# *A History of Coupled Climate Modeling*

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# Climate Calculations with a Combined Ocean-Atmosphere Model

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13 March 1969 and 6 May 1969

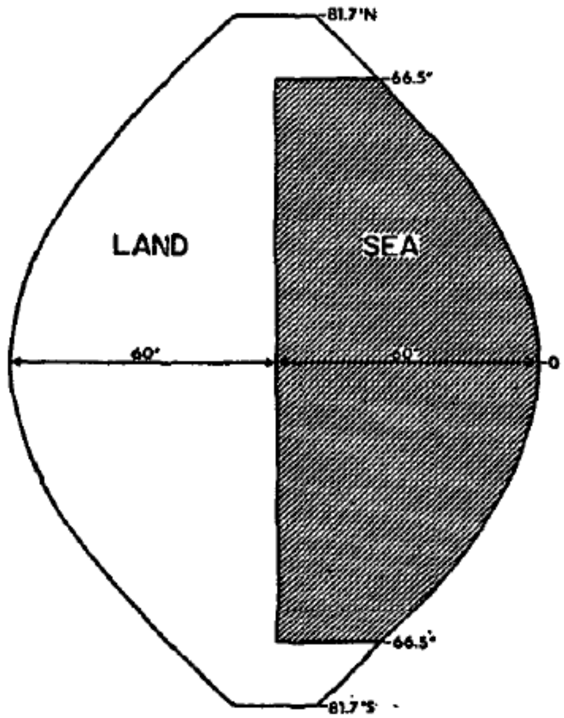


FIG. 1. Ocean-continent configuration of the model.

The first coupled ocean/ atmosphere model with idealized continents was run at the GDFL: results published in JAS in 1969.

$5^o \times 5^o$ Horizontal grid:
9 levels in atm, 5 in ocean.

# A Global Ocean-Atmosphere Climate Model. Part I. The Atmospheric Circulation

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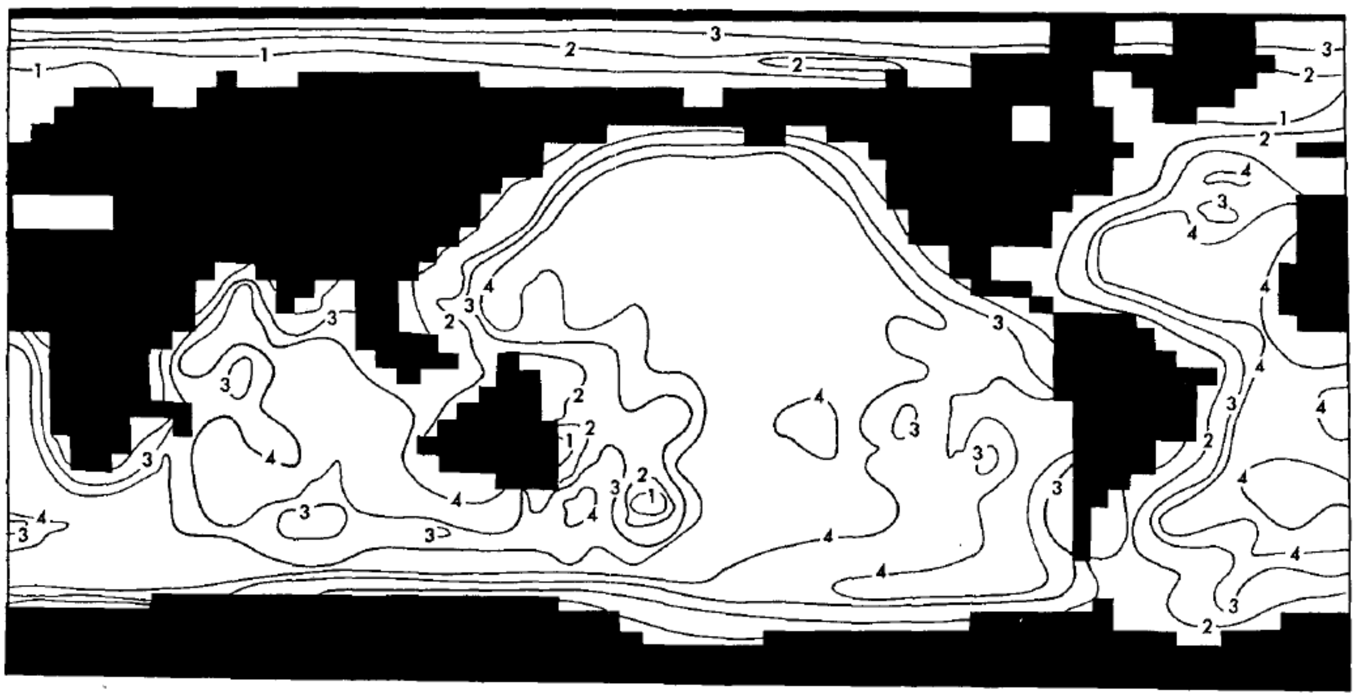


FIG. 2. The smoothed topography of the ocean model. Depth is given in kilometers.

$5^o$ x $5^o$
Hor grid

9 levels
in Atm, 5
in Ocean

JPO
1975

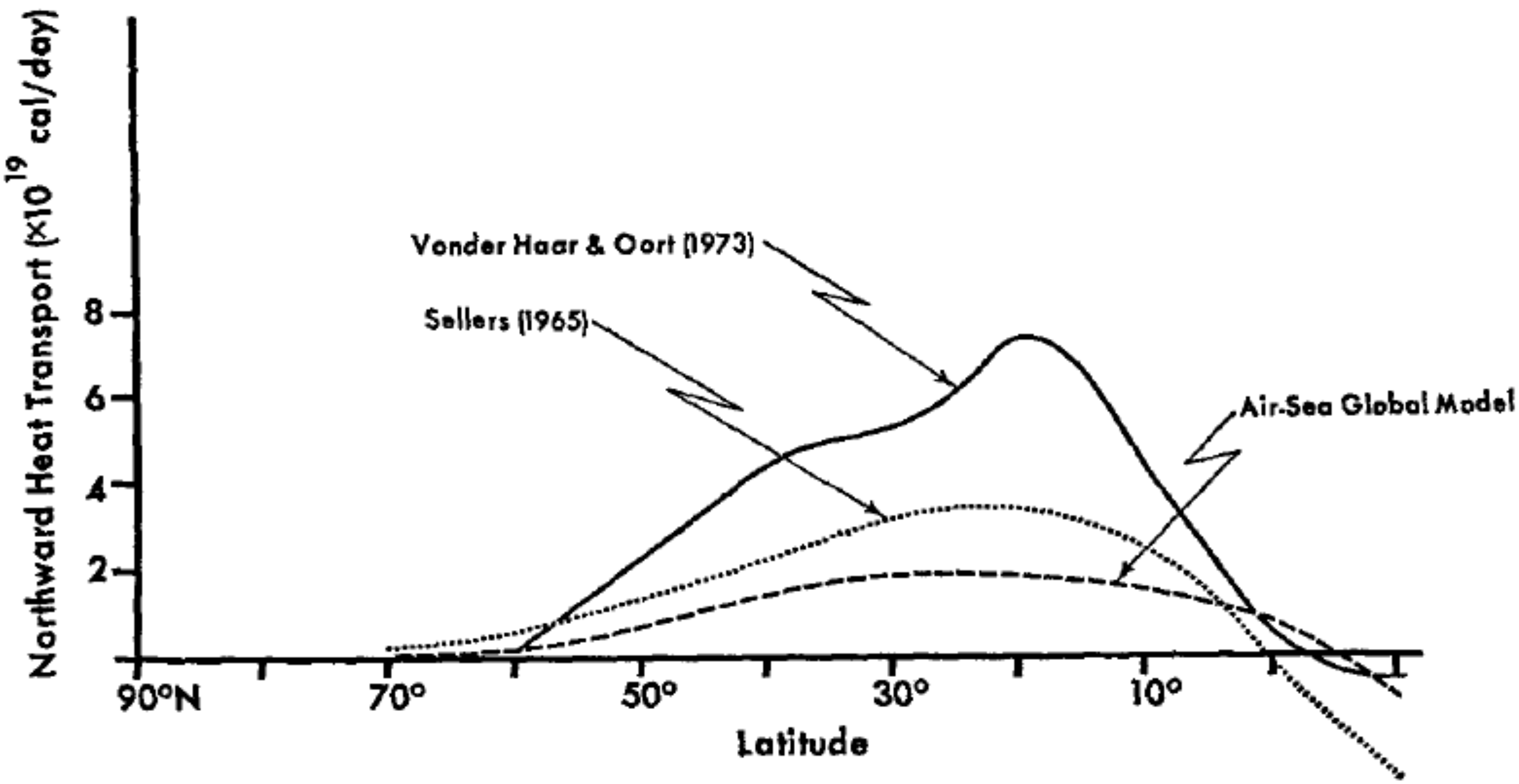



FIG. 12. Heat transport by the ocean model in a northward direction compared to estimates based on heat balance calculations.

The conservation equations for potential temperature ($\theta$) and salinity ($S$) under conditions of stable stratification are

$$(\theta,S)_t+\mathbf{v}\nabla(\theta,S)+w(\theta,S)_z=\kappa(\theta,S)_{zz}+A_H\nabla^2(\theta,S). \quad (8)$$

JPO
1975

6 Washington and Meehl: Climate

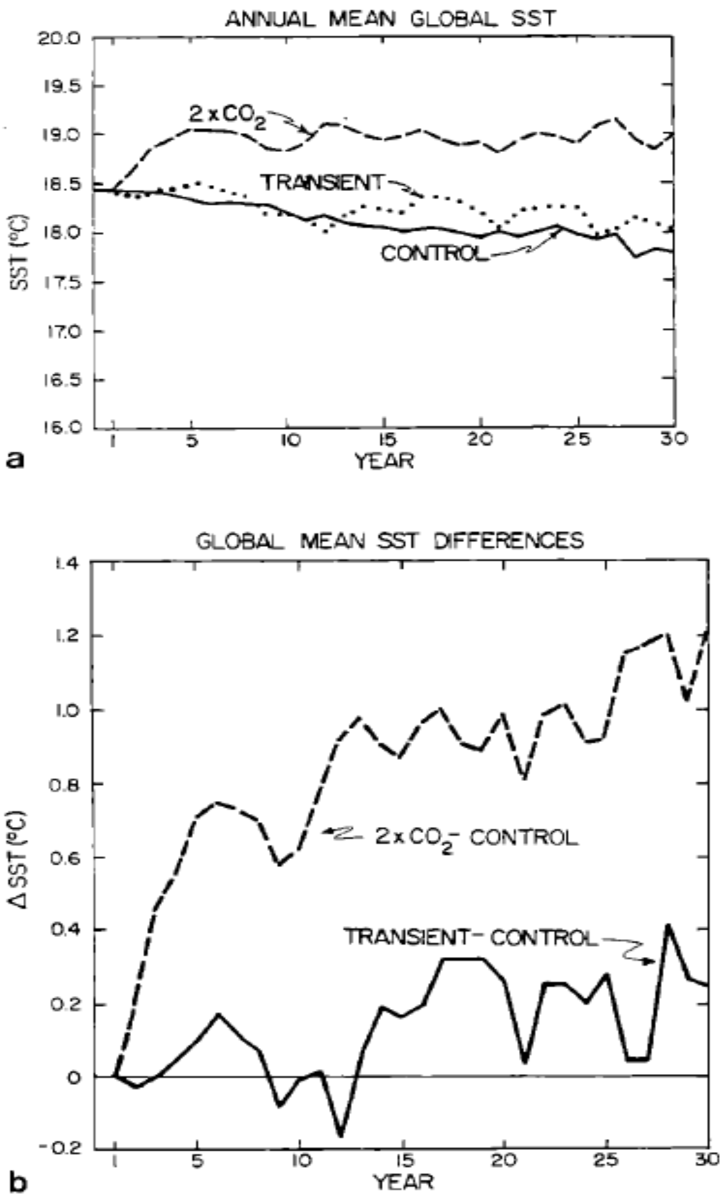



**Fig. 4.** **a** Time evolution of globally averaged ocean surface temperature (°C) for $1 \times CO_2$, $2 \times CO_2$, and transient $CO_2$ experiments; **b** time evolution of ocean surface temperature differences from part (a) (°C)

Washington and Meehl (1989).

Atm 4.5°x7.5°x9
Ocn 5°x5°x4 levels

In the control run, the global-average SST is reducing at a rate of 0.02°C/year.

If maintained, this means a 2°C SST fall in 100 year run.

# Flux Corrections or Adjustments

- Atmosphere component run with SST obs.
- Ocean component run with observed wind stress and atmosphere surface variables.
- Fluxes of heat and fresh water in these runs subtracted to form the flux corrections.
- Or coupled run with very strong relaxation back to observed SST and surface salinity.
- These corrections are totally unphysical.

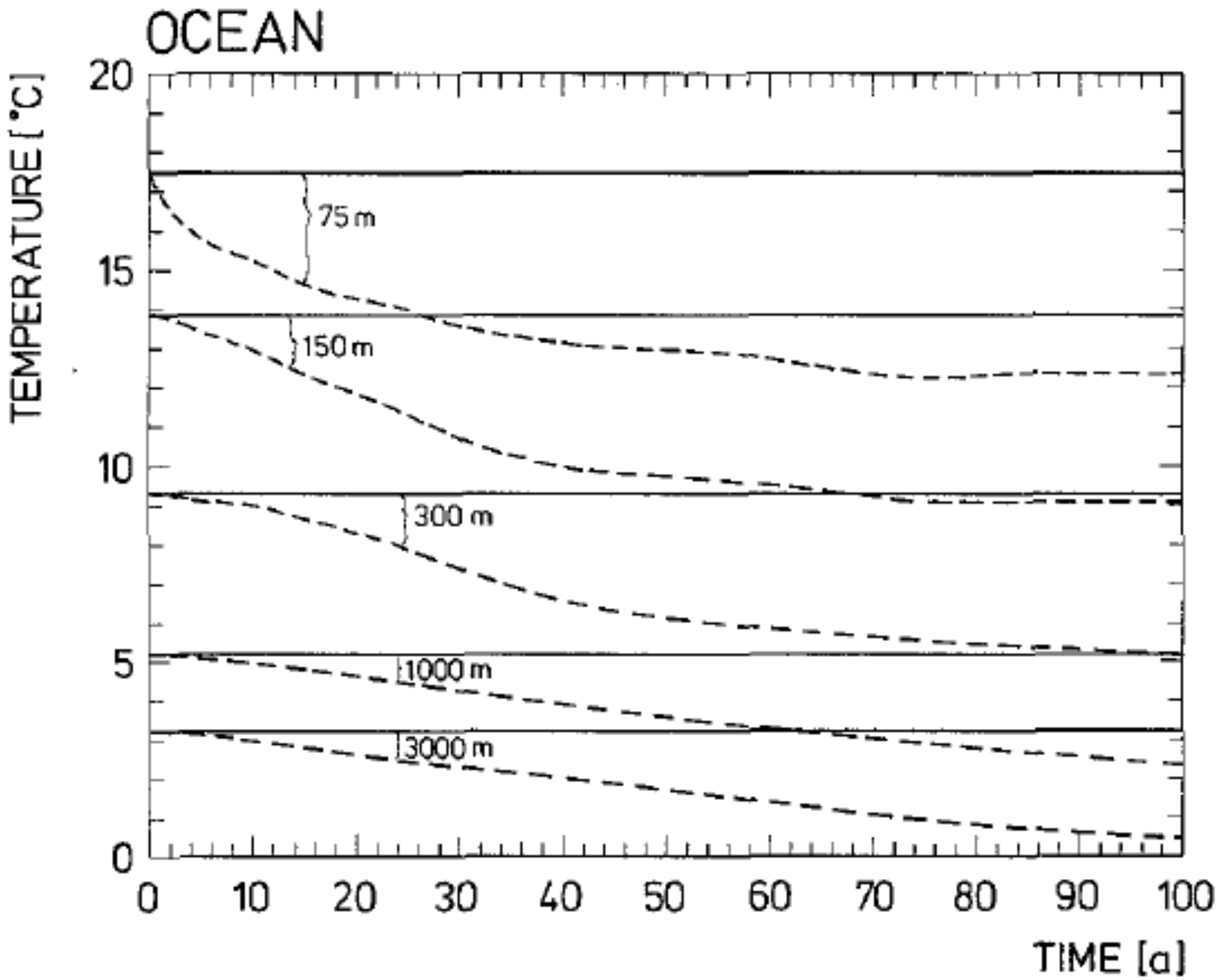



**Fig. 14.** Temporal evolution of the global mean temperatures of the ocean in the coupled model, without flux correction *(dashed line)* and with flux correction *(solid line)*

Sausen et al. (1988).

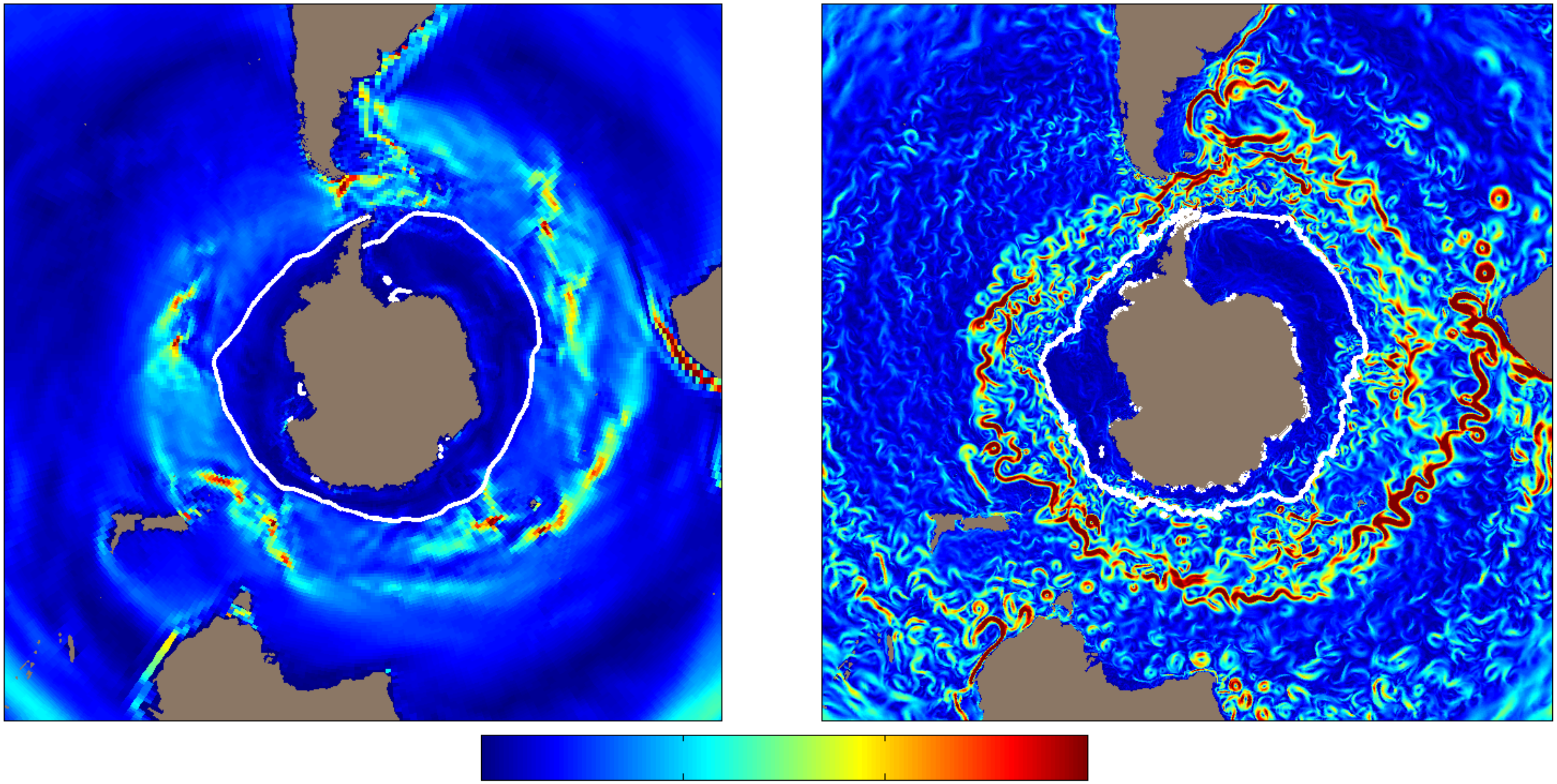
Ocean
3.5°x3.5°
x 5 levels

Diagnostic atmosphere

# *Simulated Surface Currents Around Antarctica*

1 degree Simulation

0.1 degree Simulation



0 10 20 30 40 50 60

Surface current speed in cm/s for October

# *The GM (1990) Parameterization*

$$\frac{\partial T}{\partial t} + (\underline{u} + \underline{u}^*).\underline{\nabla} T = \underline{\nabla}_\rho.(\kappa \underline{\nabla}_\rho T)$$

$$w^* = -\underline{\nabla}.(\kappa \underline{\nabla} \rho / \rho_z), \underline{\nabla}.\underline{u}^* = 0.$$

Assumes that eddies advect temperature and salinity and diffuse them along constant density surfaces. The advection represents the effects of unresolved baroclinic instability, because it ensures a global sink of mean potential energy.

$(u, v, w)$ is velocity in directions $(x, y, z)$

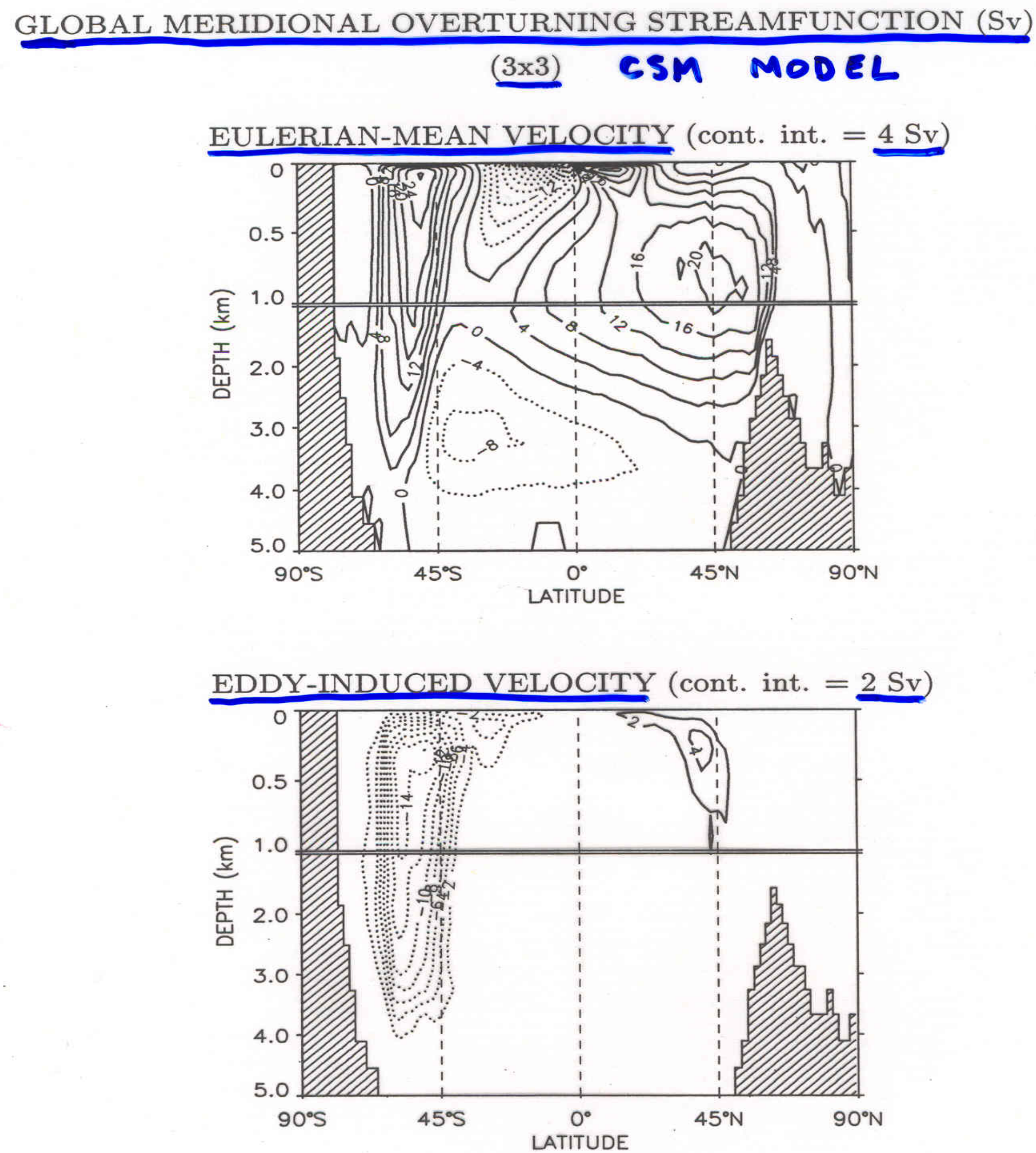
continuity equation $u_x + v_y + w_z = 0.$

Integrate over depth $\int u_x \, dz + \int v_y \, dz = 0$
form 2-D barotropic streamfunction in Sverdrups ($1 = 10^6 \, m^3/s$).

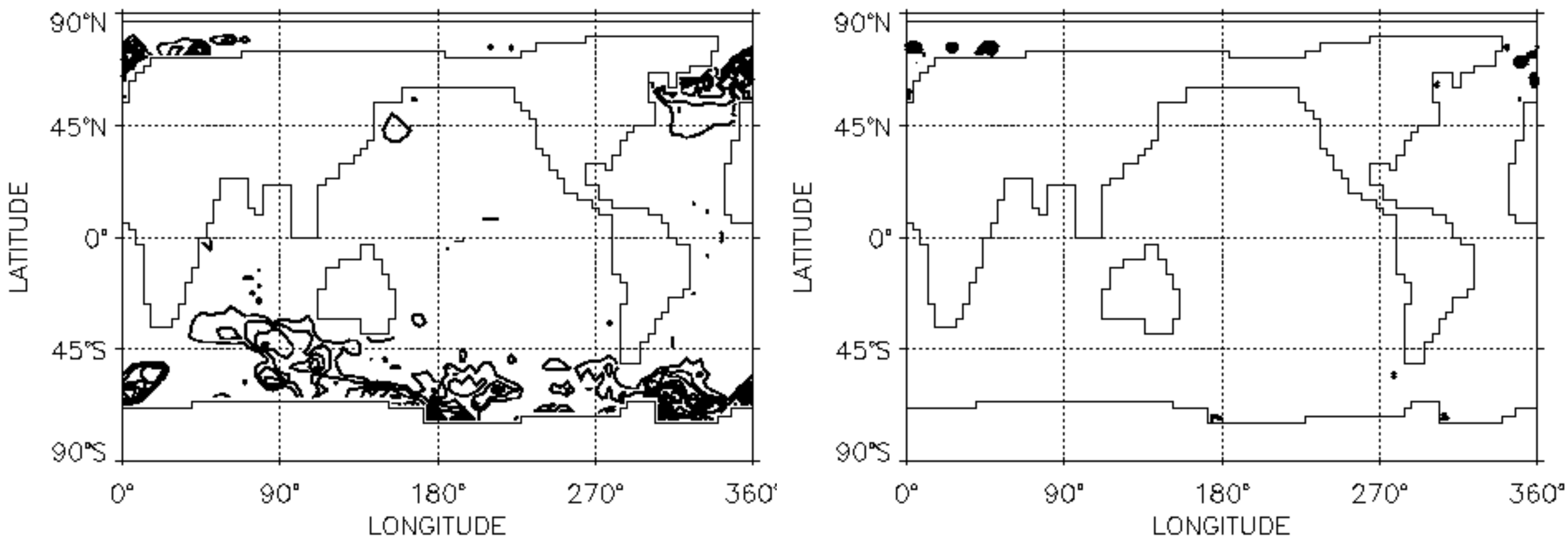
Integrate over $x$ $\int v_y \, dx + \int w_z \, dx = 0$
form 2-D overturning streamfunction.

Original GM implementation in a very low resolution $4^o \times 3^o \times 20$ levels global ocean model;

Danabasoglu et al. (1993).



# *Deep Water Formation 4°× 3°*

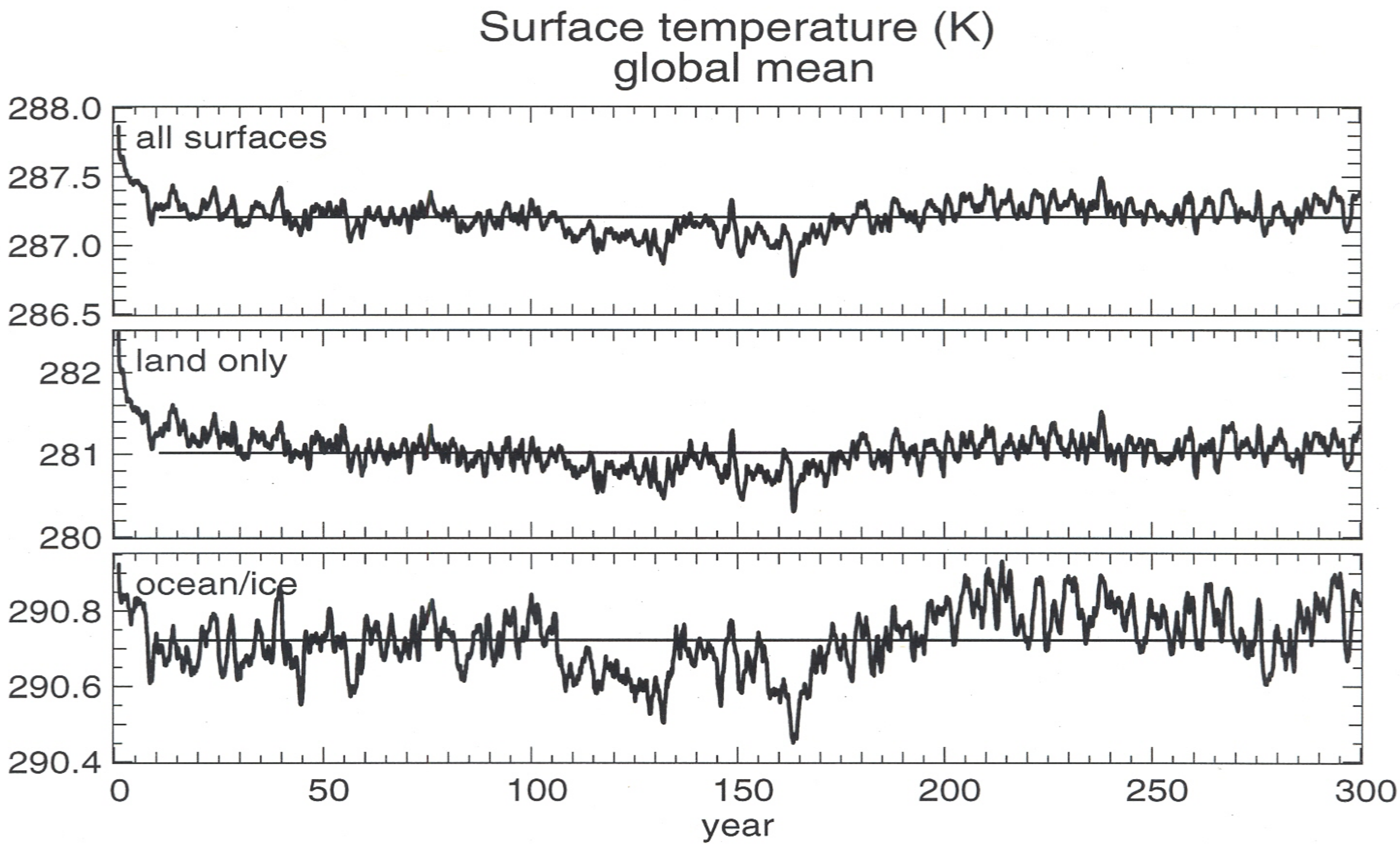



Horizontal Mixing GM 1990

Danabasoglu et al. (1993).

# CSM 1 was the first climate model to produce a non-drifting control run without “flux corrections”

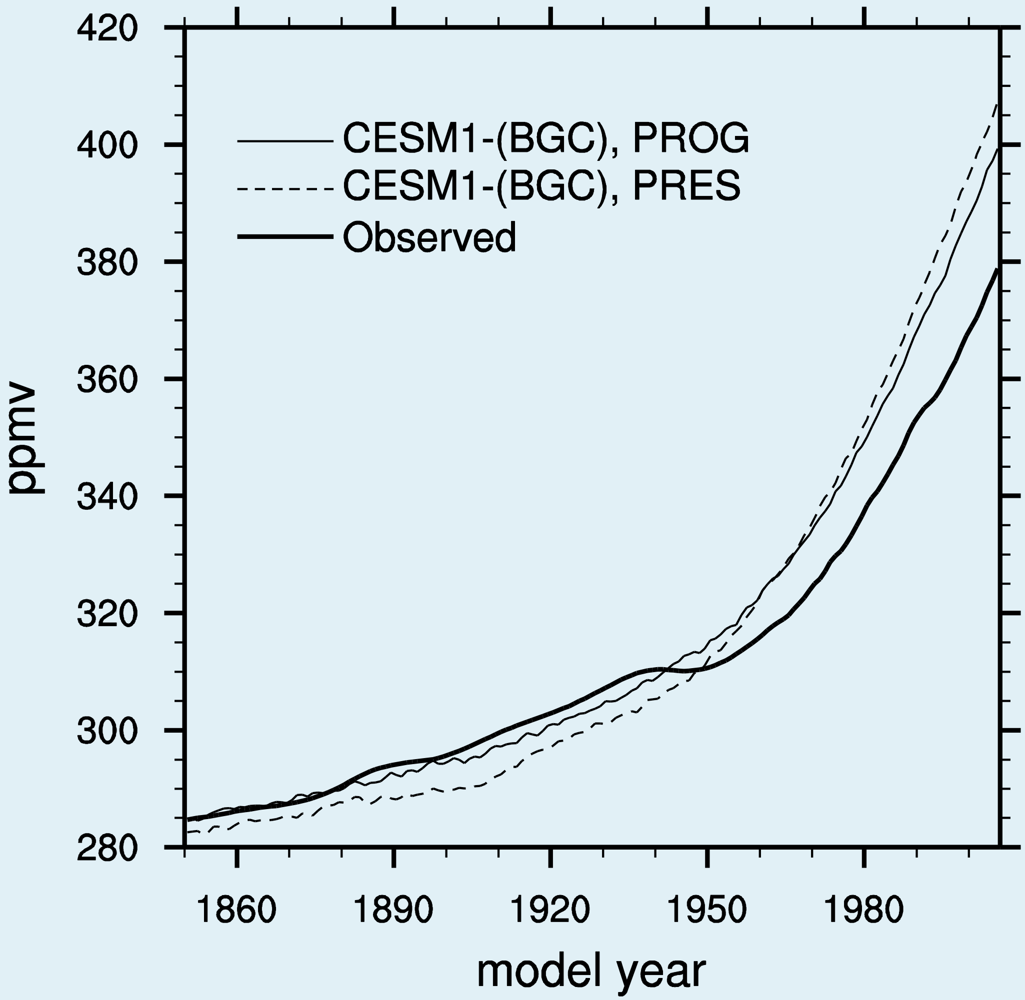
FIG 8



# *Components added to CCSM to make it into an Earth System Model (CESM)*

- **Carbon cycle components in the land, ocean & atm.**
- **A component that uses predictive chemistry.**
- **A whole atmosphere version of the atm (WACCM) that reaches up into the stratosphere and beyond.**
- **A land ice component that models the Greenland ice sheet, and will model the Antarctic ice sheet.**

# $CO_2$ in 20th Century Experiments




Modeled increase of $CO_2$ over 1850-2005 too large:

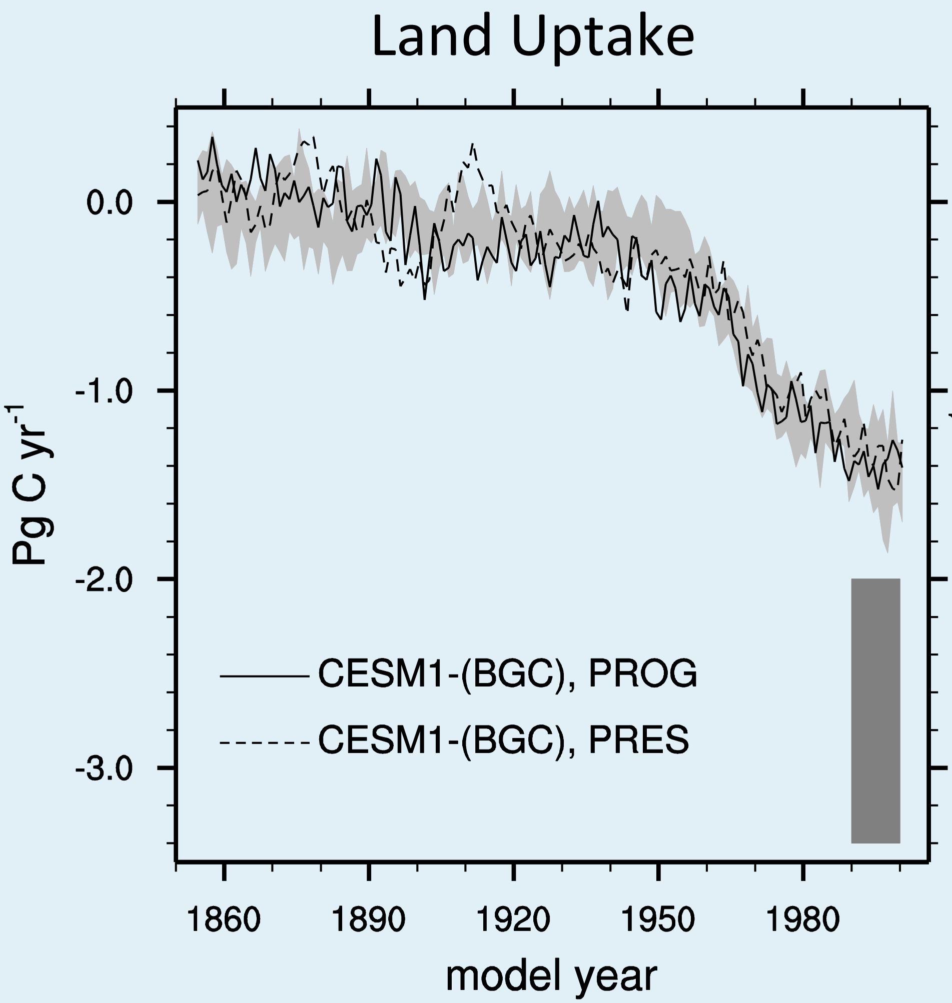
Observations: 94 ppmv

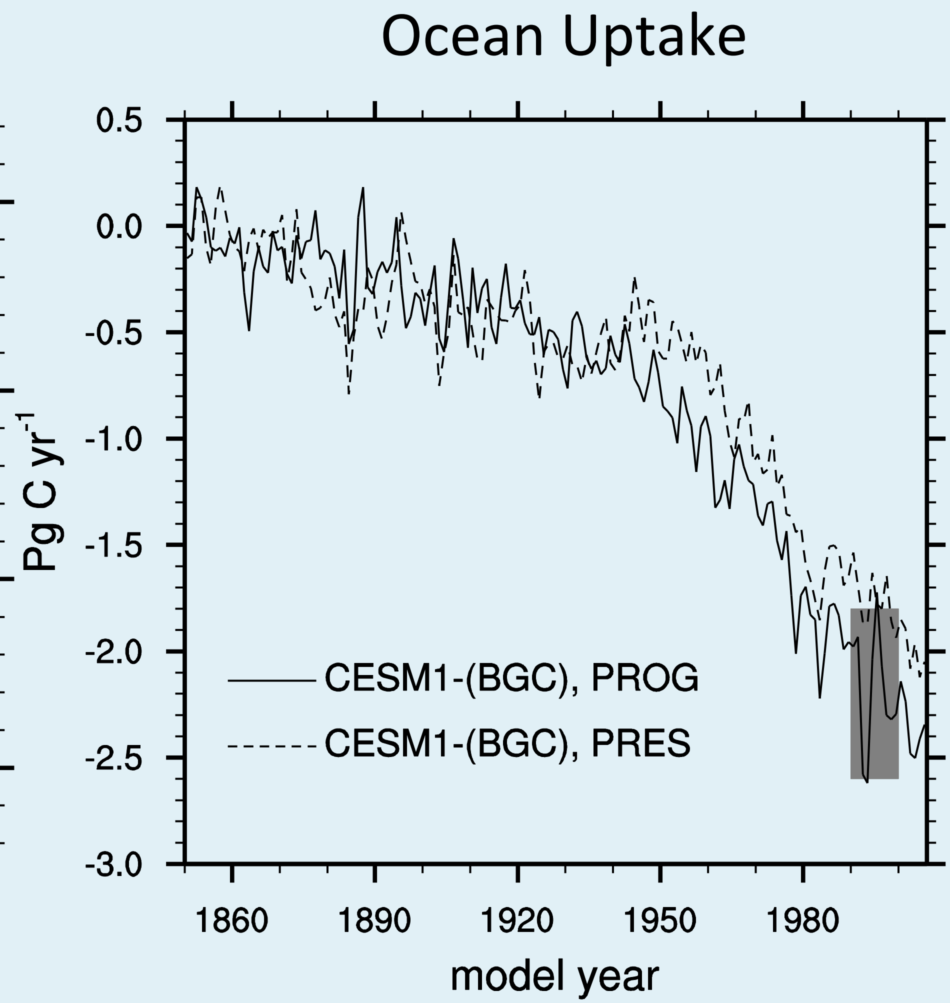
Prognostic $CO_2$: 114 ppmv

Diagnostic $CO_2$: 125 ppmv

Lindsay et al. (2013)

# 20th Century $CO_2$ Sinks from Atmosphere




Lindsay et al. (2013)

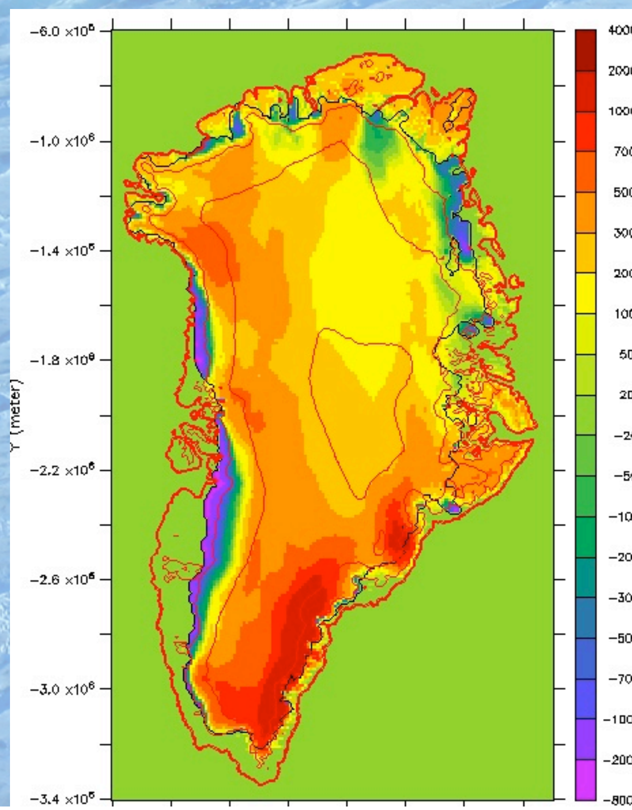
# A community ice sheet model in CESM

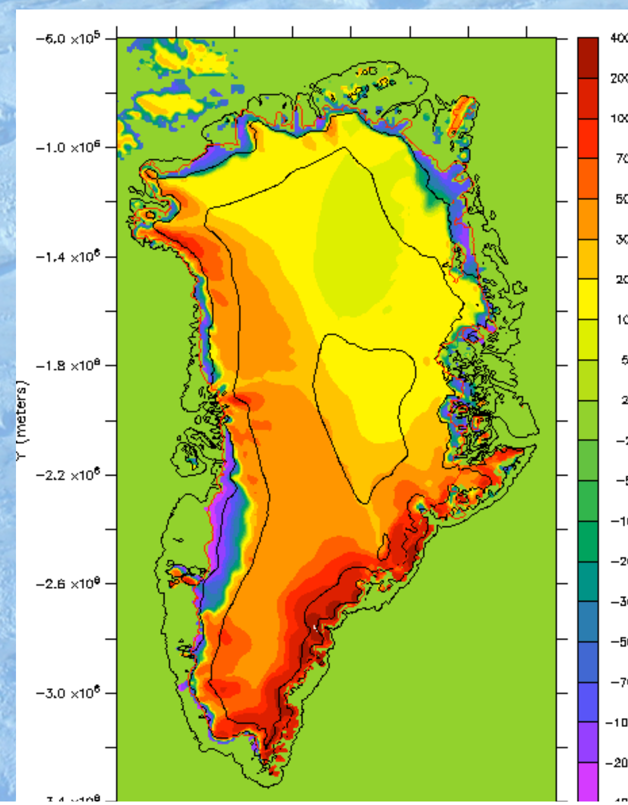
CESM1 includes Glimmer, the Community Ice Sheet Model & a new surface mass balance scheme for ice sheets in CLM.

**Left:** Greenland SMB: CLM on 1$^{o}$ grid forced by CAM output, downscaled to 10 km **Right:** Greenland SMB from a high-resolution regional climate model (Ettema et al. 2009).

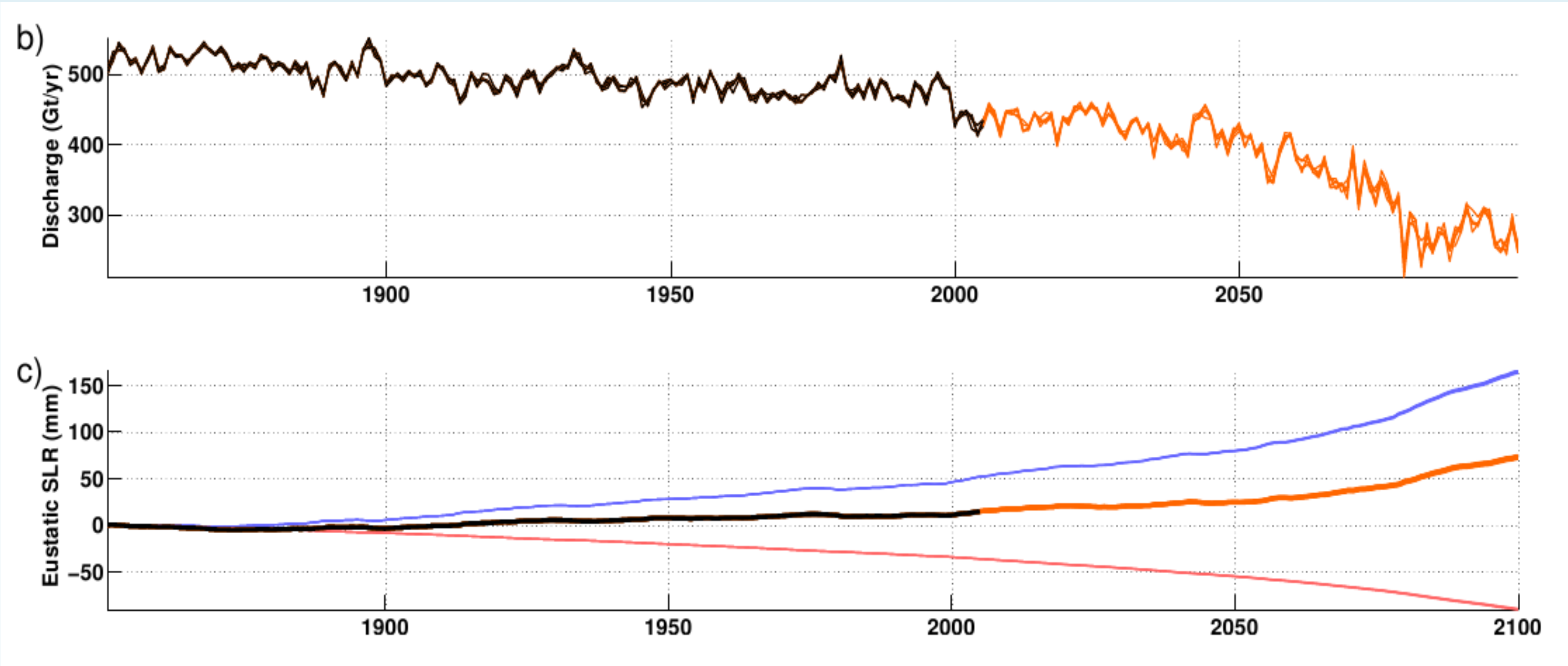
Red = net accumulation

Blue = net ablation



# Greenland ice sheet discharge and sea level rise over the 20th Century and 21st Century (RCP8.5)




c) Actual sea level rise (orange): Rise is 58mm over 2005 – 2100. Rise due to change in surface mass balance (blue): Fall due to change in Greenland ice dynamics (pink). Lipscomb et al. (2013).

# Climate Sensitivites

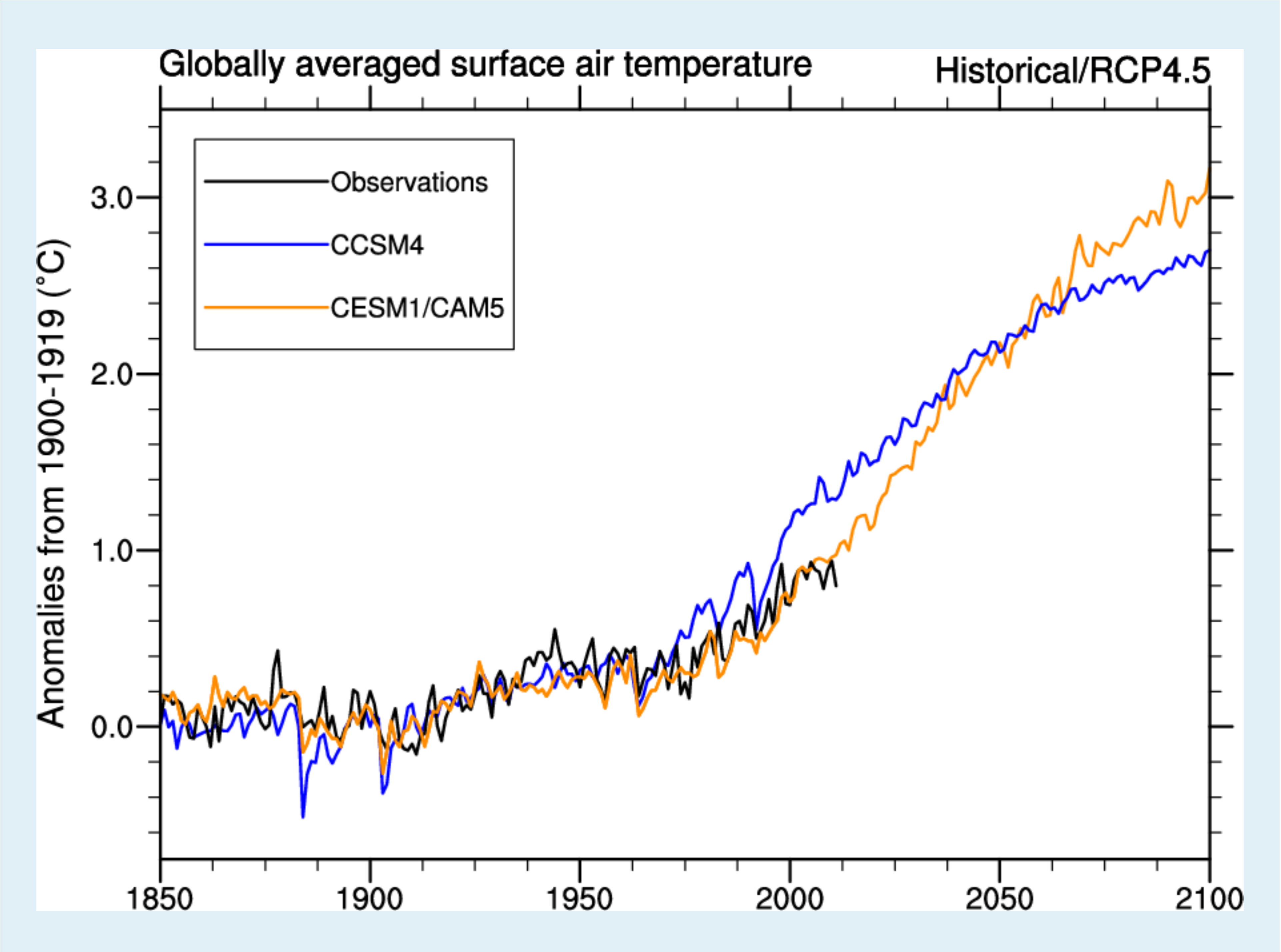
**Equilibrium**

- Globally-averaged surface temperature increase due to a doubling of $CO_2$.
- Calculated using a slab upper ocean model, so the integration comes into equilibrium in about 30 yrs.
- CCSM4 -- 3.20$^{o}$C
- CESM1 -- 4.10$^{o}$C

**Transient**

- Global surface temperature increase at doubling of $CO_2$ in a run where it increases at 1% per year: Average over years 60 -- 80.
- Calculated using the full depth ocean component.
- CCSM4 -- 1.73$^{o}$C
- CESM1 -- 2.33$^{o}$C

CESM1 includes secondary effects due to aerosols


Globally averaged surface air temperature
Historical/RCP4.5
Observations
CCSM4
CESM1/CAM5
Anomalies from 1900-1919 (°C)
3.0
2.0
1.0
0.0
1850
1900
1950
2000
2050
2100

# Decadal Forecasts with the CESM

- Fully-coupled CESM1 simulations initialized from historical ocean and sea ice states for Jan 1st of 1961, 1966, …, 2006

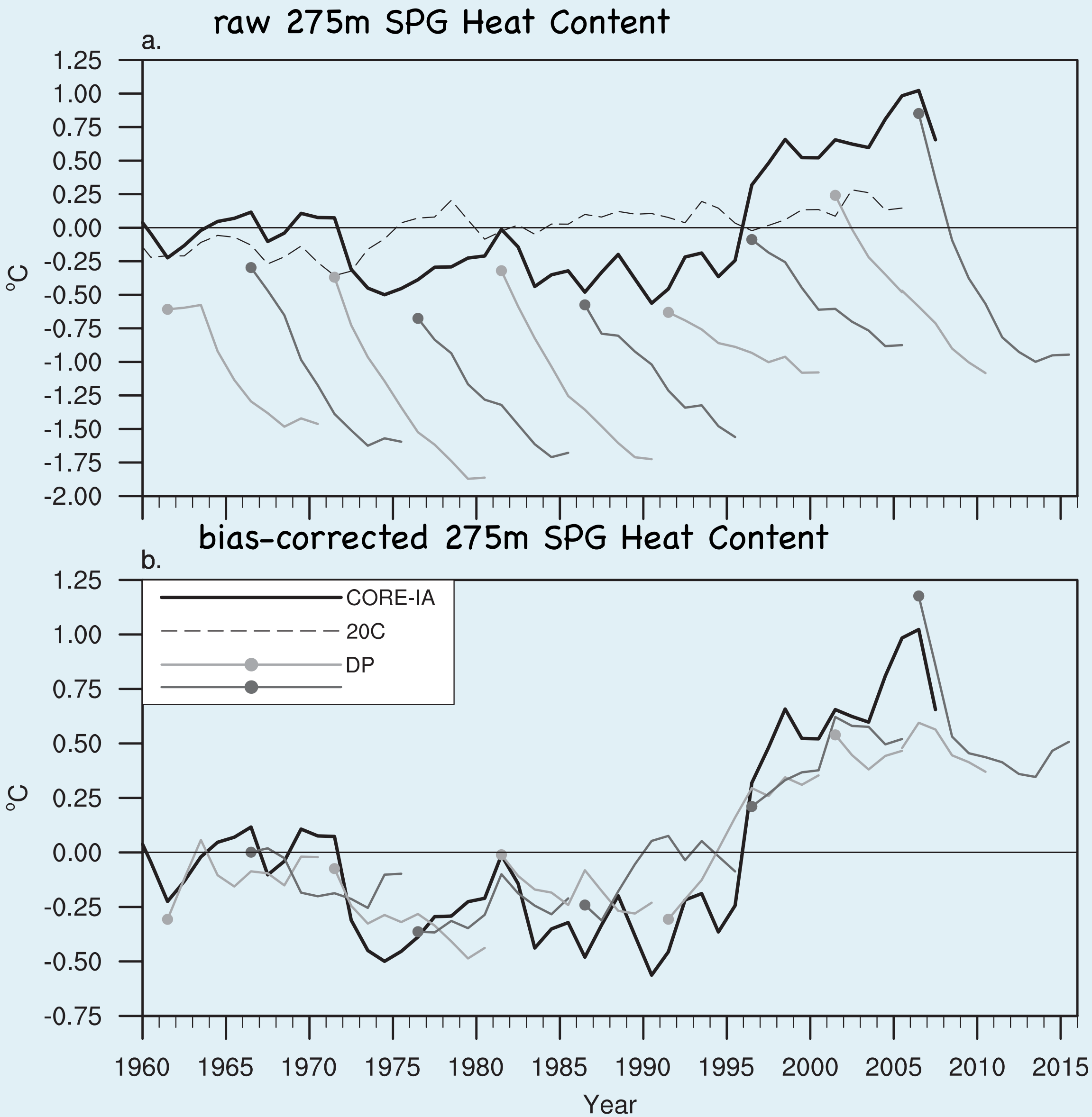
- Ocean & sea ice initial conditions from an ocean/sea-ice simulation of 1948-2007 forced by atmospheric observations.

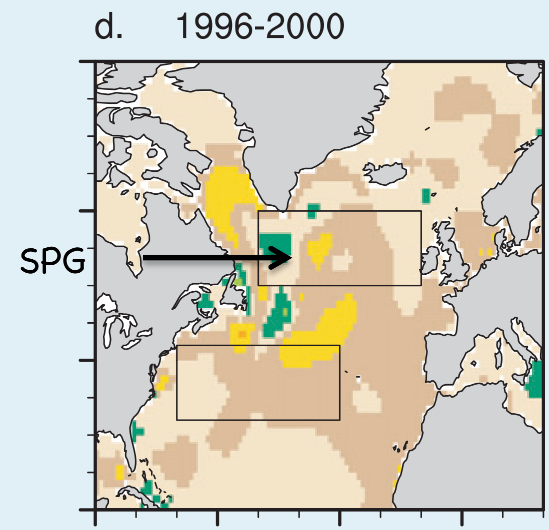
- Full-field initialization (with bias correction)

- 10-member ensembles for each of 10 start dates

- Case study of the mid-1990s warming in the subpolar gyre of the North Atlantic Ocean.

# Decadal Prediction in North Atlantic Subpolar Gyre




After bias correction, the CESM has significant skill in predicting SPG heat content & SST up to a decade in advance.

Yeager et al. (2012)

# Conclusions

- **The first coupled climate models were run in the early 1970s, and used very coarse resolution.**
- **These models had to use flux corrections in order to maintain the present climate in coupled runs.**
- **The CSM1 (run in 1996) was the first to maintain the present ocean temperatures in a coupled run.**
- **Earth System Models have interactive components for the carbon cycle, and possibly others, such as Chemistry, high-top Atmosphere and Land Ice.**