A hierarchical approach to climate sensitivity

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Based on joint work with: T. Becker, S. Bony, D. Coppin, C Hohenegger, B. Medeiros, D. Fläschner, K. Reed as part of the WCRP Grand Science Challenge on Clouds Circulation and Climate Sensitivity.

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"If you have a problem that you do not know how to solve, then there exists a simpler problem that you do not know how to solve, and your first job is to find it."

A long tradition of hierarchical thinking

A Numerical Method for Predicting the Perturbations of the Middle Latitude Westerlies

By J. G. CHARNEY and A. ELIASSEN[1]
The Institute for Advanced Study, Princeton, New Jersey[2]

(Manuscript received April 16, 1949)

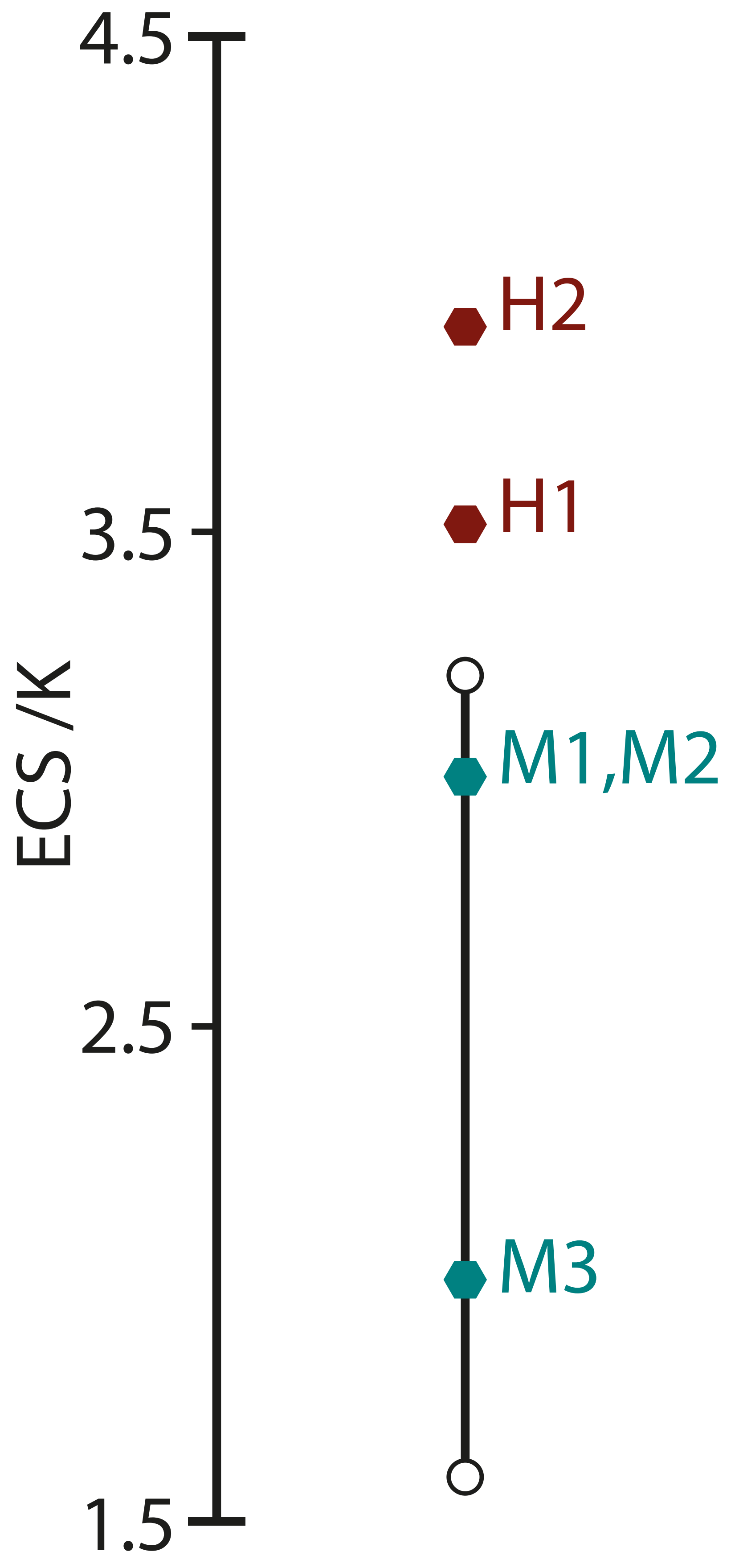
… and was very much part of Charney's mental make up.

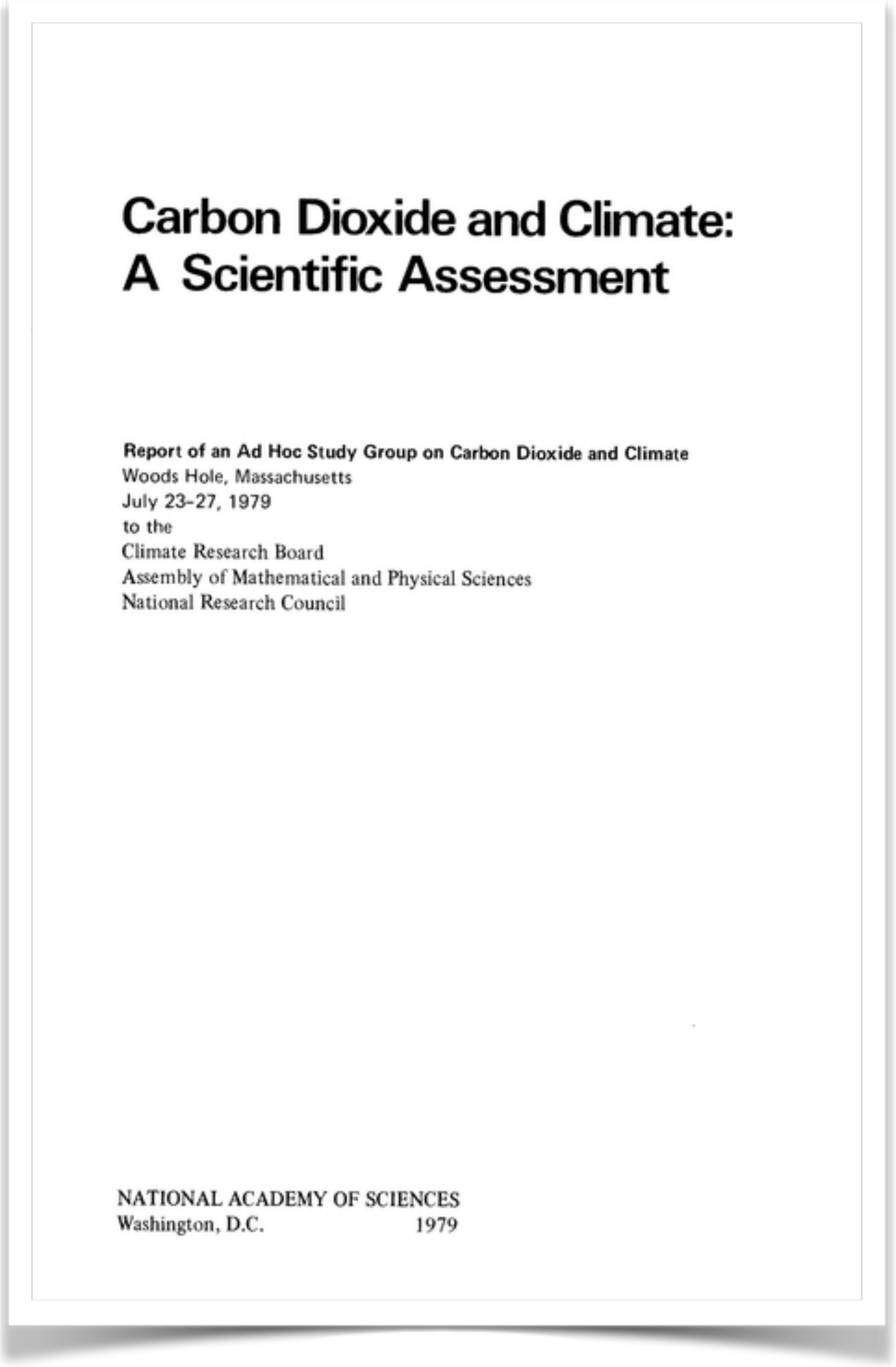
I. **Introduction**

In an article by one of the co-authors,[3] a program for numerical weather prediction was outlined in which it was proposed to consider a hierarchy of atmospheric models whose study would lead to an increasing comprehension of the physical and numerical aspects of the forecast problem. The most elementary model was a barotropic atmosphere in which the motion is regarded as consisting of small perturbations on a zonal current. The problem of forecasting these perturbations constitutes the simplest non-trivial instance of a numerical forecast problem. It is the purpose of the present article to discuss this case as a step towards the realization of the general program. It is also hoped that the treat-

“We believe, therefore, that the equilibrium surface global warming due to doubled CO_2 will be in the range 1.5°C to 4.5°C, with the most probable value near 3°C.” Charney et al., 1979

Charney et al. ‘79





Carbon Dioxide and Climate:
A Scientific Assessment

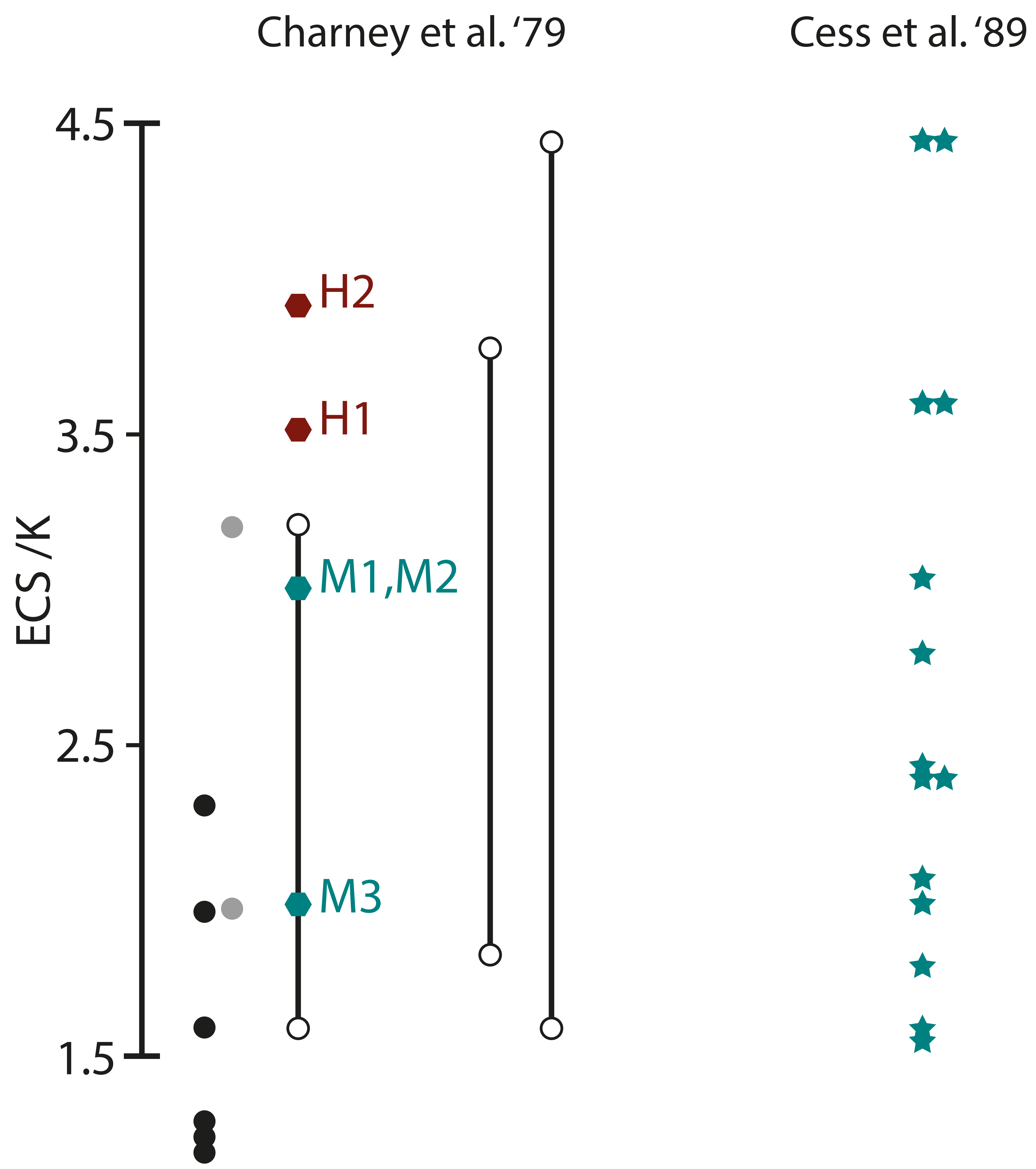
Report of an Ad Hoc Study Group on Carbon Dioxide and Climate
Woods Hole, Massachusetts
July 23–27, 1979
to the
Climate Research Board
Assembly of Mathematical and Physical Sciences
National Research Council

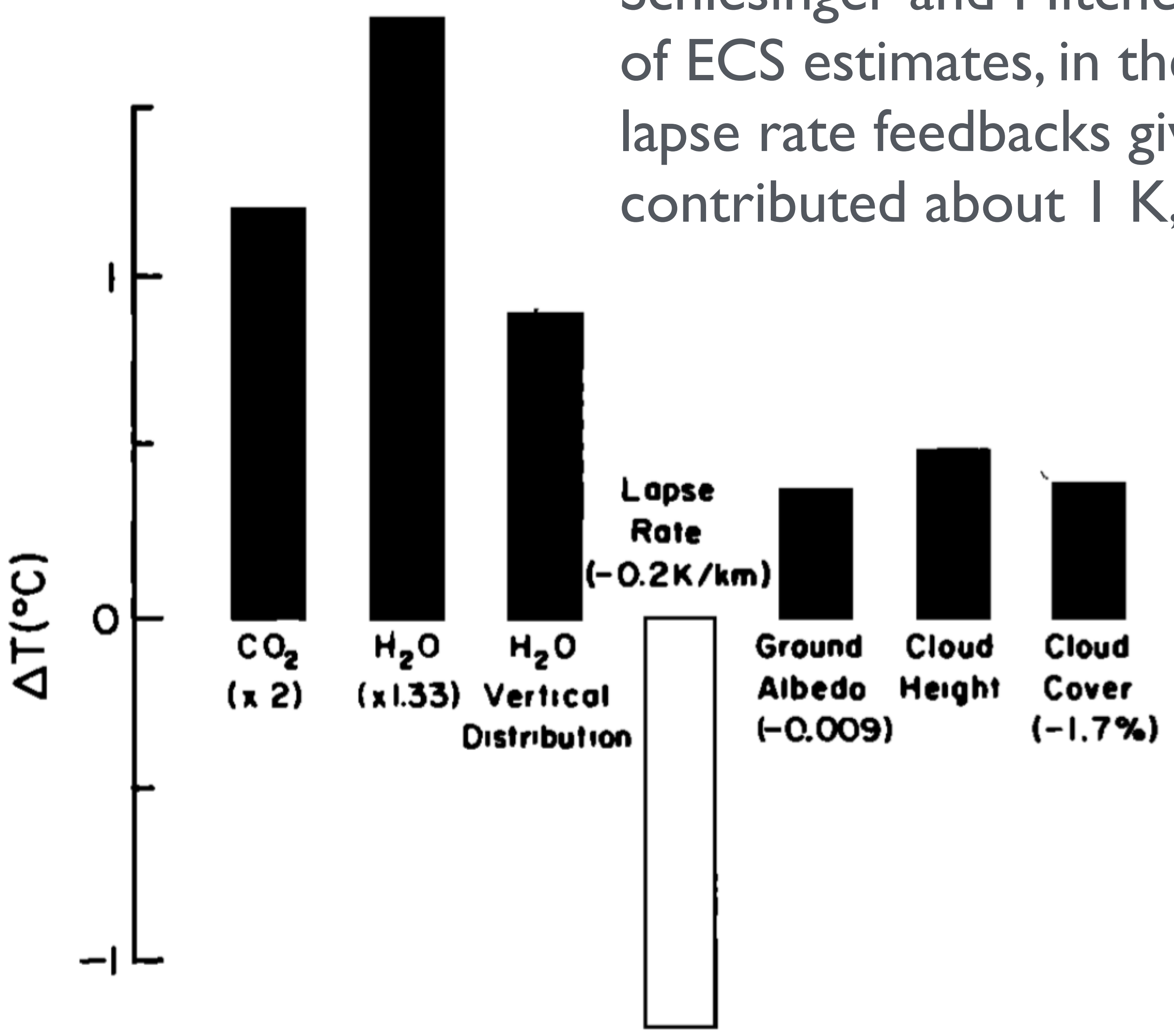
NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1979

- Reasoning from Radiative Convective Equilibrium, (RCE) corroborated by global computations with then emerging general-circulation models
- Most early RCE calculations neglected weaker bands of CO_2, including these increased the forcing and hence the ECS, Charney et al., actually corrected liberally for this. Early RCE estimates of FAT varied between 0.75 Wm^{-2} and 1.0 Wm^{-2}.
- Lapse-rate feedbacks were not included, but about 0.3 Wm^{-2} was added to account for surface albedo feedbacks.
- Uncertainty was inflated

Charney et al., *NRC Report*, 1979

The field moved on to study more complex problems



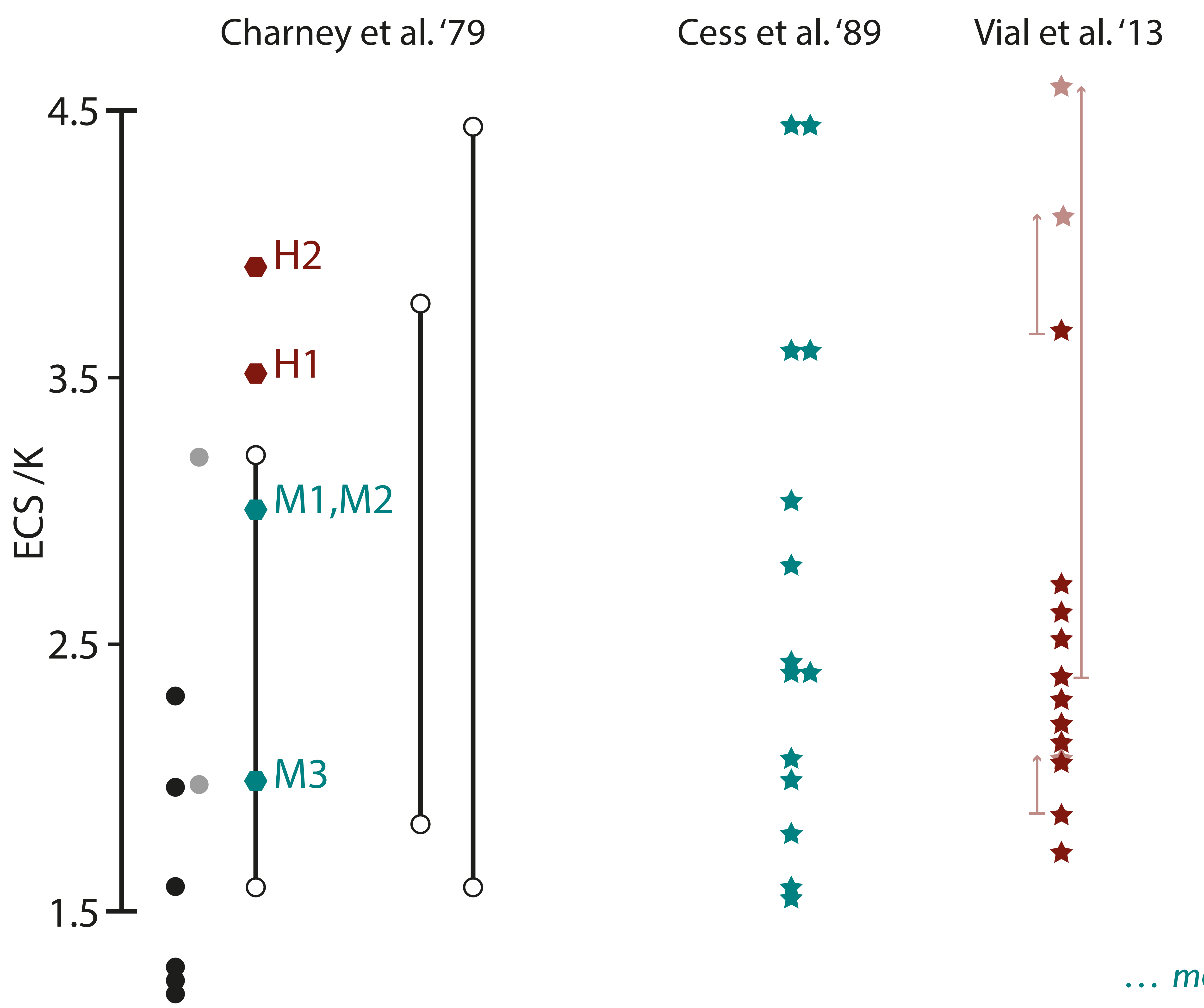


Schlesinger and Mitchell documented the diversity of ECS estimates, in their summary water vapor and lapse rate feedbacks give dT = 2.85 K, Clouds contributed about 1 K, and overall ECS was 4.2 K

In a systematic intercomparision Cess et al showed that differences in how clouds responded to warming explained most of the change.

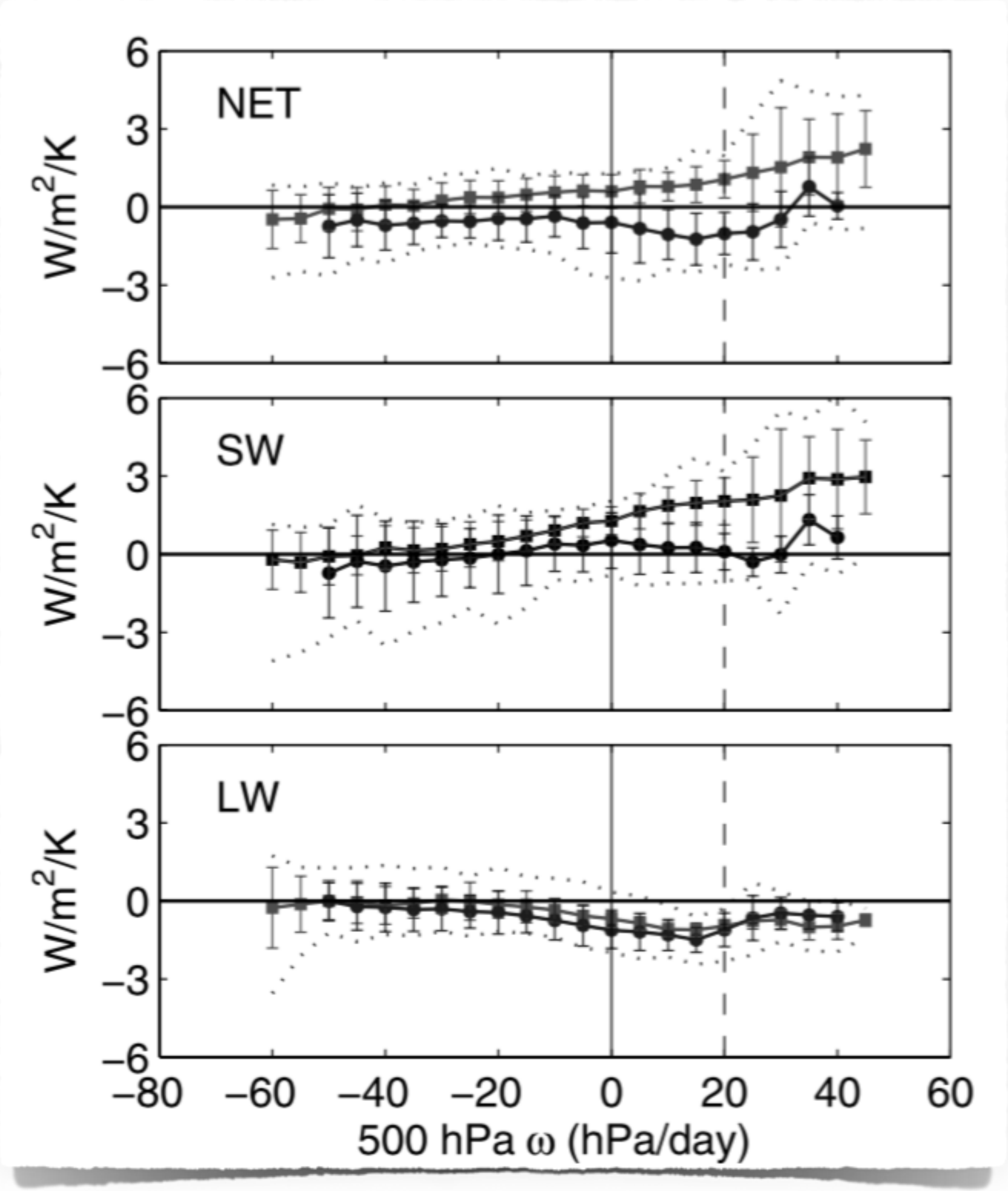
Schlesinger and Mitchell, *Reviews of Geophysics*, 1987, Cess et al., *Science*,1989

… a form of stasis

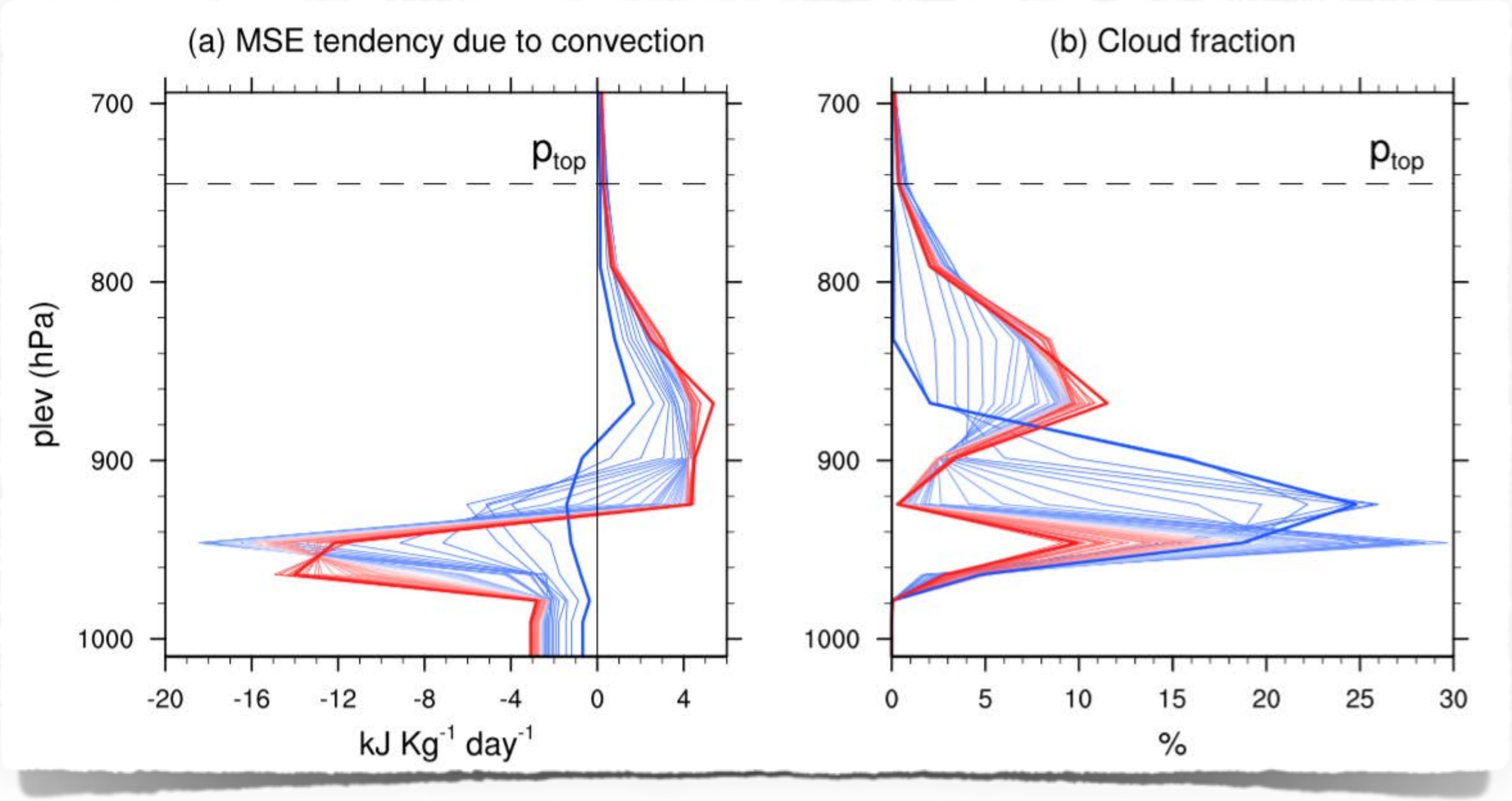


… modern models scatter as much as they did 25 years ago.

… which tends to mask great progress (and an expanded model hierarchy)

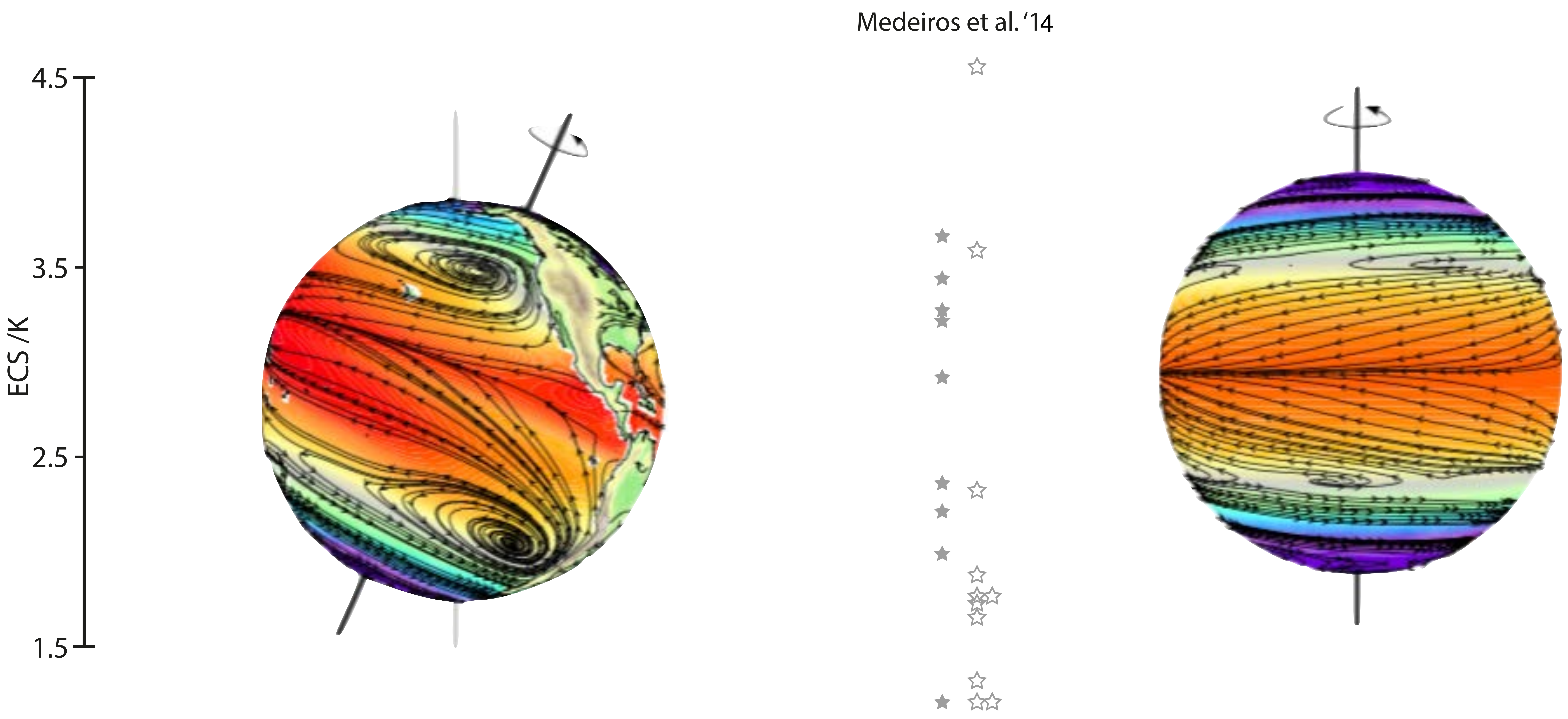


… we now have a better idea of which clouds, and the mechanisms involved. A key one is how cloudiness at the base of convective layers responds to the intensity of mixing.



This is leading us to data (field experiments) and simpler modelling frameworks.

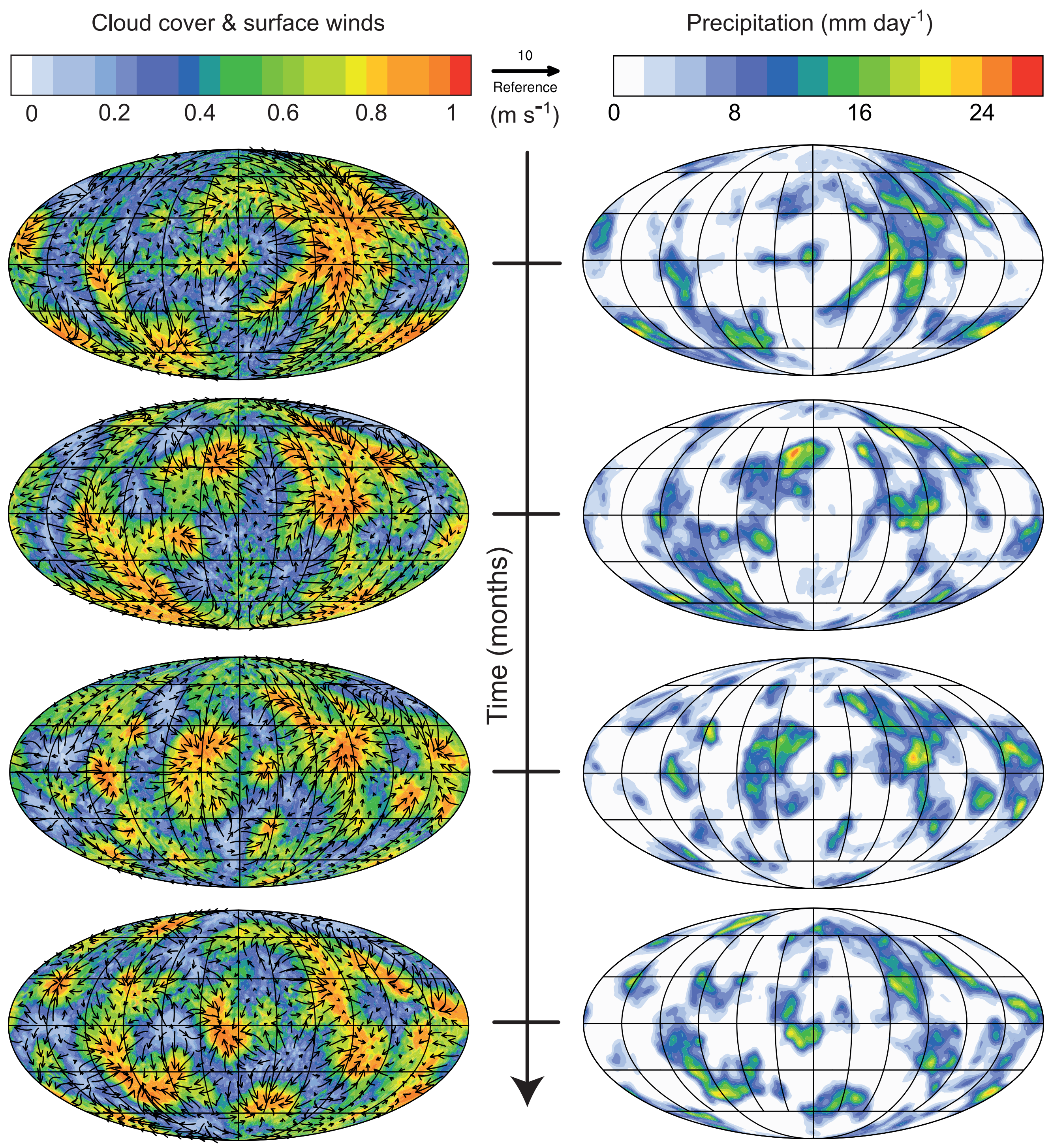
Aqua Planets

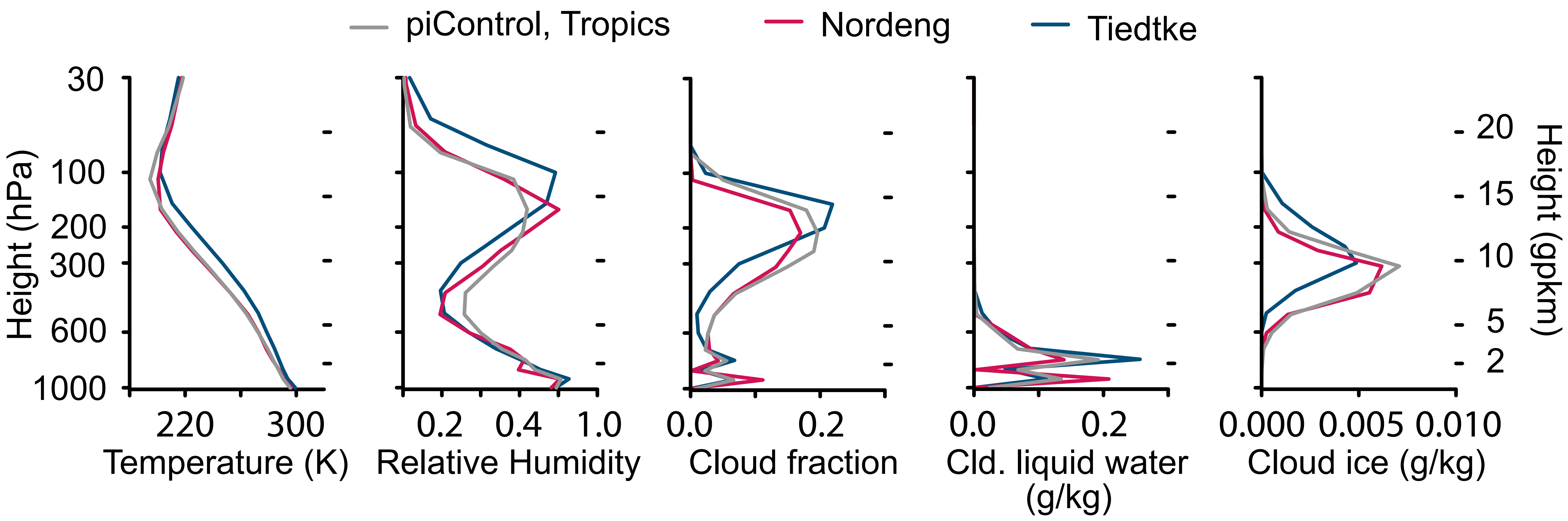


the spread is not reduced, but ECS tends to be smaller …

B. Medeiros, Stevens, B., Bony, *Climate Dynamics* (2014)

These basic interactions between deep and shallow convection should be apparent in RCE

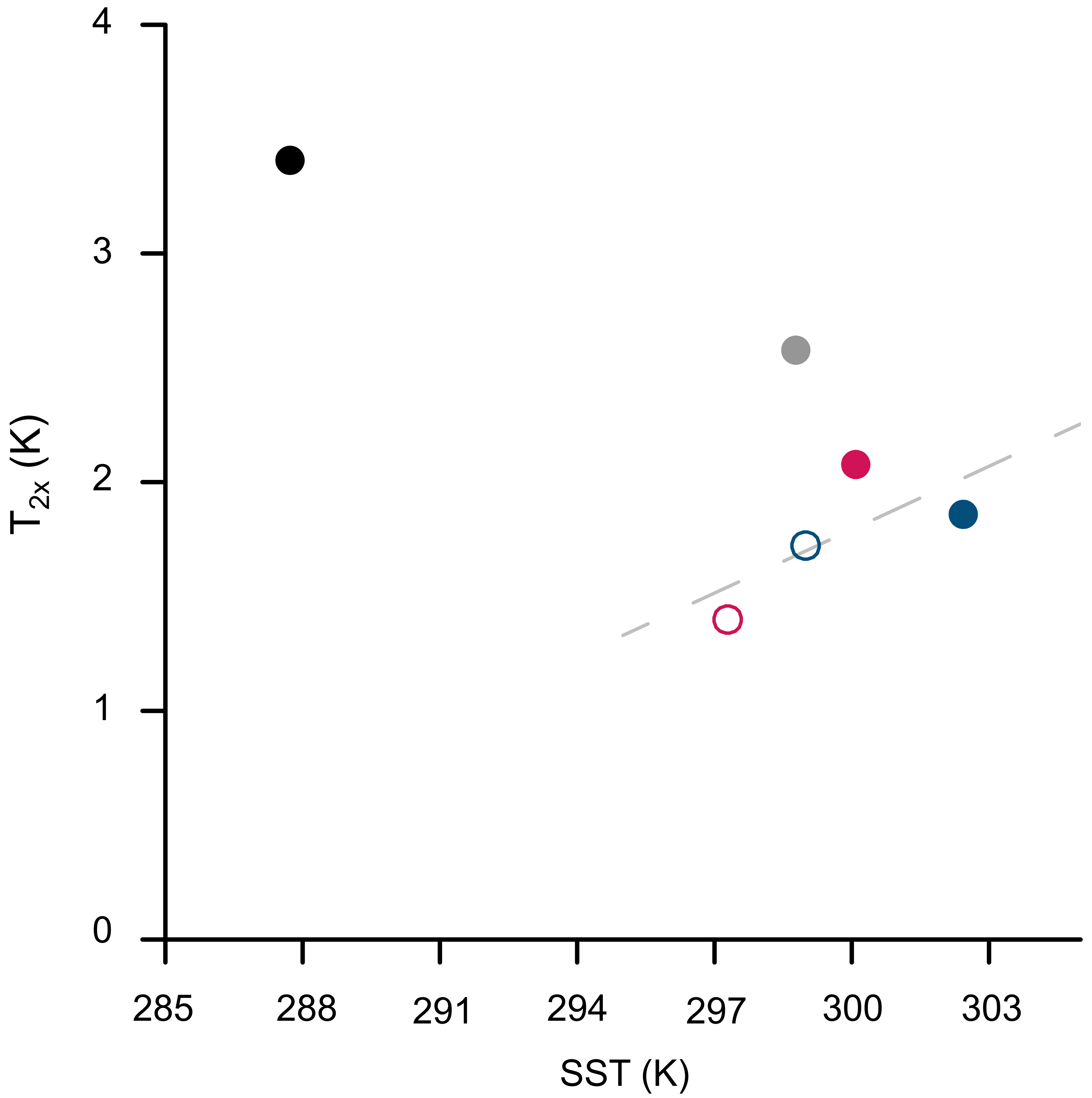


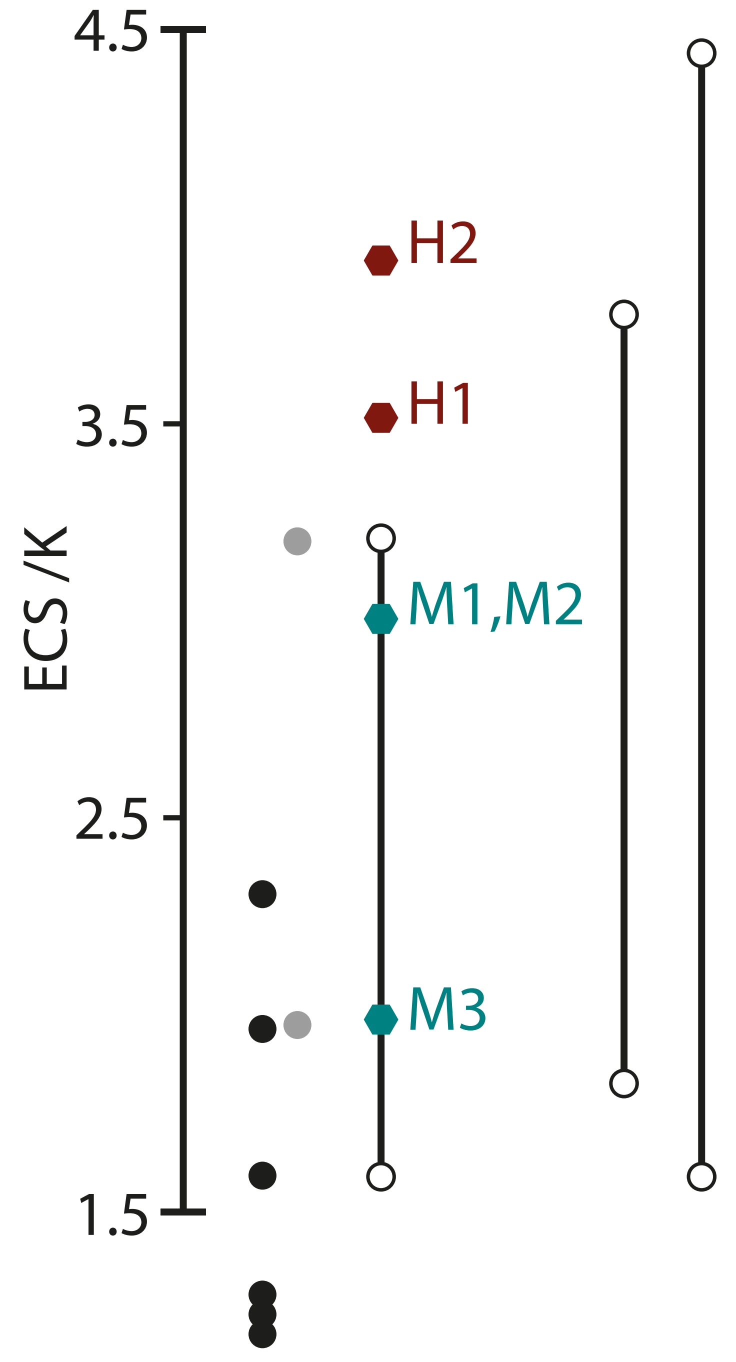


The simulations hint that basic elements of the thermal structure of the atmosphere are more dependent on the representation of deep convection than they are on continents, the carbon cycle, and so on …

Popke, D., B. Stevens, and A. Voigt, *J. Adv. Model. Earth Syst*,, 2013

These basic interactions between deep and shallow convection should be apparent in RCE



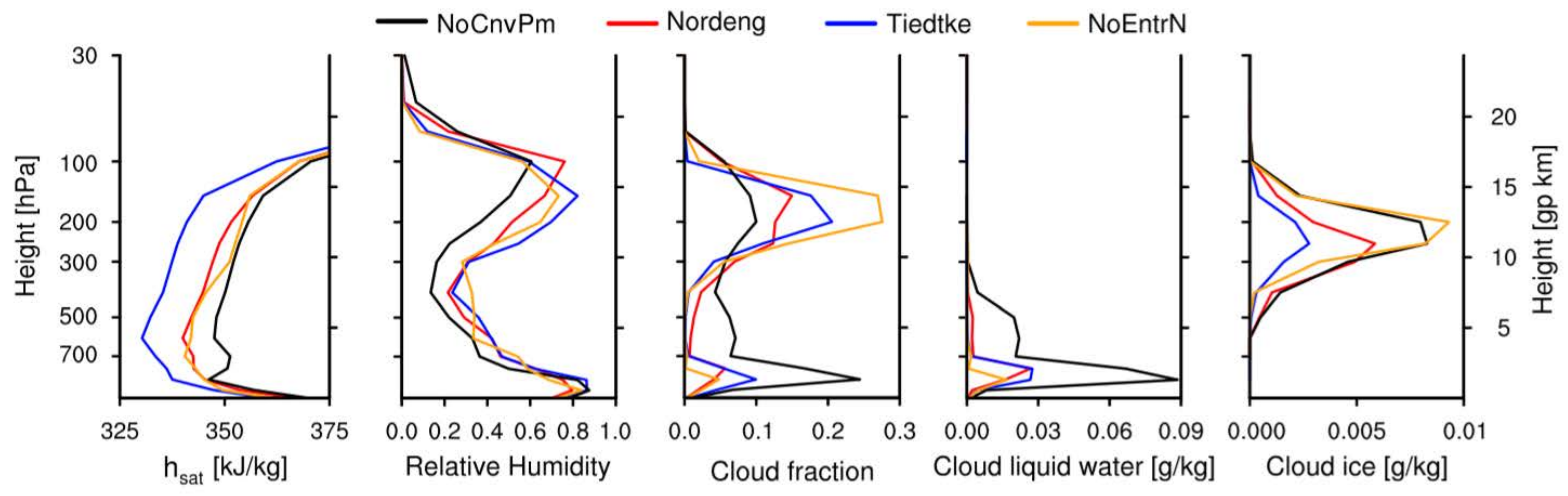


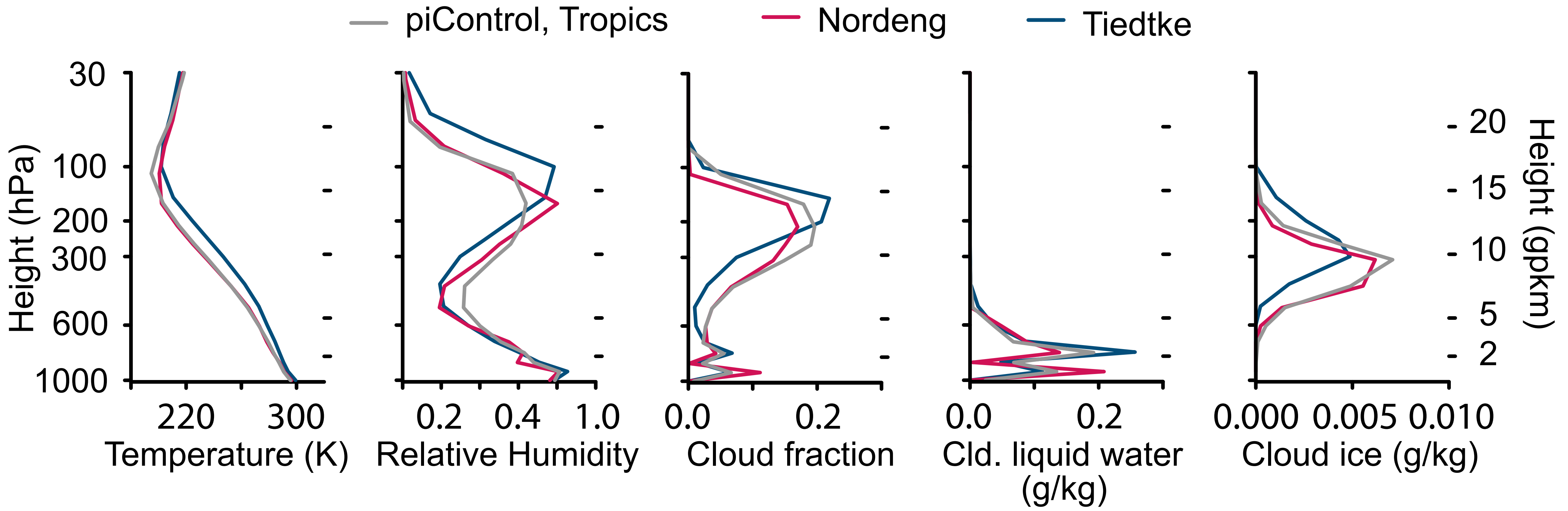
RCE estimates of ECS using comprehensive models is similar to the range of early estimates, with fixed cloud amount.

This finding opens the door to other, more fundamental approaches.

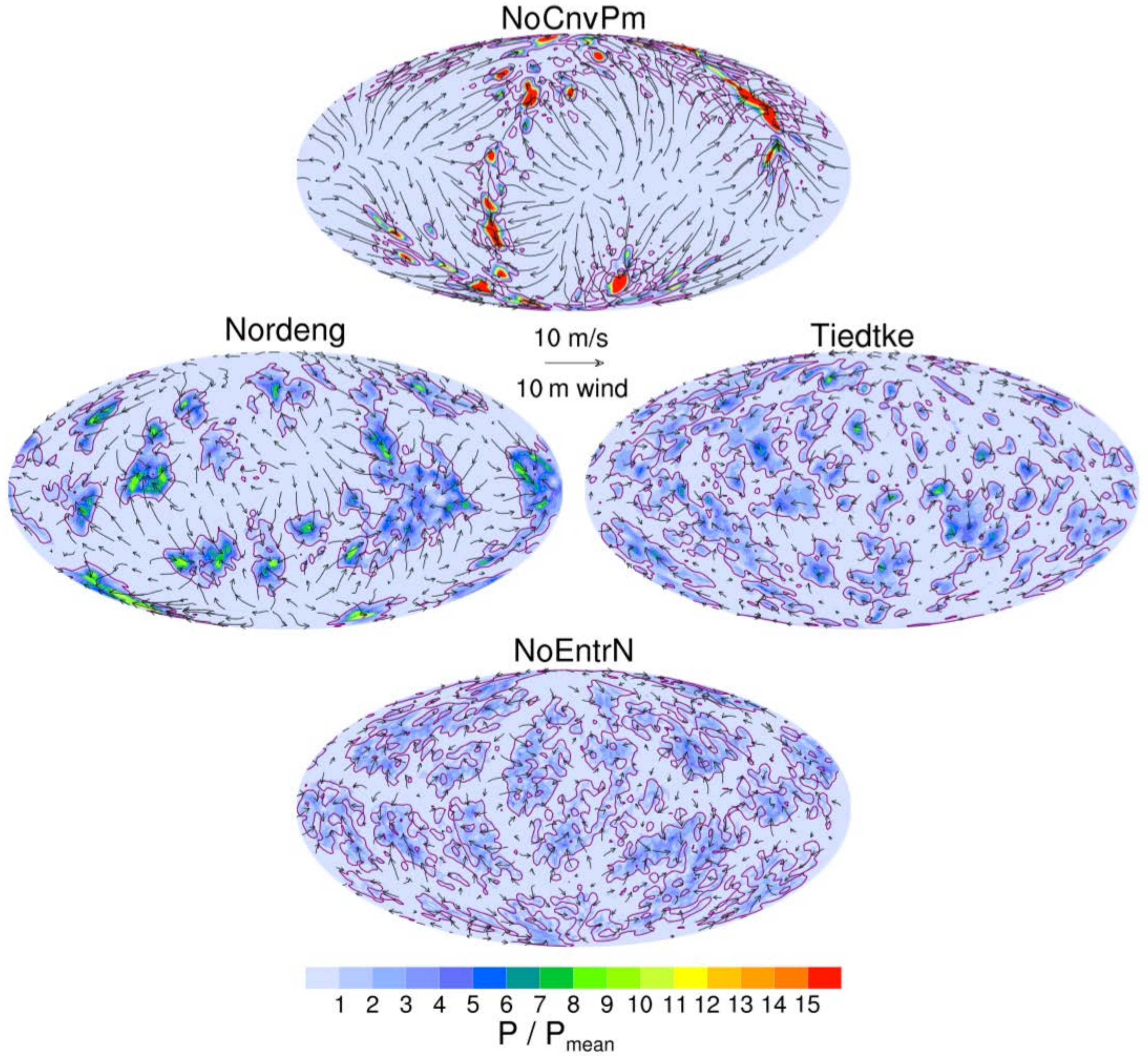
Popke, D., B. Stevens, and A. Voigt, *J. Adv. Model. Earth Syst,*, 2013

Changes in the convection influence large-scale organization



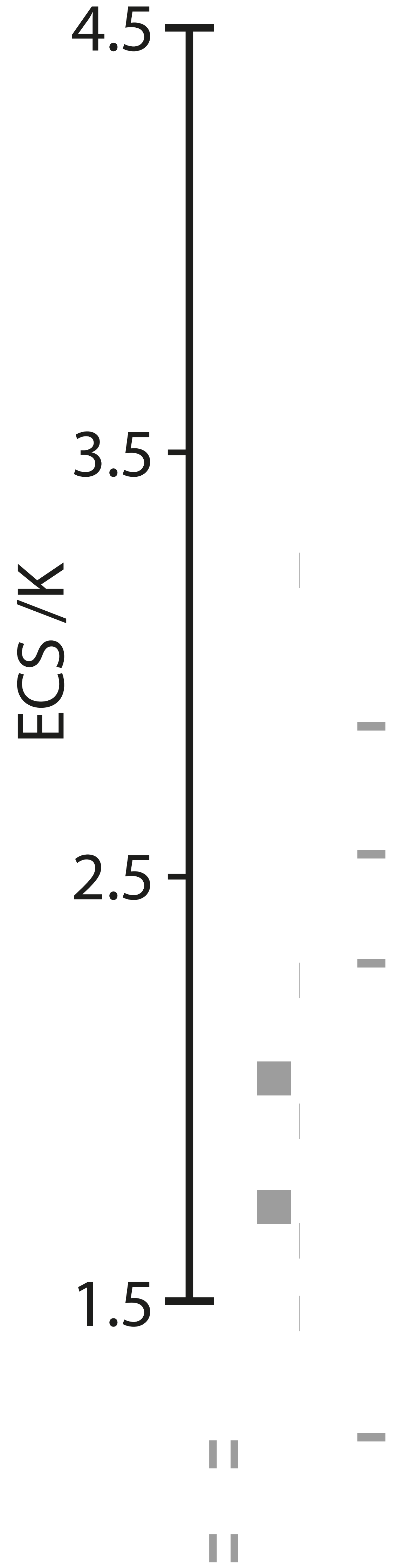


Popke et al

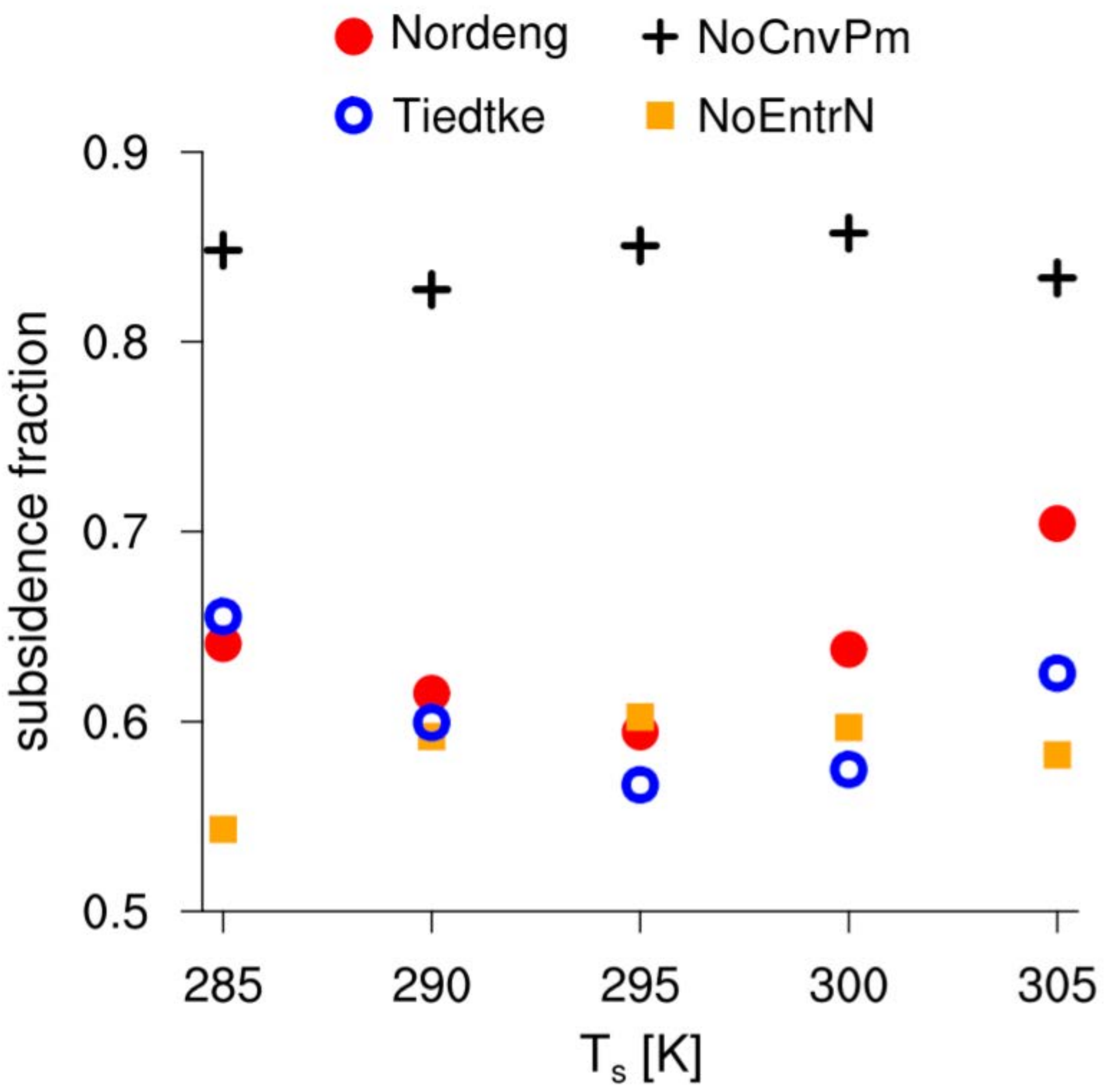


T. Becker, B. Stevens and C. Hohenegger, *J. Adv. Model. Earth Syst.* (to be submitted, 2016)

… and this has a much bigger influence on estimates of ECS



Simulation	285 - 290 K	290 - 295 K	295 - 300 K	300 - 305 K	285 - 305 K
NoCnvPm	-0.27	-0.92	-0.25	-0.35	-0.34
Nordeng	-0.33	-8.19	0.57	-0.21	-0.64
Tiedtke	-0.27	-1.88	0.92	-0.53	-0.79
NoEntrN	-0.33	-0.78	-0.51	1.54	-0.71



Changes in ECS are not stable at different temperatures, and this reflects changes in organization.

… instability of the sensitivity parameter is also evident in other models

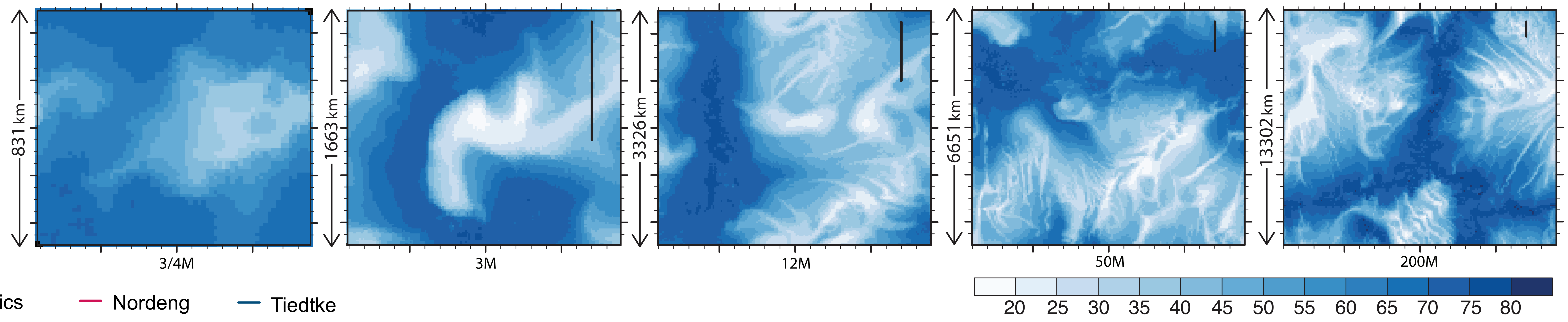
	Min	Max	Average
MPI	-2.1	32.9	2.4
IPSL	-5.2	55.5	3.9
NCAR	-7.4	13.3	3.5

1. *Even for a very simple problem the uncertain representation of clouds and convection leads to a very large range in the radiative response to forcing.*
2. *The instability in the sensitivity parameter appears related to the emergence of organization.*

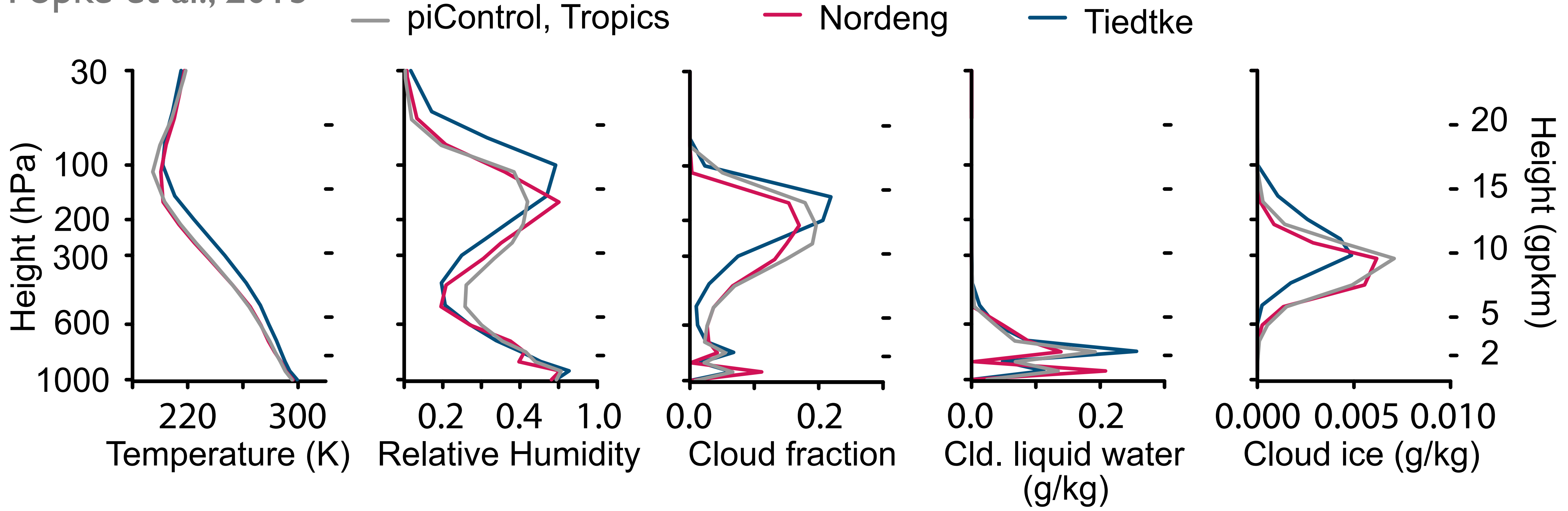
But the real advantage of RCE is that it is amenable to more fundamental approaches.

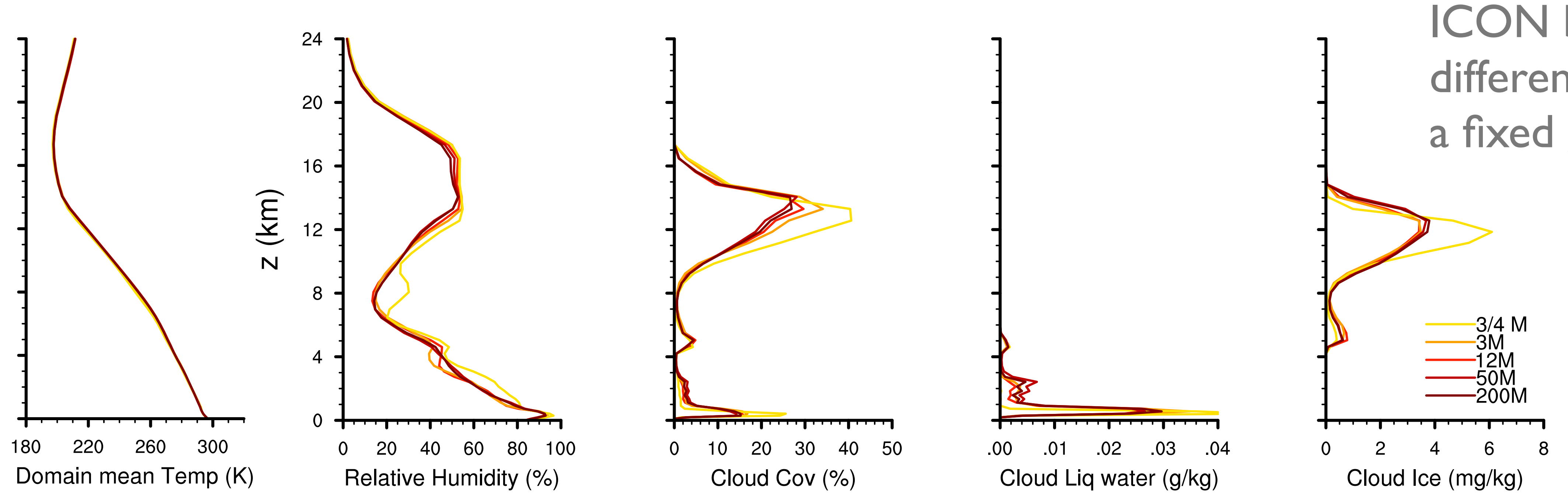
Thanks to Tobias Becker, David Coppin, and Brian Medeiros

… little evidence of a structural dependence on domain size

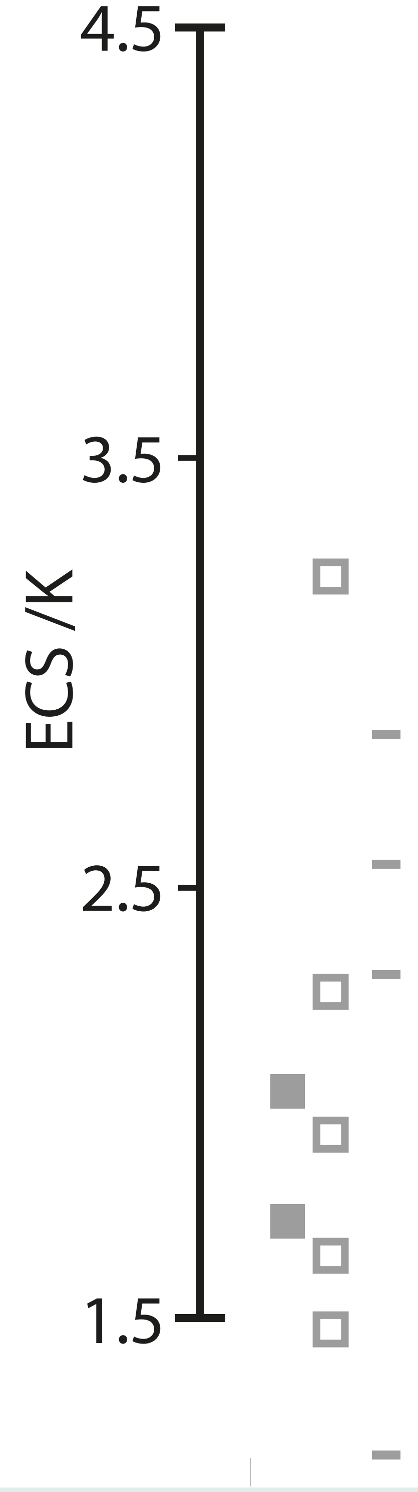


Popke et al., 2013





ICON based RCE on different sized domain, with a fixed grid spacing.



Even for a relatively stable mean climate, still considerable spread in estimates of ECS

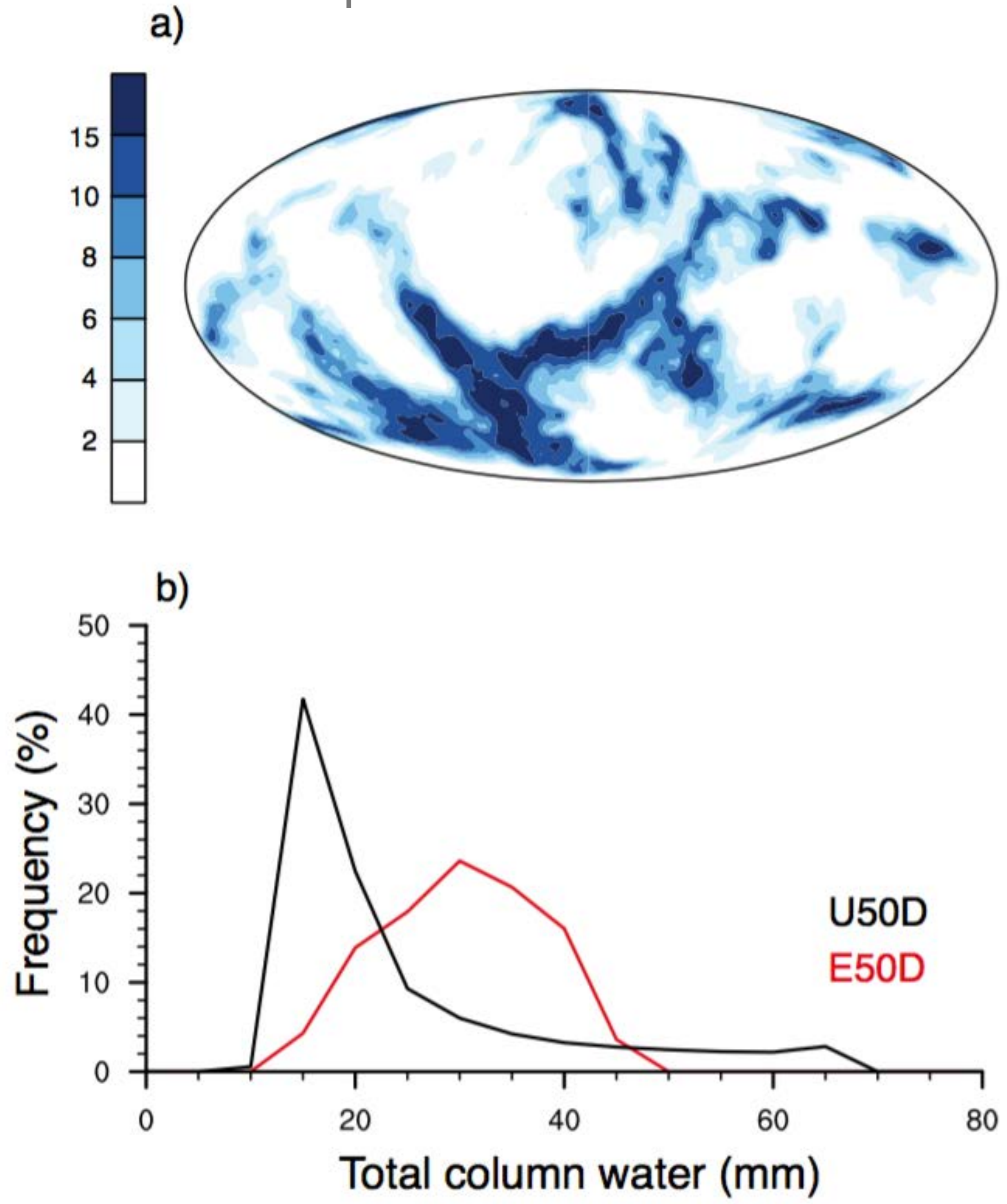
L. Silvers, et al., *J. Adv. Model. Earth Syst.* (to be submitted, 2016)

First estimates of ECS using a convection resolving model in RCE

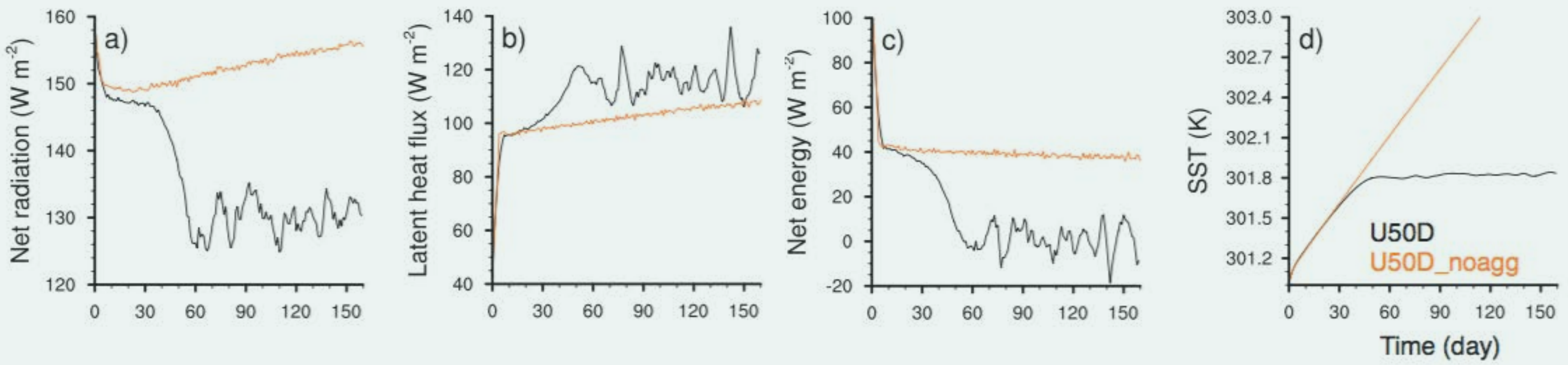
C. Hohenegger and B. Stevens., *J. Adv. Model. Earth Syst.* 2016

Aggregation is essential to stabilize the climate in the UCLA-LES

Aggregation leads to much drier areas in simulations with resolved deep convection

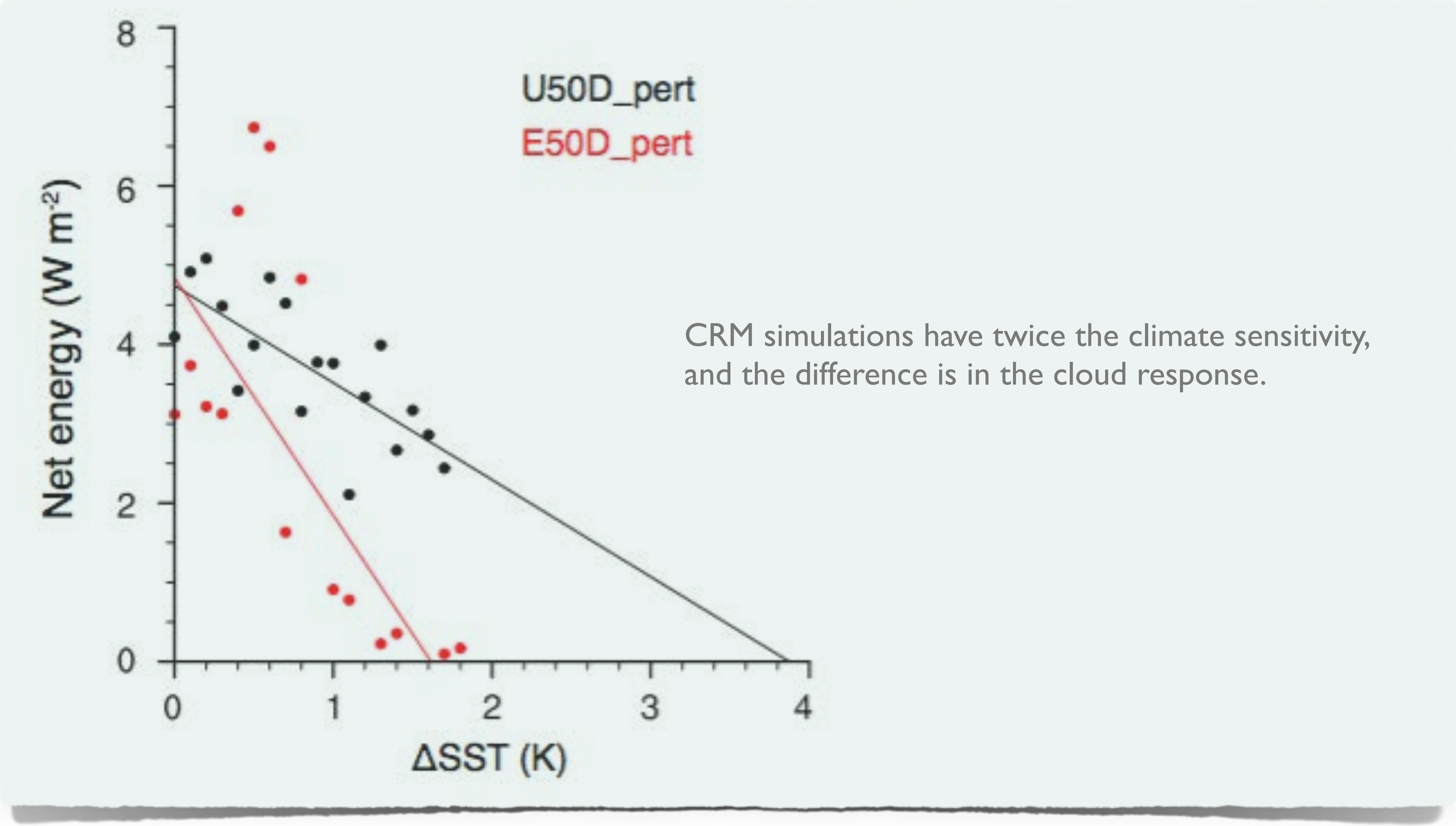


Aggregation stabilizes the climate.



C. Hohenegger and B. Stevens., *J. Adv. Model. Earth Syst.* 2016

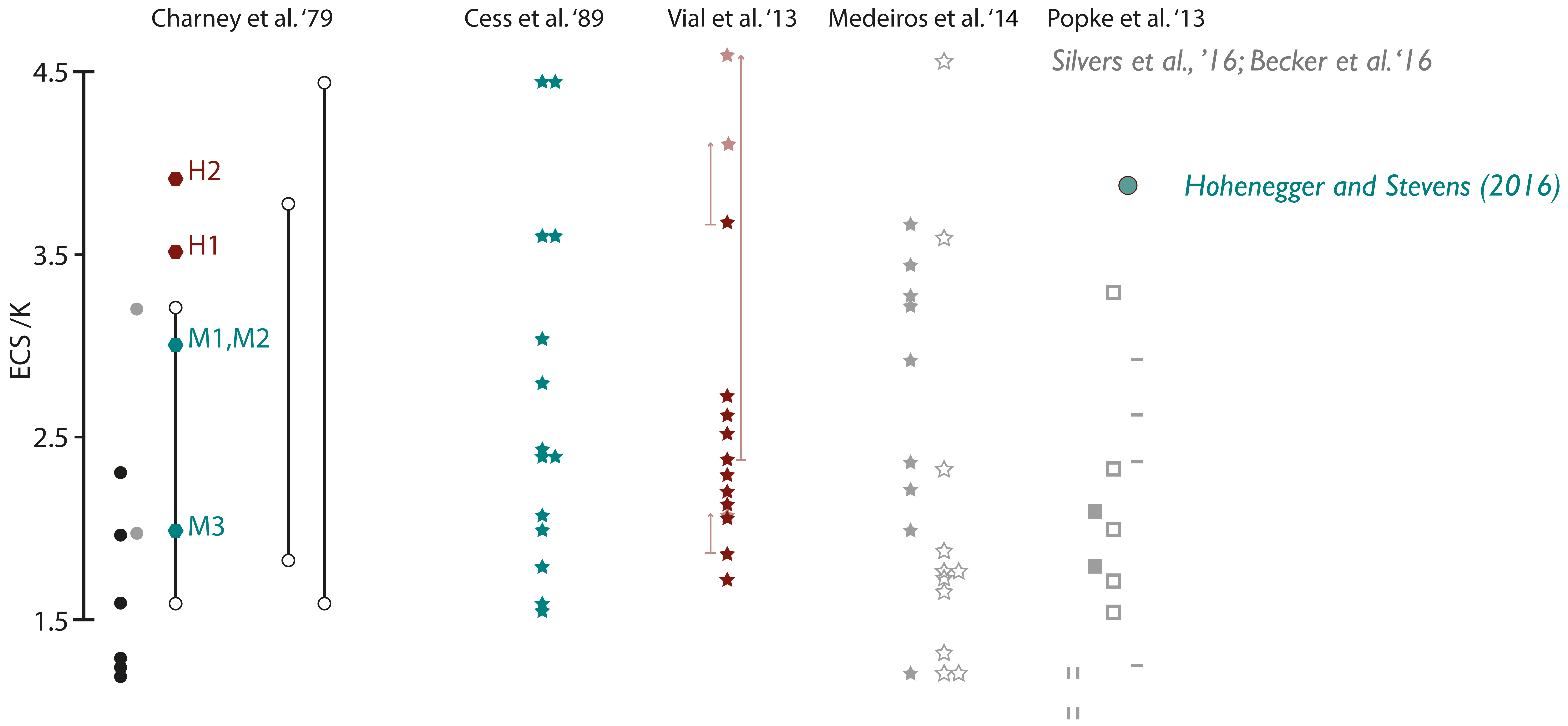
But strong SW (low?) cloud feedbacks give a much larger (3.8) ECS



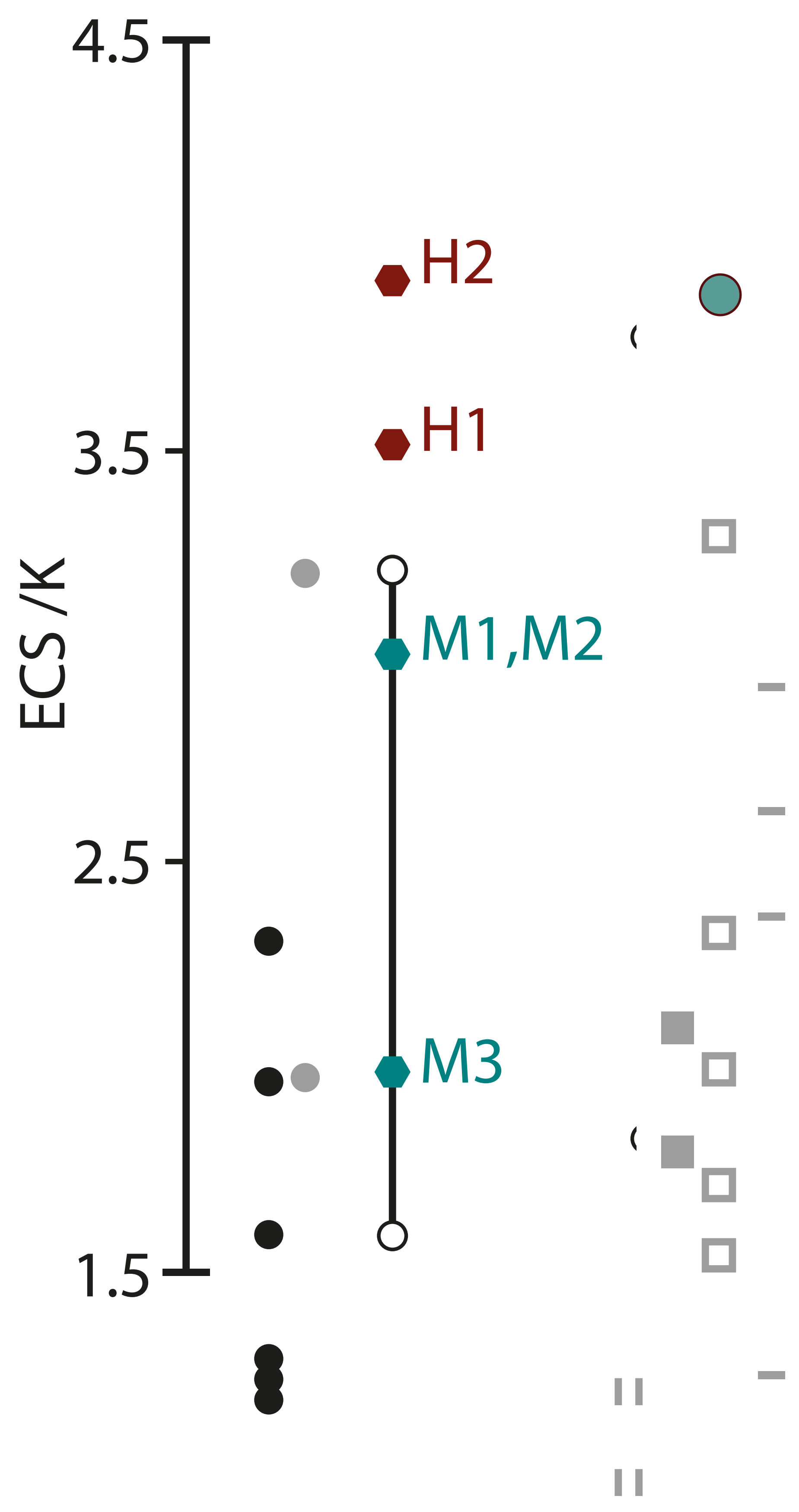
CRM simulations have twice the climate sensitivity, and the difference is in the cloud response.

unfortunately the simulations still aren't able to resolve shallow convection … but if they did they might not aggregate …

… there is a case to be made that realism is a distraction.



… ECS estimates for RCE



- ECS estimates in RCE still encompass a tremendous range.
- Large-Scale convective aggregation plays an important role, also in stabilizing the climate.
- We've settled on a simpler problem that we can solve, and perhaps an even simpler one (fixed cloud RCE) that we must solve.

… the hierarchy of problems we solve is as important as the hierarchy of models we employ.