Is CO_2 Earth's temperature knob? (Yes, err...probably)

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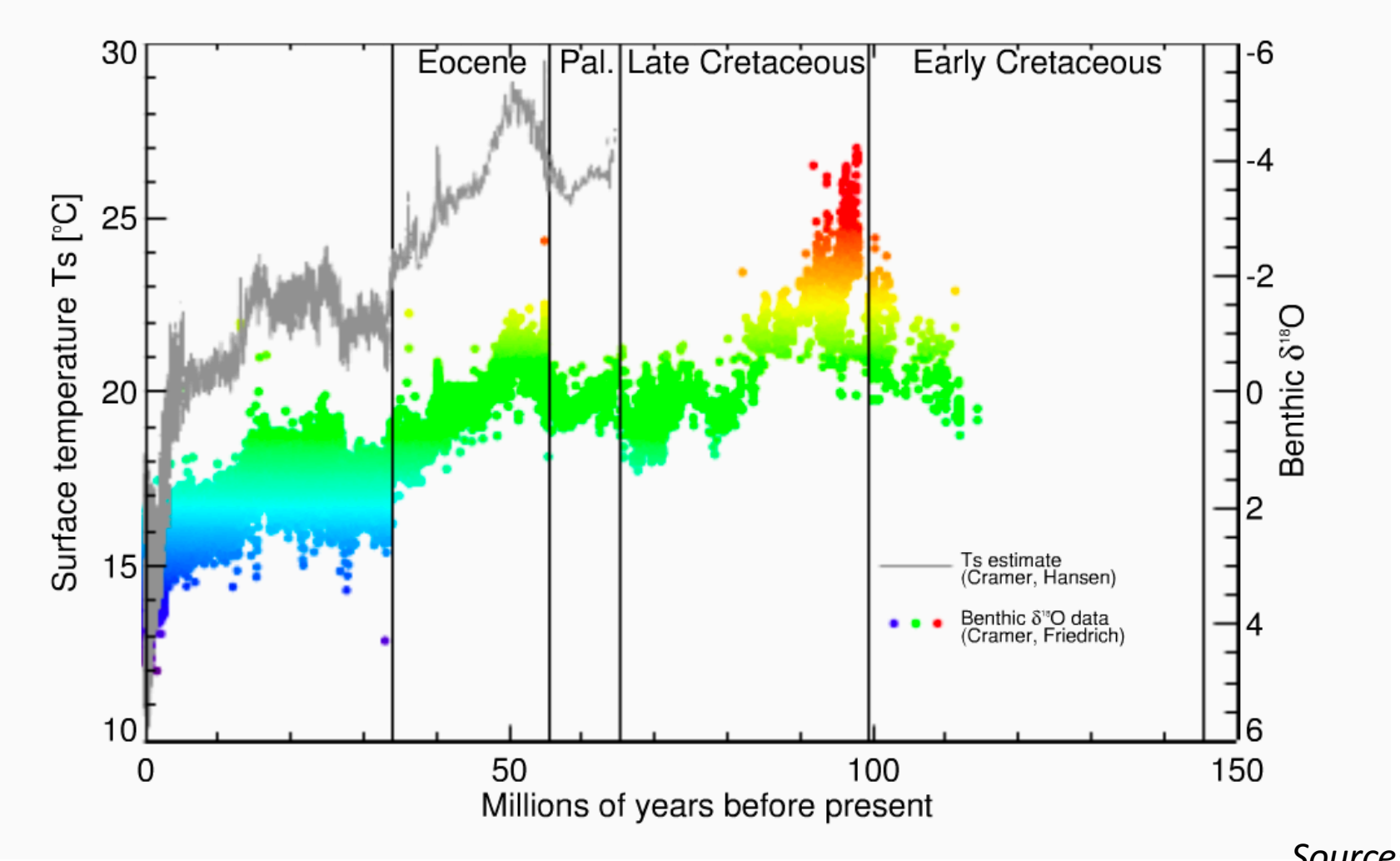
Collaborators: Jiang Zhou

Acknowledgement: Heising-Simons Foundation & National Science Foundation

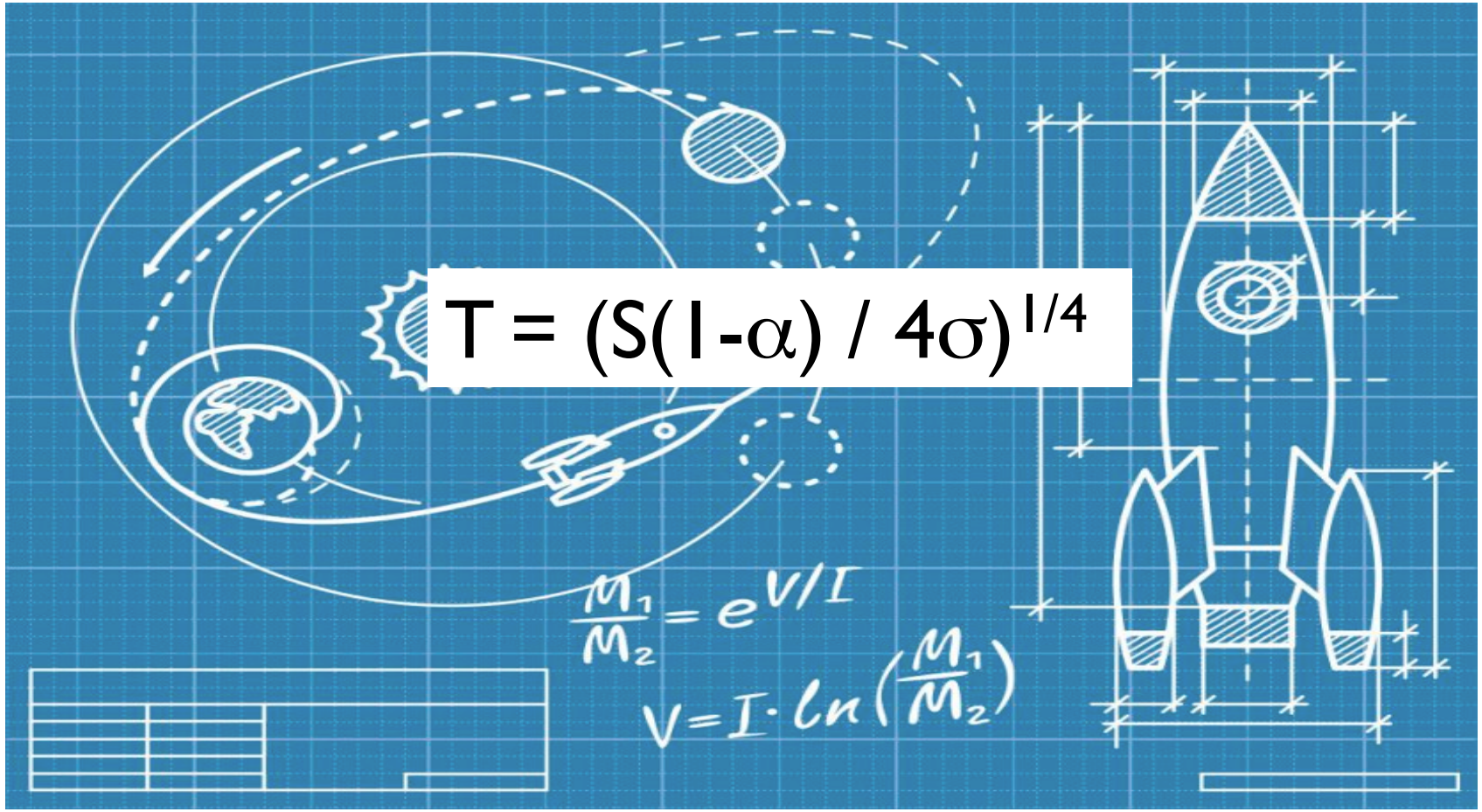
Earth's temperature history

What is the primary control on Earth's global temperature?



Sources: Lunt et al., 2016

Energy balance problem



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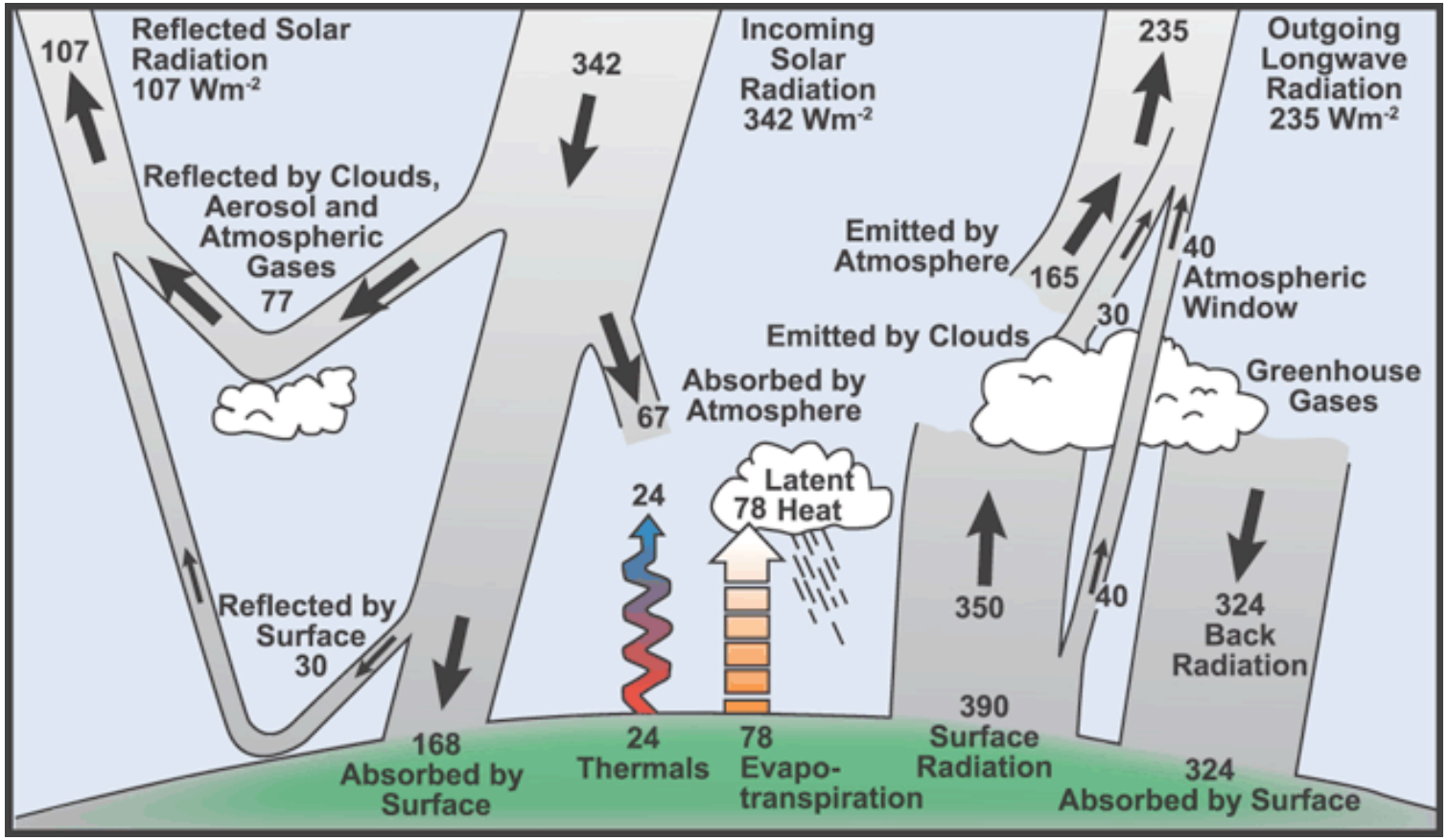

Long-term forcings and feedbacks

- **Forcings**
  - Paleogeography (continental distribution, sea level, elevation/bathymetry)
  - Land surface (vegetation)
  - Solar luminosity
  - Greenhouse gas (CO_2, CH_4, NO_2, etc.)
  - Non-greenhouse gas (N_2, O_2)
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  - Clouds and aerosols
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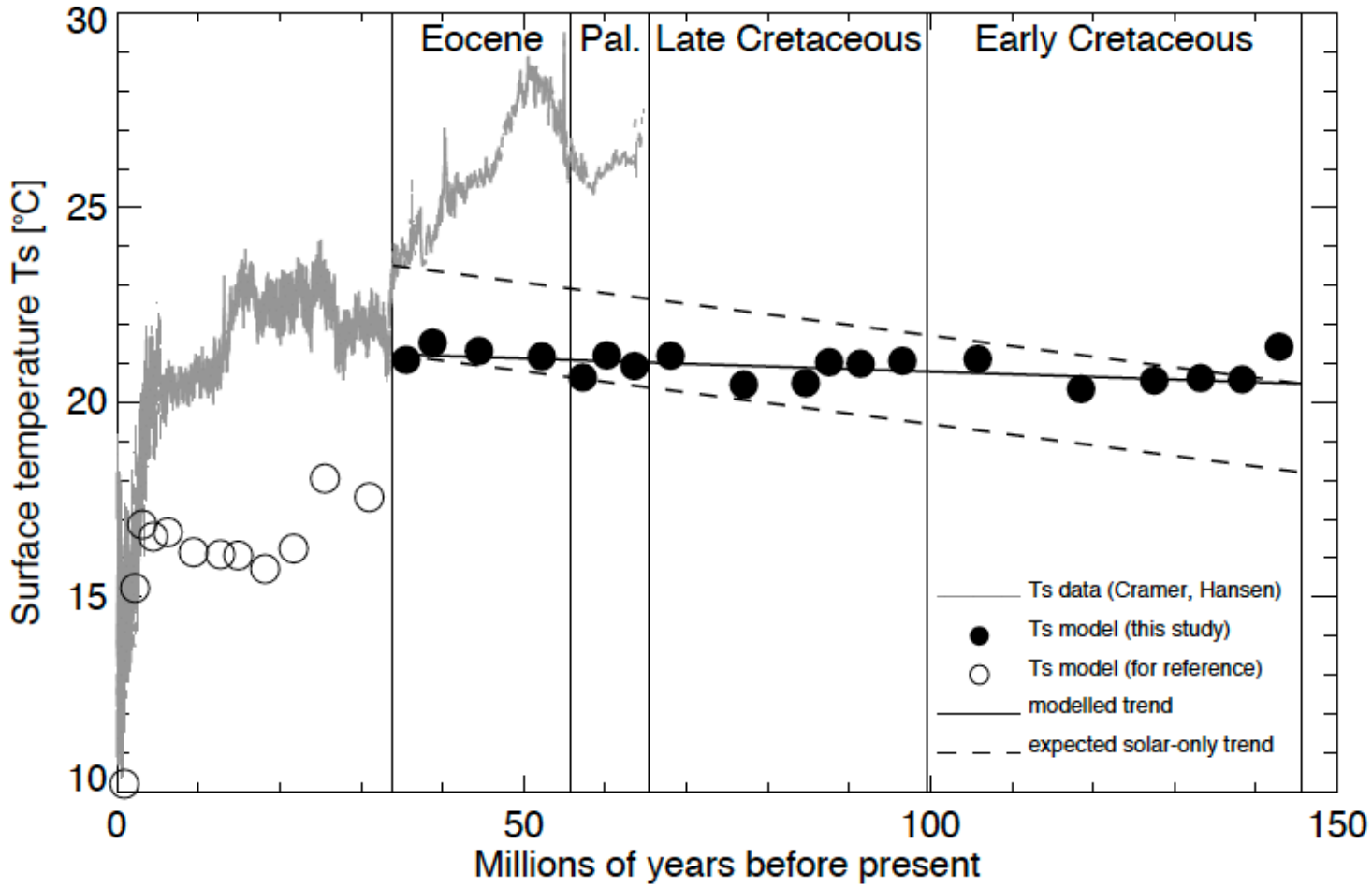
Response to geography, solar luminosity

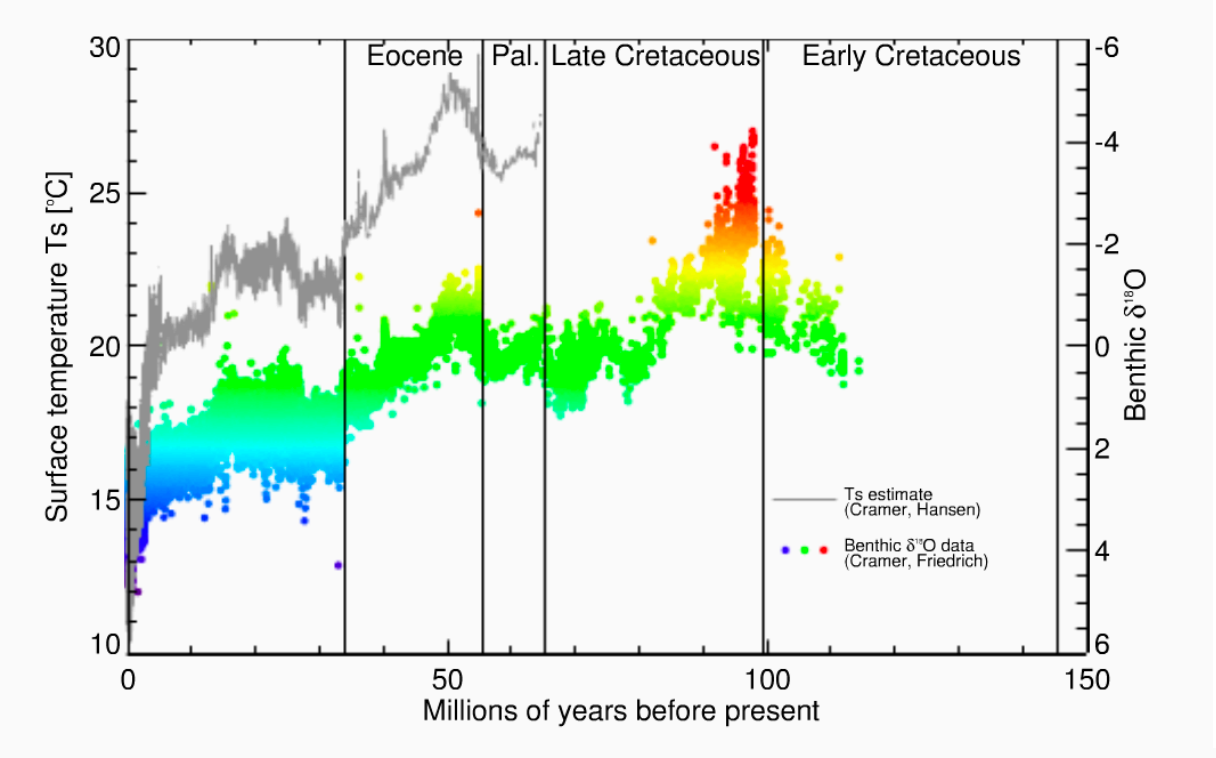
HadCM3L simulations w/constant CO_2

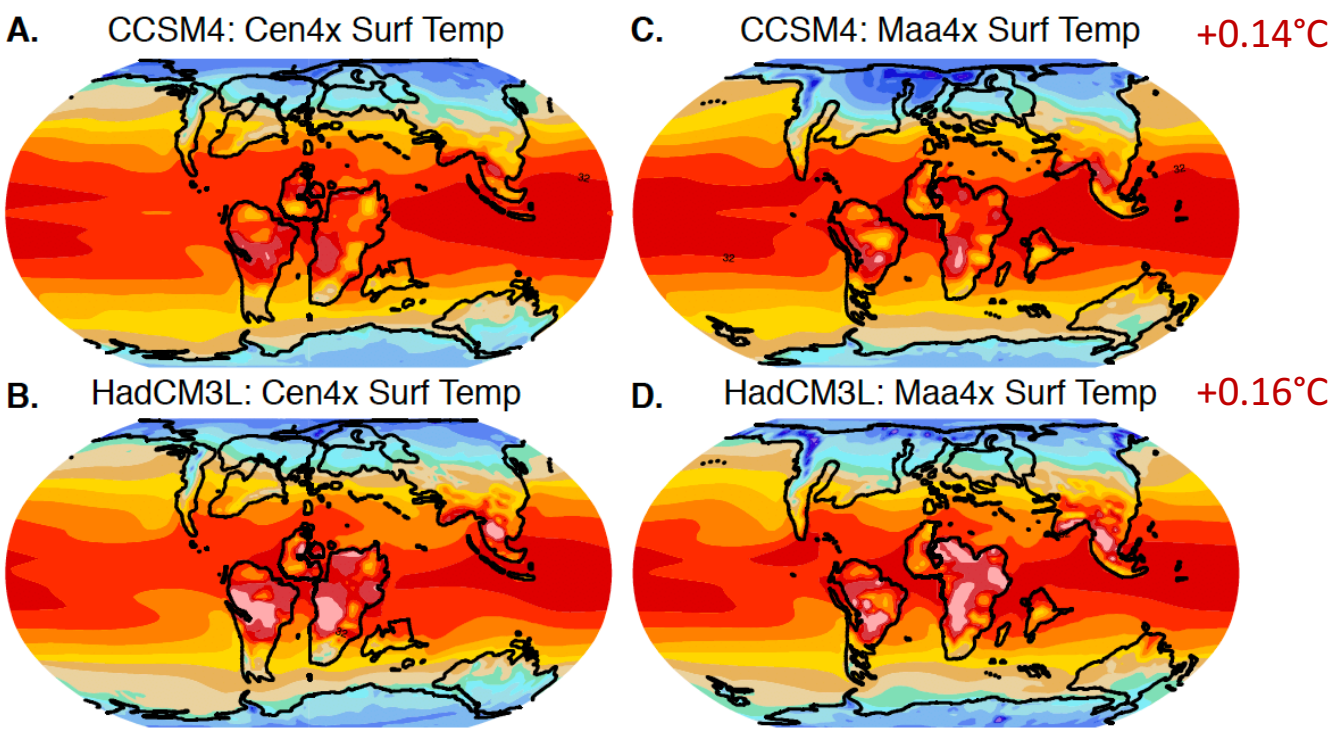


Source: Lunt et al., 2016

Response to geography, solar luminosity, land surface

CCSM4, HadCM3L simulations w/constant CO_2

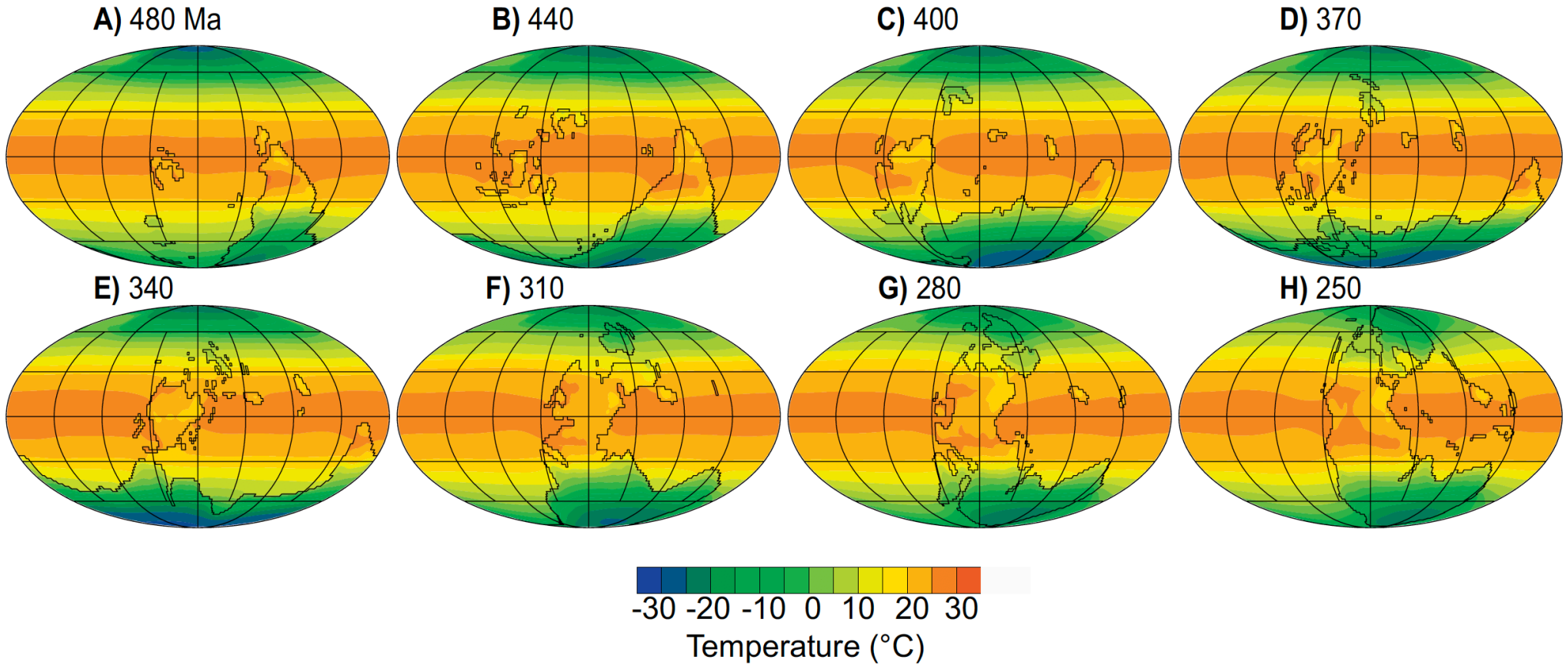




Source: Tabor et al., 2016

Response to geography, solar luminosity, land surface

GENESIS (SOM) simulations w/constant CO_2



Source: Lowry et al., 2016

Response to geography, solar luminosity, land surface

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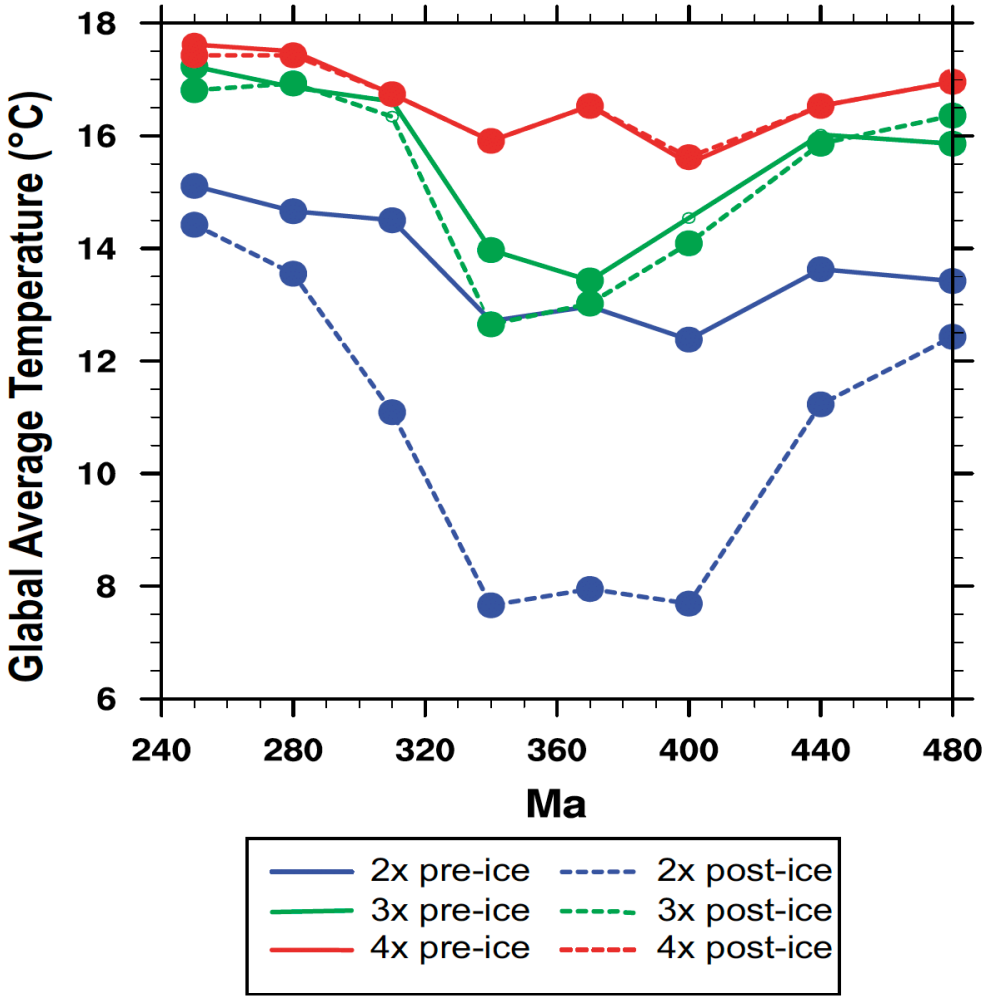

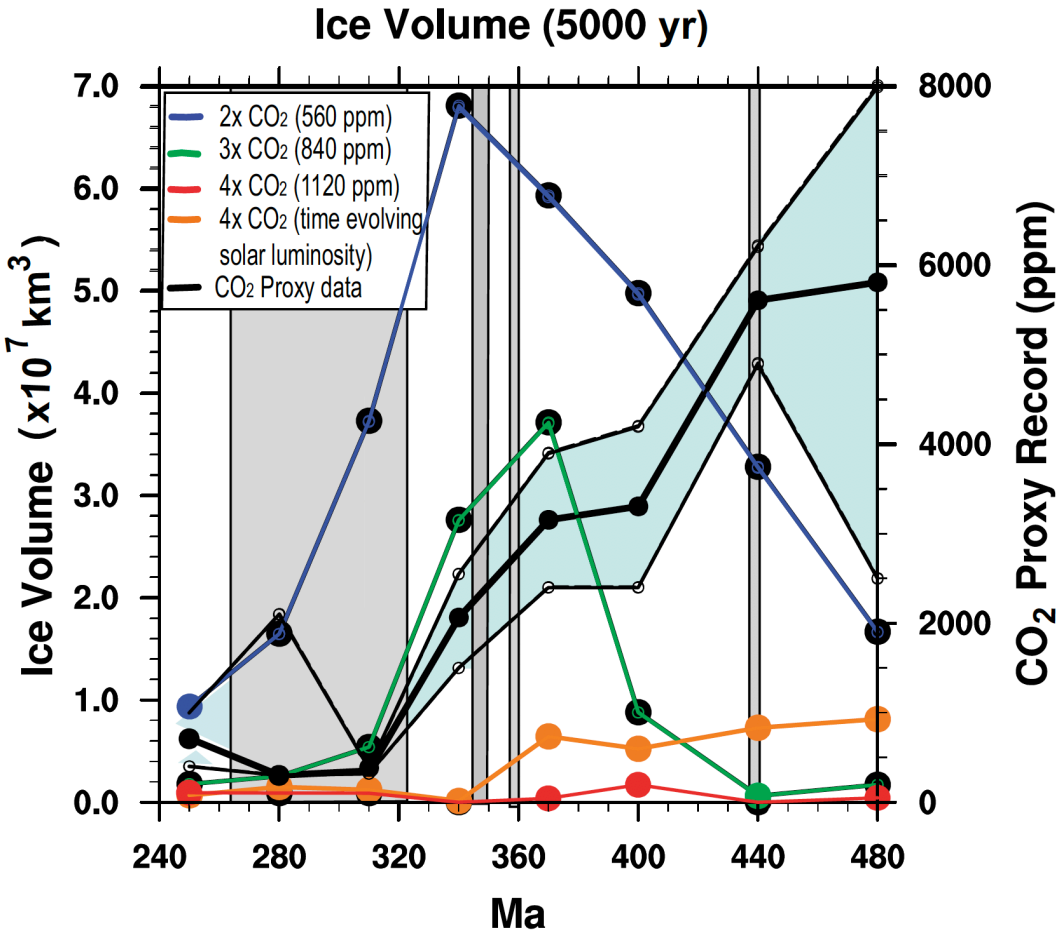

Source: Lowry et al., 2016

Forcings and feedbacks

- **Long-term forcings**
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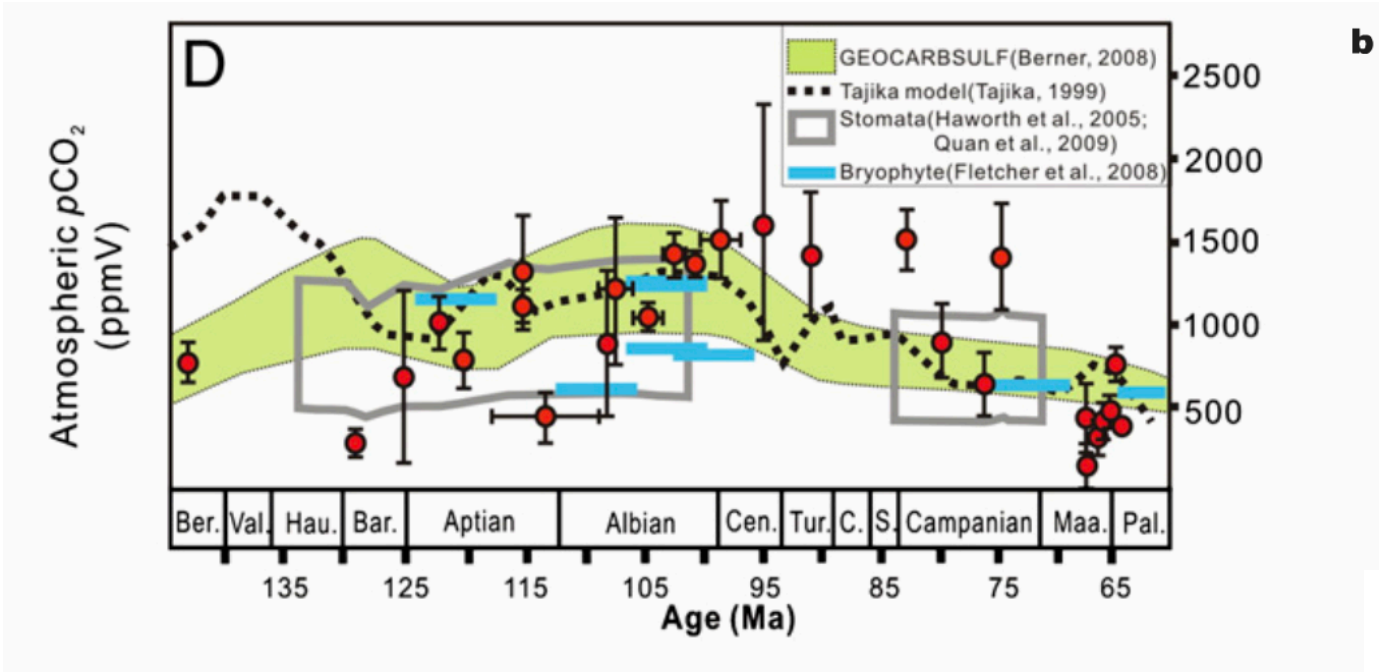
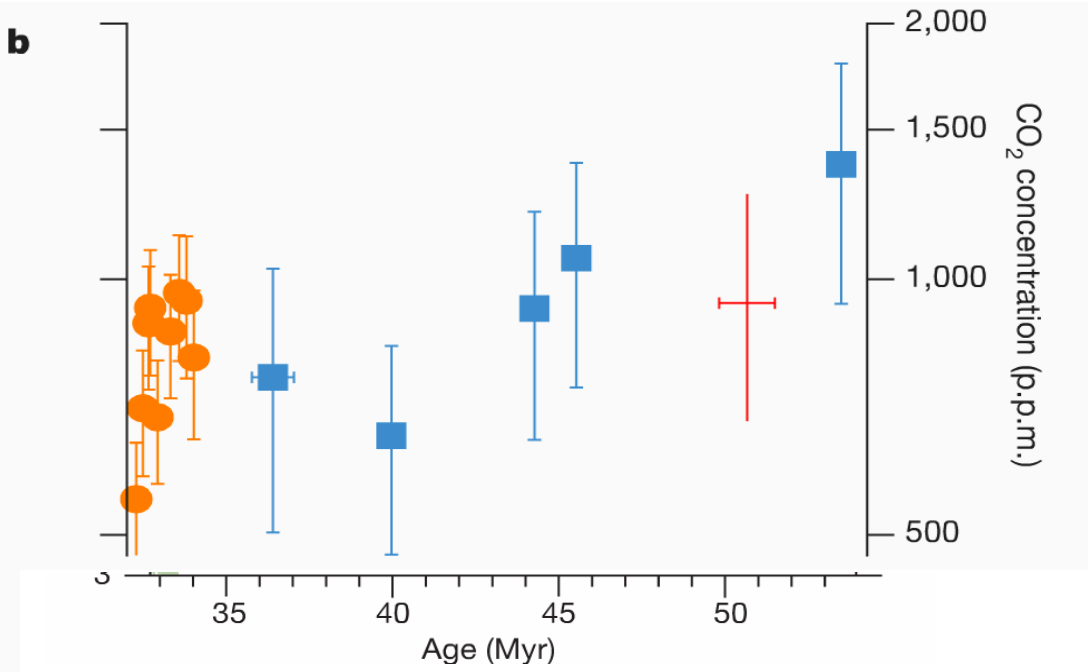
Warm climate problem

Elevating CO_2 in models doesn't produce warming sufficient to reproduce Eocene and Cretaceous climate proxy temperatures.

Eocene and Cretaceous climates are thought to be 15-30 °C warmer than modern with CO_2 levels of 3-6 x pre-industrial, implying an ESS of 6-20 °C/CO_2 doubling.





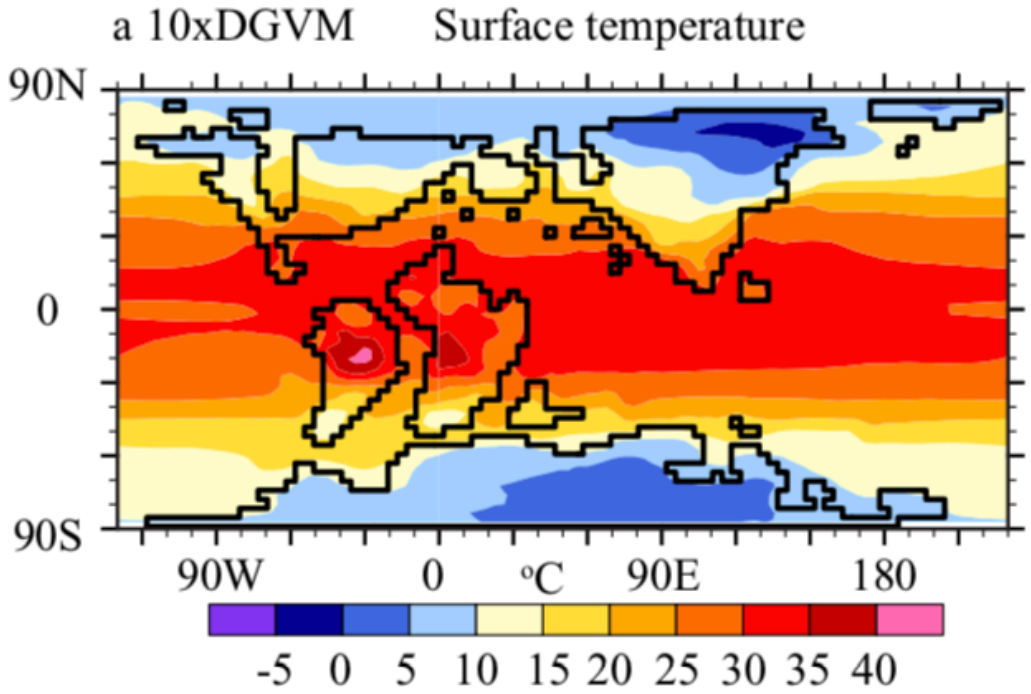
Sources: Anagnostou et al., 2016; Hong and Lee, 2012

Warm climate problem– Cretaceous

ESS: 3-4.5 C/CO_2 doubling
Slow feedbacks + solar forcing: +0.1C
Vegetation: +0.9C
CO_2: +>10 C

NCAR CCSM3 mid-Cretaceous simulation

	1xv	10xn	10xv	16xv
Global MAT (°C)	13.6	23.1	24.0	25.6
Low-latitude (30°S–30°N) MAT (°C)	23.6	30.7	31.0	32.7
Arctic (70°–90°N) SST (°C)	−1.4	6.3	8.4	9.5
Global ocean temperature (°C)	1.9	7.1	7.8	9.0
ESS (K/CO_2 doubling)			4.6	3.0

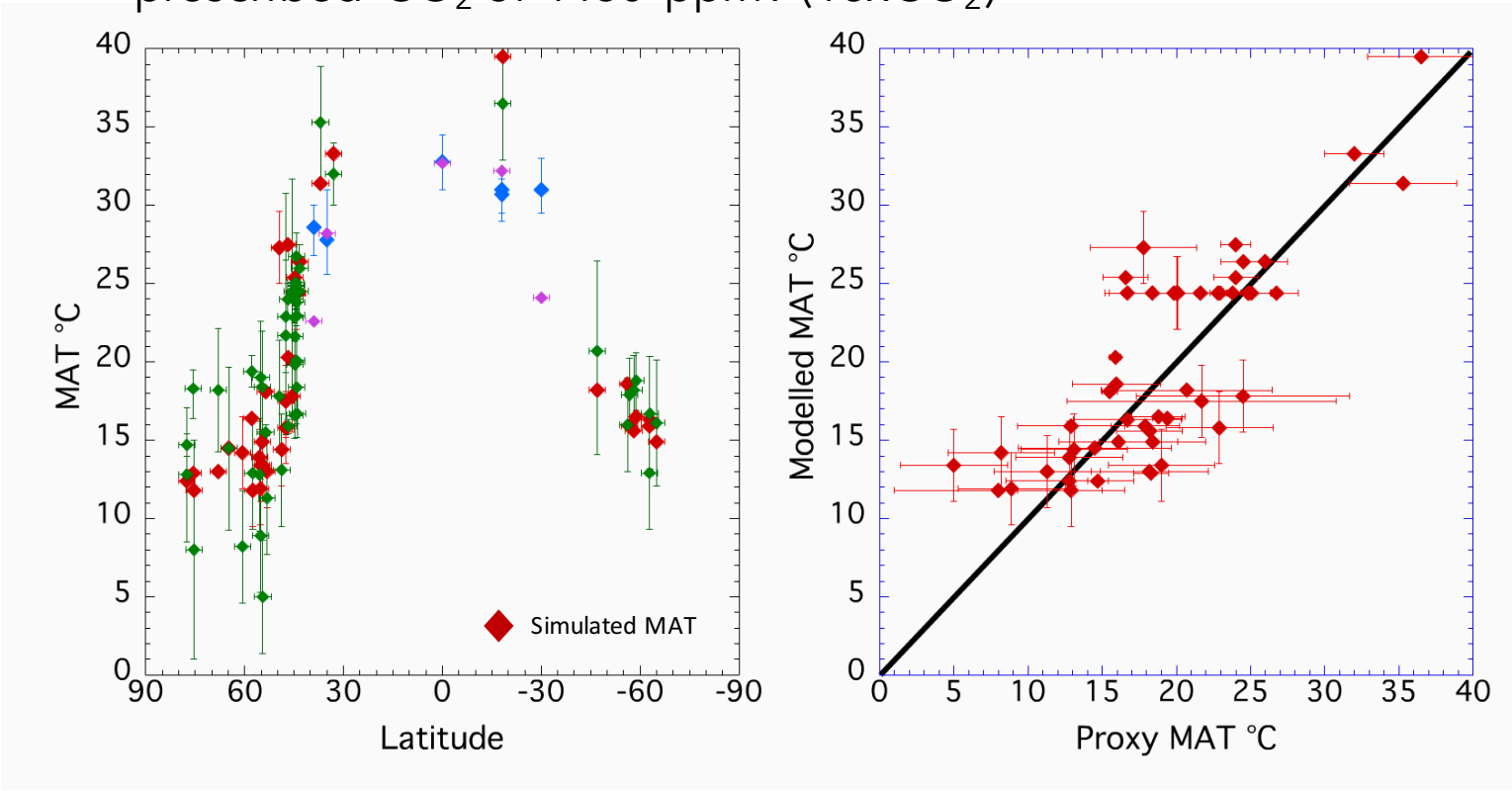


Source: Poulsen and Zhou, 2013

Warm climate problem– Eocene

ESS: ~4 C/CO_2 doubling
Vegetation: +2C
Continental ice: <1 C
Aersols: +2C
CO_2: +10C

Proxy-model comparison with Eocene CCSM3 and prescribed CO_2 of 4480 ppmv (16xCO_2)



Source: Huber and Caballero, 2011

Warm climate problem— ESS is too low?

- **Missing/incorrect physics**
  - Ocean heat transport (Barron et al., 1995)
  - Tropical cyclone-induced ocean mixing (Korty et al., 2008)
  - High-latitude convection and clouds (Sloan and Pollard, 1998; Abbot and Tziperman, 2008, Sagoo et al., 2013)
- **Missing forcings**
  - High CO_2 (Huber and Cabarello, 2011; Zhou et al., 2012)
  - Non-CO_2 GHGs, methane hydrates (Beerling et al., 2011; Bice and Marotzke, 2002)
  - Altered aerosol and cloud properties (Kump and Pollard, 2008; Kiehl and Shields, 2013)
  - Oxygen radiative forcing (Poulsen et al., 2015)

Equilibrium climate sensitivity (ECS)

Equilibrated change in global mean near-surface air temperature with a doubling of CO_2. AR5 assessed climate sensitivity to be 1.5-4.5 °C.

$$\Delta T = \Delta R_{2x} \lambda$$

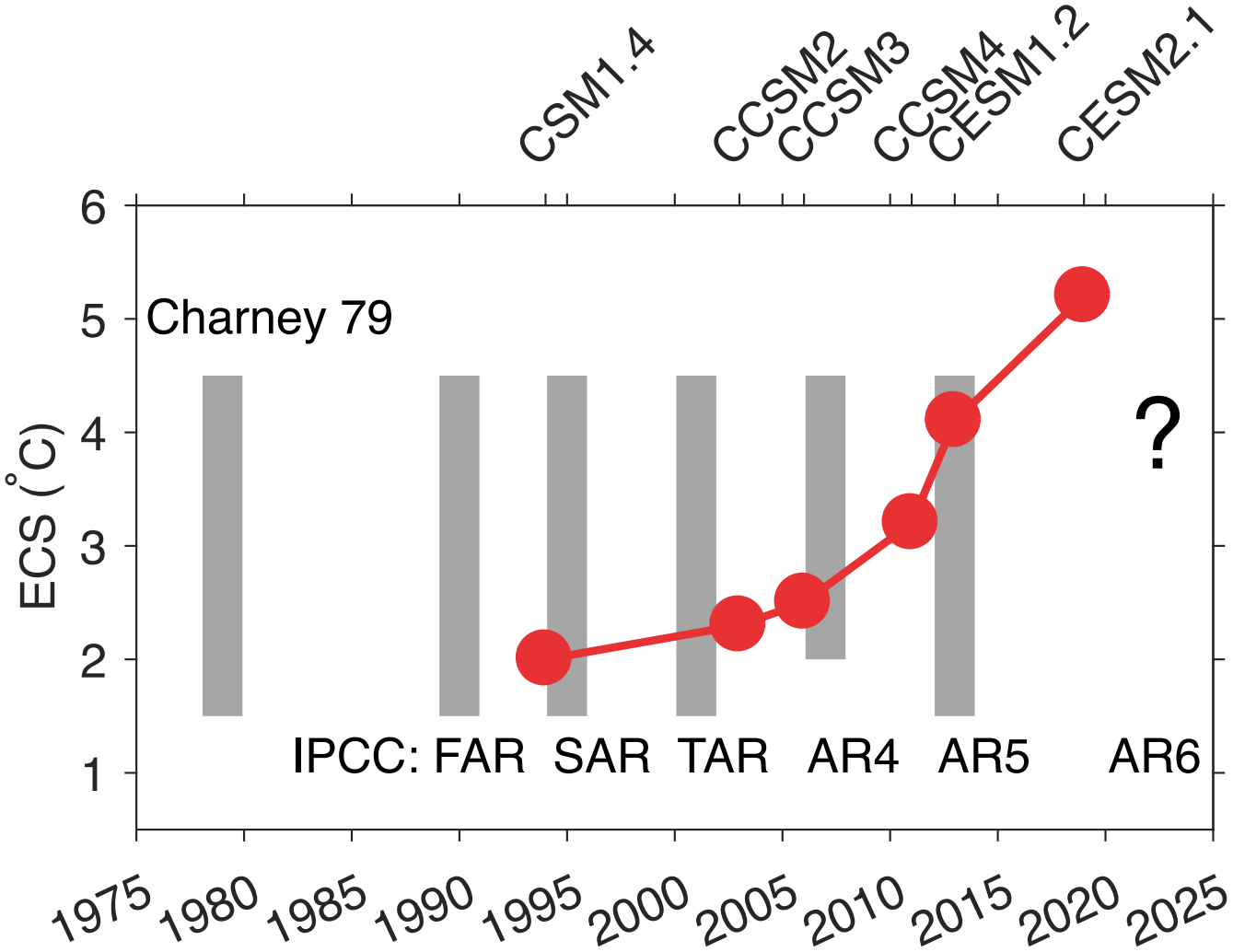
$$\lambda_{fast} = \lambda_{water\ vapor} + \lambda_{Planck} + \lambda_{lapse\ rate} + \lambda_{cloud} + \lambda_{albedo}$$

How well do we know ECS?

From “New climate models forecast a warming surge” in *Science* April 19, 2019:

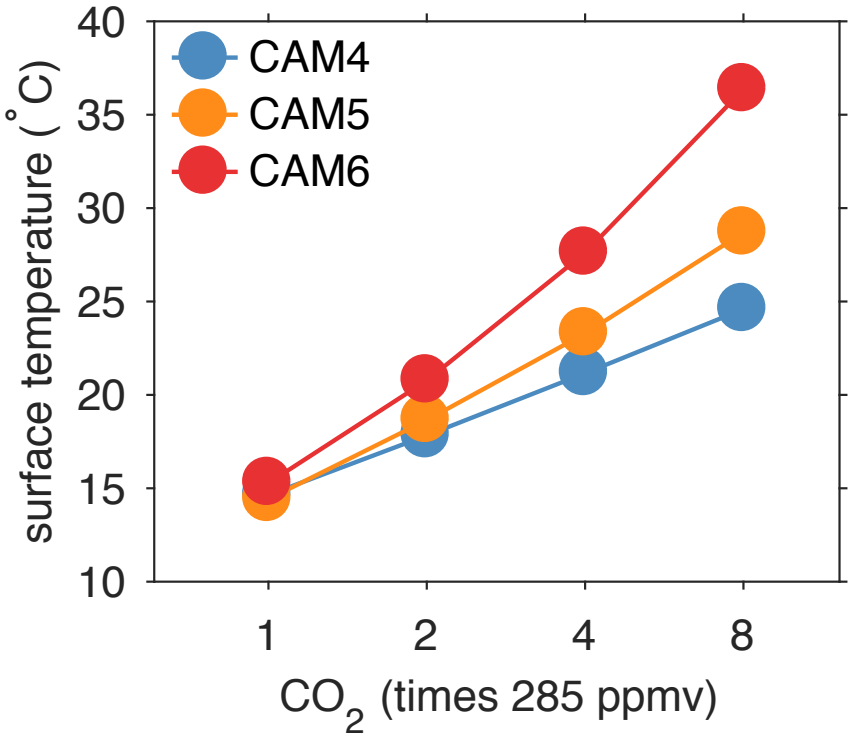
In earlier models, doubling atmospheric carbon dioxide (CO_2) over preindustrial levels led models to predict somewhere between 2°C and 4.5°C of warming once the planet came into balance. But in at least eight of the next-generation models, produced by leading centers in the United States, the United Kingdom, Canada, and France, that “equilibrium climate sensitivity” has come in at 5°C or warmer. Modelers are struggling to identify which of their refinements explain this heightened sensitivity before the next assessment from the United Nations's Intergovernmental Panel on Climate Change (IPCC). But the trend “is definitely real. There's no question,” says Reto Knutti, a climate scientist at ETH Zurich in Switzerland. “Is that realistic or not? At this point, we don't know.”

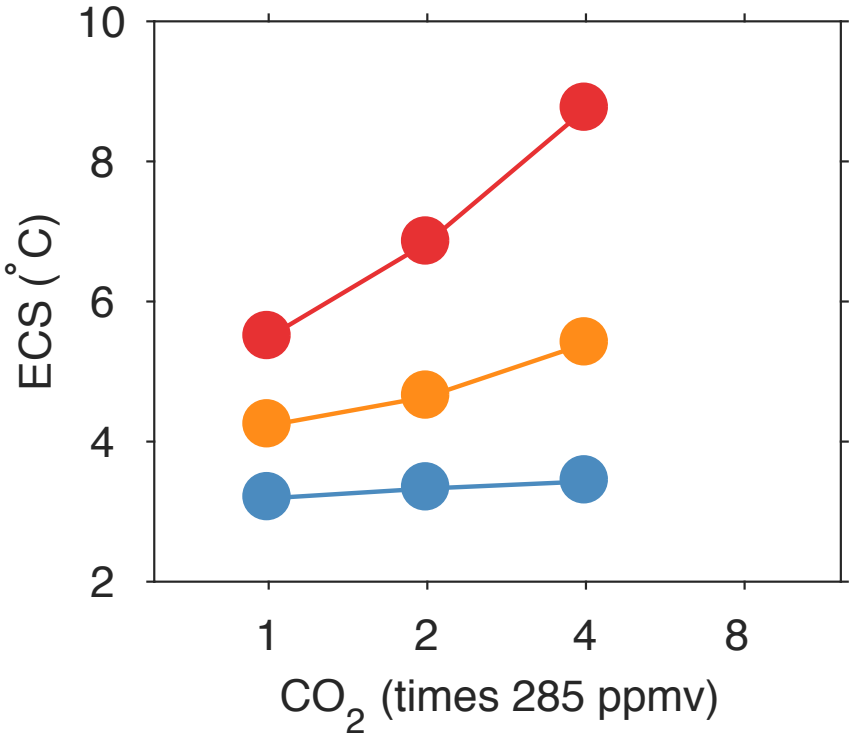
Evolving ECSs



ECS is state dependent

ECS increases with CO_2

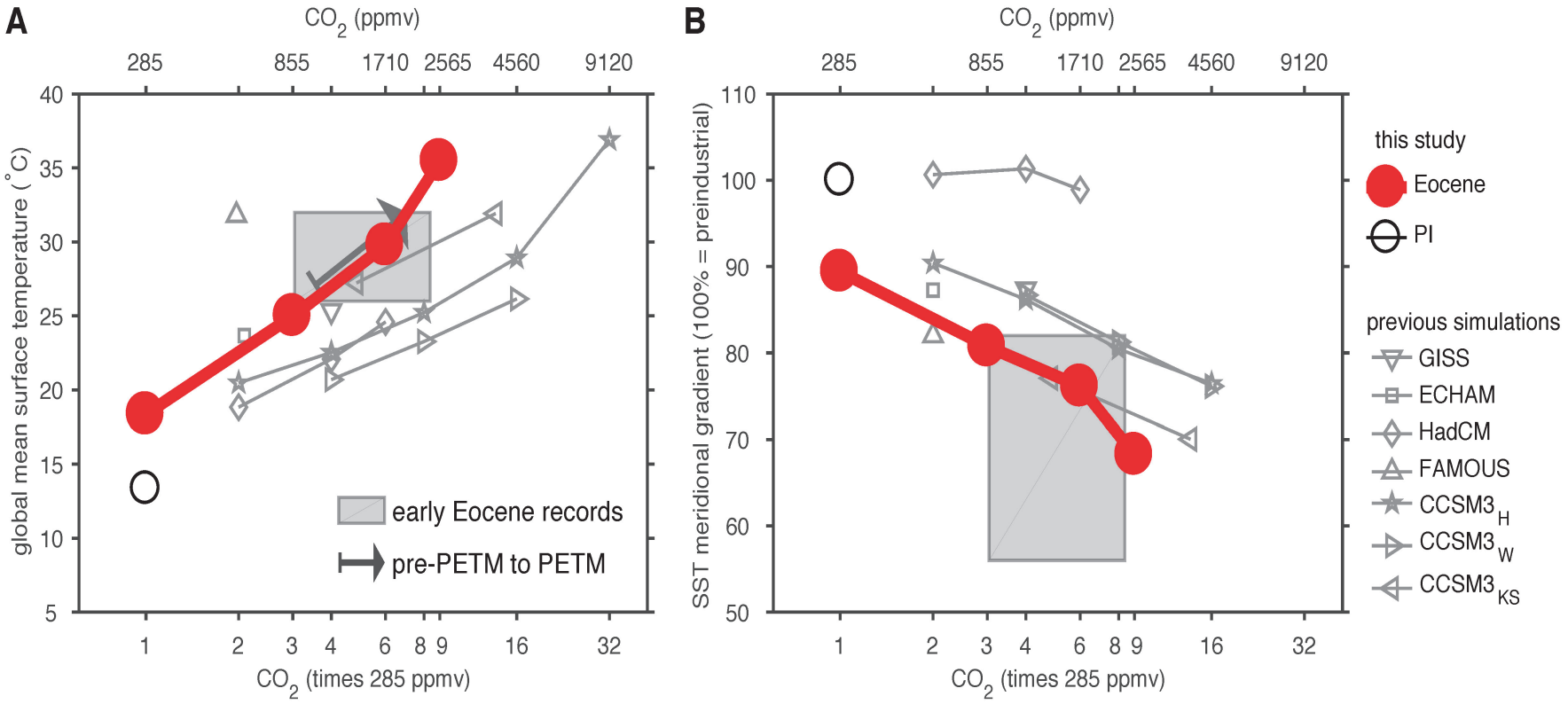




Source: J. Zhu

High Eocene ECS

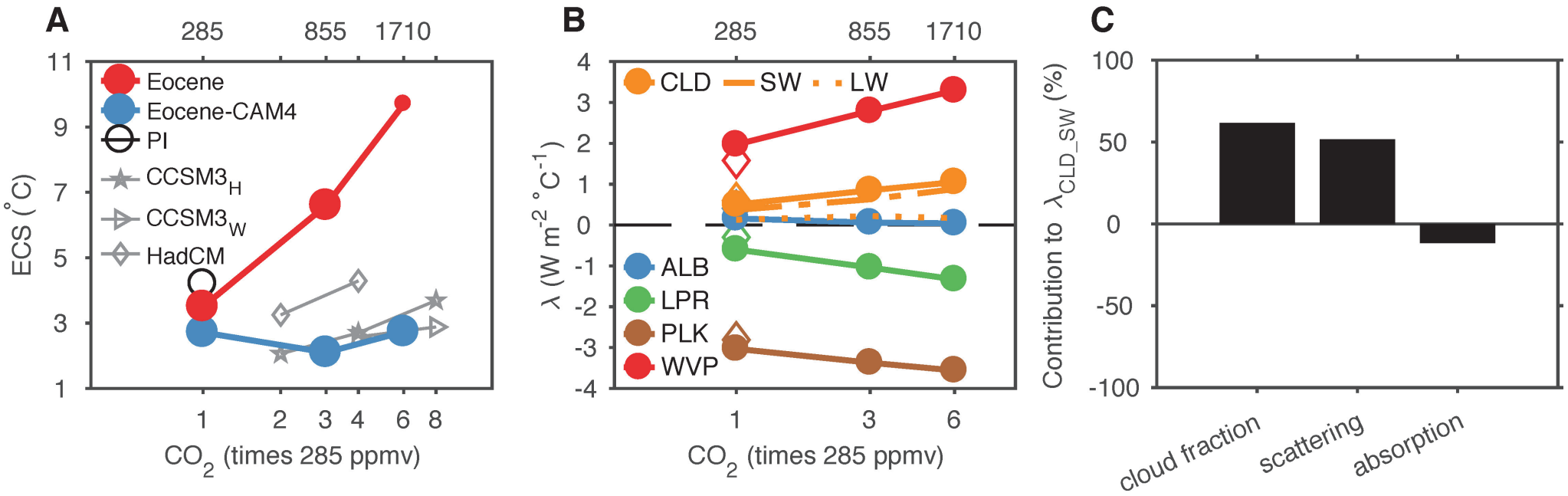
Eocene ECS: 5 C/CO_2 doubling
Eocene ESS: 6.6/CO_2 doubling



Source: Zhu et al., in revision

High Eocene ECS

High sensitivity is due to cloud shortwave response in CAM5



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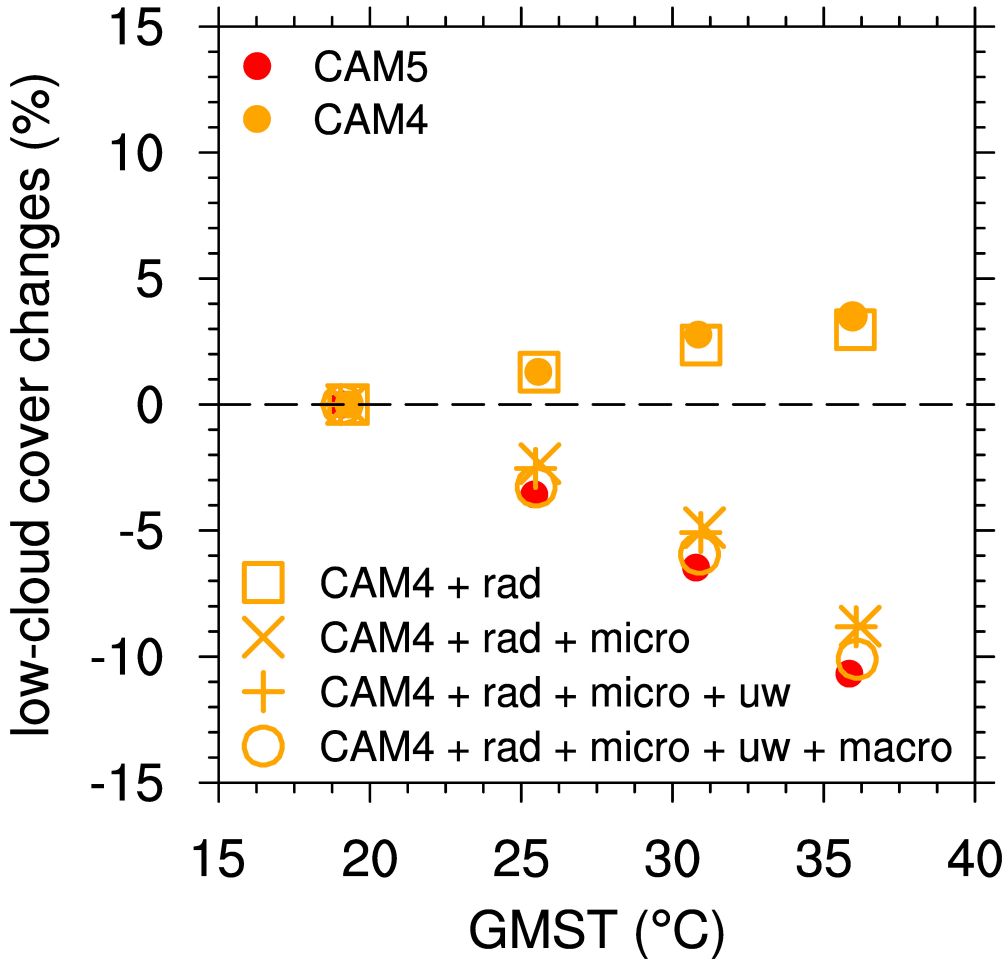
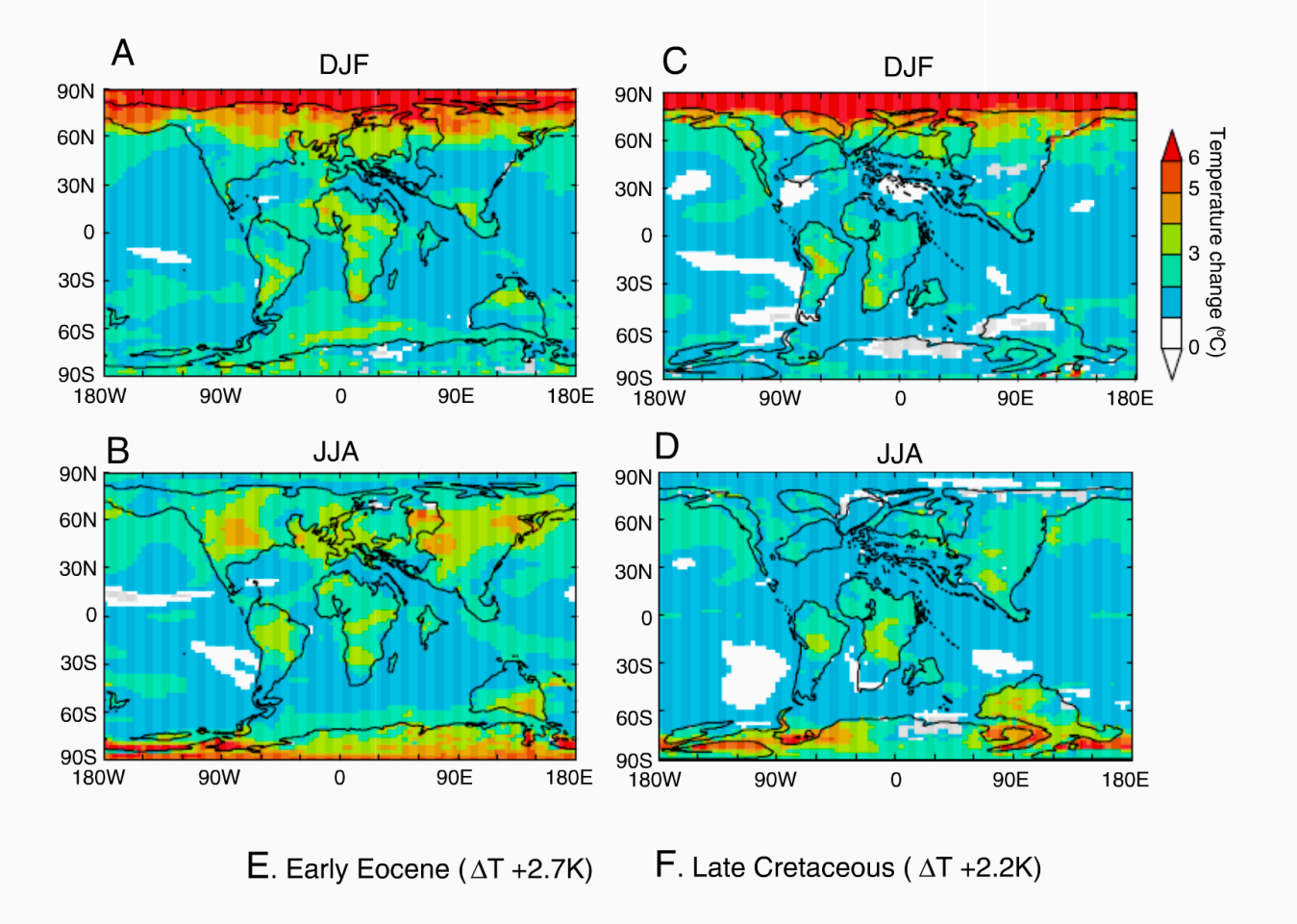


Source: Zhu et al., in revision

Additional feedbacks

ECS increases with CO_2

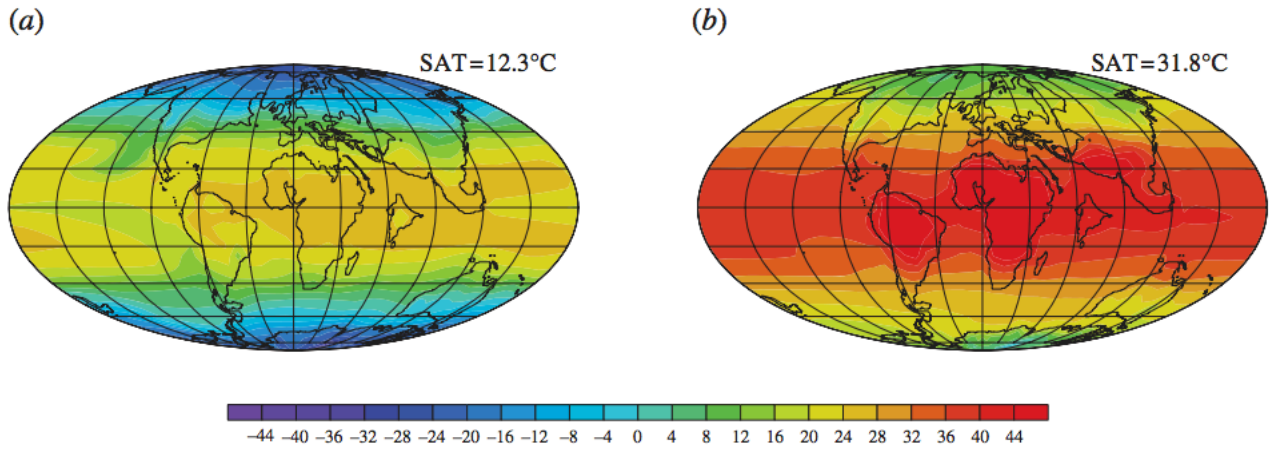


Source: Beerling et al, 2011

It doesn't have to be this way…

Perturbed physics ensemble using FAMOUS. E17 cases (b) produces high Eocene temperatures that optimize data fit. ECS for pre-industrial case with E17 parameters is low– 2.7 C.

Sagoo et al. best fit case



Source: Sagoo et al., 2013

Conclusions

- No compelling evidence that paleogeography, and resulting dynamical changes, have had significant influence on Earth's temperature.
- Slow feedbacks (vegetation, ice sheets, aerosols) have significant but relatively small influence on Earth's temperature.
- Equilibrium climate sensitivity is not well constrained. If higher estimates in newer models are correct, atmospheric CO_2 can explain most of Earth's temperature change since at least the mid-Cretaceous. If not, we'll then we're back to square one.

That’s all…thanks.

It doesn't have to be this way…

E17 matches well because it produces warm high latitudes. Low-latitude temperatures are extremely warm. Better distribution of proxy records would have produced poorer fit.

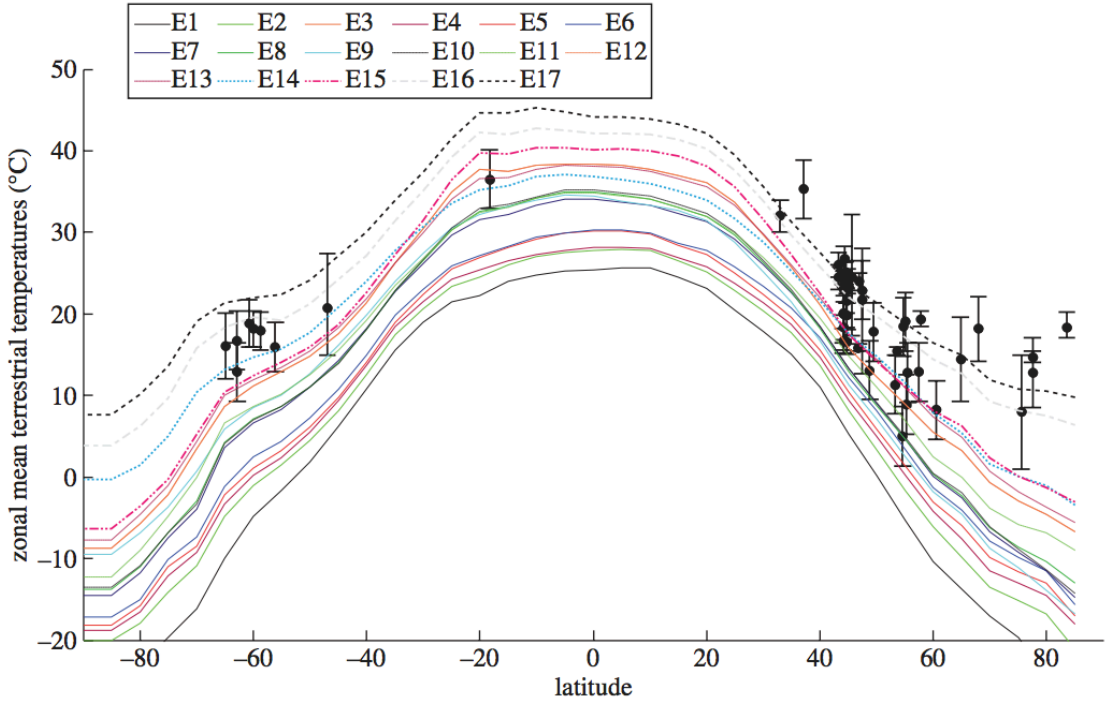


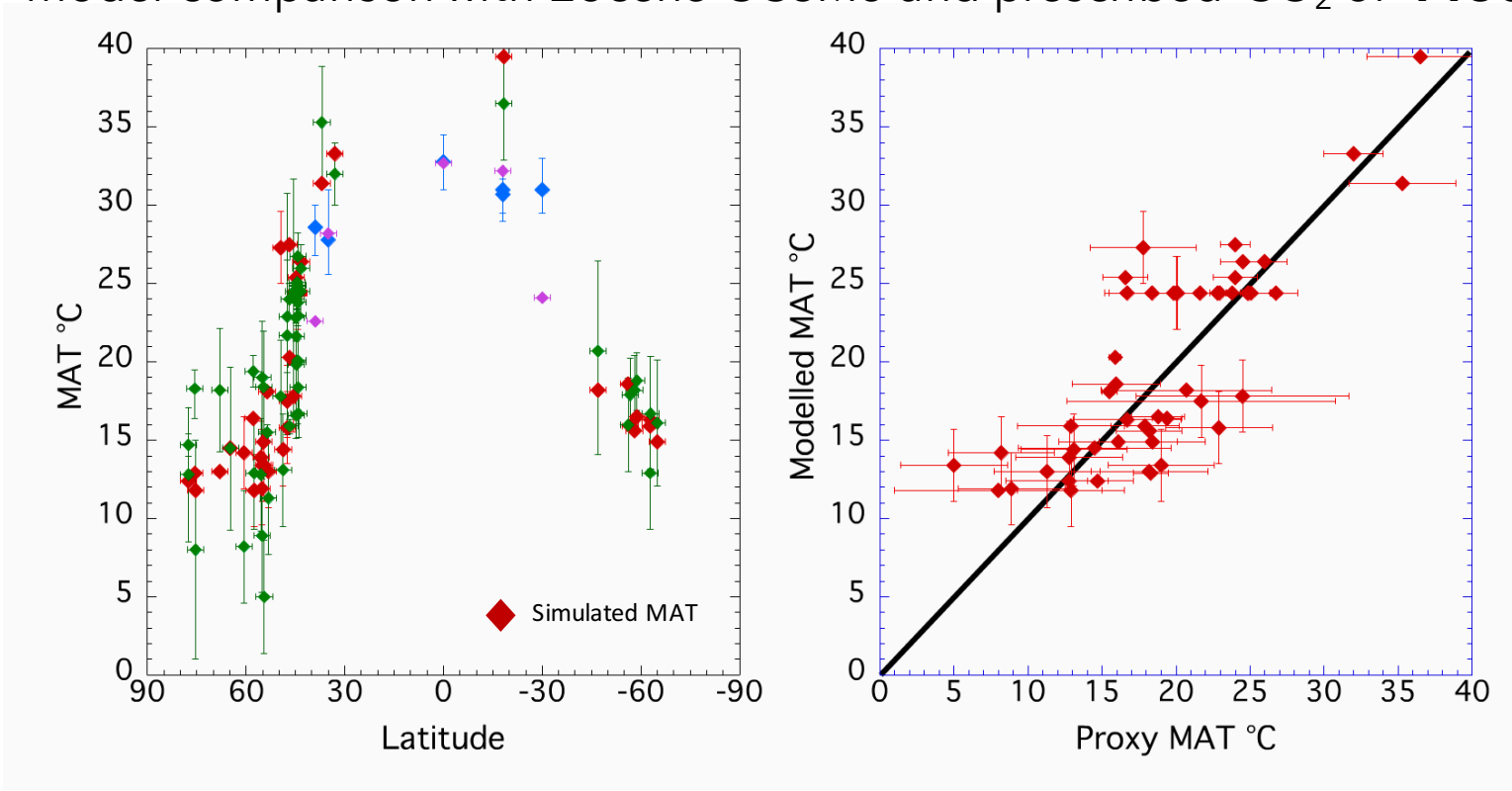
Figure 5. Early Eocene terrestrial SATs as compiled in Huber & Cabellero [3] shown as solid black circles. Upper and lower temperature error bars are shown in black and calibration errors are plotted in grey. Model simulated terrestrial zonal SATs are plotted over the top. The four warmest simulations, E14 (dotted line), E15 (dashed double-dotted line), E16 (dashed single-dotted line) and E17 (dashed line), are highlighted with thicker lines for clarity. (Online version in colour.)

Source: Sagoo et al., 2013

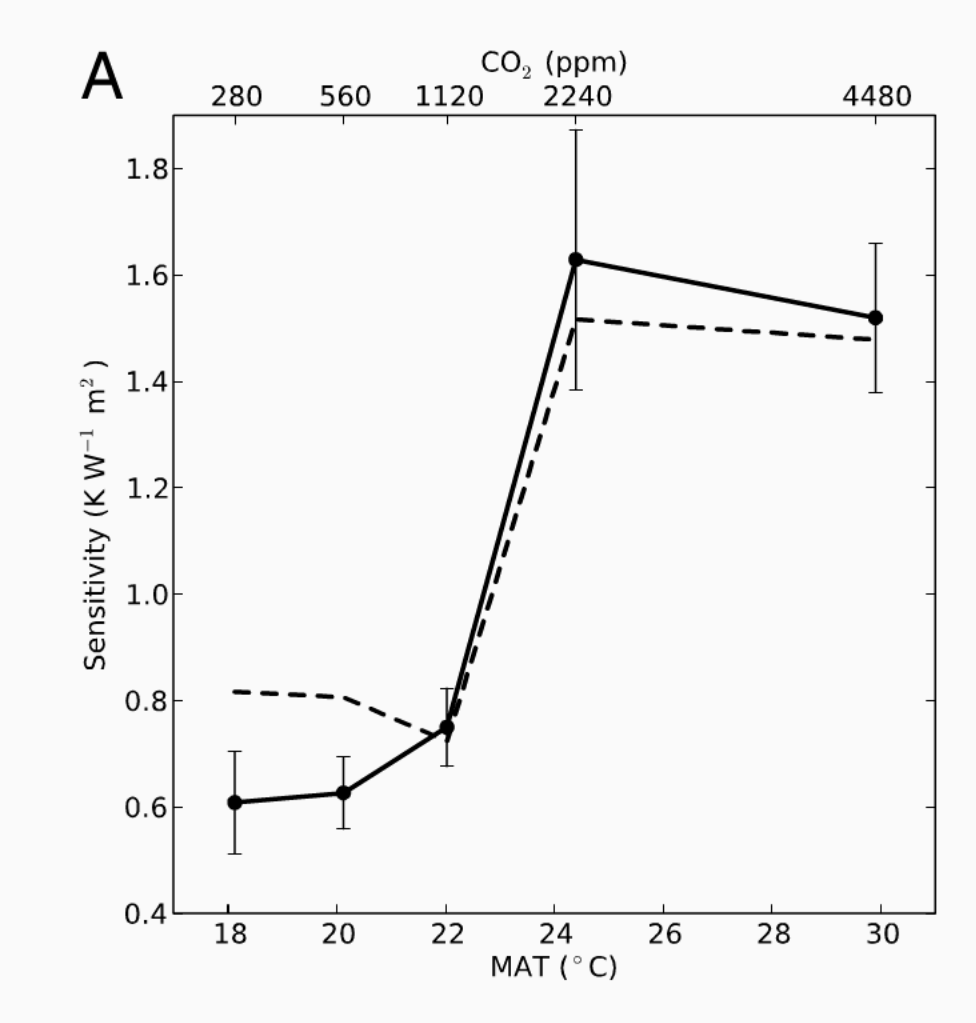
Warm climate problem– Eocene

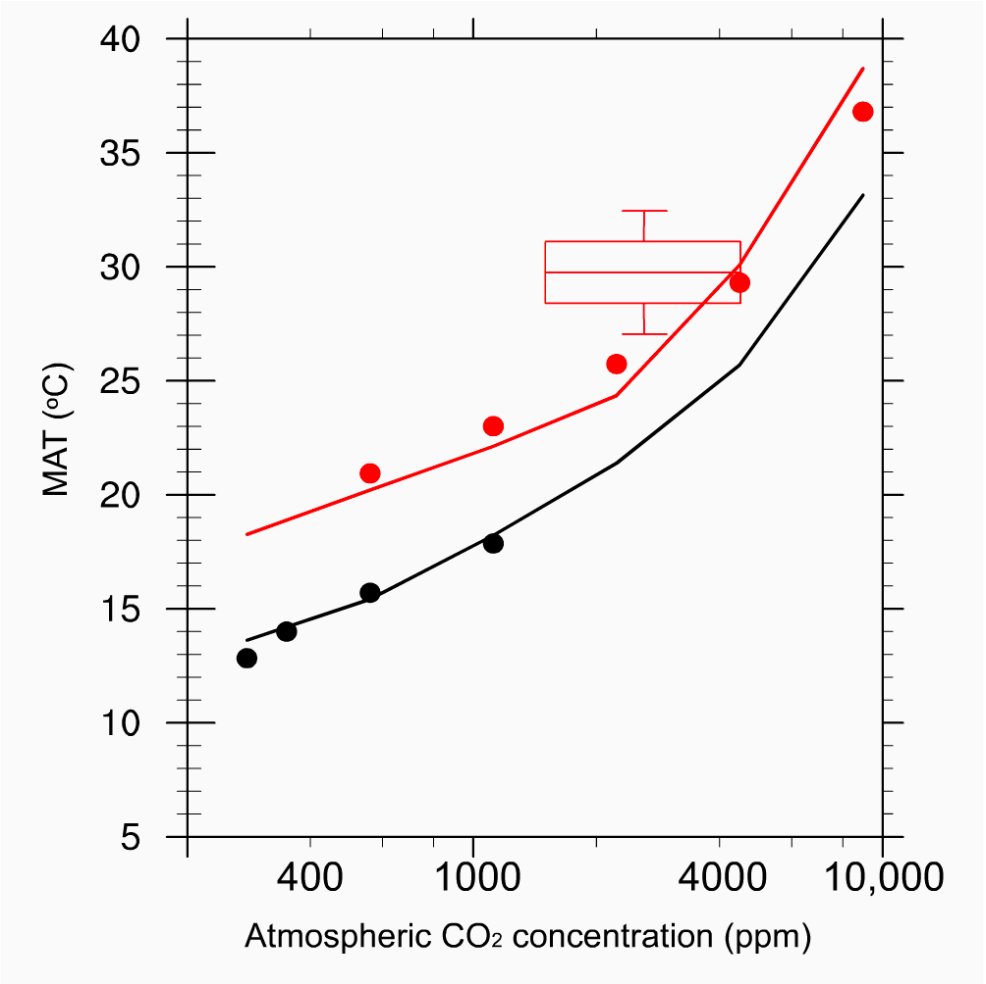
Paleoclimate models are unable to simulate sufficiently warm conditions and low thermal gradients at CO_2 levels inferred from proxies.

Proxy-model comparison with Eocene CCSM3 and prescribed CO_2 of **4480 ppmv** ($16xCO_2$)



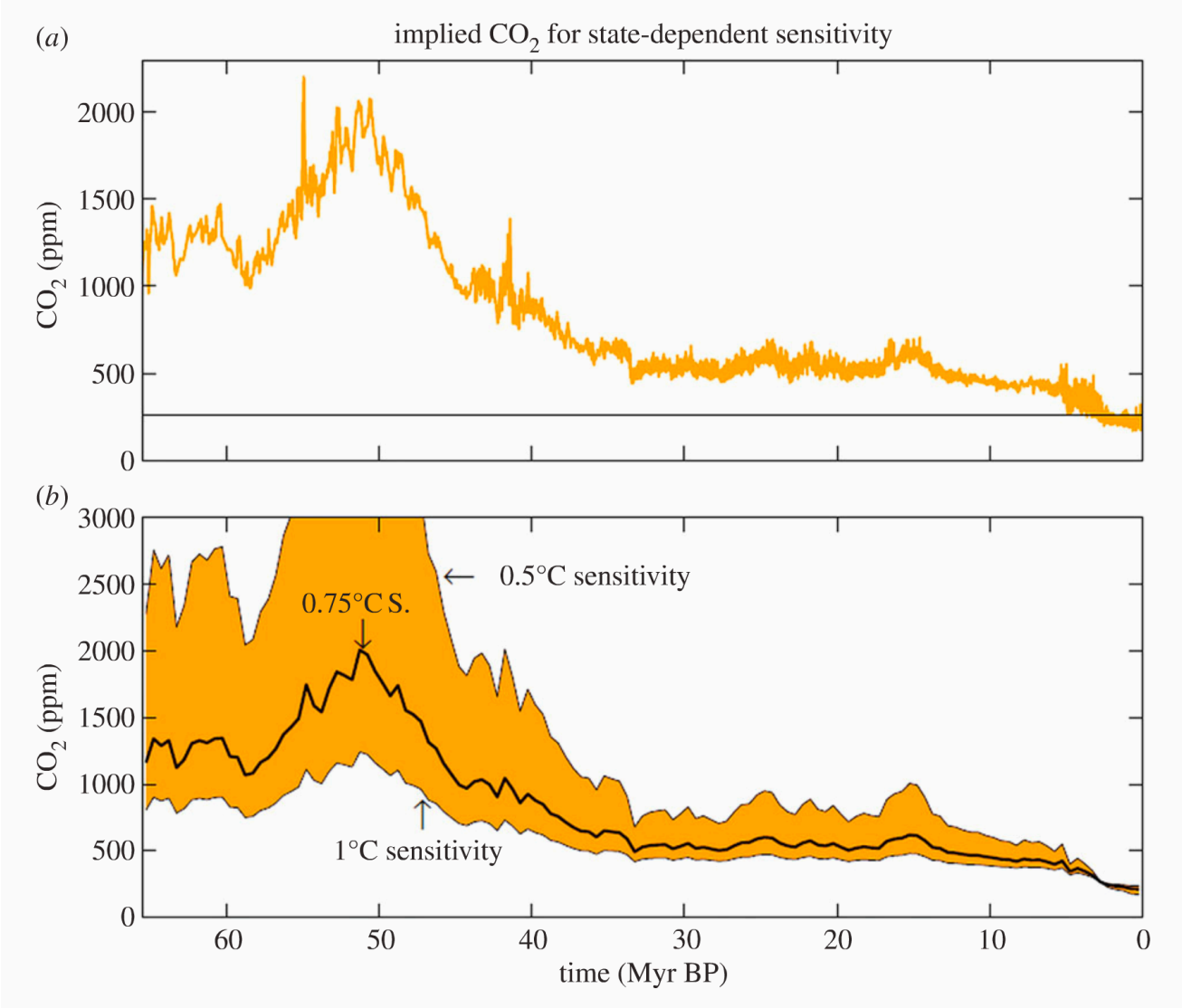
Source: Huber and Caballero, 2011





Source: Caballero and Huber, 2013

Earth system sensitivity



Source: Hansen et al., 2012

Feedbacks

- **Feedbacks**
  - Clouds
  - Aerosols
  - Greenhouse gas (CH_4, NO_2, etc.): ~2-3 C
  - Dynamic/state changes in atmosphere/ocean: small
  - Vegetation: ~1-2 C
  - Ice sheets: small