Emergent constraint on equilibrium climate sensitivity is an artefact of historical forcing

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Equilibrium climate sensitivity (ECS) is widely used in assessments of anthropogenic climate change, and the Intergovernmental Panel on Climate Change[1] has estimated the likely range of ECS to be between 1.5 and 4.5 K, with a best estimate of 3 K. Estimates of ECS from observational data are uncertain, and long time series are required due to the slow thermal response of the deep oceans. The estimates are therefore largely based on experiments in Earth system models (ESMs), and part of the uncertainty in the ECS reflects the disagreement among models. Recently, Cox *et al.*[2] presented a method for weighting the ESMs based on how well they reproduce a theoretically informed metric of the instrumental temperature record for the years 1880 to 2016. By demonstrating that the models with higher ECS deviate more from the instrumental temperature record according to this metric, they narrowed the likely range to be between 2.2 and 3.4 K, which would imply a reduced risk of dangerous global warming. This result, however, is an artefact induced by the anthropogenic trend manifest in the last forty years of the temperature record. When the analysis is repeated using data for the years 1880-1975 there is no emergent constraint on ECS.

The rationale of the approach of Cox *et al.* is an emergent relationship between ECS in climate models and a metric ψ which characterizes the solution to the stochastic energy balance model,

$$C\frac{d\Delta T}{dt} = -\lambda\, \Delta T + Q,$$

which is formally identical to the Langevin equation of statistical physics. This model is known to be inaccurate, mainly since it does not take energy uptake in the deep ocean into account, and hence assumes that the temperature response ΔT to radiative forcing is characterized by a single time scale $\tau = 1/(-\log\alpha_{1T}) = C/\lambda$, where α_{1T} is the 1-lag autocorrelation of ΔT. The ECS in the energy balance model is $Q_{2\times \mathrm{CO2}}/\lambda$, where $Q_{2\times \mathrm{CO2}}$ is the radiative forcing corresponding to doubling of CO_2 concentration. The forcing Q is a white noise process with scale parameter σ_Q, and the solution is an Ornstein-Uhlenbeck process where ΔT has variance $\sigma_T^2 = \sigma_Q^2/(2\lambda\, C)$ and auto-correlation function $e^{-t/\tau}$. It follows that

$$\mathrm{ECS} = \frac{Q_{2\times \mathrm{CO2}}}{\lambda} = \sqrt{2}\,\frac{Q_{2\times \mathrm{CO2}}}{\sigma_Q}\,\psi,$$

where $\psi = \sigma_T/\sqrt{-\log\alpha_{1T}}$ is a metric depending on the variance and autocorrelation time of the stochastic process.

Cox *et al.* contend that ψ can be estimated from the observational temperature record, and that there is an emergent relationship between ECS and estimates $\hat{\psi}$ in ESMs which allows the observed $\hat{\psi}$ in the instrumental record to constrain the model-based estimate of ECS. They choose to use sample estimators of σ_T and α_{1T} after linear de-trending in running time windows. However, the result of their analysis depends on the window length and on which part of the instrumental record that is used for analysis.

The estimated ECS versus window size is shown Fig. 1a, which is a reproduction of Fig. 4a in Cox *et al.*, but with an extended range of window sizes. We observe that the expected value of the ECS is 3.4 K for a window width of 5 years, 2.5 K for 25 years, and 2.9 K for 75 years. The constraint on the ECS found by Cox *et al.* depends critically on the existence of a theoretically informed preference of using a window size around 55 years. This preference is found from selecting the window size that makes the slope of the regression line $\mathrm{ECS} = a\,\hat{\psi} + b$ match the constant of proportionality $\sqrt{2}\ Q_{2\times\mathrm{CO2}}\ /\ \sigma_Q$ derived from the energy balance equation, when this constant is estimated as the mean of this quantity over the ensemble of ESMs.

One problem with this approach is that the constant b is added without any theoretical justification. If such a justification exists the slope a would have a different physical interpretation, and the reason for using a 55 yr window width is no longer valid. Another problem is that the approach is valid only if the estimate $\hat{\psi}$ actually measures the theoretically informed metric ψ which only depends on the properties of the Ornstein-Uhlenbeck process. This assumption is false since the estimate $\hat{\psi}$ of Cox *et al.* is strongly influenced by the anthropogenic trend in the temperature record, and more so towards the last forty years with stronger historical forcing. This is apparent from the estimates shown in their Figure 2a. In Fig. 1b we demonstrate the effect this has on the probability density function (pdf) for the ECS, by repeating their analysis while omitting the last forty years of the temperature records. The result obtained by omitting the last part of the record is least influenced by the forced trend and the estimate $\hat{\psi}$ is closer to the theoretically informed metric characterizing the unforced variability. The resulting pdf for the ECS has an expected value of 3.2 K and the standard deviation is 0.7 K. For comparison, the ECS-values of the ESM ensemble have a mean of 3.3 K and a standard deviation of 0.7 K.

The reason why this new estimate $\hat{\psi}$ fails to constrain the pdf $P(\mathrm{ECS})$ obtained directly from the ESMs can be seen from Fig. 2, where Fig. 2a shows the relation between ECS and $\hat{\psi}$ for all the models when $\hat{\psi}$ is obtained from the entire record. It corresponds to Figure 2b of Cox *et al.*, and since most models have $\hat{\psi}$ much greater than the value 0.13 K estimated from the instrumental temperature record, those models have very low weight in the estimation of the posterior pdf of the ECS. Our Fig. 2b, on the other hand, shows the same when the truncated temperature record is used. The $\hat{\psi}$-values of the models do not differ as much from each other as before, and are closer to the value estimated from the observational record. The result is that the models are more equally weighted and the model results are not effectively constrained by the observation data.

The only way to save the constraint of Cox *et al.* is to claim that it is essential to use the last part of the record. One must then assume the existence of a mysterious emergent relationship between the ECS and the estimate $\hat{\psi}$ obtained from the strongly forced part of the record, i.e. a relationship that is not "theoretically informed" by the energy balance equation. We are then left with a range of pdfs with center values ranging from 2.5 to 3.4 K depending on an arbitrary choice of window width.

Methods

Our methods are identical to Cox et al., with a few exceptions. We estimate the standard deviation of $\hat{\psi}$ from ensembles of ESM runs rather than from the instrumental record. The estimate $\hat{\psi}$ is the mean of the series of window estimates and one cannot estimate its variance from one observational record. Cox et al. have apparently used the variance of the window estimates. Our estimated variance of $\hat{\psi}$ is larger than theirs when the entire record is used, but this has almost no effect on the estimate of $P(\mathrm{ECS})$. It is the mean of $\hat{\psi}$ that is important for constraining $P(\mathrm{ECS})$. In other computations involving ESM data we have used run r1 for each model. For the years after the historical runs stop (2006-2016) we have used data from the RCP8.5 scenario. This yields similar results to Cox et al.

References

1. Collins, M. *et al.* Long-term climate change: projections, commitments and irreversibility. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Stocker, T. F. *et al.*) Ch. 12 (Cambridge Univ. Press, 2013).

2. Cox, P.M. *et al.* Emergent constraint on equilibrium climate sensitivity from global temperature variability. *Nature* **553**, 319–322 (2018).

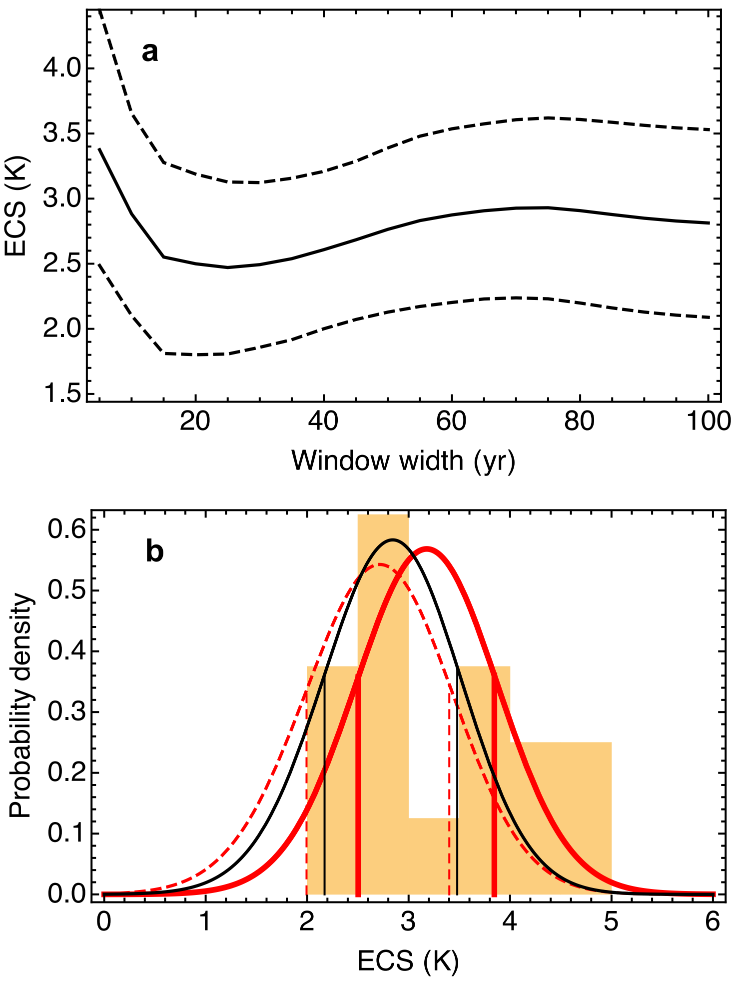

Figure 1 | Analysis of robustness of emergent constraint on ECS. a, Mean and 66% confidence intervals for a broader range of window widths than included in Figure 4a in Cox et al. **b**, The black distribution and the histogram is a reproduction of Figure 3a in Cox et al, where we also added the corresponding distributions if we only use data from 1880-1975 (thick red curve) and 1920-2016 (dashed red curve). The vertical lines represent 66% confidence intervals for the distributions.

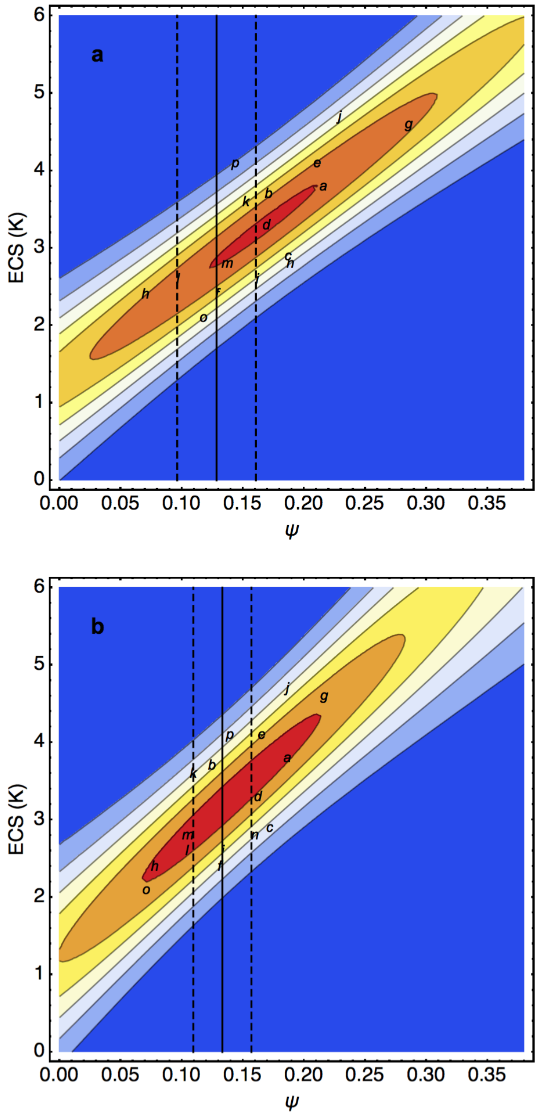

Figure 2 | Time period dependence of emergent relationship. a, Similar to Figure 2b in Cox et al., where the entire record 1880-2016 for the instrumental period has been used. A contour plot for the distribution P(ECS|Ψ) is also included. **b**, Same as panel a, but here only data for the period 1880-1975 has been used.