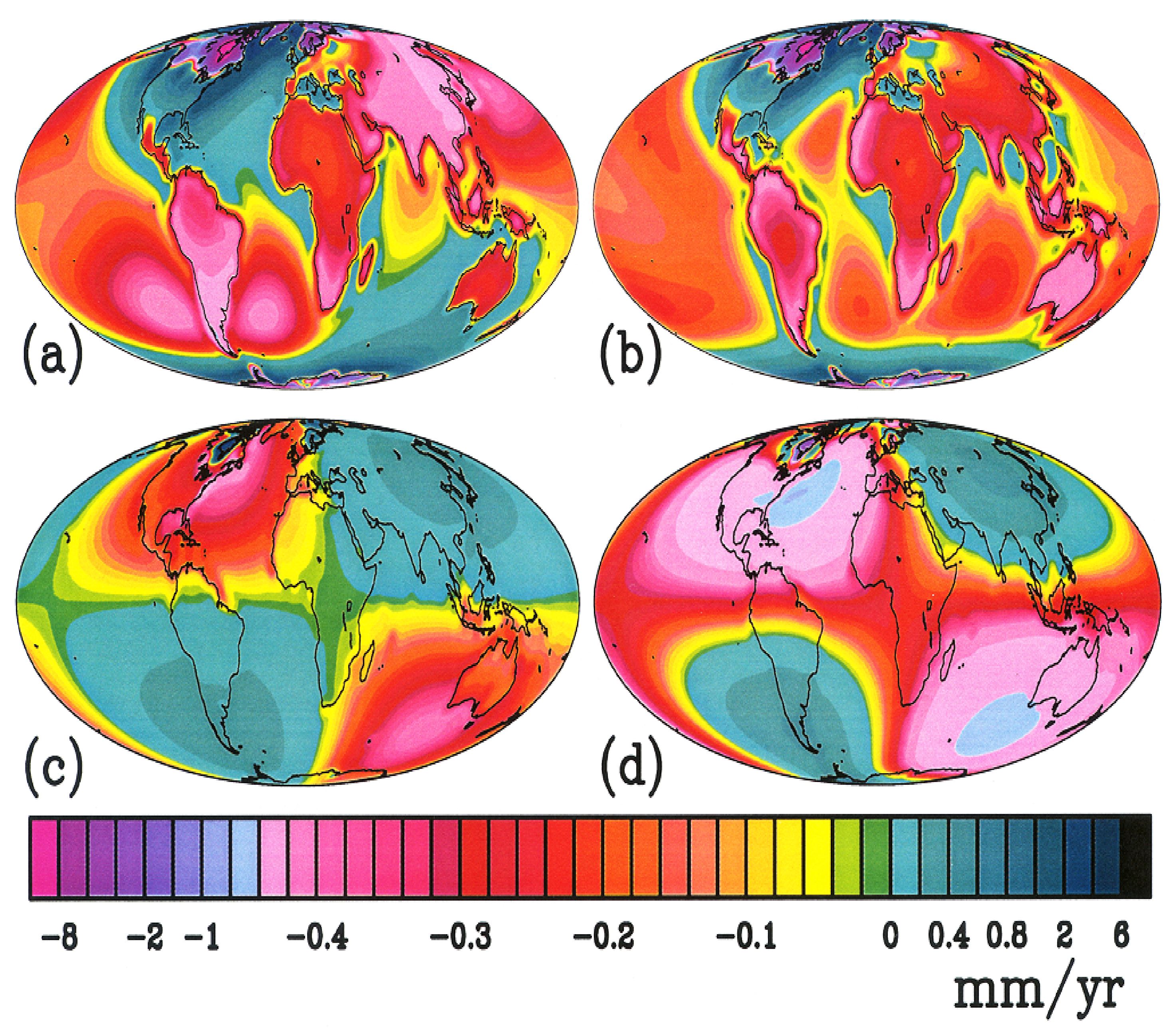
In the Toronto data base of post glacial RSL histories there are several hundred 14C dated Holocene time series that may be employed to calibrate a model of continental scale ice sheet evolution, as well as, from A. Dyke, a refined data set of margin positions



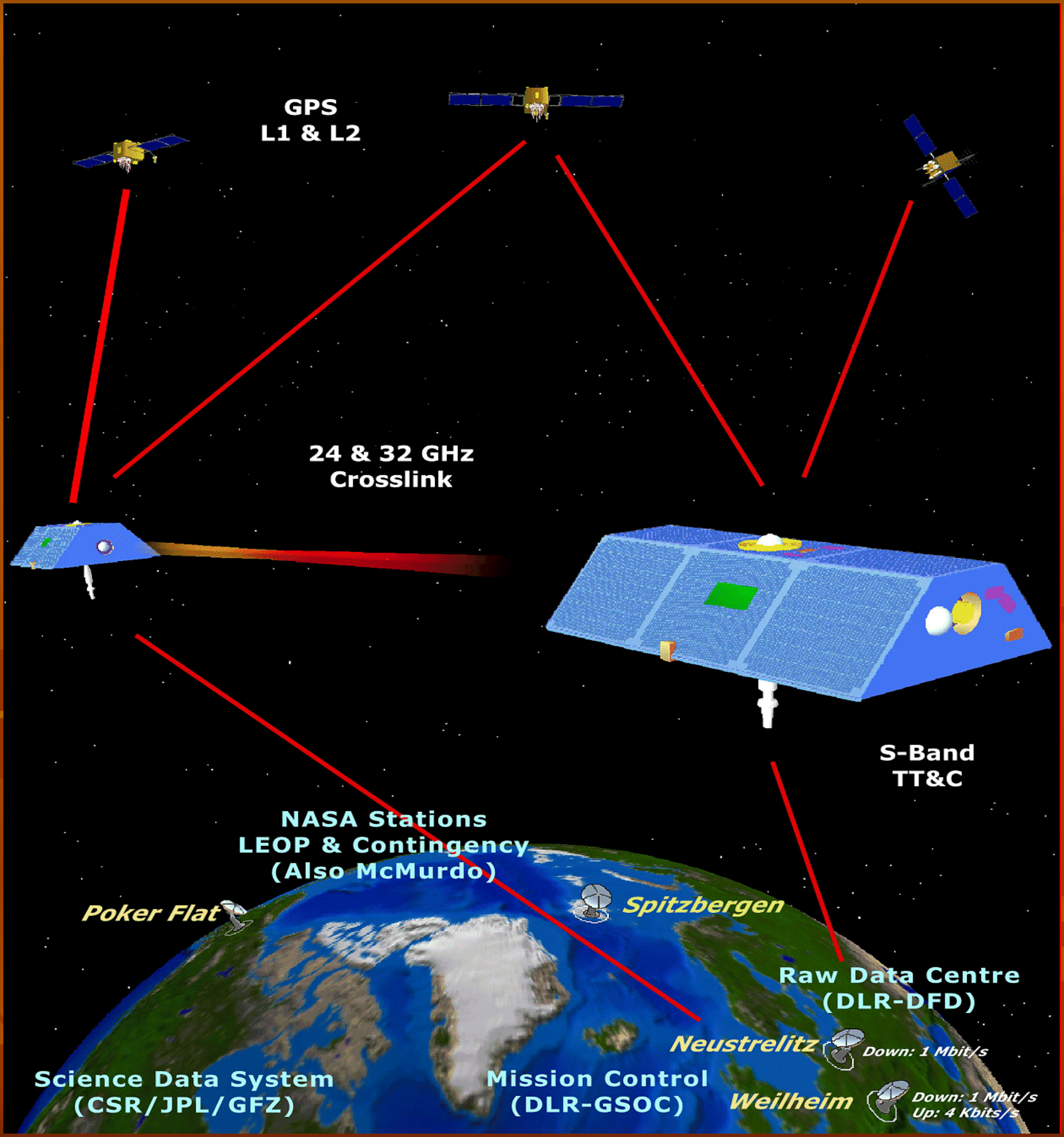
From Physics Today, 2002



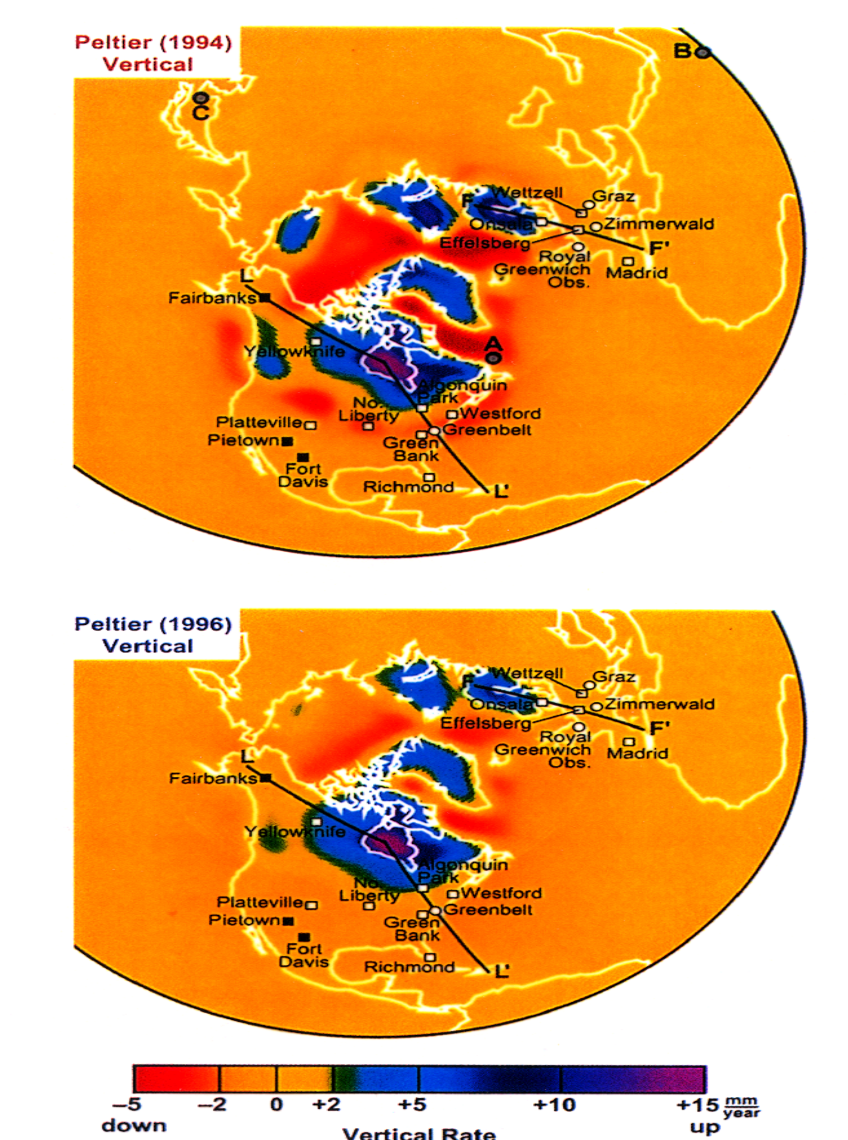
The present day rate of global sea level rise predicted to exist as a consequence of glacial isostatic adjustment alone, both including (a) and excluding (b) the influence of rotational feedback. The difference is shown in (c) and geoid height time dependence in (d).

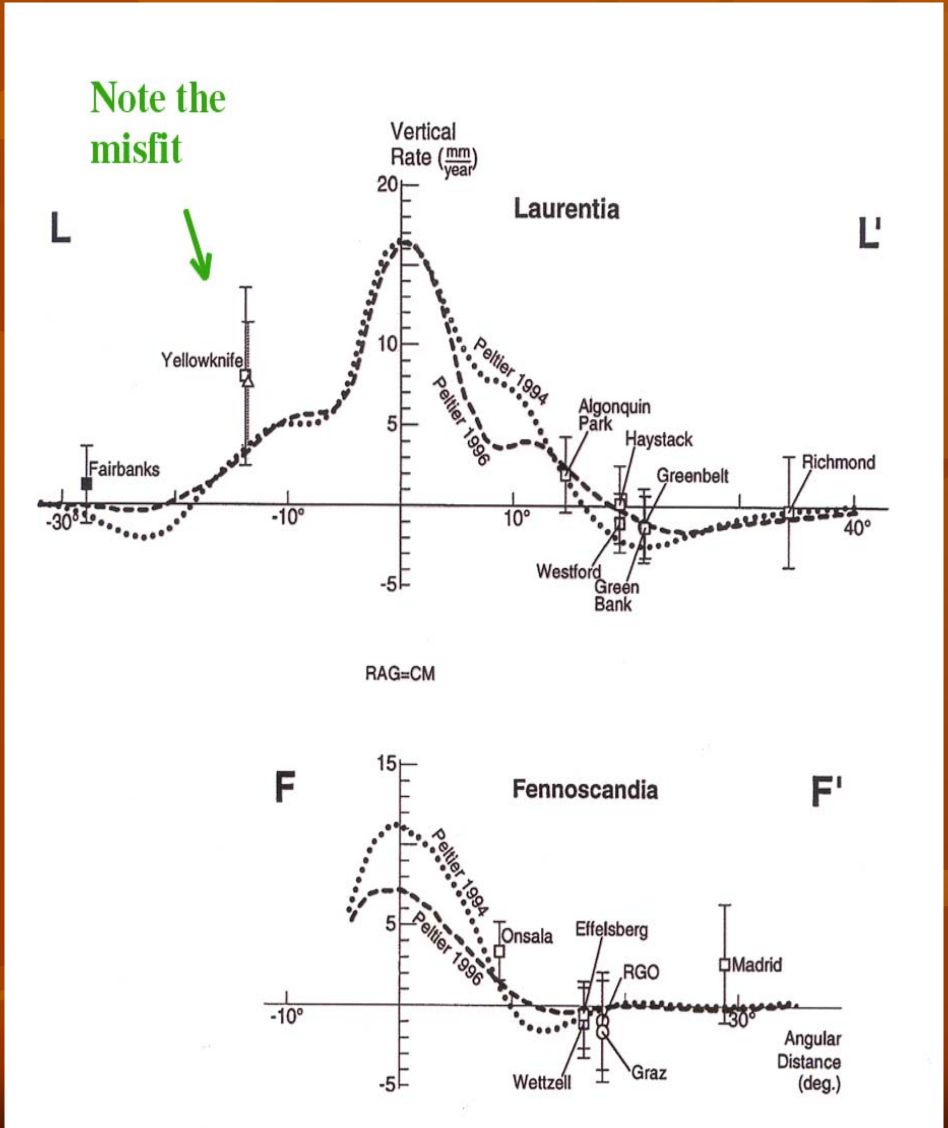


The dual satellite Gravity Recovery and Climate Experiment (GRACE) is now in space and is expected to provide fundamental insights into the magnitude and spatial variability of the modern rate of global sea level rise.

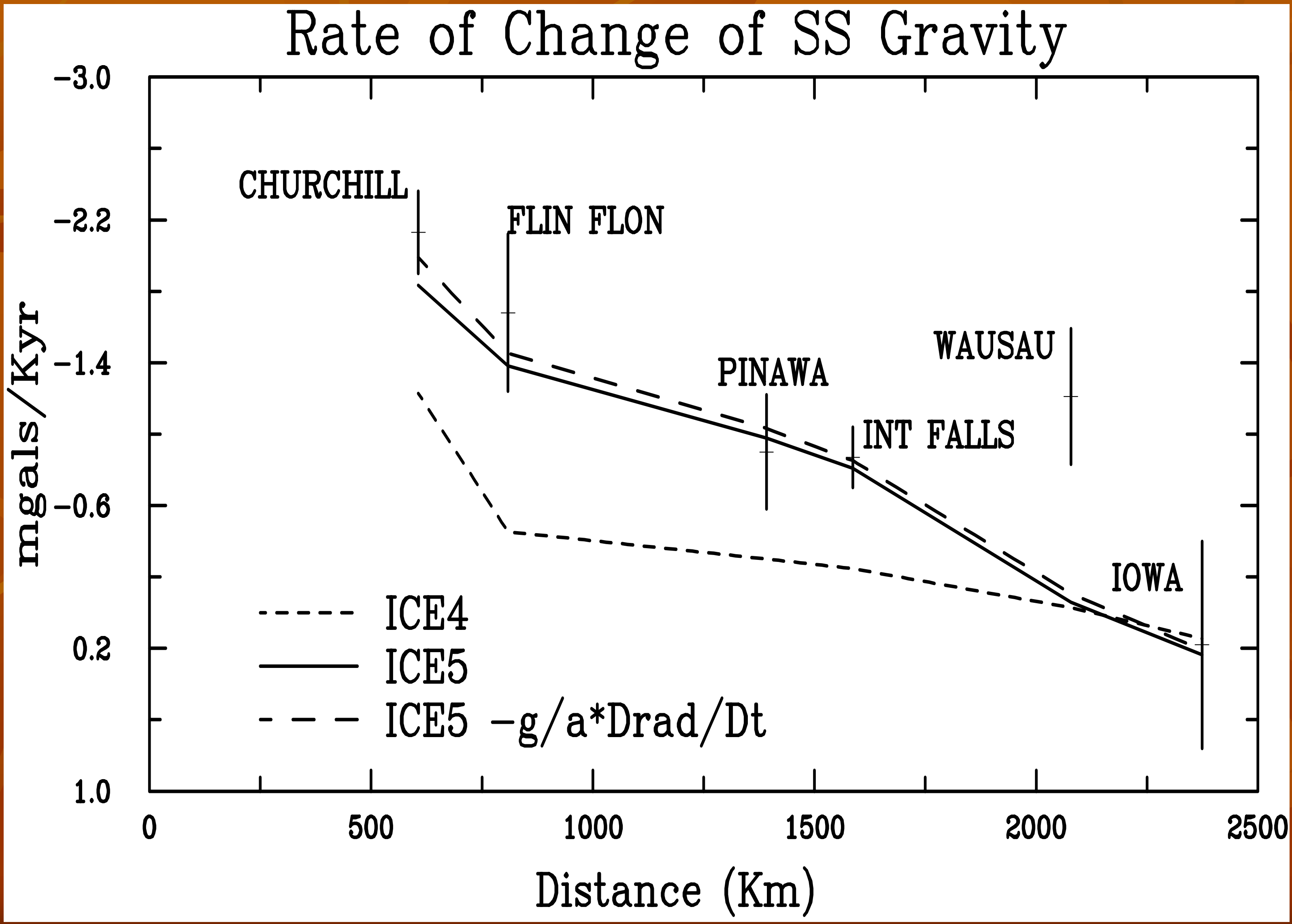


Space Geodetic constraints on ice thickness

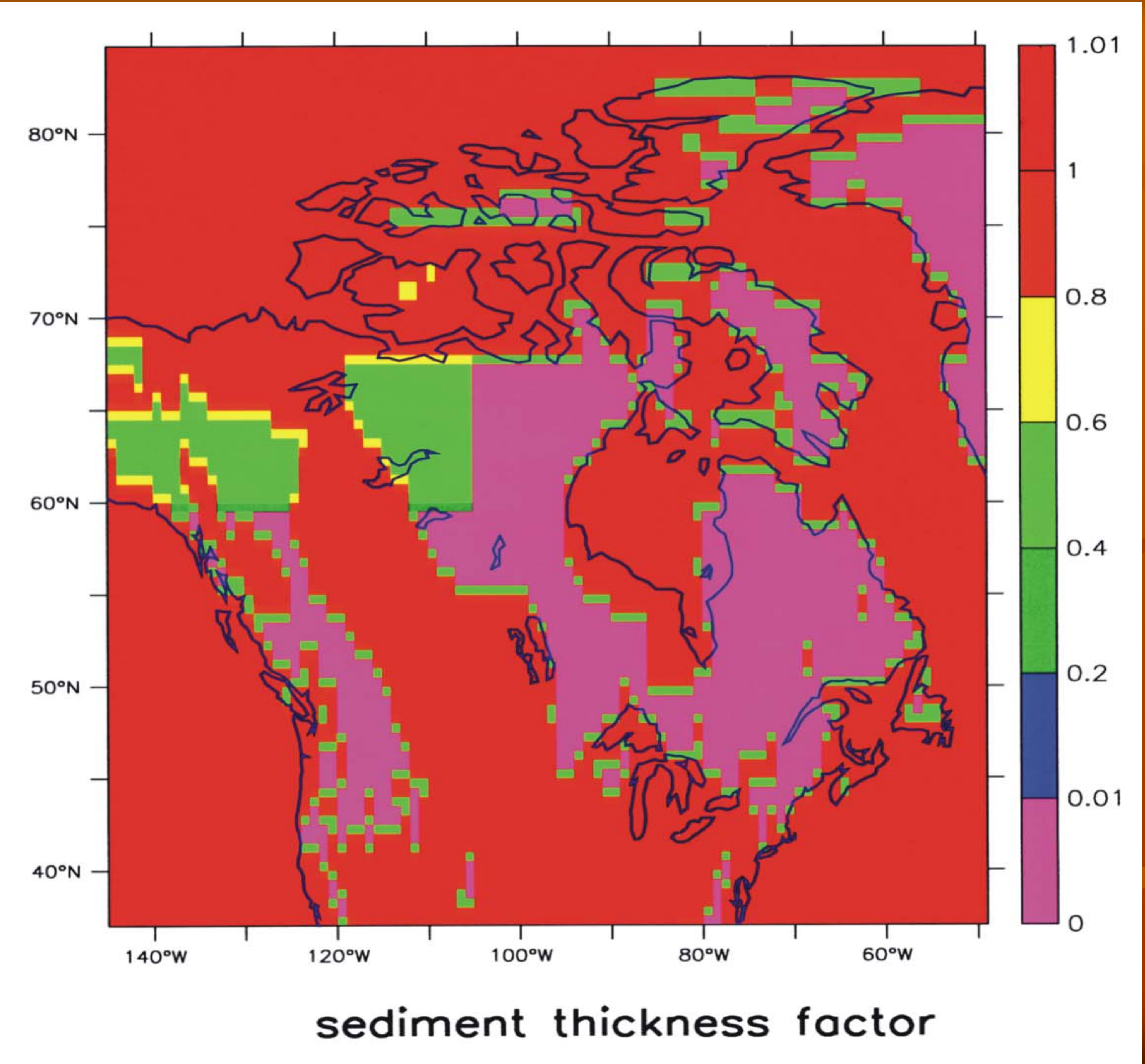




Absolute Gravity Constraints

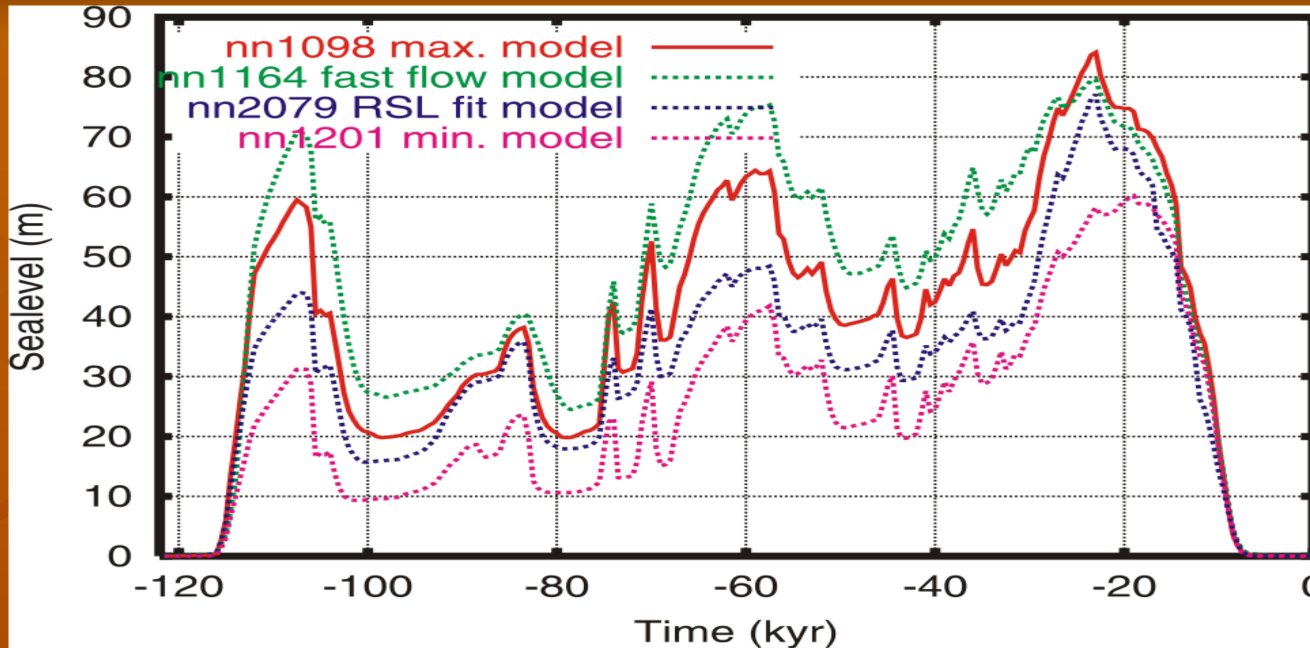


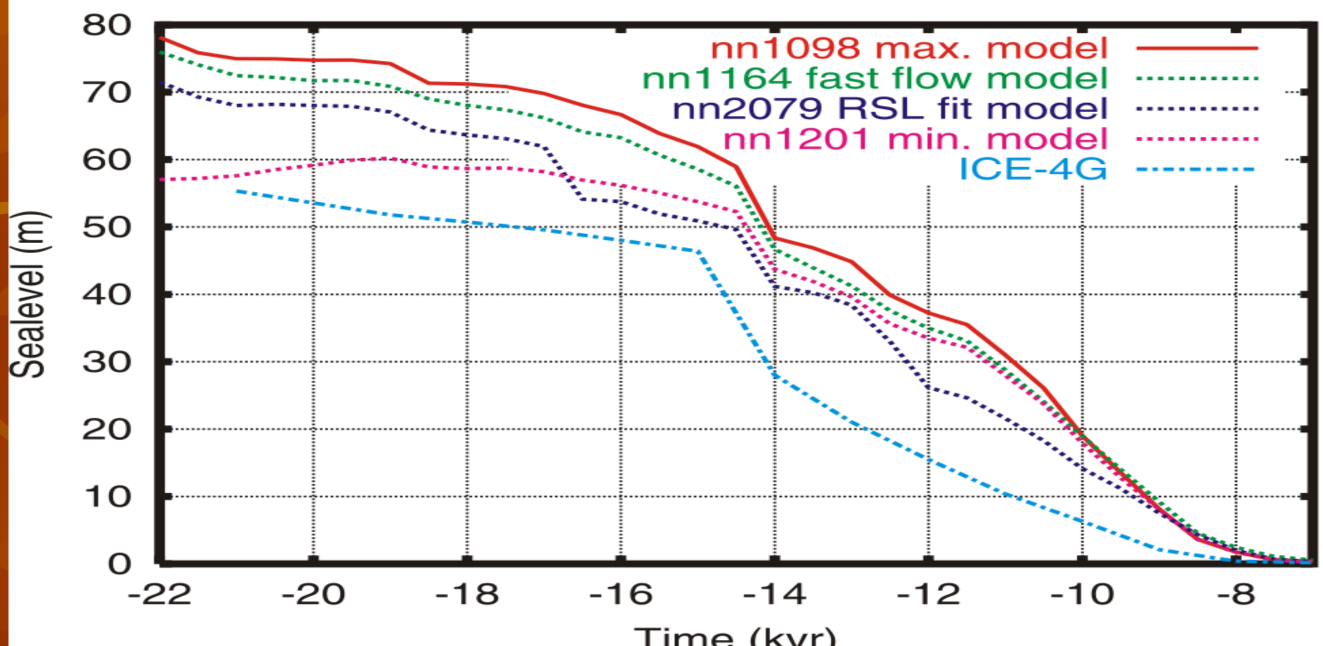
The sediment cover map employed in the ice sheet modelling is one developed for seismological applications by Laske and Masters at Scripps



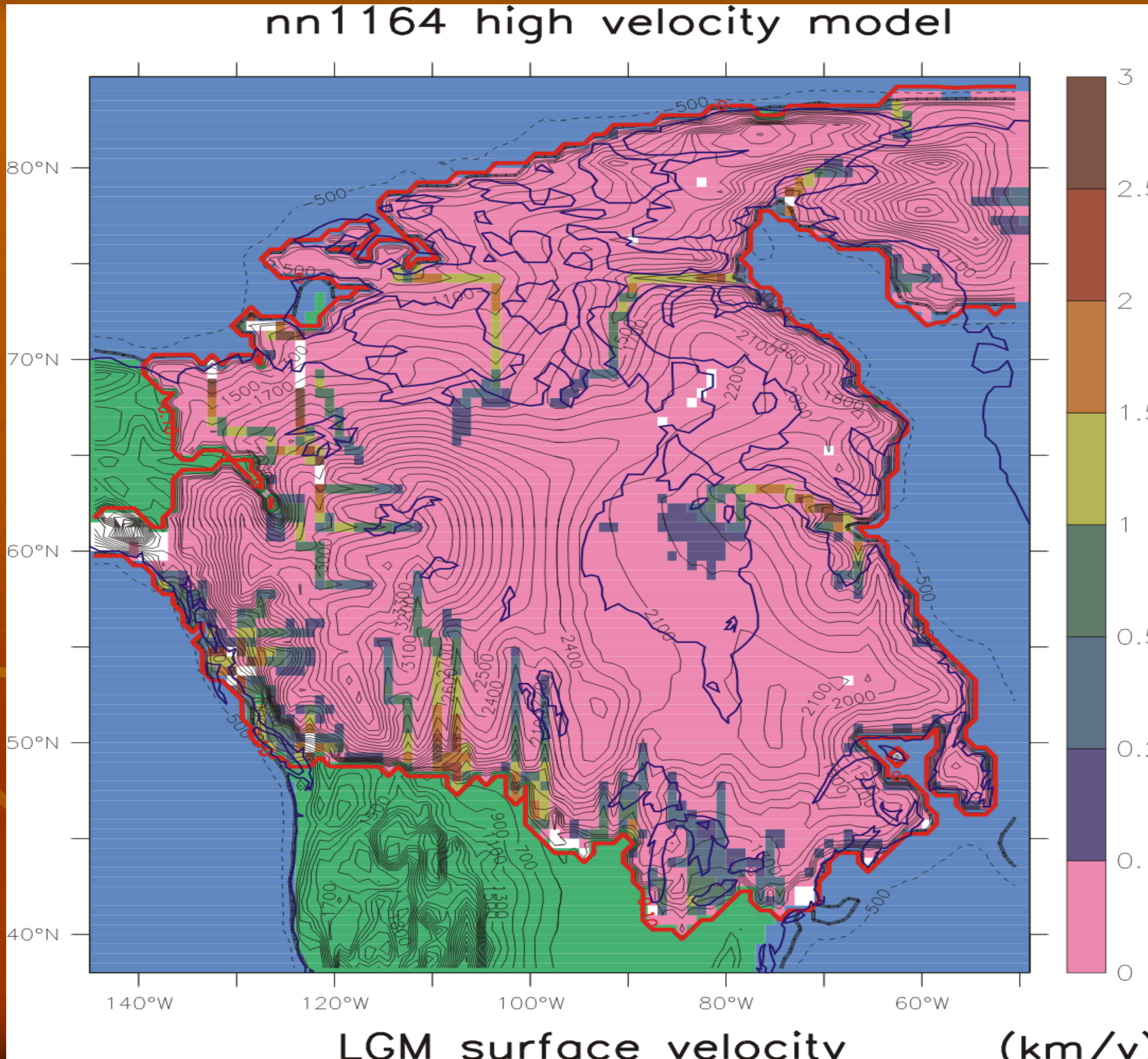
The Data Constrained Model Of the Evolution of the North American Ice Sheet Complex

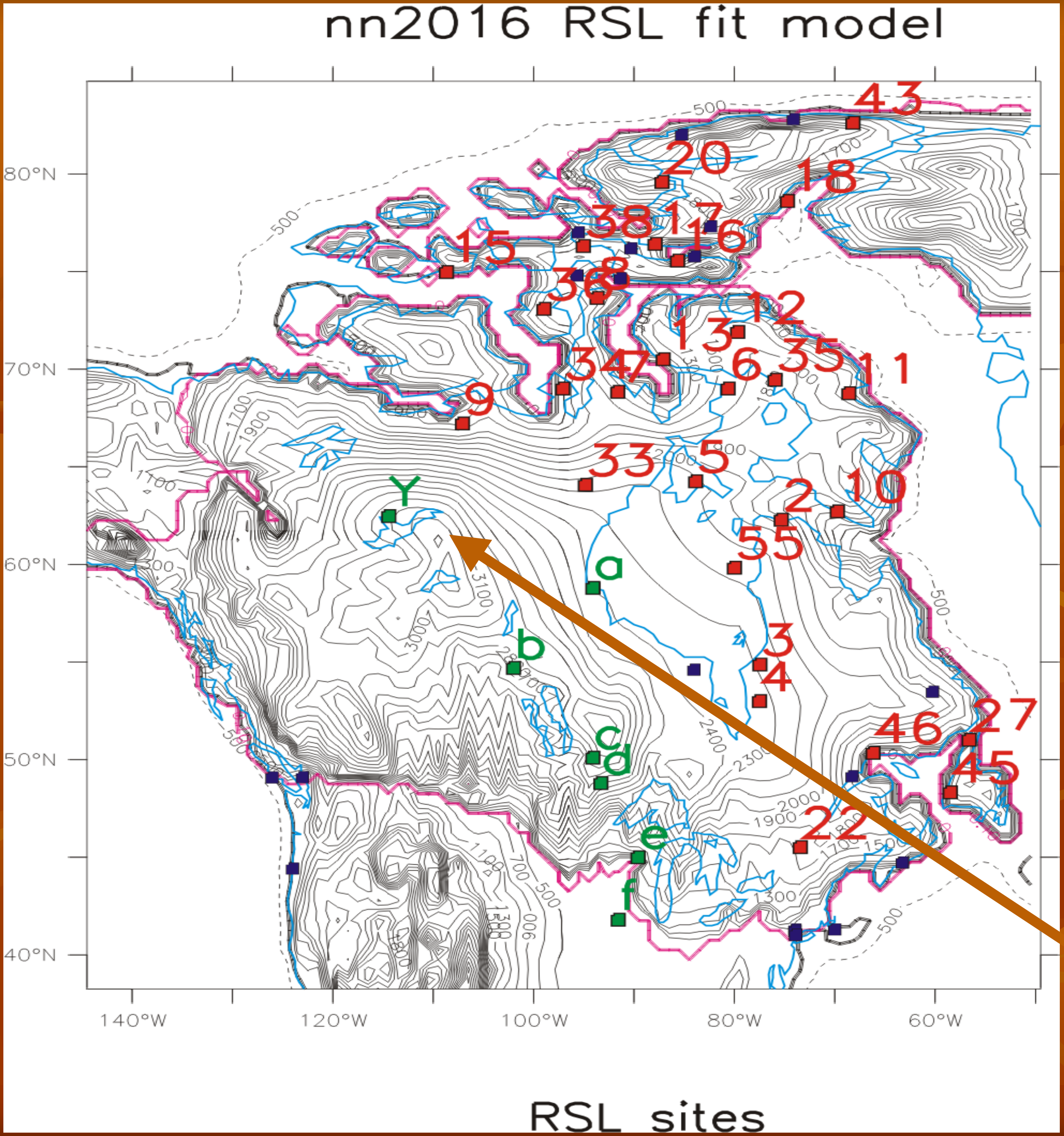
This is from the recently published analyses of Tarasov and Peltier (2004, QSR 23, 359-388) in which an ensemble of PMIP LGM runs were employed, together with the GRIP Del18O record and NCEP data, to force the ISM





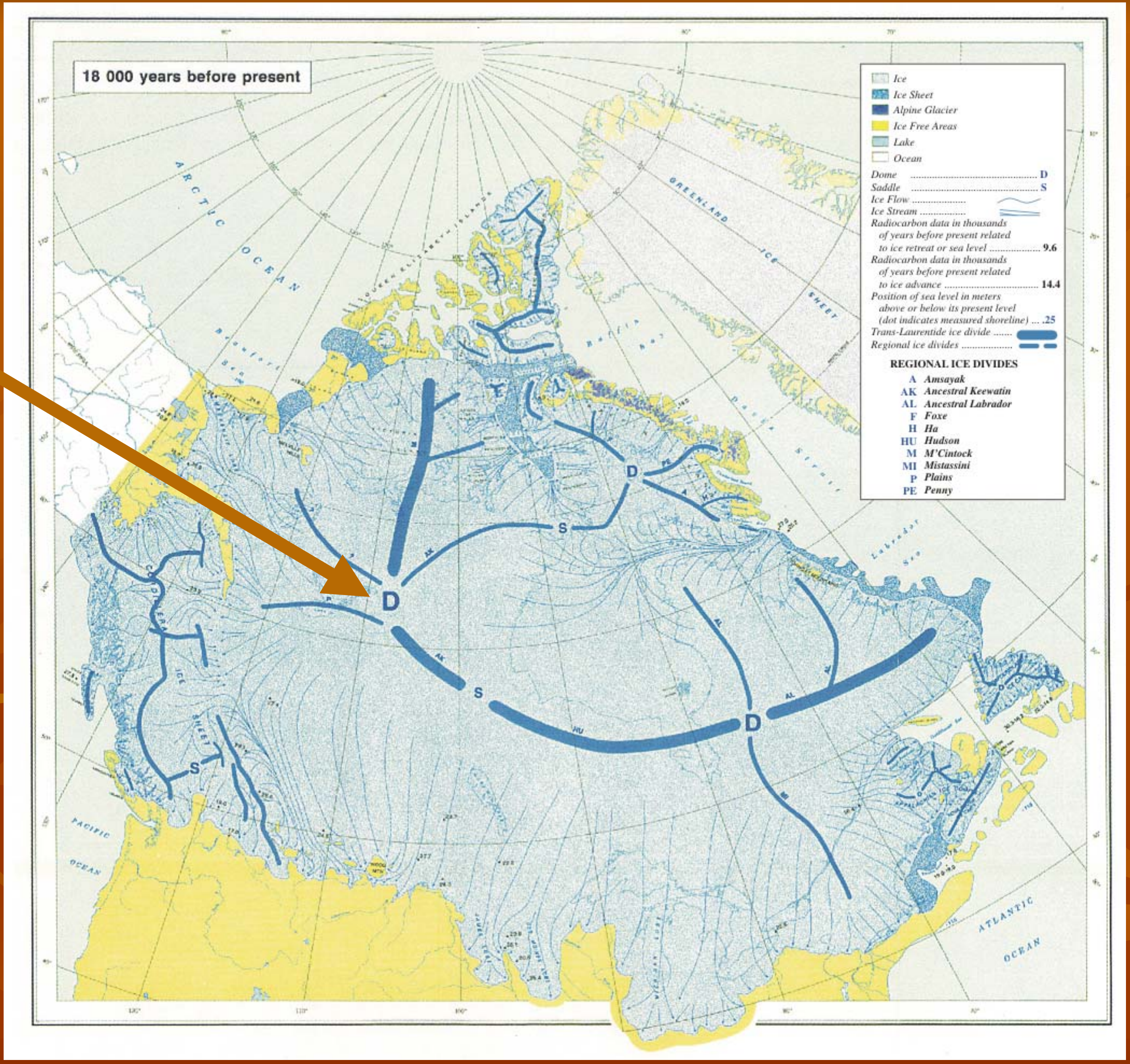
The three domed structure implied by the analyses of Dyke and Prest is obtained as a consequence of the geographical disribution of the surface sediment which enables fast flow to occur in regions such as Hudson Strait which is known to have been inhabited by an intense ice stream.





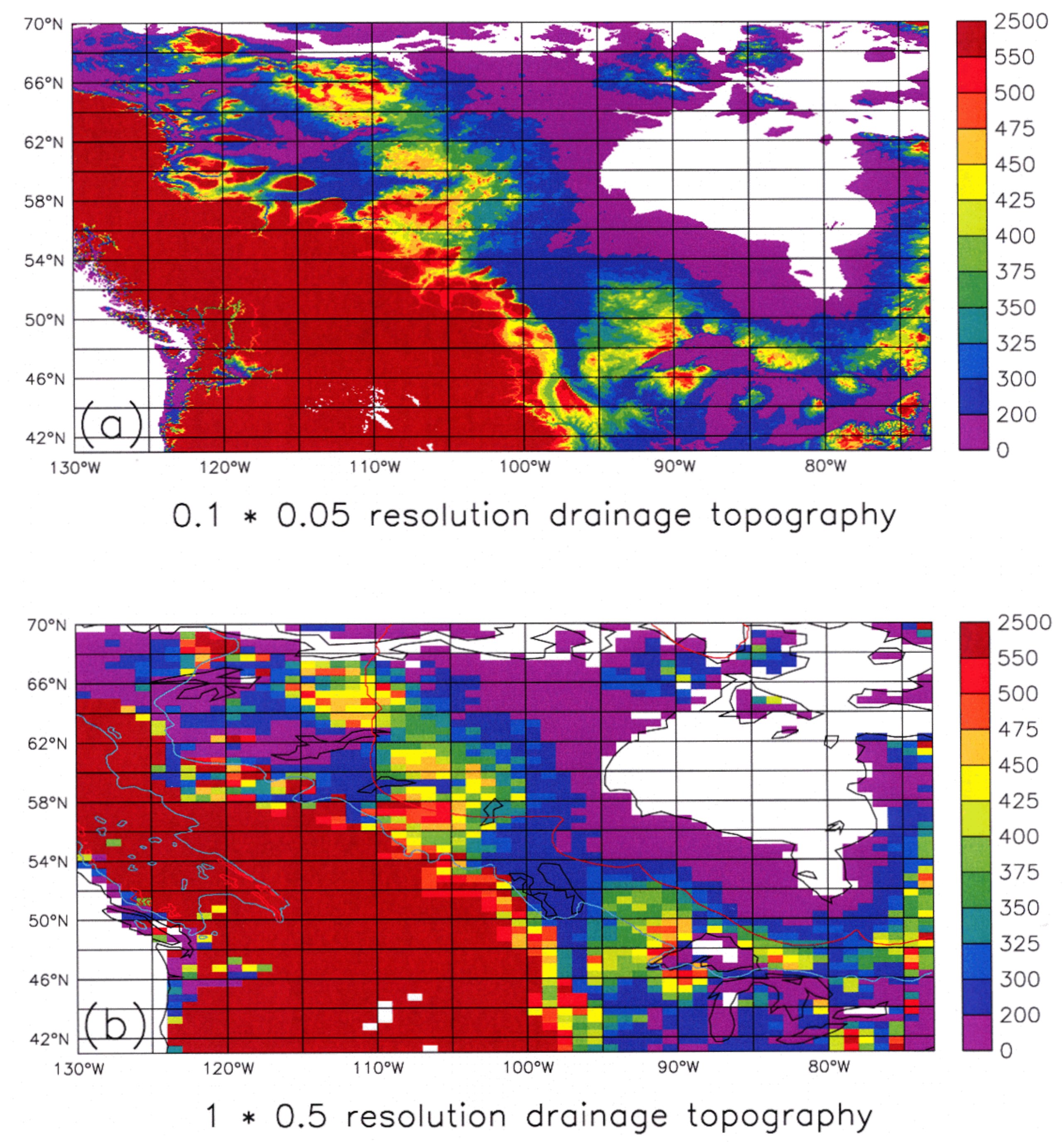
It is the geodetic data derived from the green points that provide the necessary constraints over the continental interior. Coupled with action of the basal sediment cover the model then delivers a well defined Keewatin Dome

The presence of this Keewatin Dome of the LGM LIS was first suggested in the analyses Art Dyke and Victor Prest of the Geological Survey of Canada in 1987.



Modelling the Run-off of Meltwater from the Continents

The main requirements for an accurate computation of the runoff of meltwater fom the continent during deglaciation include (1) an accurate digital elevation model for modern topography(that shown is the USGS hydrologically self consistent model), and (2) an accurate model of the glacial isostatic adjustment process, as discussed previously,



The Formal Theory of Glacial Isostatic Adjustment

The variation of relative sea level forced by the glaciation - deglaciation process is determined by the Sea Level Equation. With $S(\theta, \lambda, t)$ the history of relative sea level, then :

$$S(\theta, \lambda, t) = C(\theta, \lambda, t)\,[\,G(\theta, \lambda, t) - R(\theta, \lambda, t)\,]$$

$$= C(\theta, \lambda, t)\,\Big[\int_{-\infty}^{t}\int_{\Omega}\int L(\theta', \lambda', t') \cdot \Big\{\frac{\phi(\gamma, t-t')}{g} - \Gamma(\gamma, t-t')\Big\}\, d\Omega' dt' + \frac{\Delta\Phi(t)}{g}\Big]$$

The history of surface loading $L(\theta, \lambda, t)$ may be expanded as :

$$L(\theta, \lambda, t) = \rho_I\, I(\theta, \lambda, t) + \rho_W\, S(\theta, \lambda, t)$$

And the Green Functions ϕ & Γ have expansions :

$$\phi(\overbrace{\theta, \lambda}^{\gamma}, t) = \frac{a\,g}{m_e}\sum_{l=0}^{\infty} k_\ell\, P_\ell(\cos\gamma)$$

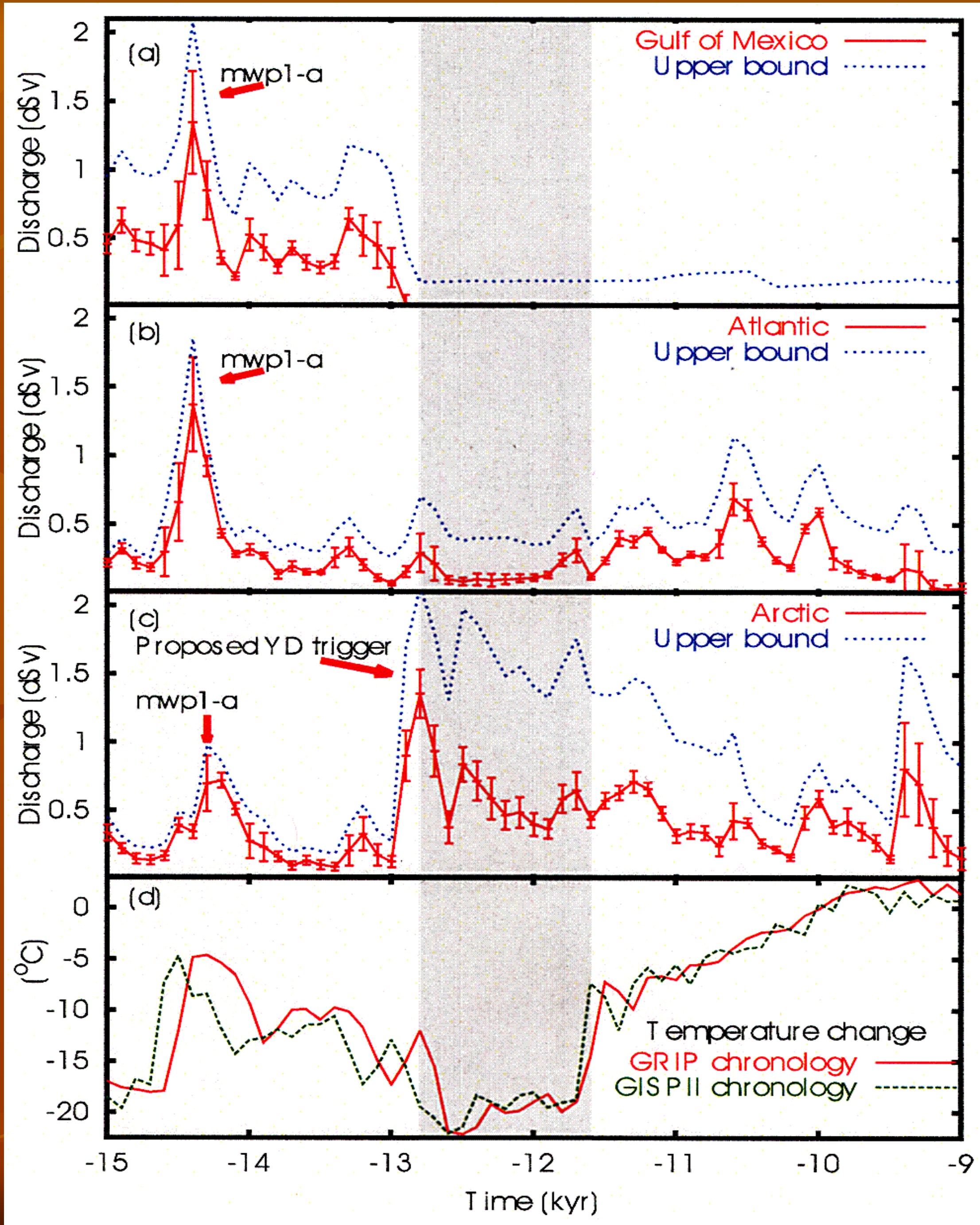
$$\Gamma(\overbrace{\theta, \lambda}^{\gamma}, t) = \frac{a}{m_e}\sum_{l=0}^{\infty} h_\ell\, P_\ell(\cos\gamma)$$

And the surface load love numbers k_ℓ & h_ℓ in turn have expansions :

$$k_\ell = k_\ell^E + \sum_{k=1}^{K} r_j^{\ell\prime} e^{-s_j^\ell t}$$

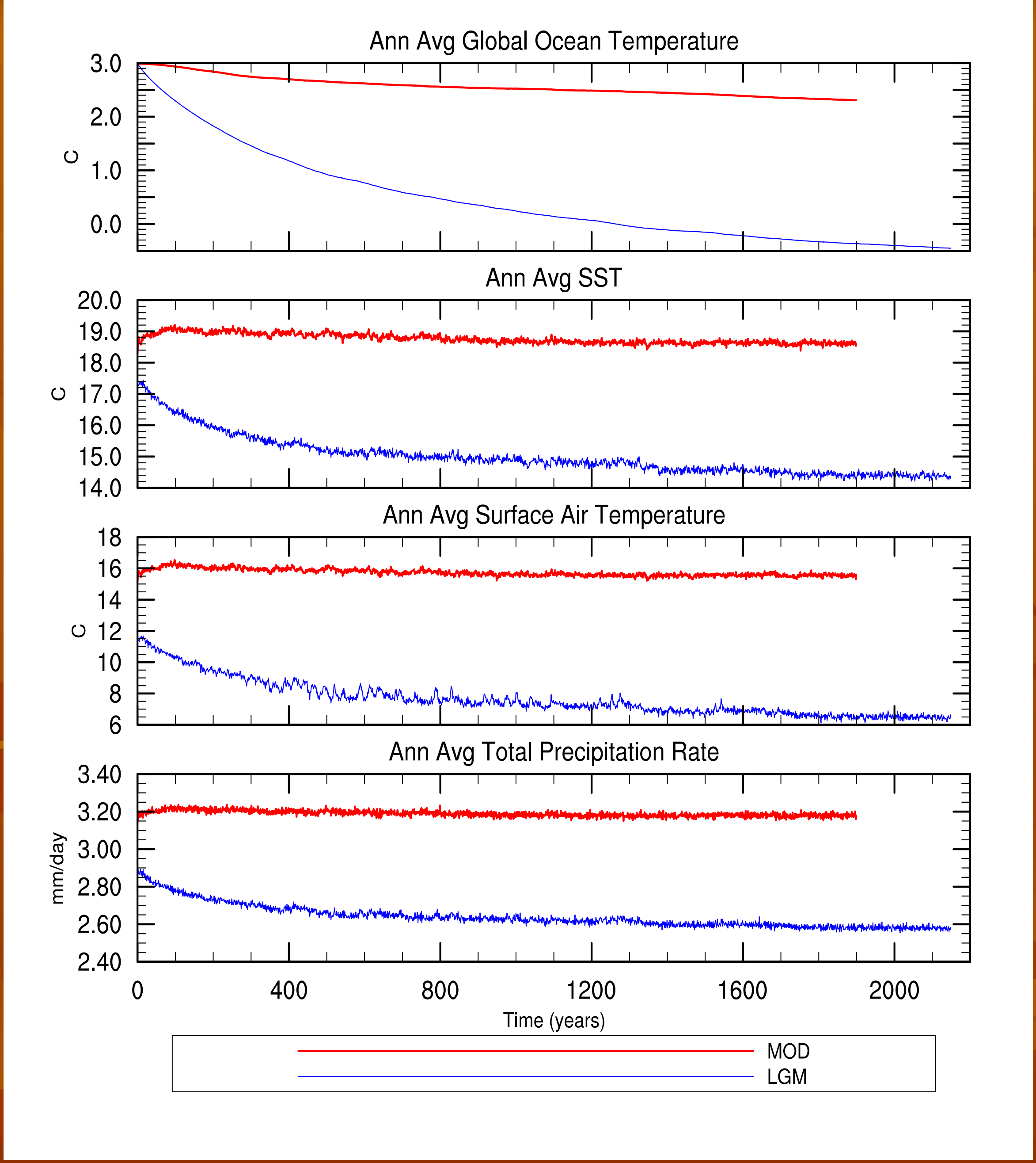
$$h_\ell = h_\ell^E + \sum_{k=1}^{K} r_j^{\ell} e^{-s_j^\ell t}$$

The main result of the detailed runoff computation is the prediction of the occurrence of an intense pulse of Meltwater into the Arctic Ocean precisely at the time of onset of the Younger-Dryas cold reversal! This is from Tarasov and Peltier, Nature, June 2, 2005.

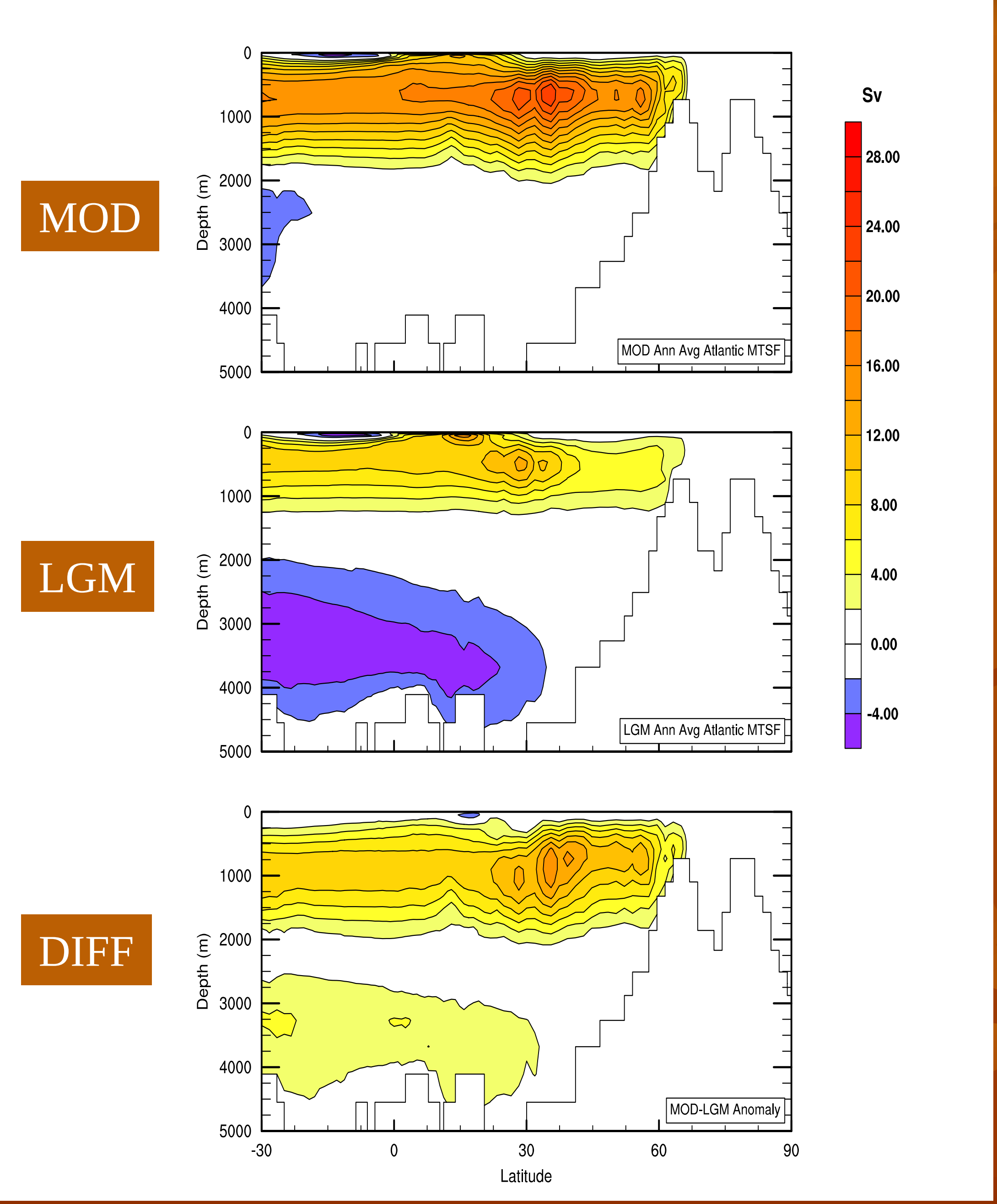


The impact of an Arctic meltwater pulse upon the strength of the Atlantic thermohaline circulation

Spin-up to statistical equilibrium of the NCAR CSM1.4 under both modern and LGM boundary conditions. The LGM run employs Vostock trace gases, ICE-4G topography and LGM orbital forcing

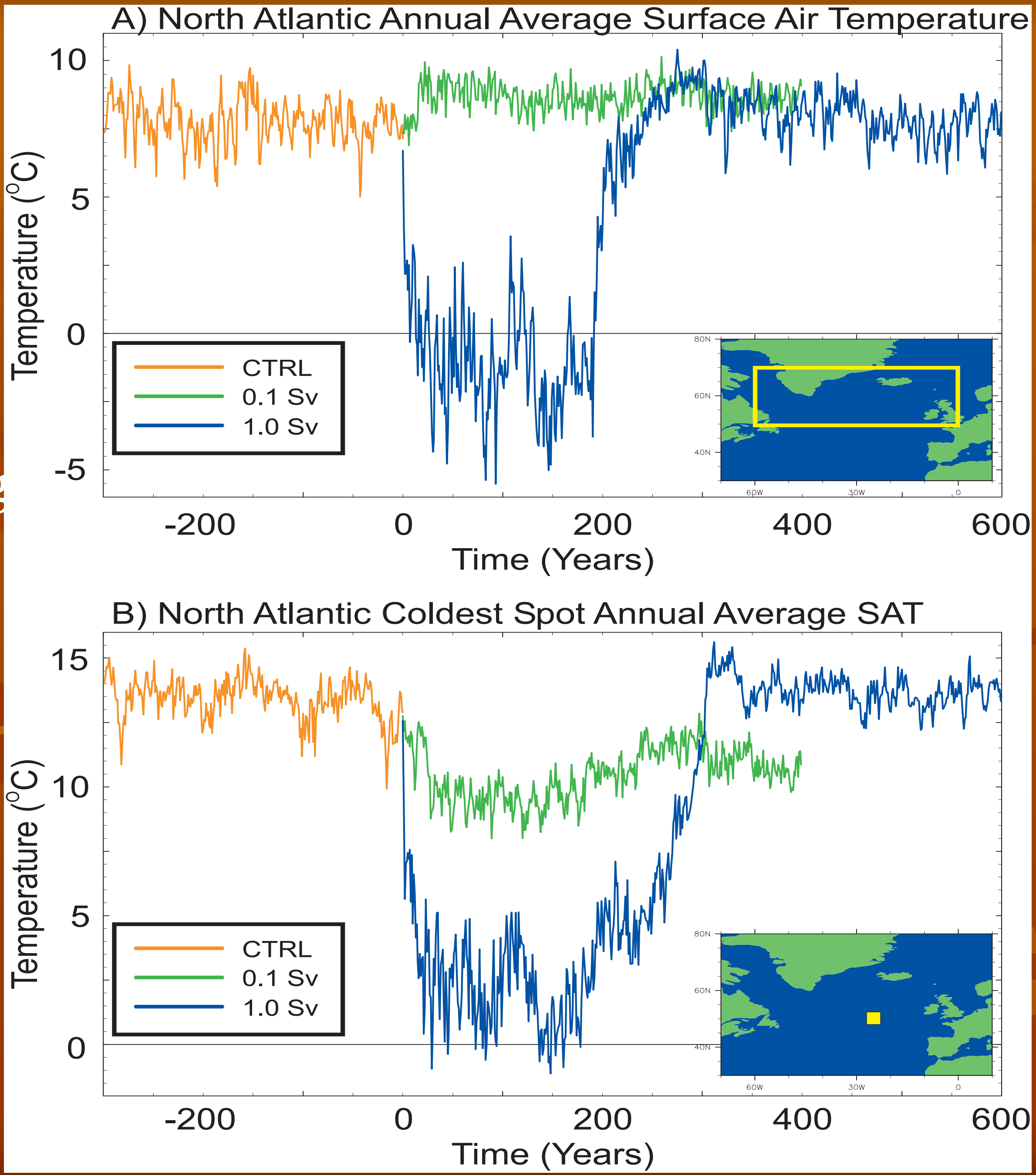


An initial test of the NCAR CSM model. Modern and LGM Equilibria of the Atlantic MOC. The LGM equilibrium is Predicted to have been ~40% weaker than Modern, in accord with The recently published Pa/Th isotopic Measurements of McManus et al, 2004. See Peltier and Solheim, 2004, QSR 23.

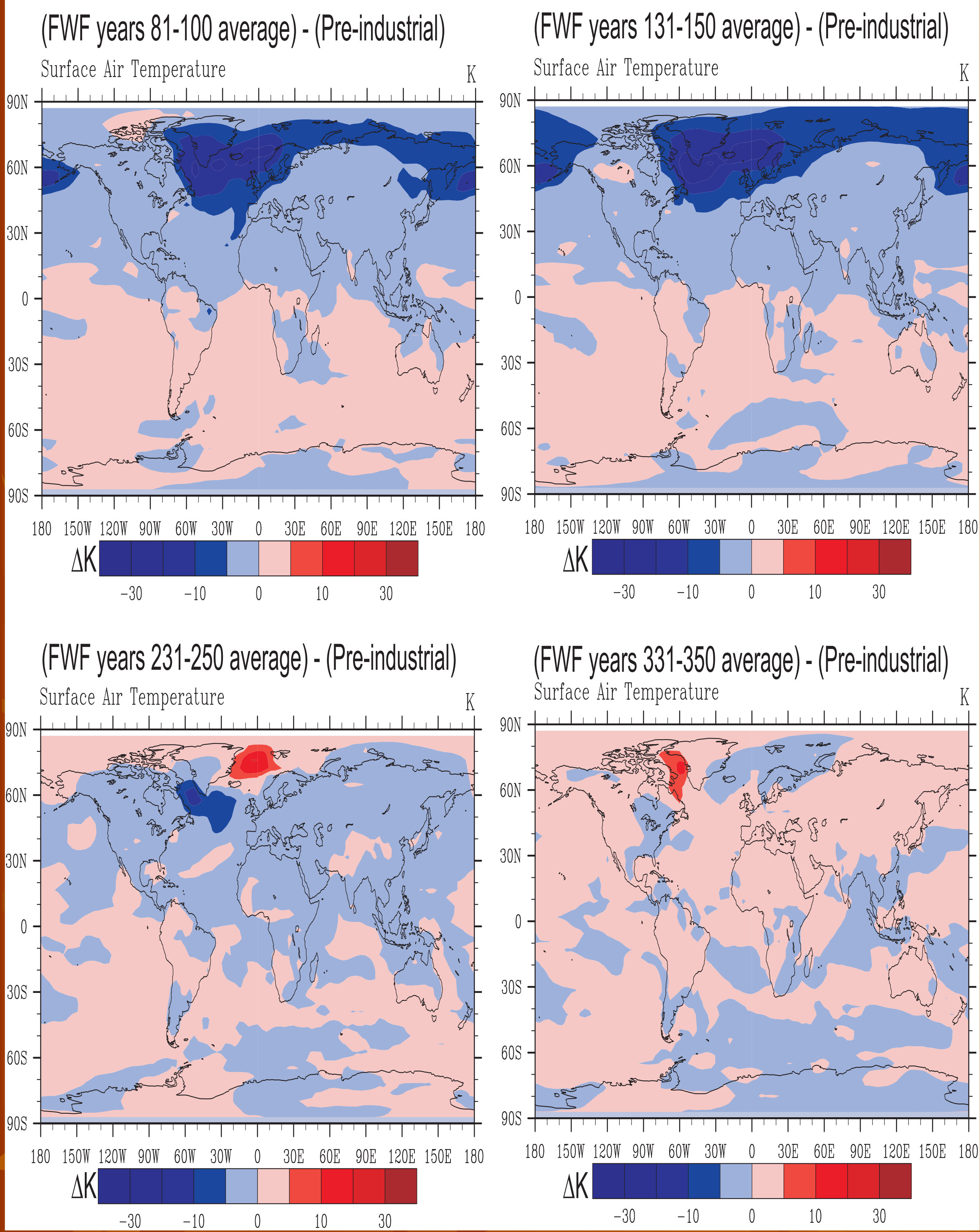


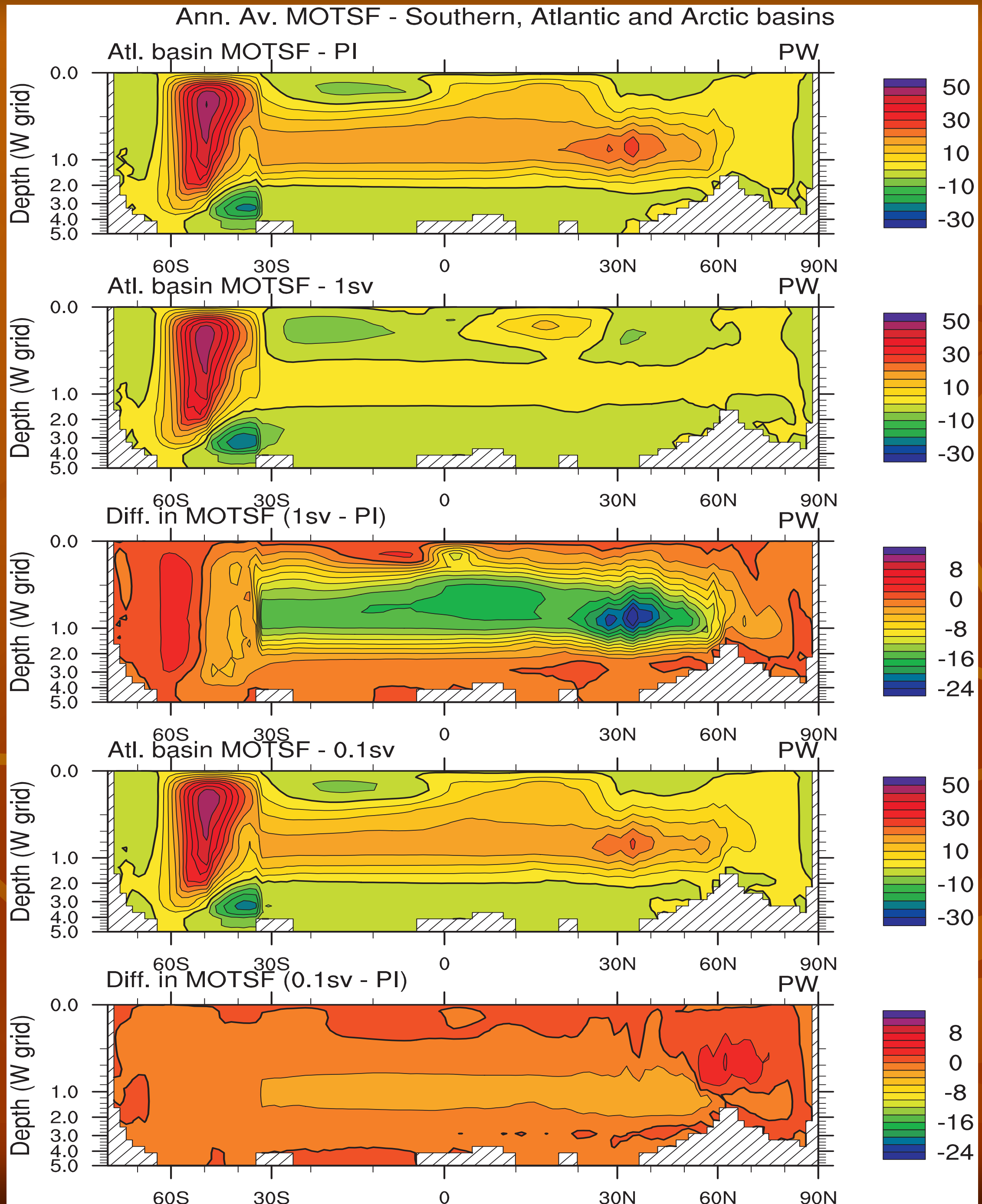
Results of the CMIP/PMIP Water hosing experiments in CSM1.4

This is from Peltier, Stastna and Vettoretti, submission to the “water hosing” intercomprison tests being conducted under the auspices of the WCRP. Part of a paper now submitted to the Journal of Climate. The unperturbed state is Modern.

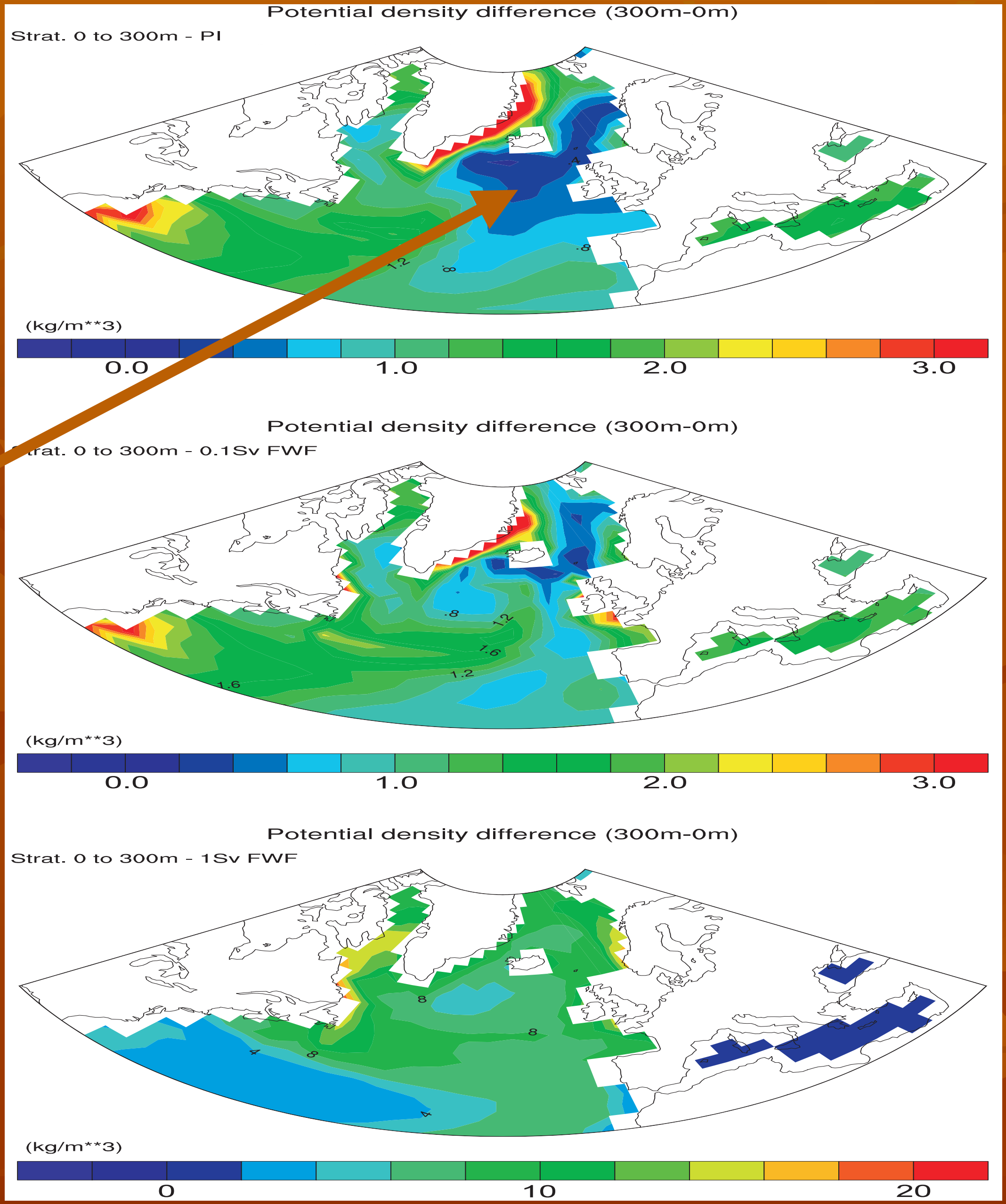


December Surface Air Temperature Anomalies

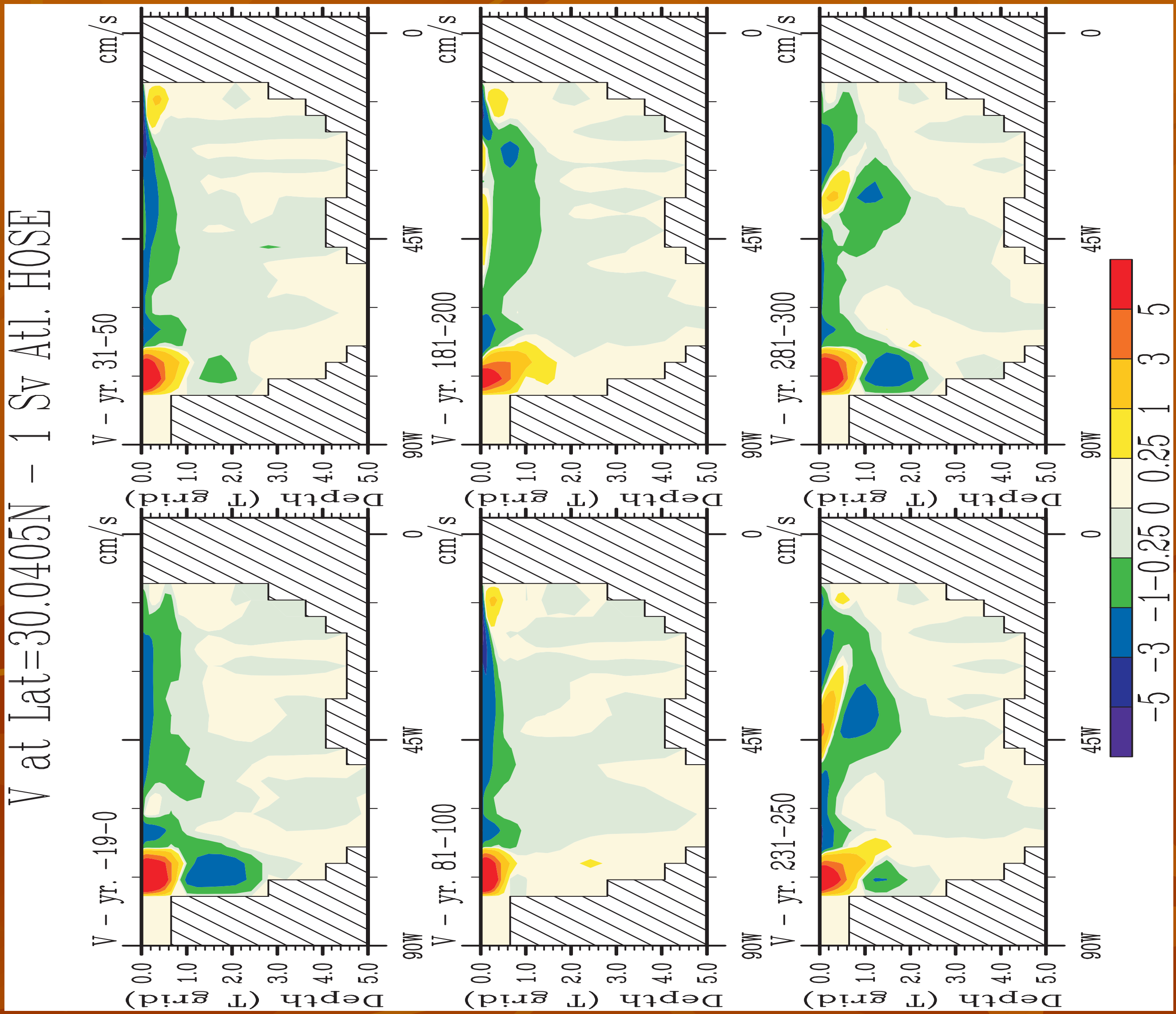



Ann. Av. MOTSF - Southern, Atlantic and Arctic basins
Atl. basin MOTSF - PI
PW
Depth (W grid)
0.0
1.0
2.0
3.0
4.0
5.0
60S
30S
0
30N
60N
90N
50
30
10
-10
-30
Atl. basin MOTSF - 1sv
Diff. in MOTSF (1sv - PI)
8
0
-8
-16
-24
Atl. basin MOTSF - 0.1sv
Diff. in MOTSF (0.1sv - PI)

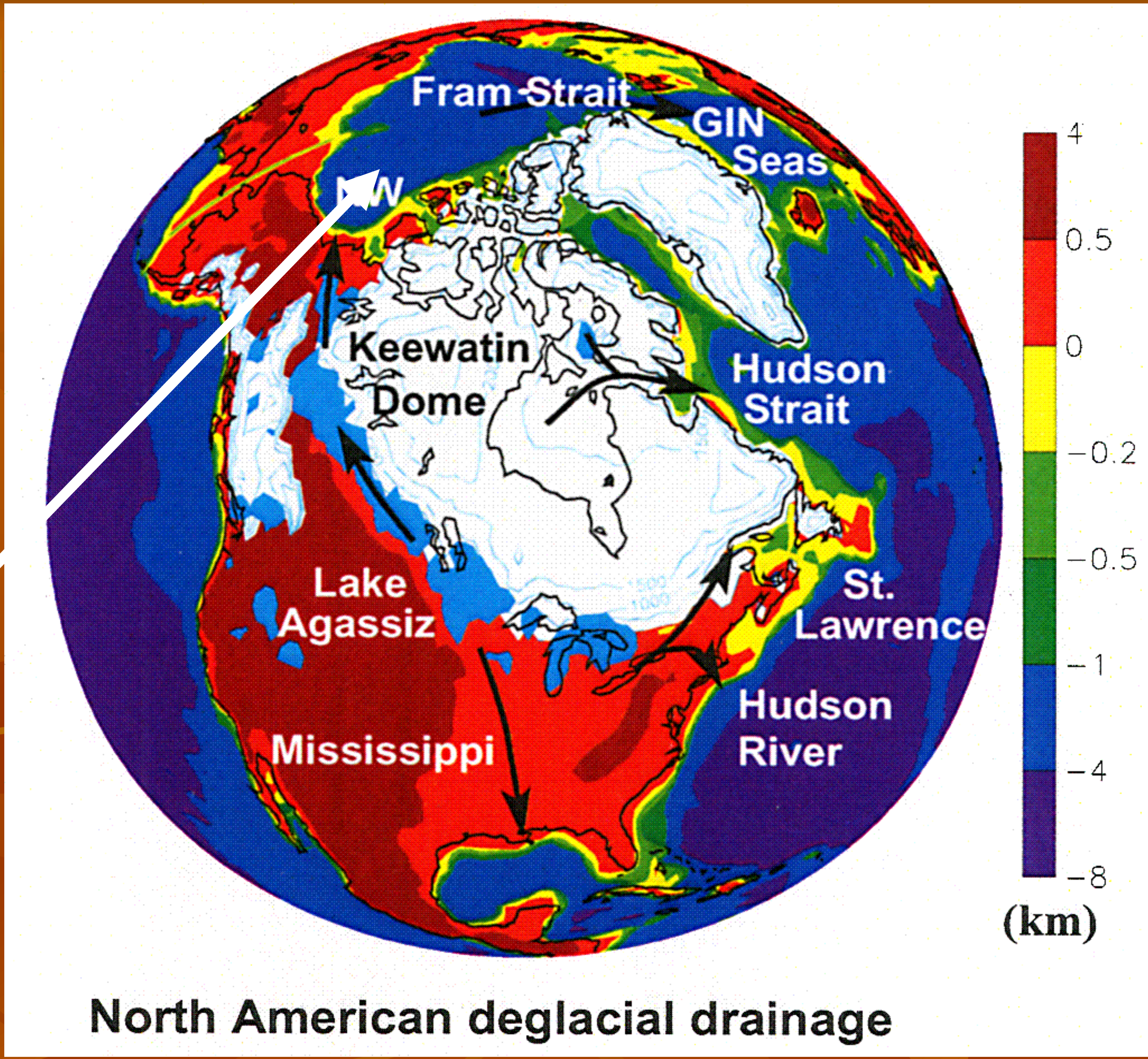
It is clearly important that the model properly accounts for the known regions of
deep water formation in the GIN Seas and the Labrador Sea in the absence of the applied freshwater forcing.



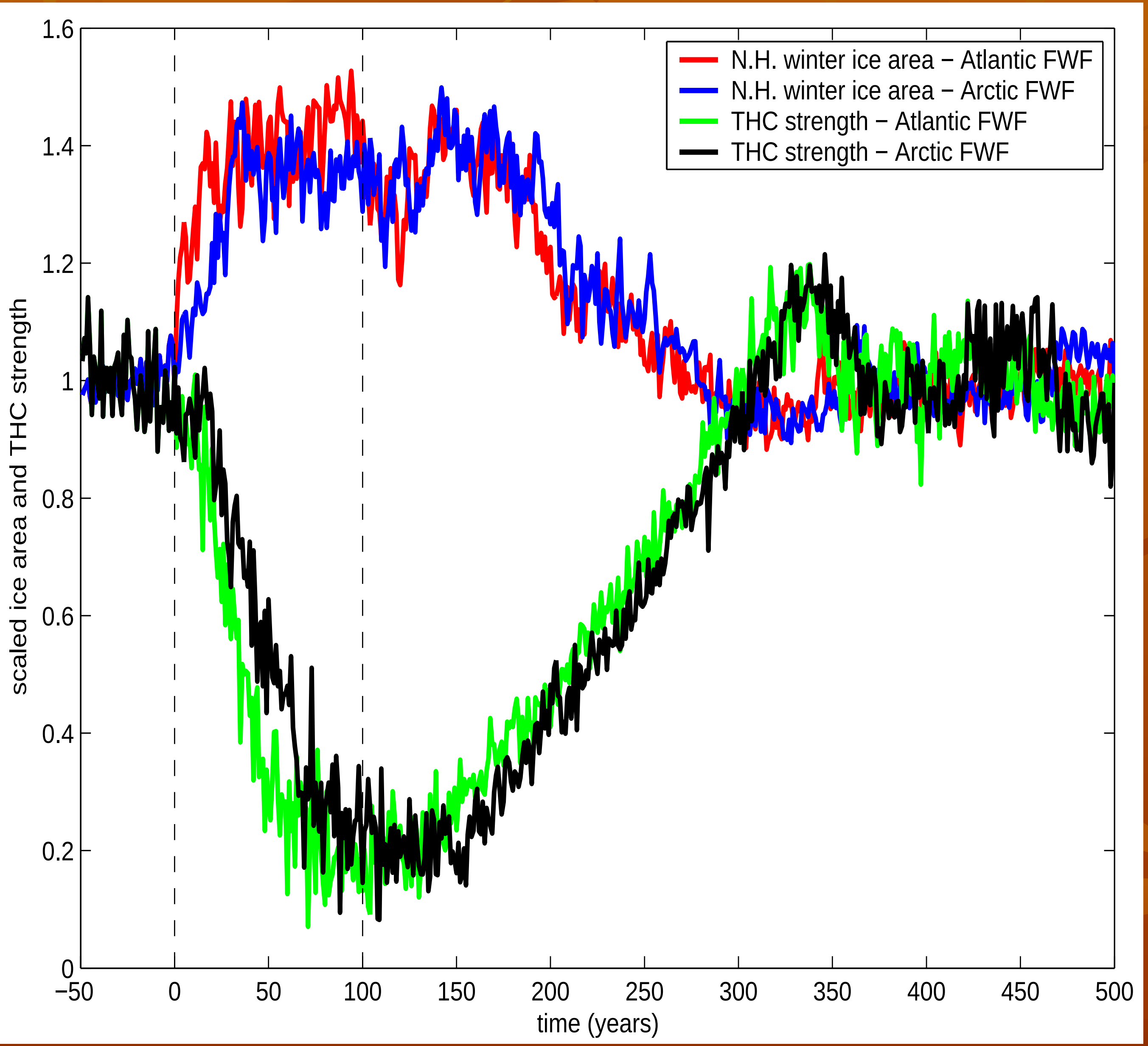
Note that the western boundary undercurrent, which is driven by the NADW formation process, is eliminated by the surface freshening of the N Atlantic whereas the wind driven Gulf Stream persists.



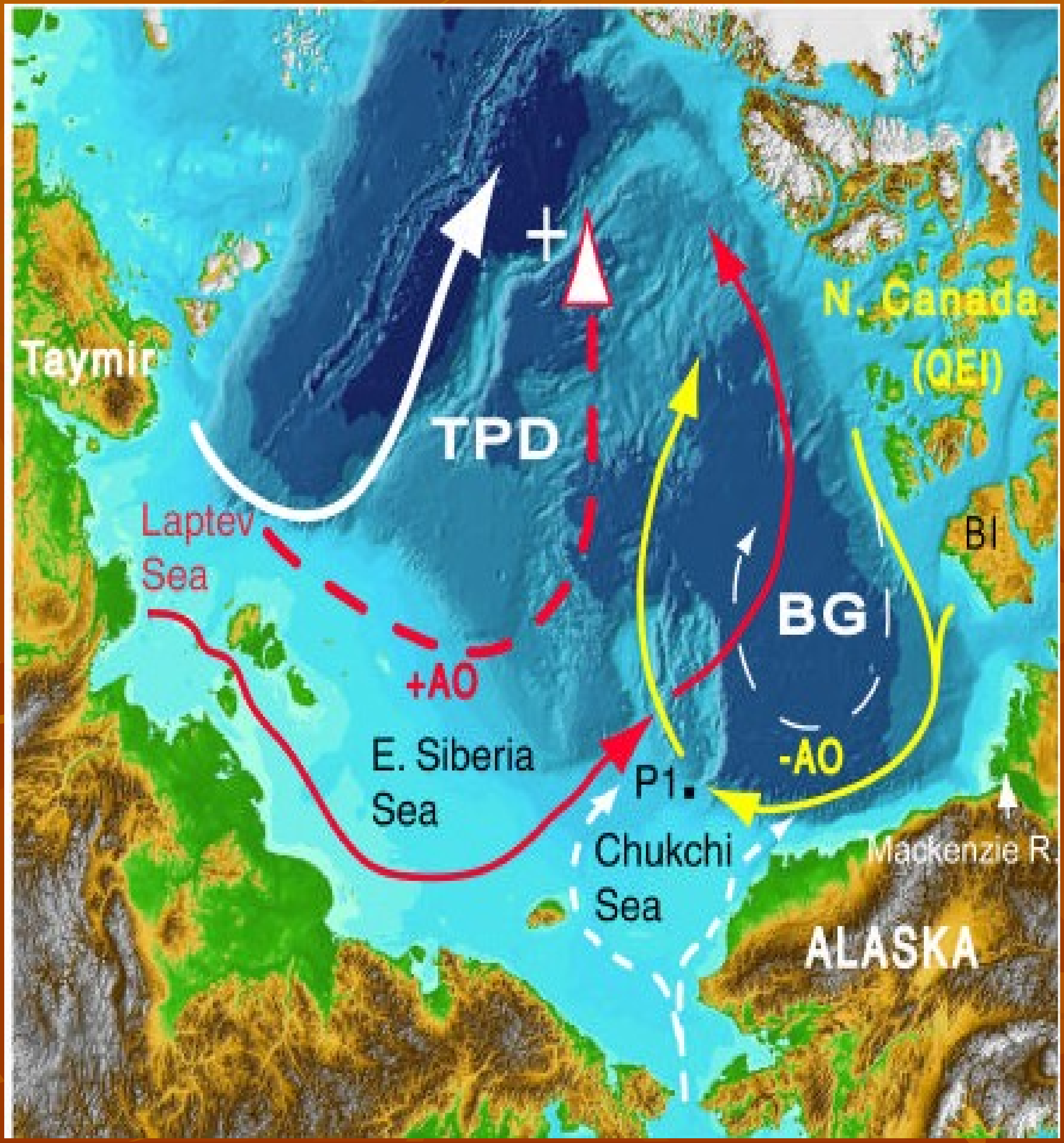
Suppose, rather than freshening the North Atlantic at 1 Sv for a period of 100 years, we were to apply exactly the same forcing to the Arctic Ocean in the Beaufort Sea, as suggested by the explicit analysis of continental runoff ?



Scaled results for the strength of the MOC and for sea ice concentration for Atlantic hosing at 1 Sv for 100 years and for Arctic hosing for the same period of time at the same strength. Note: results are essentially identical!



The point here is that just as the North Atlantic Drift will transport a surface freshwater anomaly into the region of deep water formation if this anomaly is imposed to the south of Greenland, so the Trans-Polar Drift will transport a fresh water anomaly added to the surface of the Arctic Ocean through Fram Strait and onto the region in which deep water would otherwise form.



The End

ROTATIONAL FEEDBACK IN THE SEALEVEL EQUATION

Because a change in rotational state is accompanied by a change in centrifugal potential and because sea level (msl) is constrained to lie on an equipotential, a change in rotational state will clearly induce a change in sea level.

∴ A Modified Sea Level Equation

$$S(\theta, \lambda, t) = C(\theta, \lambda, t)\Big[\int_{-\infty}^{t} dt' \int_{\Omega e}\int d\Omega' \Big\{ L(\theta', \lambda', t')\, G_\phi^L(\gamma, t-t') + \psi^R(\theta', \lambda', t')\, G_\phi^T(\gamma, t-t') \Big\} + \frac{\Delta \Phi(t)}{g}\Big]$$

Where, to first order in perturbation theory

$$\psi^R = \psi^{00} + \sum_{m=-1}^{+1} \psi_{2m}\, Y_{2m}(\theta, \lambda)$$

$$\psi_{00} = +\frac{2}{3}\,\omega_3\,\Omega_0\,a^2$$

$$\psi_{20} = -\frac{1}{3}\,\omega_3\,\Omega_0\,a^2\sqrt{4/5}$$

$$\psi_{21} = +(\omega_1 - i\omega_2)(\Omega_0 a^2/2)\sqrt{2/15}$$

$$\psi_{2\text{-}1} = -(\omega_1 + i\omega_2)(\Omega_0 a^2/2)\sqrt{2/15}$$