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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I am gratified to see a resurgence of interest in the approach of inferring the sensitivity of global mean surface temperature anomaly T to sustained forcing from fluctuations in time series of T that is reflected in this manuscript and also in Cox *et al*. (2018) and Williamson *et al*. (2018). However I note some concerns with this manuscript as well as the two earlier papers. Unfortunately there is some sloppiness in definitions in the earlier papers that carries over to the present paper that makes it tough to evaluate the quantity Ψ and interpret the inferences drawn from that quantity. I also have some concerns over the treatment of the two compartment system that the authors may wish to take into consideration. At the end of the day, however, as the finding of the present manuscript is that the determination of the climate sensitivity by the approach of Cox *et al*. (2018) fails, perhaps some of these niceties are of secondary importance. Still, one might hope for more attention to detail.

First, to the definition of Ψ (page 5, line 9)

$$\Psi = \frac{\sigma_T}{(\ln \rho_1)^{1/2}} . \tag{1}$$

Ψ is important as, at least as argued by Cox *et al*. (2018) and as examined in the present manuscript' in that it forms the basis for determination of Earth's equilibrium climate sensitivity without requirement of knowledge of forcing as

$$\lambda = \frac{\sigma_T}{\sigma_Q}\left(\frac{\ln \rho_1}{2}\right)^{1/2} \tag{2}$$

or, in terms of Ψ,

$$\lambda^{-1} = \frac{2^{1/2}}{\sigma_Q}\Psi \tag{3}$$

or in terms of equilibrium sensitivity S_{eq},

$$S_{\text{eq}} \equiv F_{2\times\text{CO2}}\lambda^{-1} = 2^{1/2}\frac{F_{2\times\text{CO2}}}{\sigma_Q}\Psi \ . \tag{4}$$

I am not sure I see σ_T and σ_Q explicitly defined in the present manuscript; presumably they are the standard deviations of the respective quantities (square root of variance) over a time window, and presumably after linear detrending. It is explicitly stated by Cox *et al.* (2018) that σ_T^2 and σ_Q^2 are the variances of the time series of T and forcing, calculated for windows of width 55 yr, after linear detrending in a given time window. For a stationary quantity, σ_T would be a constant over the time series, with only the uncertainty in σ_T being a function of the time window chosen to evaluate the quantity, decreasing with increasing time window (as the square root). However for a nonstationary time series whose mean value over a time window changes with time, σ_T calculated relative to the mean of the time series over that window depends on the location and width of the time window, generally increasing with increasing width. Further, it would seem to be essential to specify whether σ_T is calculated relative to the mean of the time series in the window or relative to the detrending function (of which a linear function is only one of a myriad of possible detrending functions). The above considerations apply also to σ_F. Similar considerations attach also to definition of the lag-1-year autocorrelation coefficient ρ_1. It thus seems essential that the authors explicitly state how these quantities are determined. Finally, it would seem that a proponent of this method would need to establish that Ψ approaches some sort of limiting value as a function of increasing (or decreasing) window width; if that is not the case then the approach must be considered suspect for that reason alone as well as for other reasons adduced in the present manuscript.

That said, there remains question about Eq (2) itself on which the present manuscript relies. Clearly the derivation given by Cox *et al.* (2018) must be viewed as flawed, the quantities on the left hand sides of each of the equations (Eqs 4 and 5 of that paper) leading to Eq (1) above having different dimension from the respective right hand sides of those equations. So there is a need for a convincing derivation of Eq (1) if it is to be the cornerstone of analyses such as this, generally, and, in particular, of the present manuscript.

On the subject of dimension of quantities, it is clear from Eq (1) above that the dimension of Ψ is temperature (unit K or ˚C). In the present manuscript (e.g., p. 7, line 2; Figure 1) it is presented as a dimensionless quantity without unit, although I note the unfortunate absence of units in axis labels of many of the figures.

Staying with the relation of Ψ to climate sensitivity, as the fluctuations that are used to determine Ψ are characteristic of the upper ocean, it would seem that for the two compartment model used by Annan *et al.*, the pertinent climate sensitivity quantity would be the transient sensitivity, not the equilibrium sensitivity.

I turn now to Equations 1 and 2 of Annan *et al.* used in their model calculations. First I would question why the efficacy term is introduced (other than that it was introduced by Winton *et al.* (2010) and the present authors have uncritically accepted it). If one defines $\gamma' \equiv \varepsilon\gamma$, $z'_{\mathrm{d}} \equiv \varepsilon z_{\mathrm{d}}$, and $C'_{\mathrm{d}} \equiv \varepsilon C_{\mathrm{d}} = \varepsilon D_{\mathrm{d}} c_{\mathrm{vsw}} = D'_{\mathrm{d}} c_{\mathrm{vsw}}$, where $D'_{\mathrm{d}} \equiv \varepsilon z_{\mathrm{d}}$, then Equations 1 and 2 describing the change in heat content in the two compartments become

$$\begin{aligned} C_{\mathrm{m}} \frac{dT_{\mathrm{m}}}{dt} &= F(t) - \lambda T_{\mathrm{m}} - \gamma'(T_{\mathrm{m}} - T_{\mathrm{d}}) + C_{\mathrm{m}}\delta(t) \\ C'_{\mathrm{d}} \frac{dT_{\mathrm{d}}}{dt} &= \gamma'(T_{\mathrm{m}} - T_{\mathrm{d}}) \end{aligned} \quad , \qquad (5)$$

identical to the equations in Schneider and Thompson (1981), Gregory (2000), Held *et al.* (2010), the only difference being the magnitudes of the transfer coefficient and the depth of the deep ocean compartment. Importantly, however, as written in this way the equations exhibit equal piston velocity in both directions and conserve energy between the two compartments, as they must. Also there are only two adjustable parameters, γ' and D'_{d} instead of the original three. The original and revised parameters corresponding to the several traces in Figure 4 of Annan *et al.* are listed in Table 1. The revised parameters clearly display the changes in the several parameters in the several traces. The difference between Blue and Cyan is increase in equilibrium sensitivity being compensated by increase in transfer coefficient γ' from the mixed layer ocean to the deep ocean; the change in the depth of the deep ocean D'_{d} confounds the comparison but it is of very minor importance because of the low rate of return of heat from the deep ocean to the mixed layer. The difference between Cyan and Magenta shows, for fixed transfer coefficient, the compensation of the increase in α, the multiplier on aerosol forcing by increase in equilibrium sensitivity S_{eq}, where $S_{eq} \equiv F_{2\times CO2}\lambda^{-1}$ in the governing equations, similar to that shown for example by Tanaka and Raddatz (2011) and Schwartz (2018). It is, of course, this compensation, together with the large uncertainty in aerosol forcing, that motivates the search for an alternative approach to determination of sensitivity as undertaken by Schwartz (2007), Cox *et al*. (2018), and the present manuscript.

Table 1. Parameters for Figure 4 of Annan *et al*. as originally presented (without ') and as re-expressed here (with ').

Trace color	S_{eq} K/2×	α	γ W m^{-2} K^{-1}	ε	D_d m	C_d J m^{-2} K^{-1}	γ' W m^{-2} K^{-1}	C'_d J m^{-2} K^{-1}	D'_d m
Blue	1.78	1.0	0.7	1.3	1000	2.94E+09	0.91	3.82E+09	1300
Cyan	2.5	1.0	1.0	1.7	1000	2.94E+09	1.7	5.00E+09	1700
Magenta	5	1.7	1.0	1.7	1000	2.94E+09	1.7	5.00E+09	1700

The transfer coefficient γ', while rather uncertain, is constrained considerably by observations of the increase in ocean heat content over the past half century. Based on measurements of increase of global temperature and ocean heat content as assessed in AR5 (Hartmann *et al*., 2013; Rhein *et al*., 2013), the heat transfer coefficient from a mixed layer of depth 75 m to the deep ocean γ' is constrained to 0.73 ± 0.20 K W m^{-2} (one sigma). The values of γ' in the examples given by Annan *et al*. thus range from the high end to well beyond the high end of this observationally constrained range. The authors might wish to consider this constraint in the examples they present.

In conclusion, despite the concerns raised here, the authors are to be applauded for revisiting the question of whether fluctuations in the observed record of global mean surface temperature can usefully constrain climate sensitivity. It seems as if the answer is no, at least so far, but I am not sure that the last word has been written.

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