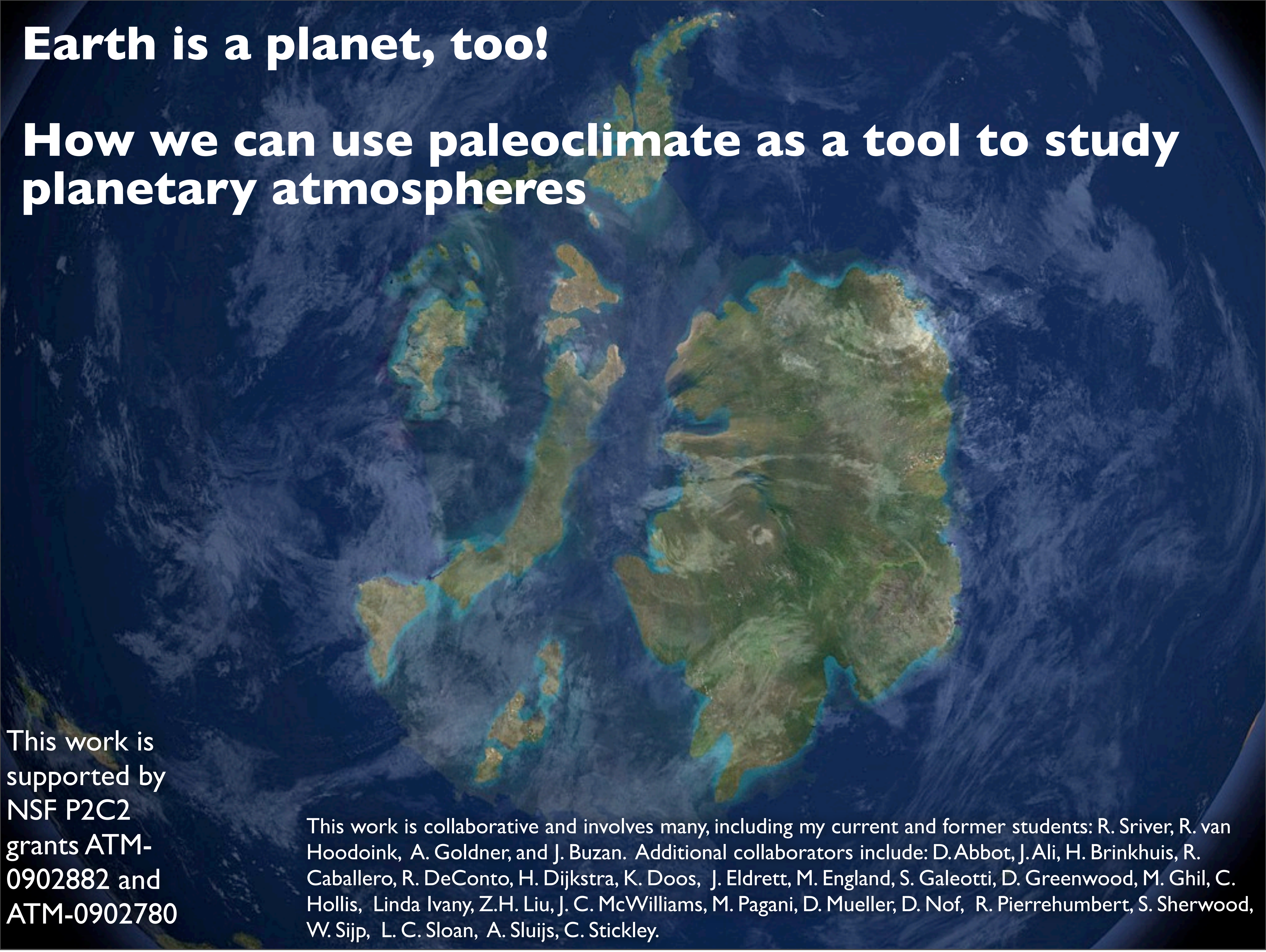
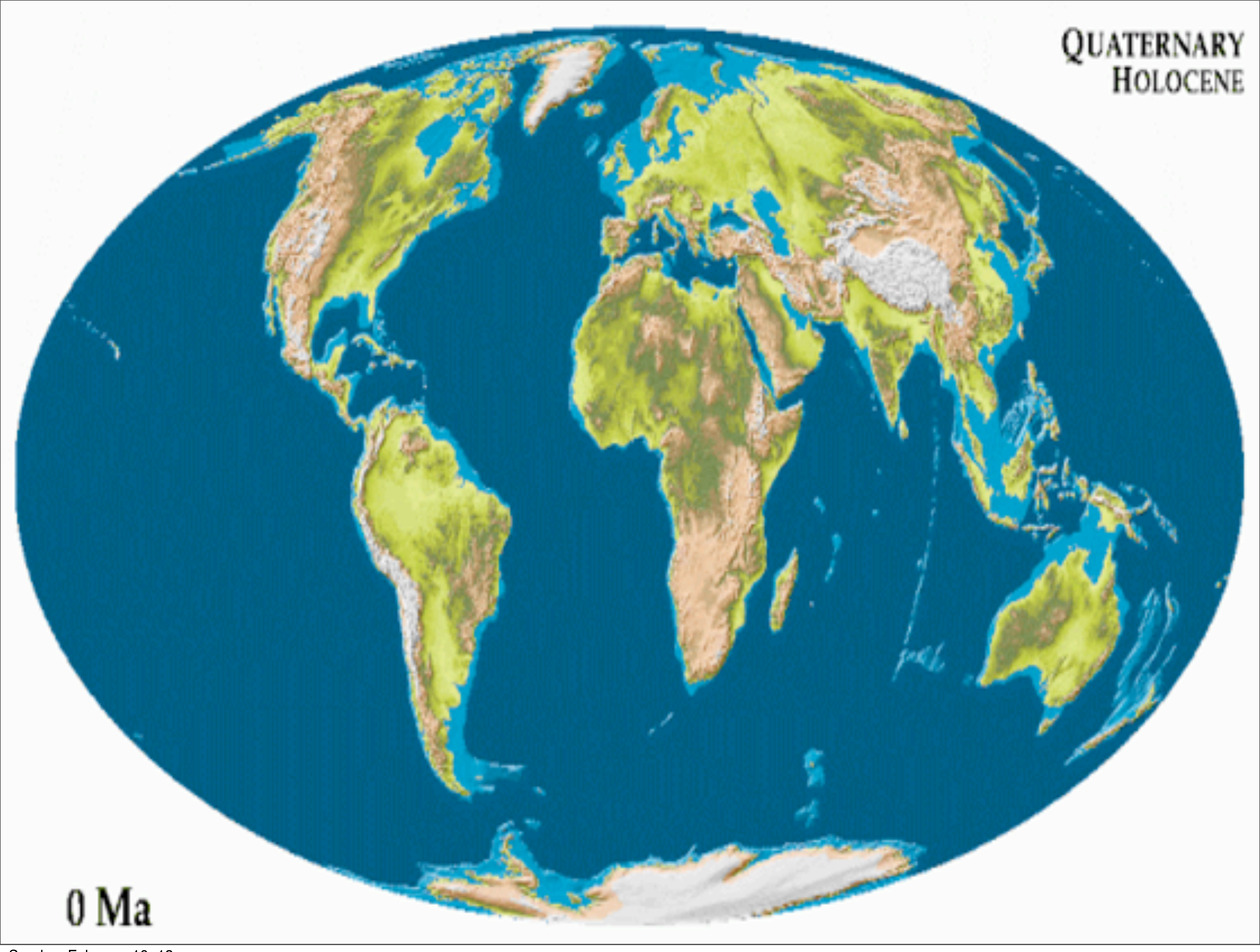


Earth is a planet, too!

How we can use paleoclimate as a tool to study planetary atmospheres

This work is supported by NSF P2C2 grants ATM-0902882 and ATM-0902780

This work is collaborative and involves many, including my current and former students: R. Sriver, R. van Hoodoink, A. Goldner, and J. Buzan. Additional collaborators include: D. Abbot, J. Ali, H. Brinkhuis, R. Caballero, R. DeConto, H. Dijkstra, K. Doos, J. Eldrett, M. England, S. Galeotti, D. Greenwood, M. Ghil, C. Hollis, Linda Ivany, Z.H. Liu, J. C. McWilliams, M. Pagani, D. Mueller, D. Nof, R. Pierrehumbert, S. Sherwood, W. Sijp, L. C. Sloan, A. Sluijs, C. Stickley.


QUATERNARY
HOLOCENE
0 Ma

Fundamental Climate Change Questions

- Is global mean temperature sensitivity to greenhouse gas forcing on the low end (<2°C) or the high end >4°C)?
- How strong is polar amplification of climate change?
- Is there a thermostat that buffers tropical climates from warming?
- Are there fundamental,qualitative transitions in the ocean-atmosphere system, which render Earth's climate non-Earth-like?
- What are the implications for life?

Climate Sensitivity

- We can define a measure of climate sensitivity, say of temperature, as:

total temperature change → dT_S

total forcing change → dQ

$$\frac{dT_S}{dQ} = \lambda_R$$

So if we know the sensitivity ratio (λ_R), we can calculate the temperature change that will occur given the change in the forcing

$$\Delta T_S = \lambda_R \Delta Q$$

Sensitivity Background

THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[FIFTH SERIES.]

APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* *By* Prof. SVANTE ARRHENIUS *.

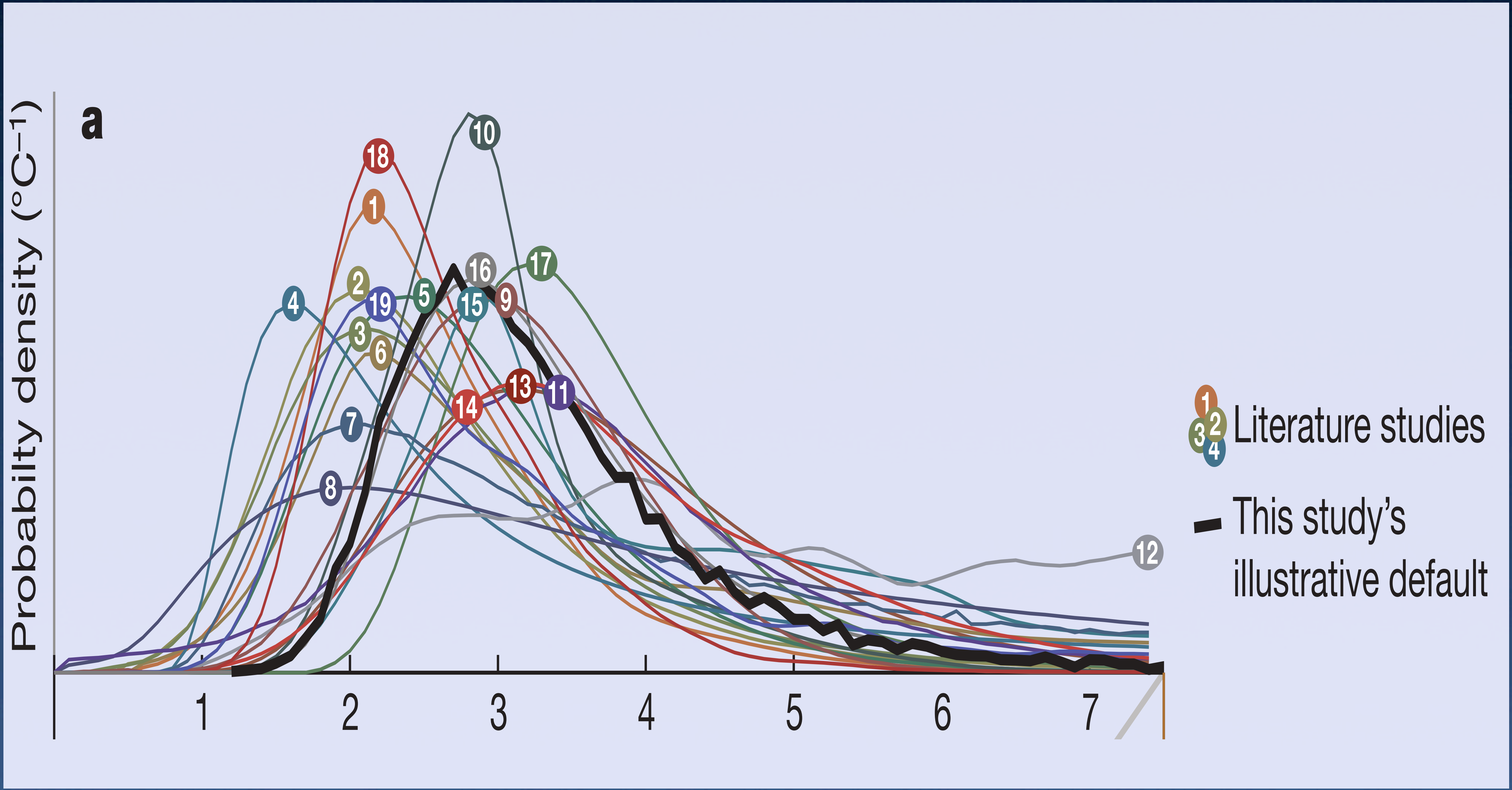
I. *Introduction: Observations of* Langley *on Atmospherical Absorption.*

A GREAT deal has been written on the influence of the absorption of the atmosphere upon the climate.

Sensitivity Background

underestimated.

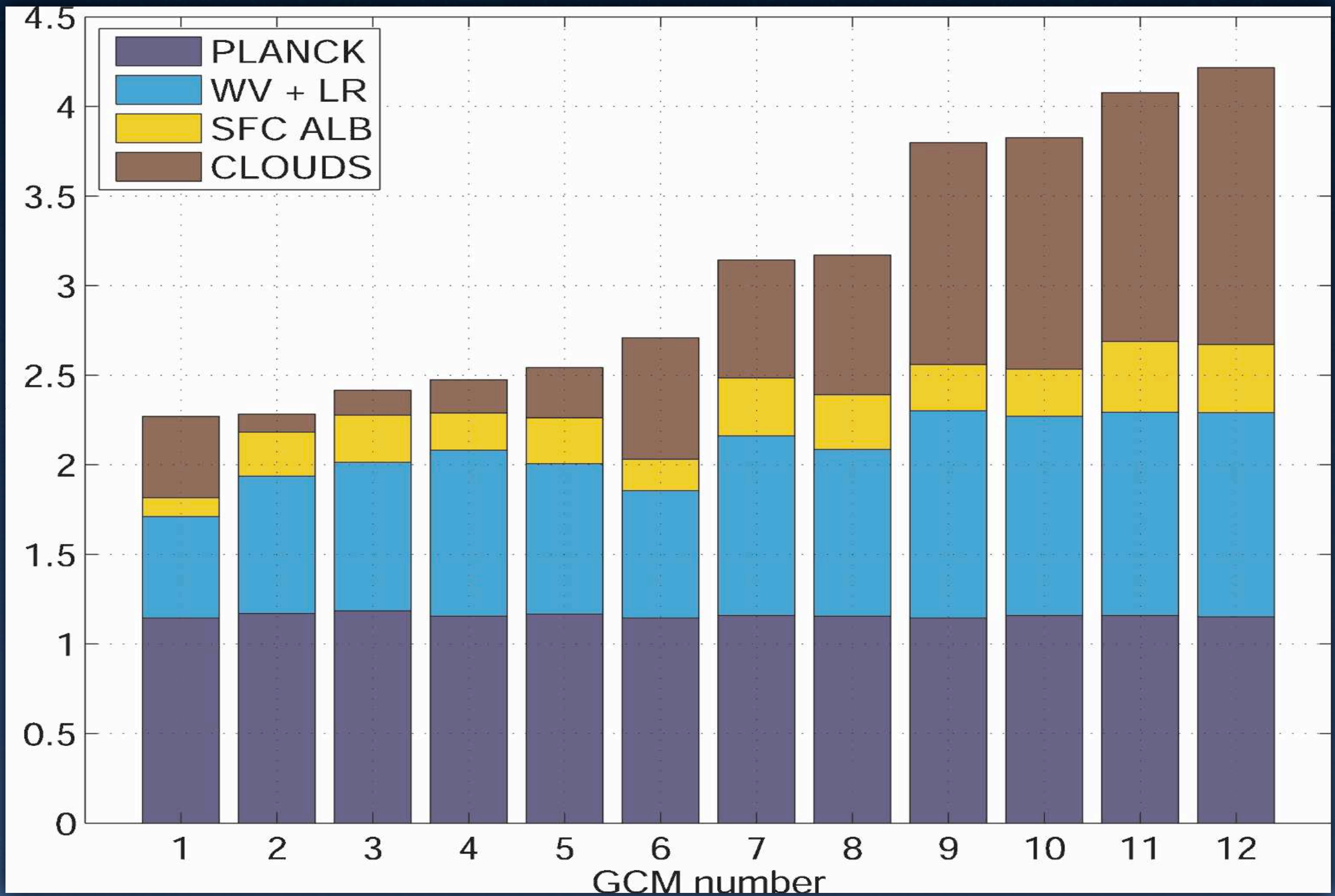
One may now ask, How much must the carbonic acid vary according to our figures, in order that the temperature should attain the same values as in the Tertiary and Ice ages respectively? A simple calculation shows that the temperature in the arctic regions would rise about 8° to 9° C., if the carbonic acid increased to 2·5 or 3 times its present value. In order to get the temperature of the ice age between the 40th and 50th parallels, the carbonic acid in the air should sink to 0·62–0·55 of its present value (lowering of temperature 4°–5° C.). The demands of the geologists, that at the genial epochs the climate should be more uniform than now, accords



Range

Meinshausen et al., 2009 (Nature)

Feedbacks in GCMs

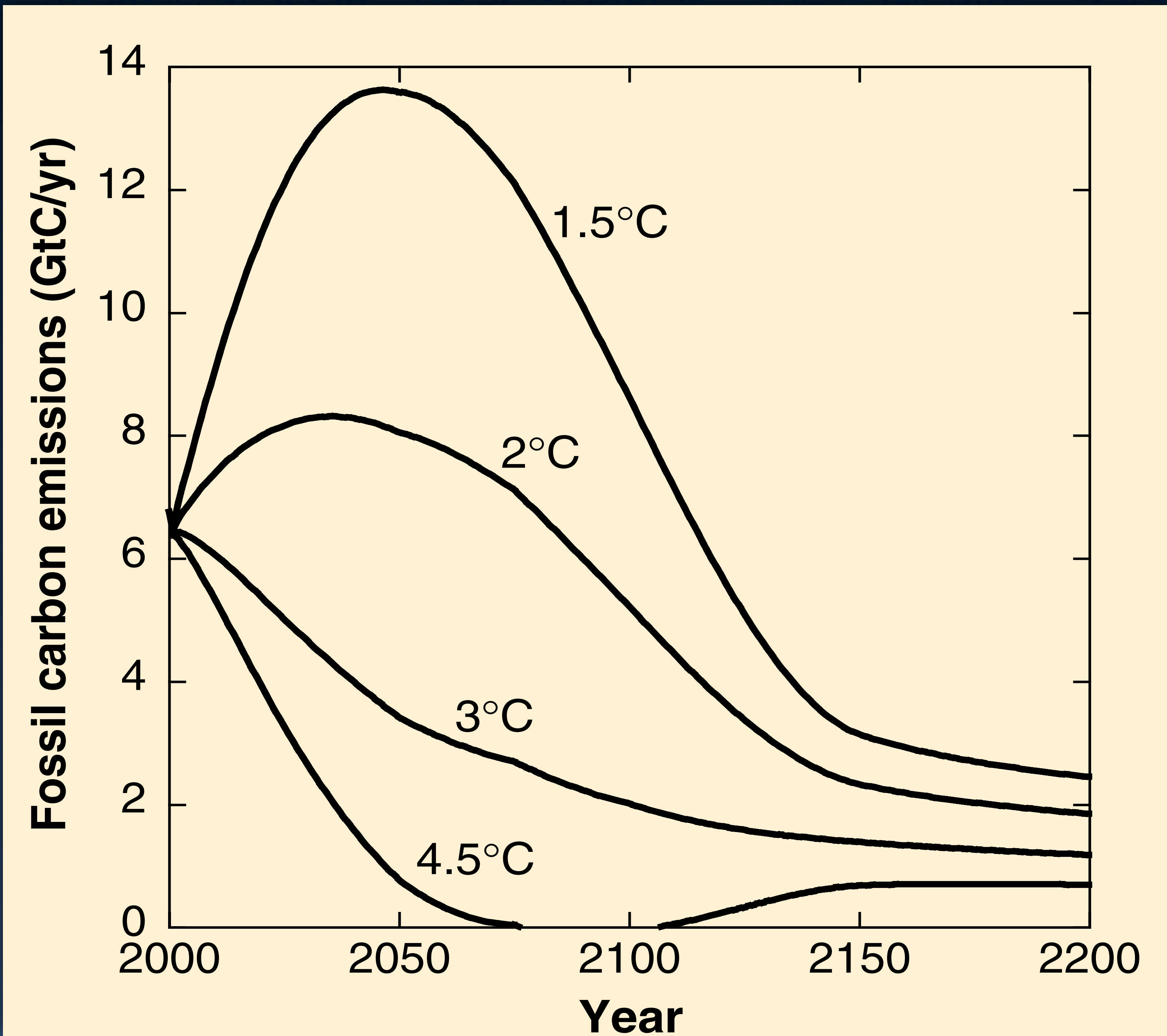


°C warming for each feedback per one doubling CO_2

Dufresne and Bony 2008

Sunday, February 10, 13

The importance of sensitivity >2



- Stabilizing below ~2°C warming above pre-industrial requires large decreases in emissions if climate sensitivity is low
- it requires a complete halt to human emissions within the next 50 years, if sensitivity is ~4.5°C

Future emissions pathways depend crucially on sensitivity

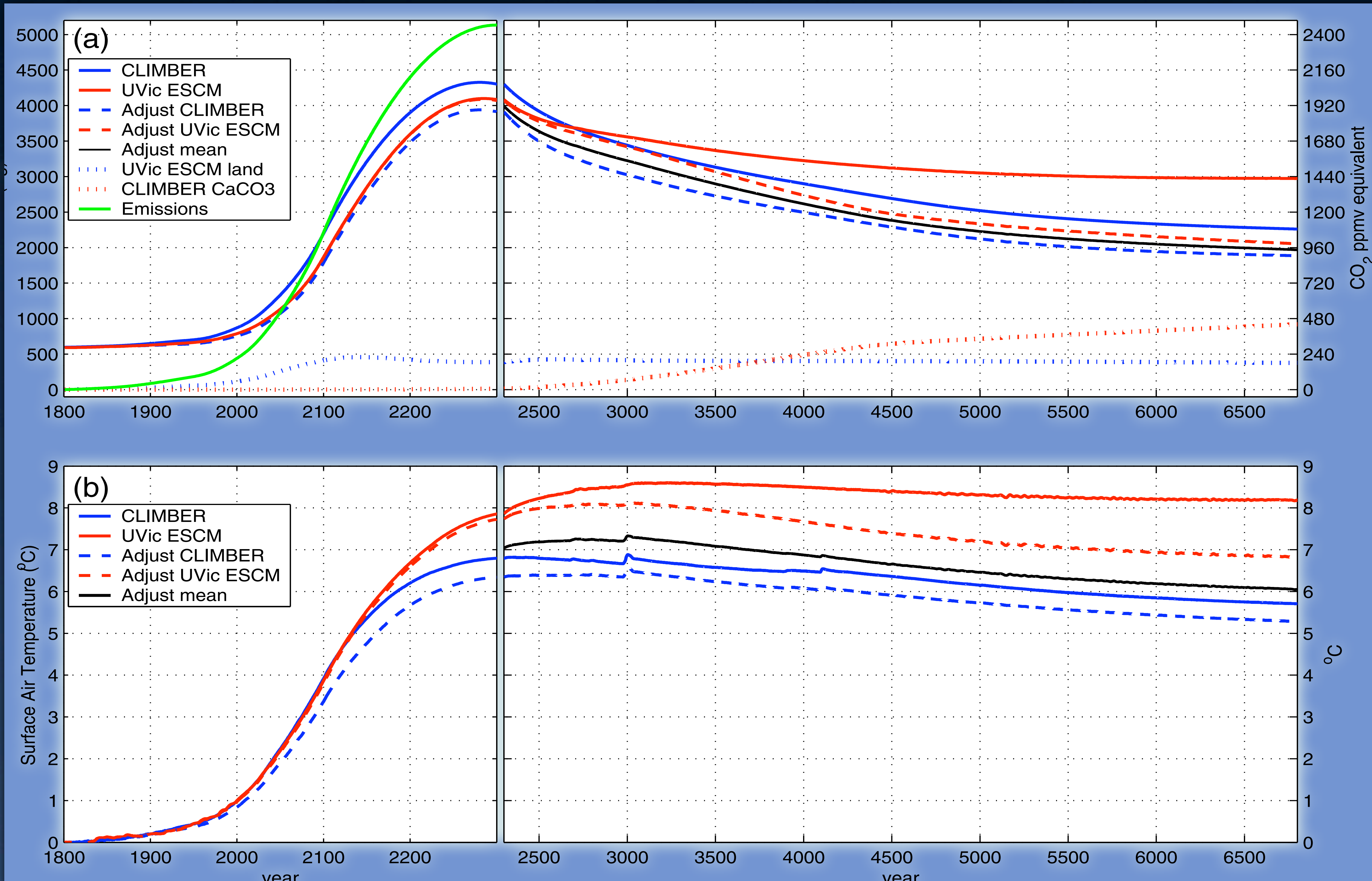
Caldeira et al., 2008 (Science)

How much carbon?

- >2500 Gt easily available CO_2
- More, if we try hard
- oil sands
- positive feedbacks with carbon uptake by ocean/land surface
- methane hydrate release
- 5000 GT is a reasonable upper bound

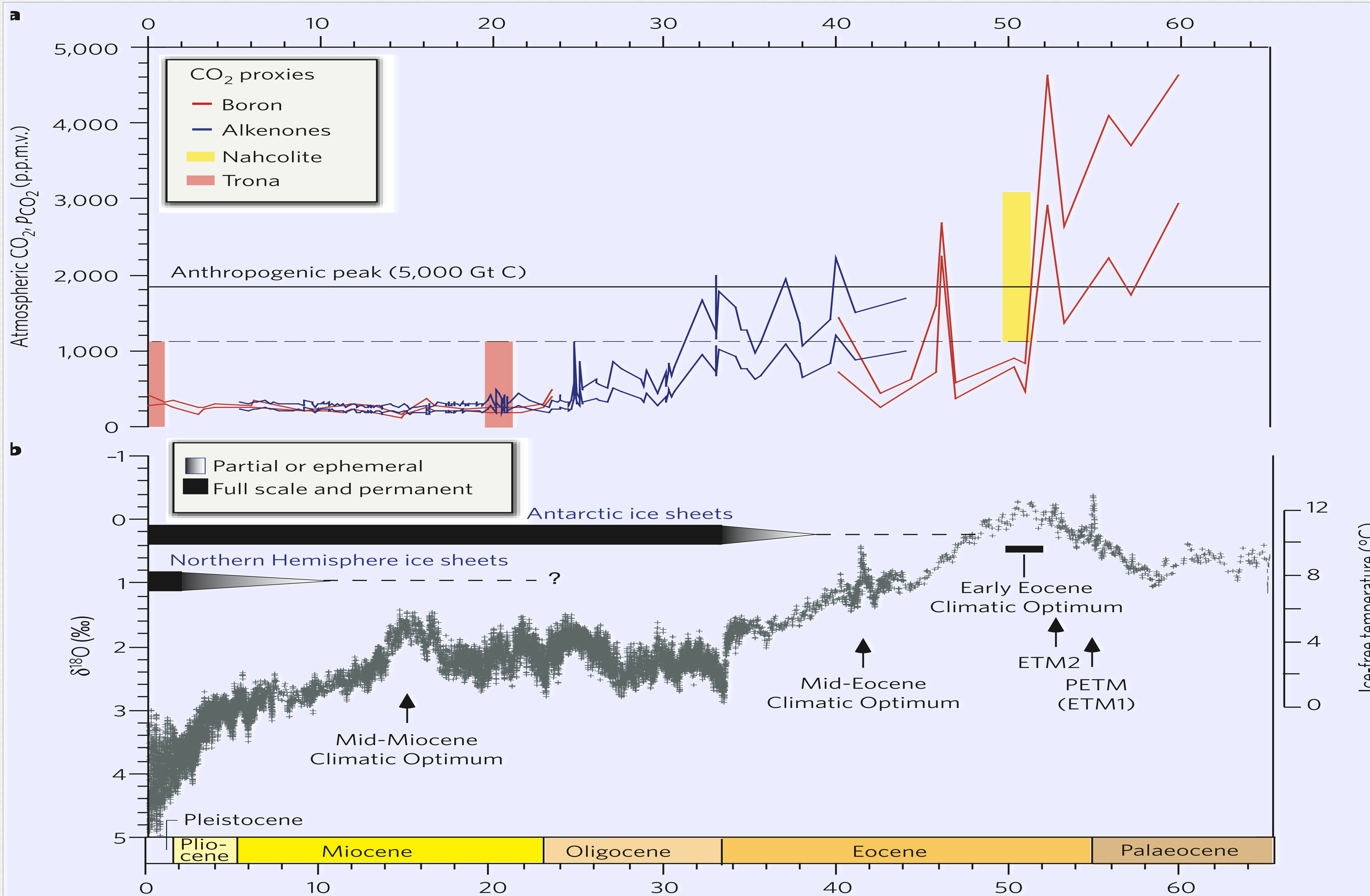
Meinshausen et al., 2009 (Nature)

Sensitivity Background



Montenegro et al., 2007 (GRL)

History of climate and forcing



Zachos et al., 2008 (Nature)

Thermostats

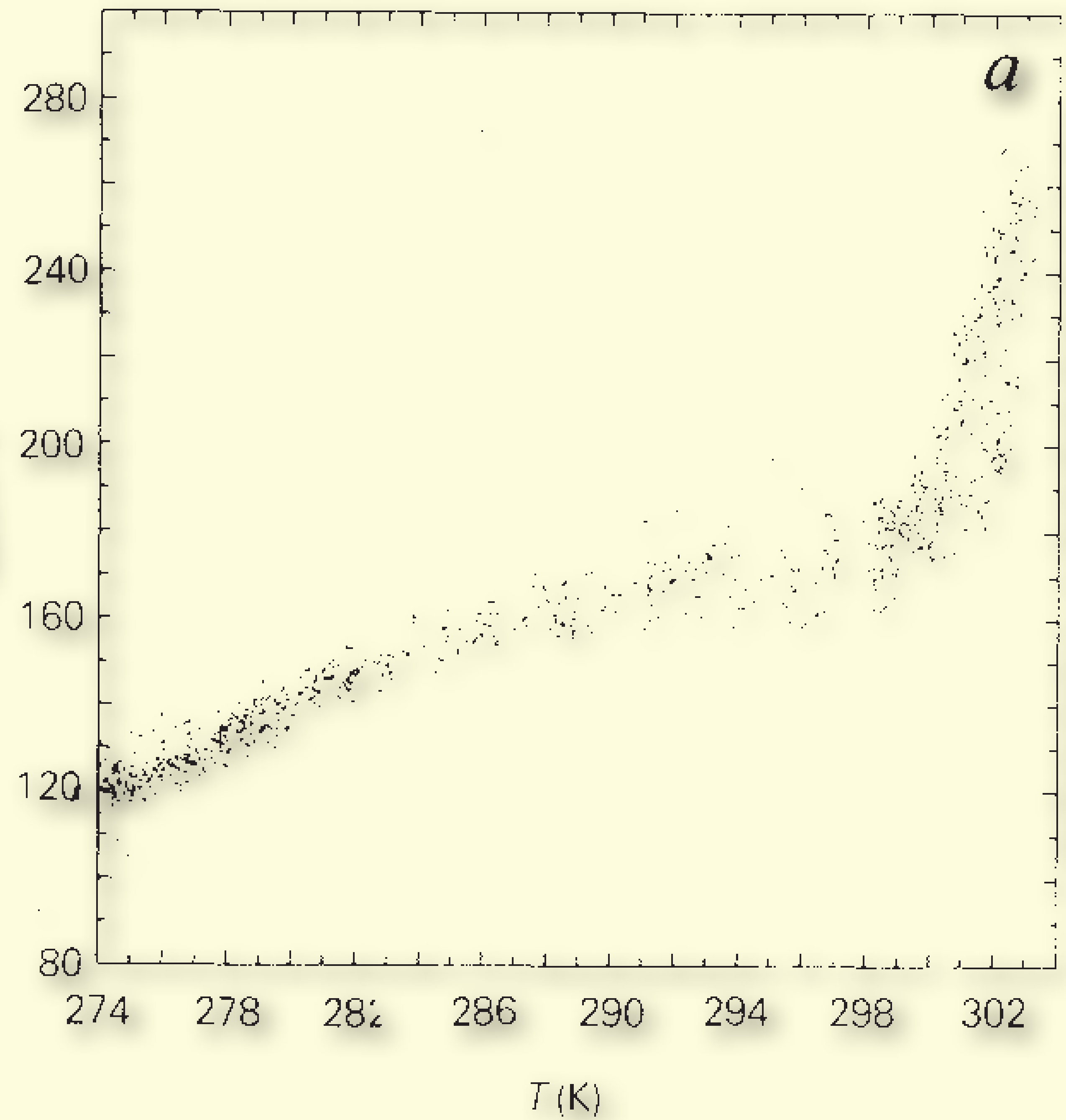
- Long history
- Linked to publication of CLIMAP LGM Sea Surface Temperatures (SSTs) and
- Shackleton and Boersma Eocene SST compilations circa 1981

Thermostat Background

Thermodynamic regulation of ocean warming by cirrus clouds deduced from observations of the 1987 El Niño

V. Ramanathan & W. Collins

Observations made during the 1987 El Niño show that in the upper range of sea surface temperatures, the greenhouse effect increases with surface temperature at a rate which exceeds the rate at which radiation is being emitted from the surface. In response to this 'super greenhouse effect', highly reflective cirrus clouds are produced which act like a thermostat, shielding the ocean from solar radiation. The regulatory effect of these cirrus clouds may limit sea surface temperatures to less than 305 K.



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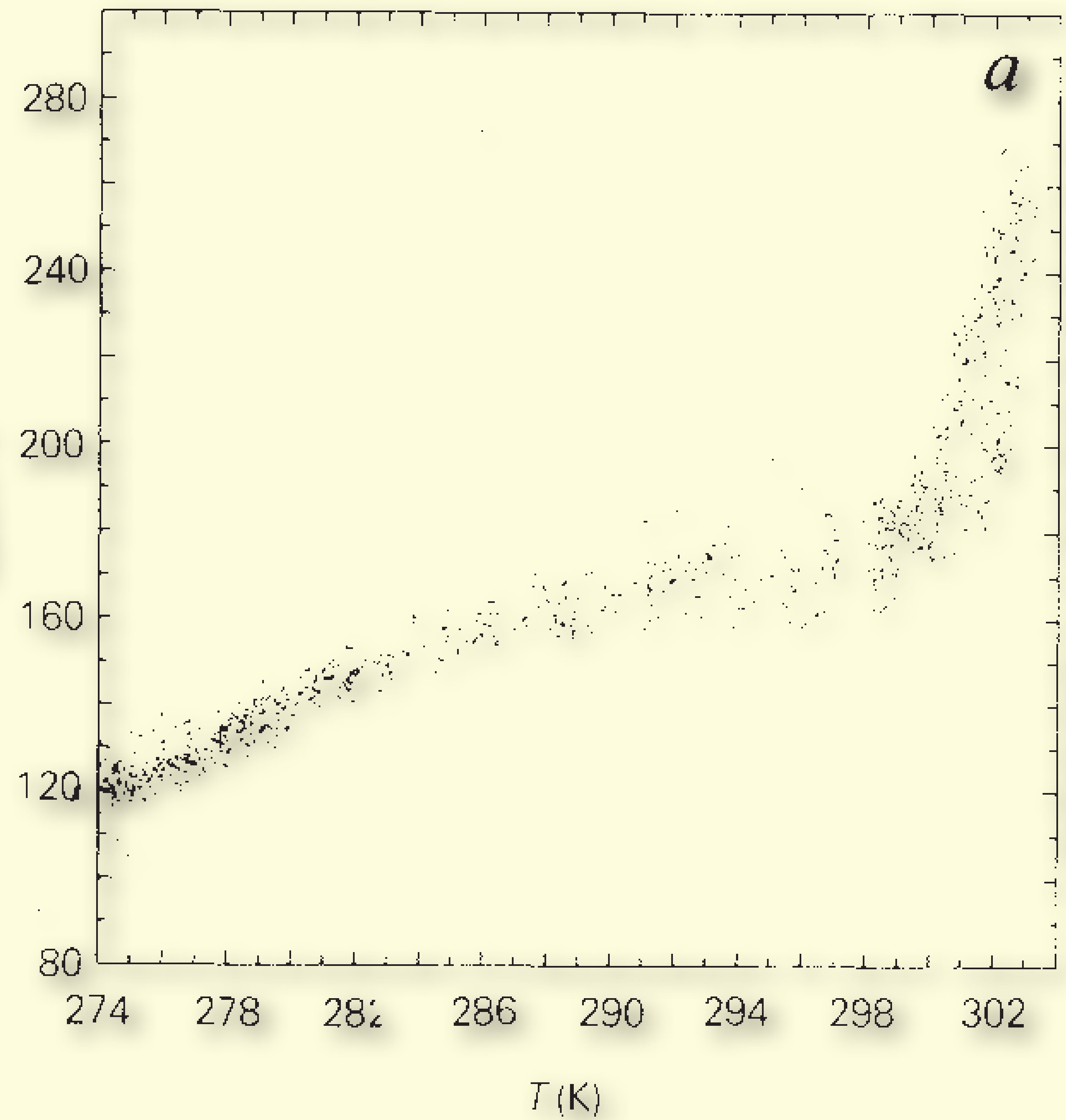
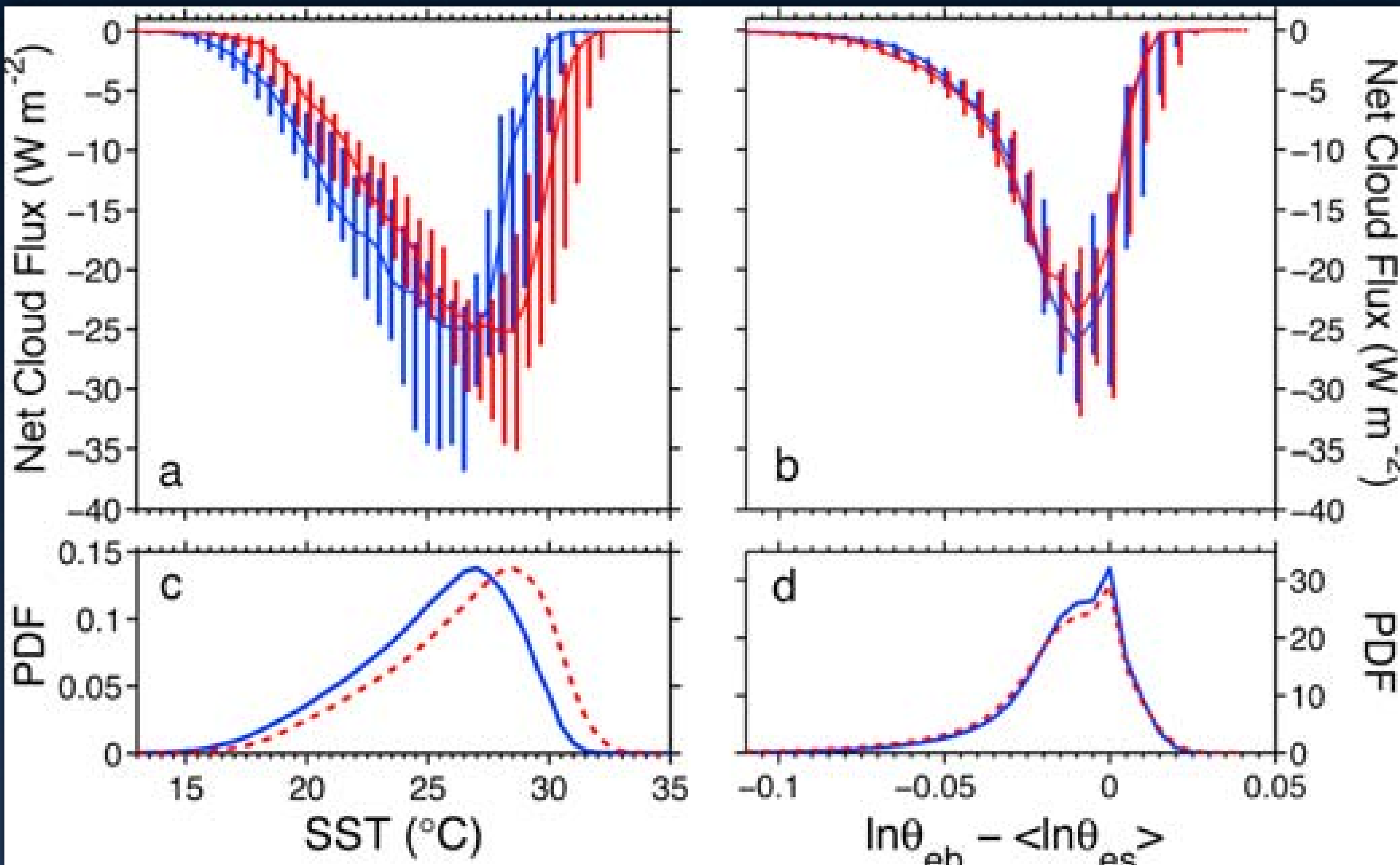
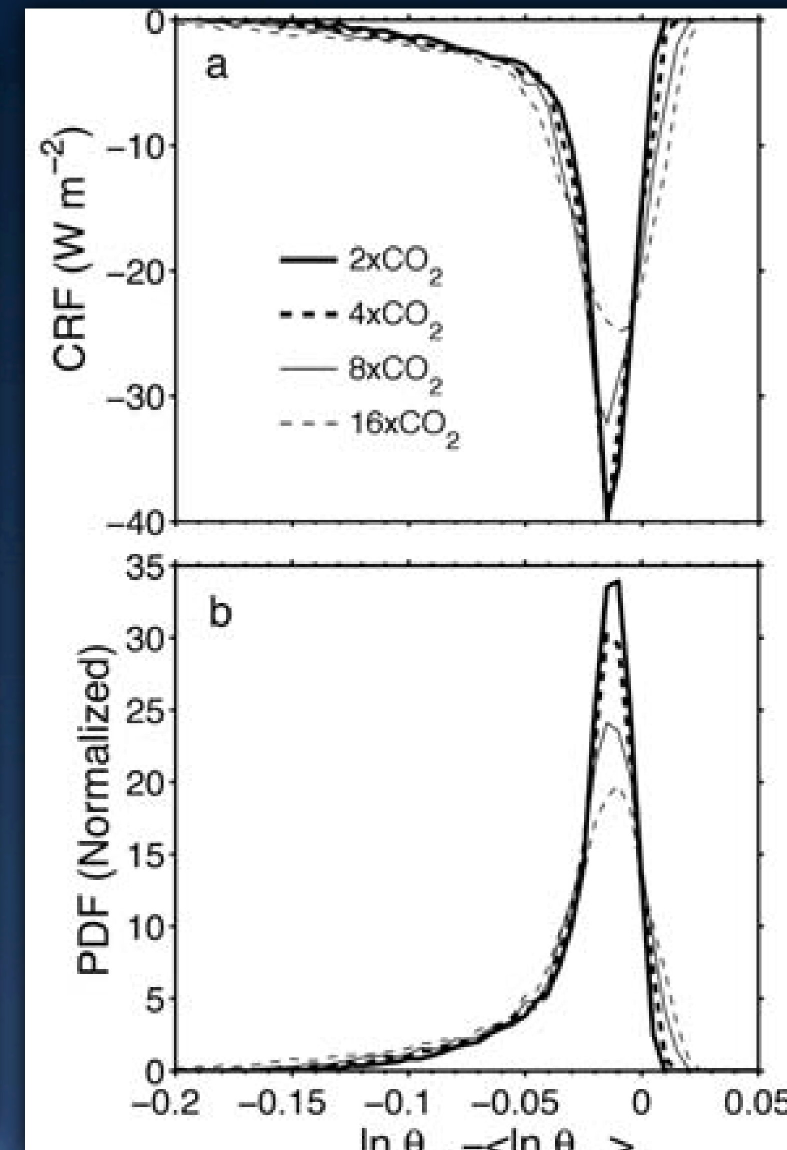


Thermostat Background

modern



Eocene

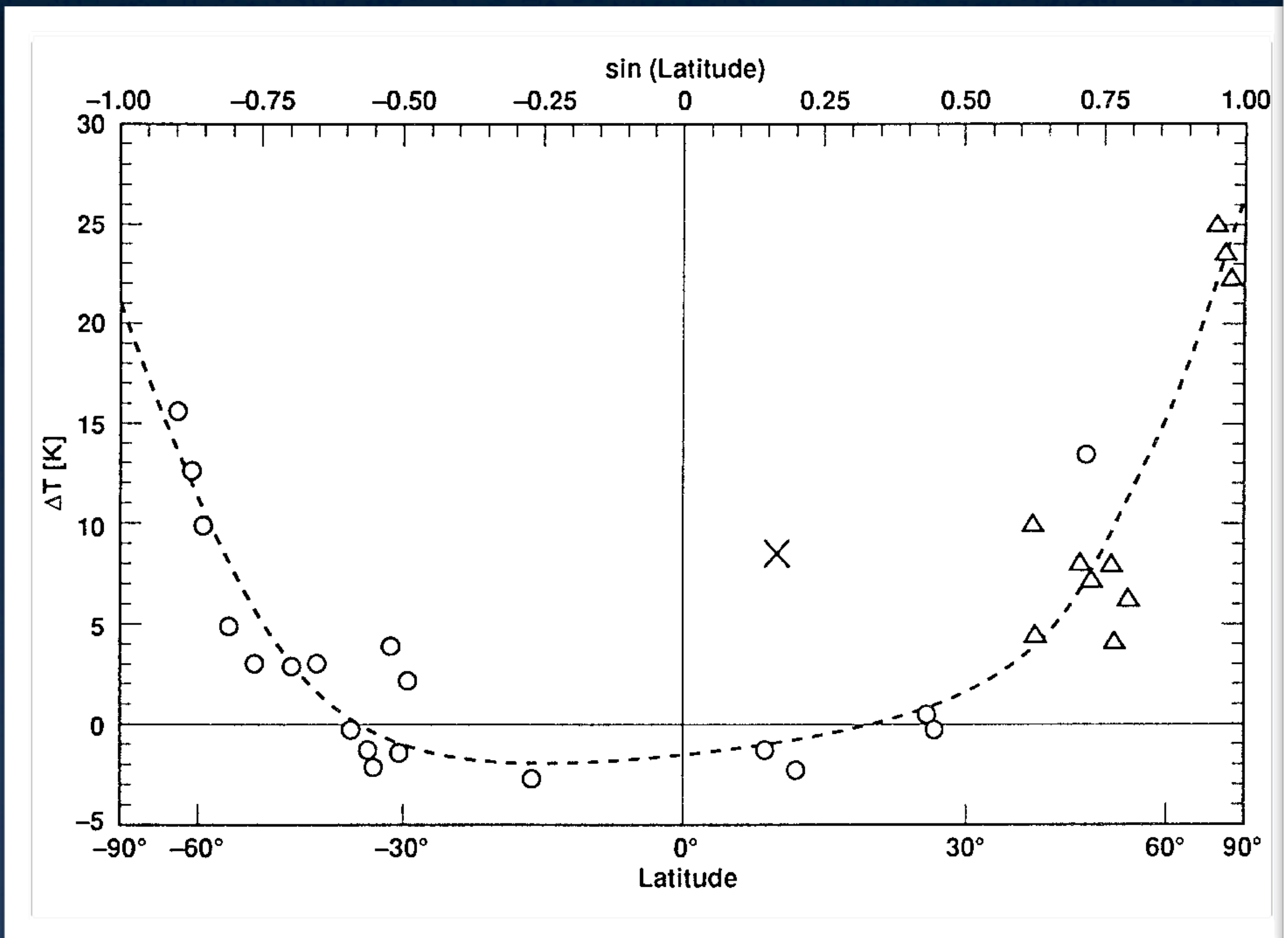


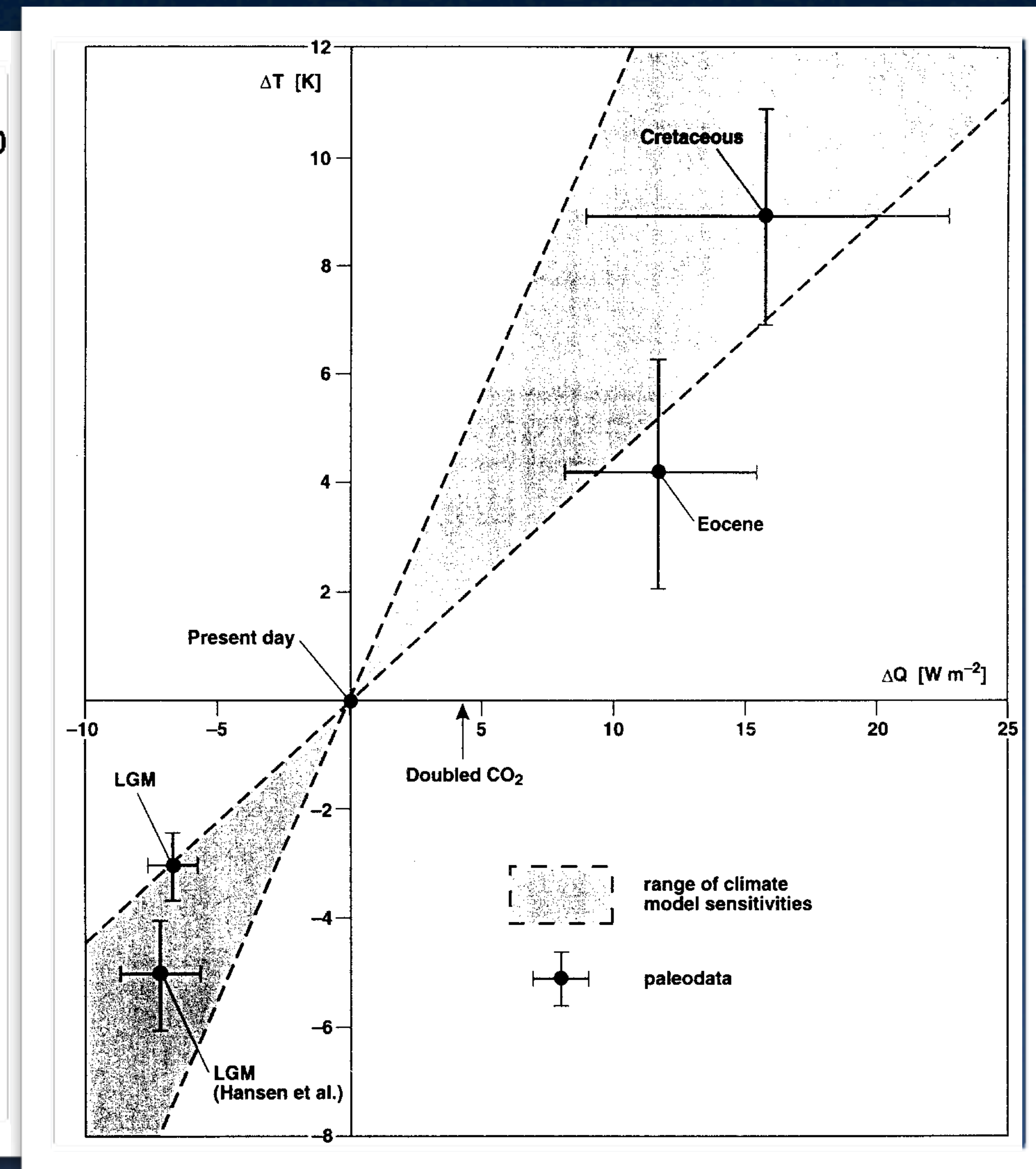
Cloud forcing is invariant under a suitable buoyancy transformation

Both in the modern world and in the Eocene

Williams et al 2009

Old Cold Tropics Paradox

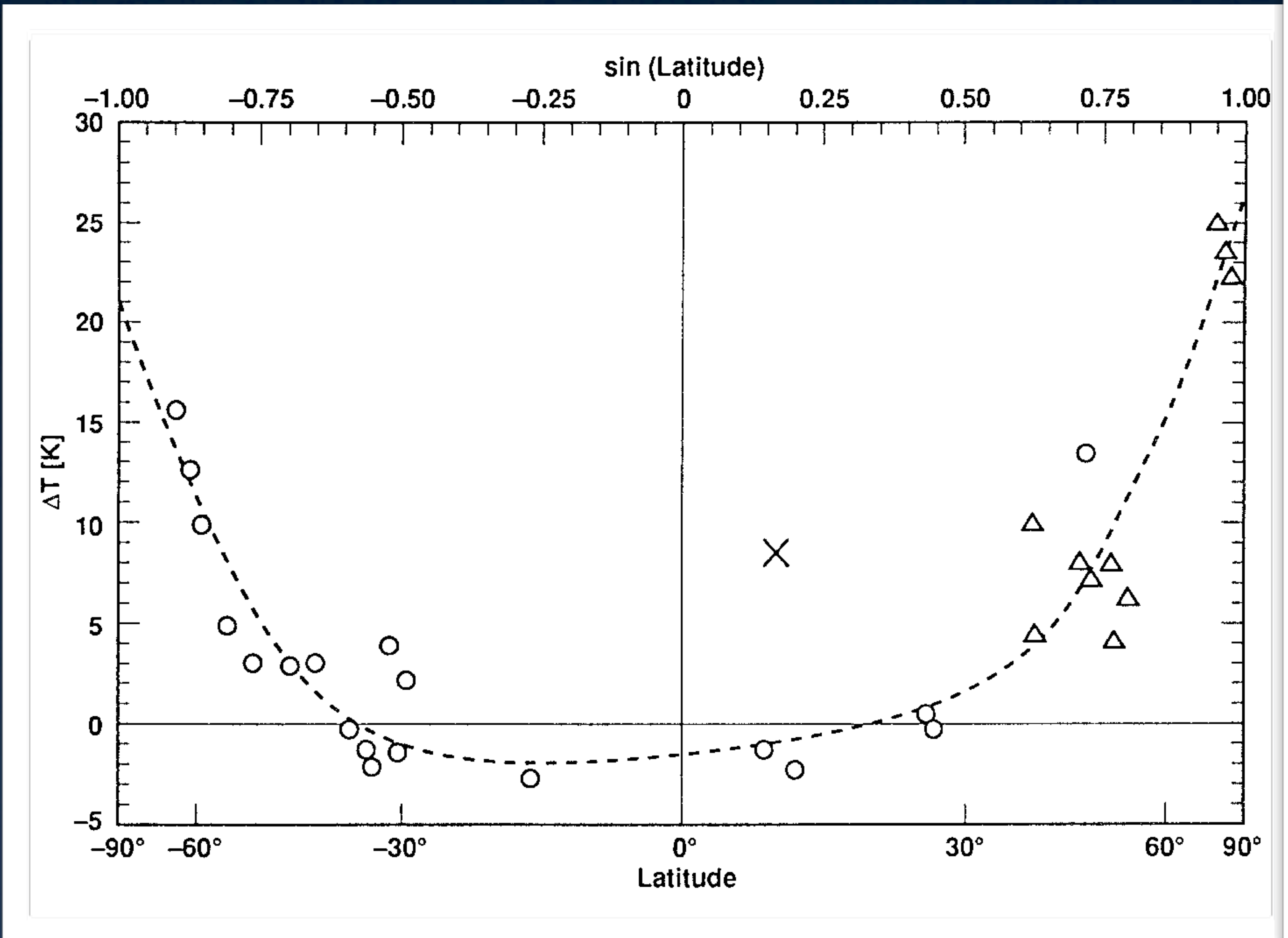


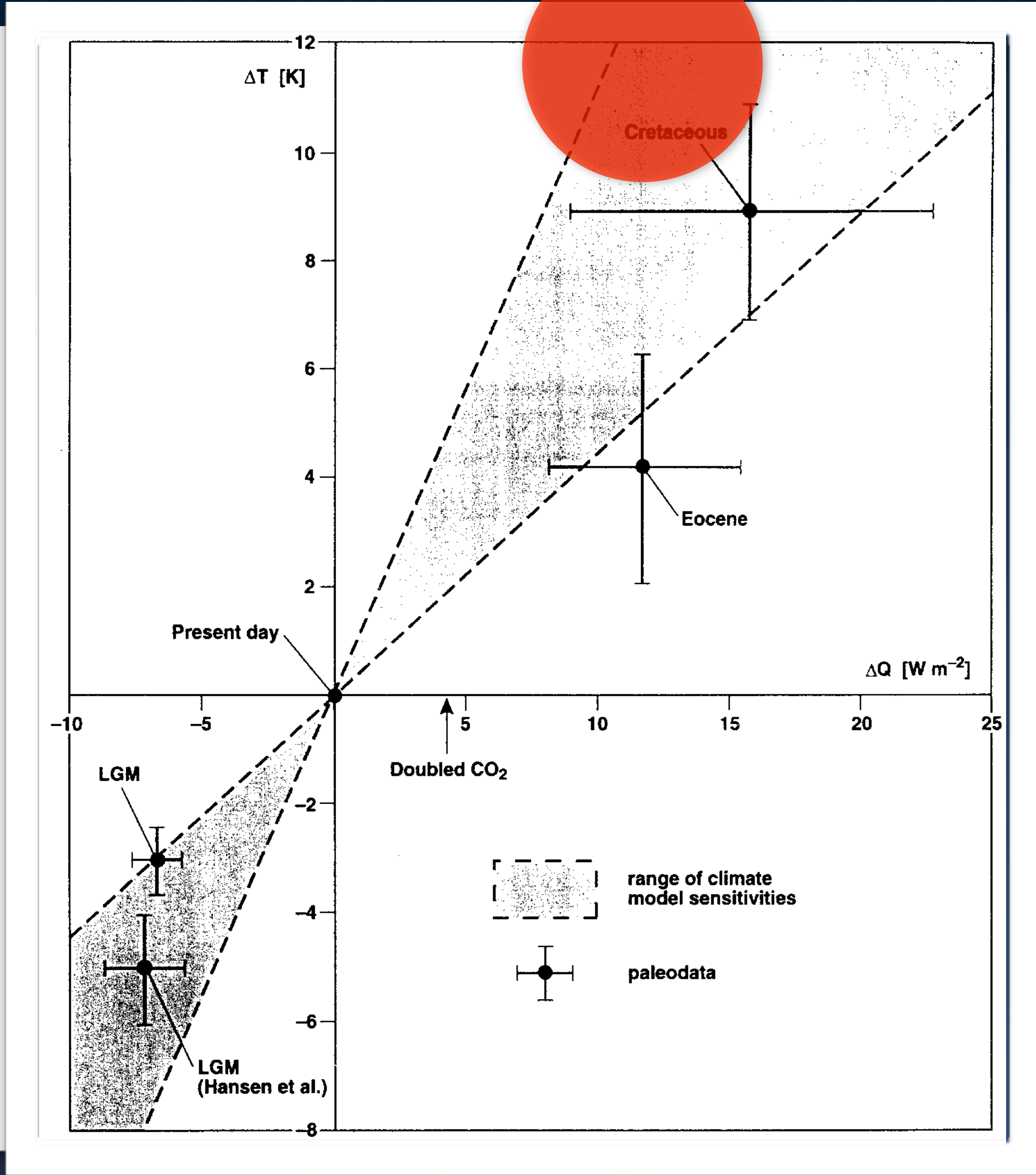


Covey et al., 1996, Barron, 1987

Old reconstructions had tropical cooling

Old Cold Tropics Paradox





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Can increasing carbon dioxide cause climate change?

RICHARD S. LINDZEN

Proc. Natl. Acad. Sci. USA
Vol. 94, pp. 8335–8342, August 1997
Colloquium Paper

ABSTRACT The realistic physical functioning of the greenhouse effect is reviewed, and the role of dynamic transport and water vapor is identified. Model errors and uncertainties are quantitatively compared with the forcing due to doubling CO_2, and they are shown to be too large for reliable model evaluations of climate sensitivities. The possibility of directly measuring climate sensitivity is reviewed. A direct approach using satellite data to relate changes in globally averaged radiative flux changes at the top of the atmosphere to naturally occurring changes in global mean temperature is described. Indirect approaches to evaluating climate sensitivity involving the response to volcanic eruptions and Eocene climate change are also described. Finally, it is explained how, in principle, a climate that is insensitive to gross radiative forcing as produced by doubling CO_2 might still be able to undergo major changes of the sort associated with ice ages and equable climates.

Indirect Approach: Eocene.... Past climates involved marked changes in the equator-to-pole temperature difference....for warmer climates, like that of the Eocene.... the reduced equator-to-pole temperature difference almost certainly called for an increased heat flux out of the tropics.....

This ought to have cooled the tropics, and, indeed, early estimates of Eocene equatorial temperatures indicated that the tropics may have been as much as 5°C cooler than they are today.....

However, recent corrections to these early estimates have reduced the equatorial cooling to less than 1°C [Zachos et al., 1994], which is more in line with the sensitivity estimates based on the sequence of volcanos around the turn of the past century....
Again, there are legitimate questions about this procedure, not the least of which concern the reliability and representativeness of the paleoclimatic data. The role of potentially higher levels of CO_2 during the Eocene could have contributed to reduced equatorial cooling, though current assessments [Sinha and Stott,

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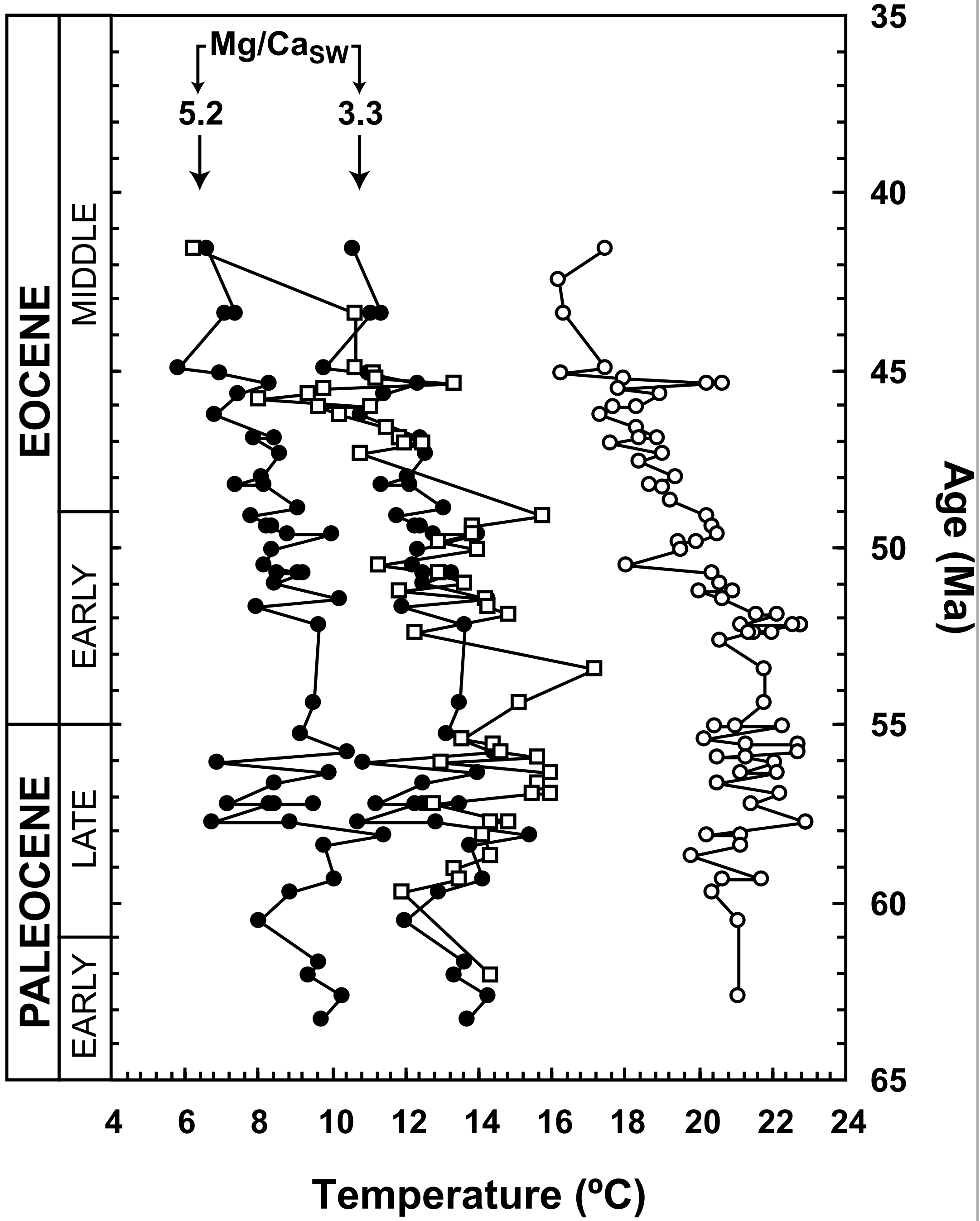
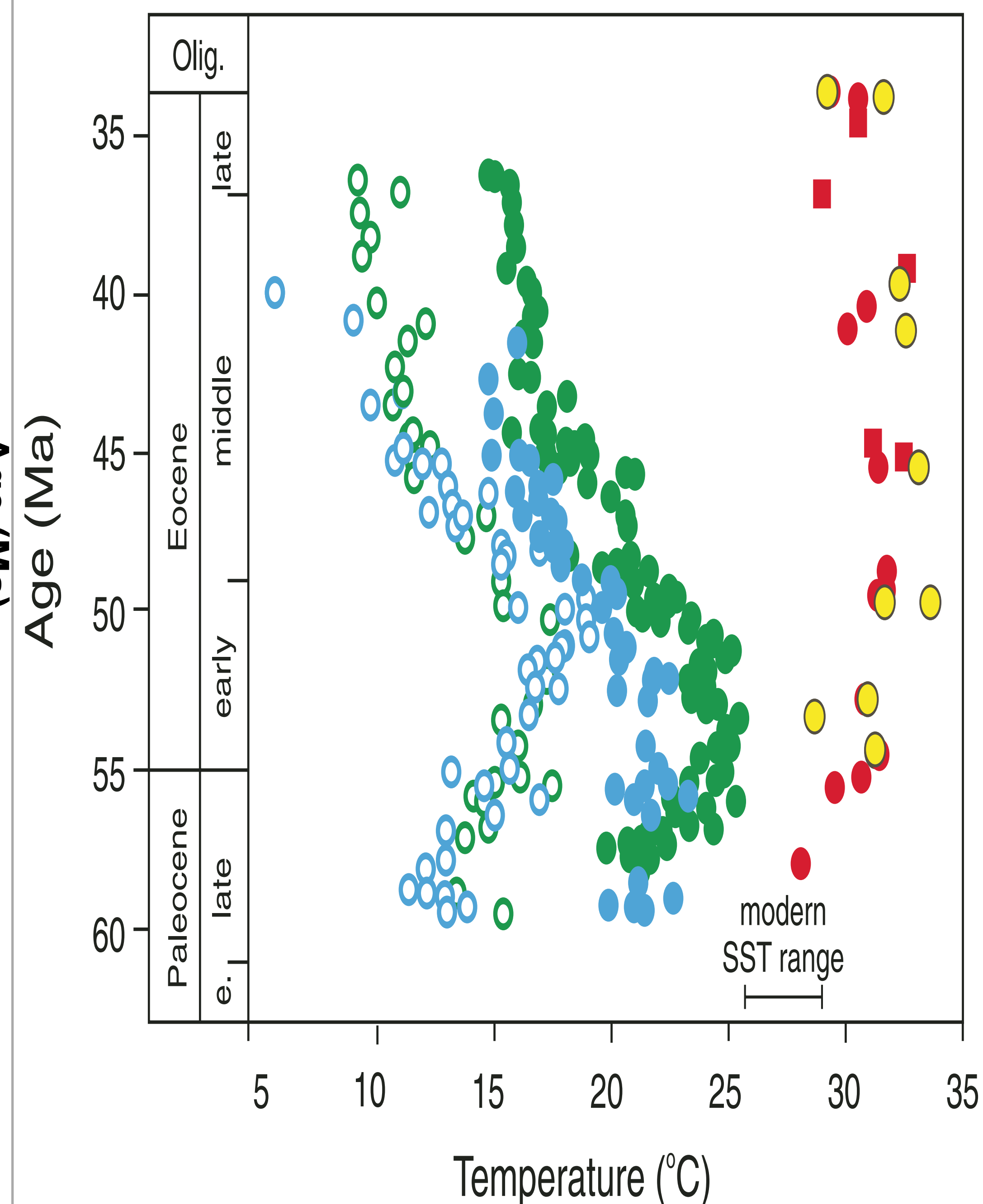




Dutton et al 2006 (left), benthic and plankton temperatures, Site 865, C. Equatorial Pacific

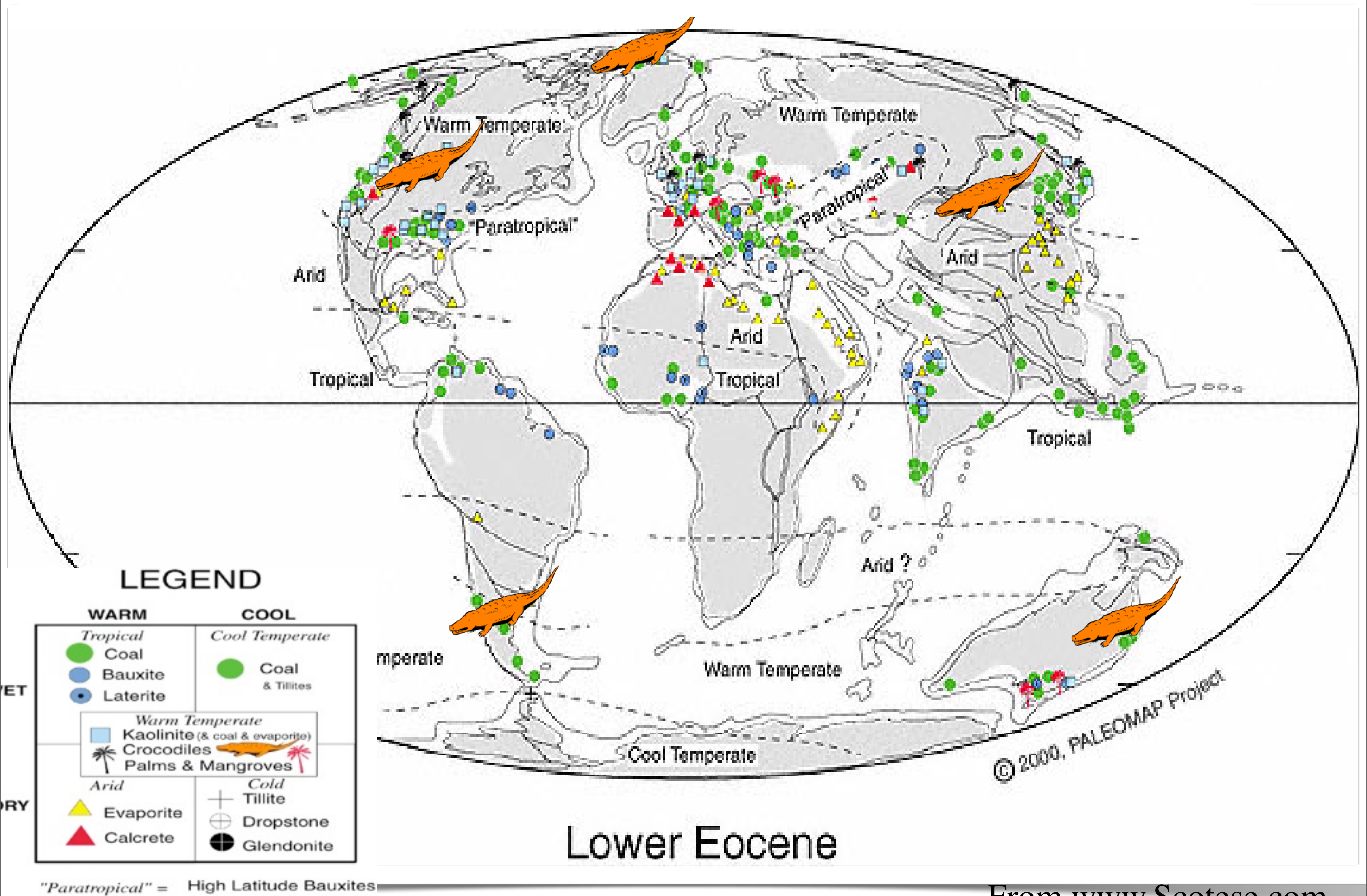
Pearson et al., 2007, surface temperatures from Tanzania (~18°S)

Polar Amplification

- Noted for all major climate changes
- Especially the early Eocene
- Polar regions warm much more than the rest of the world

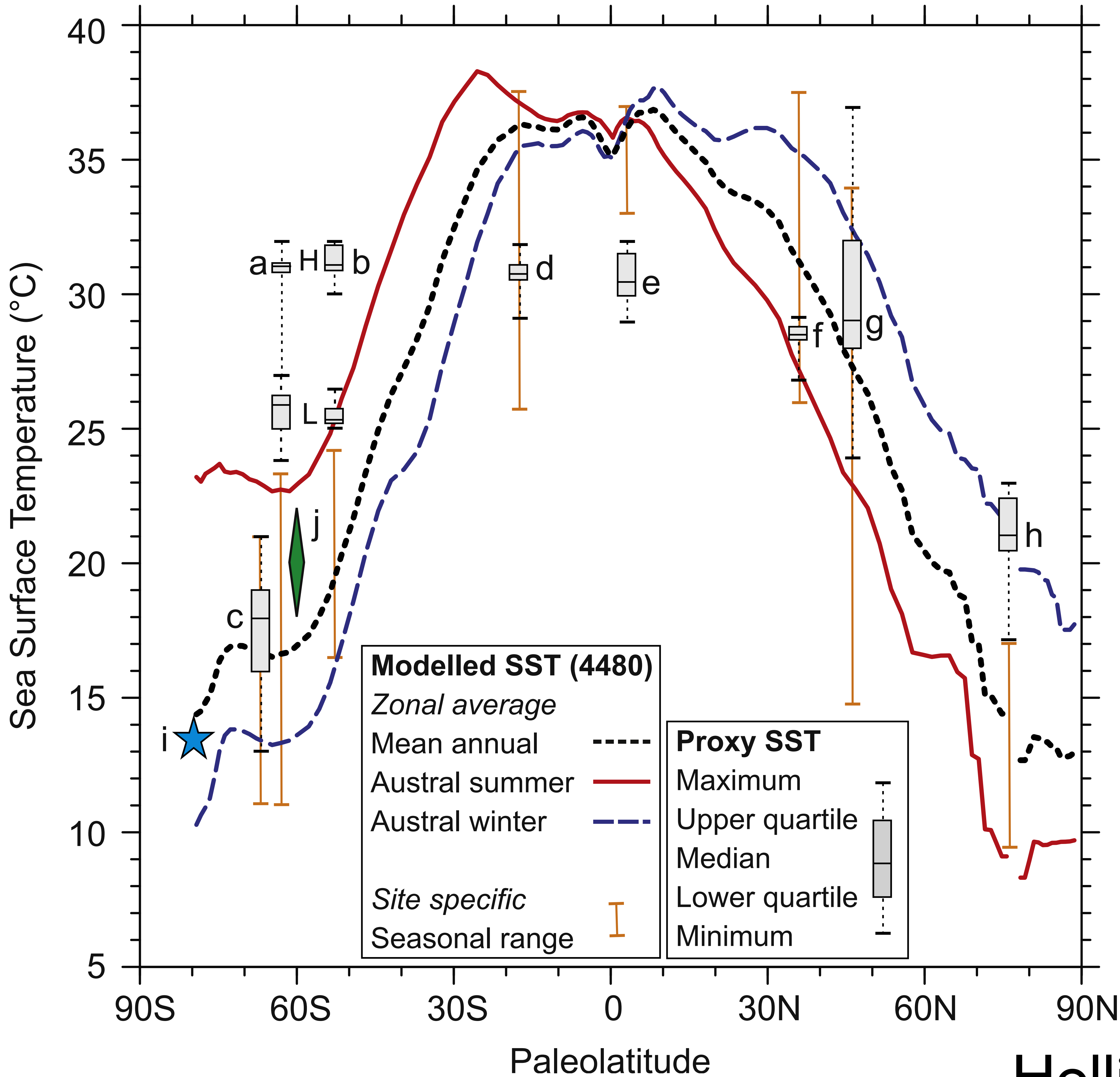
Matthew Huber

Distribution of Faunal and Floral Climate Proxies



From www.Scotese.com

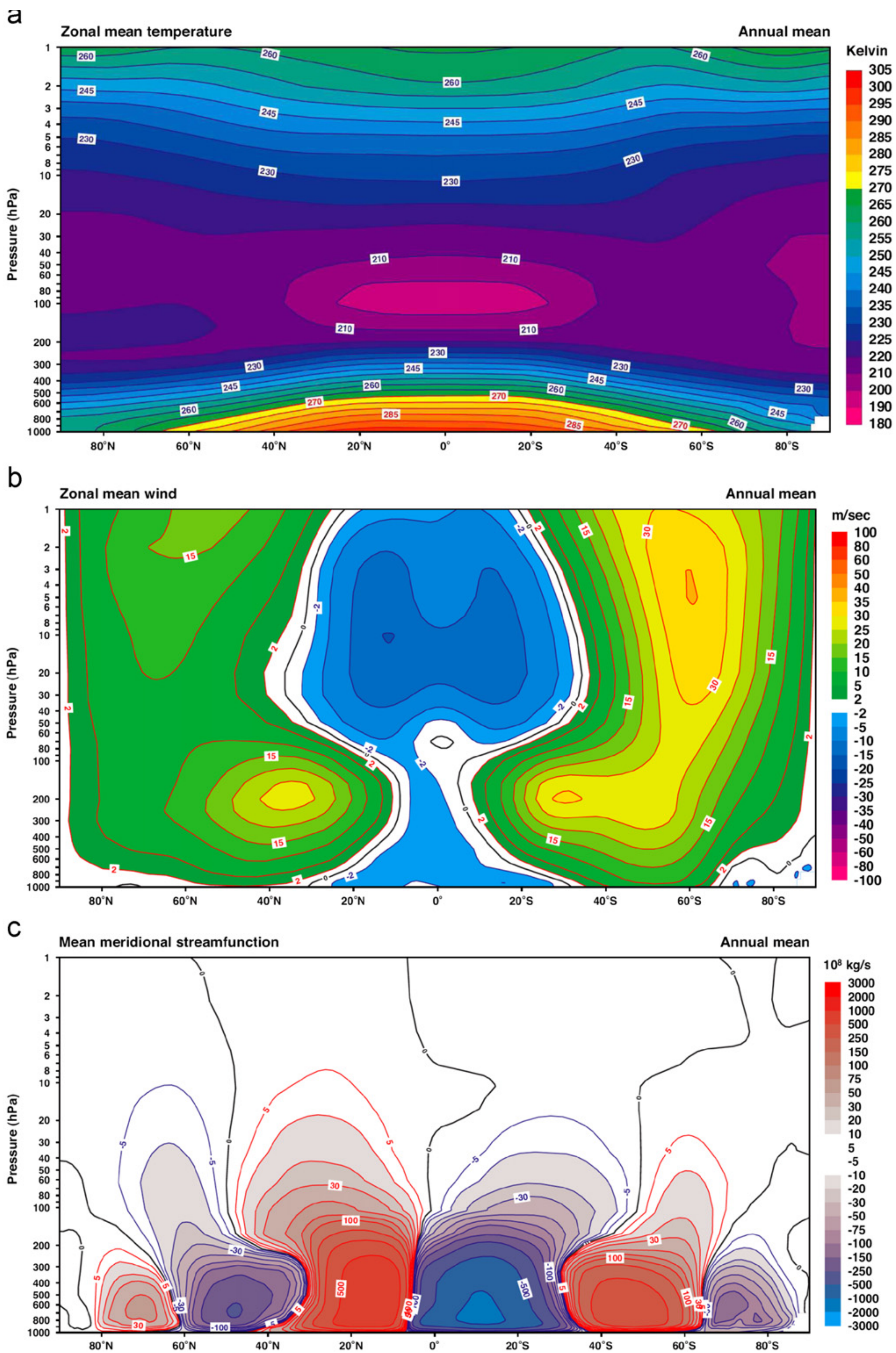
Matthew Huber



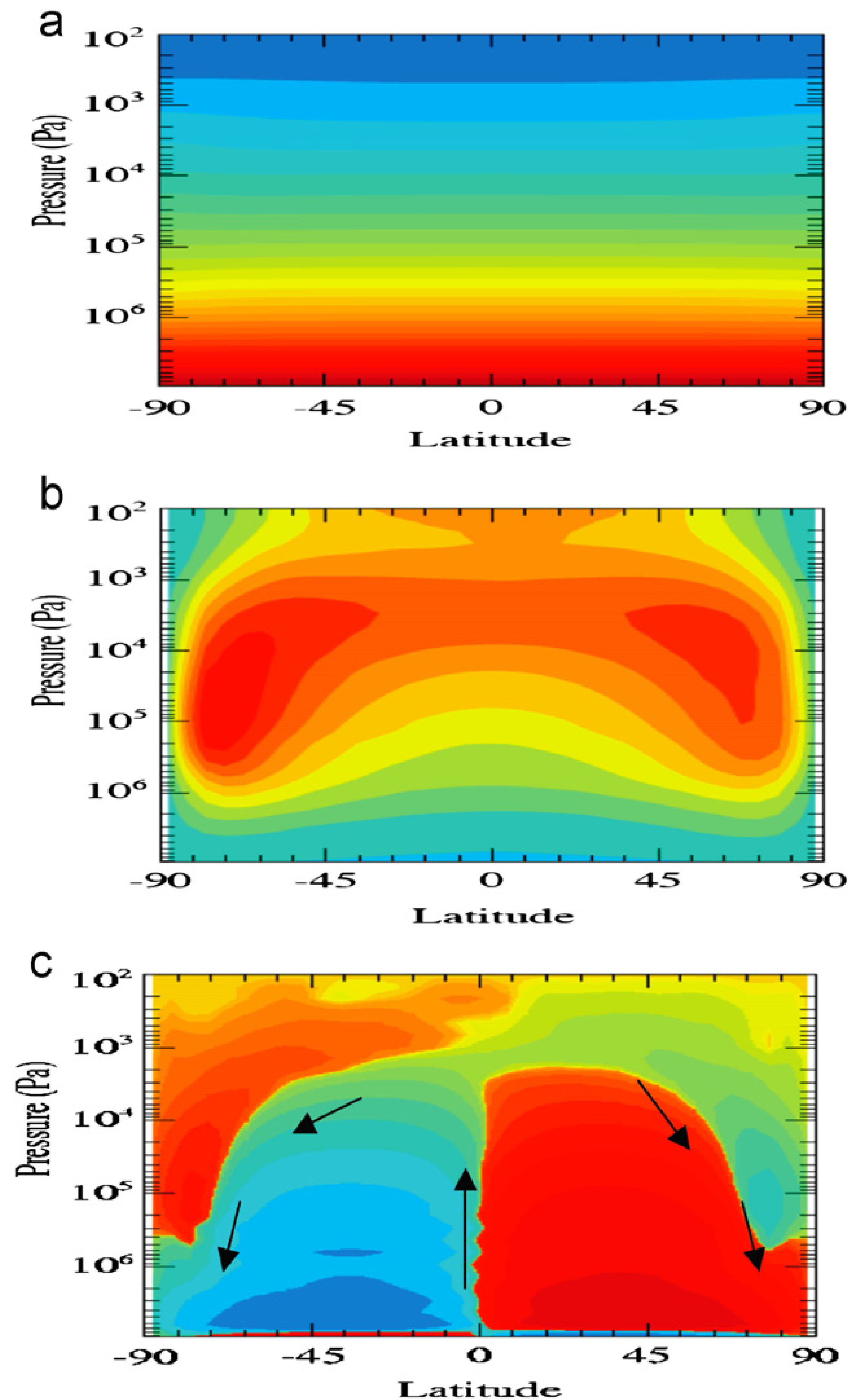
Hollis et al 2012

Are qualitatively new dynamics possible?

- The short answer is, not many people have asked this question, so we don't know
- Going back to the early Earth, some work has been done and overlap with planetary atmospheres community is clear
- But, can major changes to the basic atmospheric or ocean circulations happen for more modern earth parameters?
- How about for really hot temperatures or low temperature gradients?



Earth

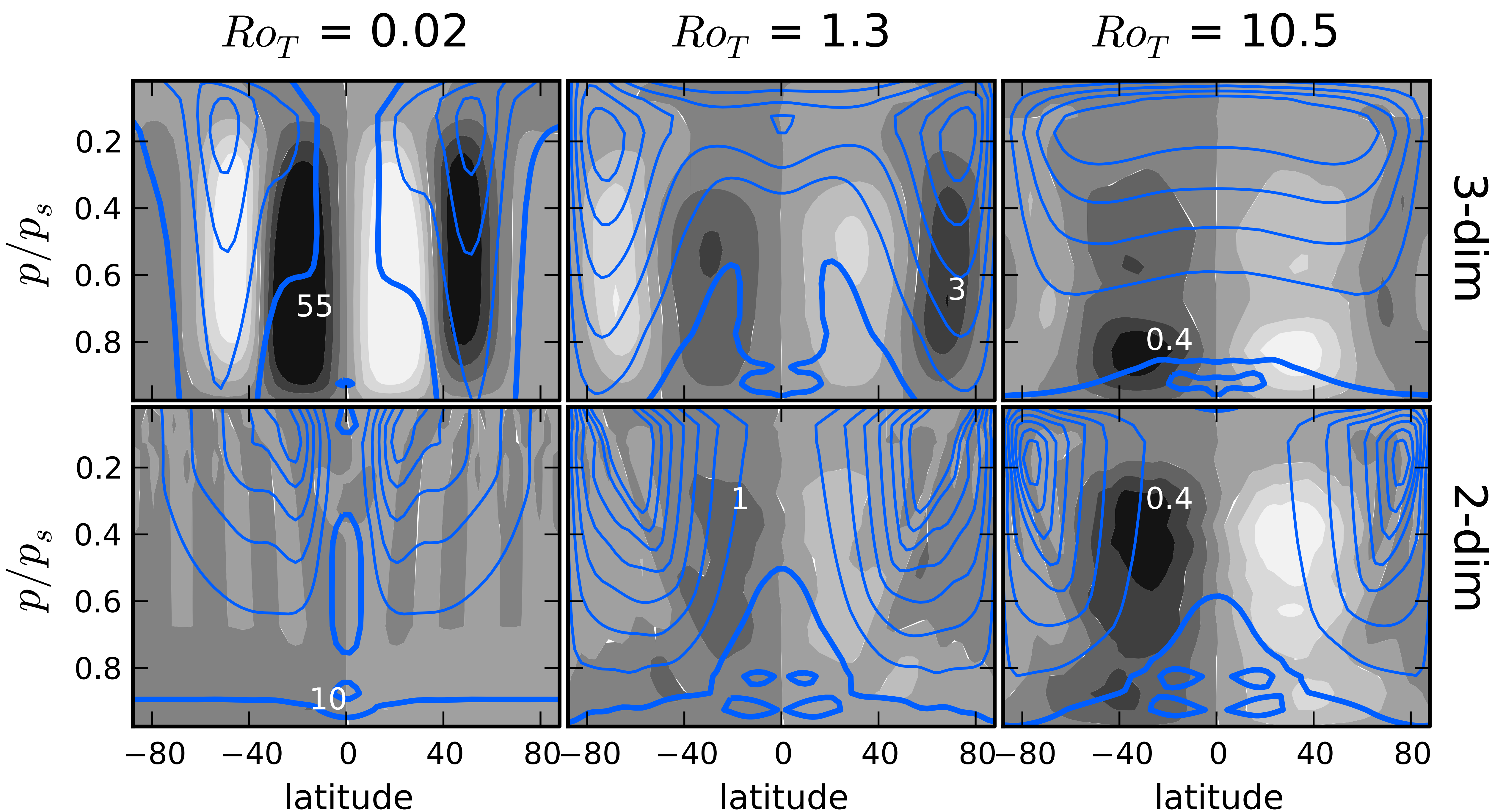


Venus

Read, 2012

$$\mathcal{R}o_T \simeq \frac{U_T}{\Omega L} = \frac{g\alpha\Delta T D}{\Omega^2 L^2}$$

Advection
----
rotation

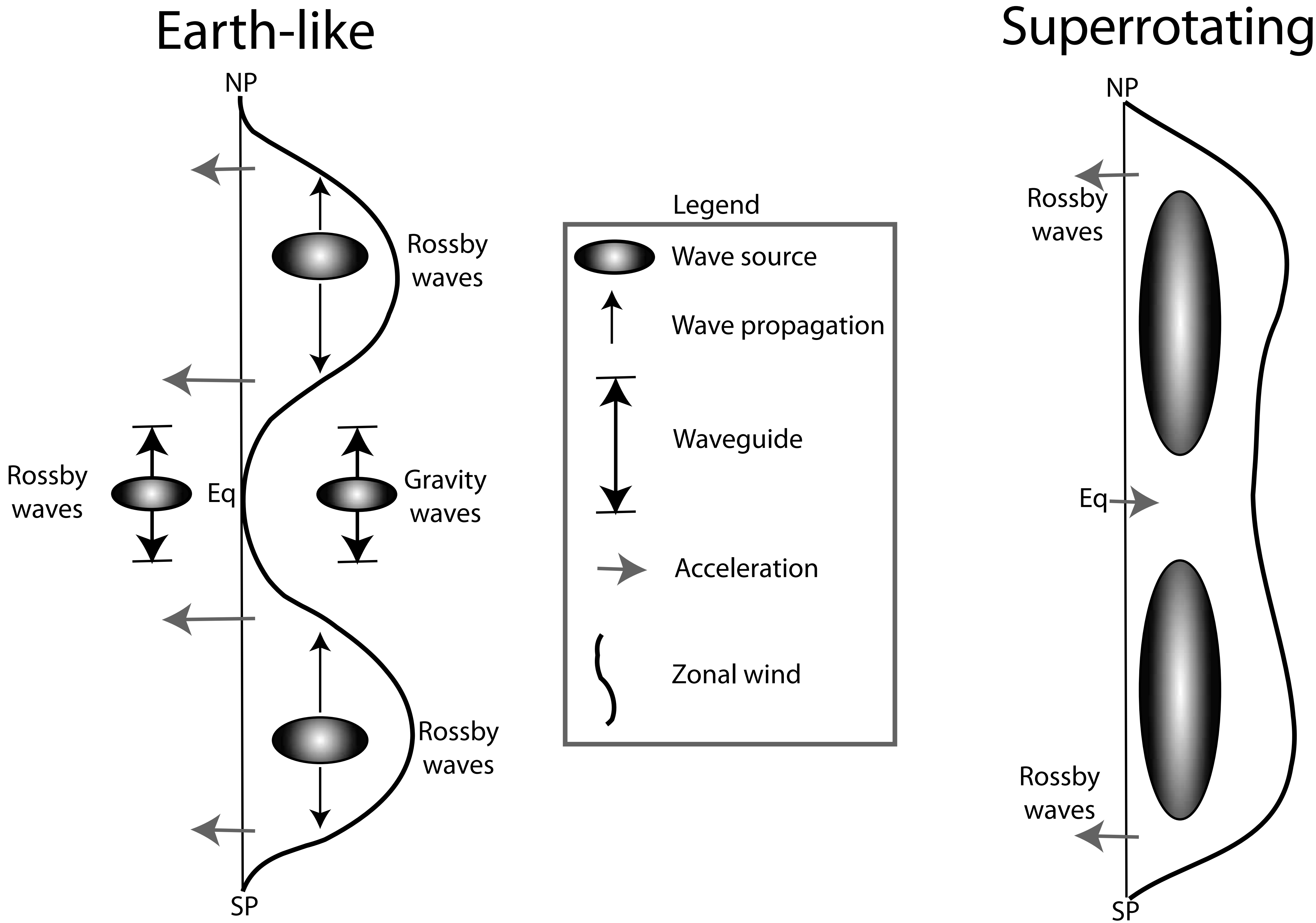


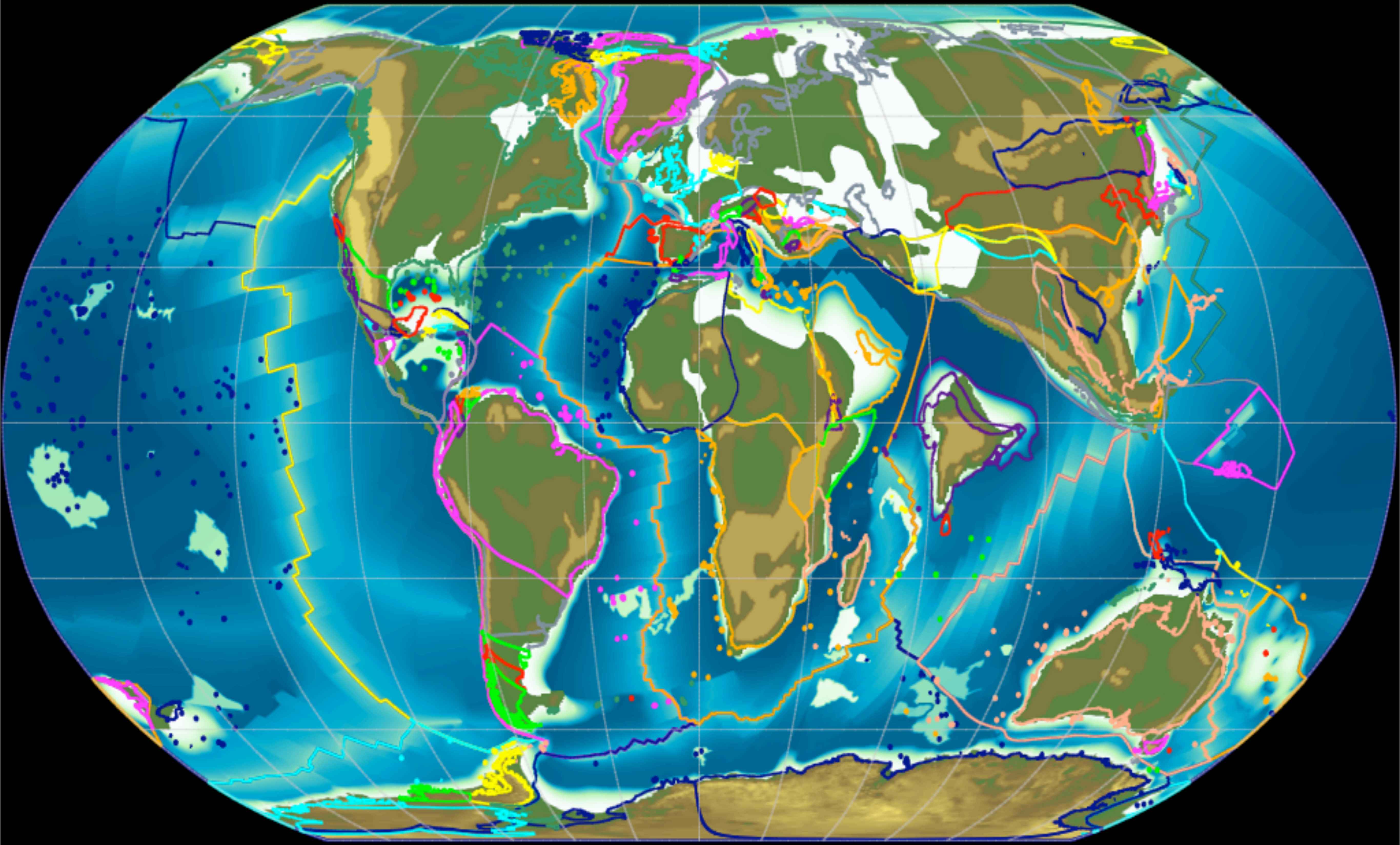
~Earth

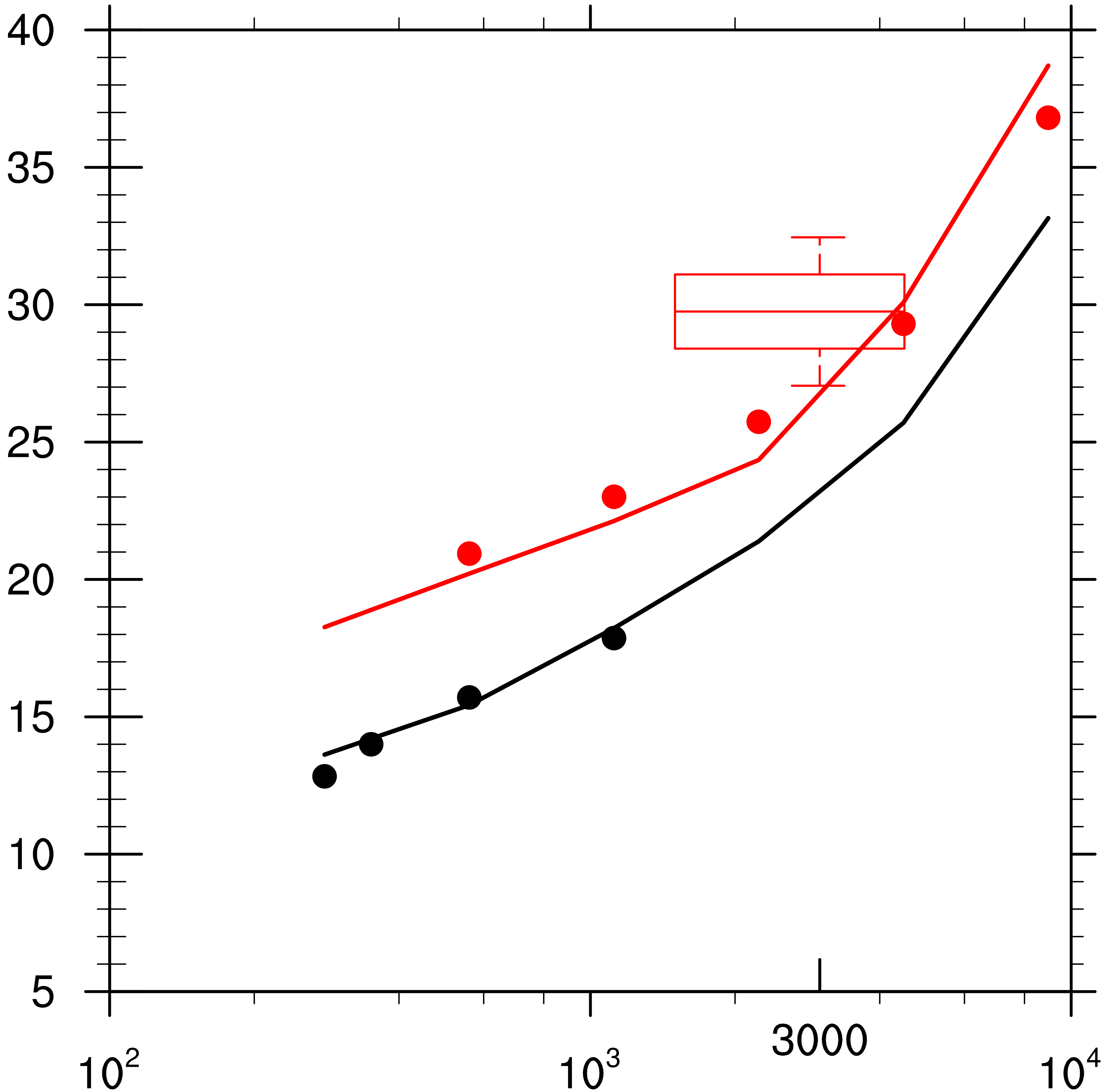
~Titan/Venus

Mitchell and Vallis, 2010, also see Liu and Schneider, 2011

Mitchell and Vallis Schematic



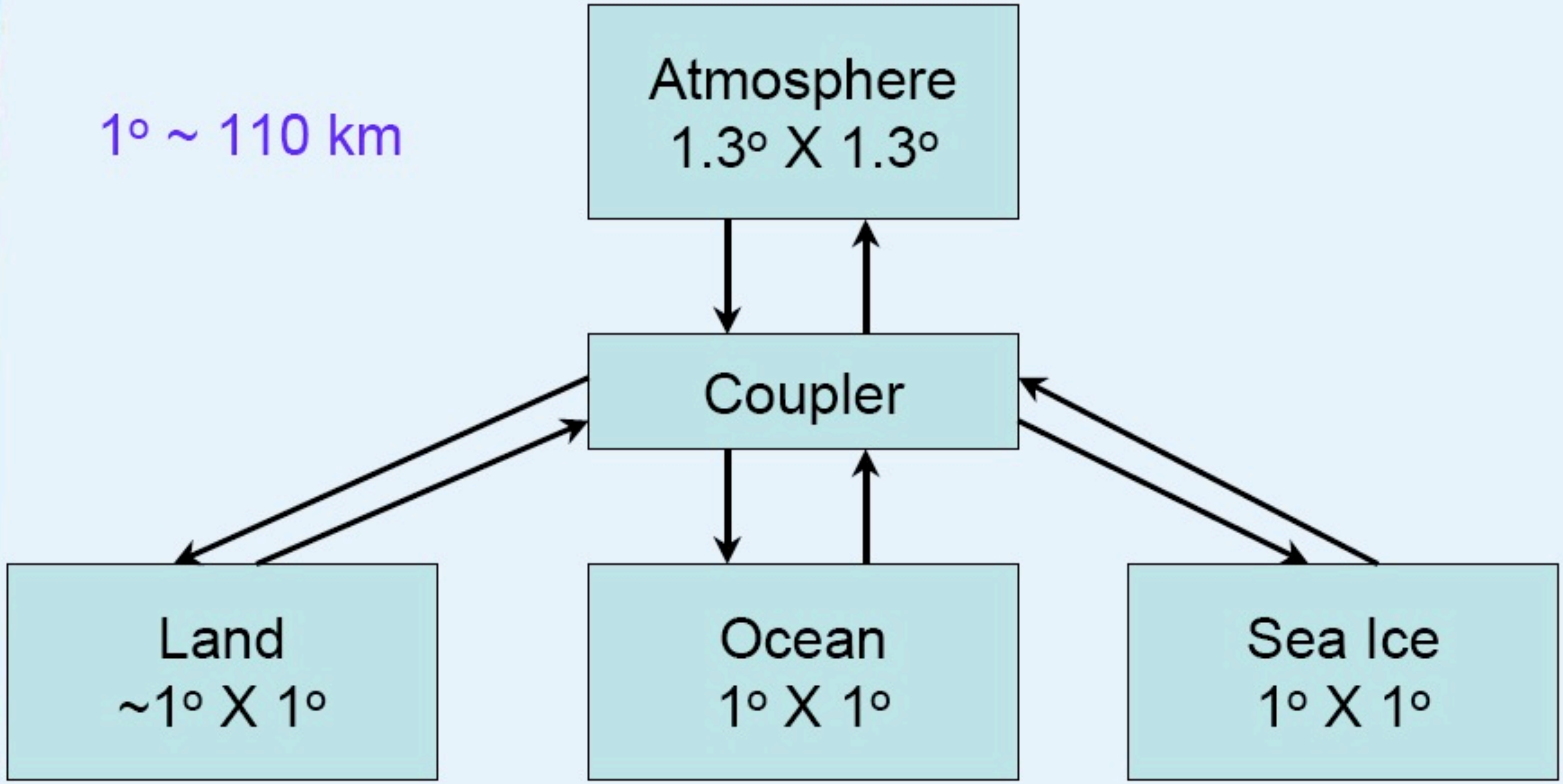




40
35
30
25
20
15
10
5
10^2
10^3
3000
10^4

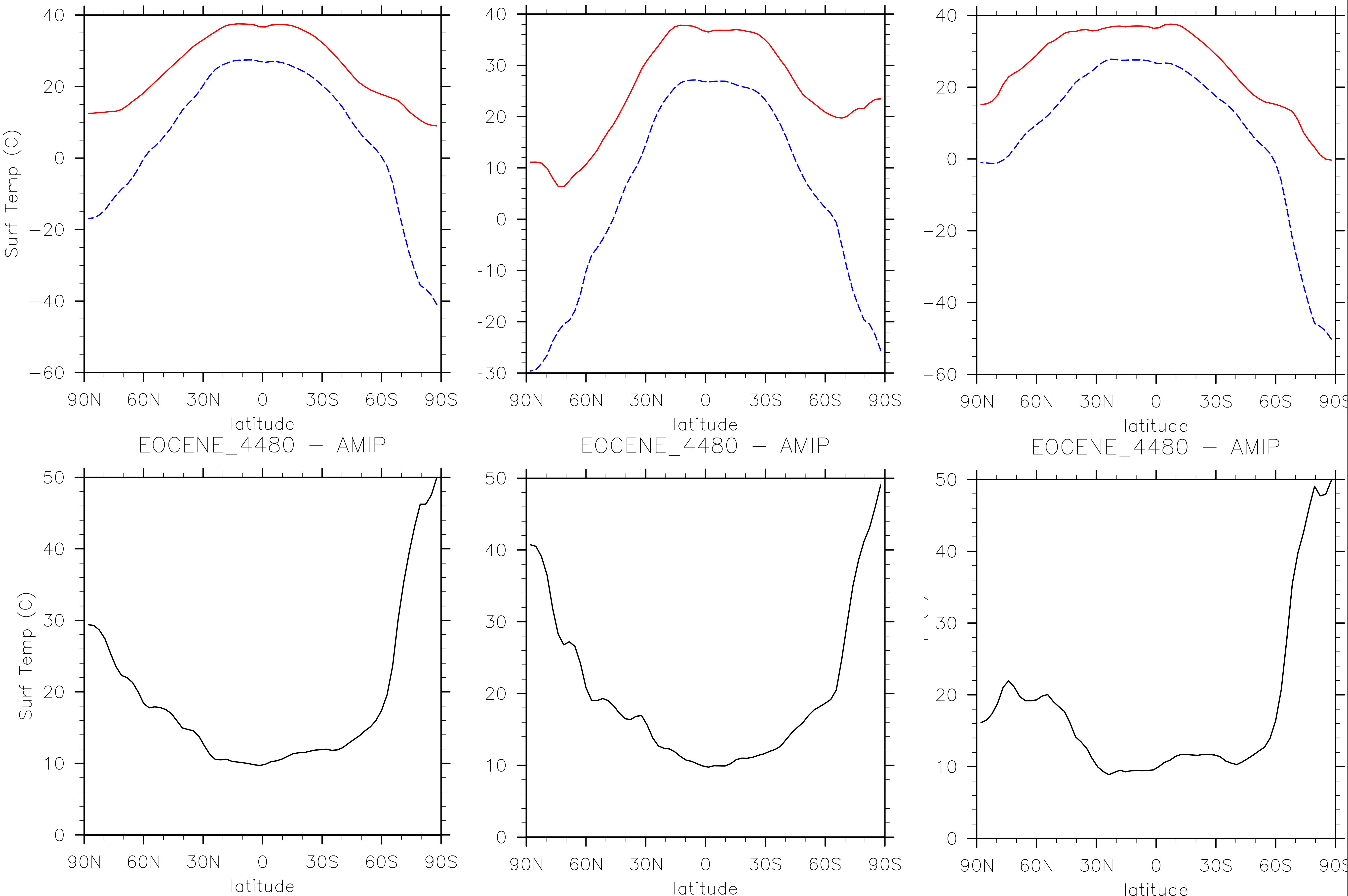
Current CCSM3 Structure

$1^\circ \sim 110$ km

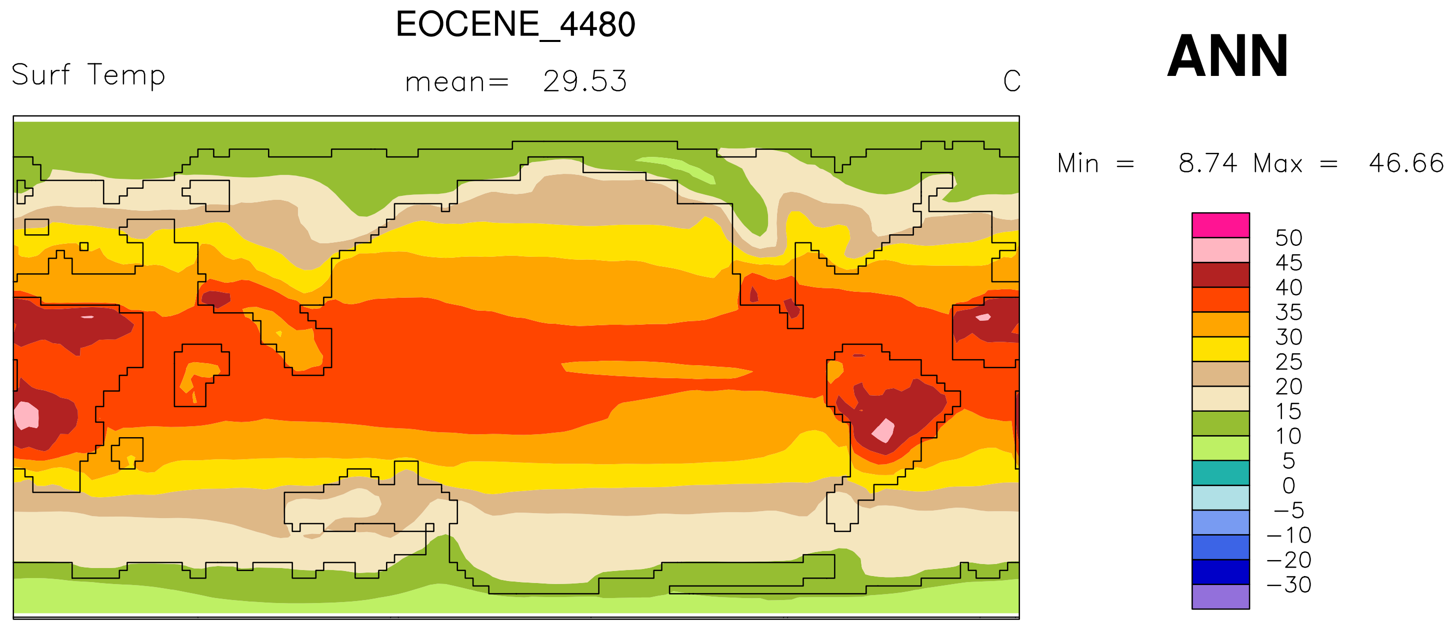


NCAR

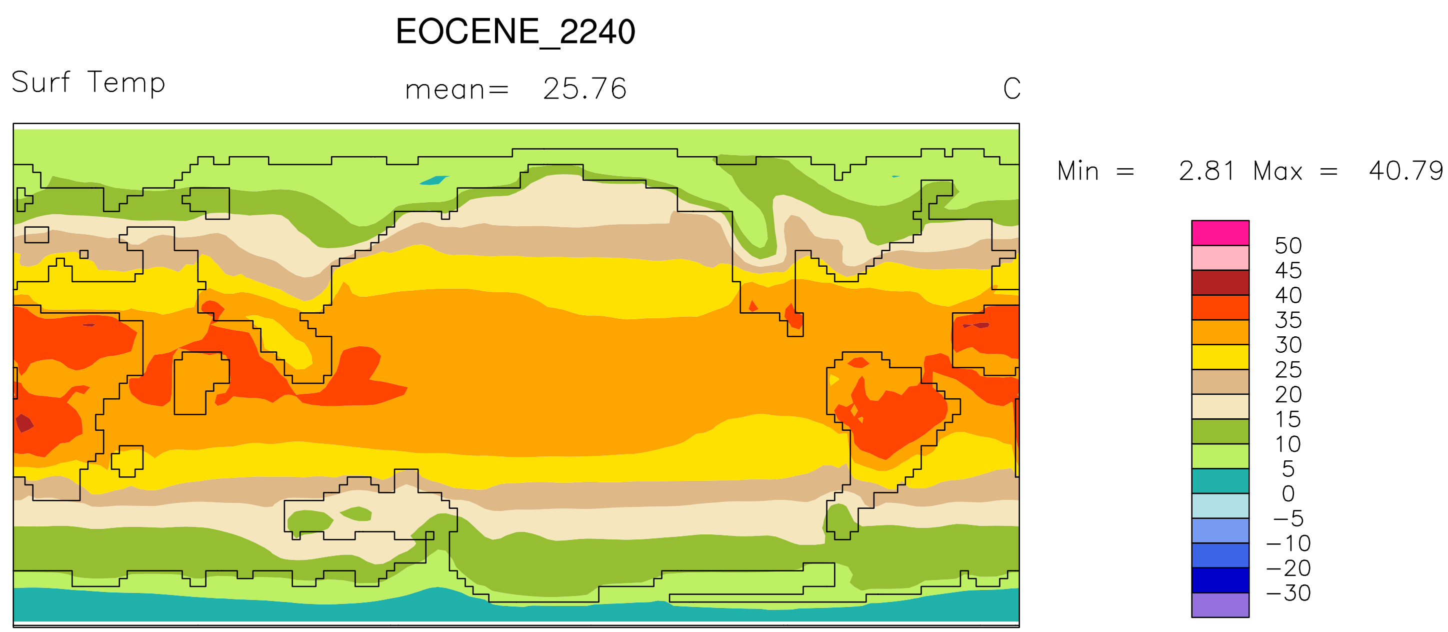
EOCENE Model at 4480 ppm CO_2 Compared with modern Model



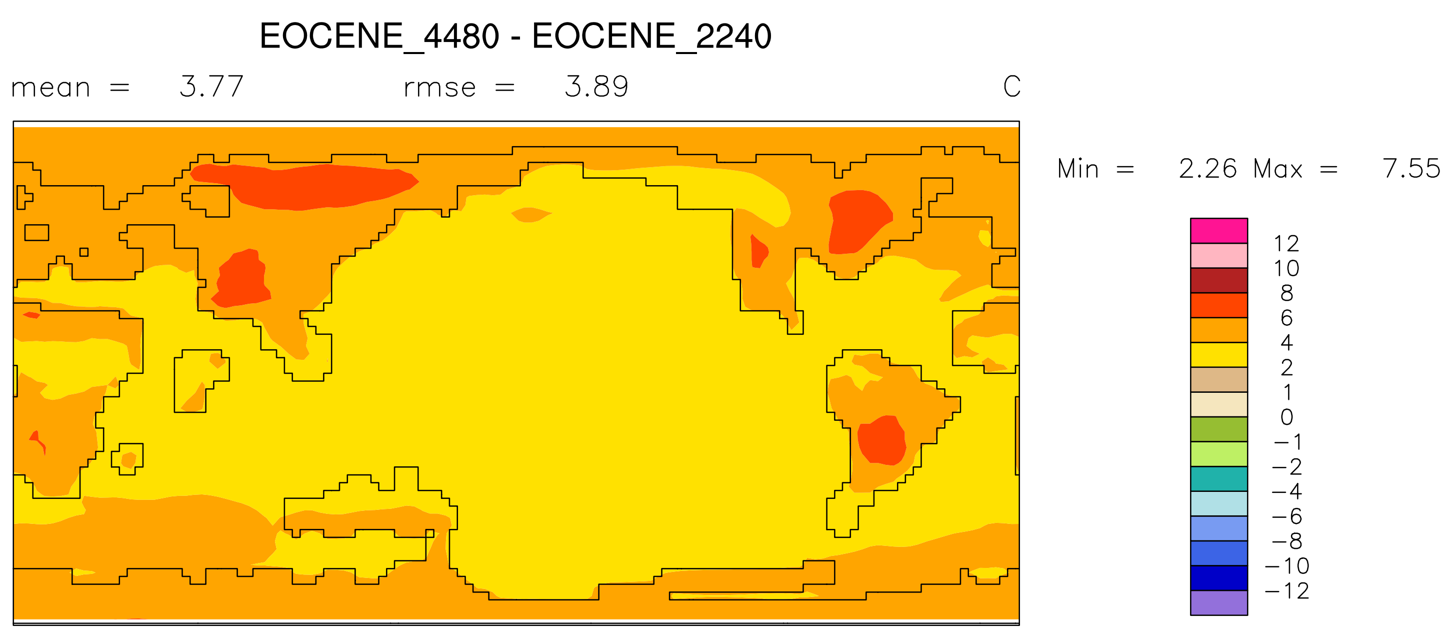
Eocene Model at 4480



Eocene Model at 2240



Anomaly

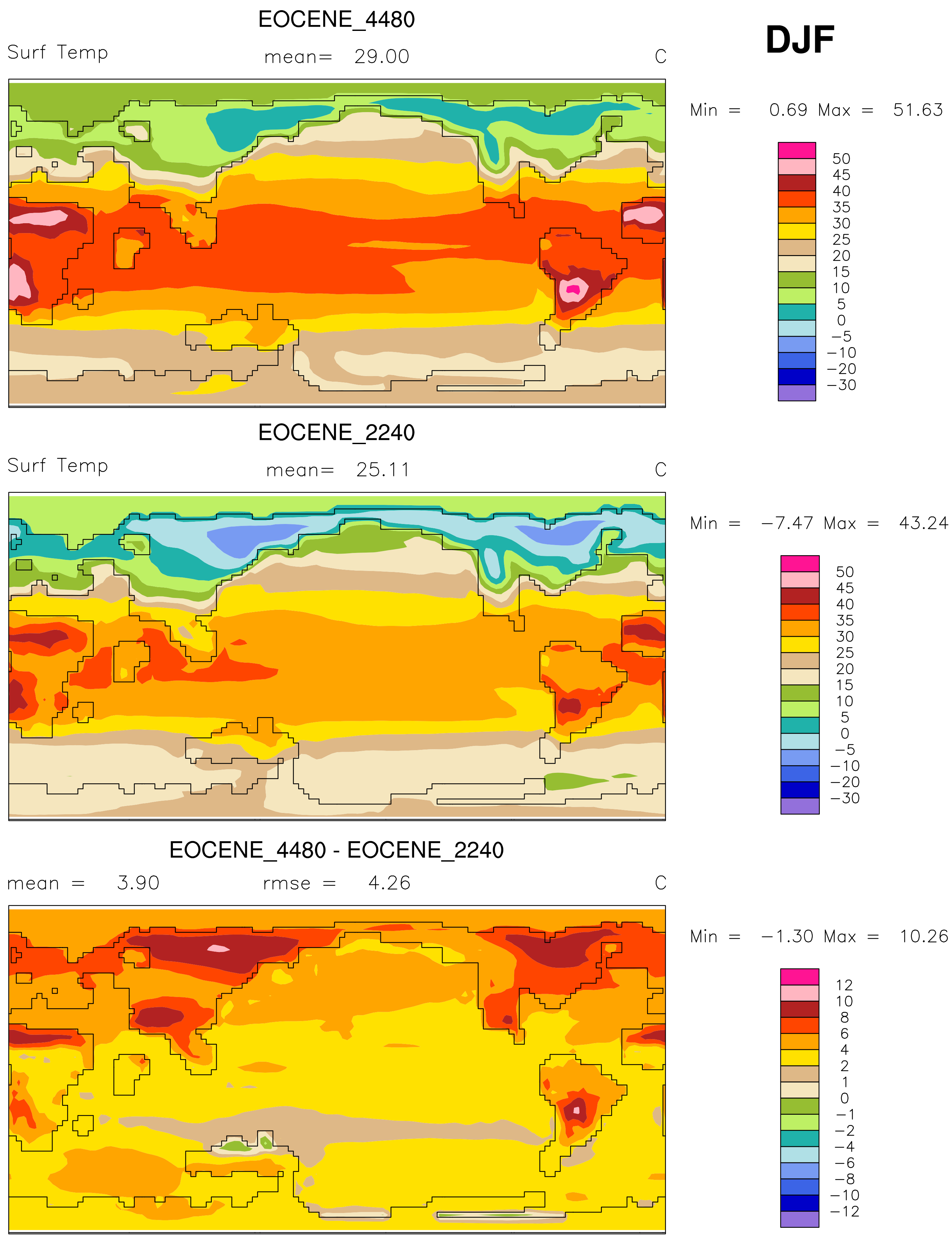


DJF

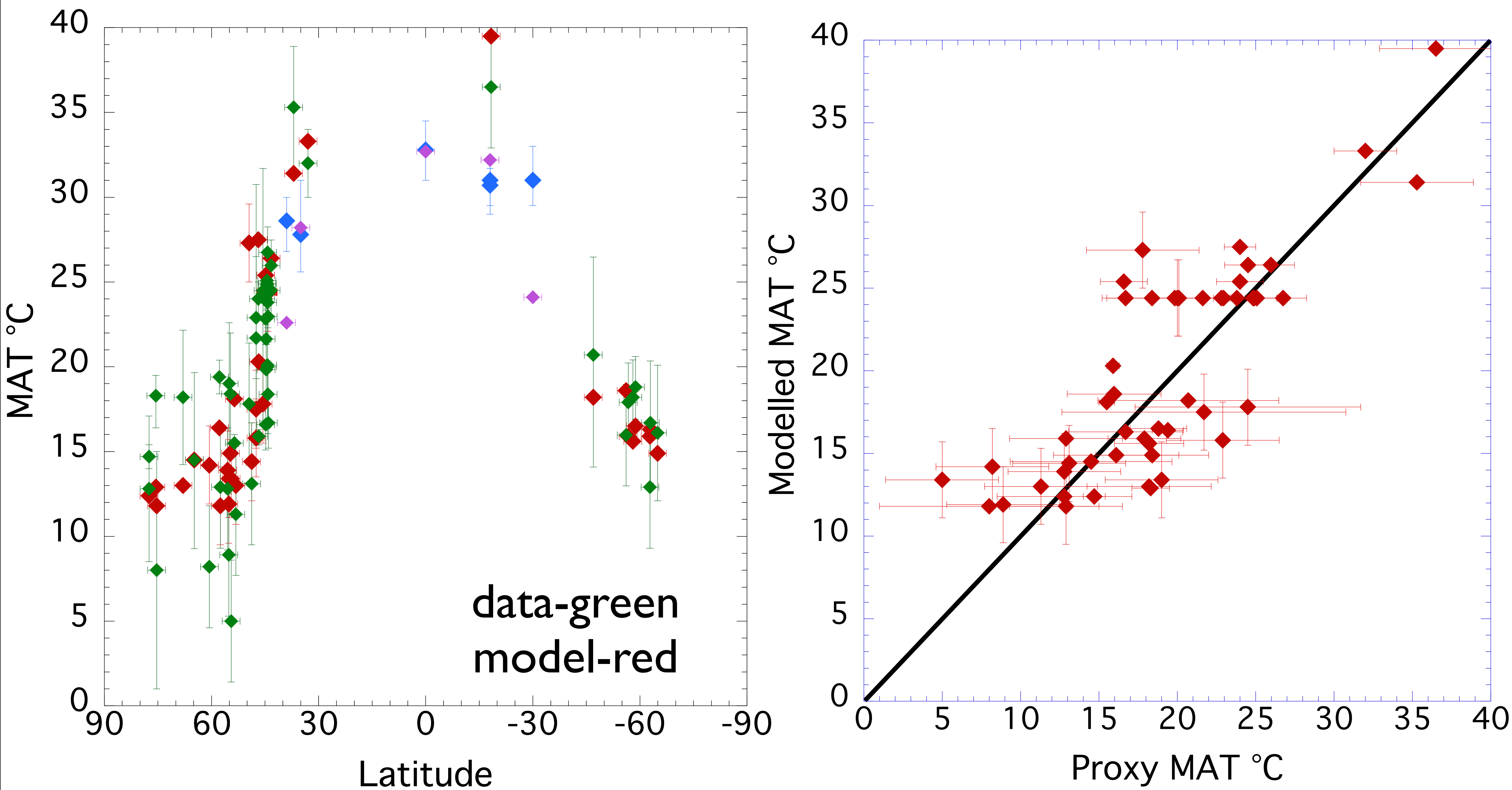
Eocene Model at 4480

Eocene Model at 2240

Anomaly

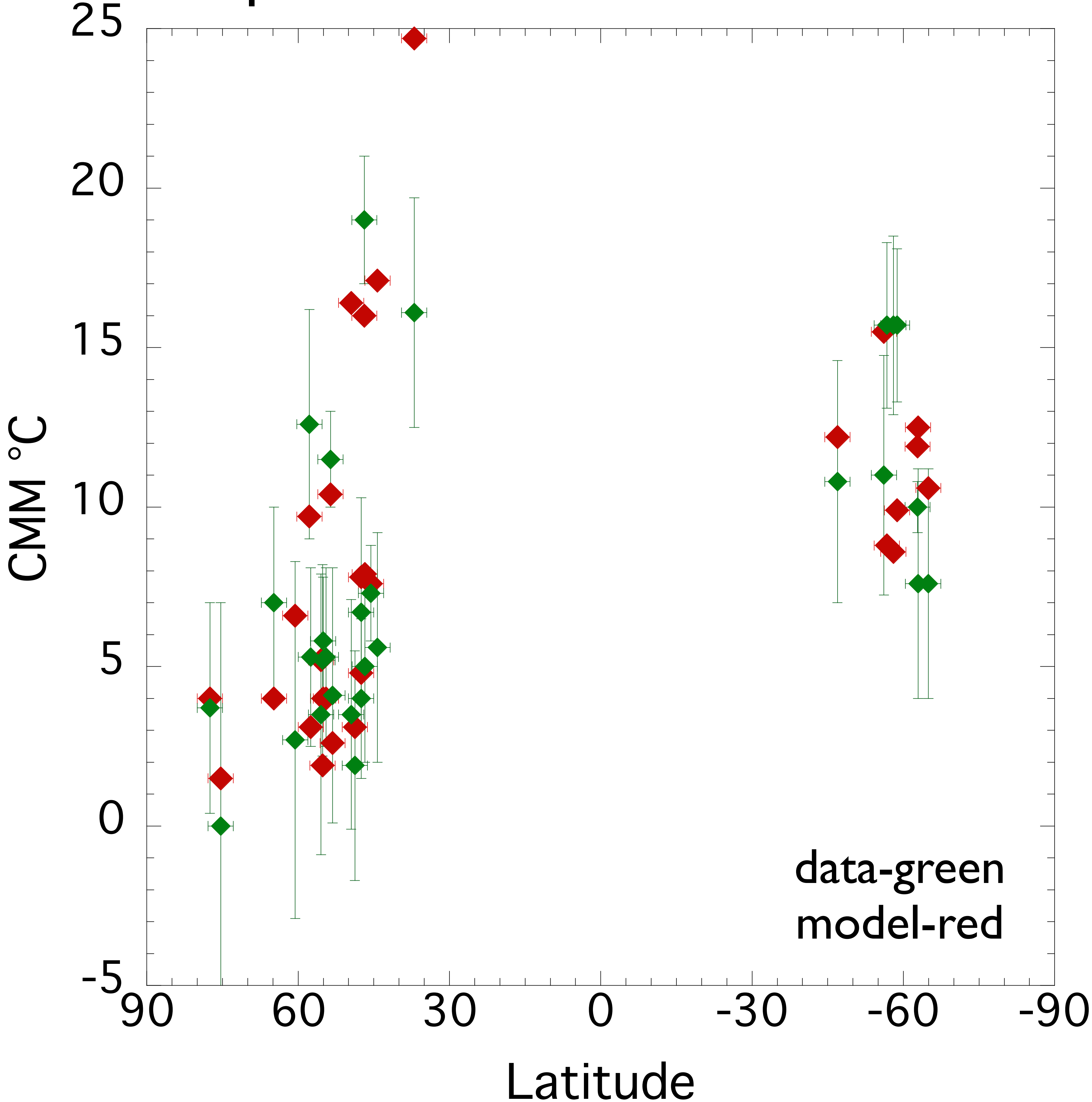


Model-data comparison

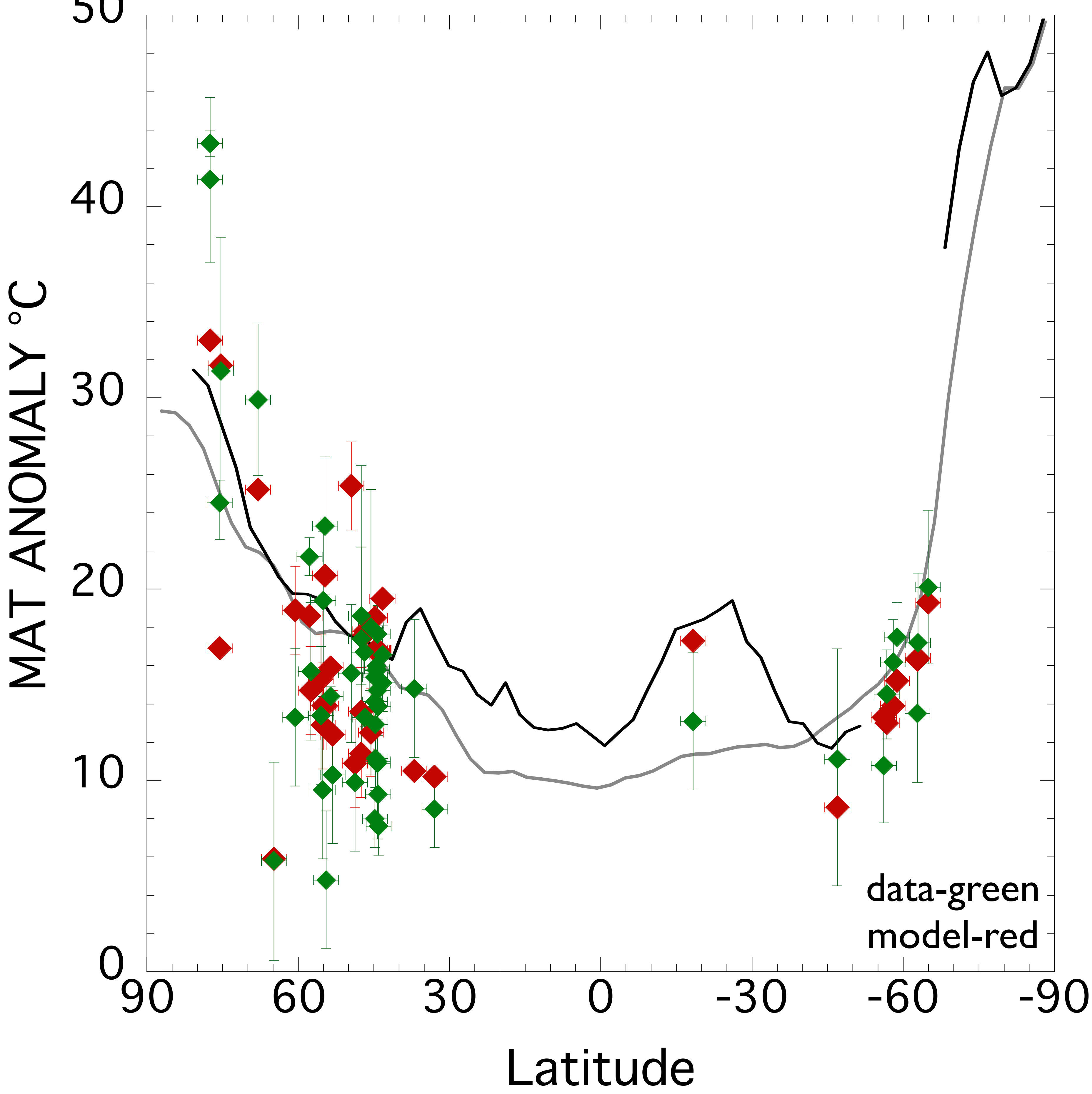


EOCENE Model at 4480 ppm, early Eocene proxy data

Model-data comparison for Cold Month Mean Temperature



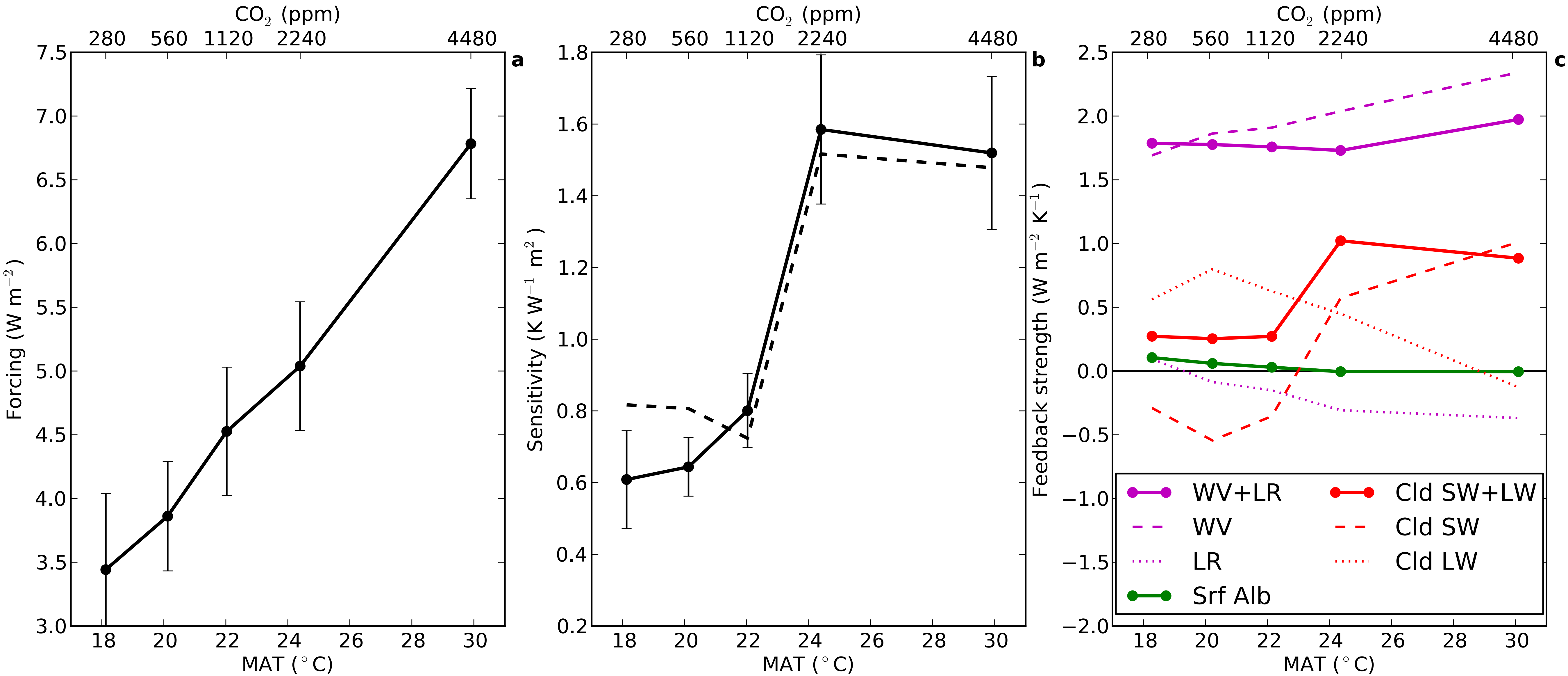
Model-data comparison for warming with respect to Modern



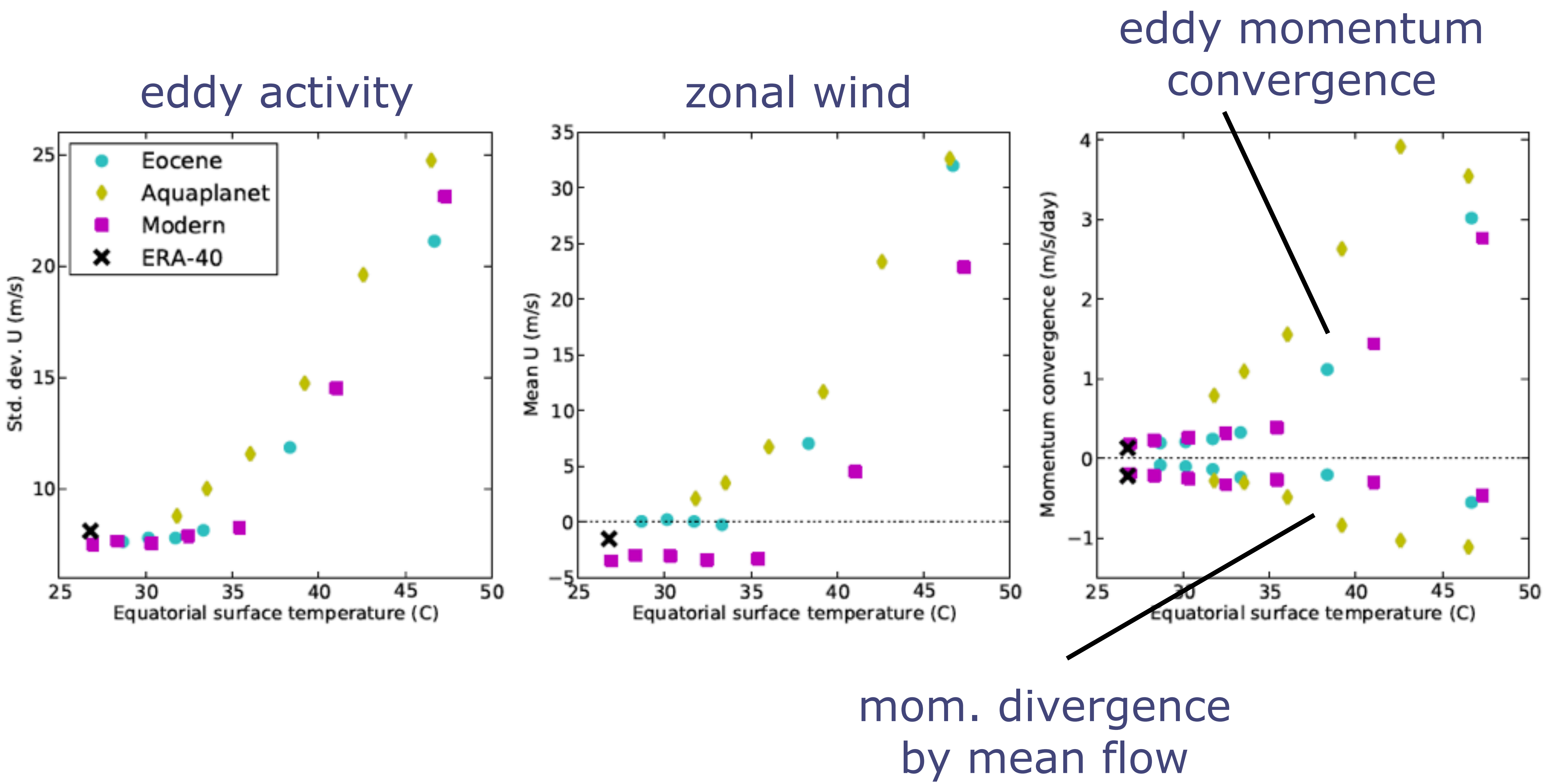
radiative forcing per doubling

sensitivity for each doubling

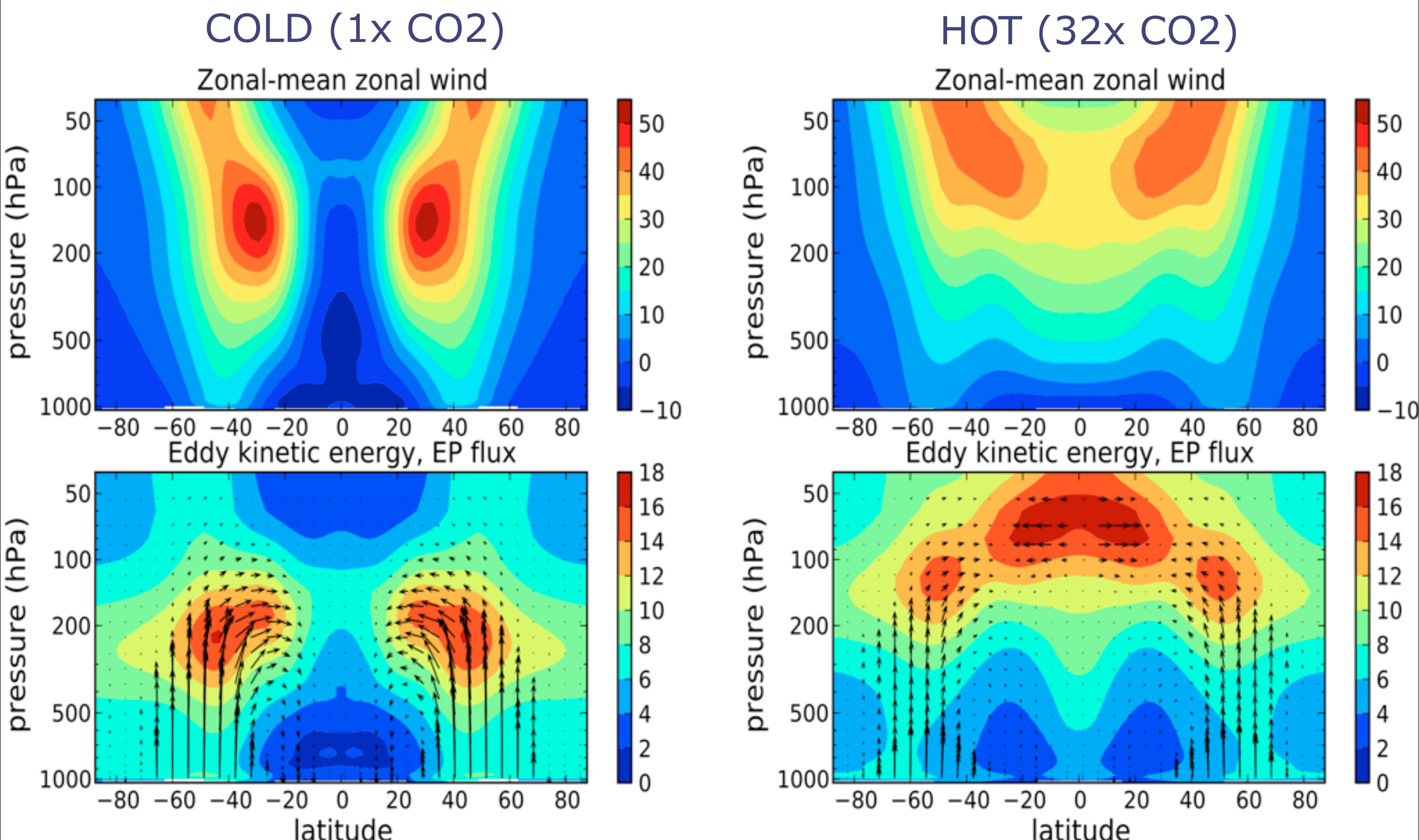
feedback



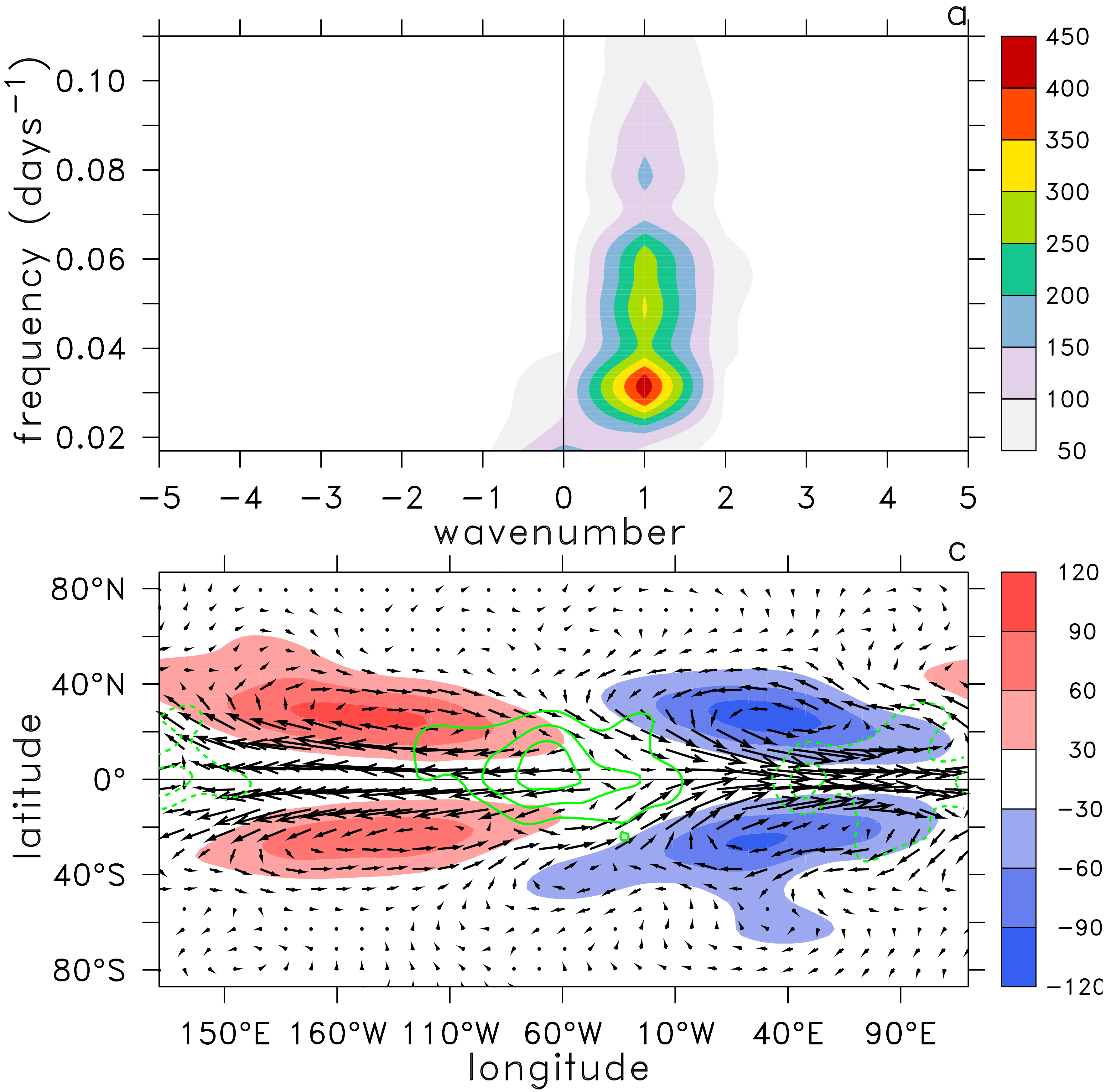
Changes in equatorial wind, eddy activity and momentum balance



Transition to superrotation

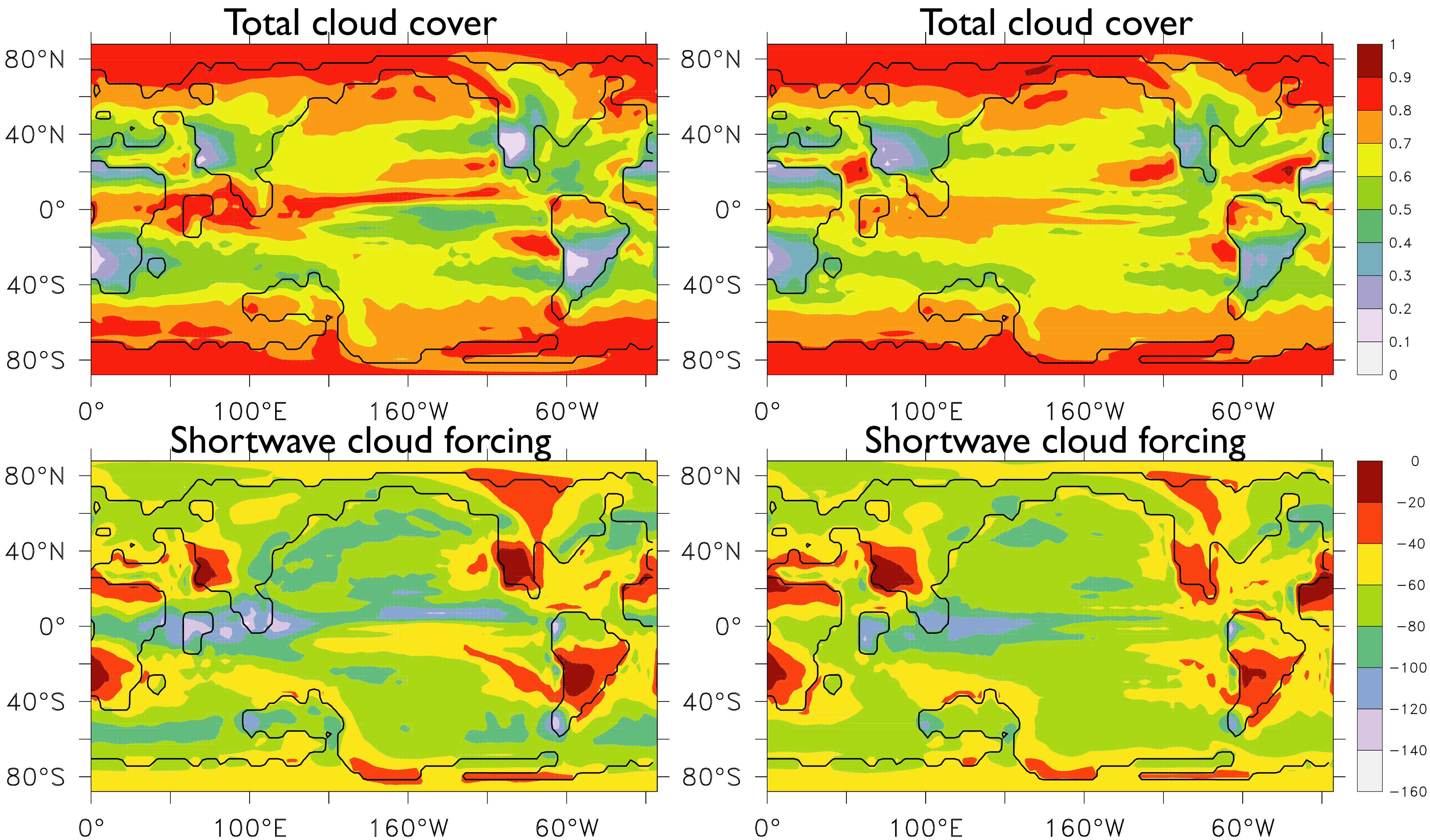


(Caballero & Huber GRL 2010)



a
frequency (days^{-1})
0.10
0.08
0.06
0.04
0.02
−5
−4
−3
−2
−1
0
1
2
3
4
5
wavenumber
450
400
350
300
250
200
150
100
50
c
80°N
40°N
0°
40°S
80°S
latitude
150°E
160°W
110°W
60°W
10°W
40°E
90°E
longitude
120
90
60
30
−30
−60
−90
−120

Eocene 2240 ppm CO_2 | Eocene 4480 ppm CO_2



in collaboration with Rodrigo Caballero

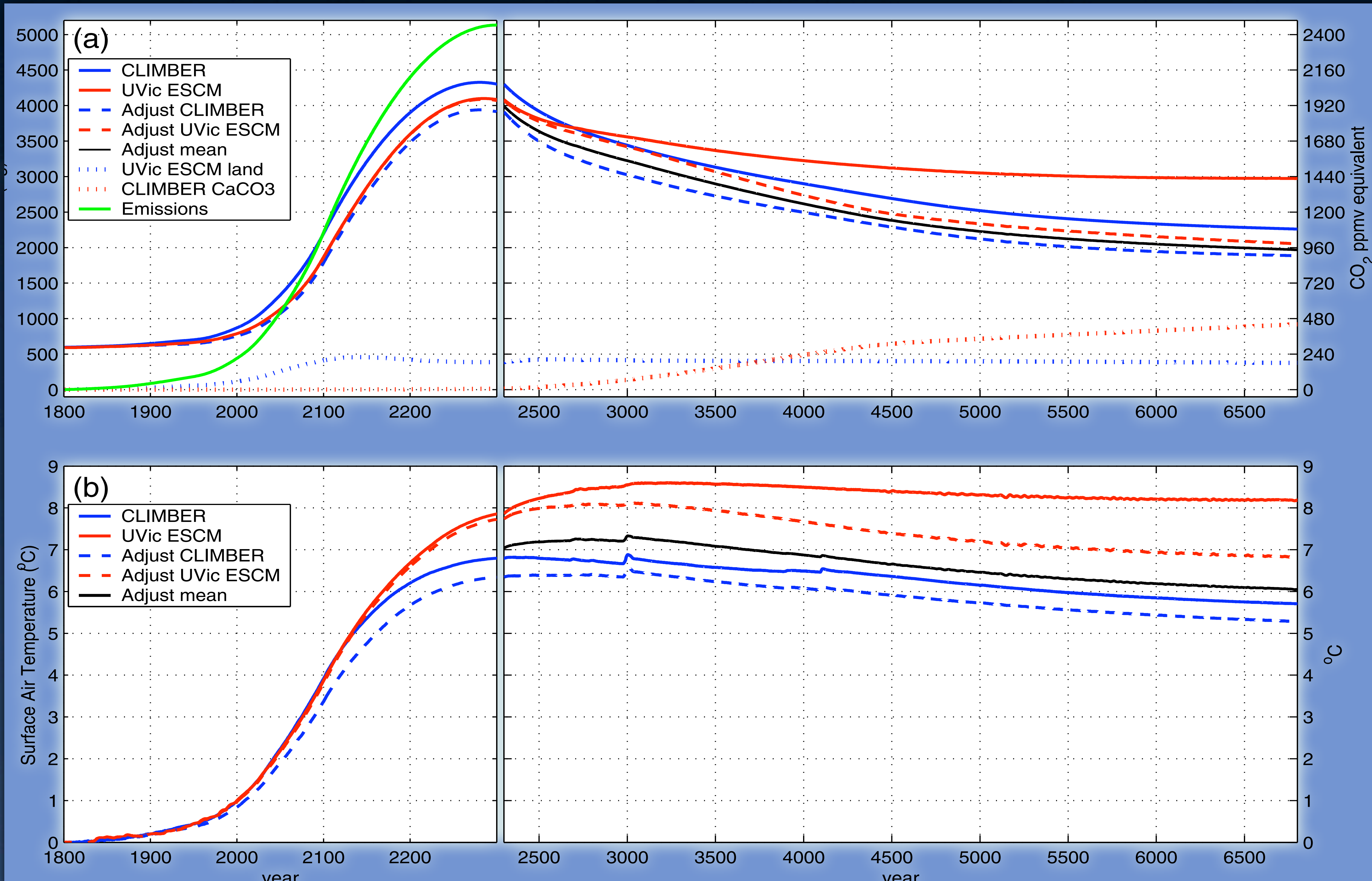
New dynamics

- The normal ‘three cell’ atmospheric circulation and associated cloud radiative forcing patterns begins to break down at hot temperatures
- Super-rotation occurs making Earth more Venus-like
- Climate sensitivity increases because of this transition
- This transition is likely to be sensitive to convective parameterization among other things and is therefore surely model-dependent and may not even be real
- nevertheless it is supported by theory and may be real

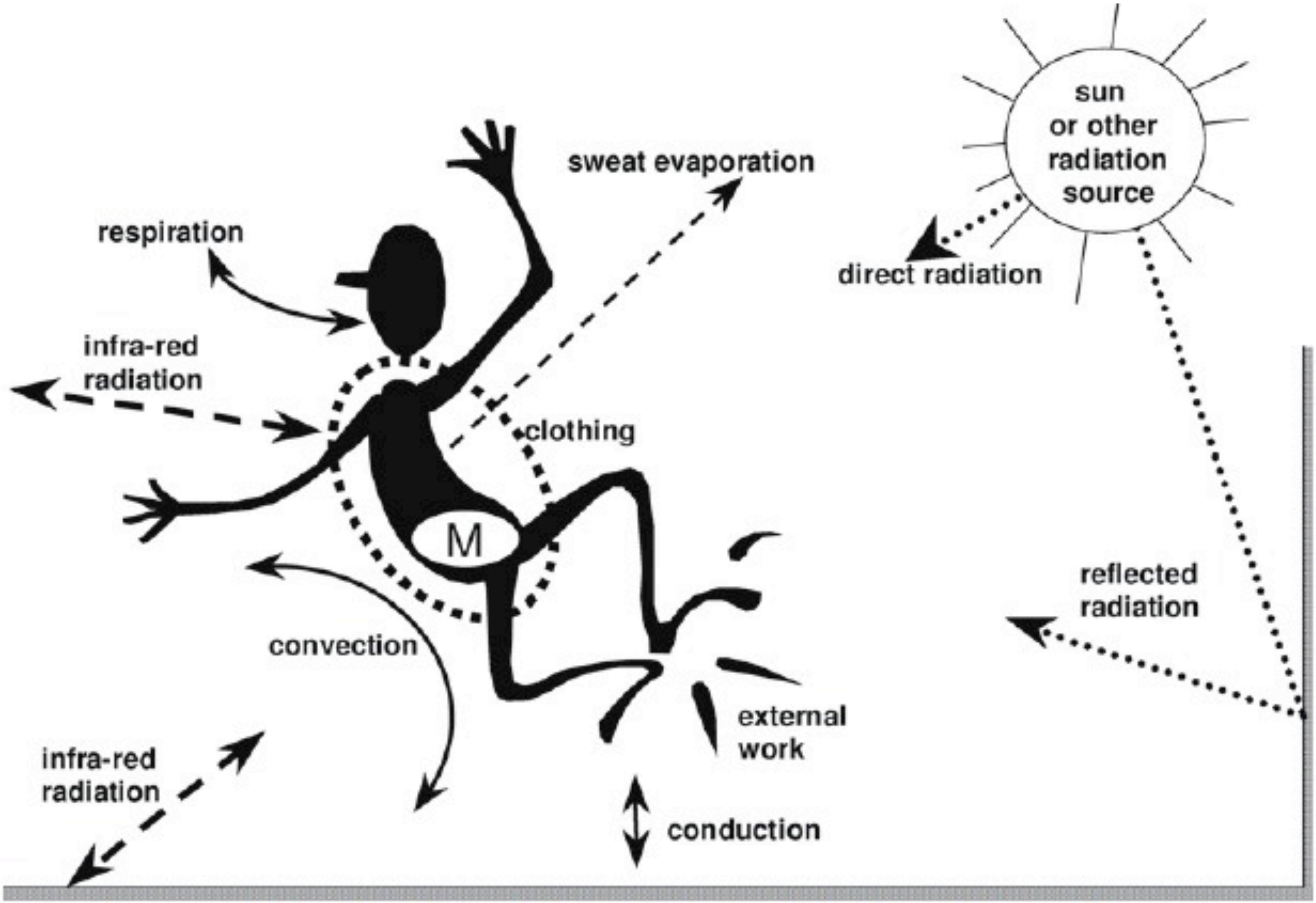
So what if we burn all the fossil fuels?

or just half of it and sensitivity is higher than 2°/doubling?

Is the world Eocene-like?



Montenegro et al., 2007 (GRL)



Schematic representation of the pathways for heat loss from the body. M = metabolic heat production (reproduced with permission, Havenith, 1999)

Human Energy Balance

- A resting human body generates ~100 W of metabolic heat which (in addition to any absorbed solar heating) must be carried away via a combination of heat conduction, evaporative cooling, and net infrared radiative cooling. Conductive cooling is inhibited by high temperature, and evaporation by high relative humidity.
- Net (latent+sensible) cooling can occur only if an object is warmer than the environmental wet-bulb temperature T_W, measured by covering a standard thermometer bulb with a wetted cloth and fully ventilating it.
- The second law of thermodynamics does not allow an object to lose heat to an environment whose TW exceeds the object's temperature, no matter how wet or well-ventilated.

Heat Stress

Mammal internal temperatures are strongly regulated below ~42°C, and skin temperature must be less than this in steady state to provide cooling to balance metabolic heat generation

cooking baboons

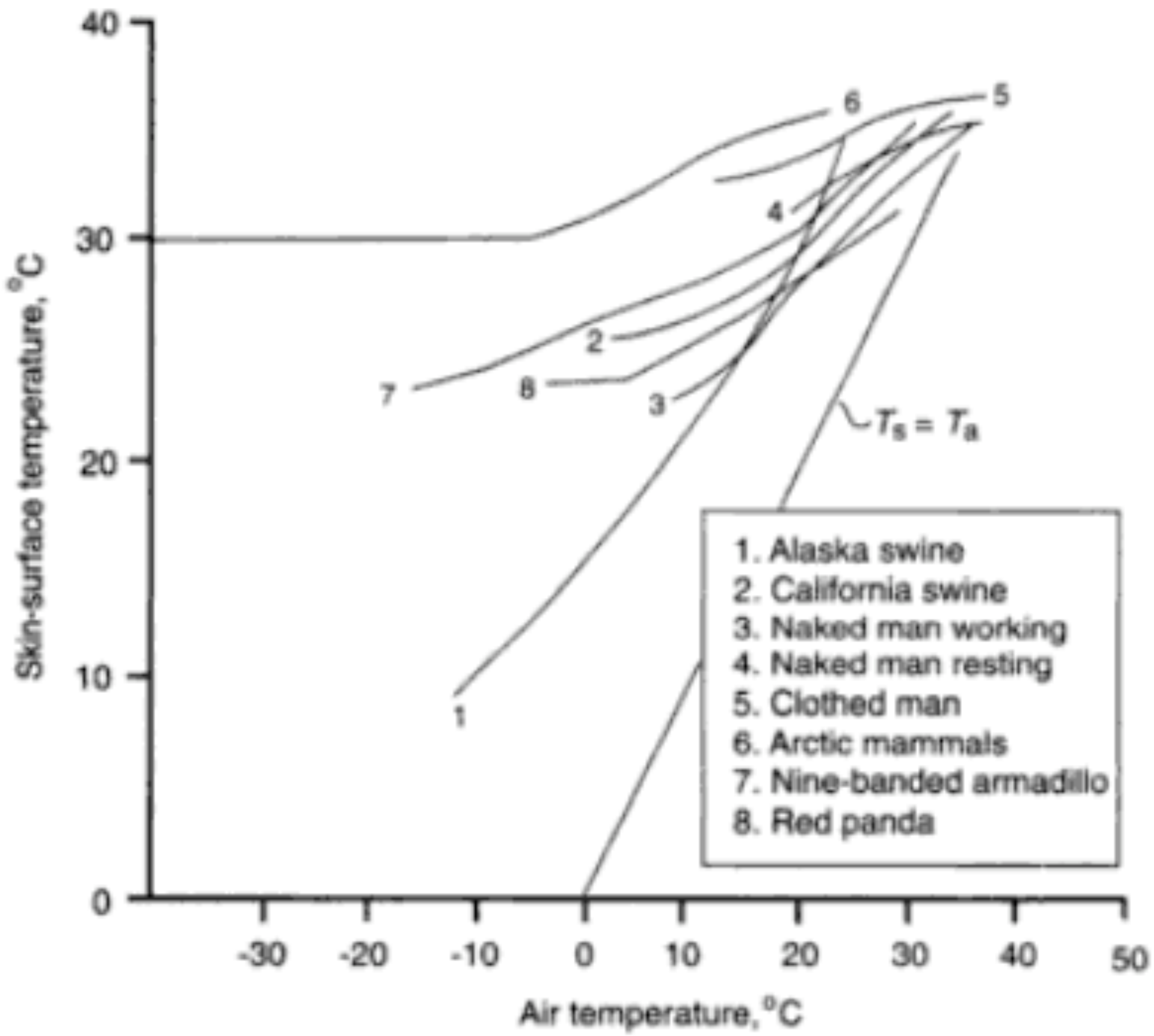
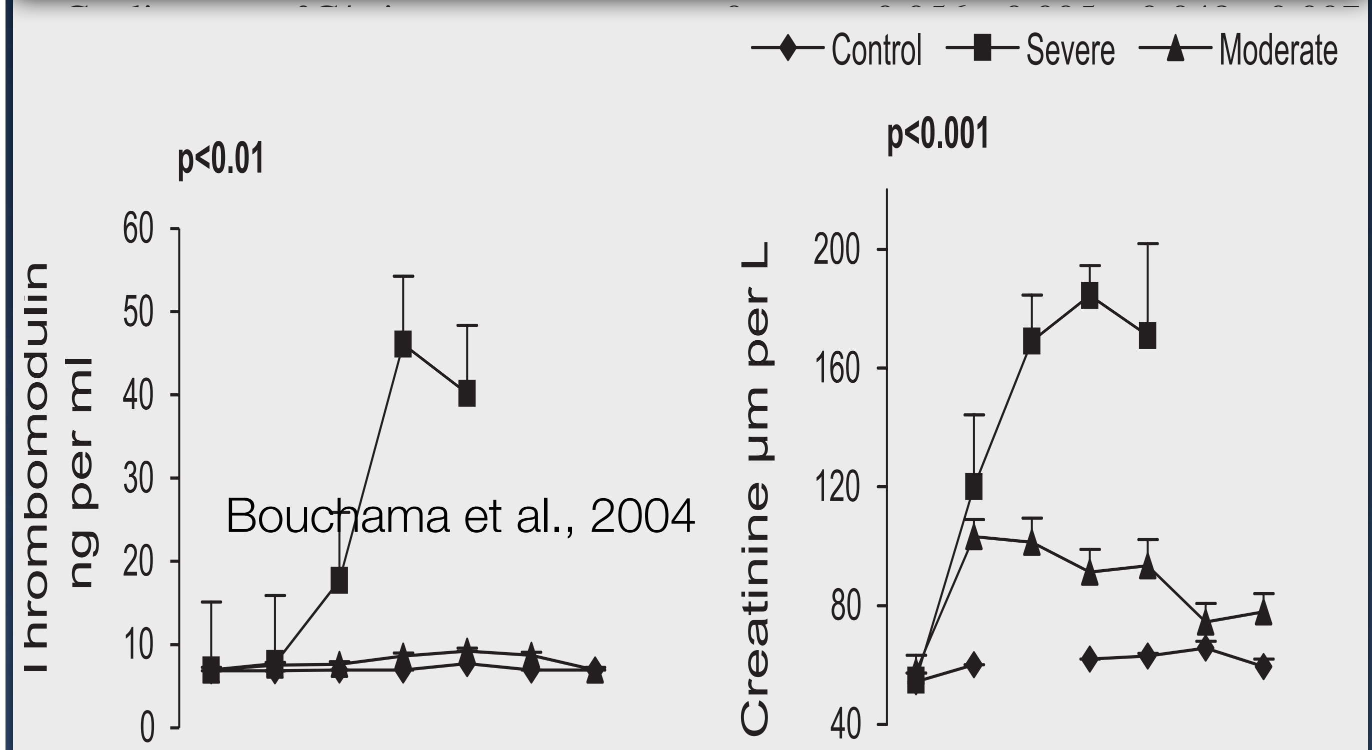


Figure 5.14 Skin temperature in mammals as a function of environmental temperature. Source: Modified from Hart (1956) with additional data from Johansen (1961) and McNab (1988c).

Table 1. *Thermal responses in baboons subjected to heat stress*

Heat Response	Sham-Heated Control	Moderate Heatstroke	Severe Heatstroke
Weight, kg	4.5±0.2	4.2±0.4	4.2±0.3
Incubator temperature, °C	27.7±0.5	44.2±0.9	44.0±0.4
Incubator humidity, %	36±3.1	35.4±1.7	36.1±1.9
Duration of heat exposure, min	267±52	303±61	361±52
T_c maximum, °C	36.5±0.3	42.5±0.0	43.3±0.1*
Heat load, °C/min	0	249±43.6	316±35.6
Heating rate, °C/min	0	0.019±0.003	0.026±0.005
Time at >40.4°C, min	0	155±47	180±45



Bouchama et al., 2004

Sunday, February 10, 13

Building and Environment

Experimental study on physiological and psychological effects of heat acclimatization in extreme hot environments

Zhe Tian, Neng Zhu, Guozhong Zheng*, Huijiao Wei

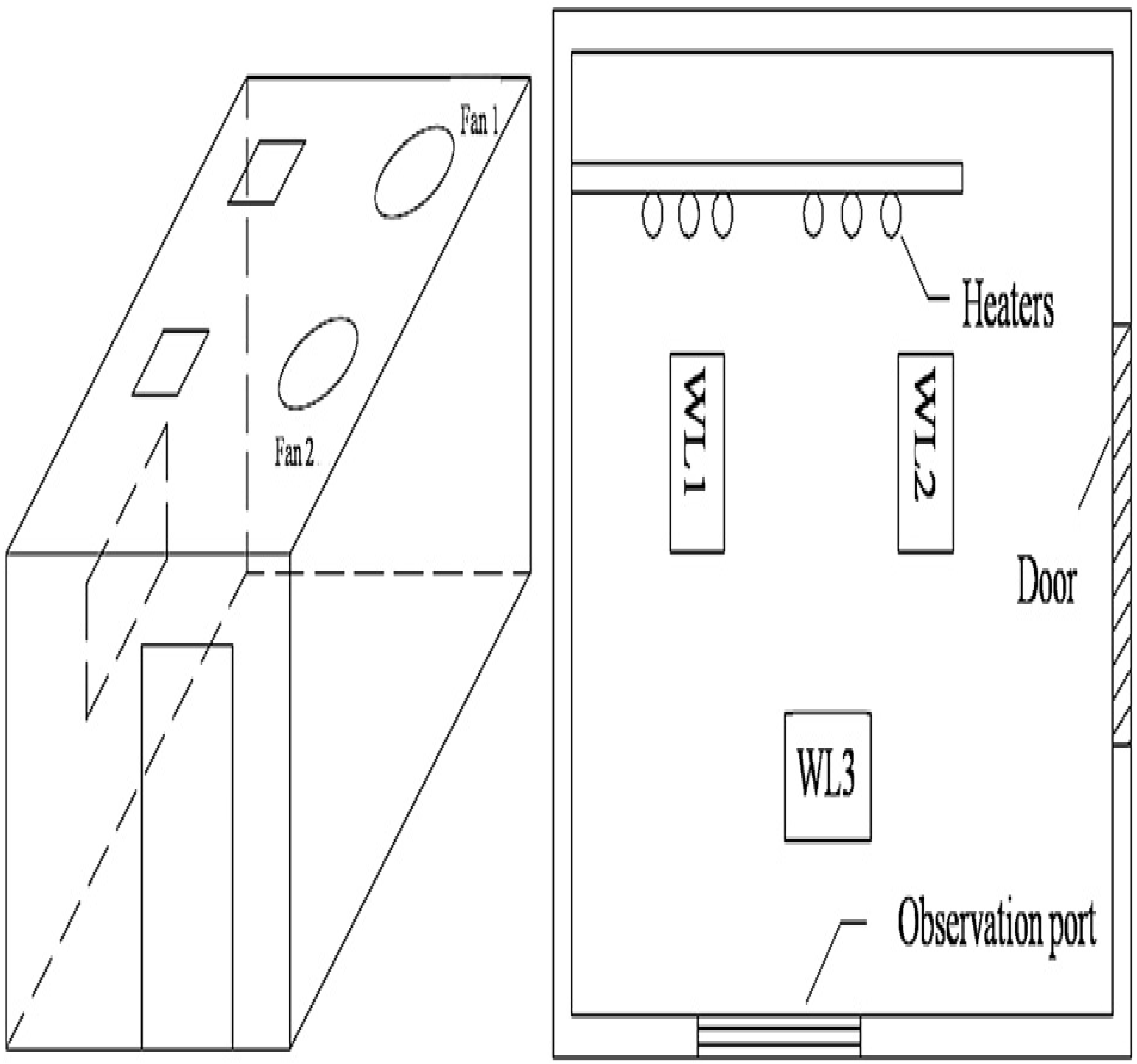


Fig. 1. The structure of this chamber and the arrangement of this experiment.

1 The subjects rested in the preparation room, and the initial parameters of the subjects were measured.

↓

2 The subjects entered into the charm room and adjusted to the new environment for 15 min.

↓

3 The subjects were asked to do stair-exercises in a prescriptive speed.

↓

4 The physiological parameters of the subjects were measured and the subjects were asked to answer the questionnaires of thermal sensation and fatigue feeling.

↓

5 The subjects rested and were permitted to drink water when they wanted.

↓

6 Repeated step 3, 4, 5 until the experiment finished.

Fig. 2. Experiment process.

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A new environmental heat stress index for indoor hot and humid environments based on Cox regression

Building and Environment 46 (2011) 2472–2479

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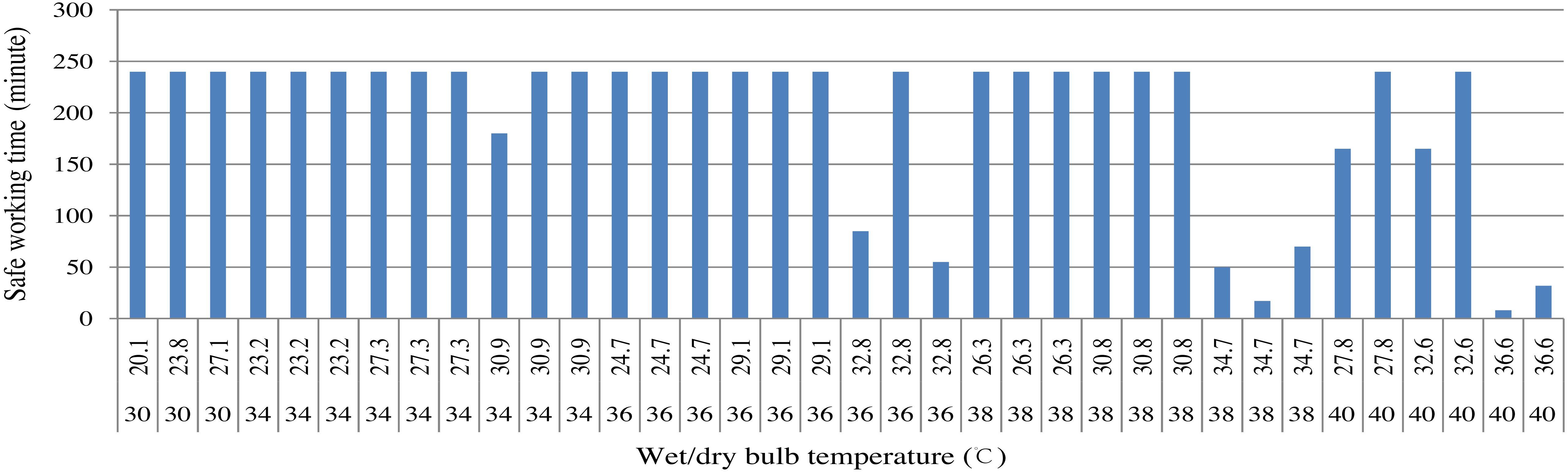


Fig. 3. The safe working time of light work in hot and humid environments.

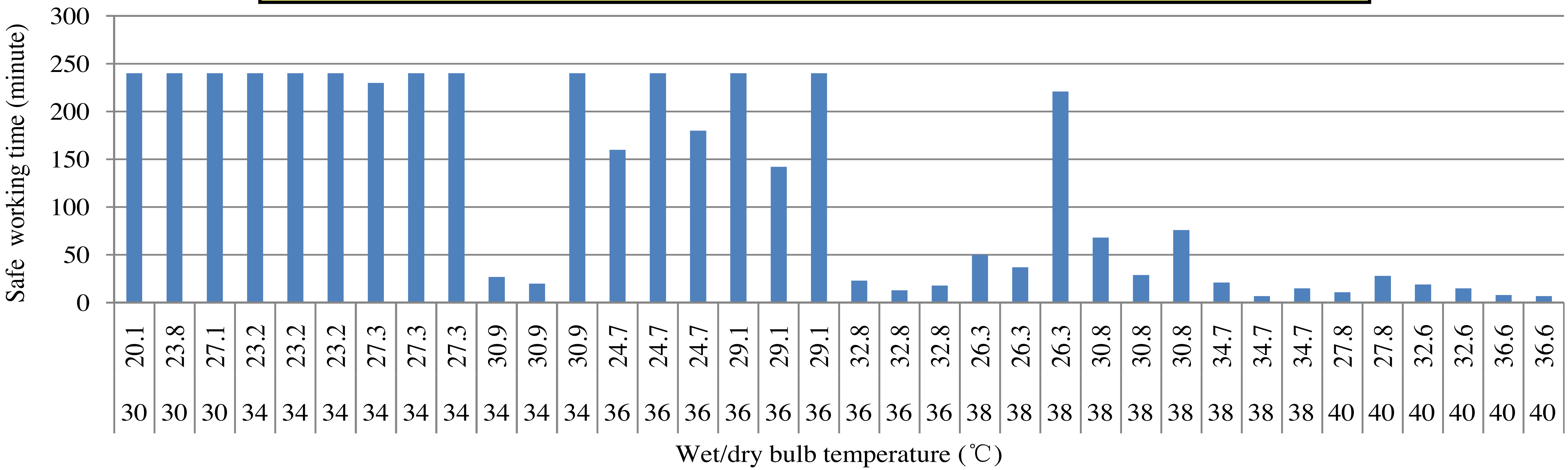
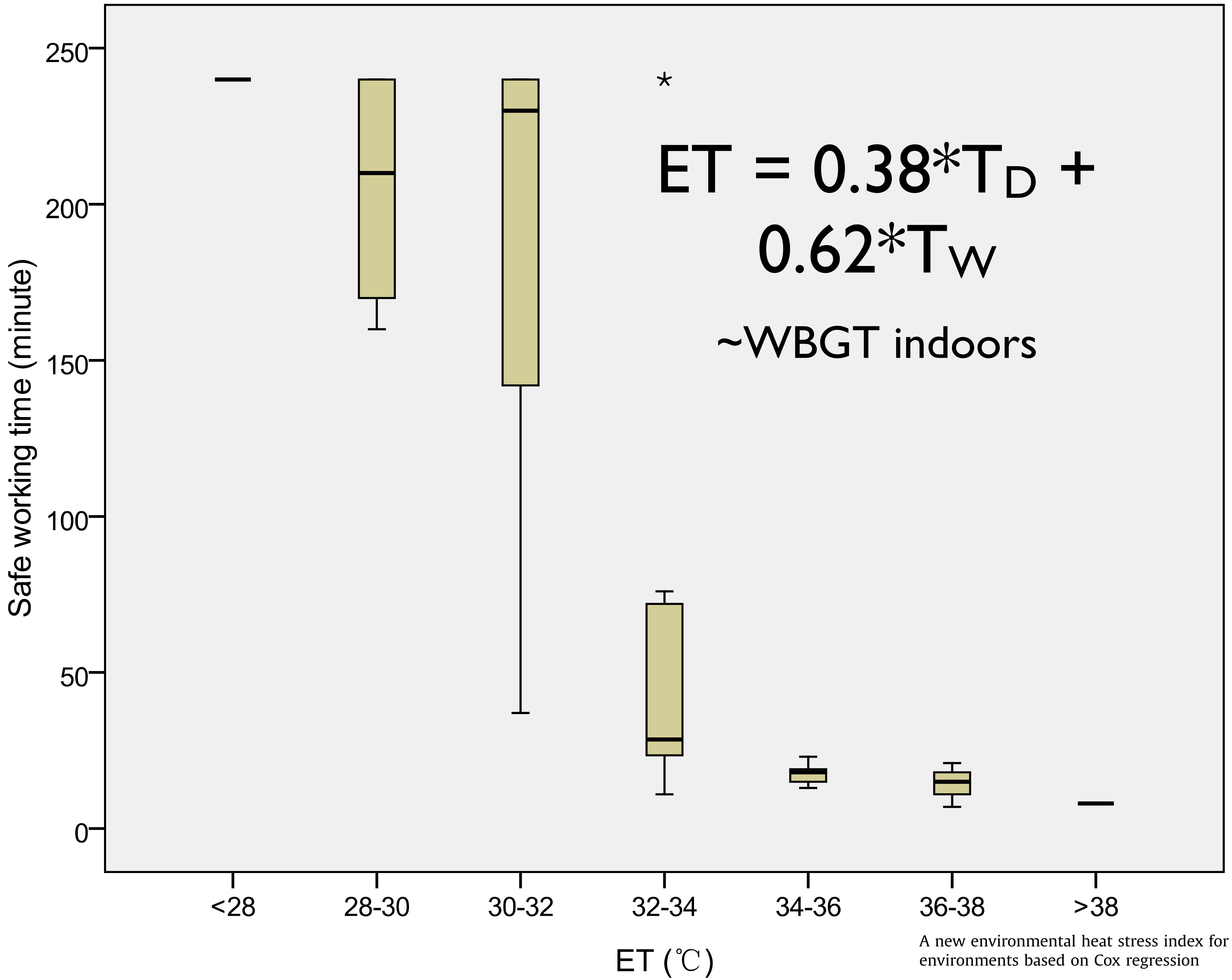


Fig. 1. The safe working time of heavy work in hot and humid environments.



A new environmental heat stress index for indoor hot and humid environments based on Cox regression

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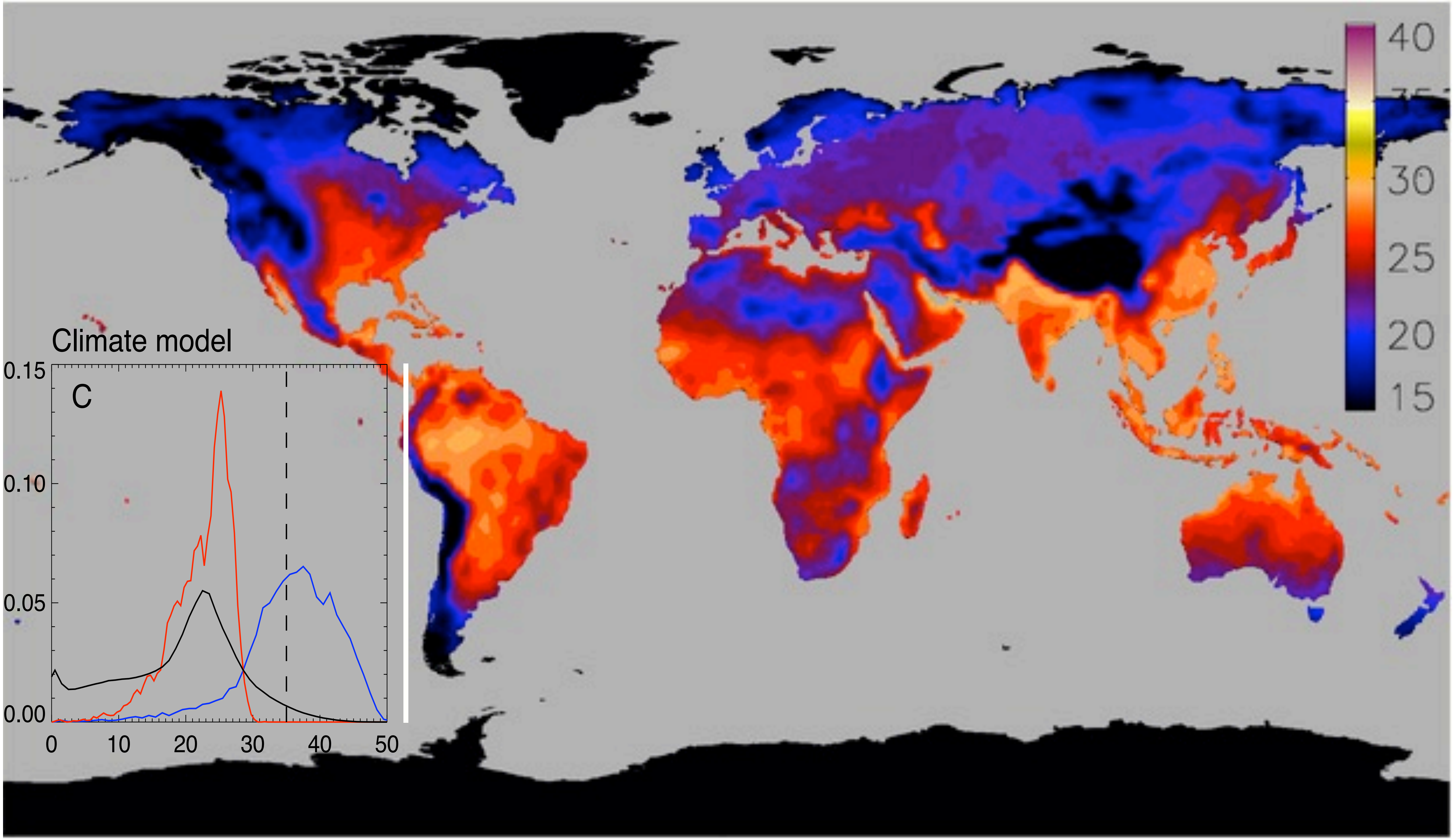
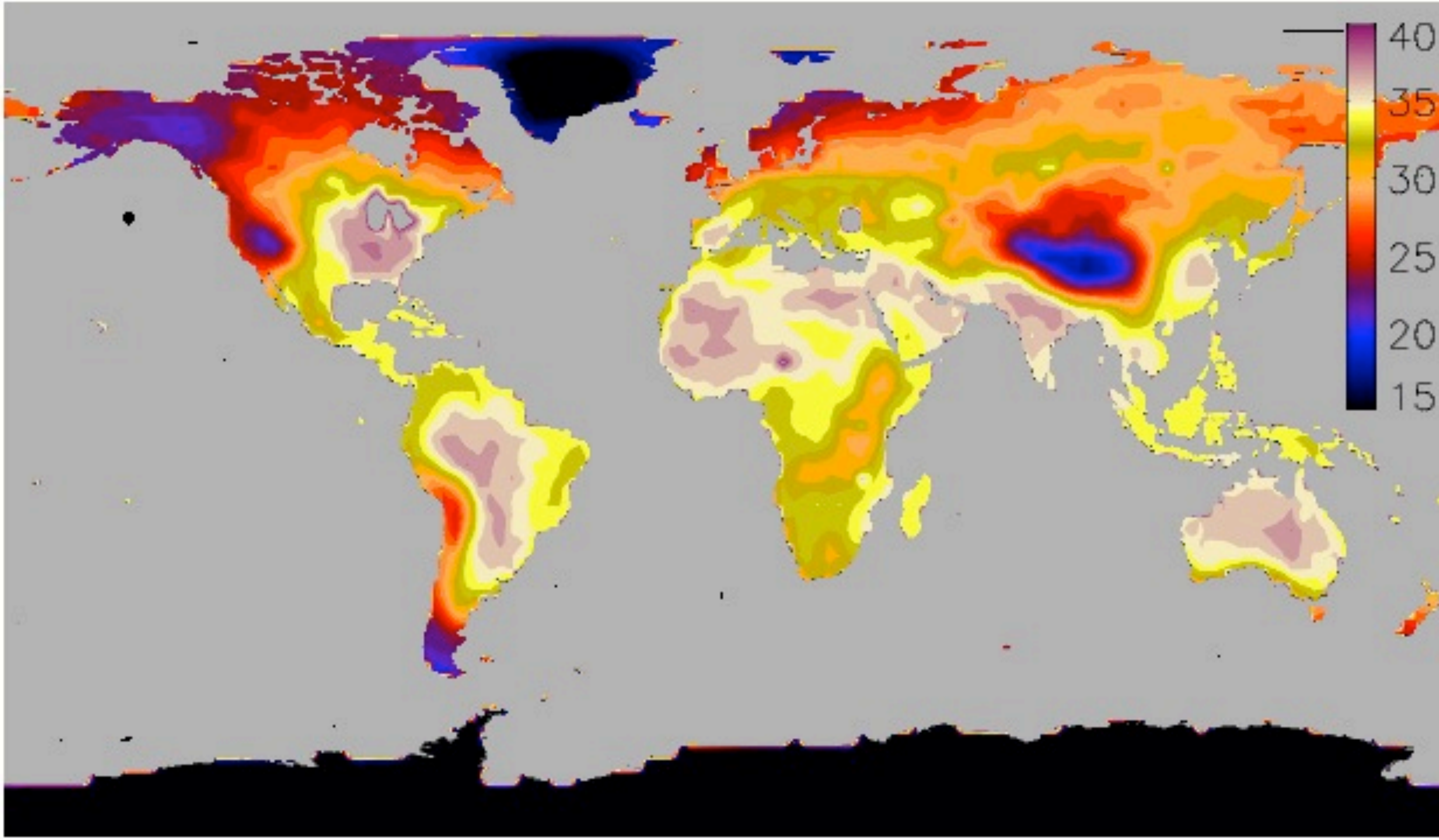
Fig. 7. The boxplot of safe working time concerned with the ET (heavy work).



Modern maximum wetbulb temperature

Sherwood and Huber, 2010

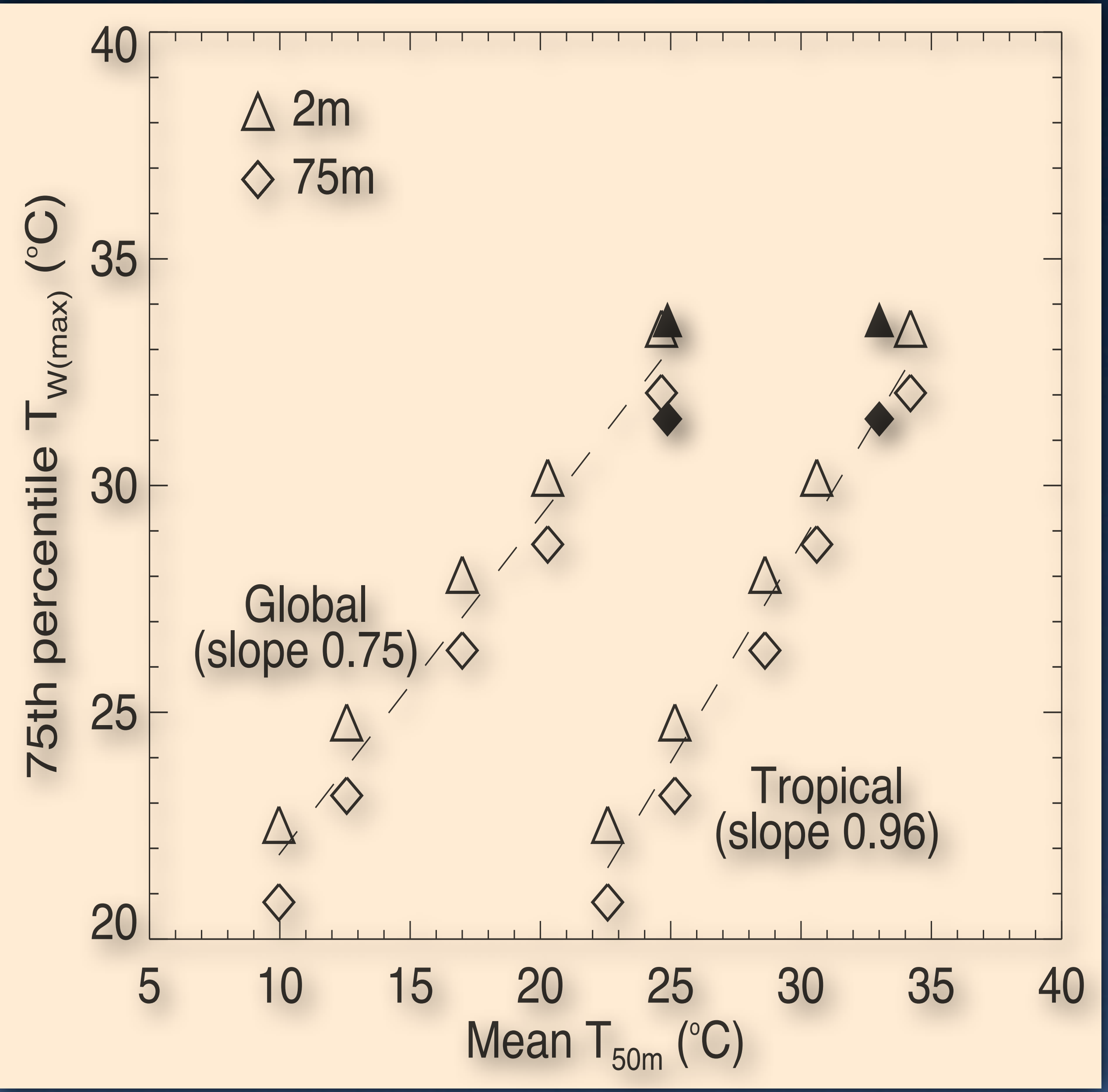


Future maximum wetbulb temperature

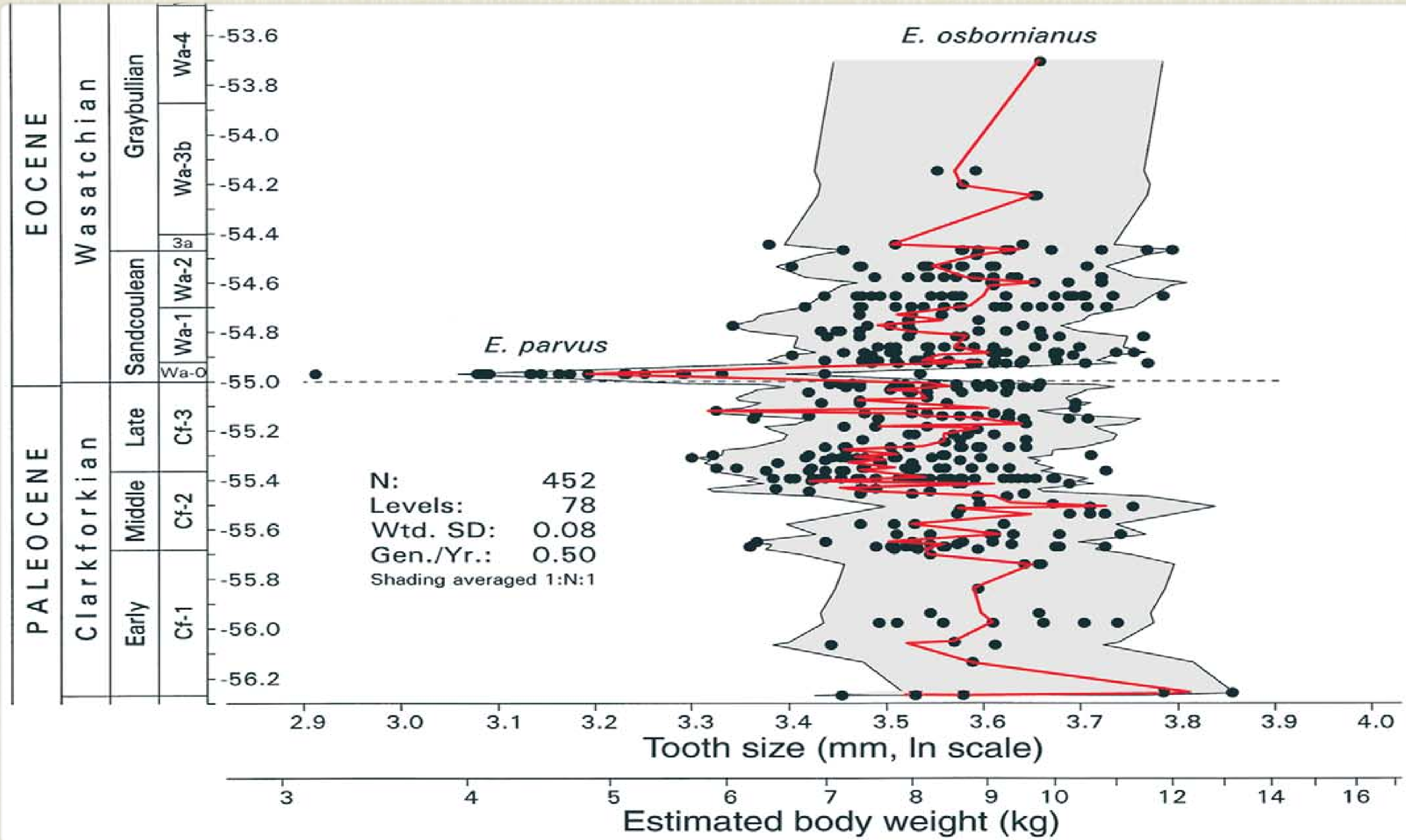
Sherwood and Huber, 2010

Scaling for Maximum wetbulb temperature

- Scales linearly with tropical mean temperature--probably robust result
- For a large, but feasible warming, regions with >50% of the worlds current population will experience lethal temperatures
- Should also be true in the past (Eocene)

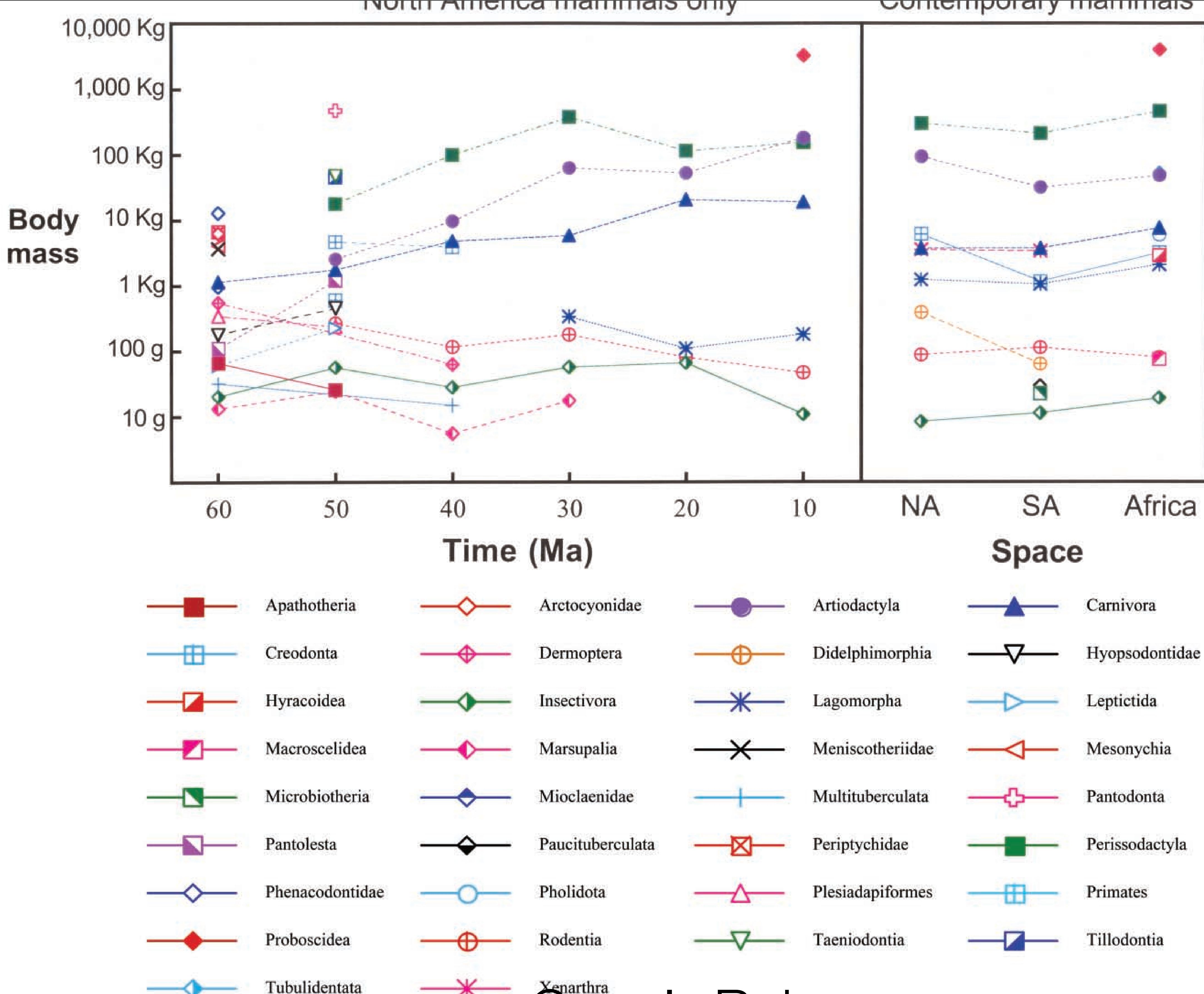


Sherwood and Huber, 2010



TRANSIENT DWARFING AT PETM

Gingerich, 2006



Cope's Rule

Smith et al., 2008

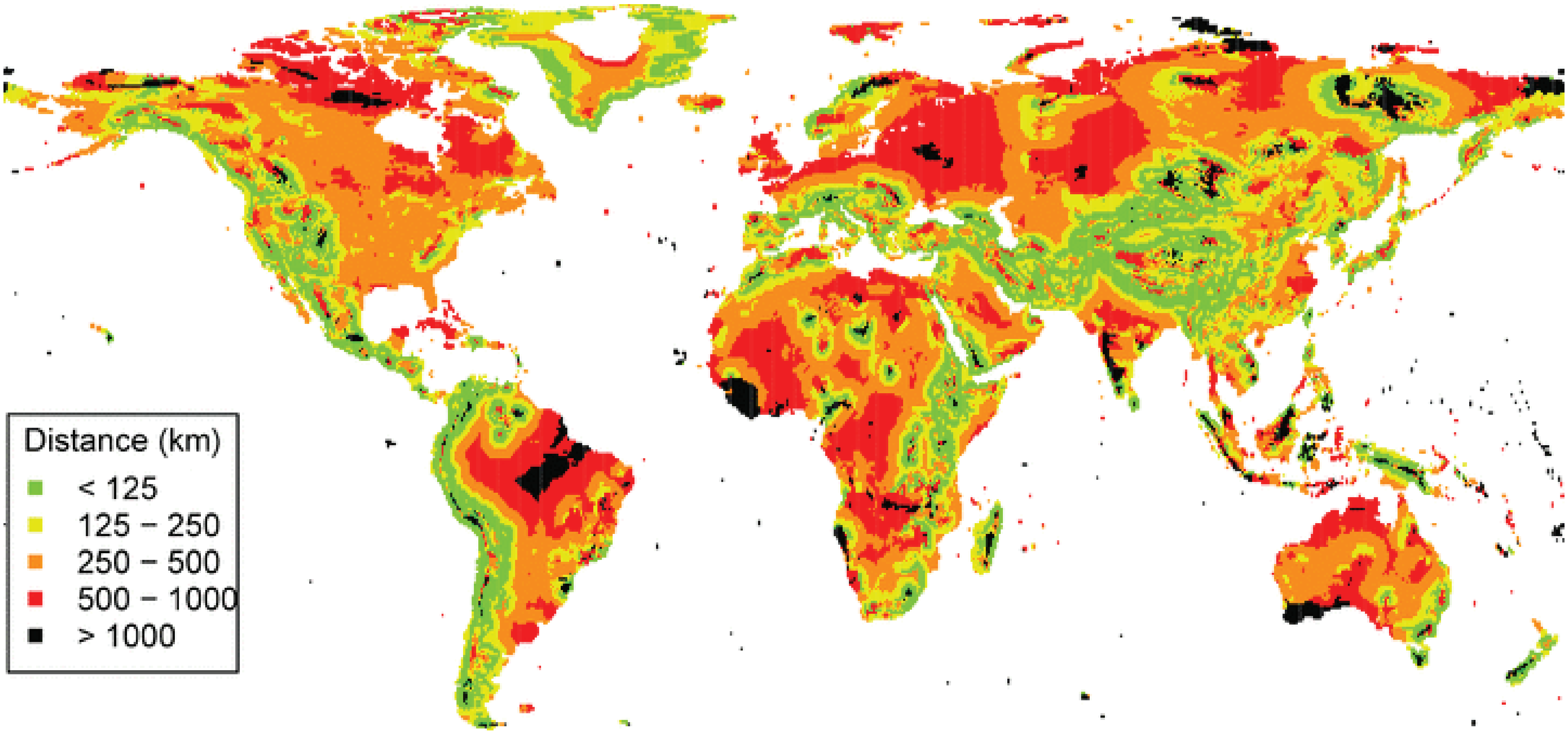


FIGURE 5.17 Map showing the distance to potential cool refuges, where cool is defined as the temperatures in 2100 are equal to or cooler than the temperatures in the 1960s. Used 0.5 x 0.5 latitude-longitude blocks. Source: Wright et al. (2009).

NRC 2011

Beginnings

- Paleoclimate data shows no evidence of strong thermostats
- Climate models can reproduce Eocene warmth and (relatively) small temperature gradients without invoking novel dynamics, but require large forcing (or larger sensitivity than ~2K/doubling pCO_2)
- at high temperatures the modelled atmosphere undergoes a fundamental dynamical transition to super-rotating state supported by wave-induced momentum fluxes
- sensitivity increases in this regime
- A much hotter world (>10°C warmer) may present existential metabolic challenges