Climate Sensitivity Estimated from Temperature Reconstructions of the Last Glacial Maximum

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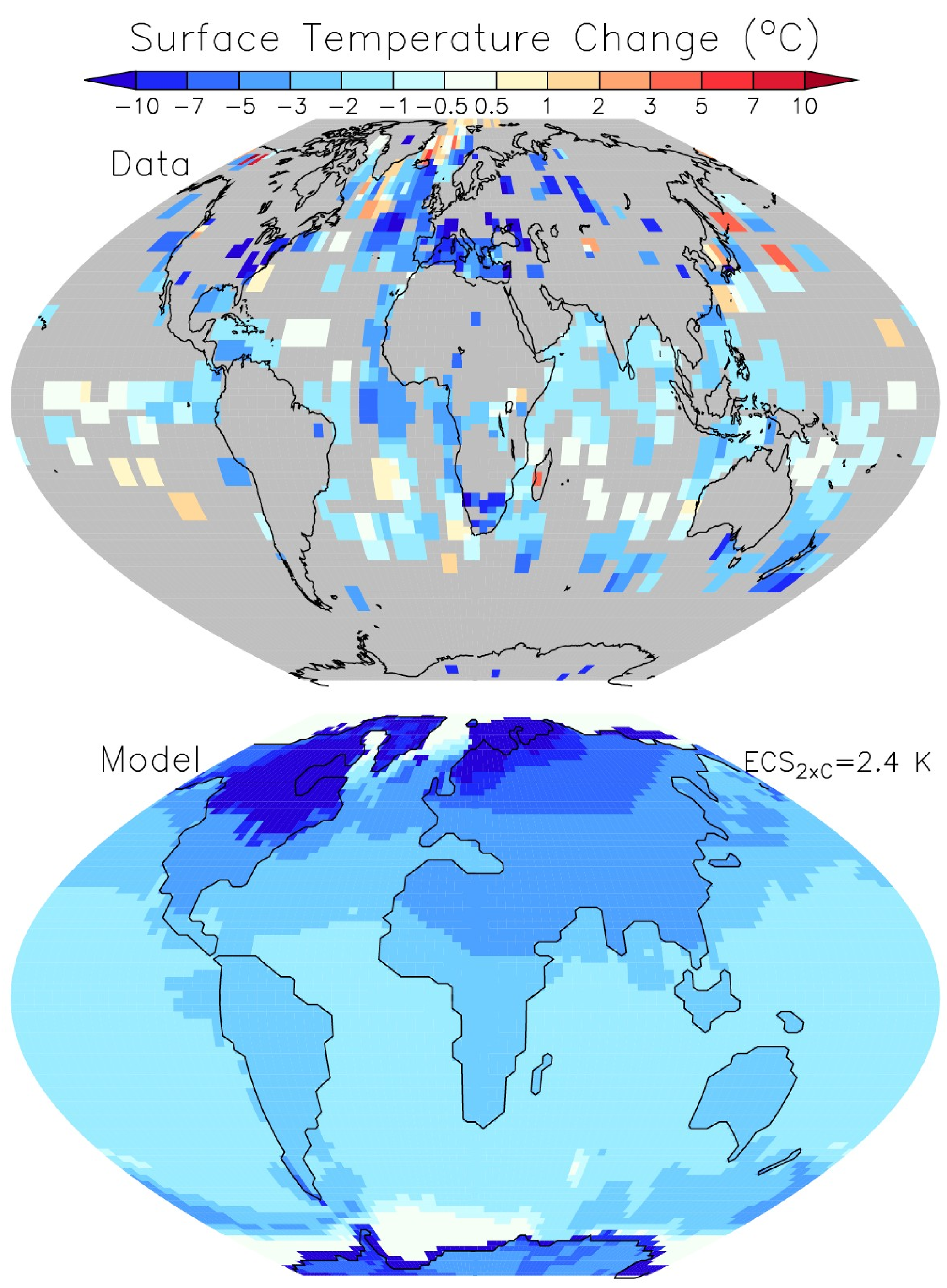
Funded by the Paleoclimate Progam



Surface temperature change LGM minus modern for the reconstructions (top) and the best fitting model (bottom).

Objective

Use temperature reconstructions from the LGM (19-23 ka) in conjunction with a climate model to infer equilibrium climate sensitivity to CO_2 doubling (ECS_{2xC}).

The Reconstructions

- ΔSSTs multiproxy MARGO (2009)
- ΔSATs land pollen Bartlein et al. (2011)
- 54 additional data Shakun et al. (in rev.)
- All data have error estimates
- Total 435 data points covering 24% of Earth's surface

The Model

University of Victoria (UVic) Climate Model

- 3D ocean (1.8x3.6, 19 levels)
- dynamic sea ice
- dynamic vegetation
- energy-moisture balance atmosphere, fixed atmospheric albedo, fixed winds

Forcing (-5.9 W/m²)

- Ice sheets (Peltier, 2004) -2.2 W/m²
- Greenhouse gases -2.8 W/m²
- Insolation 0 W/m²
- Dust 2D maps of SW & LW -0.9 W/m²

Ensemble

- 43 model versions with different parameterization of outgoing longwave radiation, dust forcing and wind stress

Statistics

Bayesian method

Assumptions:

- Observations are given by model plus error:

$$\Delta T_{obs} = \Delta T_{mod}(ECS_{2xC}) + \varepsilon$$

- Error ε ~ N(μ=0,Σ) with covariance matrix

$$\Sigma = \Sigma_{obs} + \Sigma_{model}$$

and model error

$$\Sigma_{model} = \Sigma_{spatial} + \Sigma_{nugget}$$

- Observation and nugget errors are uncorrelated with

$$\Sigma_{nugget} = \mathrm{diag}([\eta_L^2\ \eta_O^2])$$

η_L=2.5 K, η_O=0.5 K, but the model error contains a spatially correlated part:

$$\mathrm{cor}(x_i, x_j) = \exp[-d(x_i, x_j)/\lambda]$$

$$\Sigma_{spatial} = \begin{bmatrix} \sigma_L^2 c_{LL} & \sigma_L\sigma_O c_{LO} \\ \sigma_L\sigma_O c_{LO}^T & \sigma_O^2 c_{OO} \end{bmatrix}$$

with λ = 2000 km.

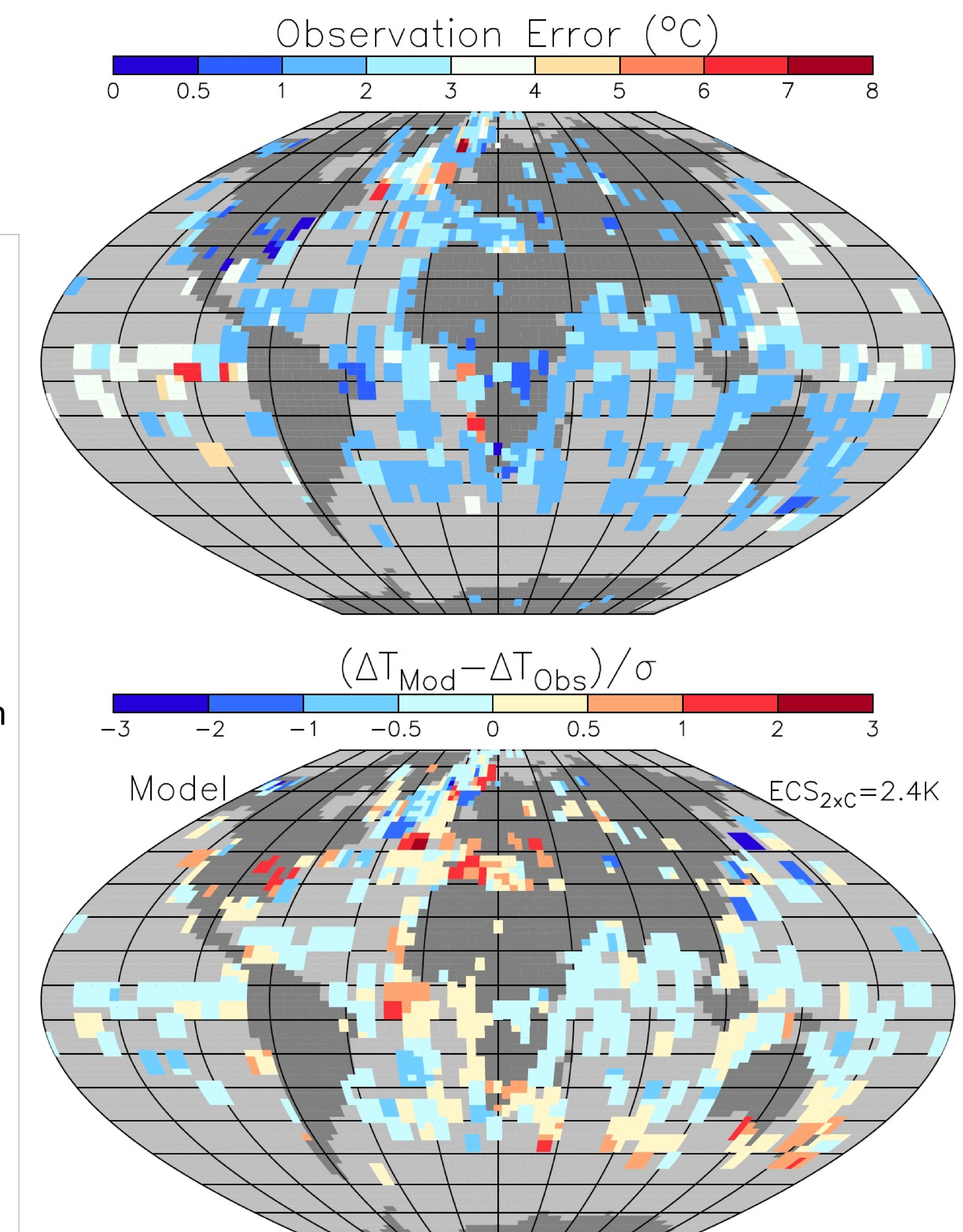
- Multivariant normal likelihood function

$$L(\Delta T_{obs} \mid ECS_{2xC}, \sigma_L, \sigma_O) = \frac{1}{\sqrt{(2\pi)^n \det\Sigma}} \exp\left[-\frac{1}{2} r^T \Sigma^{-1} r\right]$$

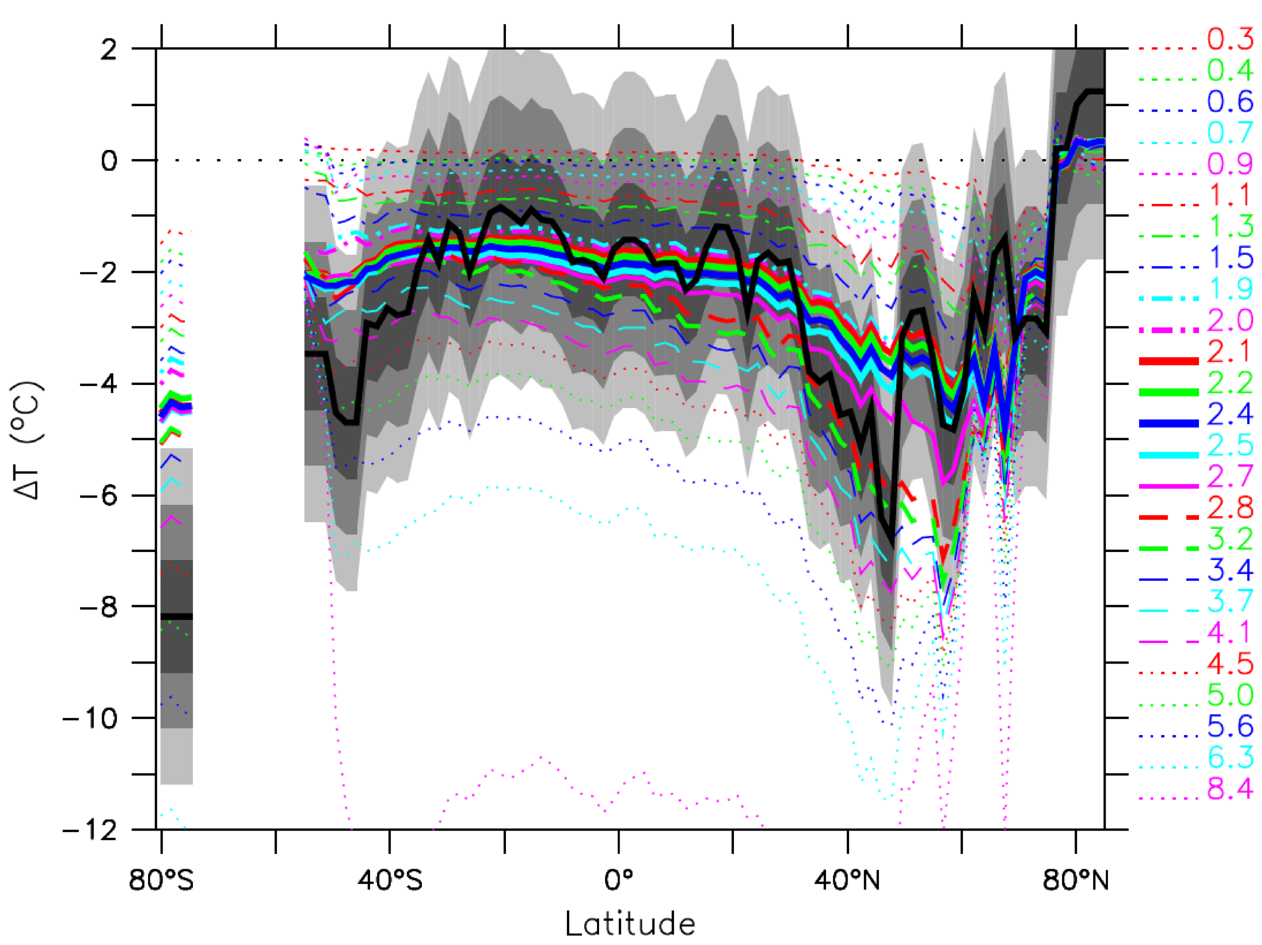
where

$$r = \Delta T_{obs} - \Delta T_{mod}(ECS_{2xC})$$

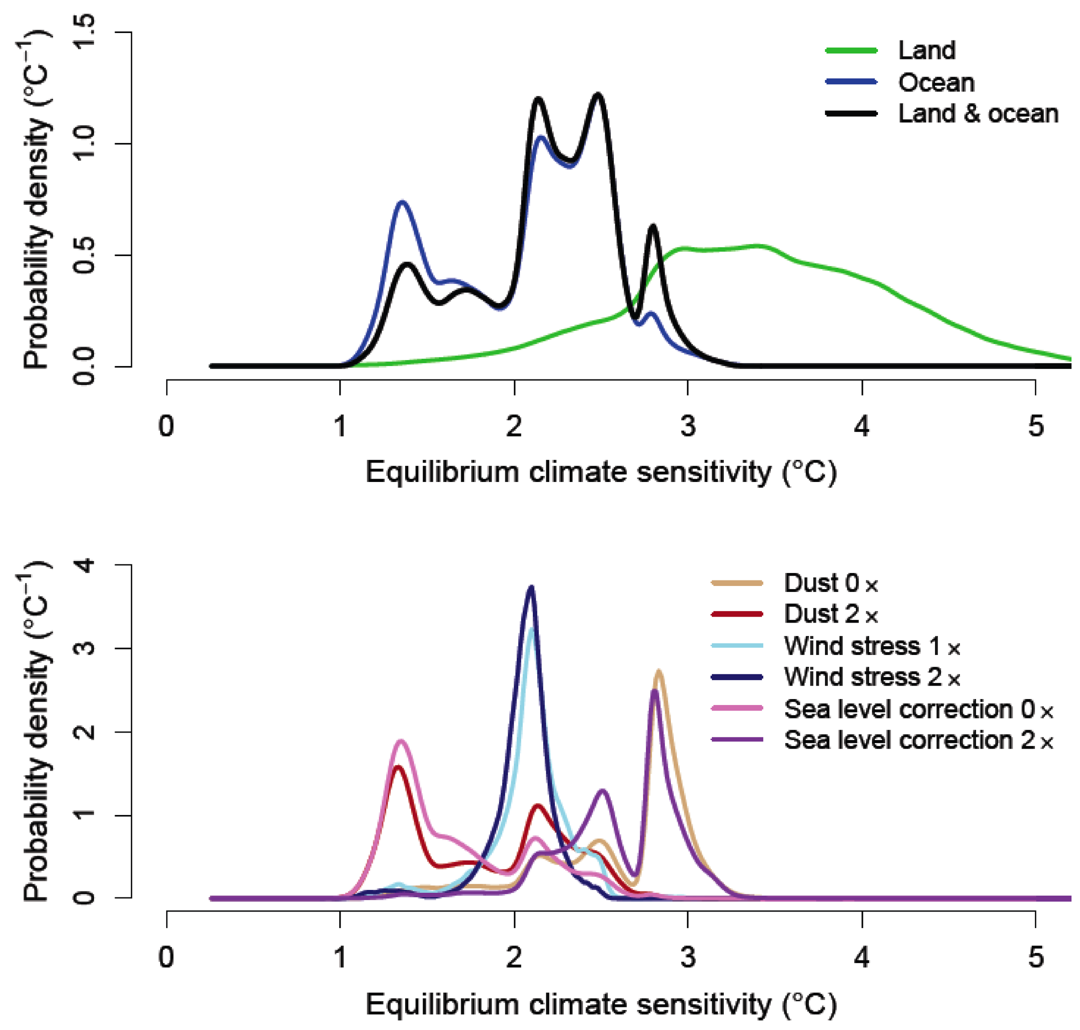
- σ_L and σ_S estimated endogenously



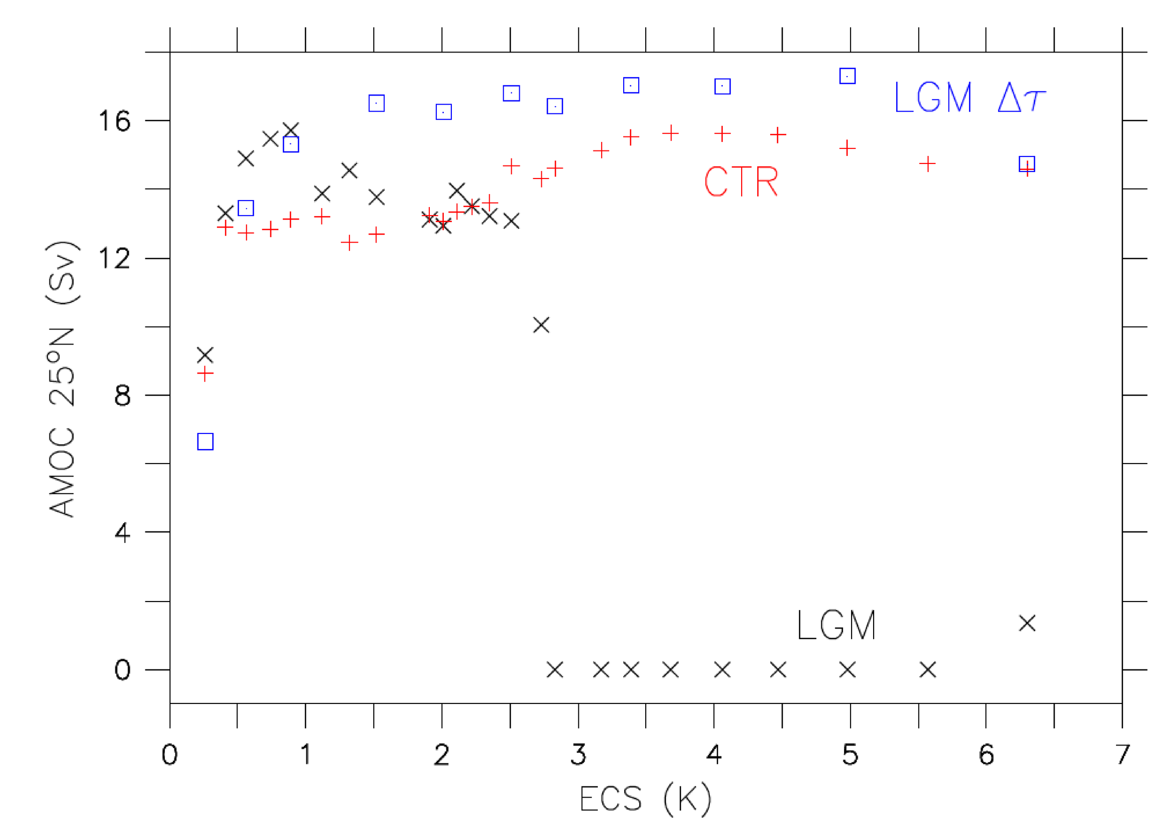
Top: published errors from the temperature reconstructions. Bottom: residuals (difference between model and observations divided by total error). The total error includes the error of the observations (top) and the model error.



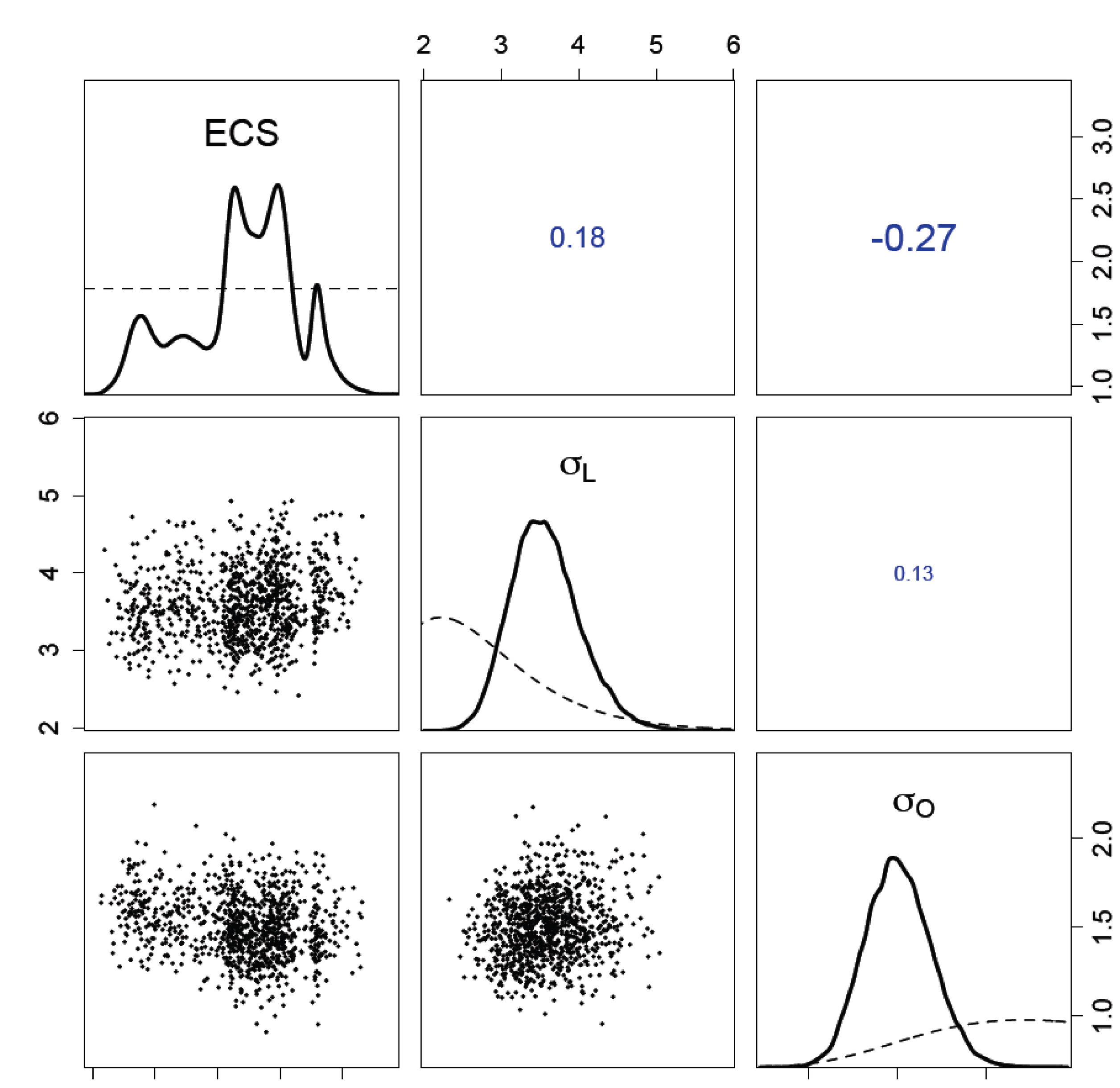
Zonally averaged surface temperature change in reconstructions (black thick line with ±1,2,3 K intervals in grey) and models (color lines) with different ECS_{2xC}. Models with high climate sensitivity (> 6.3 K) show transition to Snowball Earth.



Marginal posterior probability distribution for ECS. Top: PDF using all data (black), only ocean (blue) and only land (green) data. Bottom: Results from sensitivity tests.



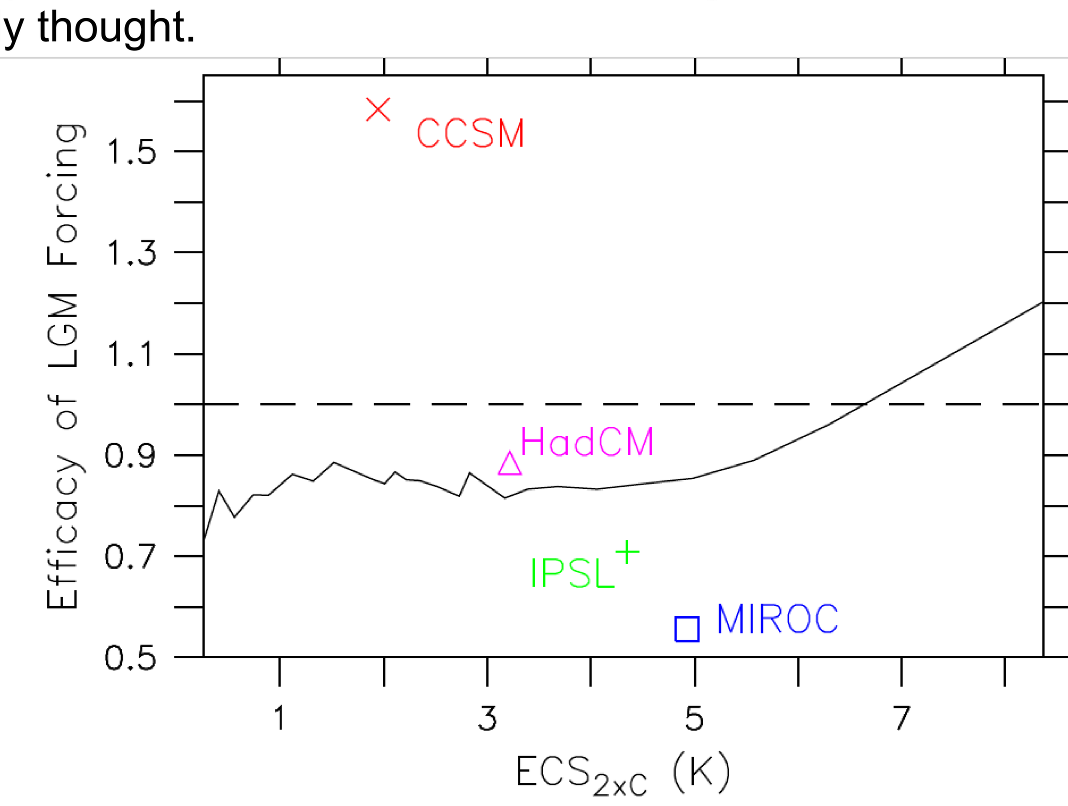
AMOC as a function of the ECS. Black: default LGM model, red: control simulations, blue: LGM runs with wind stress anomalies from GENMOM (Alder et al. 2010).



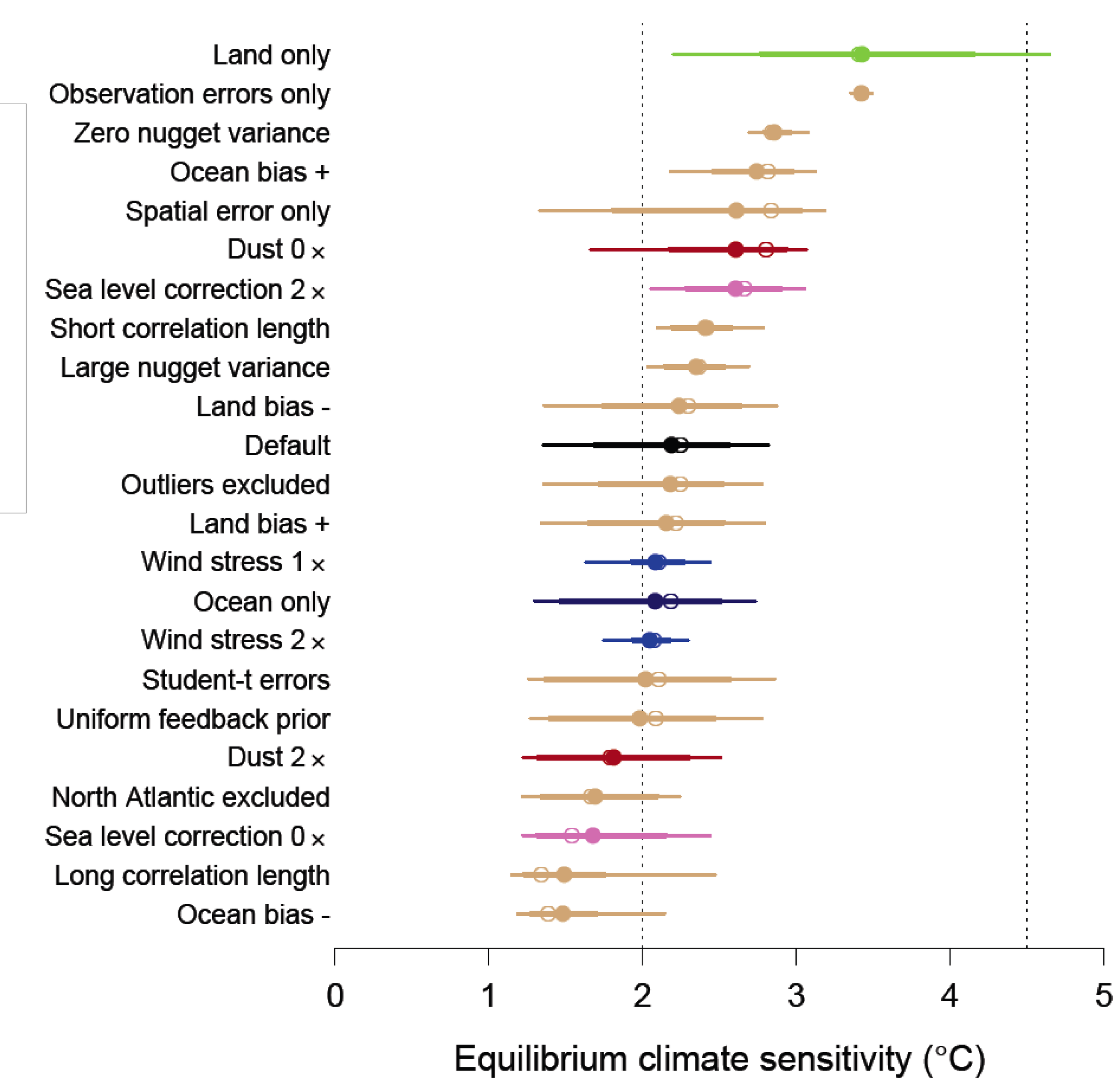
Joint posterior distributions of ECS, σ_L and σ_S. Dashed lines show priors. All units are K.

Conclusions

LGM temperature reconstructions provide unprecedented constraints on climate sensitivity. Our best estimate (2.2 K) and 66% and 90% (1.4-2.8 K) probability intervals are significantly smaller than those from IPCC (2007). Tension between land and ocean data and multi-model differences in LGM climate efficacy remain concerns. Our results suggest that high climate sensitivities and hence the probability of extreme imminent climate change are less than previously thought.



Efficacy of LGM forcing, i.e. climate sensitivity ΔSAT/ΔF for LGM divided by climate sensitivity for $2xCO_2$ forcing. Symbols are from PMIP2 coupled GCM runs (Crucifix 2006 GRL). Line is UVic model.



Results from sensitivity experiments. The IPCC 66% probability range is indicated by dotted vertical lines. Collectively the sensitivity tests imply a climate sensitivity between 1-3 K. Only if ocean data are excluded or if the model error is set to zero larger sensitivities occur.