Arctic Climate and Climate Change in CAM4 and CAM5

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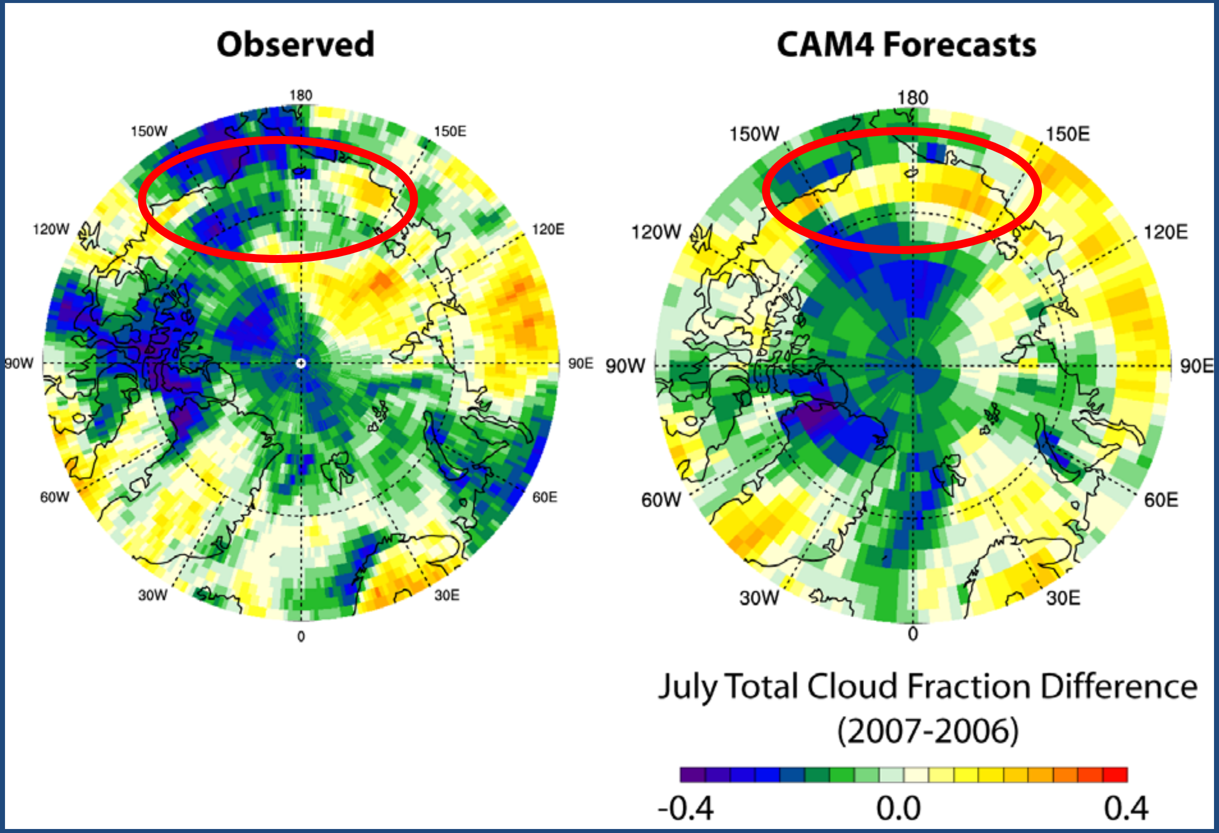
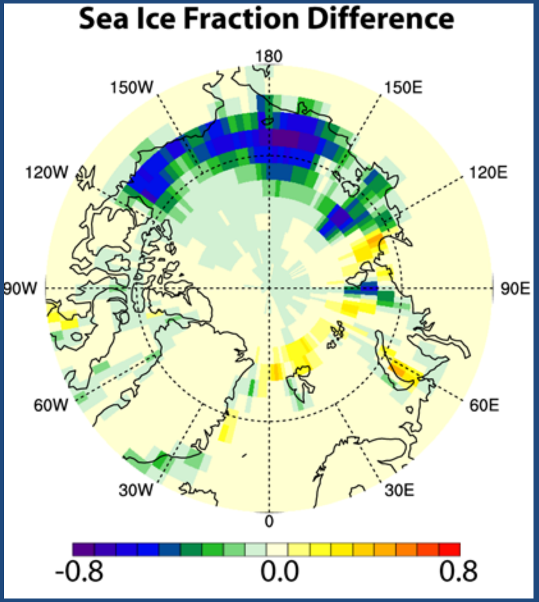
Two topics....

1) An unrealistic Arctic cloud feedback in CAM4/CCSM4 and its impact on projected Arctic climate change (Kay et al., *submitted*)

2) Arctic climate change in CAM4/CAM5 climate sensitivity experiments using a slab ocean model (SOM)

CAM4 predicts an unrealistic cloud response to sea ice loss during July 2007.



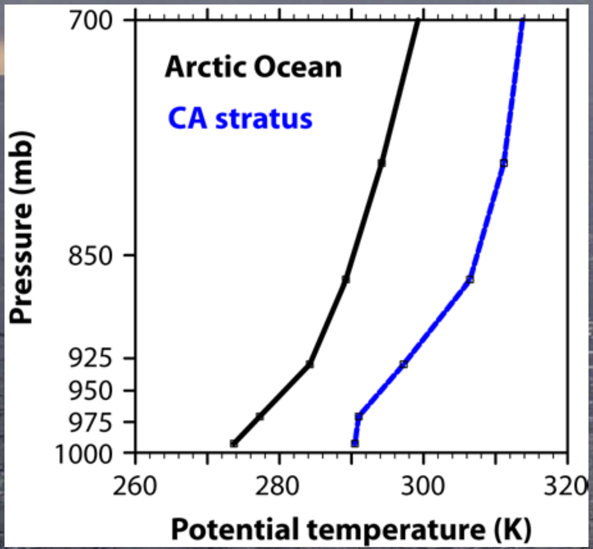


A physically motivated change to the stratus cloud parameterization improved the cloud response to sea ice loss and increased surface energy budgets in July 2007 by 11 Wm^{-2}.

Conceptual model underlying stratus parameterization in CAM4

CLDST assumptions:

1) Surface moisture source
2) Capping inversion
3) Well-mixed boundary layer



Oops! Well-mixed assumption violated in the Arctic!

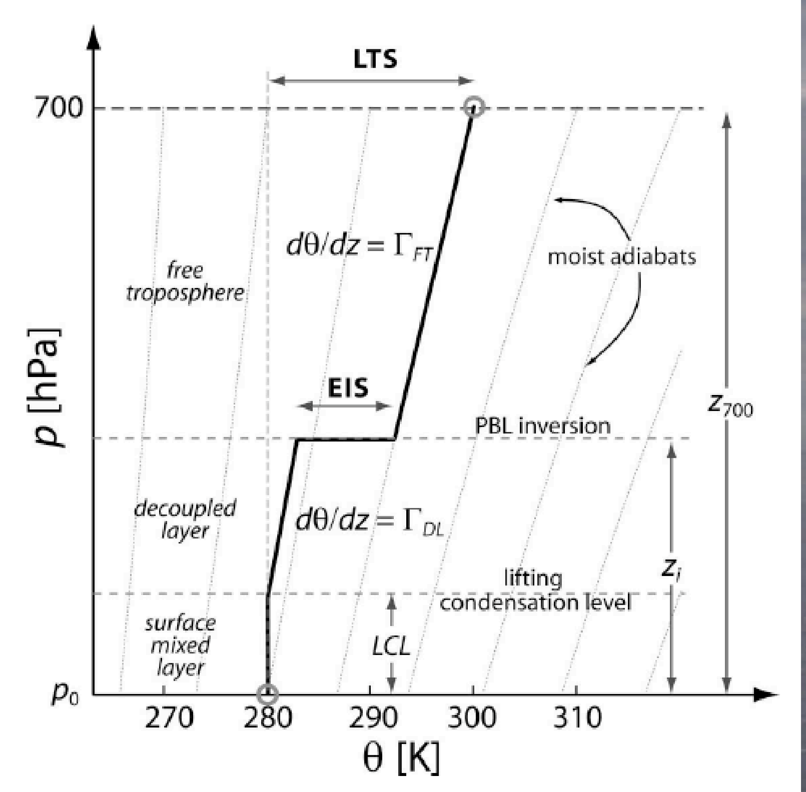
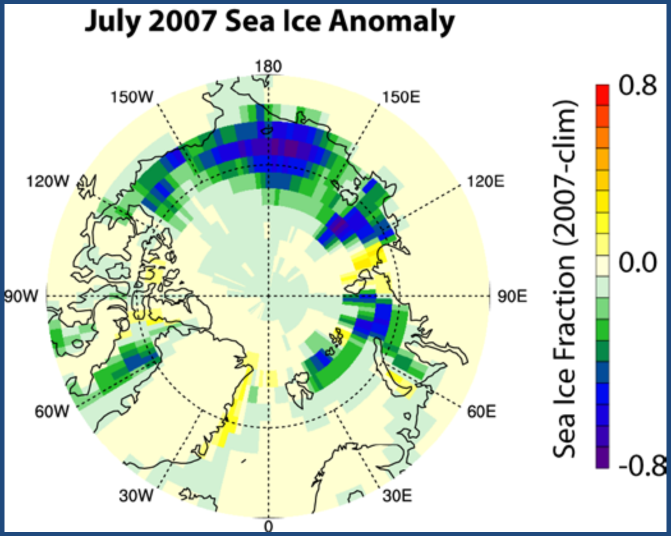
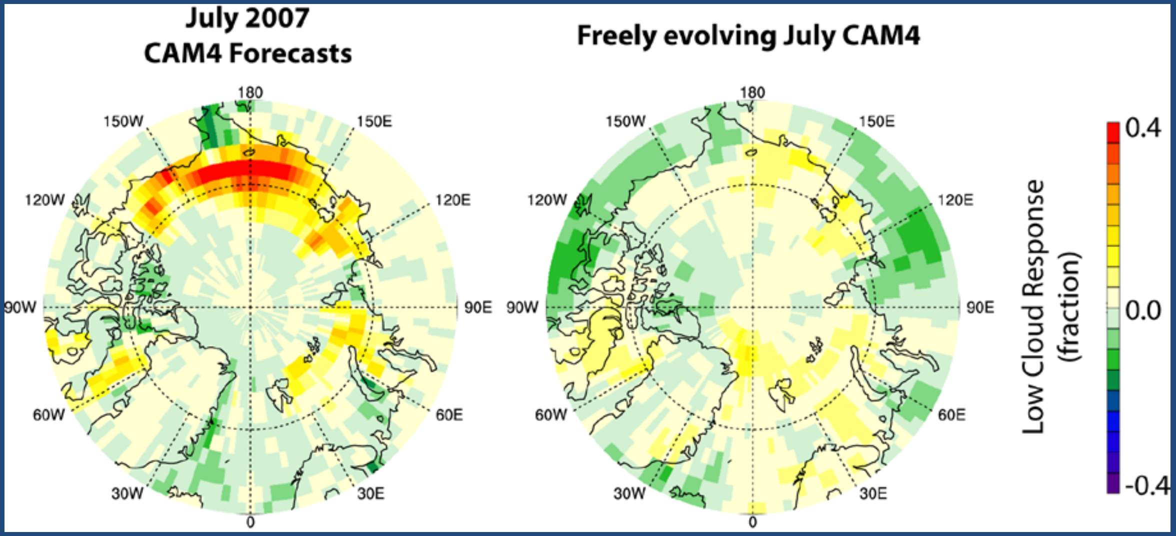


FIG. 1. Idealized profile (thick solid line) of lower-tropospheric structure during periods of undisturbed flow. Moist adiabats are shown as light dotted lines.

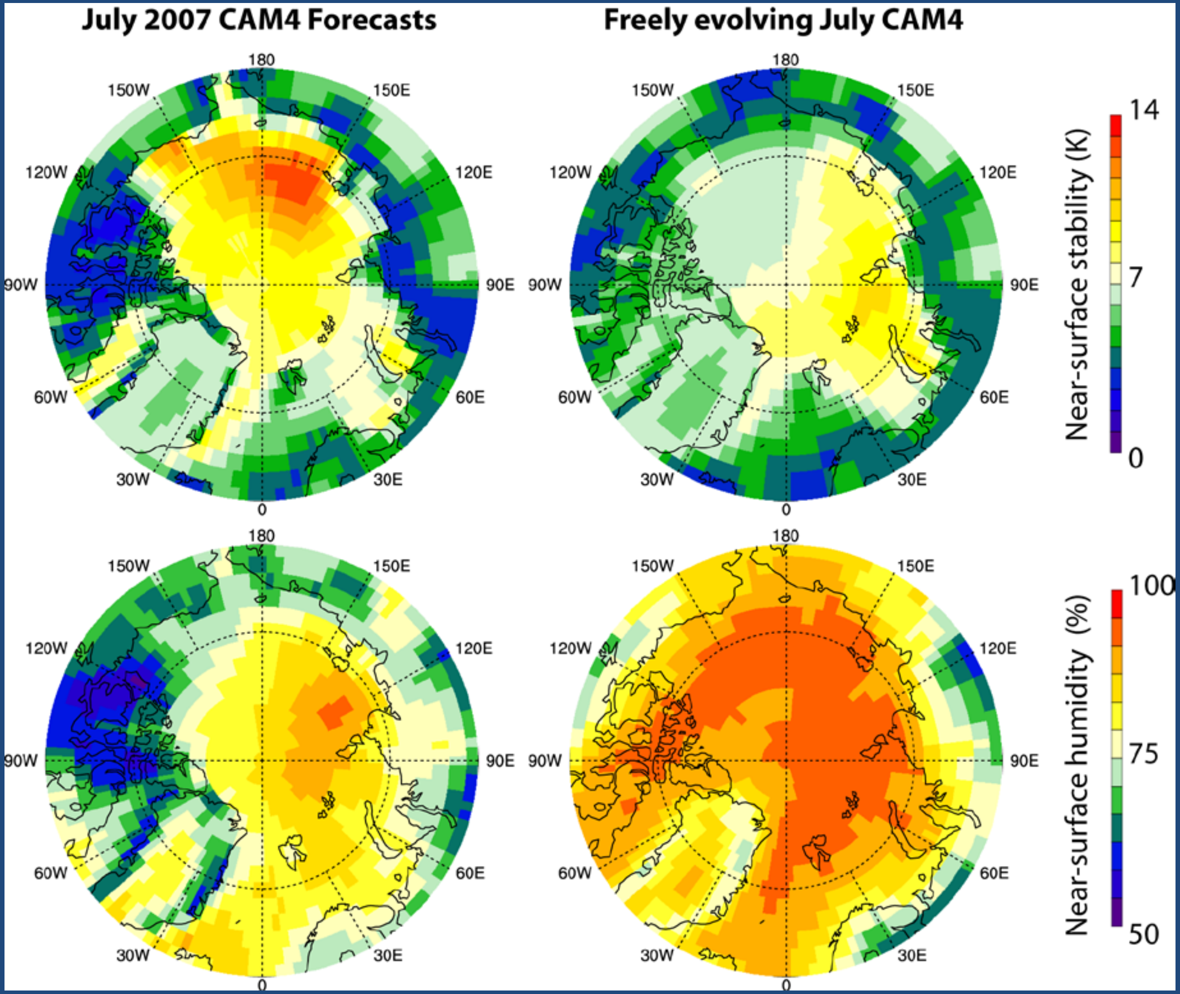
Wood and Bretherton (2006)

We found no obvious cloud response to the July 2007 sea ice anomaly in CAM4 model runs with a freely-evolving atmosphere!





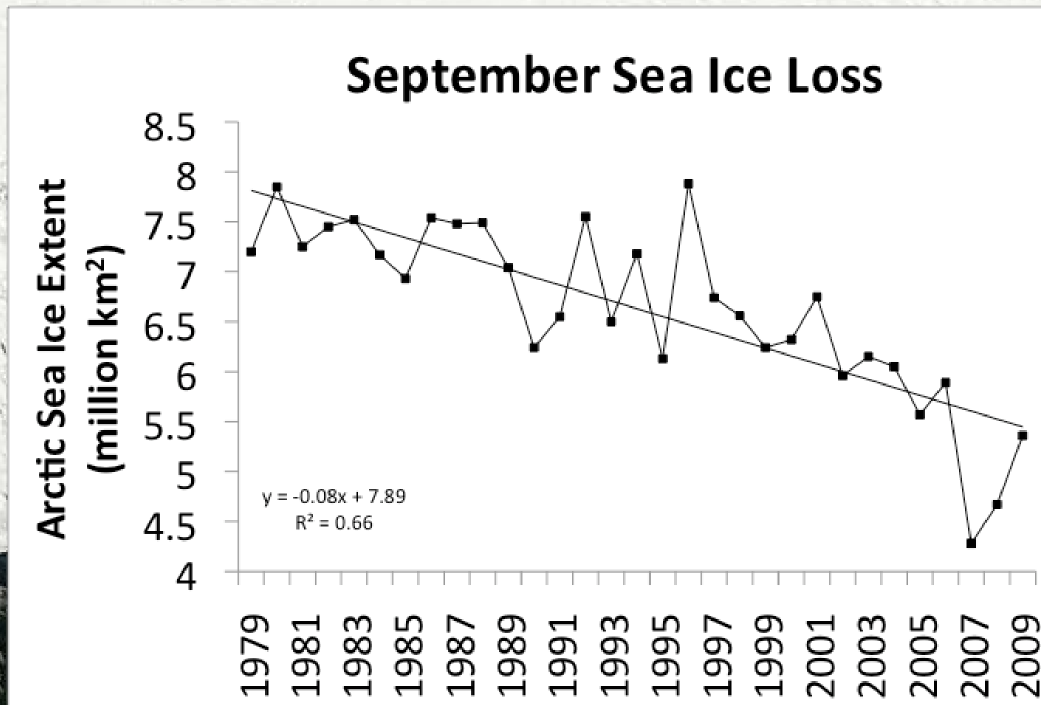
The CAM4 cloud response to sea ice loss depends on the mean atmospheric state.



Due to unrealistic Arctic cloud increases over newly open water, CCSM3/CCSM4 under-predict sea ice loss in stable atmospheric regimes (e.g., 2007-like extreme events).

Does this error affect modeled sea ice trends?

Maybe not. Little year-to-year memory in observations.

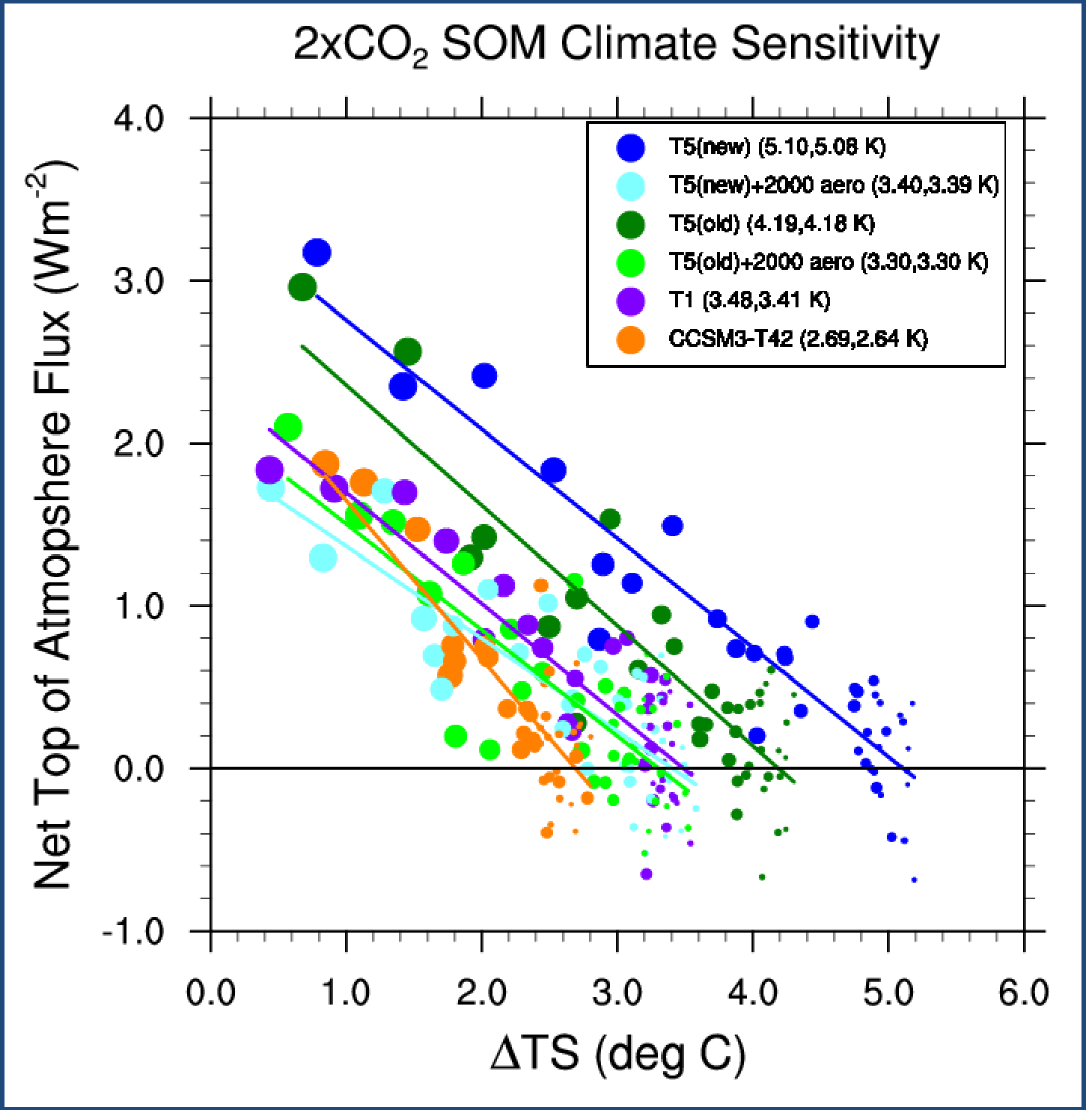


Two topics….

1) An unrealistic Arctic cloud feedbacks in CAM4/CCSM4 and its impact on Arctic climate change (Kay et al., submitted to *J. Climate*)

2) Arctic climate change in CAM4/CAM5 climate sensitivity experiments (2x $C0_2$ in slab ocean model)

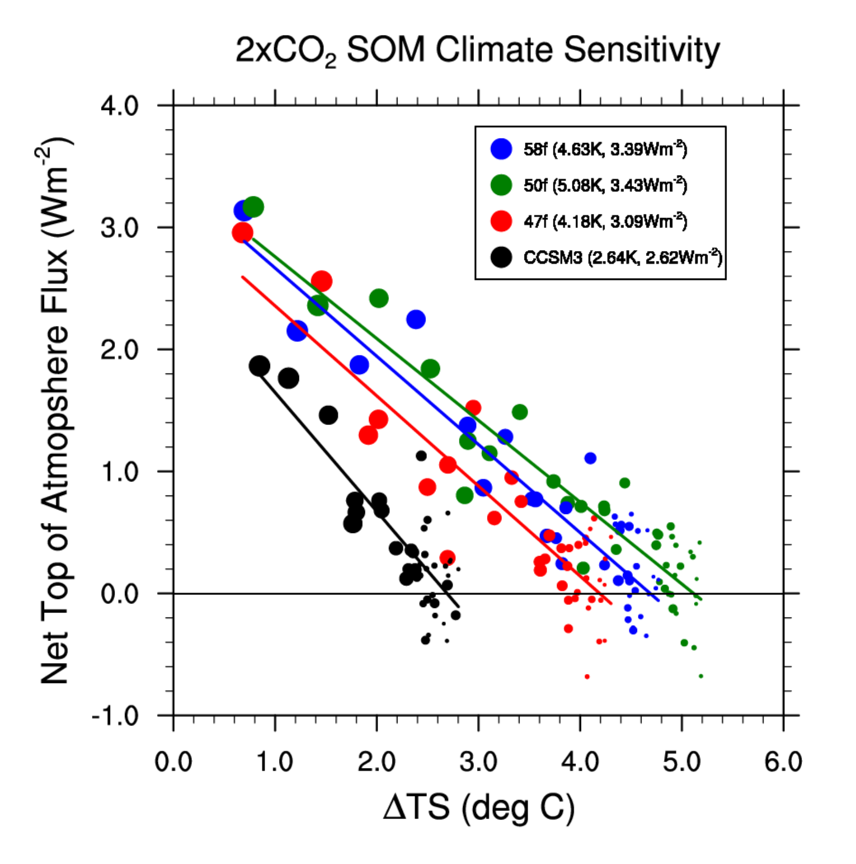
Slab Ocean Model (SOM) 2xC0$_2$ climate sensitivity experiments

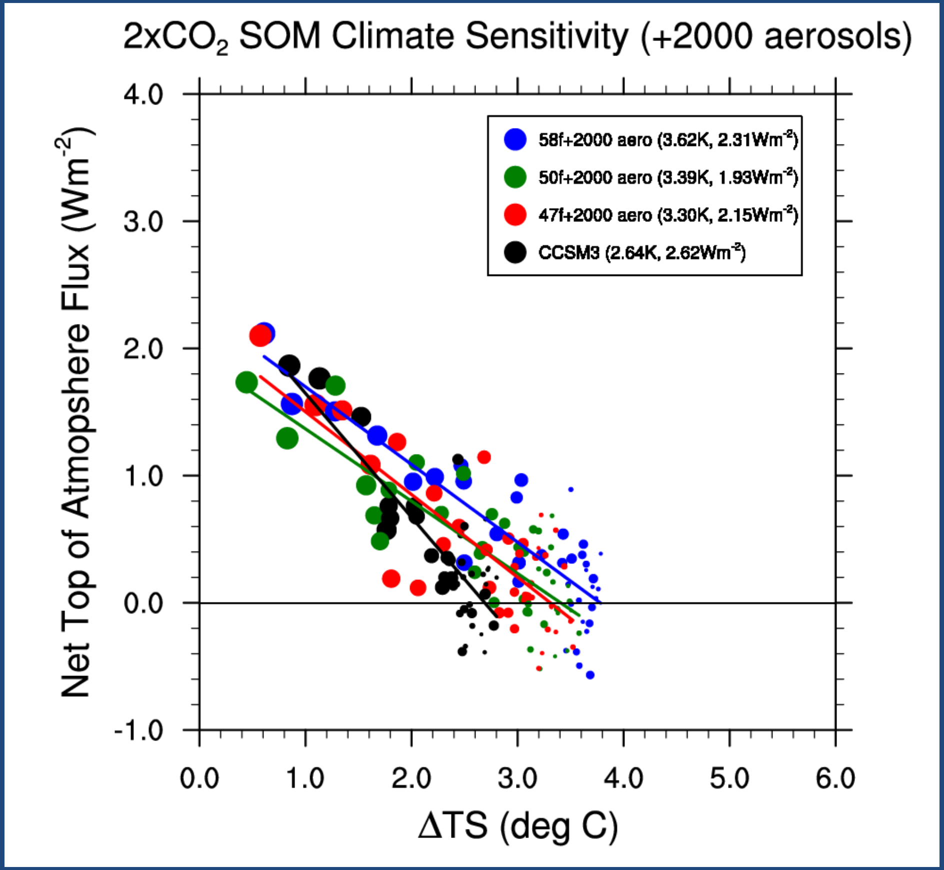


Recent SOM climate sensitivity experiments (plot from Rich Neale)

Climate sensitivity:
CAM4 – 3.4 K
CAM5 – 5.1 K

I ignore aerosol indirect effects today, but they are critical for Arctic climate change in CAM5

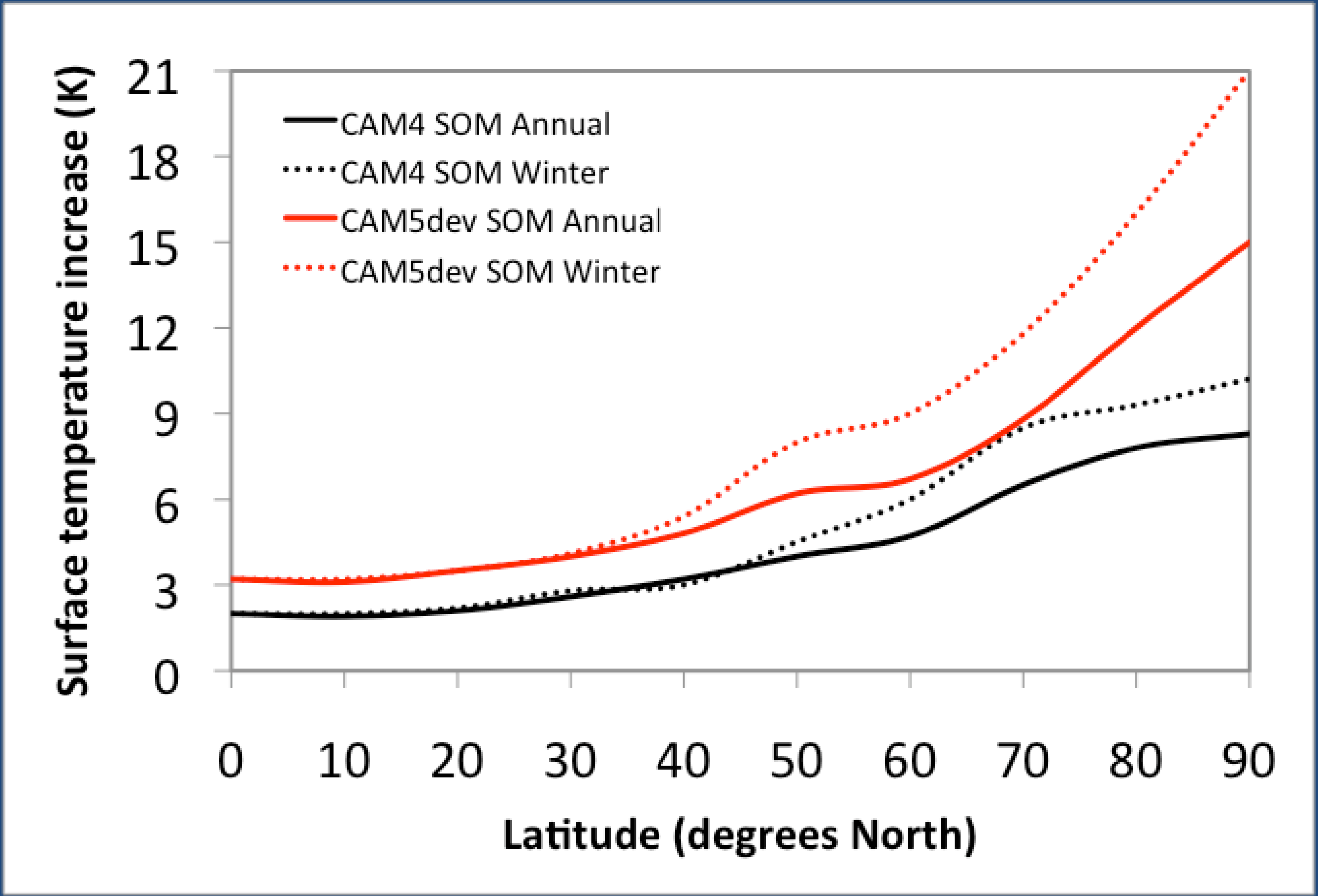




CAM5 climate sensitivity: 4.2-5.1 K

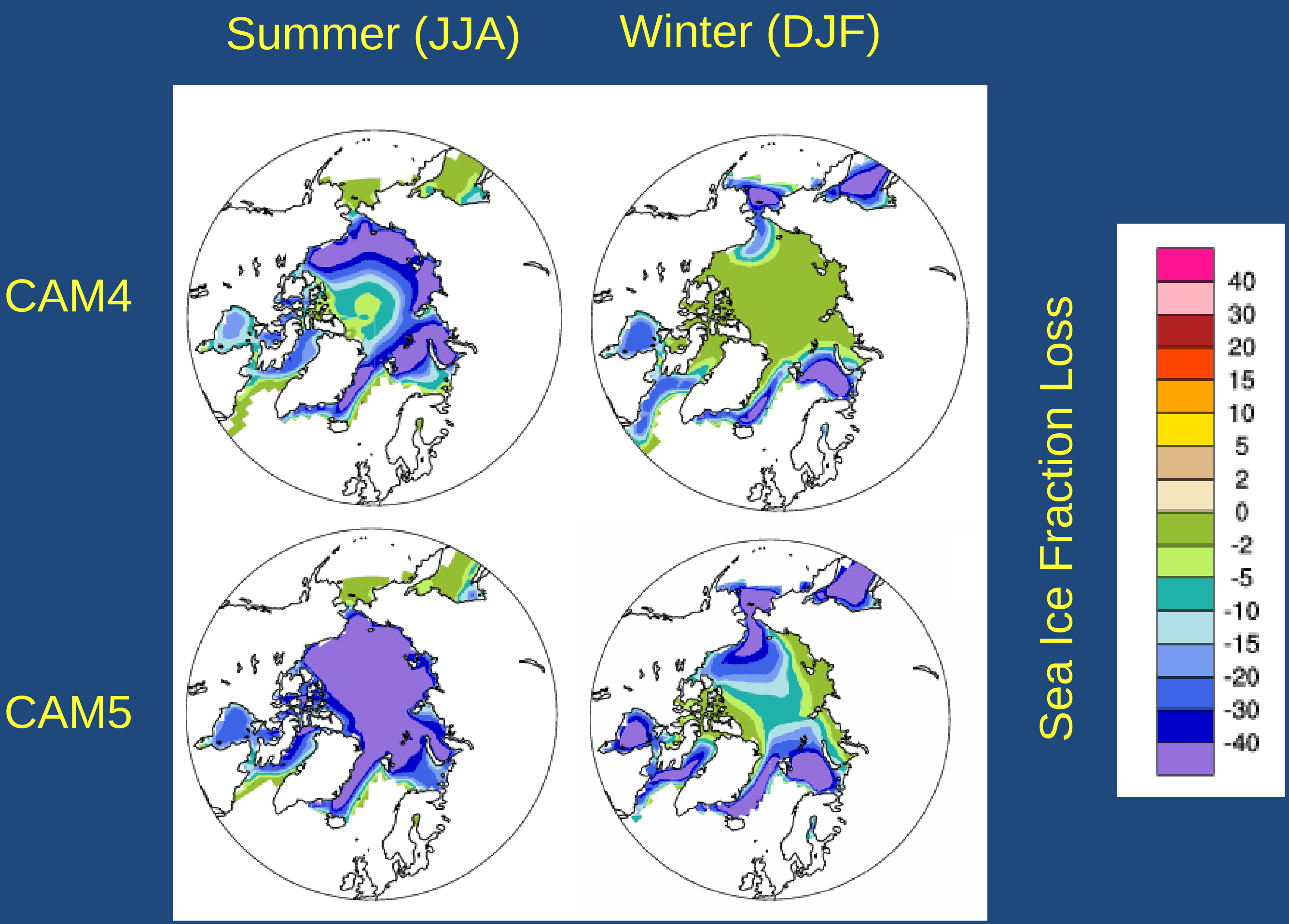
CAM5 total response: 3.3-3.6 K

How hot is the Arctic in CAM4/CAM5 climate sensitivity experiments?



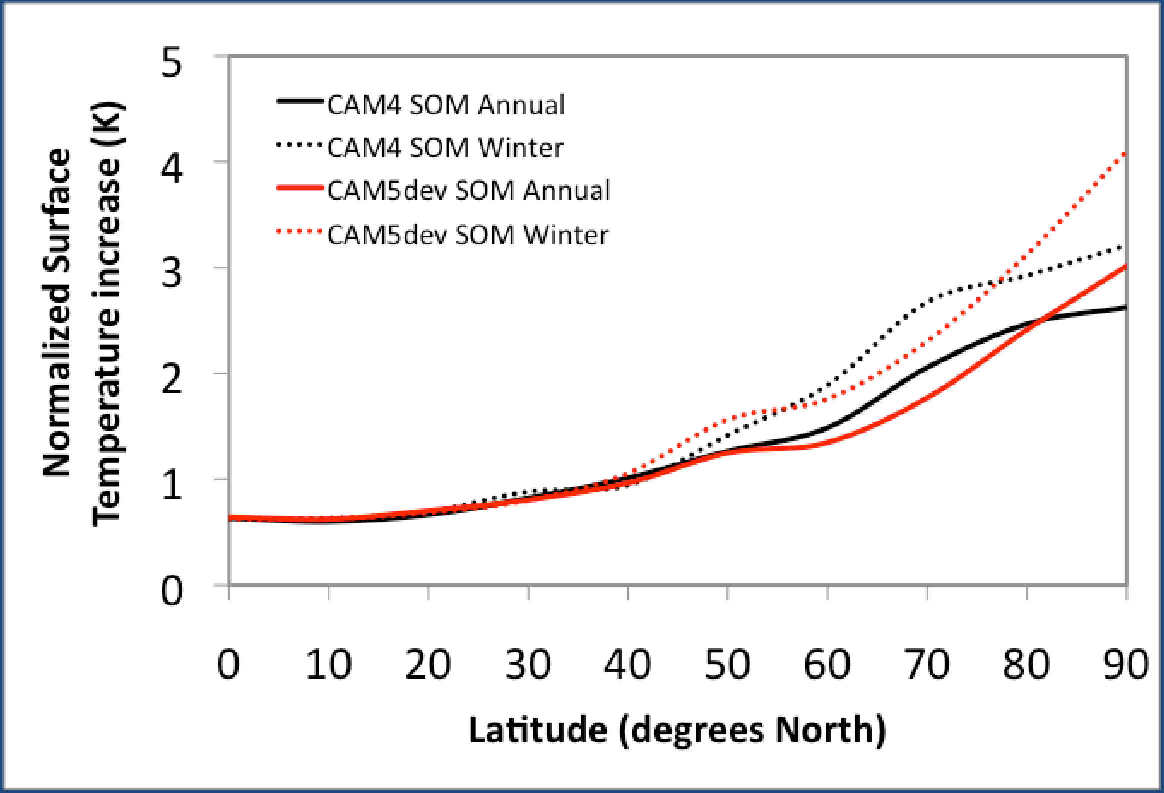
Why do recent slab ocean model experiments project dramatic differences in their equilibrium Arctic response to $2xC0_2$ forcing?

Arctic sea ice loss in response to $2xC0_2$



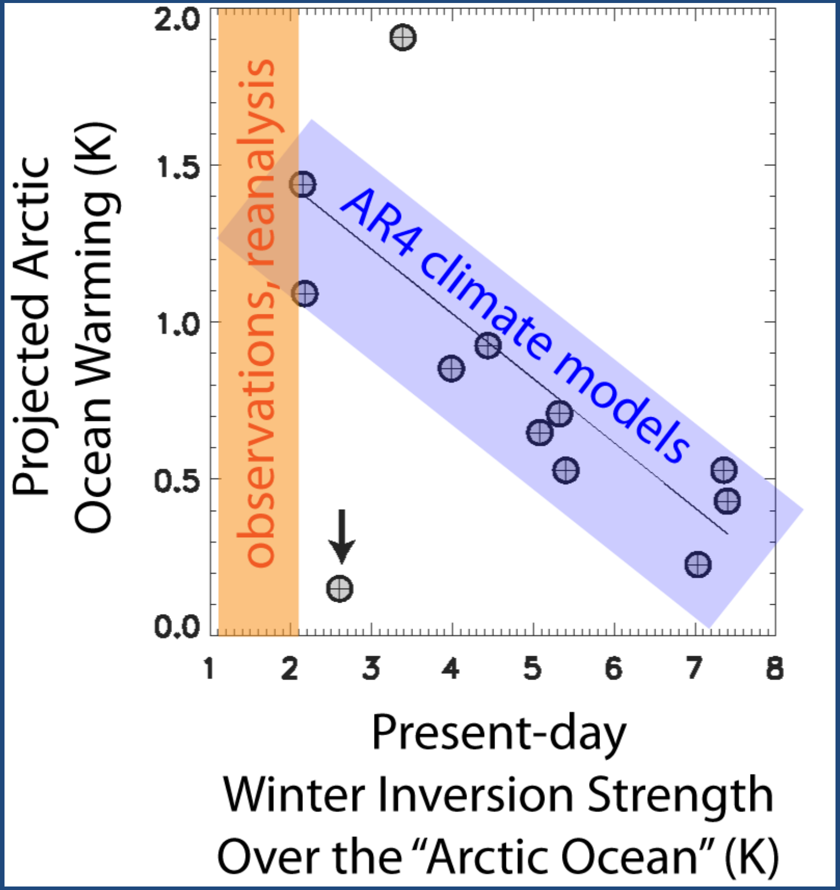
What controls the Arctic climate response in $2xC0_2$ climate sensitivity experiments?

Local or Global Feedbacks?



Assess local feedback strength

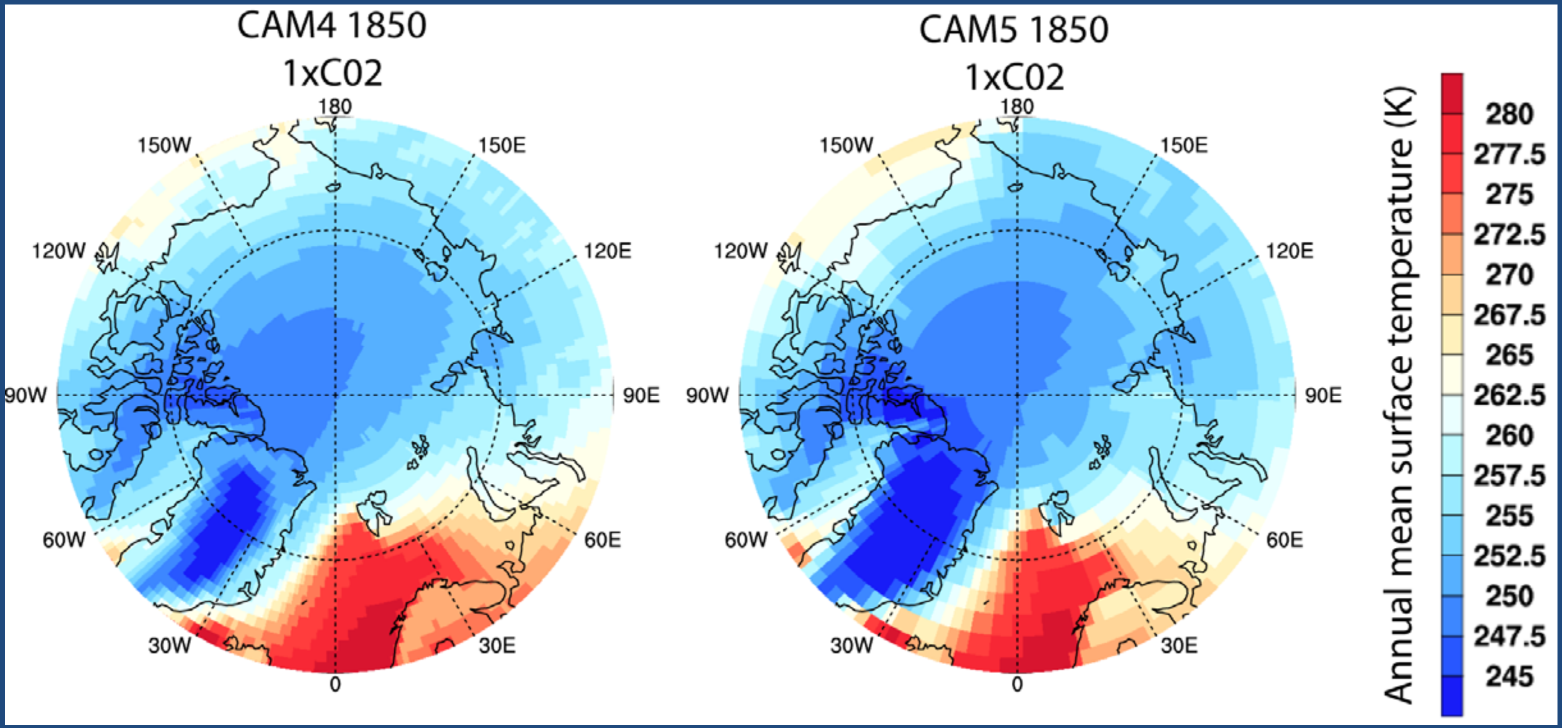
Are there clues in the 1850 control mean state (e.g., ice thickness)?



e.g., Boe et al. (2009) showed that present day winter inversion strength explains spread in projected Arctic amplification

1850 Mean State - Surface Temperature (Ts)

Arctic Ts are very similar in CAM4 and CAM5



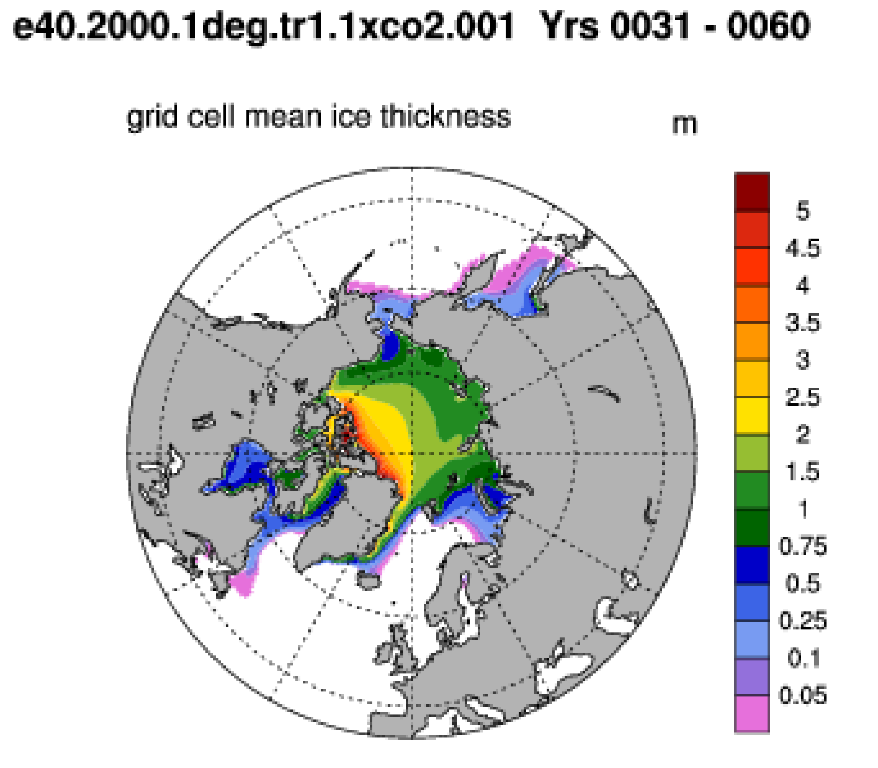
Arctic Ocean Ts (70-90 N)

	CAM4	CAM5
Annual	255	254
Winter	242	240
Summer	270	271

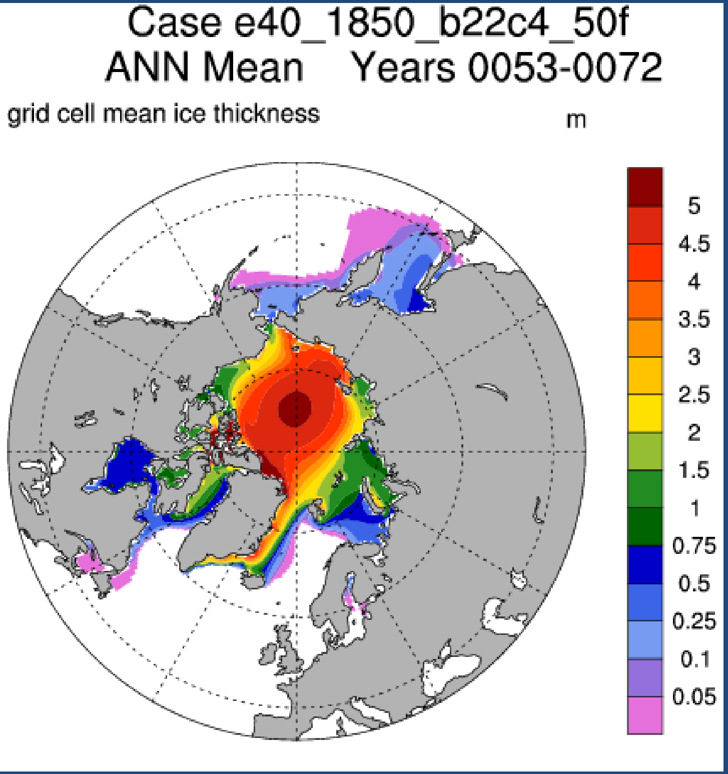
No huge differences in 1850 Arctic sea ice extent between CAM4 and CAM5.

1850 Mean State – Sea Ice Thickness

CAM4 SOM thickness

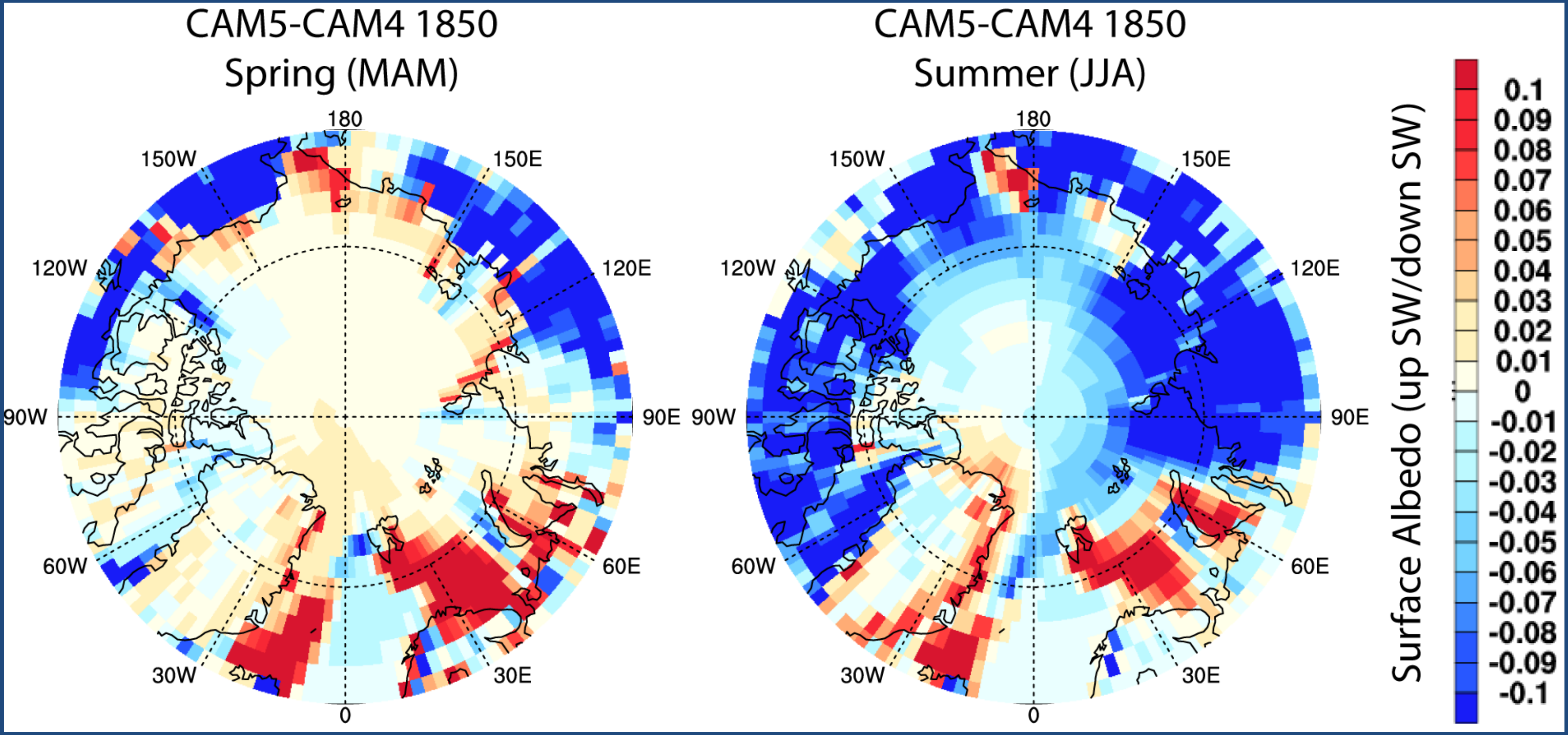


CAM5 SOM thickness



CAM5 Arctic sea ice is thicker than CAM4 in the 1850 slab ocean model (SOM).

1850 Mean State - Arctic surface albedo

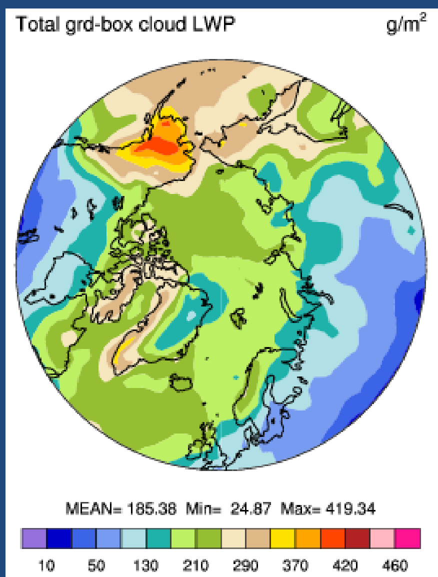


Surface albedos lower over land in CAM5 than CAM4 (CLM prognostic veg). Higher snow albedos over sea ice in CAM5 than in CAM4.

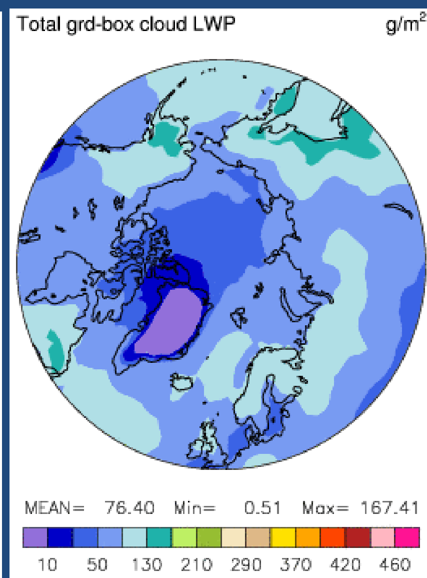
1850 Mean State – Summer clouds

Arctic clouds and shortwave radiation budgets are very different!!

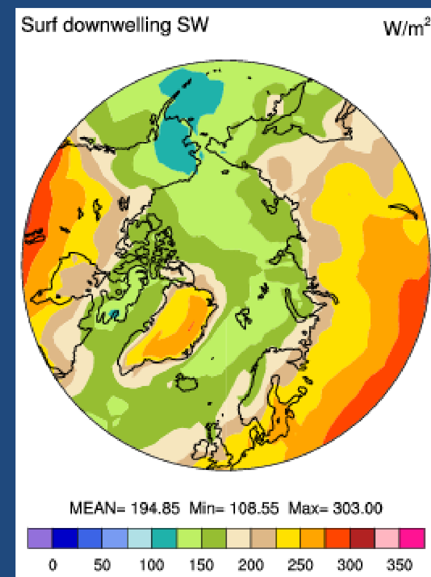
CAM4 1850



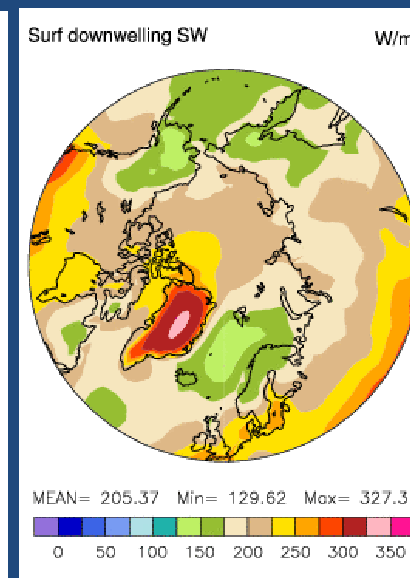
CAM5 1850



CAM4 1850



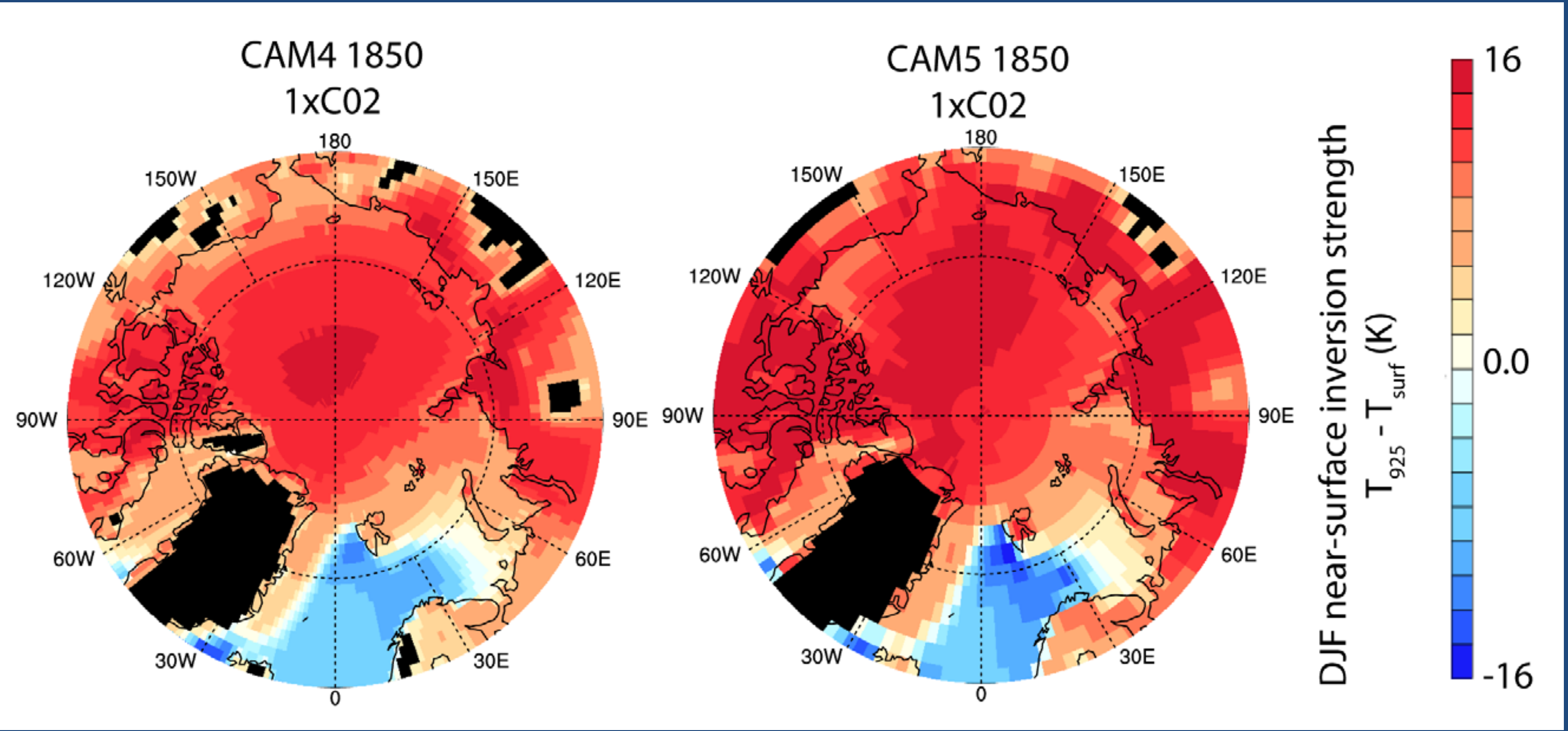
CAM5 1850



Cloud liquid water path
CAM4 > CAM5

Downwelling shortwave
CAM5 > CAM4

1850 Mean State - Arctic winter inversion



Inversion strength greater in CAM5 than in CAM4 (11.7 K vs. 10.7 K), yet CAM5 has more Arctic warming/sea ice loss than CAM4…

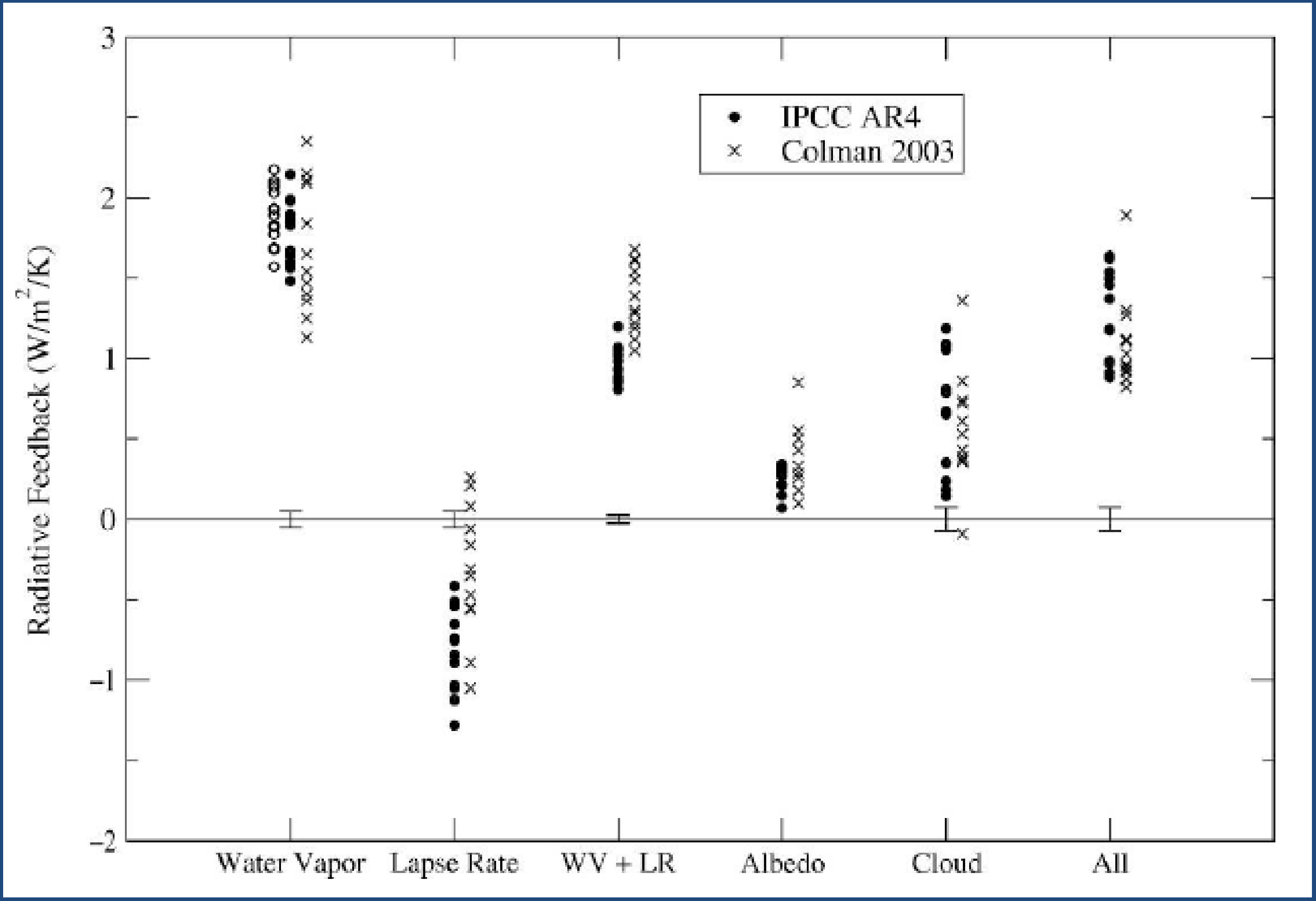
This finding is inconsistent with Boe et al. (2009)…

Mean Arctic climate in 1850 does not help explain the CAM4 vs. CAM5 differences in projected Arctic climate change.

What other tools can we use to understand the differences?

Assess feedbacks using radiative kernels

Global feedback parameters in global climate models
e.g., Soden and Held (2006)



Feedback strength in CAM4/CAM5 assessed with radiative kernels from CAM3

Global values (All feedbacks in $Wm^{-2}K^{-1}$)

	CAM4	CAM5
Surface temperature increase (K)	3.1	5.0
Lapse rate feedback	-0.7	-0.7
Water vapor feedback (SW, LW)	+0.3, +1.6	+0.3, +1.6
Surface albedo feedback	+0.3	+0.3
Cloud feedback (SW, LW)	+0.8, +0.7	+4.5, -0.2

Cloud feedbacks appear to explain the global difference!

Preliminary calculations from work with Andrew Gettelman/Karen Shell

Arctic feedback strength in CAM4/CAM5

Arctic values, 70-90 N (All feedbacks in $Wm^{-2}K^{-1}$)

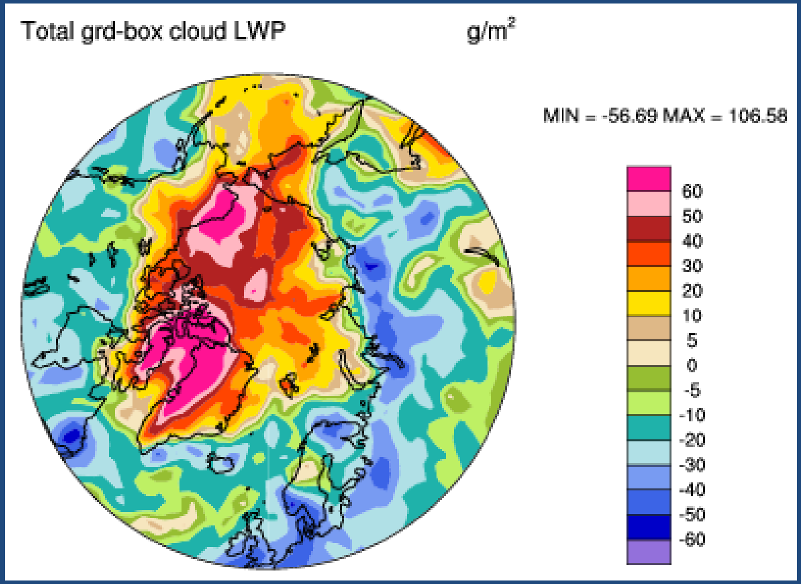
	CAM4	CAM5
Surface temperature increase (K)	3.1	5.0
Lapse rate feedback	+0.1	+0.1
Water vapor feedback (SW, LW)	+0.4, +0.5	+0.4, +0.5
Surface albedo feedback	+4.3	+6.2
Cloud feedback (SW, LW)	-0.1, +0.3	+8.6, -1.7

Cloud and surface albedo feedbacks appears to explain the Arctic difference!

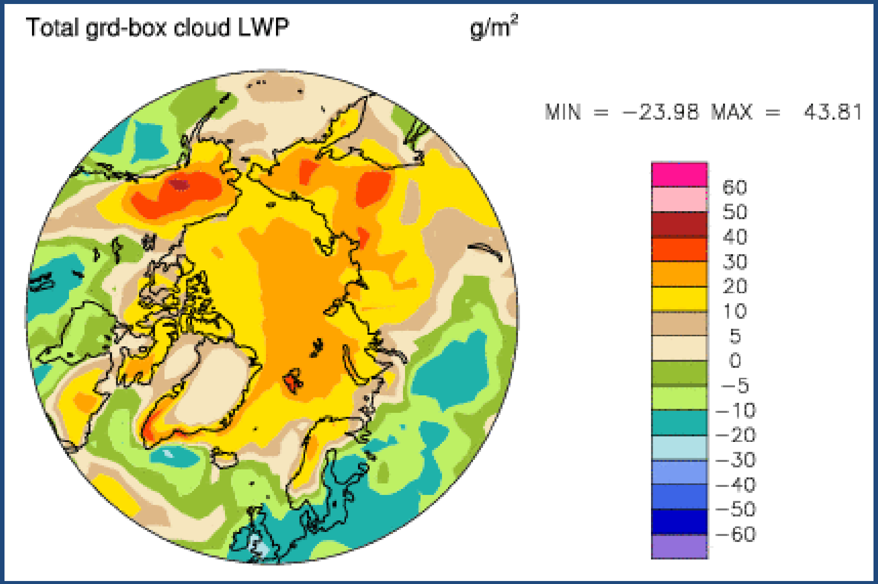
Preliminary calculations from work with Andrew Gettelman/Karen Shell

Arctic JJA cloud response to $2xC0_2$

CAM4



CAM5



JJA clouds are consistent with stronger shortwave feedbacks in CAM5 than in CAM4

Summary:

- Unrealistic CAM4 cloud increases over newly open water dampen sea ice loss in dry and stable atmospheric conditions (e.g., July 2007).

- Recent 2x$C0_2$ model experiments using CAM4 and CAM5 have dramatic differences in Arctic temperature amplification and sea ice loss. Cloud and surface albedo feedbacks appear to explain the differences in projected Arctic climate. Non-local feedbacks and forcing are critical.

EXTRA

TO DO

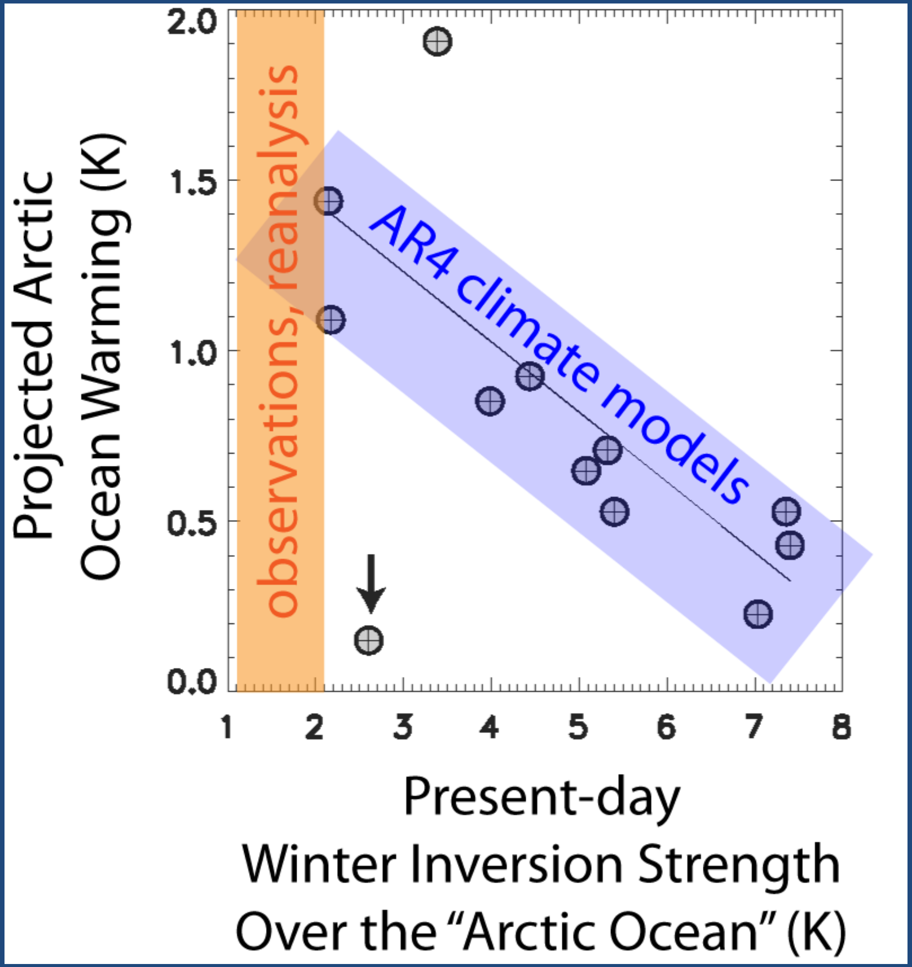
- compare cloud particle sizes
- compare ice thickness in 1850 controls
- compare sea ice and snow albedo values in CAM4 and CAM5

Summary of cloud, albedo, and radiation changes associated with sea ice loss

	CAM4	CAM5
Low cloud	+16%	-3%
Surface albedo	-13%	-8%
TOA, Surface CF (Wm^{-2})	-22.7, -18.9	-12.7, -11.5
Surface net radiation (Wm^{-2})	+13.3	+5.1
Surface shortwave fluxes (Wm^{-2})	Net: +15.0 Down: -23.7 Up: -38.7	Net: +9.9 Down: -11.3 Up: -21.2

Largest surface net radiation increase in CLDMOD CAM3.5 forecasts due to weak cloud response and large surface albedo decrease.

Inversion strength explains spread in projected Arctic warming in IPCC models



Adapted from Boé et al. (2009)

Models with excessive inversion strength may under-predict Arctic warming.

Can a local feedback parameter analysis help explain the Arctic differences?

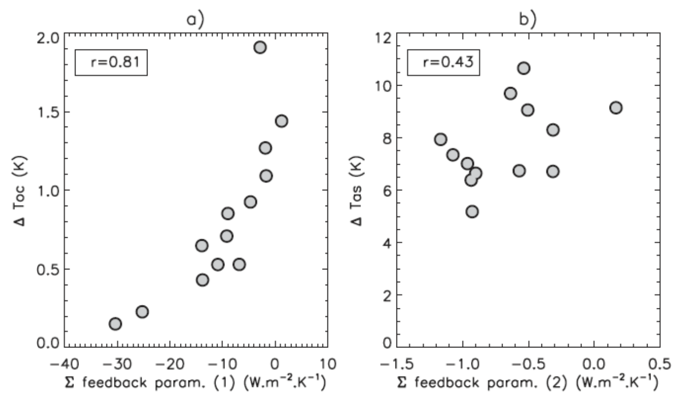


FIG. 3. Link between the sum of the longwave and shortwave feedback parameters and (a) T_{oc} when the feedback parameters are defined using T_{oc} and (b) T_{as} when the feedback parameters are classically defined using T_{as}. The value of the linear correlation coefficient is given on the graph. Note that for a sample of 13 values, the correlation corresponding to the 0.05 (0.01) significance level is 0.553 (0.684).

Boé et al. (2009): Normalizing by surface temperature not appropriate in the Arctic, use ocean temperatures.

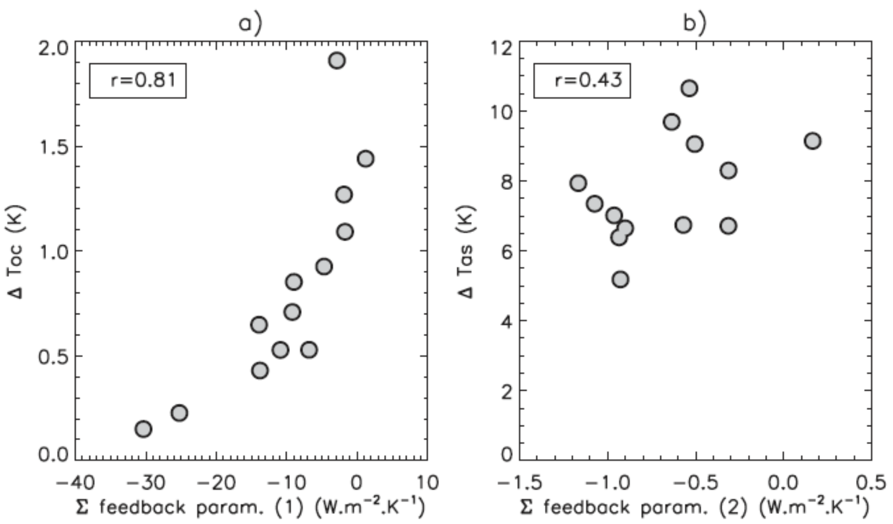
	CAM4	CAM5
ΔT_{ocean} (K)	0.3	0.5
Longwave feedback parameter $\lambda_{lw} = \Delta_{netlwTOA}/\Delta T_{ocean}$ ($Wm^{-2}K^{-1}$)	-20.2	-27.8
Shortwave feedback parameter $\lambda_{sw} = \Delta_{netswTOA}/\Delta T_{ocean}$ ($Wm^{-2}K^{-1}$)	23.1	32.7

Conclusions not affected by using approximate mixed layer temperature (T_{ocean}) instead of surface temperature (T_{surf}).

Arctic Feedback Parameter Comparison

$$\lambda_{LW} = \frac{\Delta F}{\Delta T_{oc}},$$

$$\lambda_{SW} = \frac{\Delta Q}{\Delta T_{oc}}.$$



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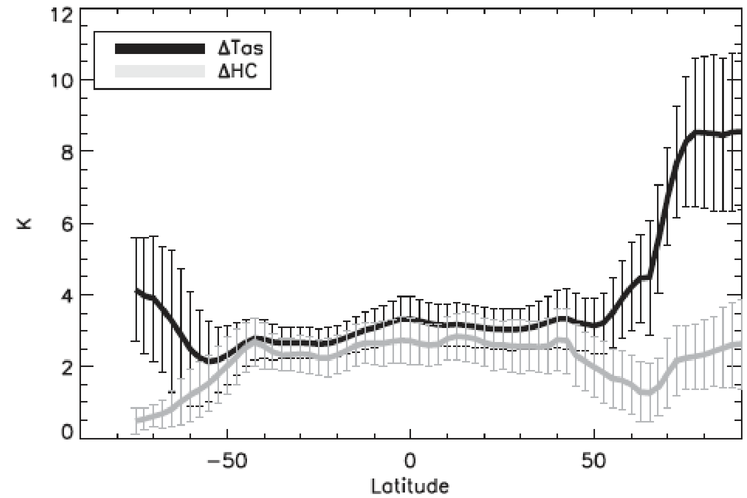

FIG. 1. Annual zonal mean change of surface temperature (T_{as}, K) over oceans and of heat content of the oceanic mixed layer–atmosphere system expressed as a change of temperature within the uppermost 70 m of ocean (HC, K) (see text for the calculation of the heat content) at the end of the twenty-second century. The lines stand for the ensemble means and the bars stand for the intermodel spread measured by one std dev.

Boé et al. (2009)

Soden and Held (2006)

TABLE 1. Tabulated values of the feedback parameters shown in Fig. 1. Model integrations for the Goddard Institute for Space Studies (GISS) atmosphere–ocean model (AOM) and GISS EH models end at year 2100 and therefore estimates of the effective sensitivity and cloud feedback are not performed.

	Planck	Lapse rate	Water vapor	Surface albedo	Effective sensitivity	Cloud feedback
CNRM	−3.21	−0.89	1.83	0.31	−1.17	0.79
GFDL CM2_0	−3.20	−0.85	1.87	0.33	−1.18	0.67
GFDL CM2_1	−3.24	−1.12	1.97	0.21	−1.37	0.81
GISS AOM	−3.25	−1.27	2.14	0.27		
GISS EH	−3.26	−1.12	1.99	0.07		
GISS ER	−3.24	−1.05	1.86	0.15	−1.64	0.65
INMCM3	−3.18	−0.51	1.56	0.32	−1.46	0.35
IPSL	−3.24	−0.84	1.83	0.22	−0.98	1.06
MIROC MEDRES	−3.20	−0.75	1.64	0.31	−0.91	1.09
MRI	−3.21	−0.65	1.85	0.27	−1.50	0.24
MPI ECHAM5	−3.22	−1.03	1.90	0.29	−0.88	1.18
NCAR CCSM3	−3.17	−0.54	1.60	0.34	−1.62	0.14
NCAR PCM1	−3.13	−0.41	1.48	0.34	−1.53	0.18
UKMO HADCM3	−3.20	−0.74	1.67	0.22	−0.97	1.08

Feedback parameters in 2x C02 climate sensitivity experiments?

Global feedback parameters

	CAM4	CAM5
ΔT_{surf} (K)	3.1	5.0
Longwave feedback parameter $\lambda_{lw} = \Delta_{netlwTOA}/\Delta T_{surf}$ ($Wm^{-2}K^{-1}$)	-0.7	-1.2
Shortwave feedback parameter $\lambda_{sw} = \Delta_{netswTOA}/\Delta T_{surf}$ ($Wm^{-2}K^{-1}$)	0.8	1.2

Local feedback parameters for 70-90 N

	CAM4	CAM5
ΔT_{surf} (K)	7.2	12.6
Longwave feedback parameter $\lambda_{lw} = \Delta_{netlwTOA}/\Delta T_{surf}$ ($Wm^{-2}K^{-1}$)	-0.9	-1.2
Shortwave feedback parameter $\lambda_{sw} = \Delta_{netswTOA}/\Delta T_{surf}$ ($Wm^{-2}K^{-1}$)	1.1	1.4