The role of North Atlantic Ocean dynamics in simulating glacial inception: a study with CCSM4

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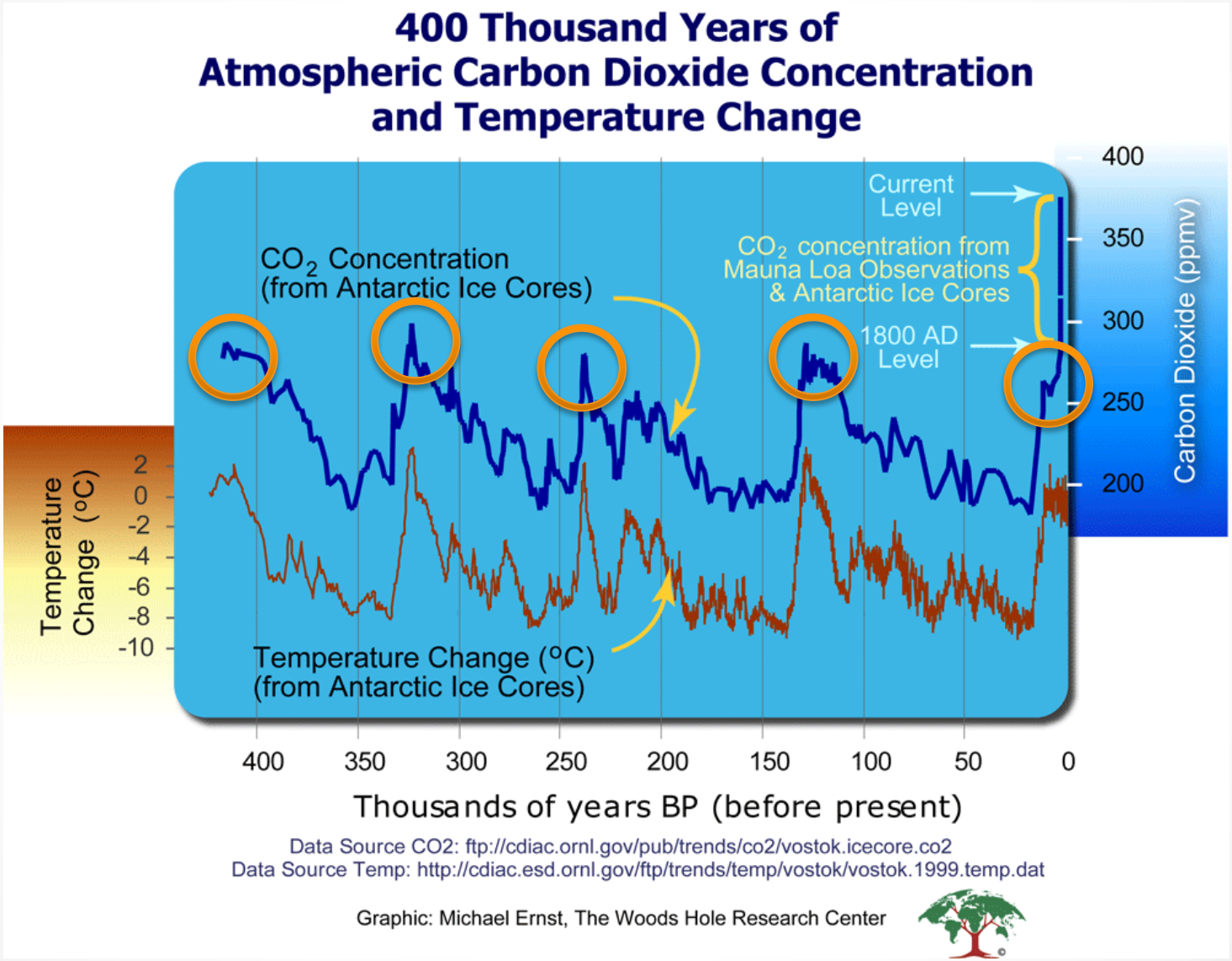
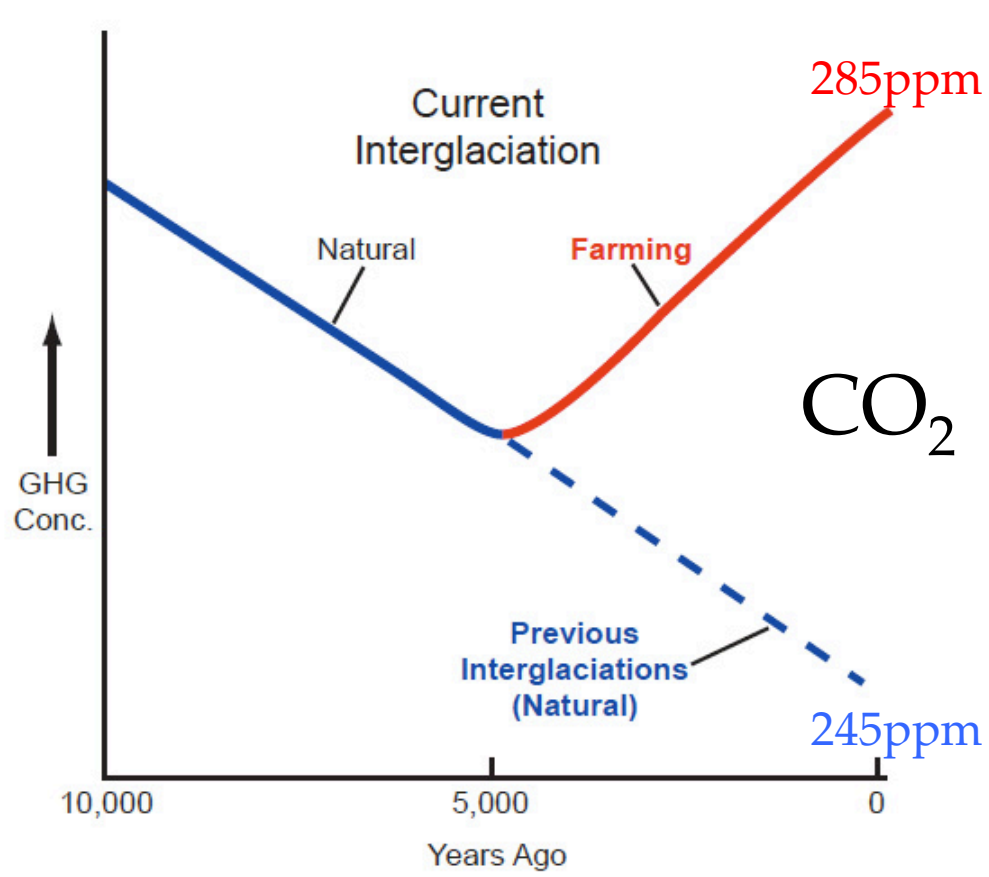

400 Thousand Years of
Atmospheric Carbon Dioxide Concentration
and Temperature Change
Current Level
CO2 concentration from Mauna Loa Observations & Antarctic Ice Cores
1800 AD Level
CO2 Concentration (from Antarctic Ice Cores)
Temperature Change (°C) (from Antarctic Ice Cores)
Temperature Change (°C)
2
0
-2
-4
-6
-8
-10
Carbon Dioxide (ppmv)
400
350
300
250
200
400
350
300
250
200
150
100
50
0
Thousands of years BP (before present)
Data Source CO2: ftp://cdiac.ornl.gov/pub/trends/co2/vostok.icecore.co2
Data Source Temp: http://cdiac.esd.ornl.gov/ftp/trends/temp/vostok/vostok.1999.temp.dat
Graphic: Michael Ernst, The Woods Hole Research Center

CCSM4 simulations of Glacial inception



CO_2

Farming 285 ppm

Natural 245 ppm

NoAnthro (NA)

http://www.realclimate.org/index.php/archives/2011/04/an-emerging-view-on-early-land-use/

CCSM4 Simulations: 3 fully-coupled & 3 slab ocean runs

Ocean dynamics:
difference between fully-coupled and slab-ocean runs

1° resolution	Fully-Coupled (FC)	Slab Ocean Model (SOM)
PD	355 ppm	355 ppm
PI	285 ppm	285 ppm
NA (NoAnthro)	245 ppm	245 ppm

CCSM4 Simulations: initialization of fully-coupled runs

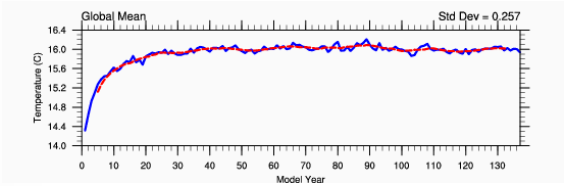
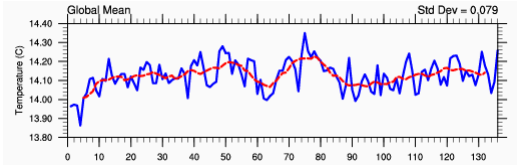
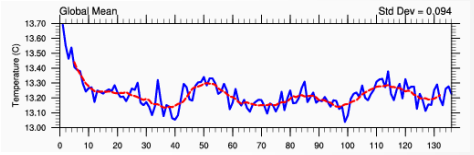
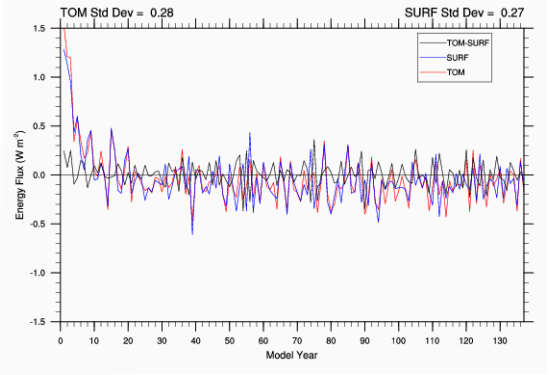
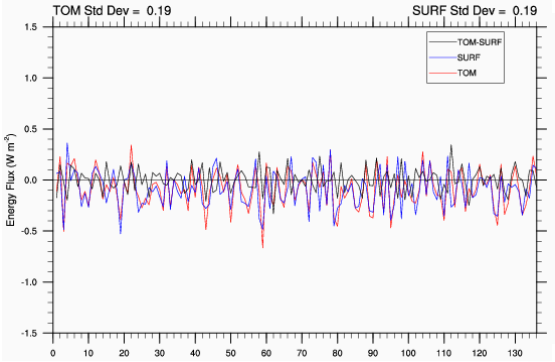
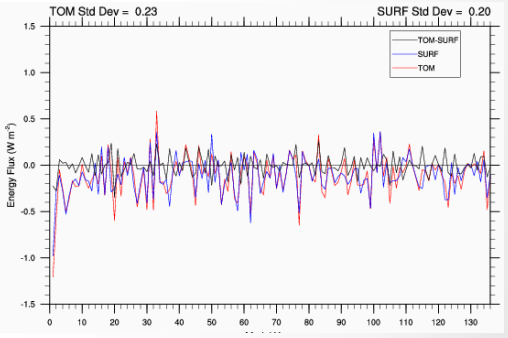
Fully-coupled run	Initialization	Run length
PD	Year 1990 of NCAR 20th Century Ensemble Member (b40.20th.track1.1deg.004)	360 years
PI (NCAR)	Performed by NCAR	1,300 years
NA (NoAnthro)	Year 1300 of NCAR Pre-Industrial Control run (b40.1850.track1.1deg.006)*	180 years

NA run:
*With modified T,S initial condition to account for the cooling from lowered GHG

CCSM4 simulations:

135-year slab ocean runs: equilibrium is OK

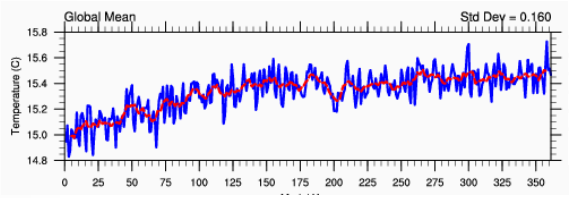
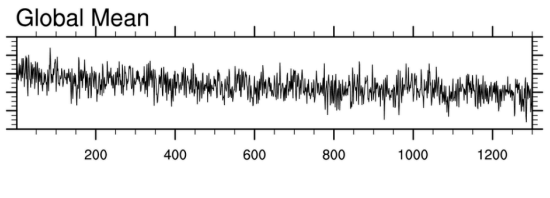
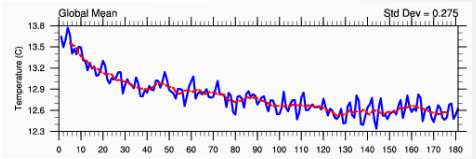
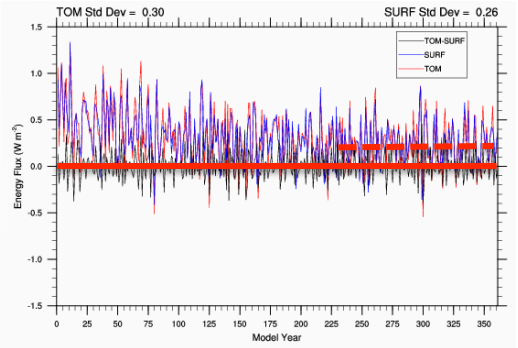
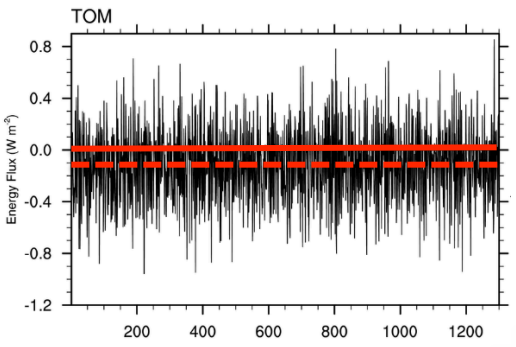
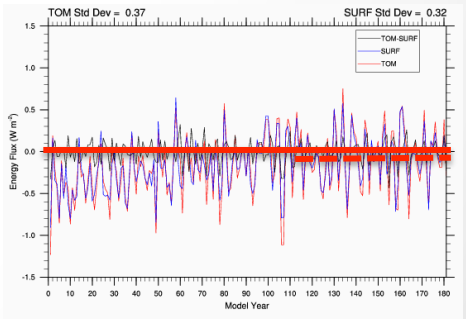
Climatology is calculated as the average of the last 50 years

	PD	PI	NA
Global SAT			
Top of atmosphere net radiation flux			

CCSM4 simulations:

Fully-coupled runs: near equilibrium

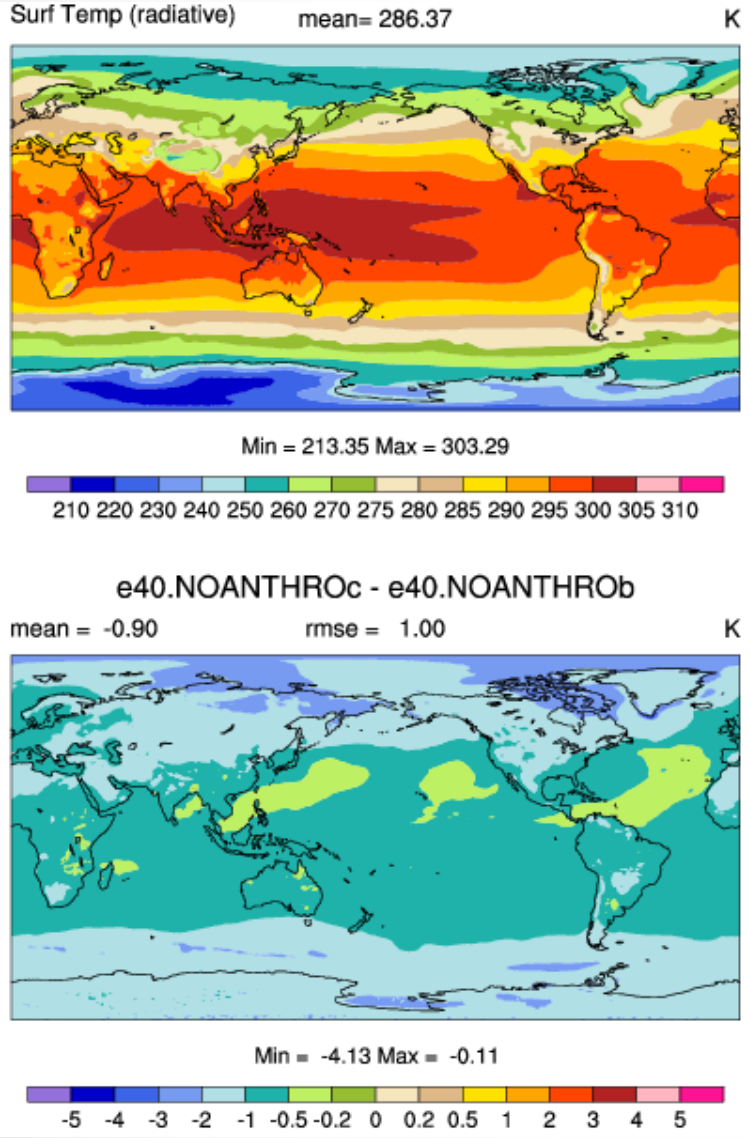
Climatology is calculated as the average of the last 50 years

	PD	PI (NCAR)	NA
	(360 years)	(1300 years)	(180 years)
Global SAT			
Top of atmosphere net radiation flux			
	+0.2 Wm^{-2}	-0.1 Wm^{-2}	-0.1 Wm^{-2}

SOM Run (NA vs. PI)

Global Surface temperature:

CO_2 (245ppm vs. 285 ppm)



ΔT= -0.90 K

Radiative forcing
ΔF= -1.01 W/m^2

Climate Sensitivity:
$\Delta T/\Delta F^*\Delta F_{2xco2}$

= (-0.90)/(-1.01)*3.7
= 3.3 K

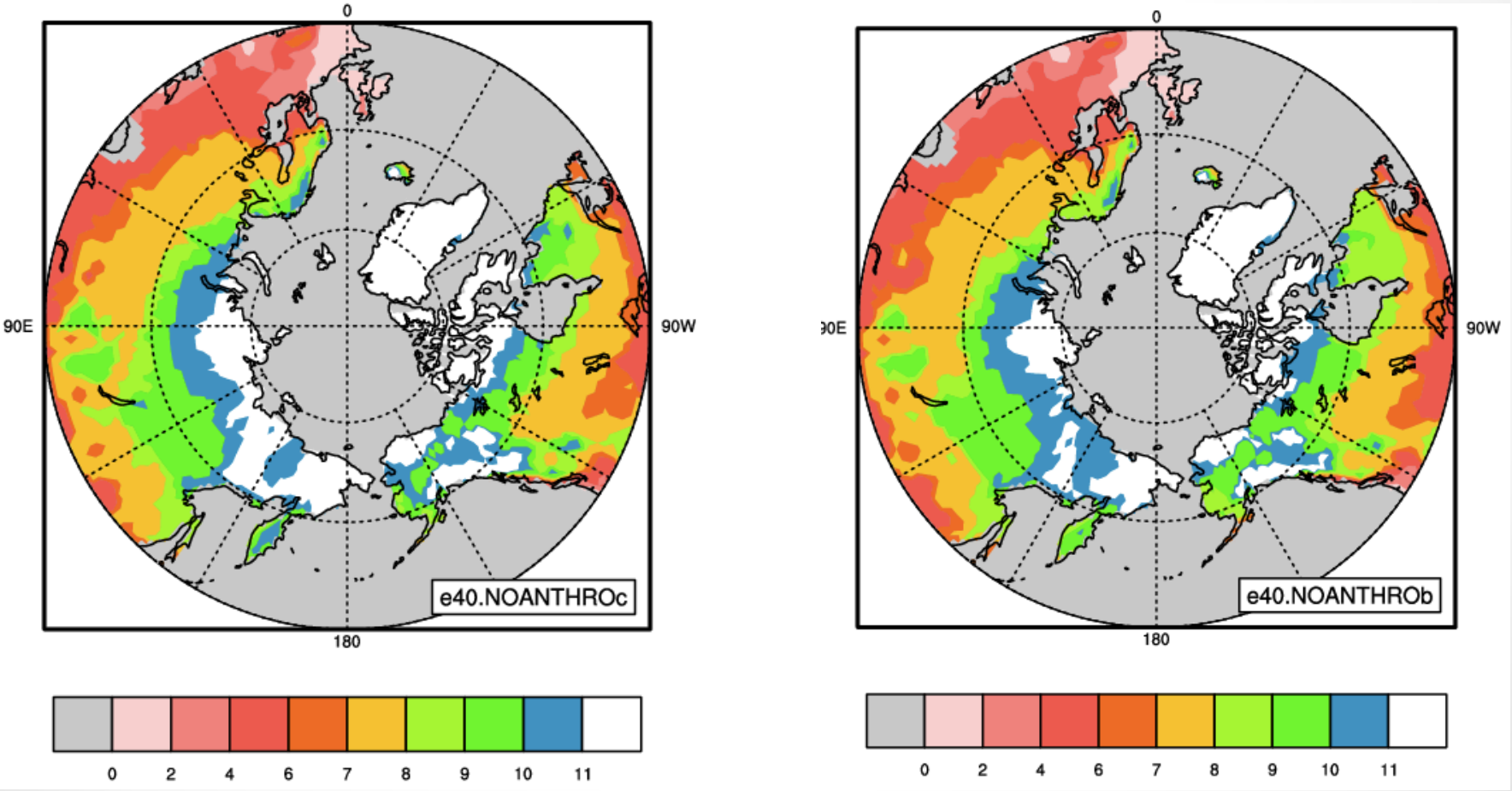
Consistent with
Bitz et.al (2012): 3.2 K

SOM Run (NA vs. PI)

Permanent (12-month) snow: **CO_2 (245ppm vs. 285 ppm)**

NA: 8.6 million km^2 PI: 6.9 million km^2

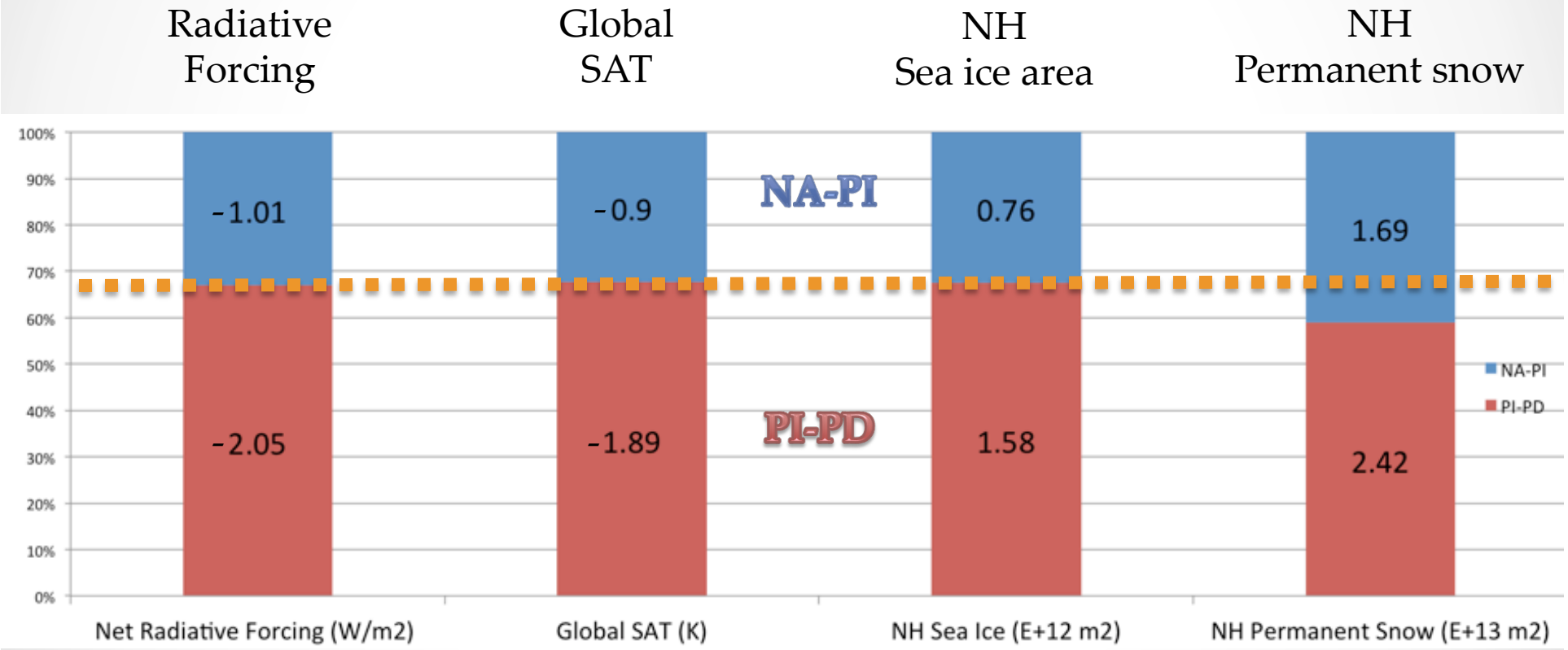
NA-PI: 1.7 million km^2 (25% more than PI)



Months of Snow Cover

Climate transition in CCSM4 SOM runs:

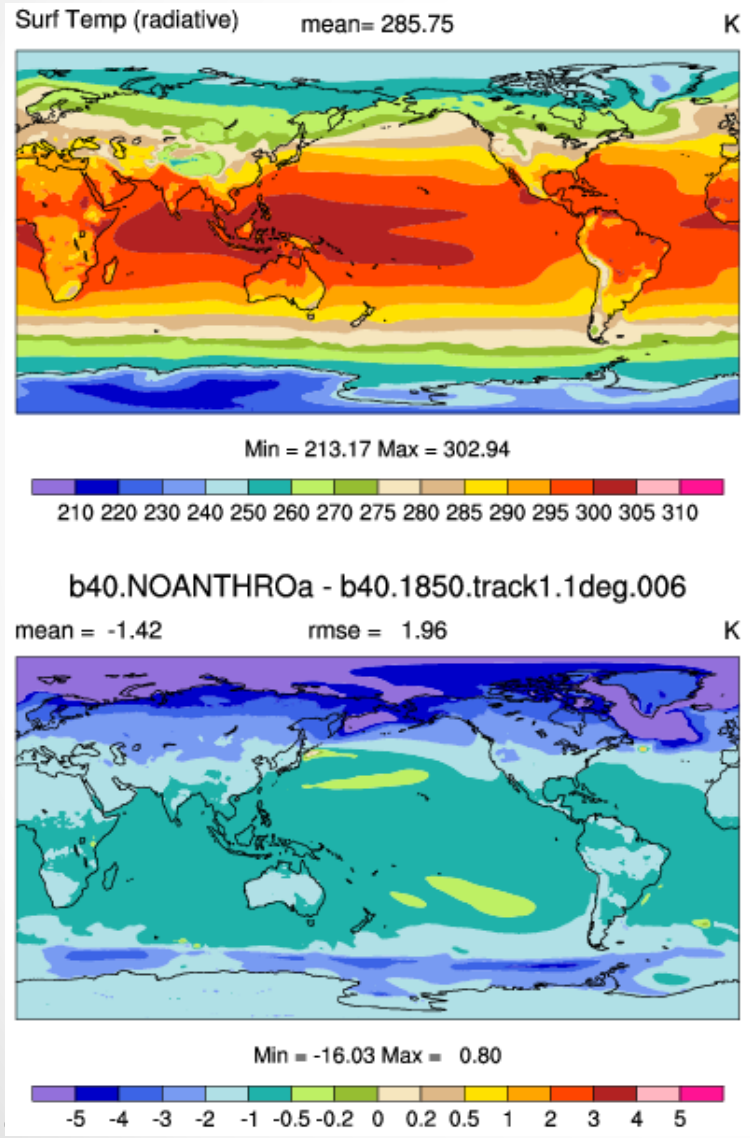
NA-PI vs. PI-PD



Without ocean dynamics, the climate transition is quasi-linear with respect to the radiative forcing

Fully-coupled run (NA vs. PI)

Global Surface temperature:



CO_2 (245ppm vs. 285 ppm)

ΔT= -1.42 K,
~60% more than SOM(0.90K)

Climate sensitivity:
$\Delta T/\Delta F^*\Delta F_{2xco2}$

= (-1.42)/(-1.01)*3.7
= 5.2 K

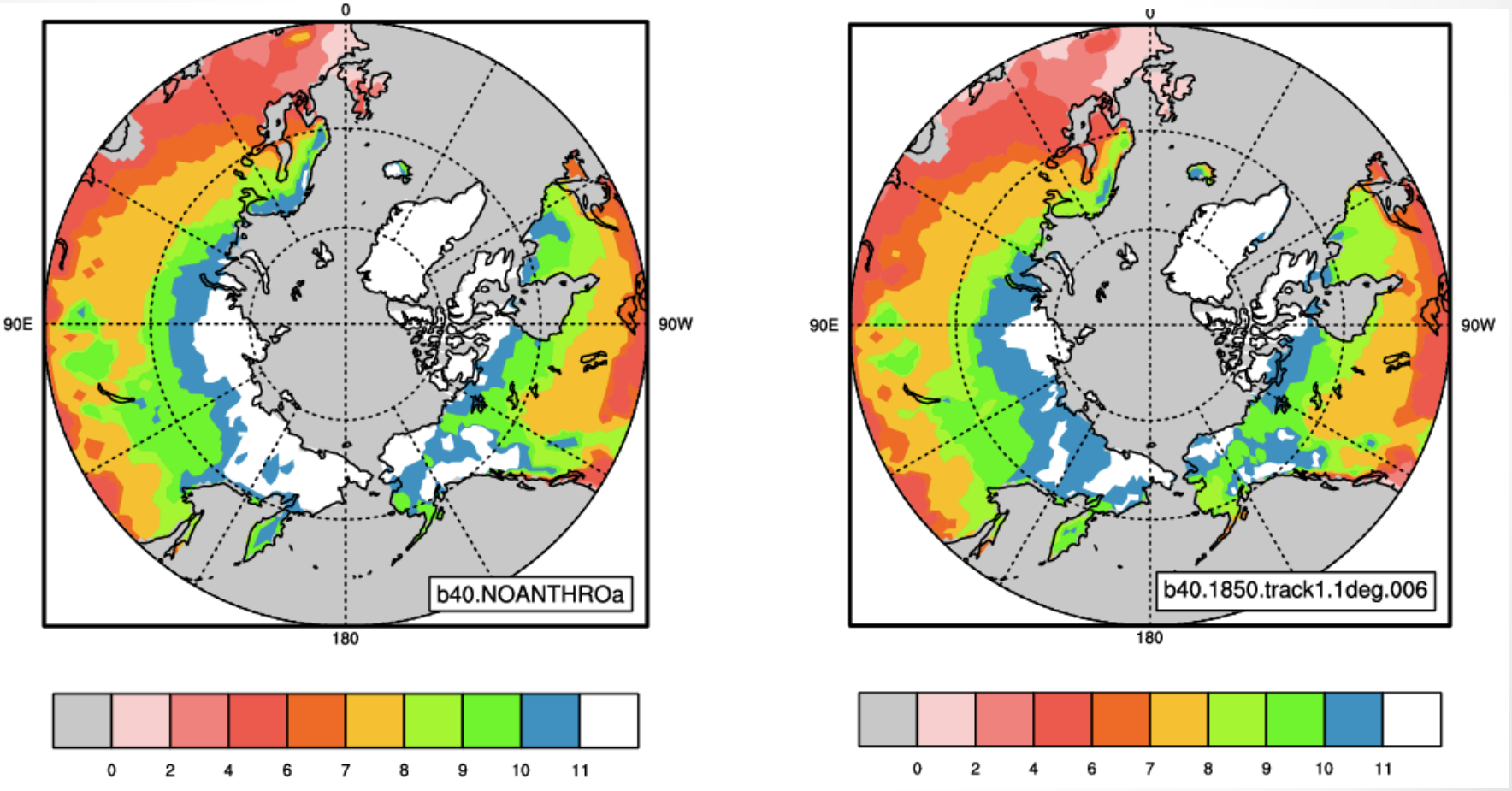
Climate sensitivity for NA/PI transition in fully-coupled run is ~60% larger than SOM (3.2 K)

Fully-coupled run (NA vs. PI)

Permanent (12-month) snow: **CO_2 (245ppm vs. 285 ppm)**

NA: 10.3 million km^2 PI: 6.2 million km^2

NA-PI: 4.1 million km^2, **140% more than SOM** (1.7 million km^2)



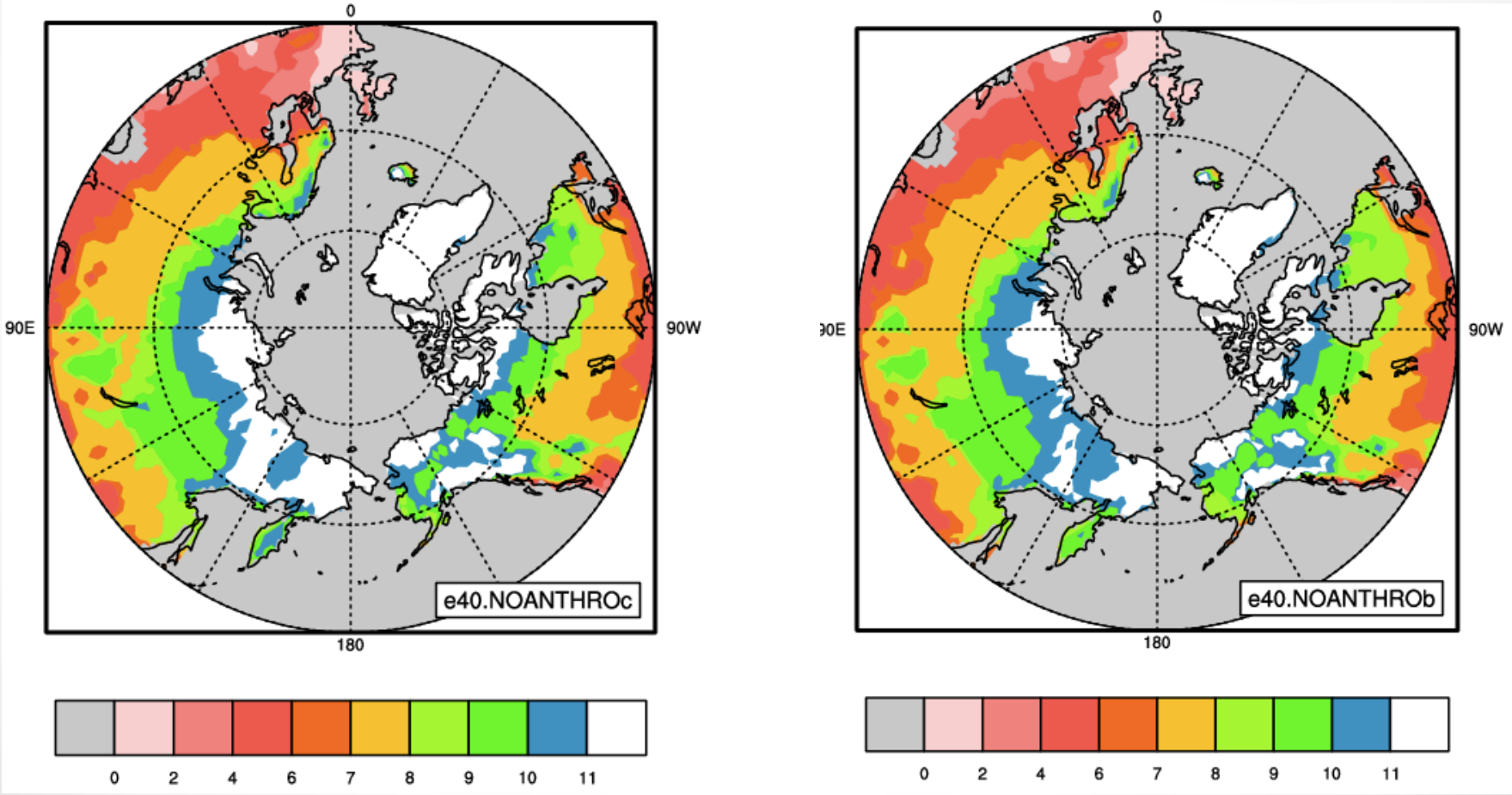
Months of Snow Cover

SOM Run (NA vs. PI)

Permanent (12-month) snow: **CO_2 (245ppm vs. 285 ppm)**

NA: 8.6 million km^2 PI: 6.9 million km^2

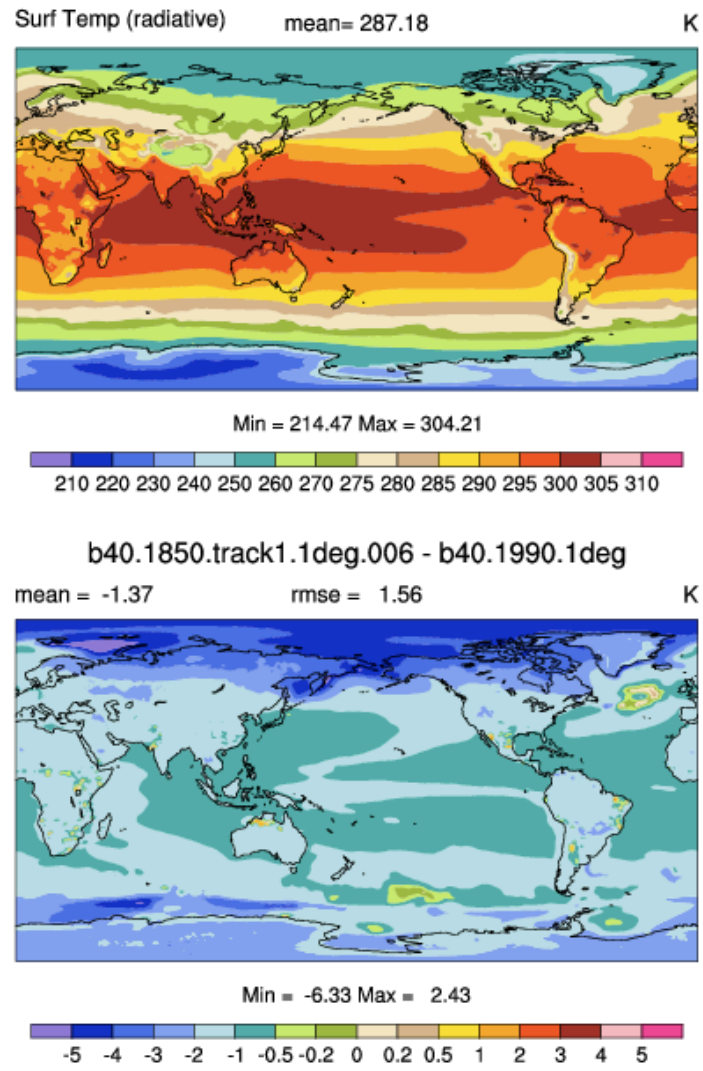
NA-PI: 1.7 million km^2



Months of Snow Cover

Fully-coupled Run (PI vs. PD)

Global Surface temperature:



CO_2 (285ppm vs. 355 ppm)

ΔT= -1.37 K

Climate sensitivity:
$\Delta T/\Delta F^{*}\Delta F_{2xco2}$

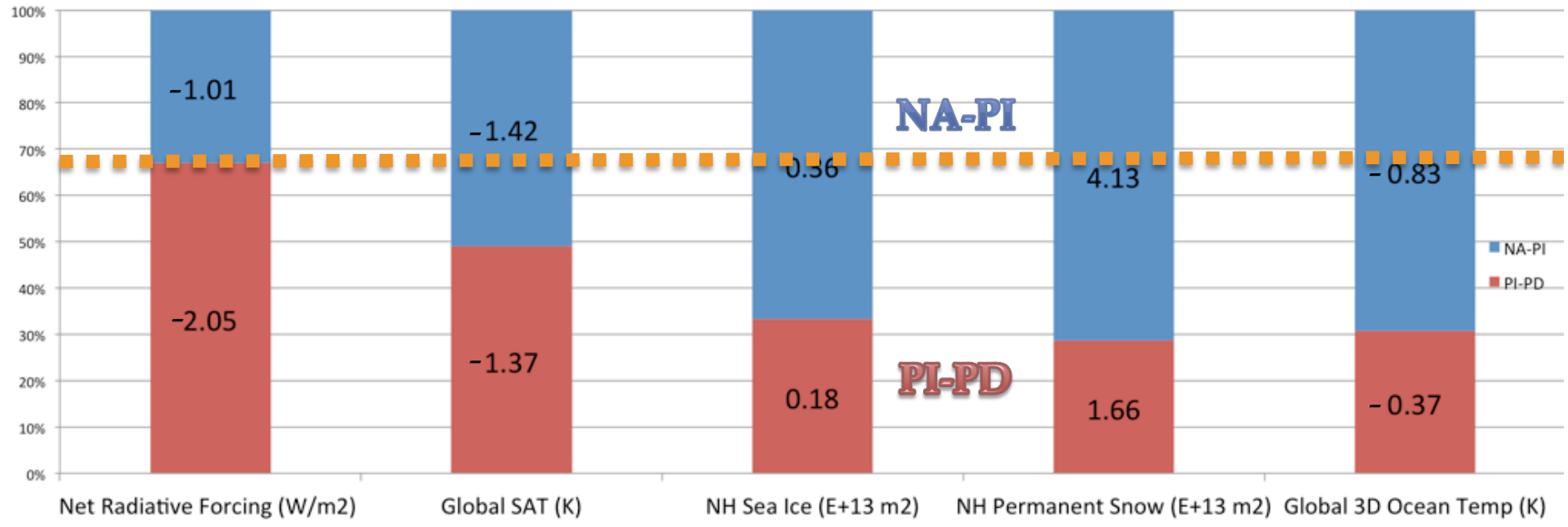
= (-1.37)/(-2.05)*3.7
= 2.5 K

Climate sensitivity for PI/PD transition in fully-coupled run is ~20% less than SOM (3.2 K)

Climate transition in fully-coupled runs:

NA-PI vs. PI-PD

Radiative Forcing | Global SAT | NH Sea ice area | NH Permanent snow | Global 3D Ocean Temp

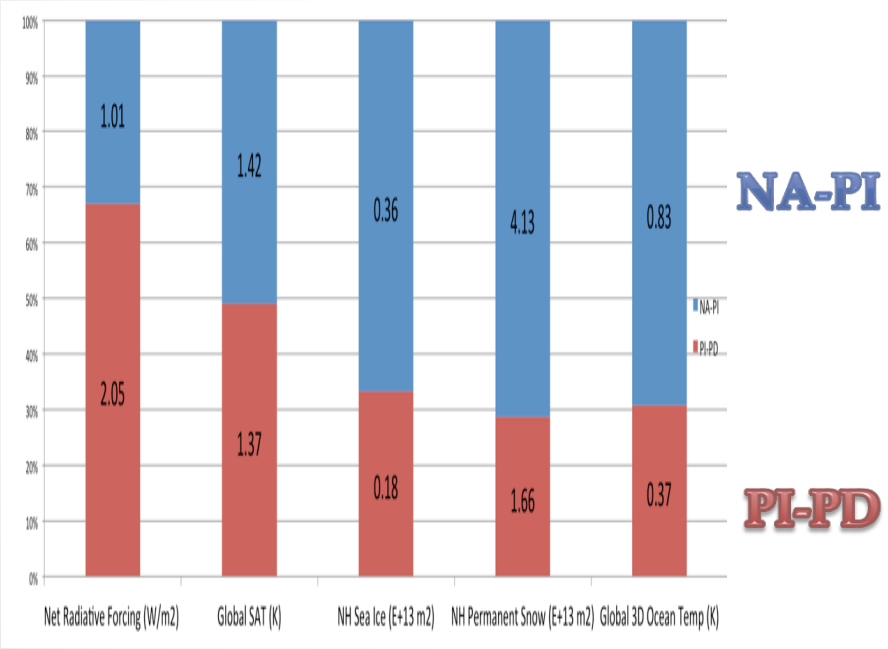


With ocean dynamics, the climate transition is nonlinear.

- Larger climate sensitivity during colder climate transition.

Larger climate sensitivity during colder climate transition in fully-coupled runs

Manabe & Bryan (1985)



NA-PI

PI-PD

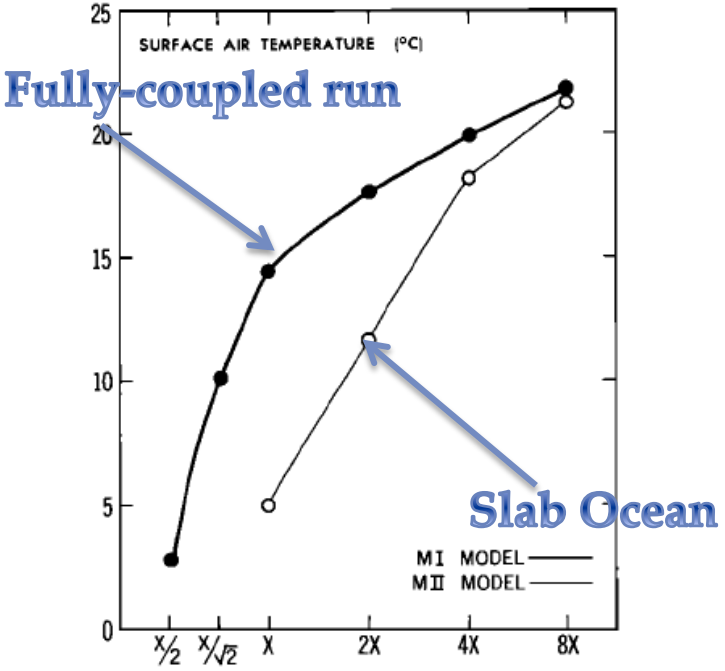
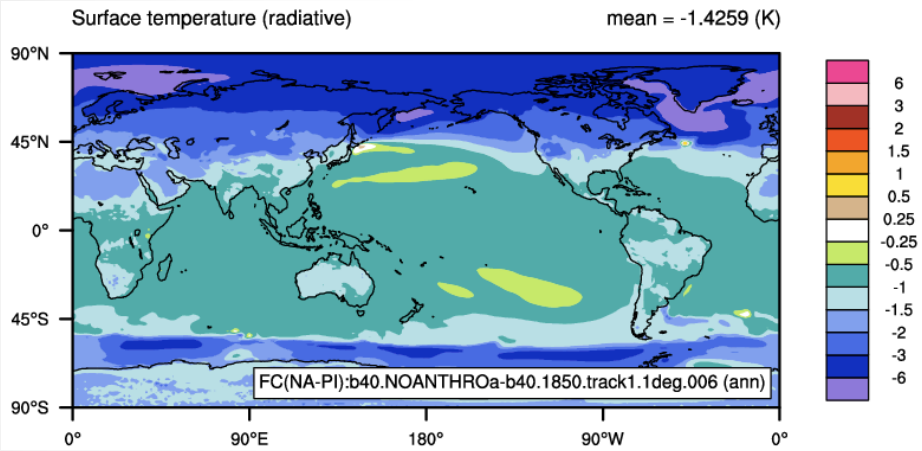


Fig. A2. The area mean surface air temperature from two series of the CO_2 experiments. The thick solid line denotes the MI model. The thin solid line denotes the MII model.

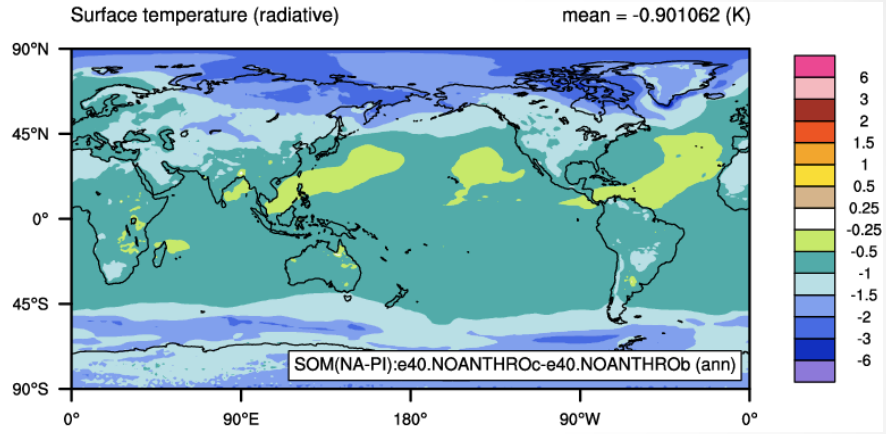
Manabe & Bryan (1985)

Ocean dynamics increases the climate sensitivity during colder climate transition NA - PI

Fully-coupled



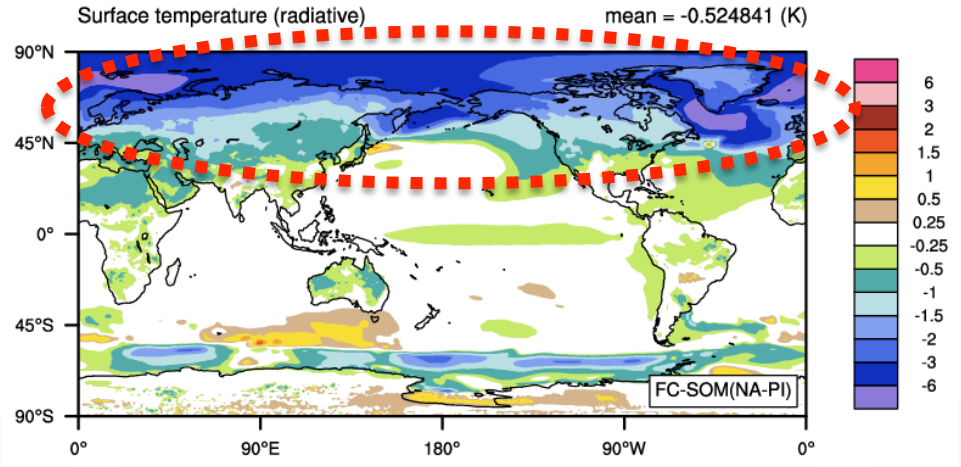
Slab Ocean



Fully-coupled

minus

Slab Ocean

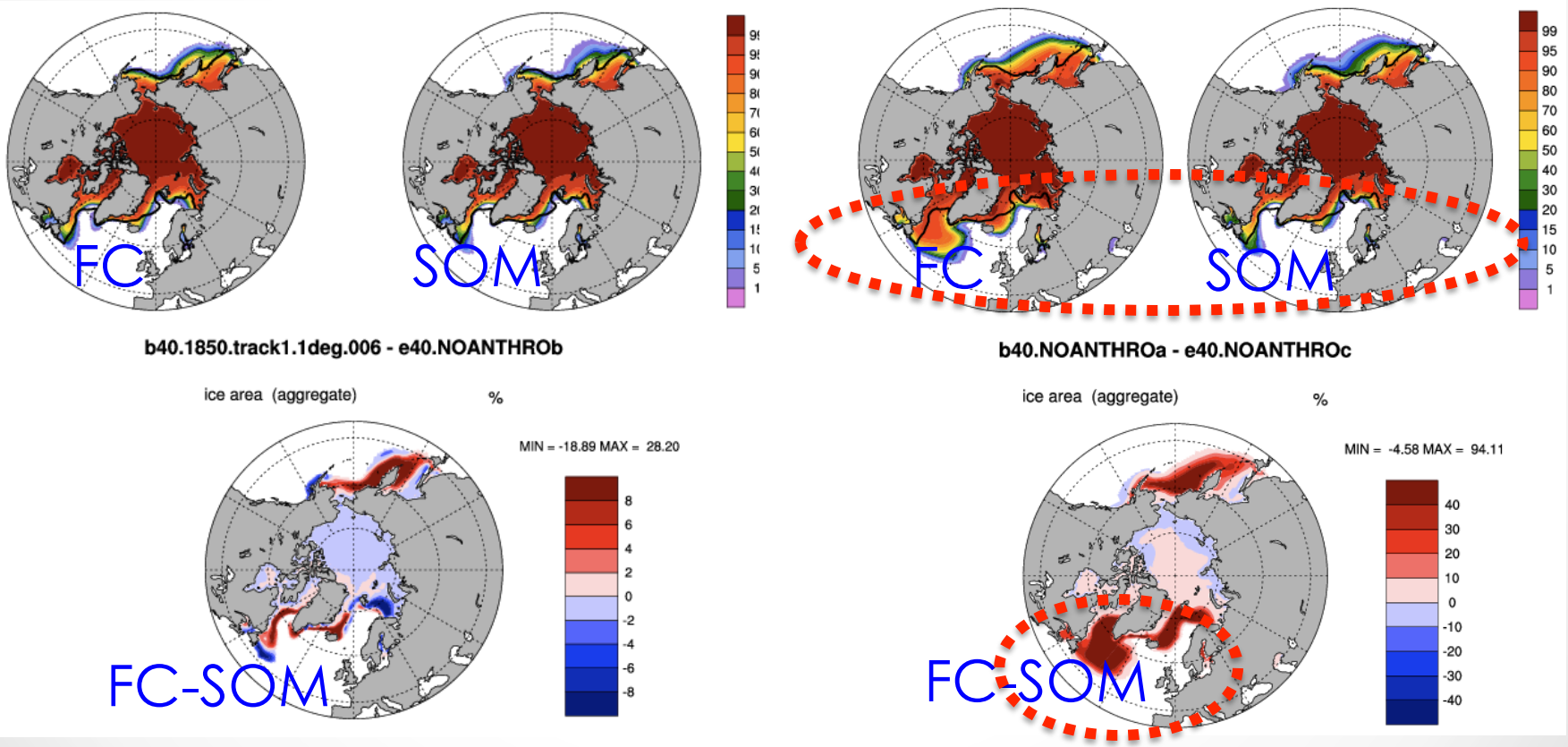


Ocean dynamics

Ocean dynamics causes larger sea ice increase south of Greenland (PI/NA)

PI (280 ppm)

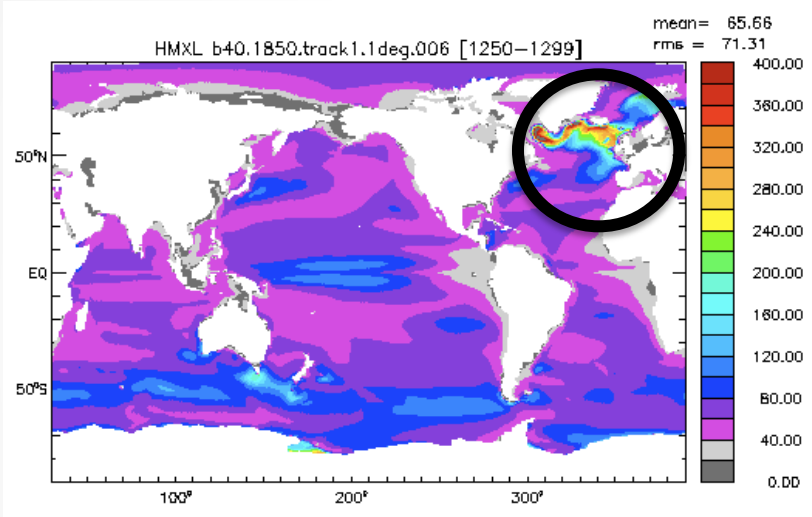
NA (245 ppm)



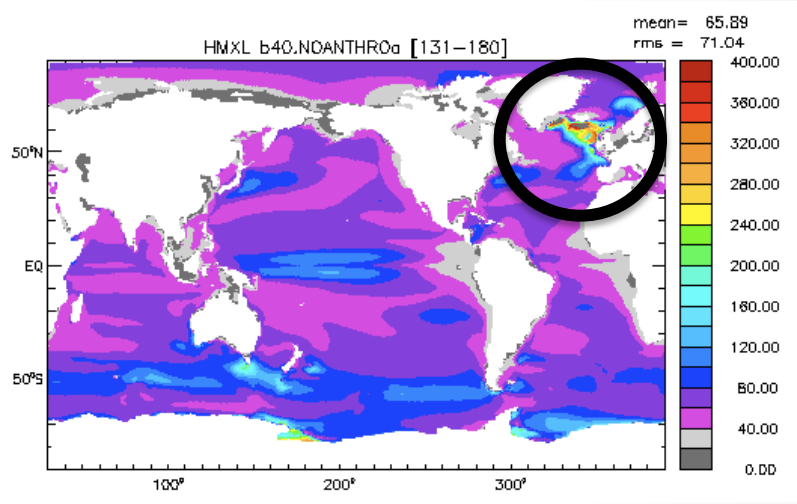
JFM sea ice concentration

Ocean convection is shut off south of Greenland (PI/NA transition)

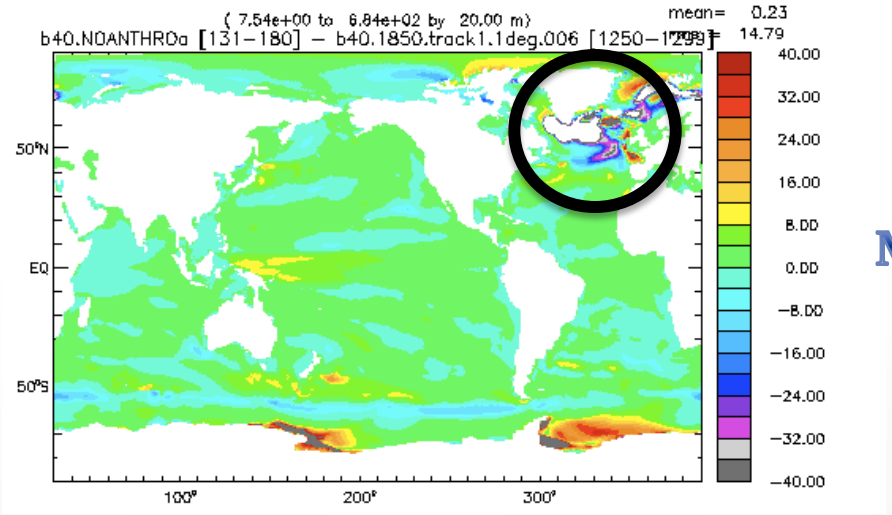
PI (280 ppm)



NA (245 ppm)

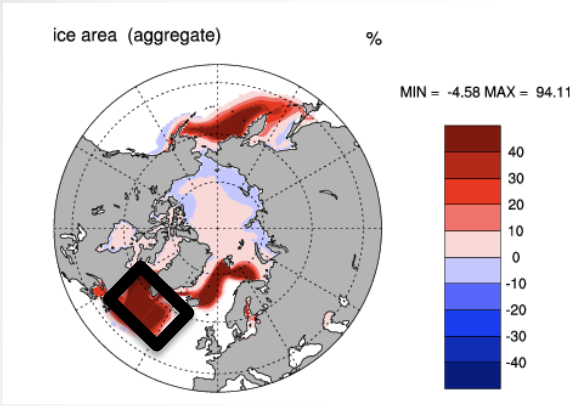


PI-NA

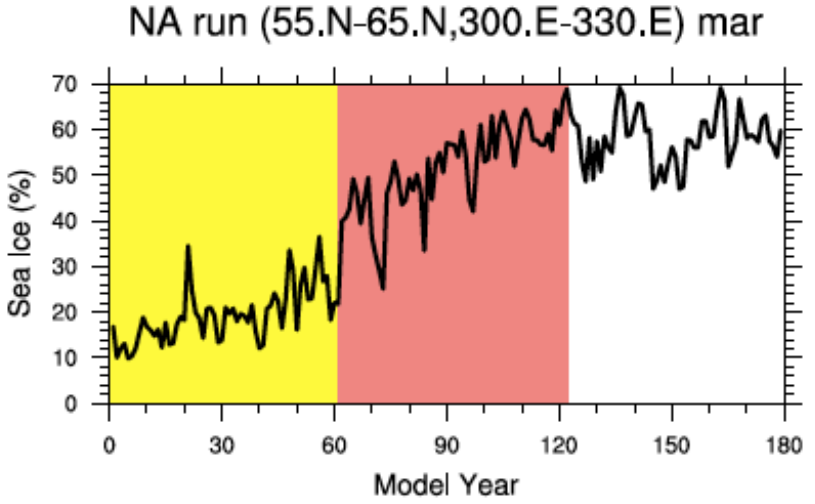


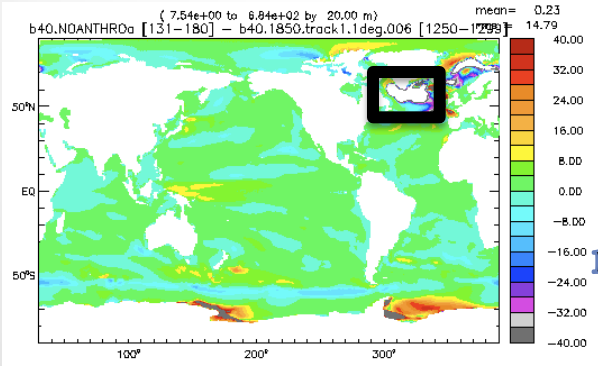
Mixed-Layer Depth

Suppressed ocean convection accelerates sea ice growth south of Greenland during PI/NA transition

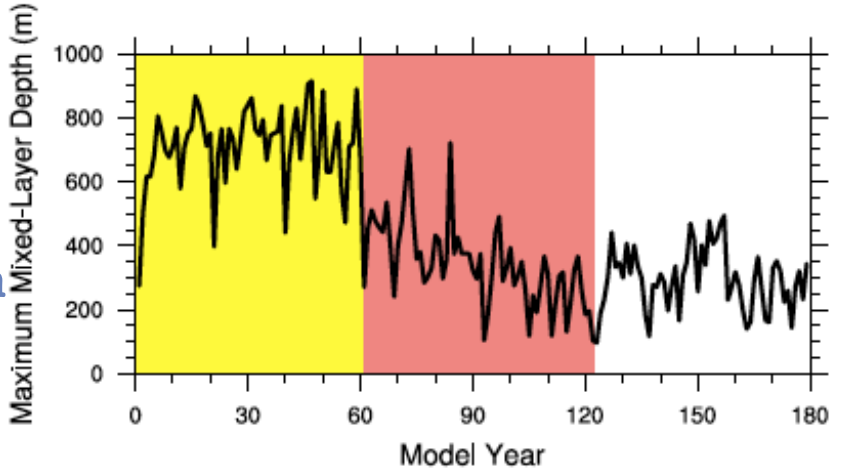


Sea ice in March





Maximum mixed-layer depth



Suppressed ocean convection accelerates sea ice growth

CO_2 reduction

cooling

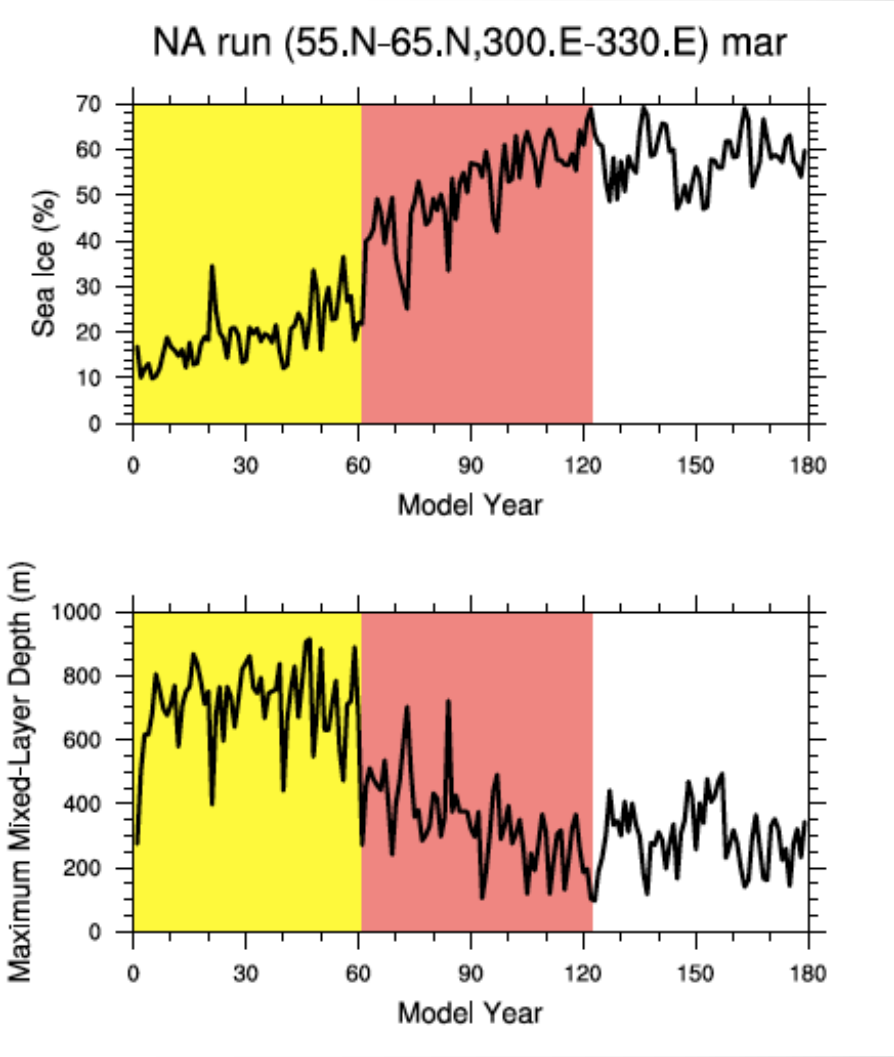
Gradual Sea ice growth
Active ocean convection

Threshold crossed
Sea ice blocks air-sea interaction

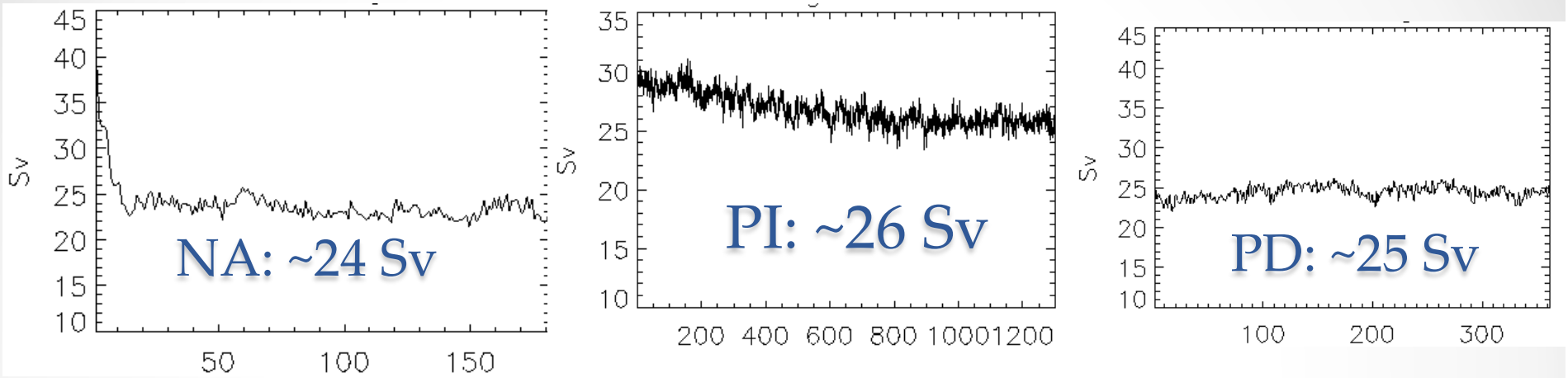
Reduction of ocean convection,
less heat flux out of the ocean
accelerate sea ice growth

New equilibrium

ocean convection collapses
Sea ice spreads across
south of Greenland



AMOC



AMOC in all three simulations are about 25 Sv. So AMOC does not contribute to the nonlinearity of the climate sensitivity

PI has the largest AMOC

Not clear why the collapse of the deep water formation does not affect the strength of AMOC during PI/NA transition

Conclusion

Fully-coupled CCSM4 simulations exhibit nonlinear climate sensitivity, with larger climate sensitivity during colder climate transitions (Manabe & Bryan 1985)

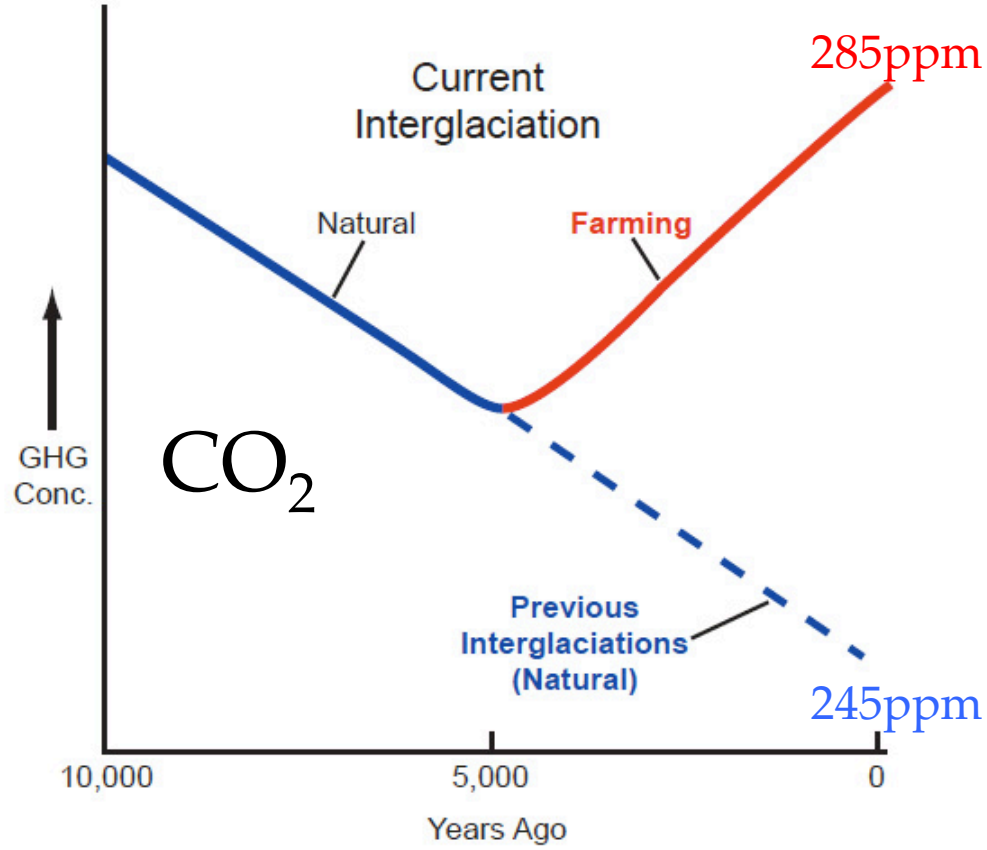
Ocean dynamics reduces climate sensitivity during PI/PD transition, but amplifies climate sensitivity during NA/PI transition

During NA/PI transition, the larger climate sensitivity results from the positive feedback between sea ice formation and ocean convection south of Greenland

For PI/NA transition, ocean dynamics amplifies the cooling by 57% (1.42 vs. 0.90 K), and amplify the increase of the permanent snow by 140% (4.1 vs 1.7 million km2)

Larger climate sensitivity during colder time

Without the 40 ppm CO_2 increase from early agriculture, incipient glacial inception might have begun in late Holocene



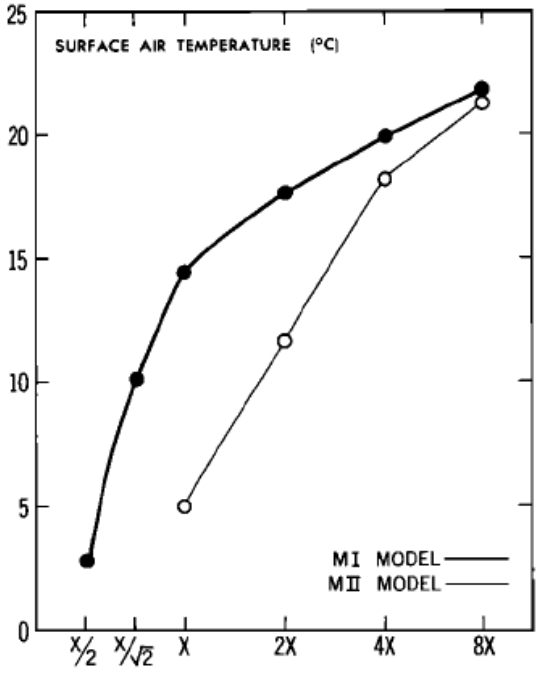


Fig. A2. The area mean surface air temperature from two series of the CO_2 experiments. The thick solid line denotes the MI model. The thin solid line denotes the MII model.