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# *Interactive comment on* "What could we learn about climate sensitivity from variability in the surface temperature record?" *by* James Douglas Annan et al.

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1. Page 5 line 9: the Cox, Huntingford and Williamson (2018) assertion that $\Psi$ = $\sigma$T /$\sqrt{-}$ln $\alpha$_1 (here using rho_1 rather than the original $\alpha$_1 to denote the year-one-lag autocorrelation) is linearly related to the equilibrium climate sensitivity S is adopted. Cox et al. derived that relationship using an one-box model with no representation of the deep ocean, which is generally viewed as unrealistically simple.

Williamson, Cox and Nijsse (2019) subsequently extended the Cox, Huntingford and Williamson analysis to a more realistic 2-box model, as used in this paper except in their case without the deep ocean heat uptake efficacy parameter ($\varepsilon$). However, the



original Cox, Huntingford and Williamson assertion about $\Psi$ is fairly obviously incorrect for a 2-box model. The Williamson, Cox and Nijsse analysis is made on the valid basis of the slow time constant of the two box model being much longer than the fast time constant, so that the fast mode dominates the variance and autocorrelation. Combining their equation (22) with the definition of $\Psi$, gives $\Psi \approx \sigma$_T $\sqrt{\tau}$_f. Using this relation to substitute for $\tau$_f in their equation (21) then yields $\Psi \approx$ ($\sigma$_Q/$\sqrt{2}$) a_f/$\lambda$. They then use the relation ECS = Q_2xCO2 / $\lambda$ to obtain from this ECS $\approx$ ($\sqrt{2}$Q_2xCO2/$\sigma$_Q a_f) $\Psi$, on the basis that a_f is unrelated to $\lambda$.

However, as Williamson, Cox and Nijsse correctly state, over the CMIP5 range of [fitted 2 box model] parameters a_f $\approx$ $\lambda$/($\lambda$ + $\gamma$). Regression analysis across 34 CMIP5 models gives an R-squared of 0.996 for this approximation to a_f, with an intercept of $-0.03$ and a slope coefficient of 1.03. In the context of a 2-box-$\varepsilon$ model with an added deep ocean heat uptake efficacy parameter $\varepsilon$, this approximation becomes af $\approx$ $\lambda$/($\lambda$ + $\varepsilon\gamma$). Regression analysis across 34 CMIP5 models gives an R-squared of 0.998 for this approximation to a_f, with an intercept of $-0.02$ and a slope coefficient of 1.015.

Accordingly, for the 2-box-$\varepsilon$ model used, substituting af $\approx$ $\lambda$/($\lambda$ + $\varepsilon\gamma$) in a_f/$\lambda$ $\approx$ $\sqrt{2}$ $\Psi$/$\sigma$_Q one gets 1/($\lambda$ + $\varepsilon\gamma$) $\approx$ $\sqrt{2}$ $\Psi$/$\sigma$_Q. Multiplying by Q_2xCO2 implies that $\sqrt{2}$ Q_2xCO2 $\Psi$/$\sigma$_Q $\approx$ Q_2xCO2/($\lambda$ + $\varepsilon\gamma$).

However, Q_2xCO2/($\lambda$ + $\varepsilon\gamma$) represents a measure of short term transient climate response, not of equilibrium response.

When regressing Q_2xCO2/($\lambda$ + $\varepsilon\gamma$) on ECS and TCR, both as estimated from the fitted 2-box-$\varepsilon$ model, across 34 CMIP5 models, the R-squared is 0.983 but the coefficient on ECS is very small ($-0.04$) and significant only at the 3% level. When regressing without an intercept term (which appears more appropriate) the R-squared is 0.999, the coefficient on TCR is 1.04 $\pm$ 0.03 but the coefficient on ECS is $-0.03$ and insignificant even at the 10% level.

This analysis implies that in a 2-box-$\varepsilon$ model, and in AOGCMs insofar as their behaviour can be fit by that model, $\Psi$ is mathematically (and indeed physically) linearly related to TCR, and only indirectly related to ECS. It is accordingly unsound to regard $\Psi$ as an emergent constraint on ECS save through the relationship between ECS and TCR, irrespective of the strength of the correlation between $\Psi$ and ECS in a particular model ensemble, at least insofar as it is valid to use a 2-box model.

In CMIP5 AOGCMs $\Psi$, as derived from locally detrended piControl simulation data, does nevertheless appear to be more strongly correlated with ECS than with $1/(\lambda + \varepsilon\gamma)$, all as estimated from a fitted 2-box-$\varepsilon$ model. That suggests that a 2-box-$\varepsilon$ model is poor at representing AOGCM behaviour on the inter-year timescales relevant to $\sigma$_T and rho_1, possibly because near surface temperature over land, sea ice and shallow water responds much more quickly to forcing than does temperature over the open ocean.

This analysis throws doubt on the validity of assessing what can be learnt about equilibrium, as opposed to transient, climate sensitivity from variability in the surface temperature record in a 2-box-$\varepsilon$ model, and potentially also on the physical basis for the related emergent constraint on ECS.

2. Page 6 lines 31-35 & page 7 lines 1-5 : the authors quite rightly use the likelihood ratio rather than the Bayesian posterior density to infer the strength of the constraint. However, the use of a likelihood ratio (Bayes Factor) of 10 or more as suggested by Kass and Raftery (1995) for comparing two competing point hypotheses seems unduly demanding here, where the aim is instead to derive an uncertainty range. A 5-95% uncertainty range can be derived directly from the likelihood ratio, on the assumption that - as is commonly the case - the likelihood function approximately follows a normal distribution or a one-to-one transformation of the parameter exists under which it would do so (e.g., Pawitan et al 2001). The simplest way of doing so is to use the signed root log-likelihood ratio (SRLR), as was done in Allen et al (2009). The SRLR method implies that a 5-95% range spans likelihoods that exceed 0.258 times the maximum likelihood, a likelihood ratio of 3.87, much lower than 10. Uncertainty in additional



parameters can be allowed for by considering all parameters jointly and applying the SRLR method to the profile likelihood.

Also three small points:

3. Page 3 line 20: the model in equations (1) and (2) is not the Winton et al (2010) model: it is the Held et al (2010) model. The Winton et al model, although similar to the Held et al. model, has a basic difference in that its efficacy parameter $\varepsilon$ applies to total ocean heat uptake, and is found to vary significantly over time in AOGCMs, whereas in the Held et al model $\varepsilon$ only applies to deep ocean heat uptake, as in equation (1), and is found to fit AOGCM behaviour with (as here) a constant $\varepsilon$ value. The cited Geoffroy et al (2013a) paper uses the Held model, not the Winton model.

4. Page 4 Table 1: there is a sign error in the default value for the radiative feedback parameter, $\lambda$. The way this parameter is used in equation (1) implies it is negative, but Table 1 defines it as 3.7/S not $-$3.7/S.

5. Page 13, line 30: the title of Kass and Raftery's 1995 paper is just "Bayes Factors".

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