Sensitivity of nascent ice sheet growth rates to the frequency of GCM updates: towards optimal coupling of GCMs and ice sheet models

Adam R. Herrington
Christopher J. Poulsen
University of Michigan

Based on results from: Herrington, A. R. and C. J. Poulsen, 2012: Terminating the last interglacial: the role of ice sheet-climate feedback in a GCM asynchronously coupled to an ice sheet model. *J. Clim.*, **25**, 1871-1882.

Outline

I. Modeling North American Ice Sheet Inception:

Motivations and Geological Requirements

II. Models and Experimental Design

III. Results

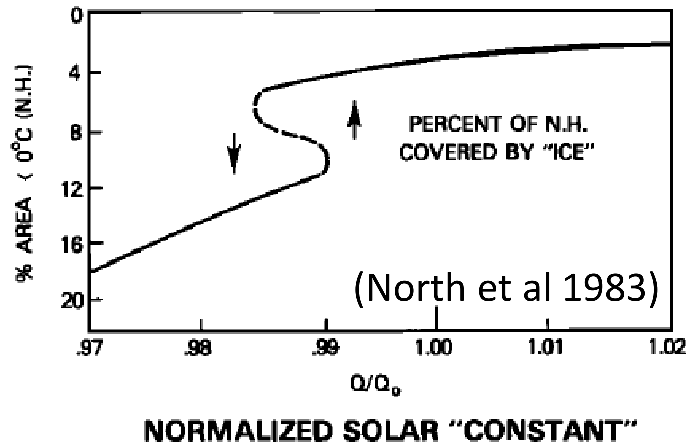
IV. "Mutual Interactions"

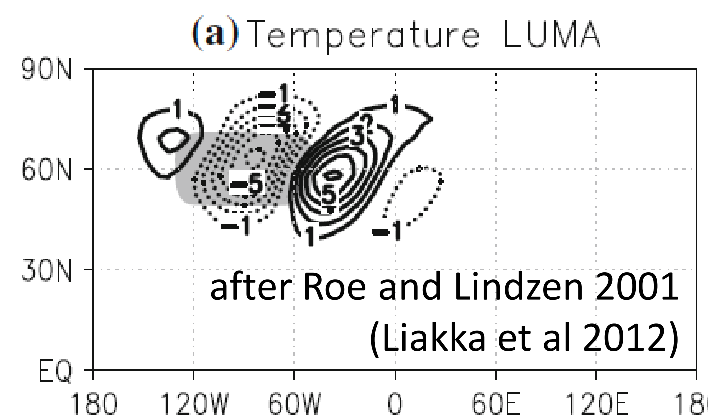
Ice-Albedo Feedback (SICI)

Stationary Wave Feedback

V. An Optimal Coupling Scheme

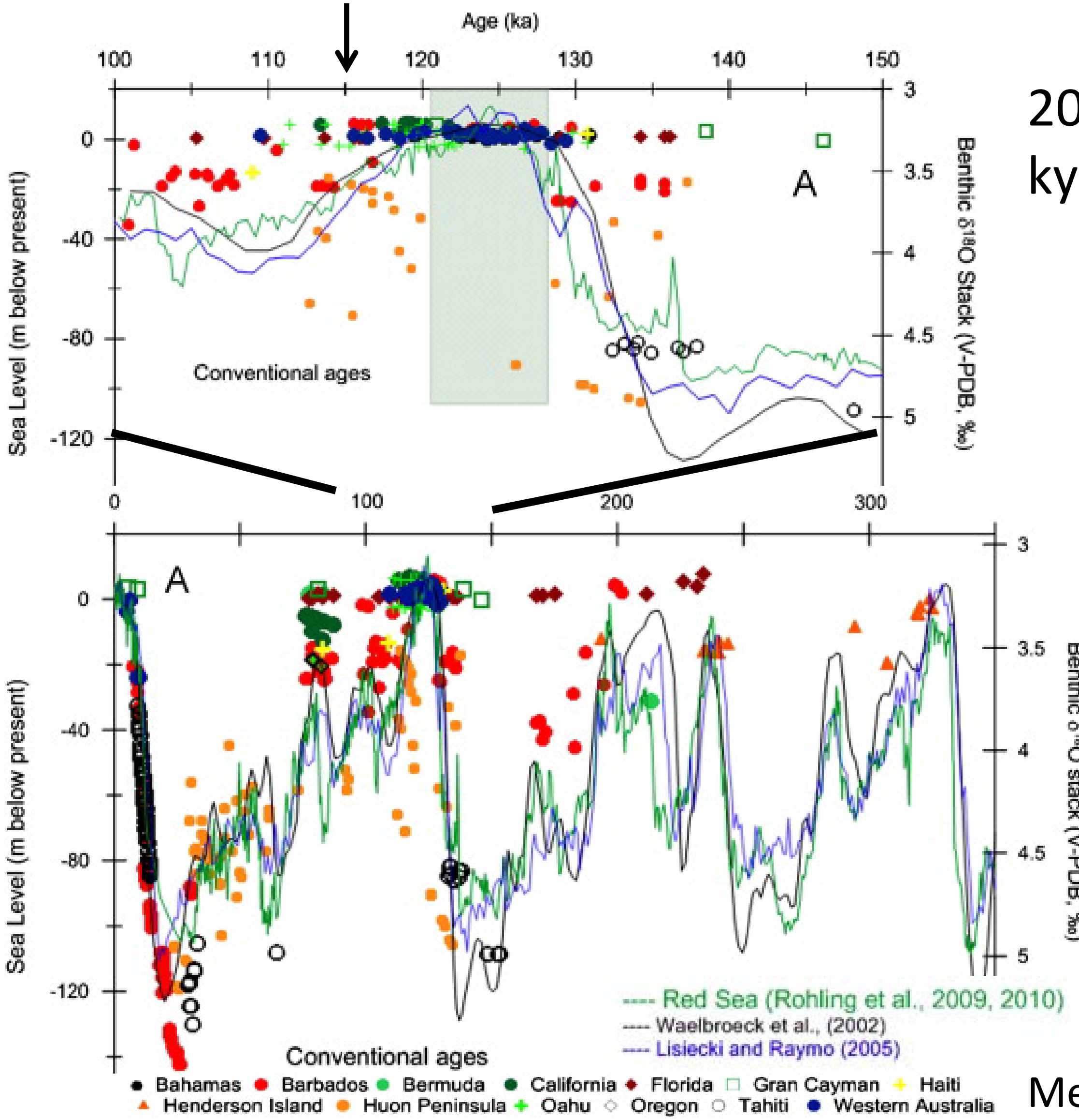
VI. Conclusions





Into an Ice Age

NH summer insolation minimum



20 - 75 m eustatic lowering in 10 kyrs (Andrews and Mahaffey 1976)

Medina-Elizalde (2013) EPSL

Into an Ice Age

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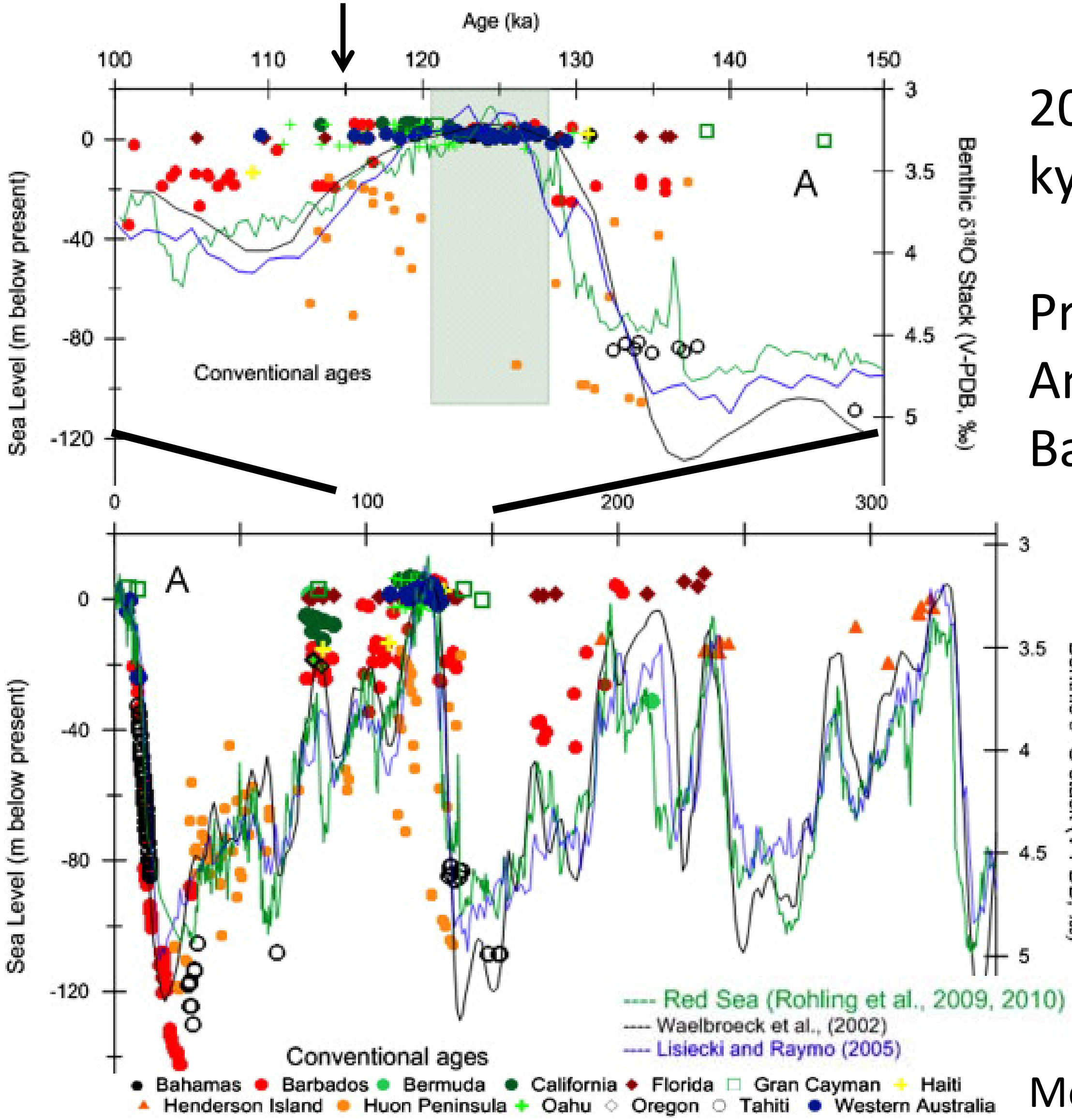
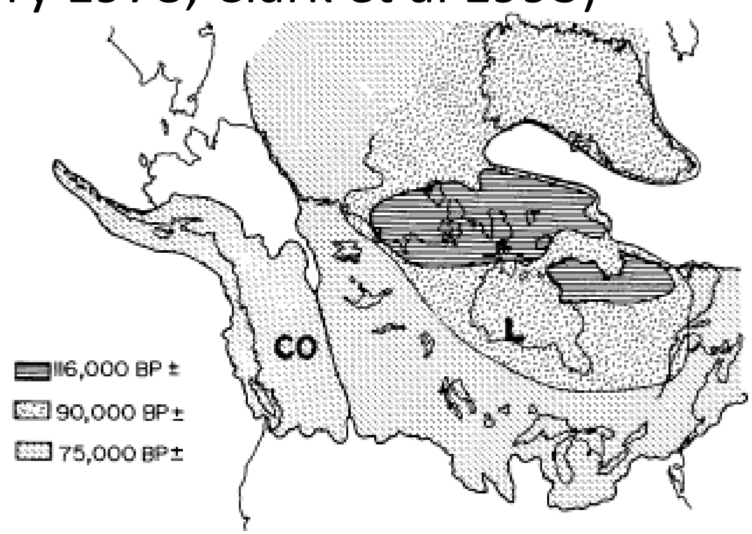


20 - 75 m eustatic lowering in 10 kyrs (Andrews and Mahaffey 1976)

Primarily from growth of N. American ice sheets (Andrews and Barry 1978; Clark et al 1993)



Andrews and Barry (1978)

Medina-Elizalde (2013) EPSL

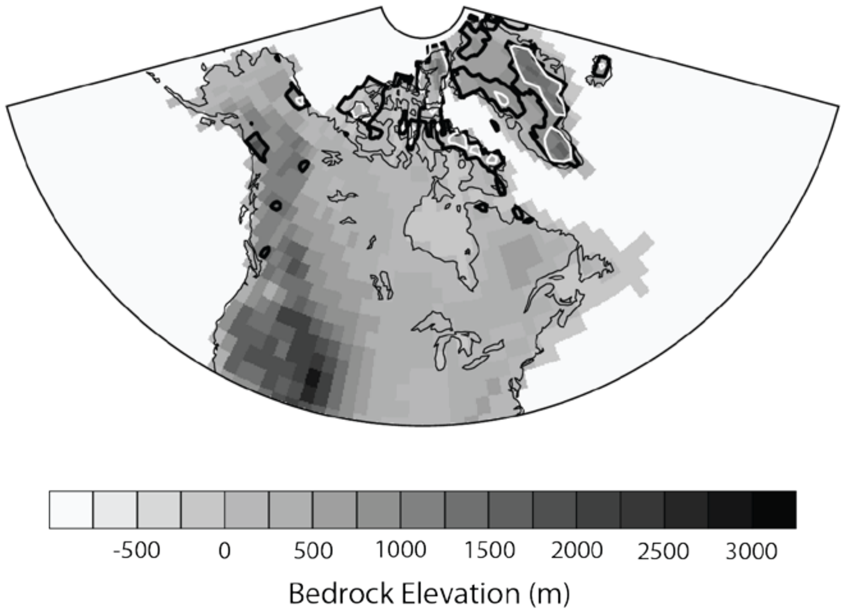
Models

GCM - GENESIS v3.0 Branch off of CCM1, developed with an emphasis on biophysical processes for paleoclimate applications

Component	Description	Reference
Core		
Dry dynamics	Eulerian spectral	Williamson 1987
Resolution	T31, 18 hybrid levs	
Moisture Advection	Semi-Lagrangian	Williamson and Rasch 1989
Radiation	NCAR CCM3	Kielhl et al 1998
Subgrid convection	buoyant plume model	Thompson and Pollard 1997
Clouds	prognostic 3D clouds	-
Land Surface Model	LSX model; multilayer column model of soil, snow and sea ice	-
snow albedo	f(snow temperature, sfc type)	-
cell snow fraction	f(snow mass/m^2, roughness)	-
cell albedo	f(snow frac, backgrnd albedo)	-
Ocean	50 m slab	-

Ice Sheet Model (ISM) developed by David Pollard

Core		
Mechanics	shallow ice	Pollard and DeConto 2005
Resolution	0.5x1.0 lat-lon	-
Velocity solver	ADI method	Huybrechts 1991
Thermodynamics	3D ice, 1D upper bedrock (G = 50 mW/m2)	
Basal cliding	f(driving stress) if ice is melting	-
Isostasy	none	-
Calving	750 m fixed claving depth	-
SMB		-
Climate	GCM interpolated T_{2M} and precip	-
Snowfall	Precipitation rate if T_{2M} is freezing	-
Melt	Monthly T-index (PDD)	Braithwaite 1984
Refreezing	60% of melt stored in snowpack	-



ELA (solid black line) and July 0° isotherm (solid white line) simulated in the initial ice-free state and overlain on a map of the bedrock topography used in the ISM.

Perennial Snow Problem

Table 1 AGCM simulations (1) (after Mitchell:1993)

Studies	Atmosphere model
Royer et al. (1983; 1984)	EERM 32×20/L10
Rind et al. (1989)	NASA GISS 10°×8°/L9
Oglesby (1990)	NCAR CCM1 7.5°×4.5°/L12
Verbitsky and Oglesby (1992)	NCAR CCM1 7.5°×4.5°/L12
Mitchell (1993)	Hadley Centre 3.75°×2.5°/L19
Syktus et al. (1994)	CISRO4 R21/L4
Phillipps and Held (1994)	NOAA GFDL R15/L9
Gallimore and Kutzbach (1995)	NCAR CCM1 T10/L5
Dong and Valdes (1995)	UGAMP T42/L19
Gallimore and Kutzbach (1996)	NCAR CCM1 T10/L5
Schlesinger and Verbitsky (1996)	OSU 5°×4°/L2
de Noblet et al. (1996)	LMD 5.3, 64×50/L11
Pollard and Thompson (1997)	NCAR GENESIS2 T31/L18
Vavrus (1999)	NCAR GENESIS2 T31/L18
Yoshimori et al. (2001)	CCCma GCMII T32/L10

Yoshimori et al 2001

No perennial snow at inception sites (simulations too warm)

Newer generation of models: No Problem

- CCSM3 (Otieno et al 2011; Vetteroti and Peltier 2011)
- CCSM4 (Jochum et al 2012)
- IPSL CM2 (Khodri et al 2001)
- IPSL CM4 (Born et al 2009)
- ECHO-G (Kaspar and Cubasch 2007)

Experimental Design

Asynchronous coupling method

- The ISM runs continuously while the GCM (i.e., the climate) is updated with ice topography and extents only periodically
- The period between climate updates is referred to as the coupling interval

	Description	**Reference**
Insolation (fixed)	116 ka	Berger and Loutre 1991
GHGs (fixed)		
CO_2	260 ppm	Petit et al 1999
CH_4	500 ppb	-
N_2O	260 ppb	Sower et al 2003
Initial ice		
Greenland	none, isostatically adjusted	
NE Canada	present day	
Bias correction	monthly climatology	Legates and Willmott (1990)
Experiment Length	10 000 yrs	
Experiments		
F500	500 yr coup intrvl	
F1000	1000 yr coup intrvl	
F2500	2500 yr coup intrvl	
F5000	5000 yr coup intrvl	

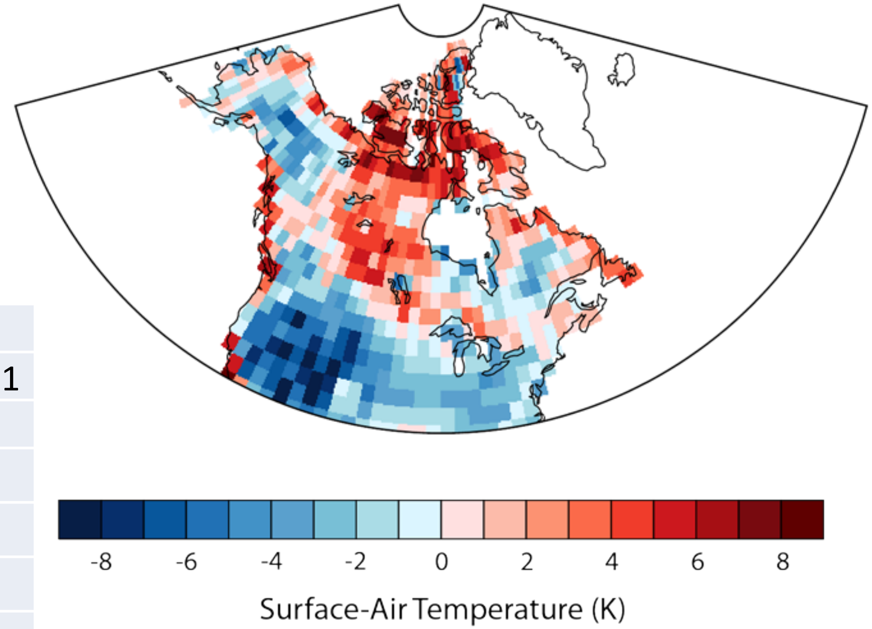
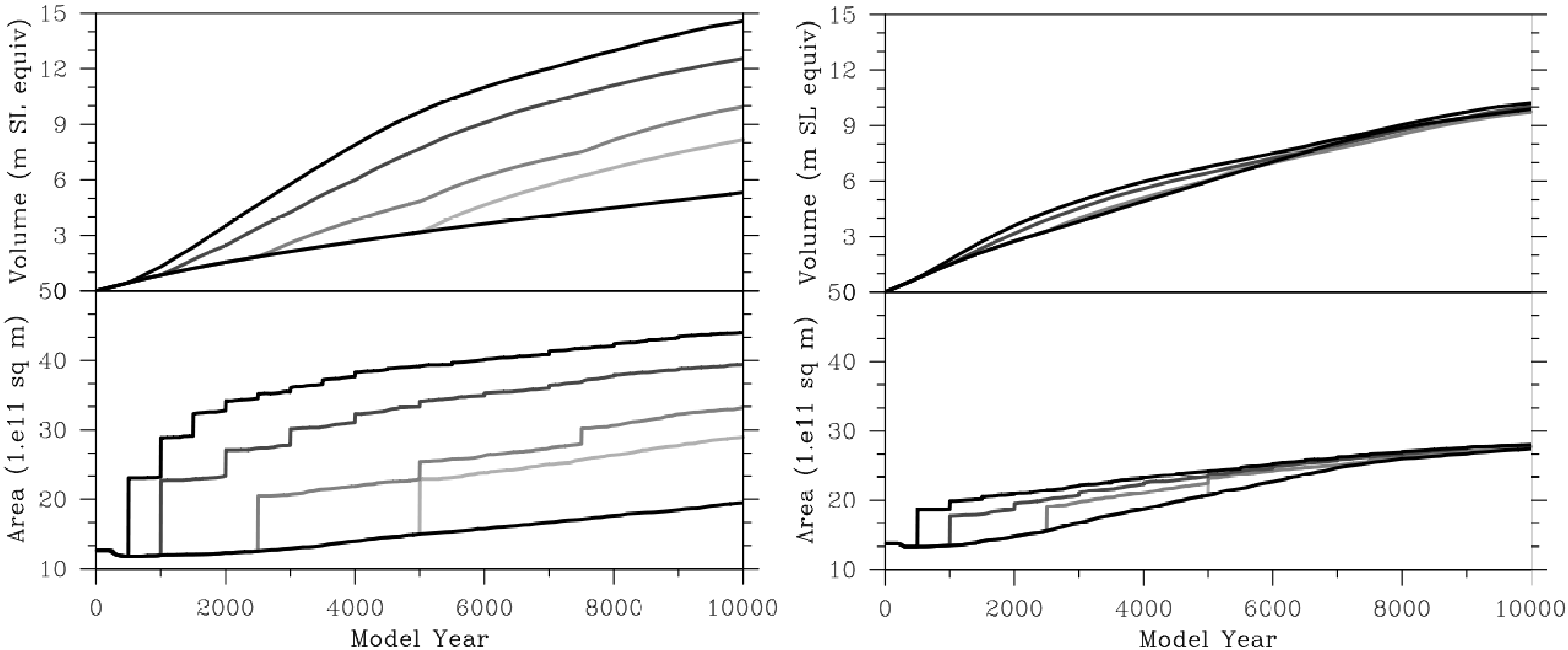


FIG. 1. GENESIS July surface air temperature bias over North America measured as the difference between a present-day simulation and the Legates and Willmott (1990) observational dataset.

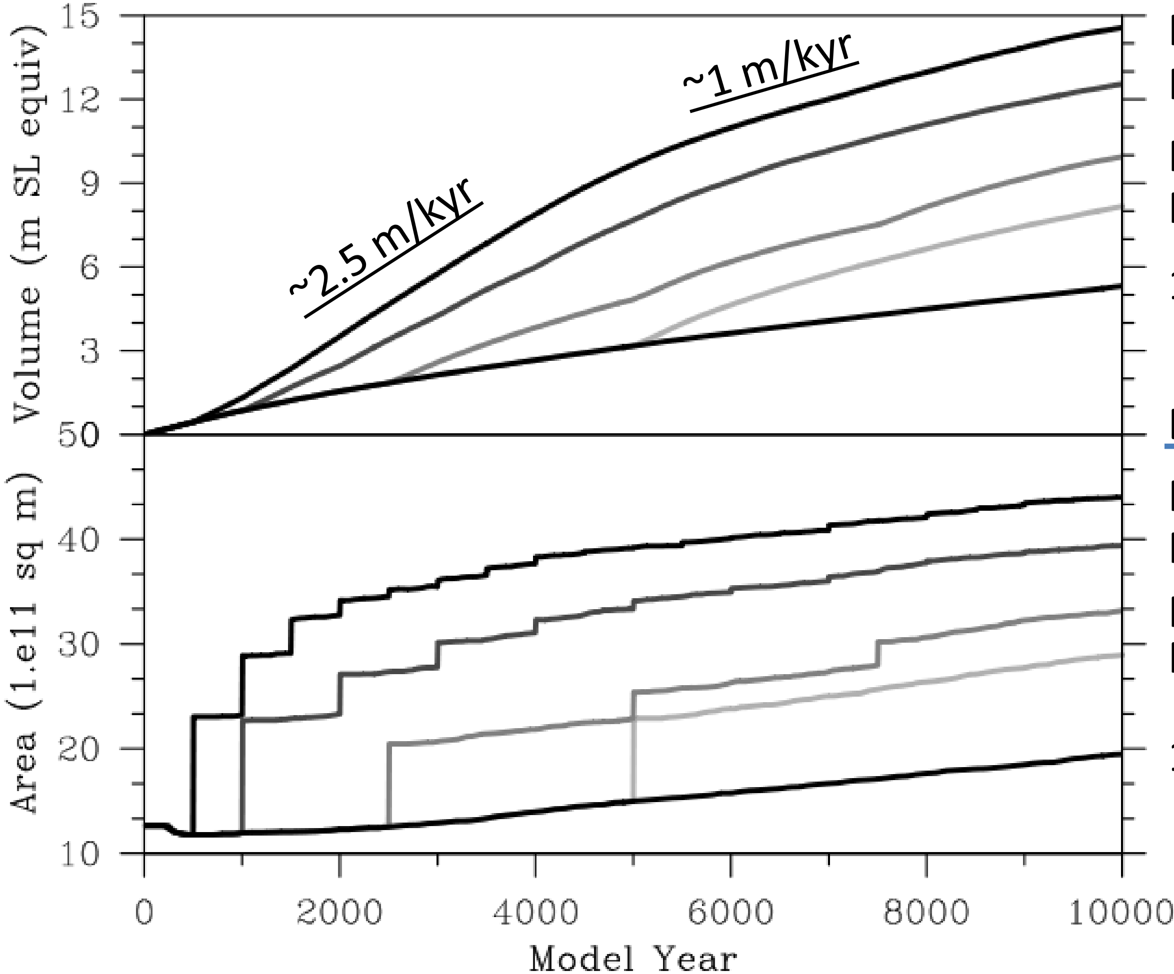
Ice Evolution

N. America

Greenland



Ice Evolution – N. America



Exp.	Volume	(% F500)
F500	5.9×10^6 km^3	(100%)
F1000	5.0×10^6 km^3	(85%)
F2500	4.0×10^6 km^3	(68%)
F5000	3.2×10^6 km^3	(54%)
1-way	2.1×10^6 km^3	(36%)

Exp.	Area	(% F500)
F500	4.4×10^6 km^2	(100%)
F1000	3.9×10^6 km^2	(89%)
F2500	3.3×10^6 km^2	(75%)
F5000	2.9×10^6 km^2	(66%)
1-way	1.9×10^6 km^2	(43%)

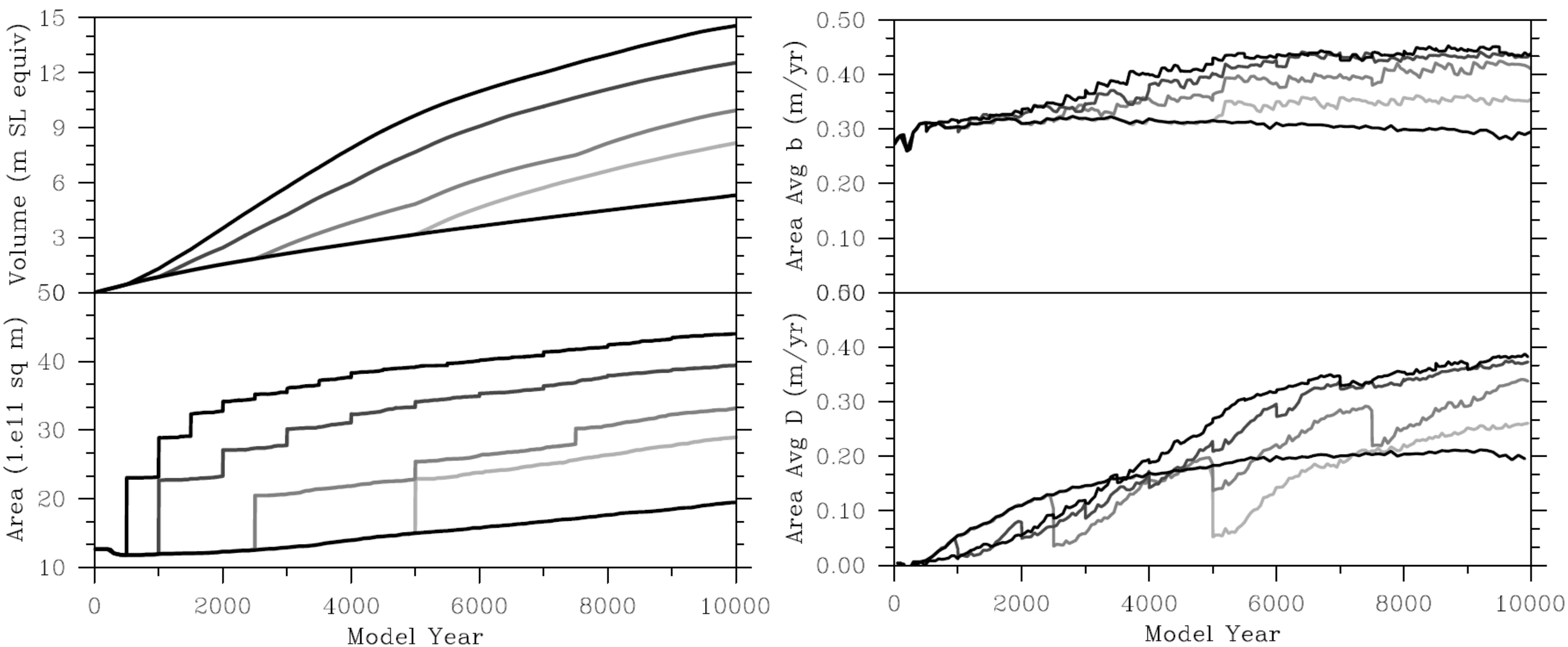
Mass Balance Evolution – N. America

Ice Area

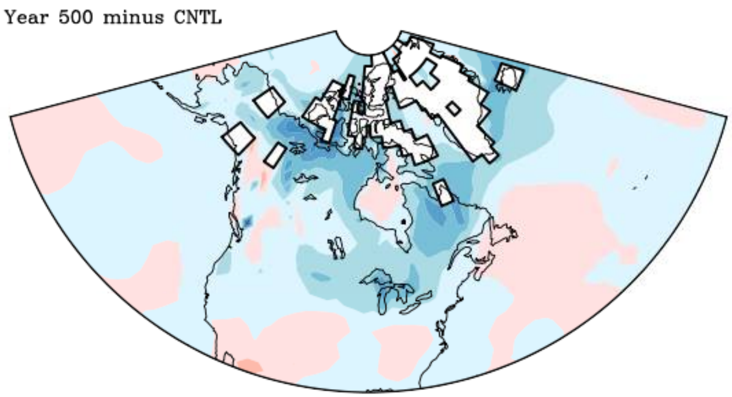
Calving Flux

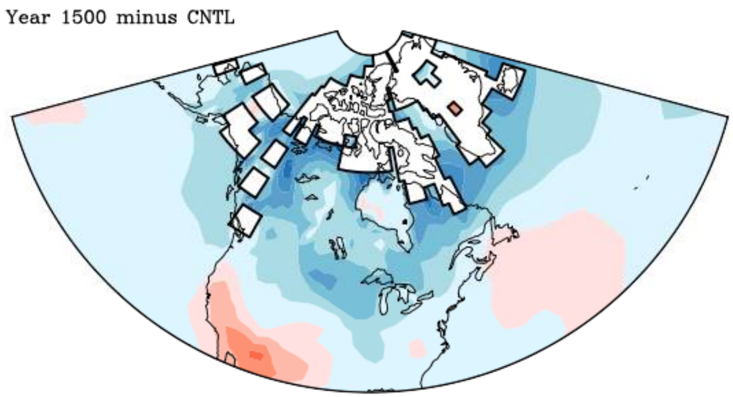
$$\frac{dV}{dt} = \bar{b}A - D$$

Area Avg SMB

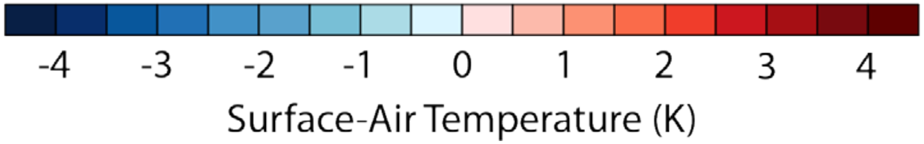


GCM Updates in F500

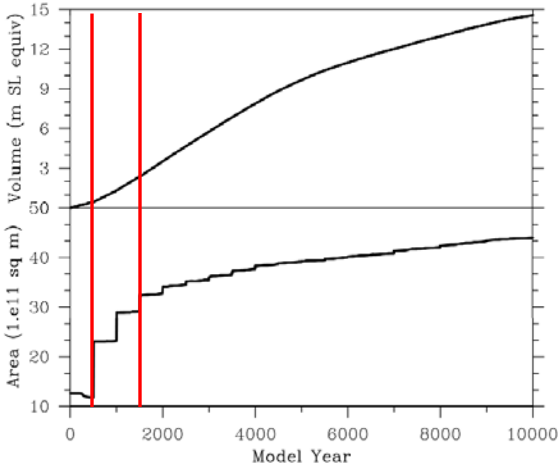




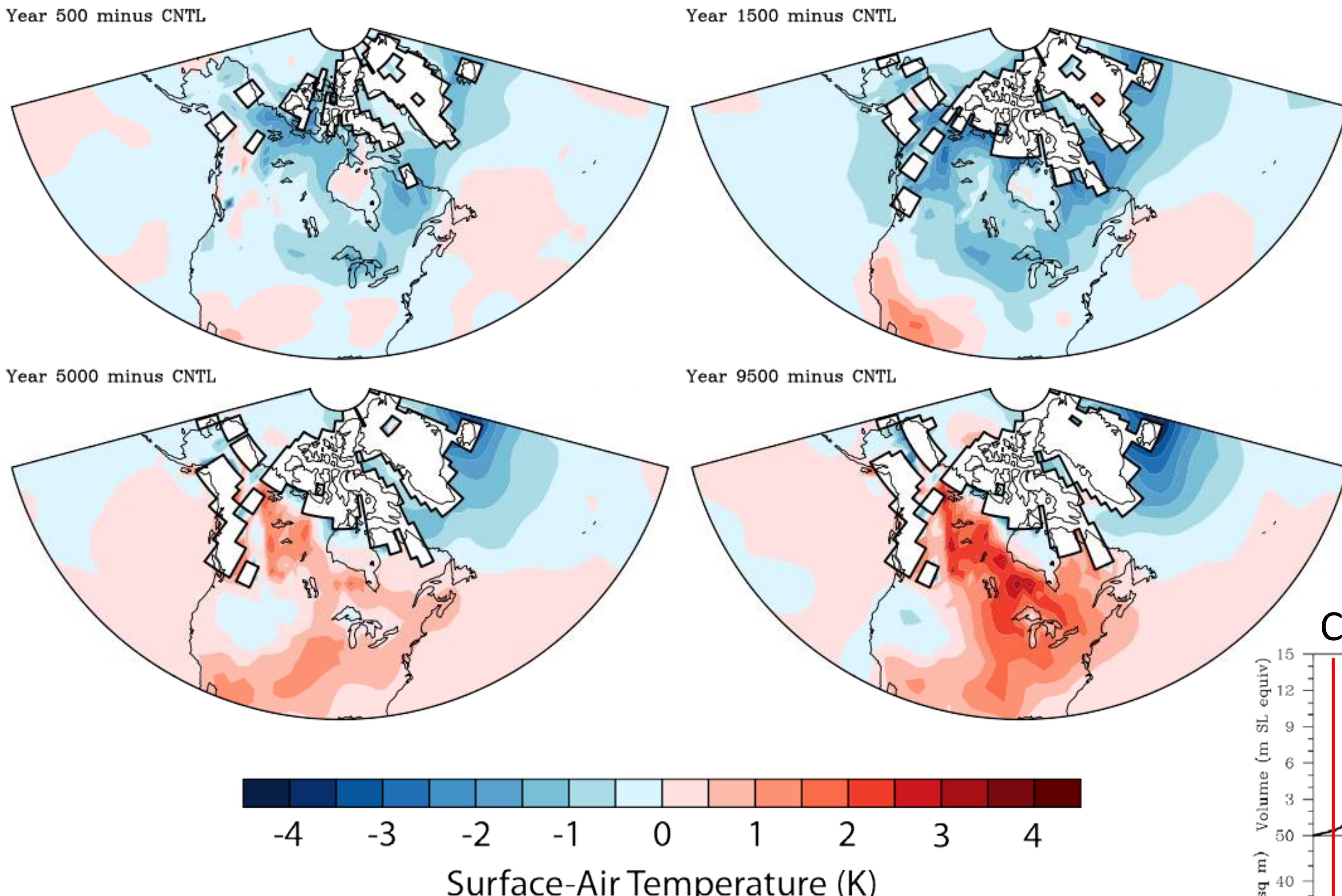
GCM predicts ice albedo cooling is damped horizontally, creating stepwise increases in ice area when passed to SMB algorithm of the ISM



Canada



GCM Updates in F500



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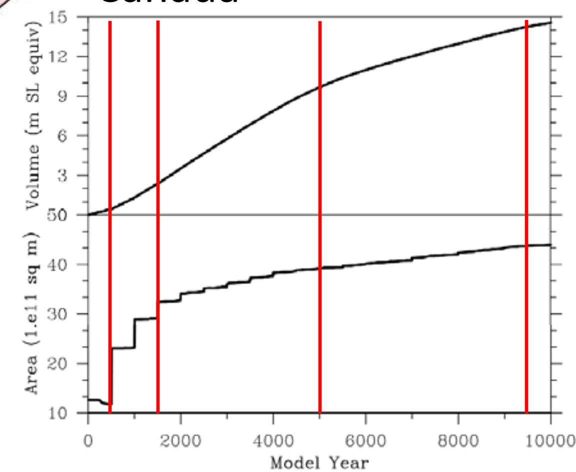
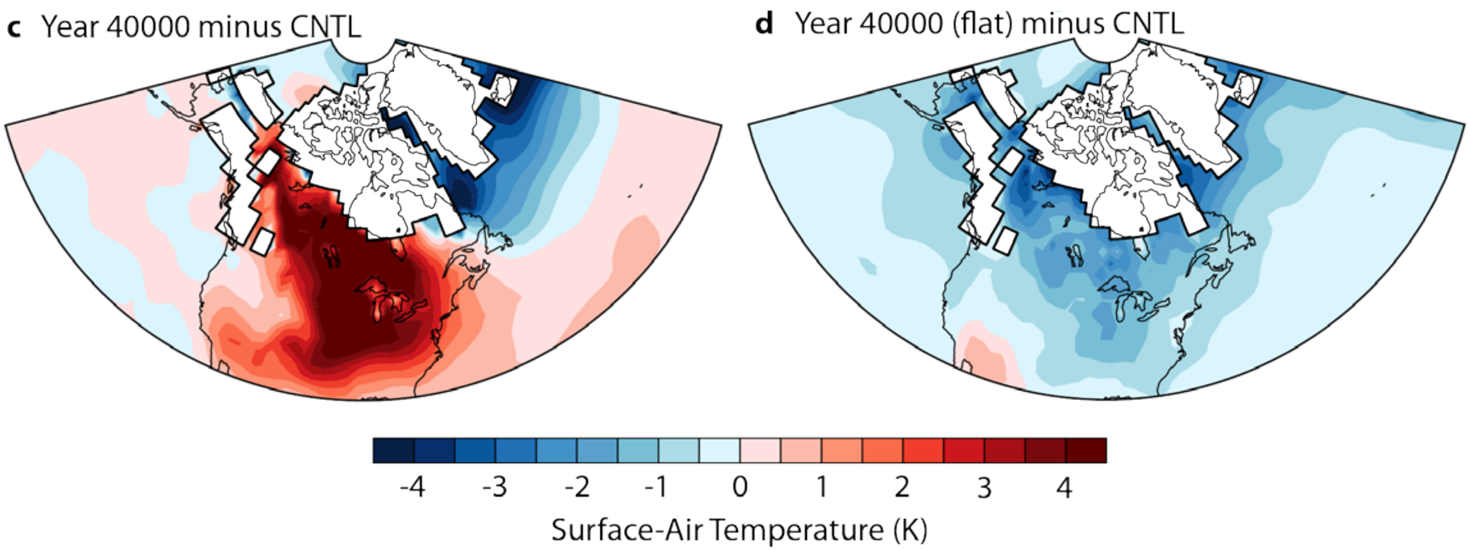


Is warming effect due to increases in ice thickness or ice extent?

Full vs. Flat Ice Sheet Experiment

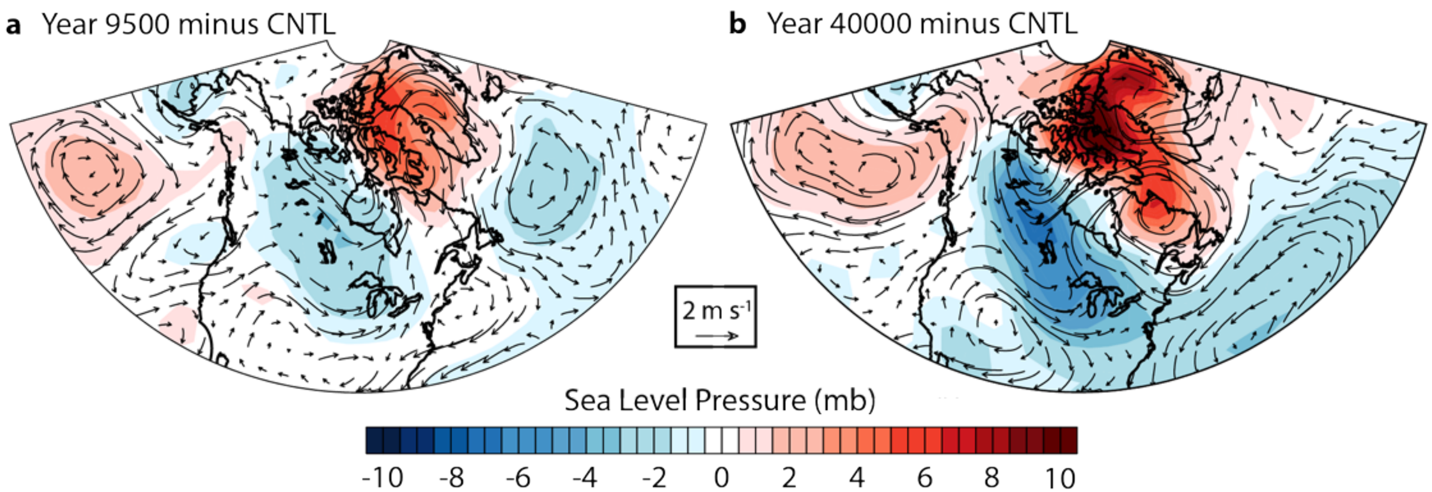
- Developed large ice sheet by continuing f500 simulation offline for additional 30 kyrs
- Synthetic flat ice sheet interpreted as an infinitely thin ice surface above bedrock



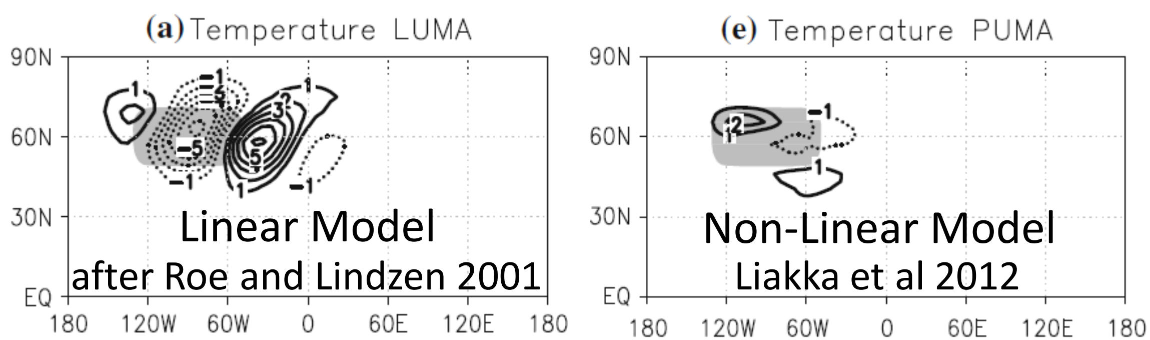
The cooling influence of flat ice sheets indicates that the development of ice sheet topography opposes horizontal dampening processes in the GCM and warms the southern margin of the Laurentide Ice Sheet

Stationary Wave Feedback

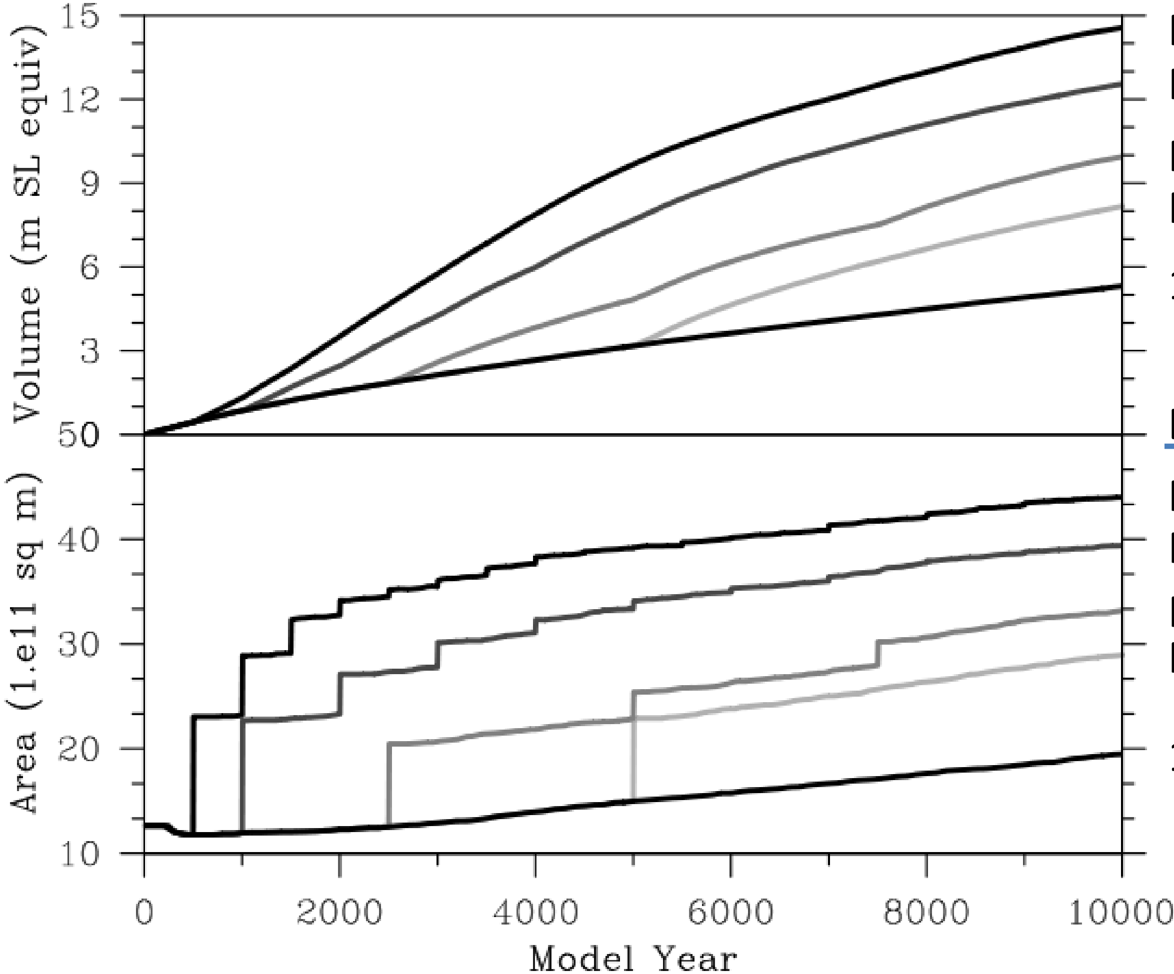
- Development of ice topography facilitates anticyclonic flow over regional summits
- Brings warm southerly air to southern Laurentide Ice Sheet margin



Stationary Wave Feedback is Negative. Opposite to Roe and Lindzen (2001)
Probably due to failure of linear approximation (Liakka et al 2012)



All Experiments – N. America



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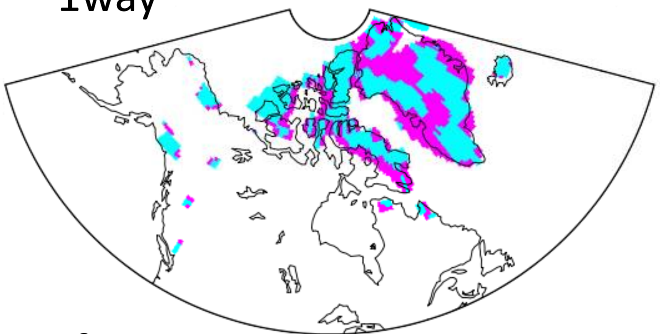
Ice Albedo Feedback

Ice area split into contributions:

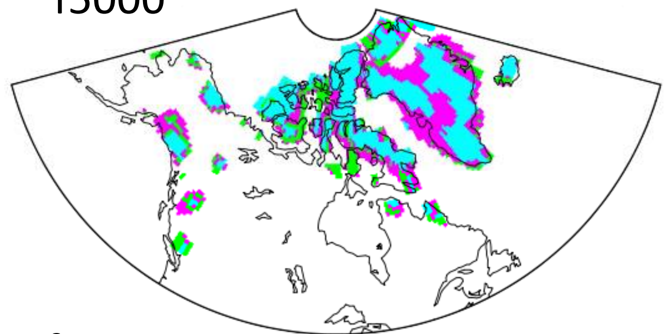
initial ELA (INIT) spreading (SPR) ice-albedo feedback (IAF)

1way



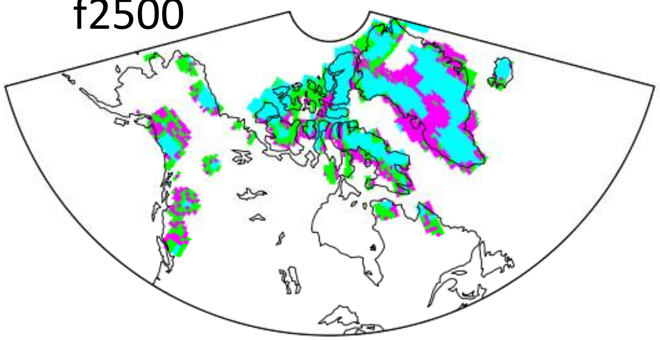
4.79 x 10^6 km²
INIT - 55.2%
SPR - 44.8%
IAF - 0.0%

f5000



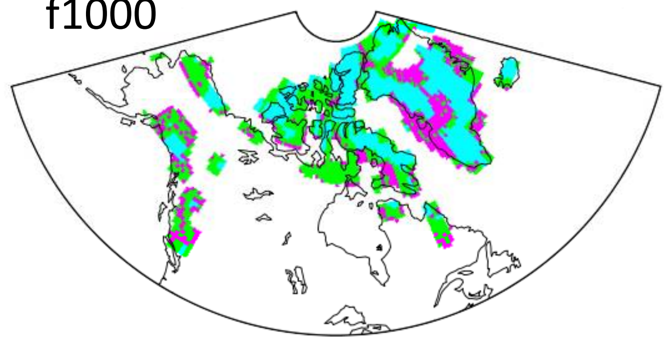
5.75 x 10^6 km²
INIT - 45.8%
SPR - 36.0%
IAF - 18.2%

f2500



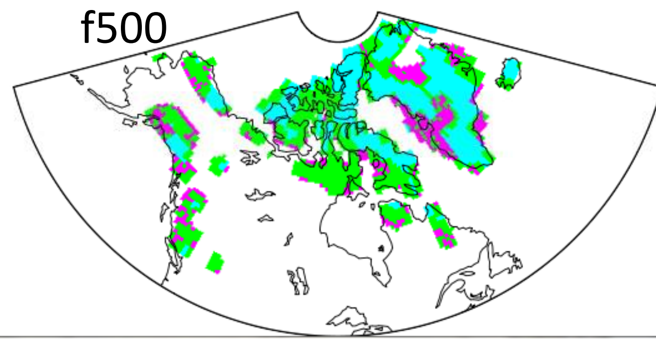
6.15 x 10^6 km²
INIT - 42.7%
SPR - 29.4%
IAF - 28.0%

f1000



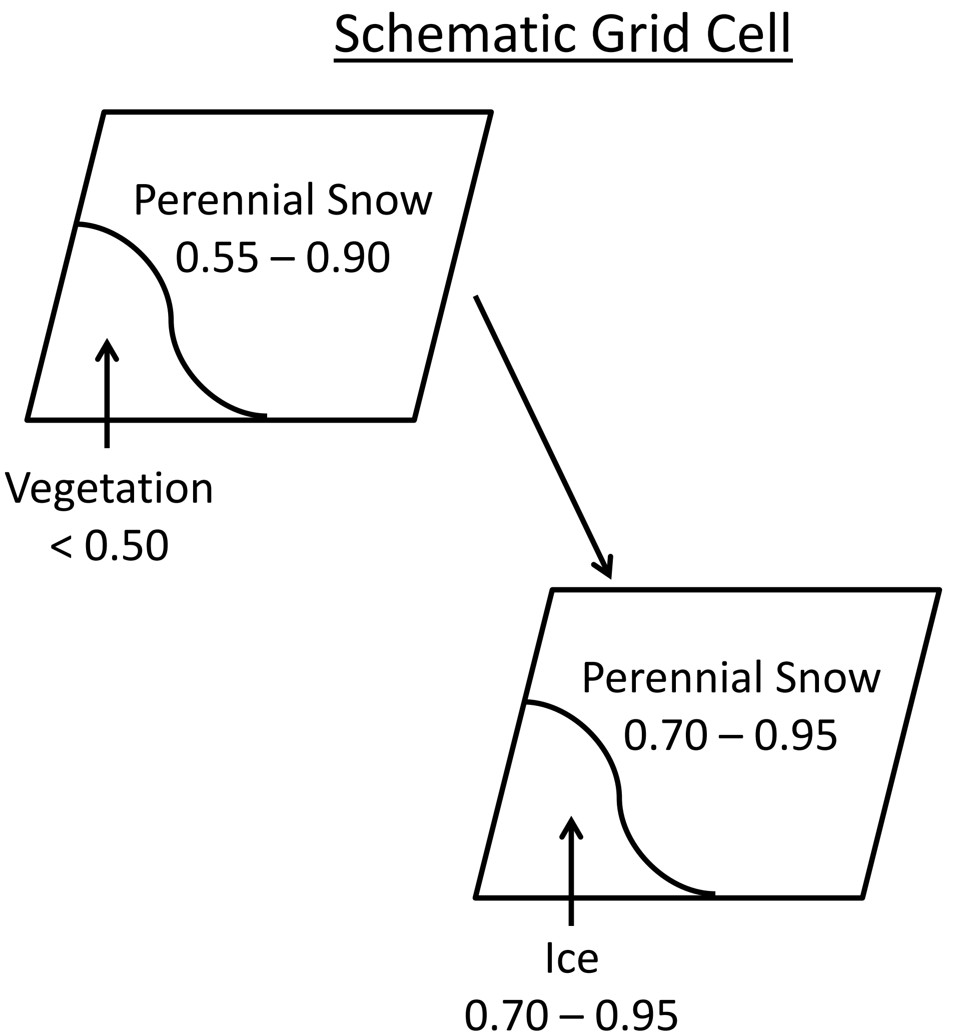
6.79 x 10^6 km²
INIT - 37.9%
SPR - 22.8%
IAF - 39.3%

f500



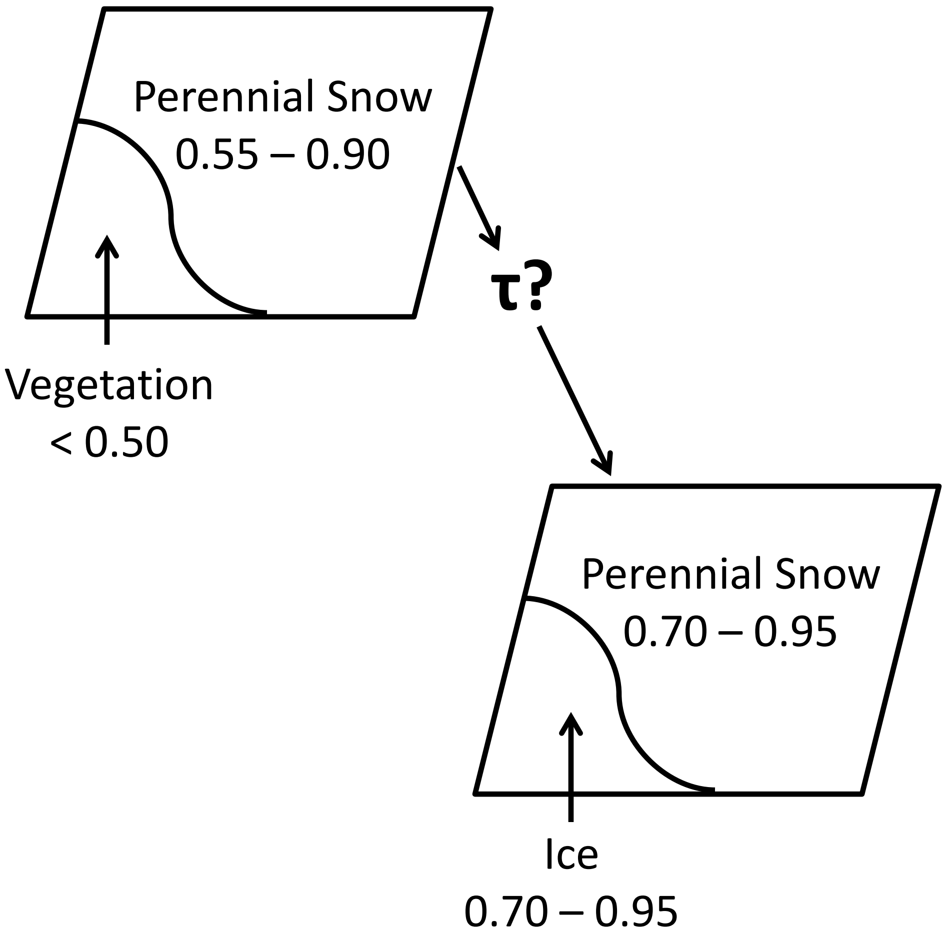
7.26 x 10^6 km²
INIT - 35.2%
SPR - 17.2%
IAF - 45.8%

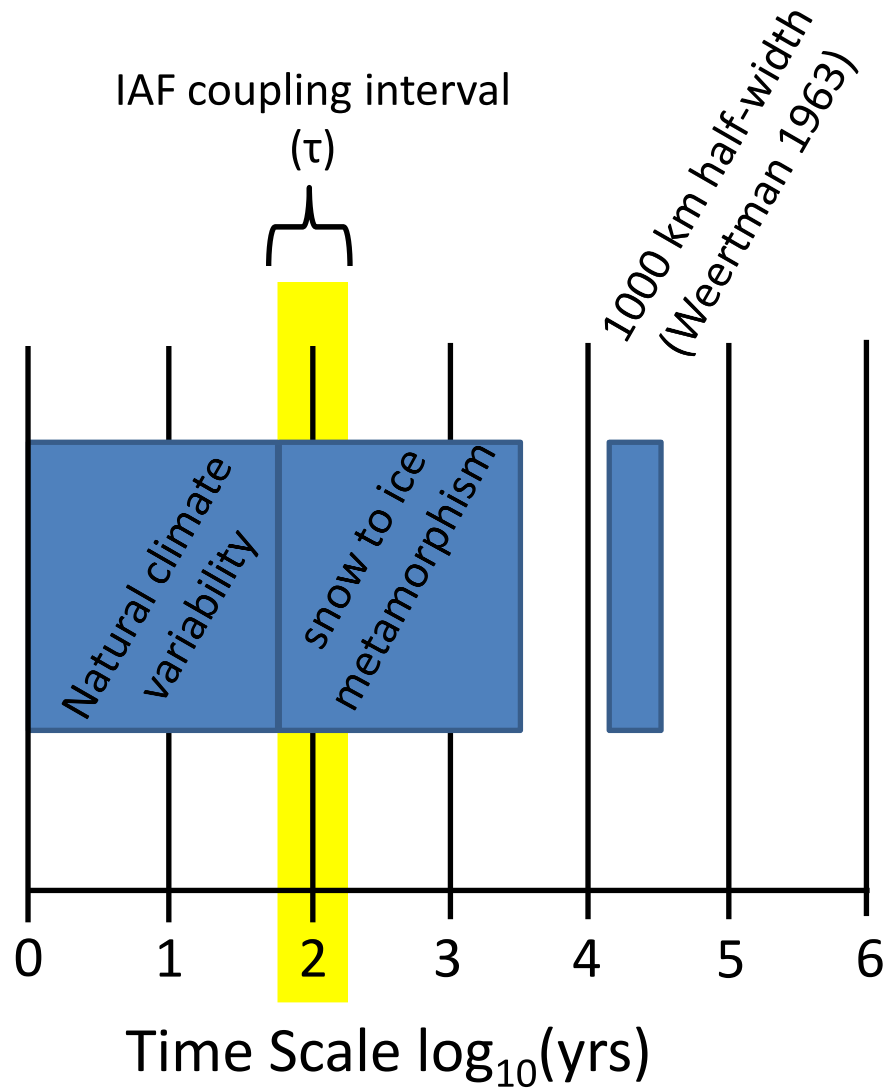
Ice Albedo Feedback



An Optimal Coupling Scheme

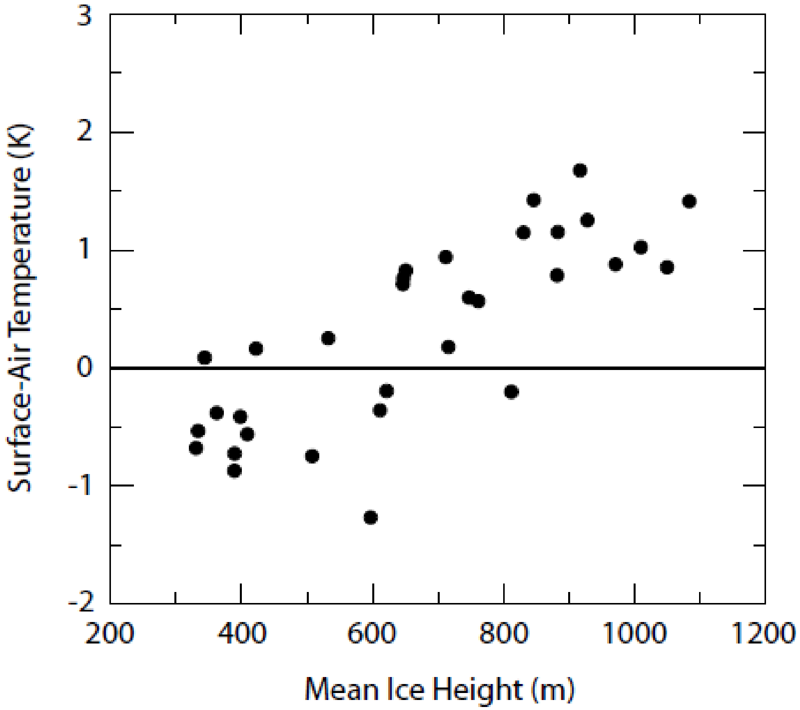
Schematic Grid Cell





An Optimal Coupling Scheme

- After the albedo feedback is exhausted, the coupling interval may be lengthened
- New coupling interval should resolve developing stationary waves



- Sensitivity of ~0.5 K per 100 m
- Mean elevation of ~1 km in 10 kyrs
- **Suggests relaxation of coupling interval to order 10^3 yrs**

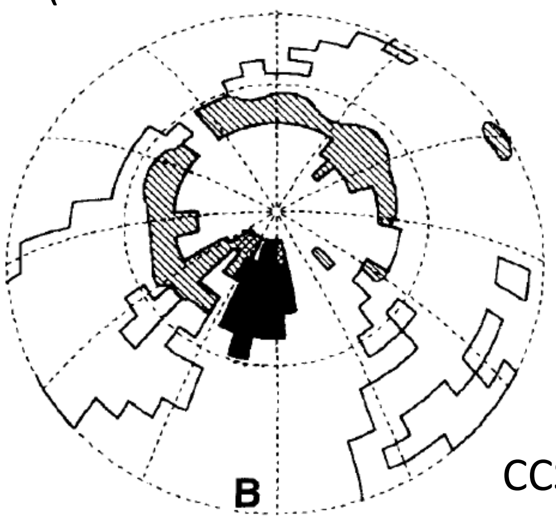
Figure 6. Scatter plot of July surface air temperature relative to the ice-free run for all climate updates averaged over a land region between the Laurentide and Cordilleran ice sheets against mean height of the Laurentide Ice Sheet lying under anti-cyclonic flow.

Conclusions

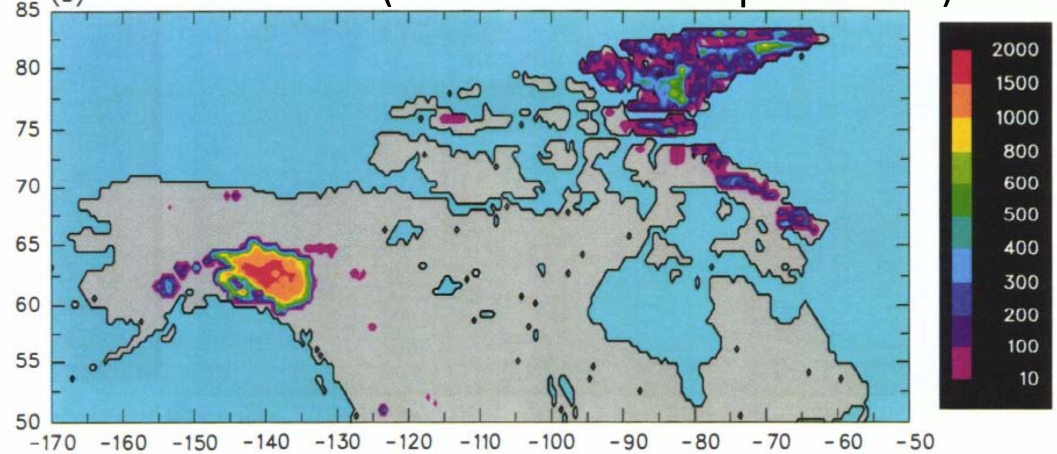
- 10X reduction in coupling interval causes doubling of N. American ice volume
- Due to competition of ice albedo and stationary wave feedbacks
- Shortest coupling interval (500 yrs) produces ~15 m sea level equivalent in 10 kyrs
- Indicates an optimal coupling interval of about 100 years until albedo feedback is exhausted, then relaxing to order 10^3 years

Perennial Snow Problem

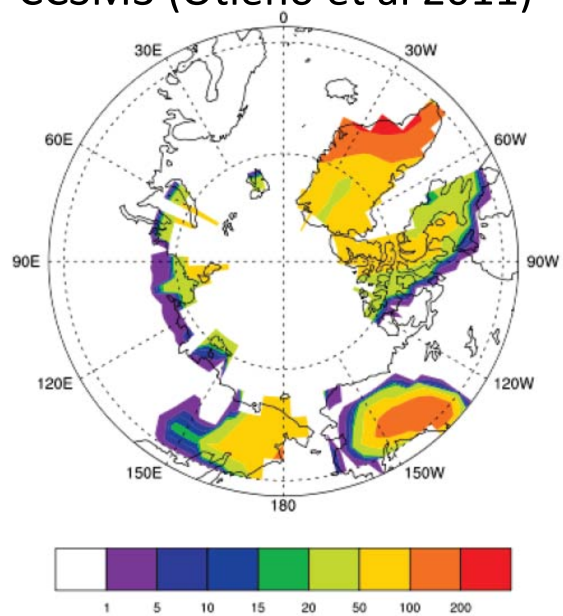
CCM1 (Gallimore and Kutzbach 1996)



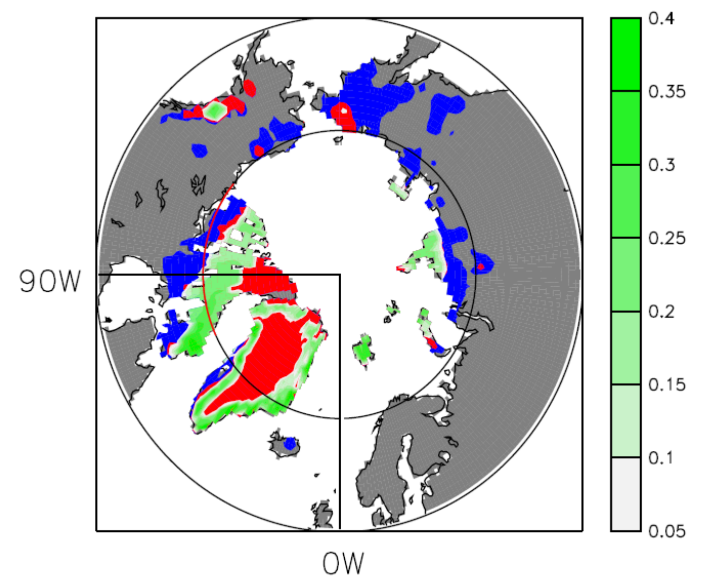
GENESIS 2.0 (Pollard and Thompson 1997)



CCSM3 (Otieno et al 2011)



CCSM4 (Jochum et al 2012)



Higher grid scale snow albedo in CAM3 (Niu and Yang 2007, Cook et al 2008)