# What controls Arctic warming in coupled climate models?

**Jennifer Kay**

**National Center for Atmospheric Research (NCAR)**

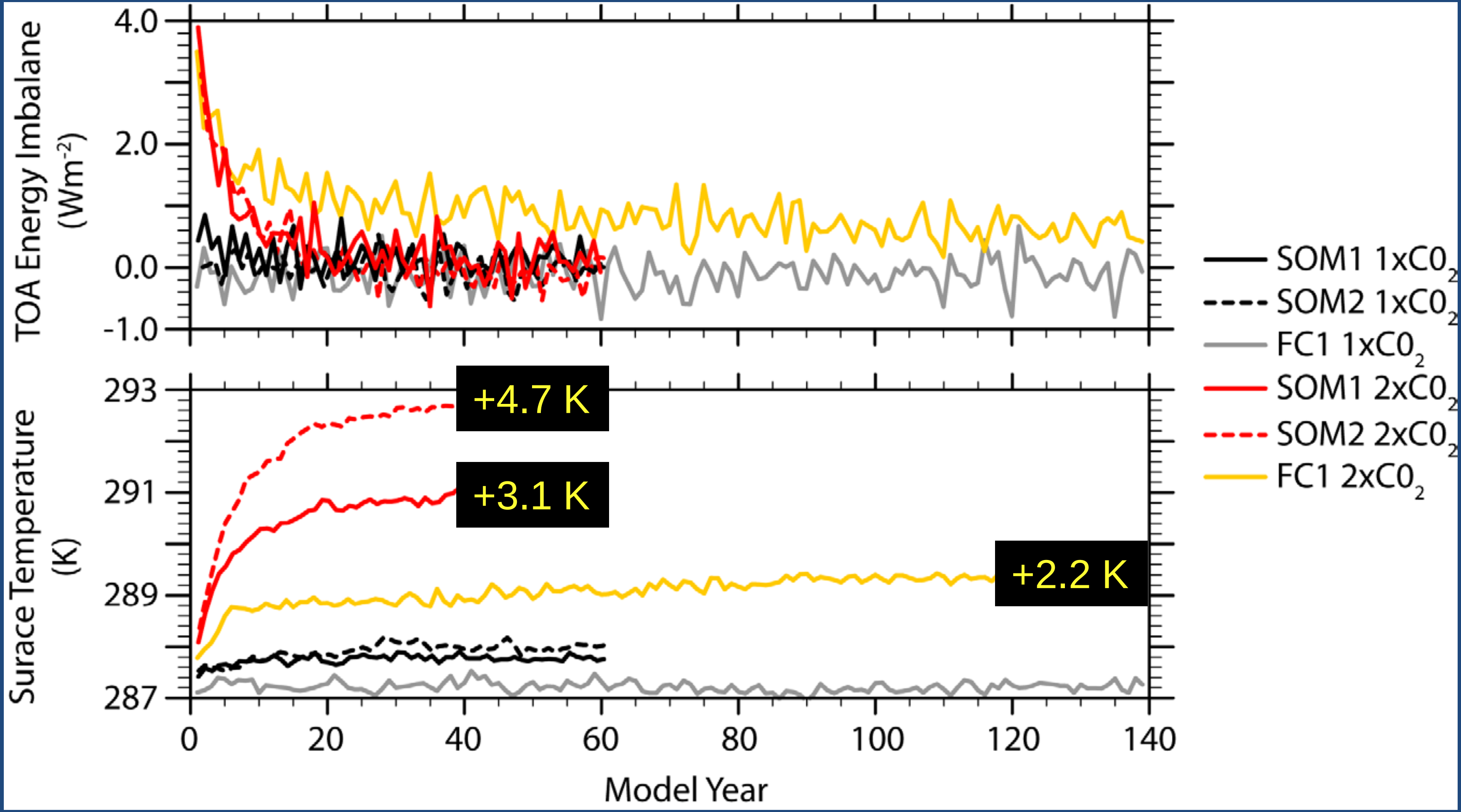
**Boulder, Colorado USA**

**Collaborators:** Marika Holland (NCAR), Cecilia Bitz (U. Washington),
Andrew Gettelman (NCAR), David Bailey (NCAR)

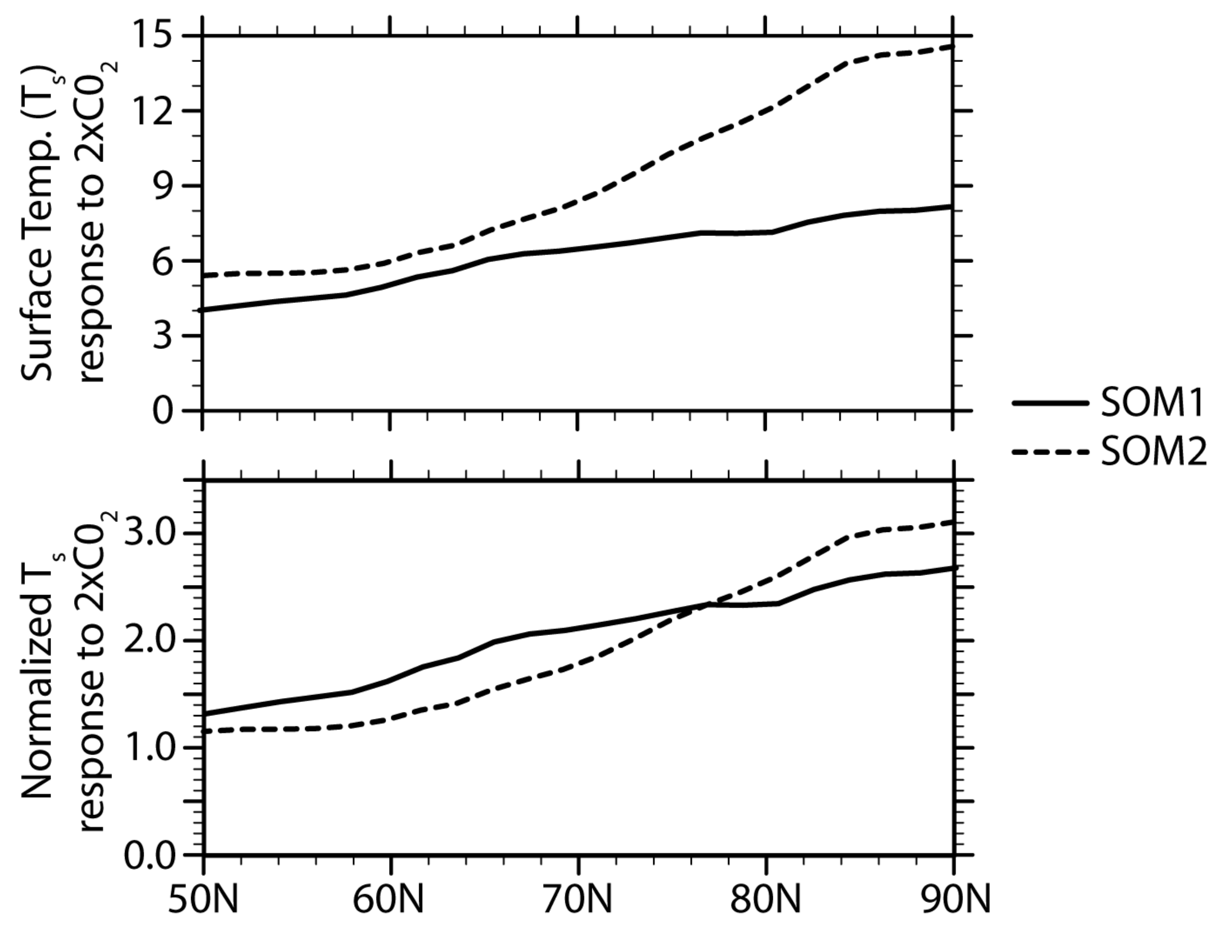
# Our “data”: global coupled climate model experiments

| Name | Model type | Experiment conditions |
|---|---|---|
| **SOM1** | Slab ocean model<br>2 deg. CAM4/CCSM4<br>(60 years) | 1850 control<br>1850+2x$C0_2$<br>1850+2x$C0_2$+2000 aerosols |
| **SOM2** | Slab ocean model<br>2 deg. CAM5-dev/CCSM4<br>(60 years) | 1850 control<br>1850+2x$C0_2$<br>1850+2x$C0_2$+2000 aerosols |
| **FC1** | Fully coupled model<br>1 deg. CAM4/CCSM4<br>(140 years) | 1850 control<br>1850+2x$C0_2$ |

# What is the global energy and surface temperature response to $2xC0_2$ forcing?

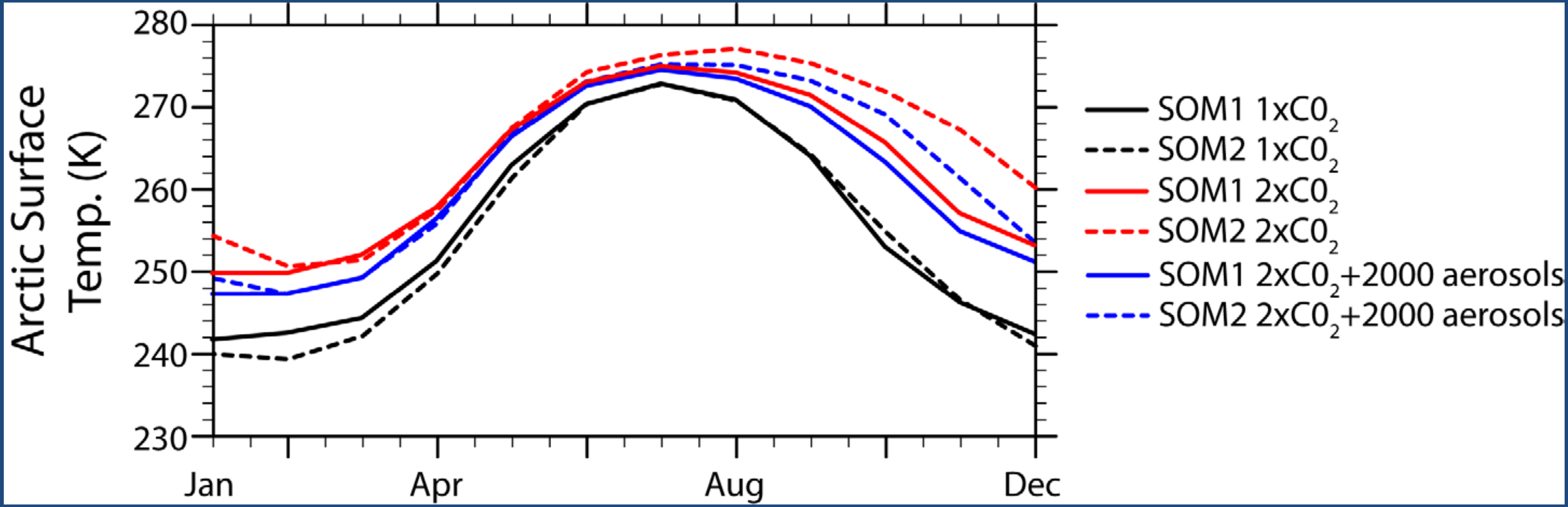


# Zonal mean temperature response to 2xC0$_2$

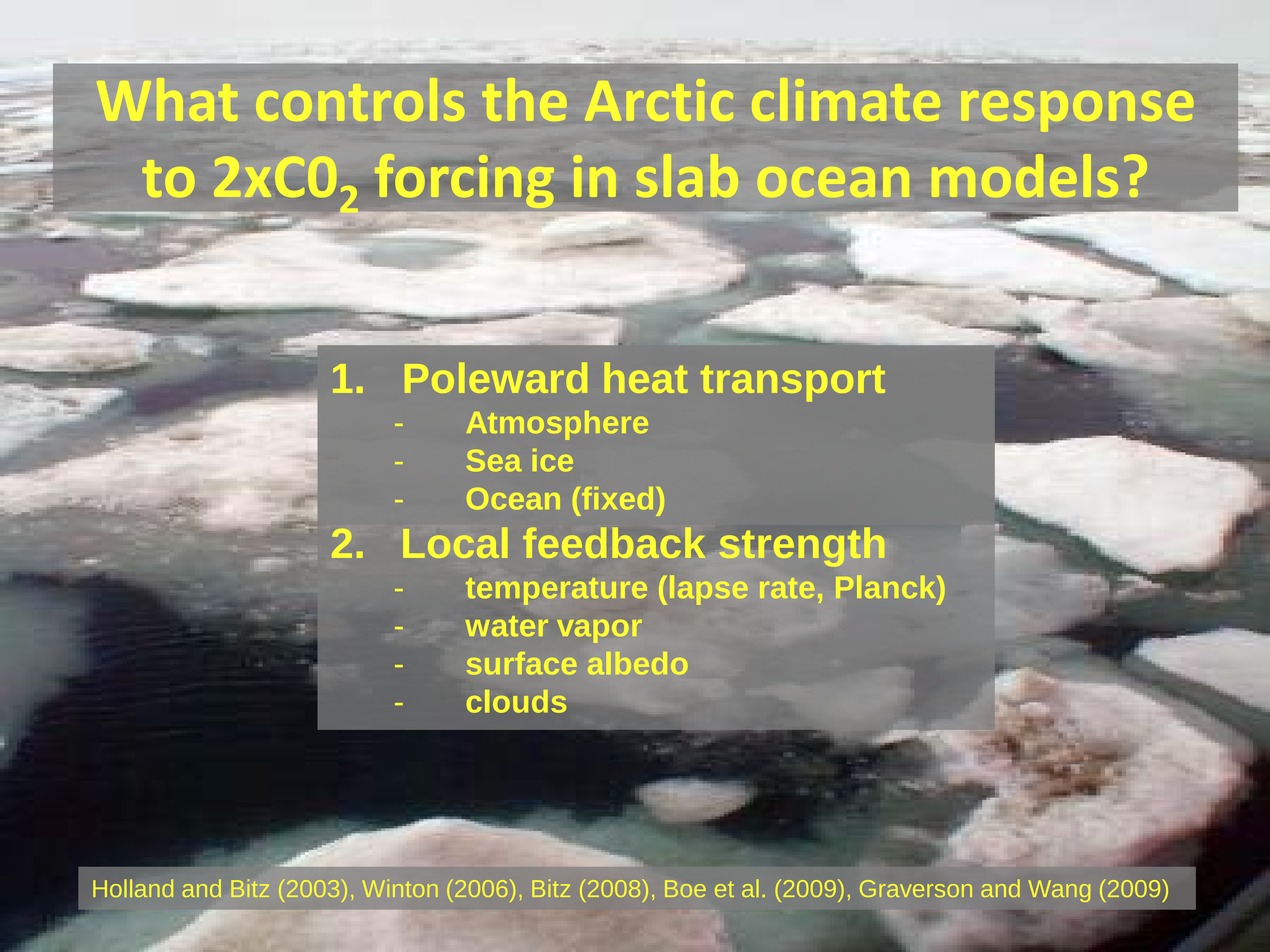


**SOM2 has greater Arctic amplification than SOM1, but a small difference when compared to 1.5-4.5 range reported in Holland and Bitz (2003).**

# Large seasonal variations in Arctic surface temperature increases are evident.



**For the rest of the talk,**
**I will focus on the Arctic response to 2xC0$_2$ forcing in SOM1 and SOM2.**



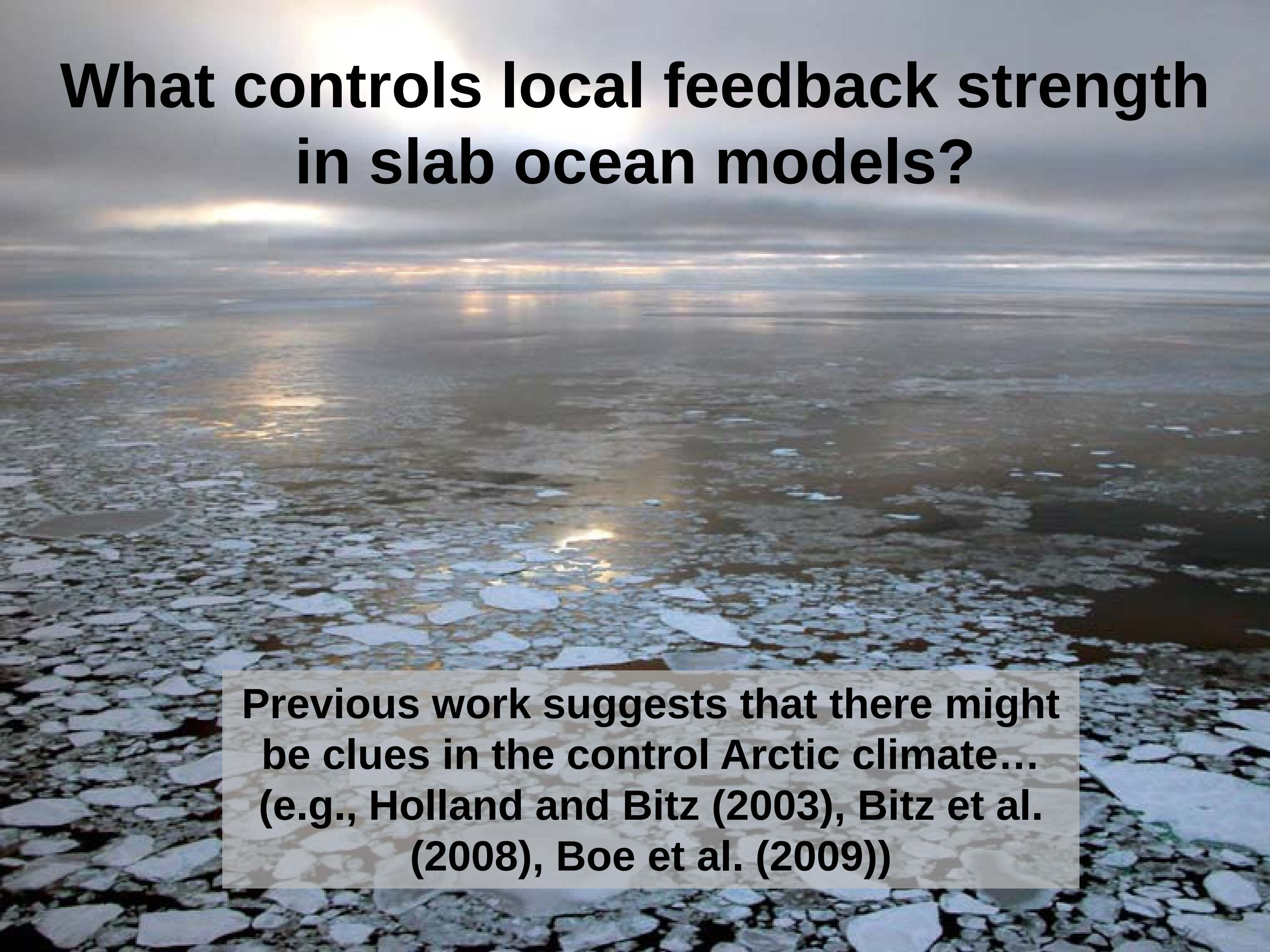
# What controls the Arctic climate response to 2xC0$_2$ forcing in slab ocean models?

1. **Poleward heat transport**
   - **Atmosphere**
   - **Sea ice**
   - **Ocean (fixed)**
2. **Local feedback strength**
   - **temperature (lapse rate, Planck)**
   - **water vapor**
   - **surface albedo**
   - **clouds**

Holland and Bitz (2003), Winton (2006), Bitz (2008), Boe et al. (2009), Graverson and Wang (2009)

# Does poleward heat transport (PWHT) @70 N *change* with 2xC0$_2$ forcing?

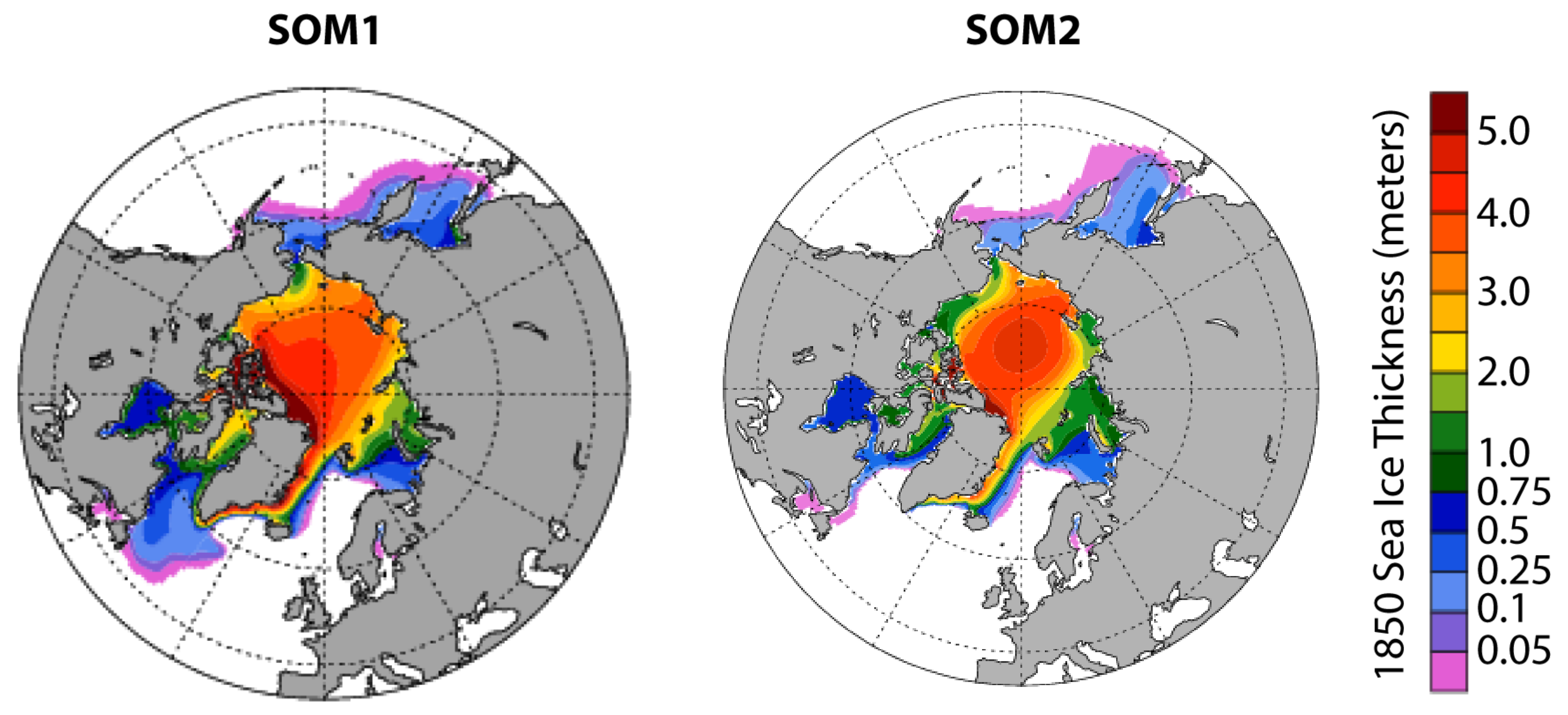
# What controls local feedback strength in slab ocean models?



Previous work suggests that there might be clues in the control Arctic climate… (e.g., Holland and Bitz (2003), Bitz et al. (2008), Boe et al. (2009))

# 1850 Mean State – Sea Ice Thickness

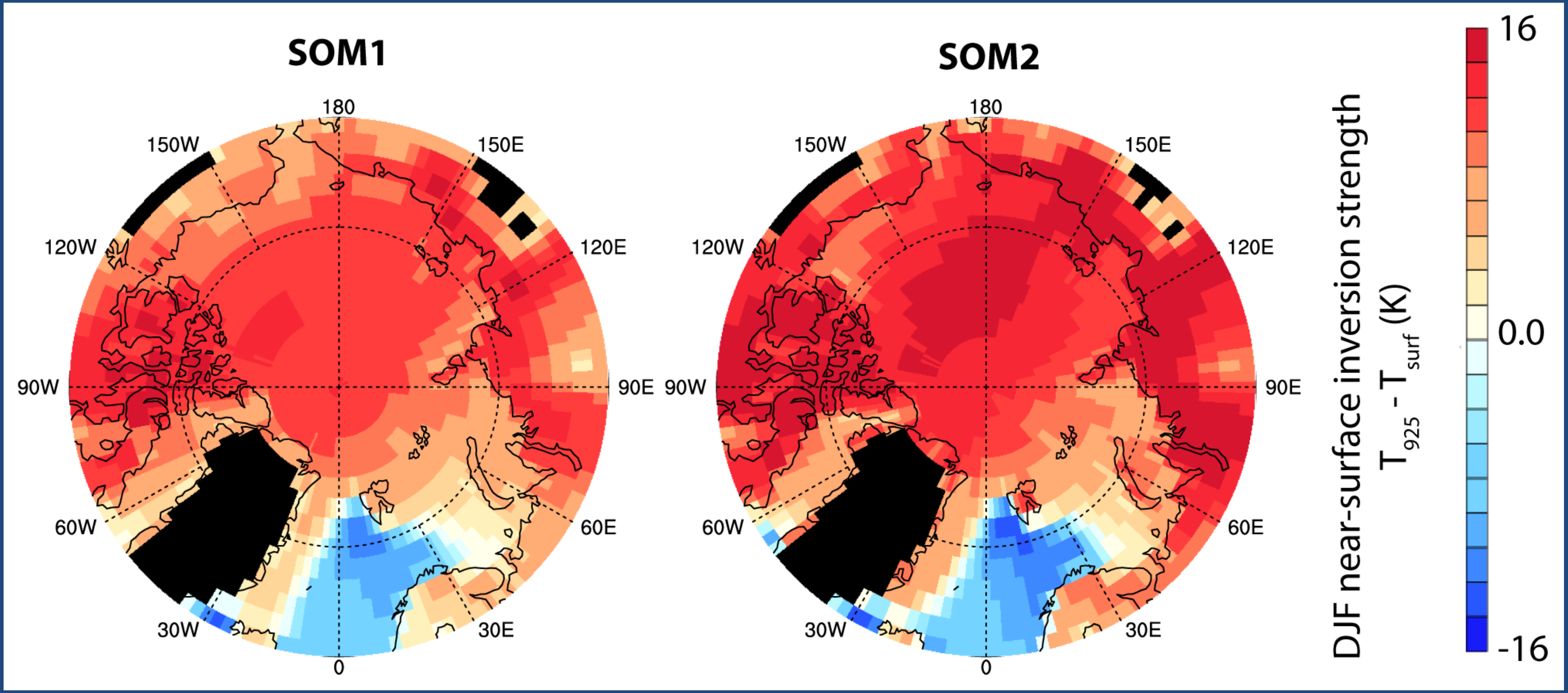
*Holland and Bitz (2003), Bitz (2008) – Models with relatively thin ice in the control climate tend to have more polar amplification/sea ice loss.*



**Sea ice thickness may help explain the differing responses to 2xC0$_2$ in SOM1 and SOM2.**

# 1850 Mean State – Arctic Winter Inversion

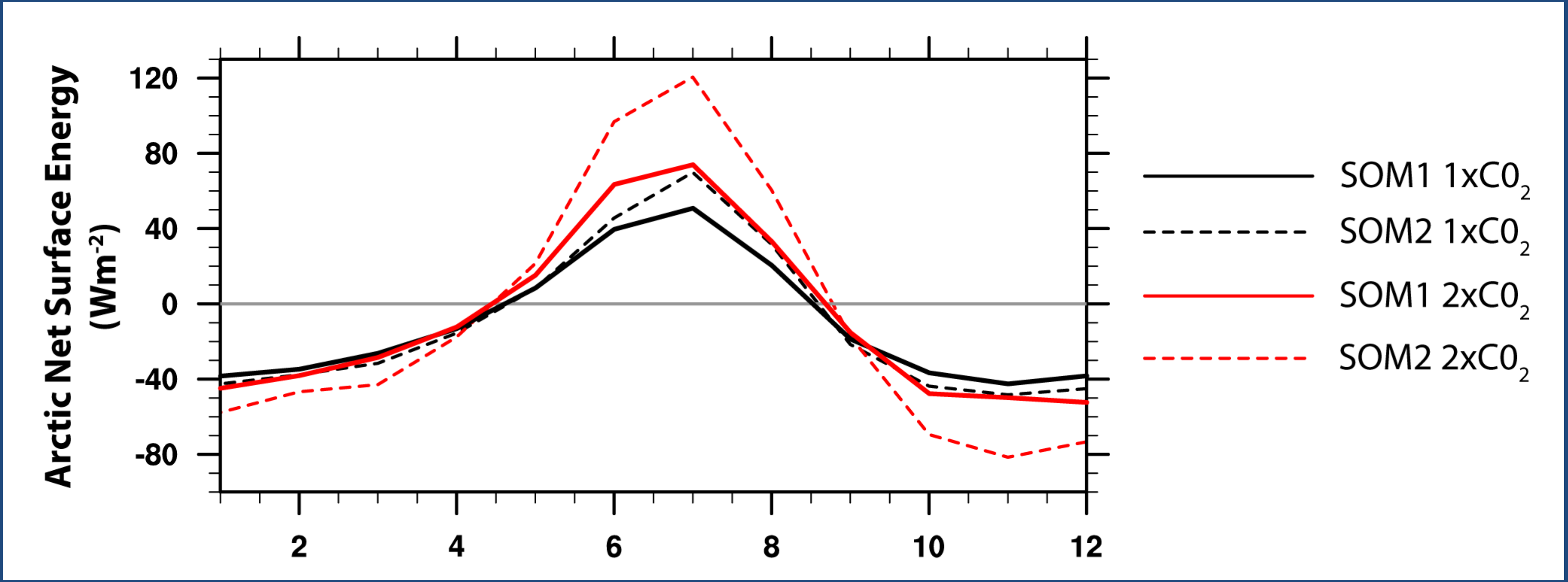
*Boe et al. (2009) – Models with excessive present day inversion strength underpredict Arctic warming in response to future greenhouse gas increases.*



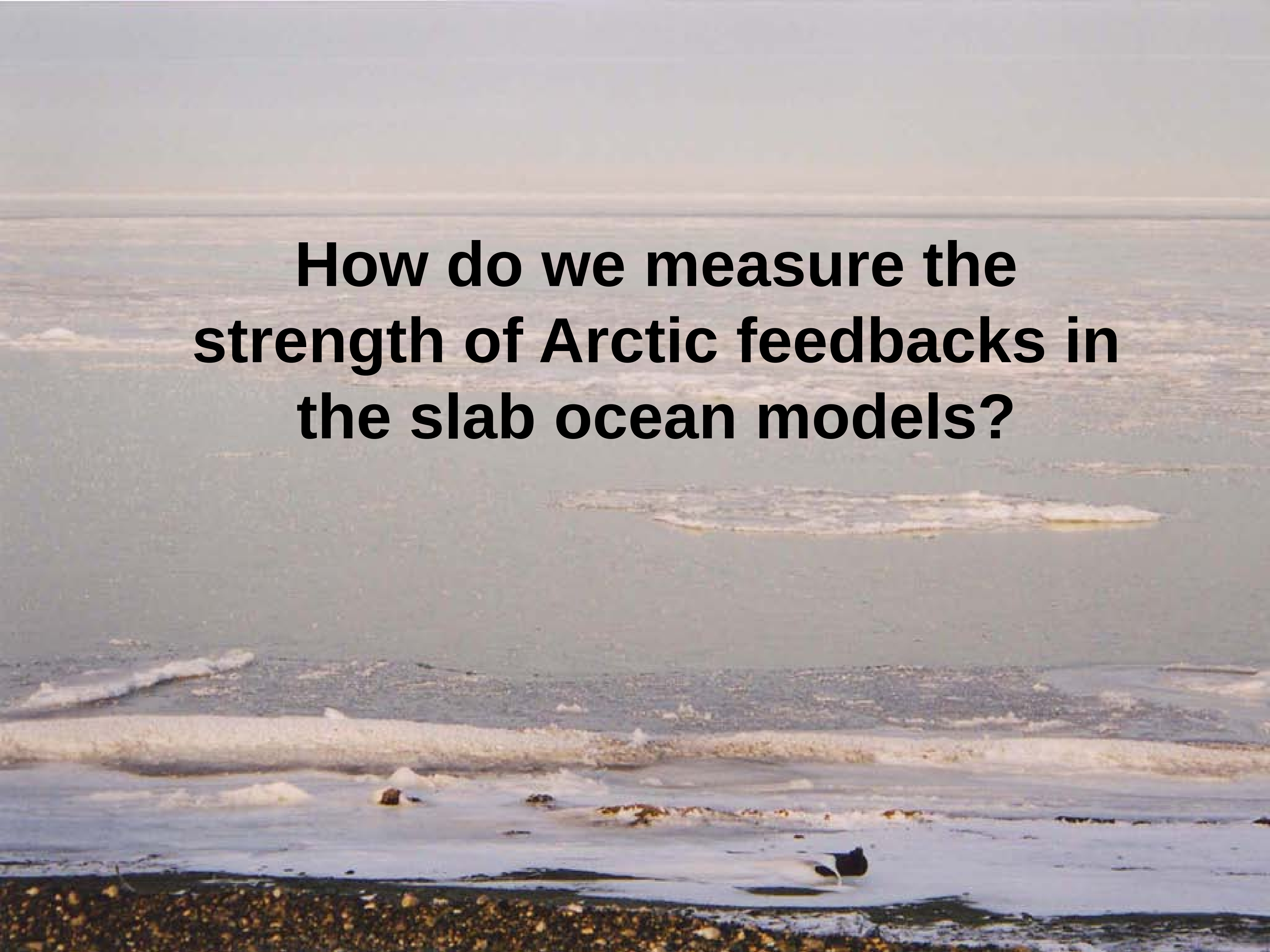
**Inversion strength does not explain the differing responses to $2xC0_2$ in SOM1 and SOM2.**

# 1850 Mean State – Surface Energy Budget

*Literature on the influence of the mean state surface energy budget on the response to $2xC0_2$?*



**SOM2's mean state surface energy budget makes it more sensitive than SOM1 to $2xC0_2$.**



# How do we measure the strength of Arctic feedbacks in the slab ocean models?

# Method #1: Arctic feedback strength from temperature and TOA flux changes

*Method used to asses global feedback strengths (e.g., Gregory and Mitchell, (1997)).*
*We extend it to assess local feedback strengths by incorporating advection.*

| | **SOM1** | **SOM2** |
|---|---|---|
| **Surface temperature increase $\Delta T_{surf}$ (K)** | 7.0 | 11.0 |
| **Longwave feedback**<br>$\lambda_{lw} = \Delta_{netlwTOA}/\Delta T_{surf}$ | -0.90 | -1.20 |
| **Shortwave feedback**<br>$\lambda_{sw} = \Delta_{netswTOA}/\Delta T_{surf}$ | 0.80 | 1.19 |
| **Advective feedback**<br>$\lambda_{sw} = \Delta_{ADV}/\Delta T_{surf}$ | +0.08 | +0.01 |

***Annual values for 70-90 N.***
***All feedback parameters in $Wm^{-2}K^{-1}$.***

# Method #2:
# Arctic feedback strength from radiative kernels

*Method used for global analysis (e.g., Held and Soden (2006), Soden et al. (2008)).*
*We apply it locally ignoring advection.*

| | SOM1 | SOM2 |
|---|---|---|
| **Surface temperature increase $\Delta T_{surf}$ (K)** | 7.0 | 11.0 |
| **Lapse rate feedback** | -0.1 | -0.3 |
| **Water vapor feedback (SW, LW)** | +0.4, +0.5 | +0.4, +0.5 |
| **Surface albedo feedback** | +4.3 | +5.7 |
| **Cloud feedback (SW, LW)** | -5.2, +0.4 | -3.7, +0.2 |

***Annual values for 70-90 N.***
***All feedback parameters in $Wm^{-2}K^{-1}$.***

# Summary:

1) We found large differences in the Arctic response to 2xC0$_2$ and present day aerosol forcing in 2 recent slab ocean model (SOM) configurations of NCAR’s climate model.

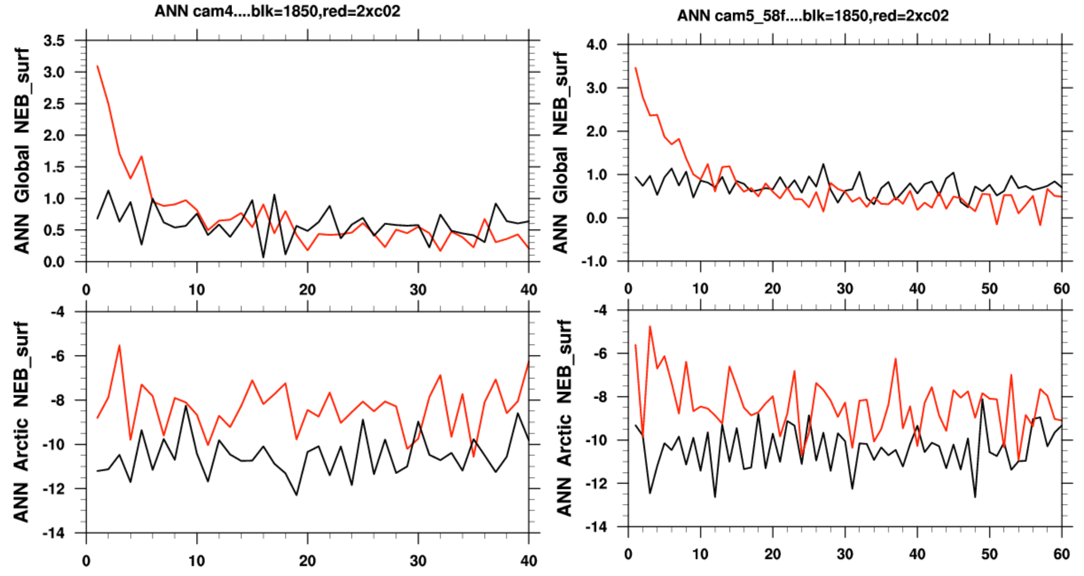
2) Annual Arctic warming in response to 2xC0$_2$ forcing alone was +7 K (SOM1) and +11 K (SOM2). Cooling due to present day aerosol forcing was of secondary importance, mitigating 19% (SOM1) and 26% (SOM2) of the 2xC0$_2$ Arctic warming.

3) Poleward heat transport @ 70 N increased with 2xC0$_2$ forcing in both SOMs, but PWHT does not explain the Arctic warming difference between SOM1 and SOM2.

4) Because of 3), local feedback strength differences must explain the 2xC0$_2$ Arctic climate response differences. In particular, SOM2 had weaker negative shortwave cloud feedbacks and stronger surface albedo feedbacks than SOM1.

# EXTRA

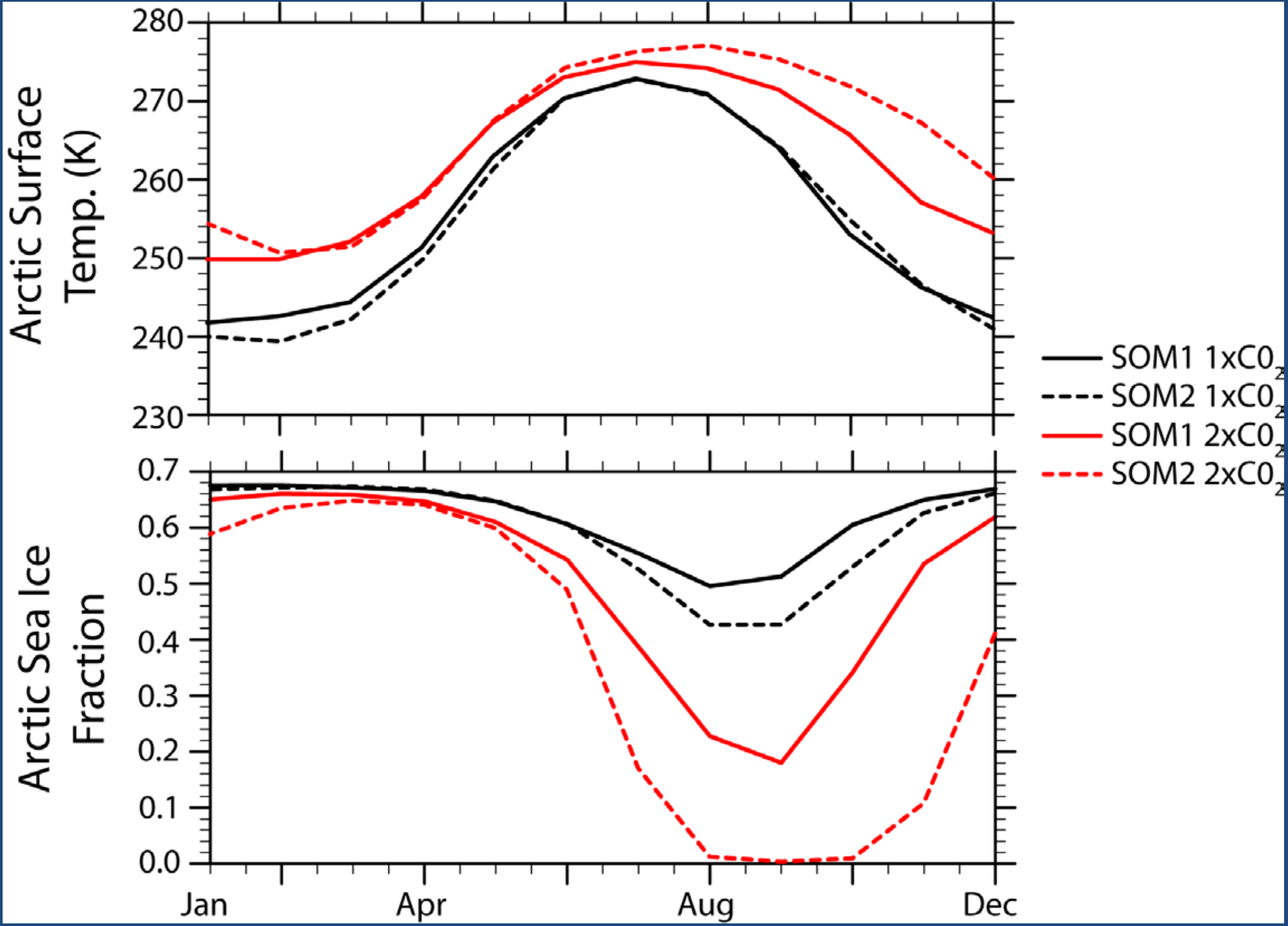
# ANN Average Energy Budget in 1x, 2x C02



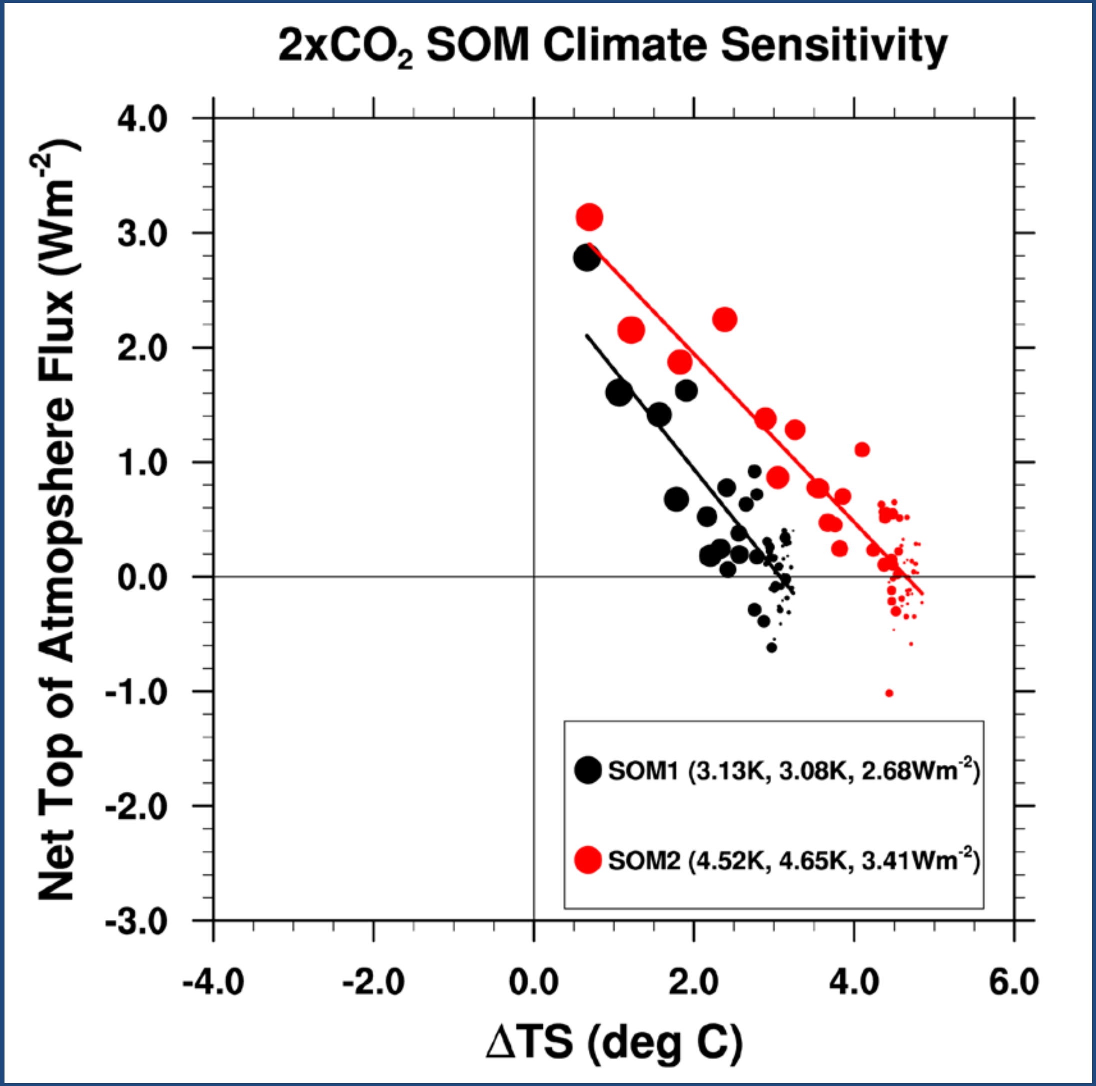
| 1xC02, 2xC02, 2x-1xC02 | SOM1 | SOM2 |
|---|---|---|
| Annual mean NEB_TOA | -115.9, -116.5, -0.6 | -112.8, -112.9, -0.1 |
| Annual mean NEB_surf | -10.6, -8.3,+2.4 | -10.2, -8.8,+1.4 |

***Annually averaged surface energy budget response to 2xC02 and mean state are pretty similar between SOM1 and SOM2… yet SOM2 warms so much more!***

# Seasonal Arctic surface temperature and sea ice response to 2xC0$_2$ forcing



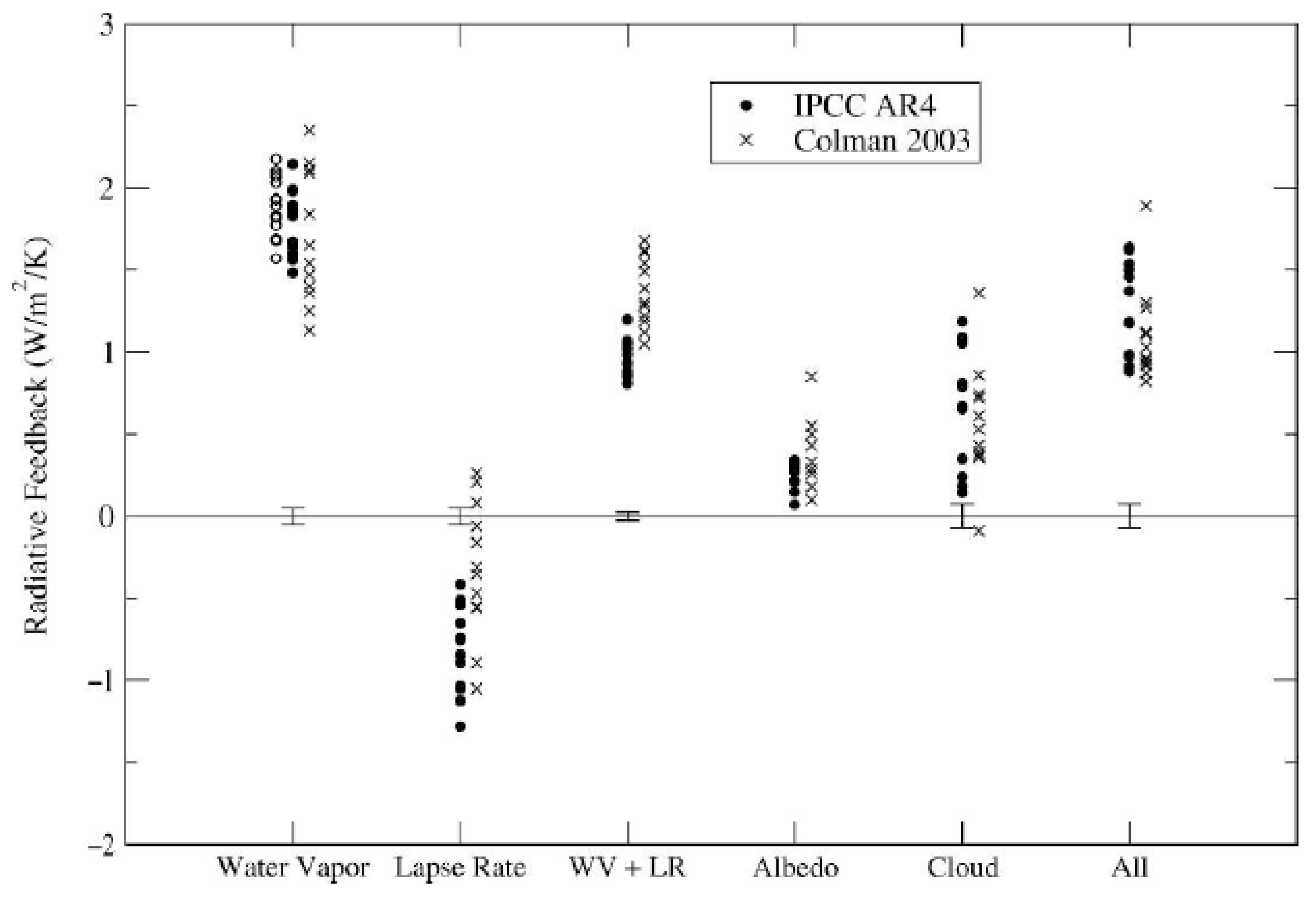
# SOM2 has a larger global climate sensitivity than SOM1.



Climate sensitivity:
SOM1 – 3.1 K
SOM2 – 4.7 K

# Assess feedbacks using radiative kernels

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



# Using kernels to assess the reasons for the differences in global climate sensitivity.

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

| | SOM1 | SOM2 |
|---|---|---|
| **Surface temperature increase (K)** | 3.1 | 4.7 |
| **Lapse rate feedback** | -0.7 | -0.7 |
| **Water vapor feedback (SW, LW)** | +0.3, +1.6 | +0.2, +1.6 |
| **Surface albedo feedback** | +0.3 | +0.3 |
| **Cloud feedback (SW, LW)** | +0.8, +0.7 | +0.7, -0.5 |

***Cloud feedbacks appear to explain the global difference!***

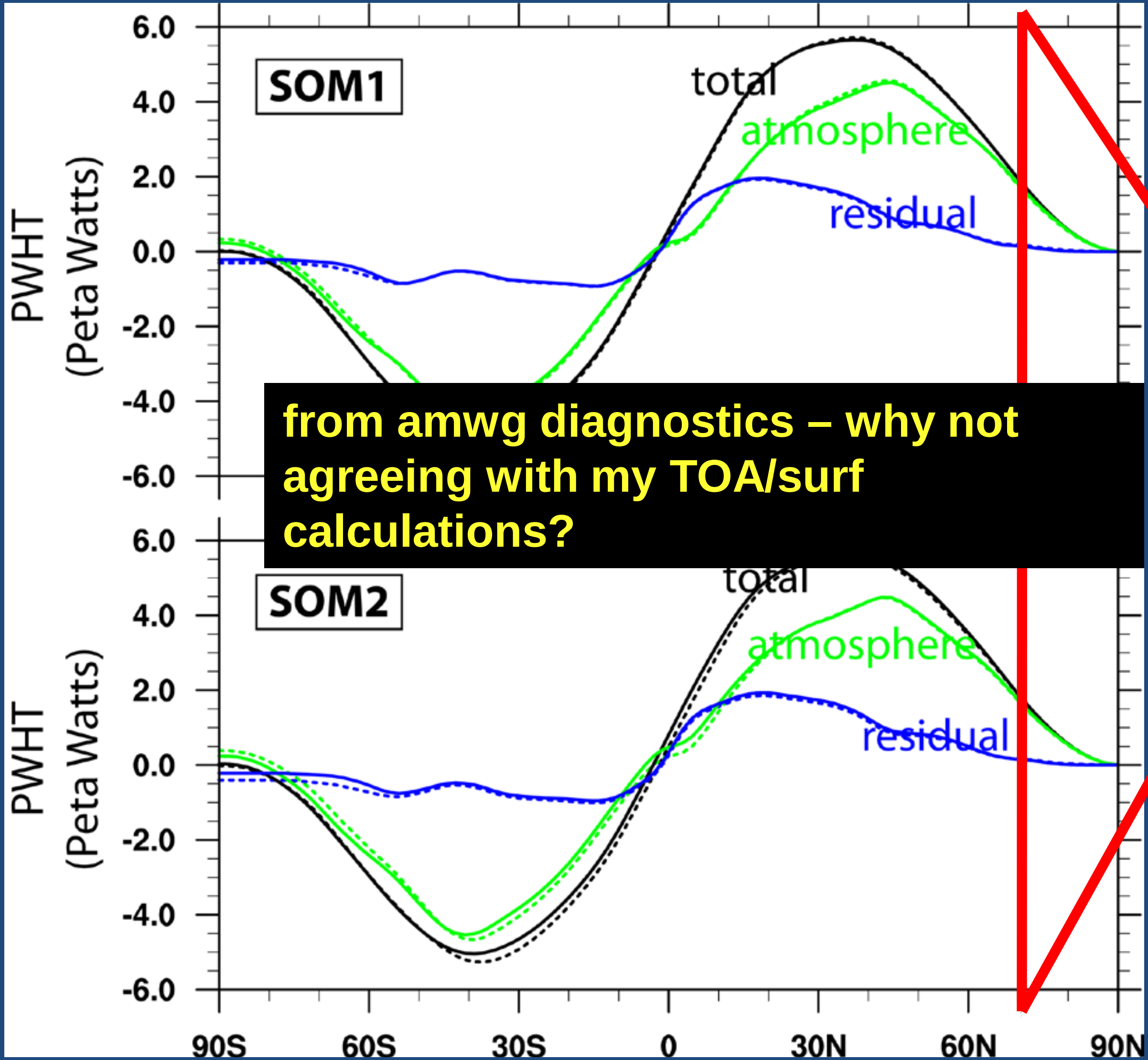
*Preliminary calculations from work with Andrew Gettelman/Karen Shell*

# Compare atmosphere energy budgets in SOMs with observational estimates from Serreze et al. (2007)

| | SOM1 | SOM2 | Table 1 S07 ERA40 (NCEP) |
|---|---|---|---|
| Annual mean NEB_TOA | -116.5 | -112.9 | -110 |
| Annual mean NEB_surf | 8.3 | 8.8 | 11 |
| Annual mean heat transport - atm | 108.2 | 104.1 | 100 (103) |

*Annual values for 70-90 N.*
*All values in $Wm^{-2}K^{-1}$.*

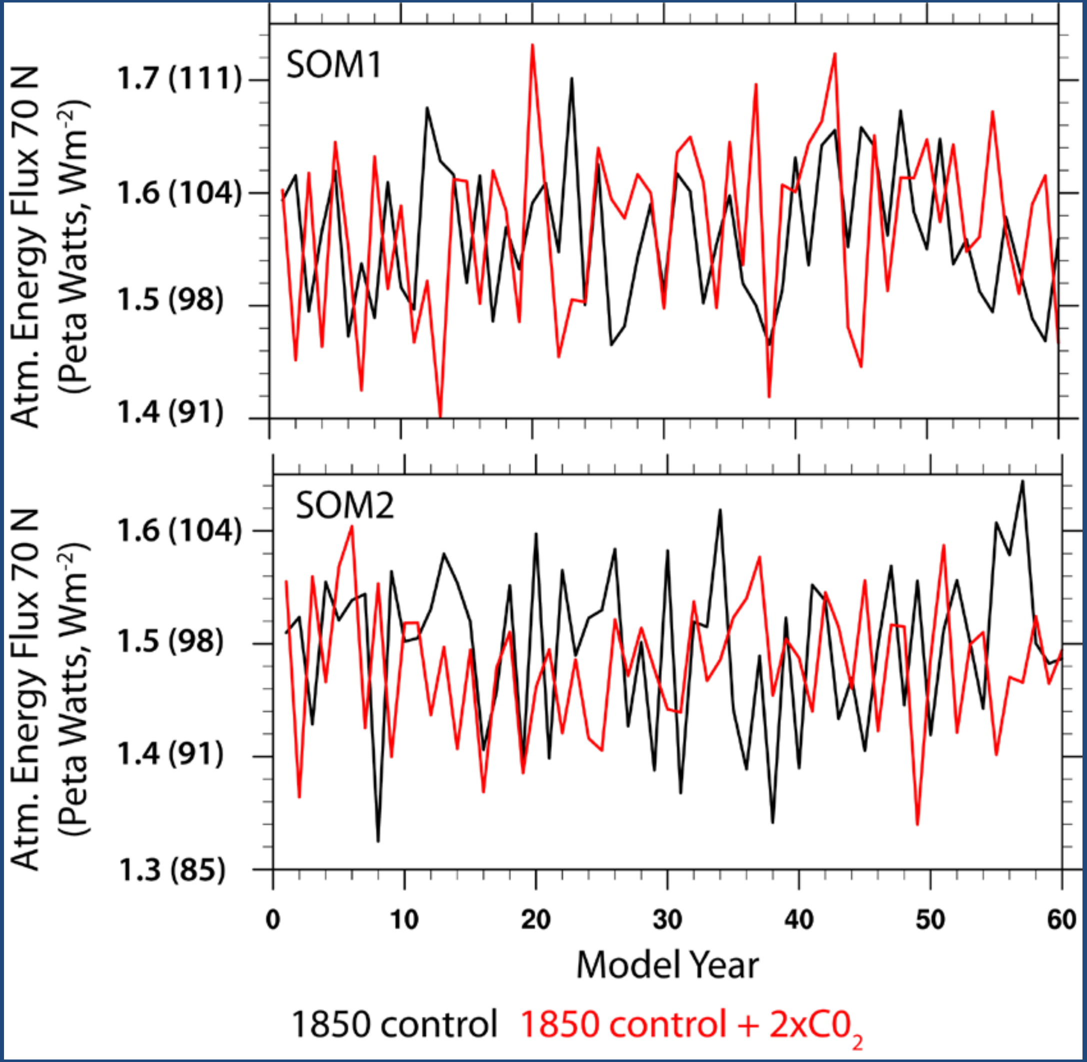
# Poleward Heat Transport (PWHT) at 1xC0$_2$



**from amwg diagnostics – why not agreeing with my TOA/surf calculations?**

| PWHT @ 70 N (Wm$^{-2}$) | SOM1 1xC0$_2$ | SOM2 1xC0$_2$ |
|---|---|---|
| Total | 135 | 131 |
| Atmosphere | 123 | 120 |
| Residual (ocean, sea ice) | 12 | 11 |

# Time series of atmospheric heat transport ax 70 N in SOM1 and SOM2?



**Lots of variability, no trend or change with 2xC02.**

**Absolute values do not agree with TOA/surf EB residual.**

**This is likely because I am using monthly mean output in calculations. Problem with sigma coordinates which vary – need to do this calculation inside the model. Calculate first, average later…**

# HB03 Figure 8, models with high aa have high ocean control pwht and dpwht

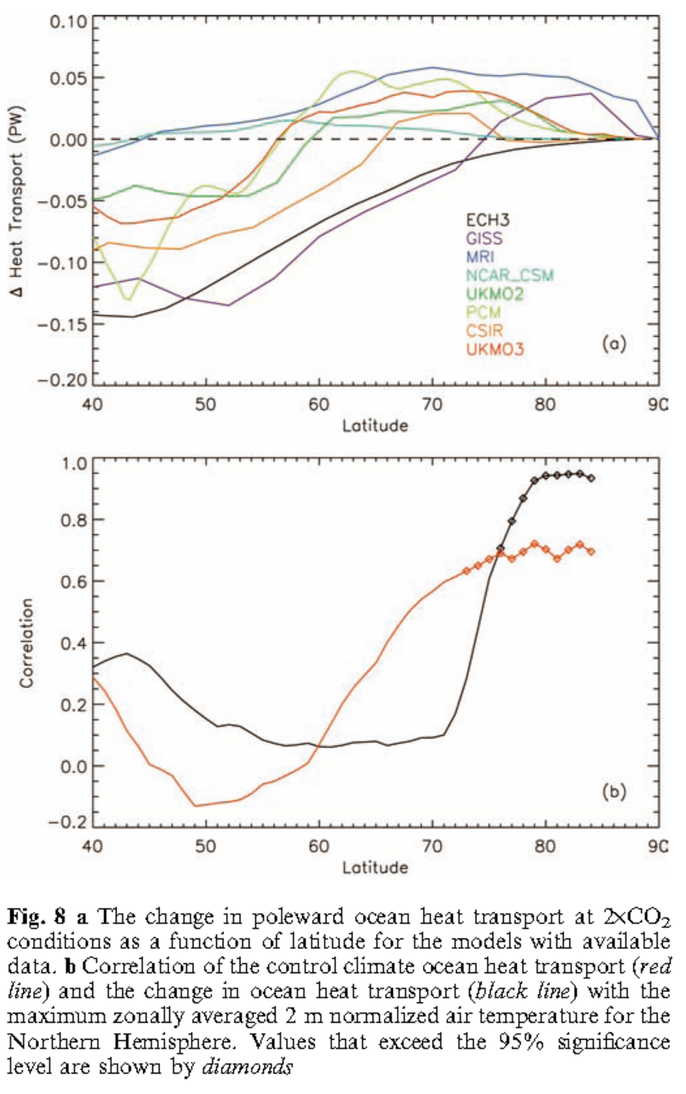
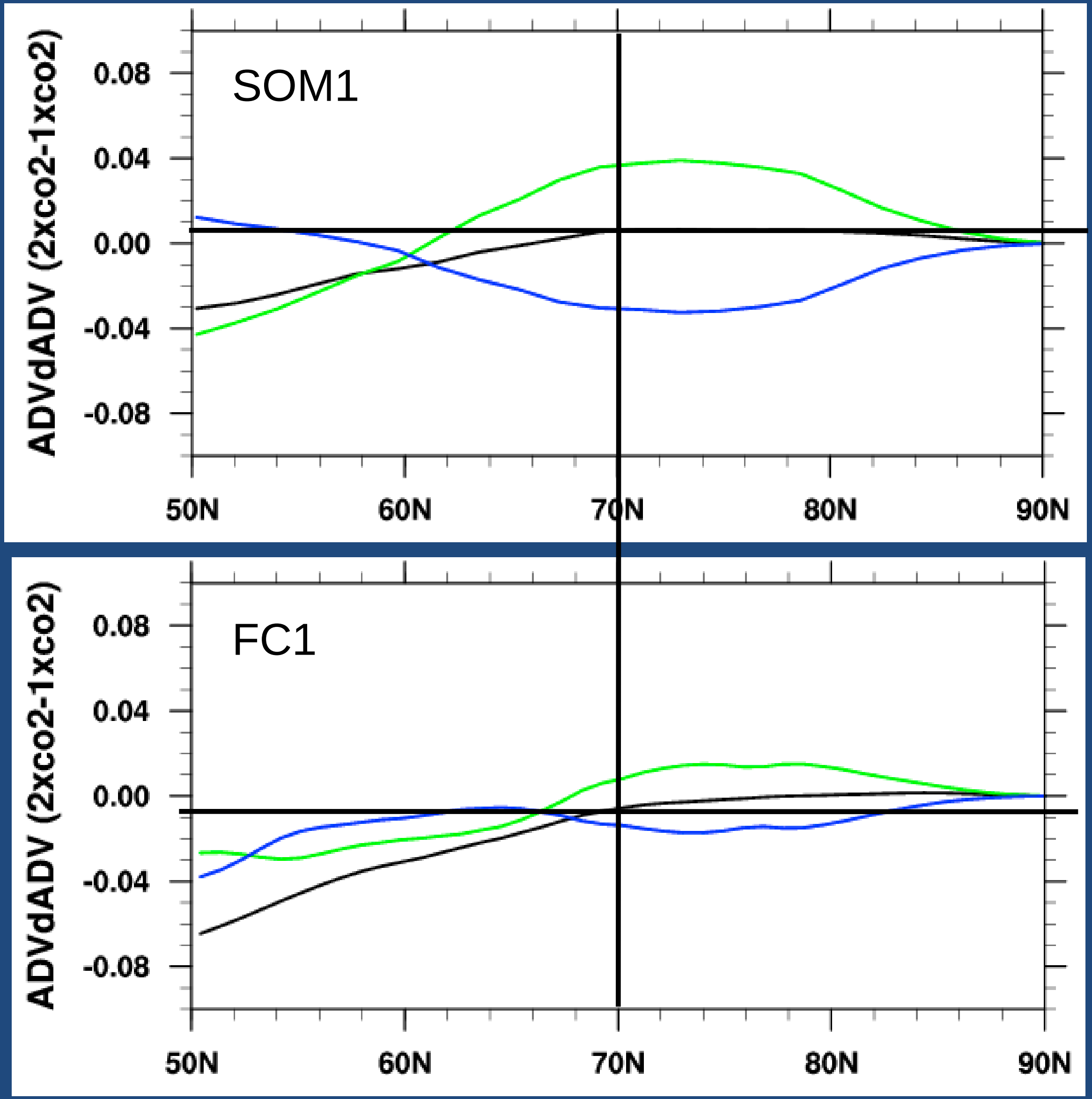


**Fig. 8** **a** The change in poleward ocean heat transport at 2×$CO_2$ conditions as a function of latitude for the models with available data. **b** Correlation of the control climate ocean heat transport (*red line*) and the change in ocean heat transport (*black line*) with the maximum zonally averaged 2 m normalized air temperature for the Northern Hemisphere. Values that exceed the 95% significance level are shown by *diamonds*

**expect small values for change in pwht < 0.05 PW**
**note: these are transient runs**

# SOM1 vs FC1 role of deep ocean in PWHT?



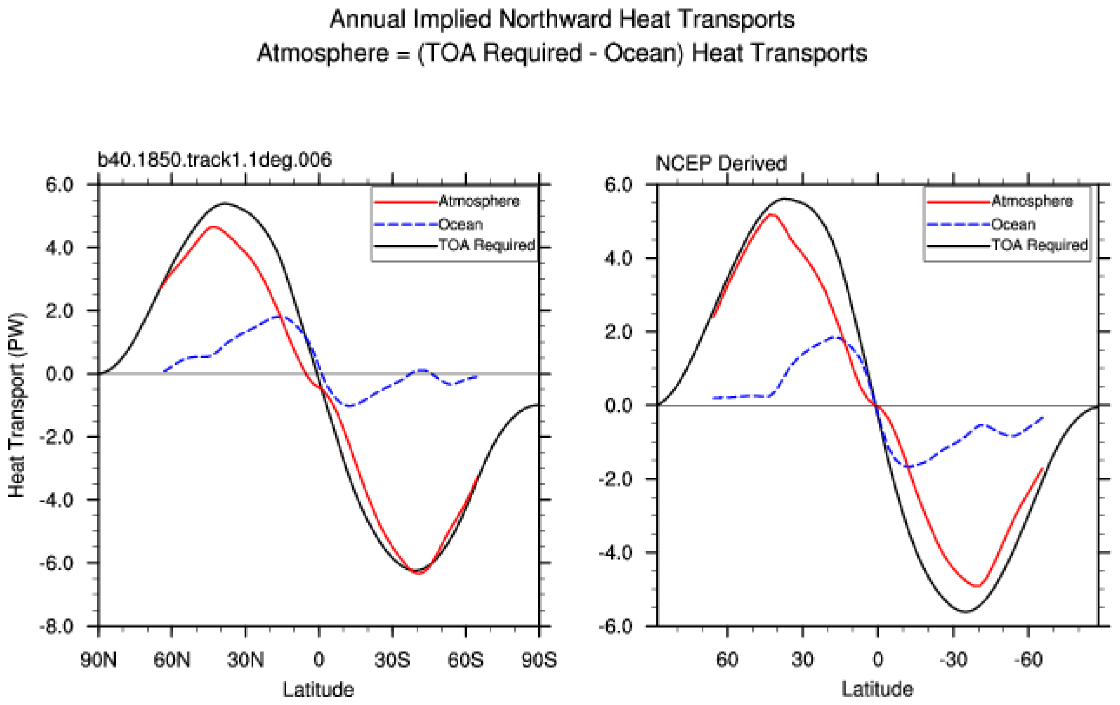
In both SOM1&FC1, the total change is < 0.01 PW @ 70 N.

FC1 vs. SOM1
ADV-atm less positive
ADV-res less negative

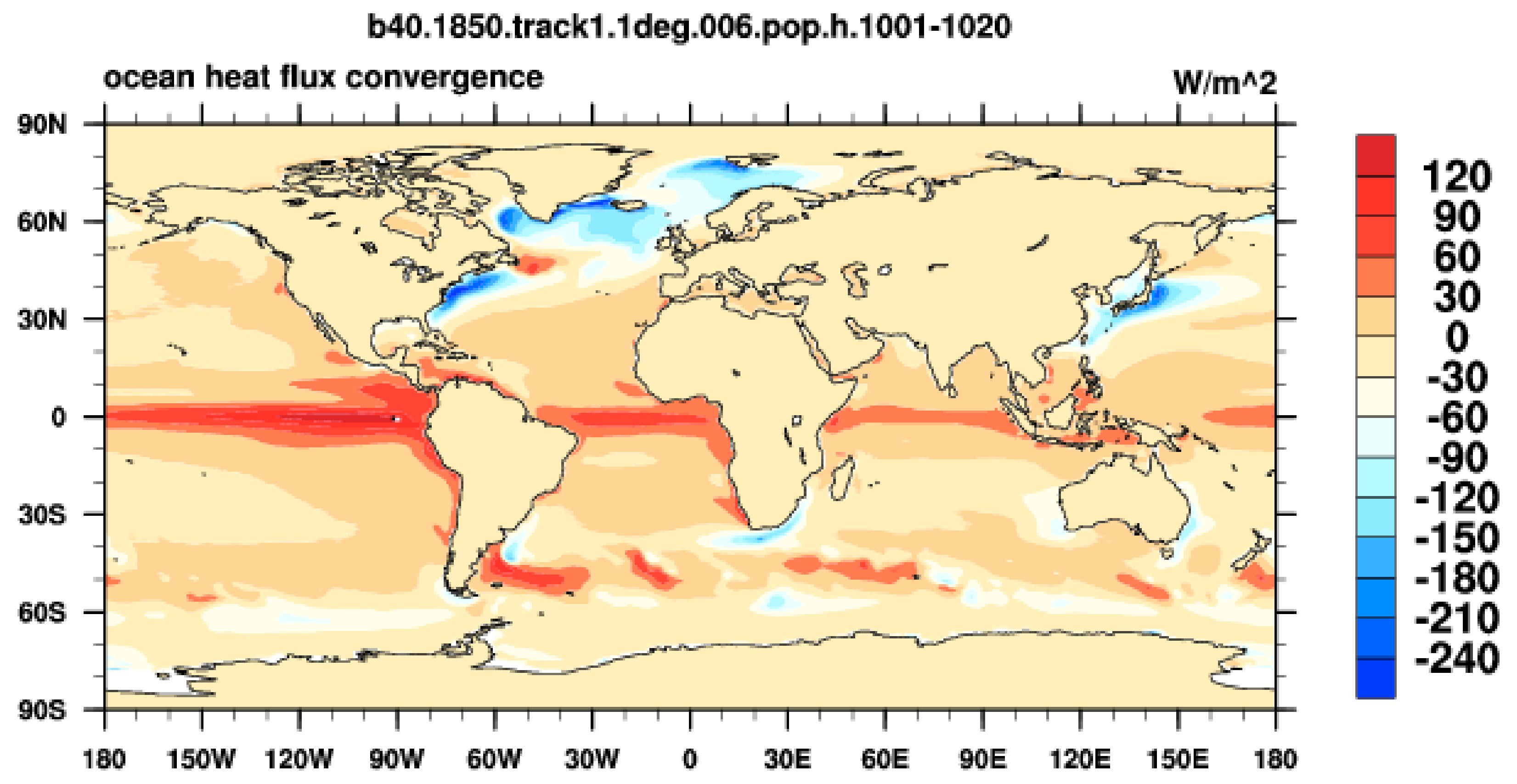
FC1 not in equilibrium – Can I use the residual method?

# Compare oceanic heat transport in coupled runs used to produce QFLUXES for SOM1 and SOM2 with observations

Need to run
58f diagnostics
With ocean heat
Transport turned on

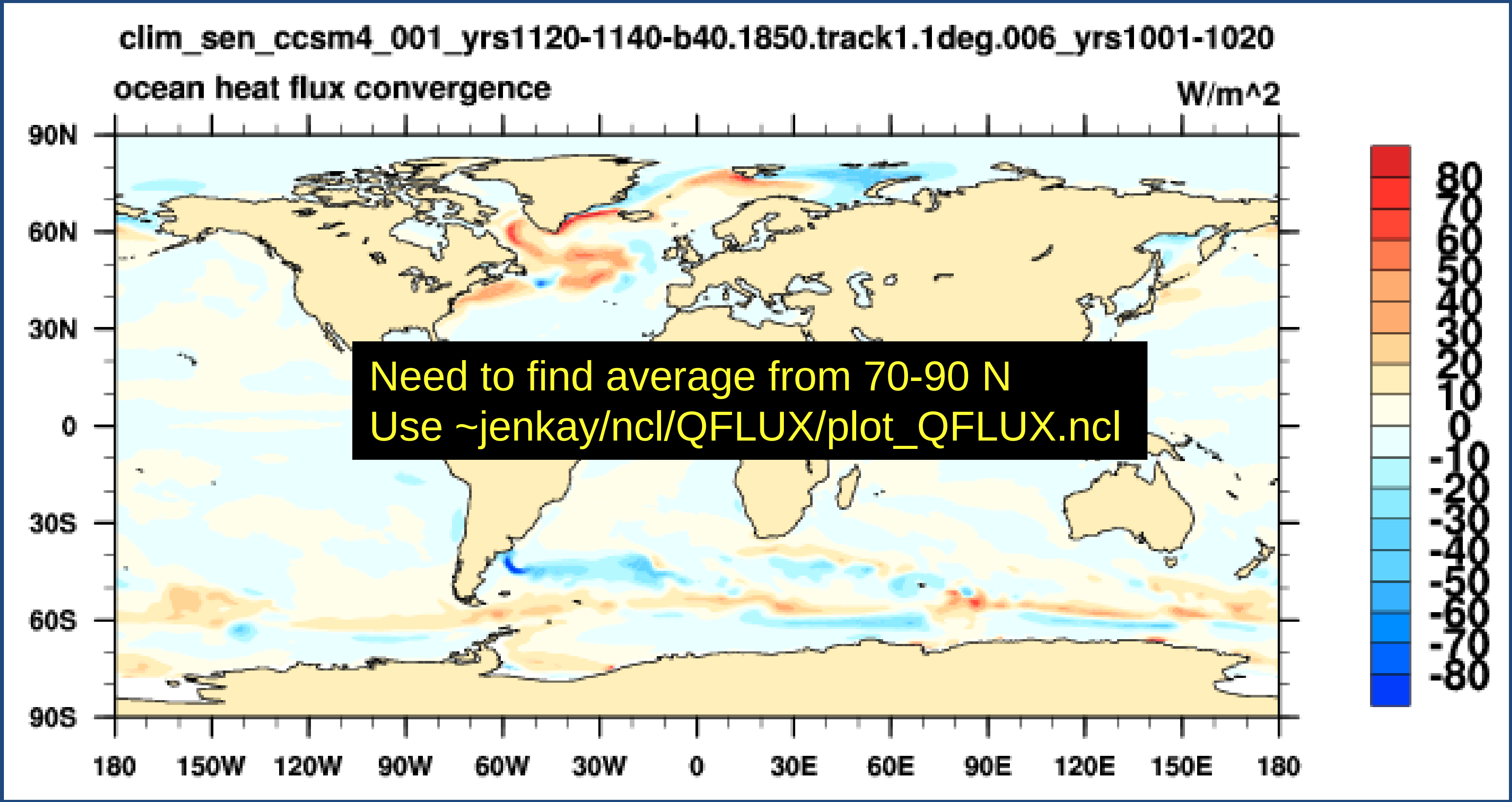


# 1850 control QFLUXES from FC1



Mixed layer losing heat to the deep ocean in North Atlantic, off East Coast NA/Asia
Mixed layer gaining heat from deep ocean in tropics and southern hemisphere storm tracks.

# FC1 QFLUX changes in response to 2xC02 (2xC02-1xC02 QFLUX)



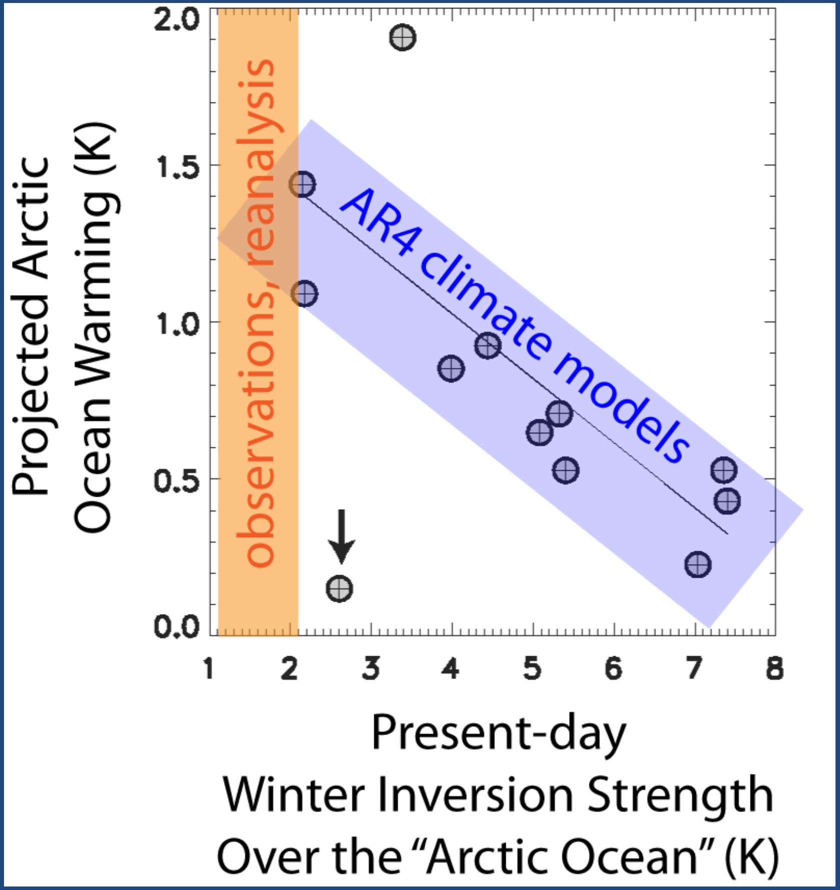
Need to find average from 70-90 N
Use ~jenkay/ncl/QFLUX/plot_QFLUX.ncl

Compare oceanic heat transport in coupled runs used to produce QFLUXES for SOM1 and SOM2 with observations

Are these low or high ocean PWHT models?

# 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**

# Compare timescale for response – transient planck feedback in SOM1, SOM2, FC1