

Test of FUND's Temperature Response to CO₂

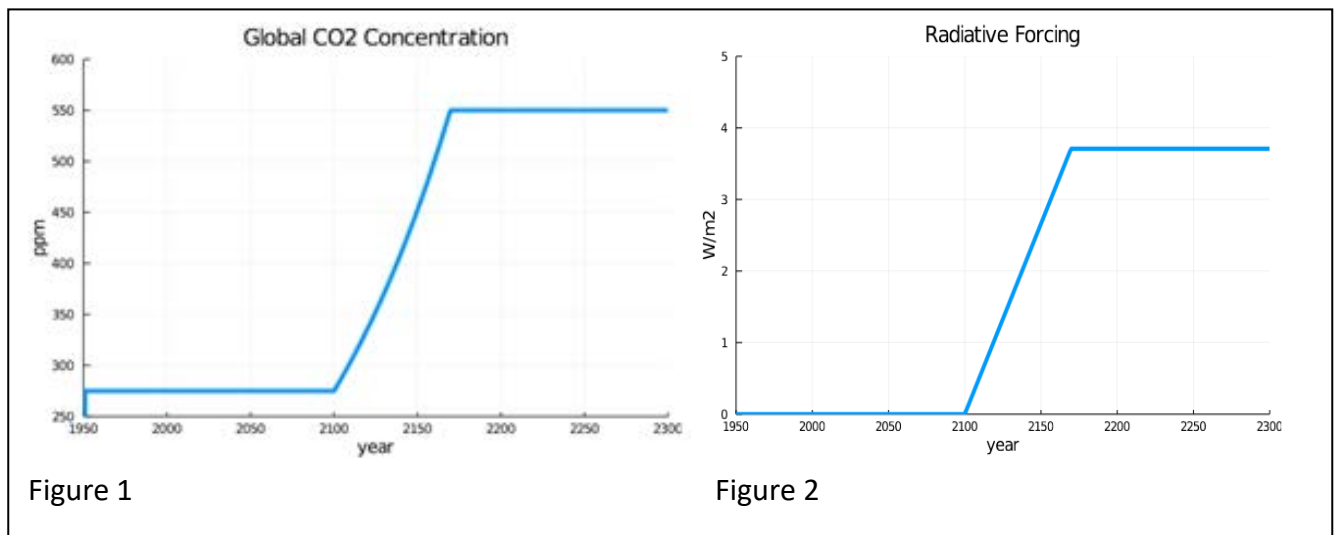
By Ken Gregory, P.Eng.

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[FUND](#) is one of the three most widely cited integrated assessment models used to advise governments about climate change economic impacts and the social cost of carbon dioxide. I tested the FUND equilibrium climate sensitivity (ECS) and the transient climate response (TCR) to various inputted ECS values. The TCR is defined as the temperature change starting from equilibrium, of a 1% per year increase of CO₂ concentration to the time when it doubles. The ECS is the temperature change due to a doubling of CO₂ after allowing the oceans to reach temperature equilibrium. I want to confirm if the equilibrium temperature change in FUND due to a CO₂ doubling equals the inputted ECS, and to check that the TCR at various ECS values are reasonable. I created a modified FUND model where the CO₂ concentration was increased at 1% per year from pre-industrial levels until it doubled then held constant. All other greenhouse gas concentrations were held constant. Aerosol forcing was set to zero.

The temperature response to radiative forcing in FUND is determined by a simple climate model that is intended to emulate the average of the global climate models. The sensitivity of the temperature response to increasing greenhouse gases is determined by setting the ECS parameter. There is no TCR parameter.

Figures 1 and 2 show the CO₂ concentration and the radiative forcings versus time, respectively, of the modified model.



The CO₂ increase starts in 2100 to ensure that temperatures were stable at that time. The first graph shows the exponential increase of CO₂ at 1% per year until it doubles from 275 ppm to 550 ppm. The second graph shows only the radiative forcing of CO₂, which at a doubling is 3.708 W/m². The graph confirms that all other forcings were removed from the model. The CO₂ radiative forcing increases linearly over the period because the exponential increase of the CO₂ concentration is offset by the logarithmic radiative effect.

The FUND temperature response at five ECS values is shown in figure 3, where year 1 is the first year of the 1% CO₂ concentration increase and year 70 is when the CO₂ concentration has doubled. The TCR corresponding to each ECS is the temperature anomaly at year 70. The model was run to 3000 corresponding to 900 years after the start of the CO₂ increase. The set of TCR/ECS and TCR given at the top of the graph correspond to the ECS values in the legend.

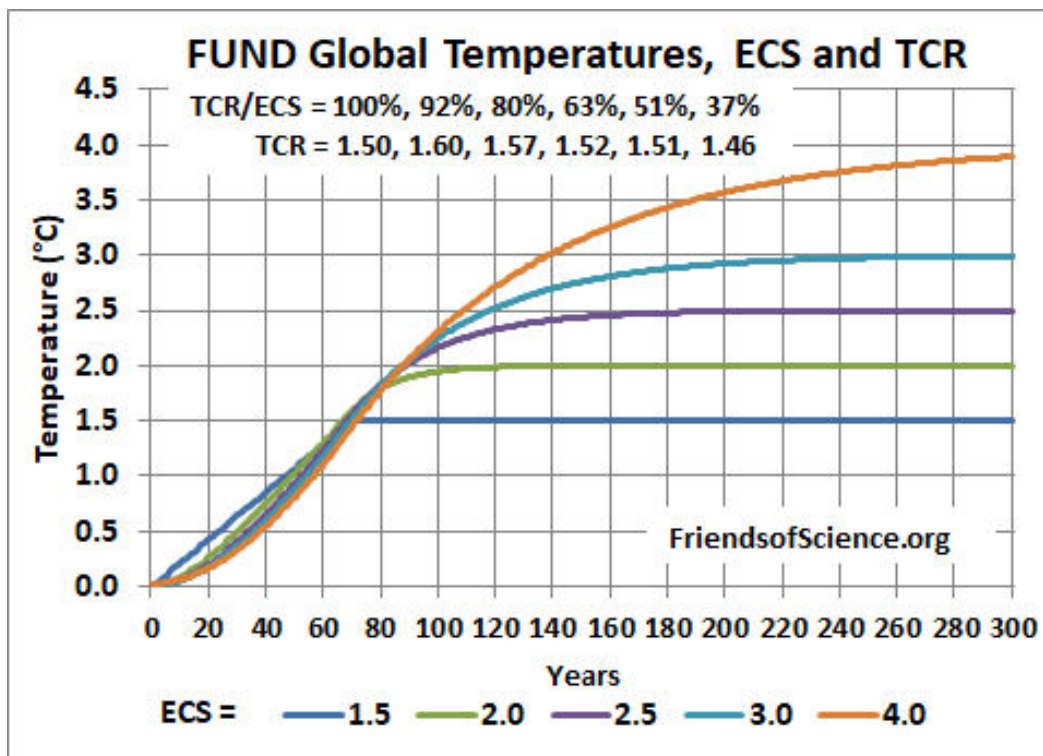


Figure 3

The model output confirms that the equilibrium temperature change due to the doubling of the CO₂ concentration is indeed exactly equal to the inputted value of each ECS. The figure also shows that the time to temperature equilibrium varies greatly with ECS. At ECS = 4.0 °C, the temperature is still increasing at 230 years after the end of the CO₂ increase (year 300 of the graph). At ECS = 1.5 °C, the temperature does not increase at all after the CO₂ had doubled at year 70.

Table 1 shows the ECS, TCR, the ratio of TCR/ECS and the number of years from the start of the CO₂ increase to reach 99% ECS. For comparison, it also show the ECS and TCR of the multi-model mean (MMM) reported in Intergovernmental Panel on Climate Change (IPCC) fifth assessment report (AR5) and from the measurement-based values from the Lewis and Curry 2018 paper (L&C2018) using HadCRUT4 temperatures.

| Model | ECS (°C) | TCR (°C) | TCR/ECS | Years to 99% ECS |
|---------|----------|----------|---------|------------------|
| FUND | 4.0 | 1.46 | 0.365 | 373 |
| FUND | 3.2 | 1.51 | 0.472 | 268 |
| MMM AR5 | 3.2 | 1.80 | 0.563 | N/A |
| FUND | 3.0 | 1.52 | 0.508 | 241 |
| FUND | 2.5 | 1.57 | 0.628 | 176 |
| FUND | 2.0 | 1.60 | 0.800 | 115 |
| FUND | 1.7 | 1.57 | 0.923 | 83 |
| FUND | 1.5 | 1.50 | 1.000 | 69 |
| L&C2018 | 1.5 | 1.20 | 0.800 | N/A |

Table 1

Despite the large range of ECS, 1.5 to 4.0 °C, the corresponding TCR has a very small range of 1.46 to 1.60 °C. The smallest TCR corresponds to the largest ECS. The TCR should always increase with increasing ECS. The FUND TCR corresponding to the ECS of the MMM of 3.2 °C is significantly smaller (1.51 °C) than the TCR of the MMM (1.80 °C). The L&C2018 energy balance study estimated the ECS is 1.5 °C and the TCR is 1.2 °C. The FUND temperature response at an ECS of 1.5 °C shows the TCR is equal to the ECS, also 1.5 °C! This implies that the oceans are instantaneously in temperature equilibrium with the atmosphere, with no delay, in FUND at ECS values of 1.5 °C and lower. This is physically impossible. The temperature responses to greenhouse gas emissions in FUND with ECS at or below 1.7 °C are much too high. Figure 4 shows the TCR as a function of ECS in FUND.

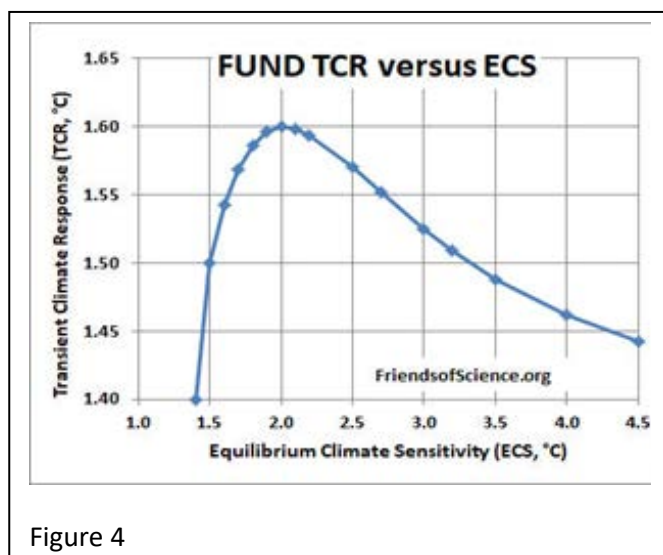


Figure 4

The L&C2018 analysis was deficient in that the natural climate change from the base to final periods were not considered and no correction was applied to remove the urban heat island effect (UHIE) from the temperature record. Correcting the L&C2018 study for urban warming and natural climate change, the likely range of ECS is 0.76 - 1.39 °C and the best estimate is 1.04 °C as per [this paper](#). The failure of FUND to forecast a reasonable temperature response at ECS below 1.7 °C is serious because the likely

range of ECS is well below 1.7 °C.

At an assumed 1.0 °C ECS, and using FUND's default greenhouse gas emissions scenario, FUND calculates a temperature change from 2020 to 2050 of 0.45 °C whereas using a TCR/ECS ratio of 0.8 it should give a temperature change of only 0.36 °C. The calculated social and economic impacts of warming in FUND are therefore incorrect.

[Table 9.5](#) of AR5 gives both the ECS and TCR of 23 climate models. These values are compared to the values calculated by the FUND model in figure 5.

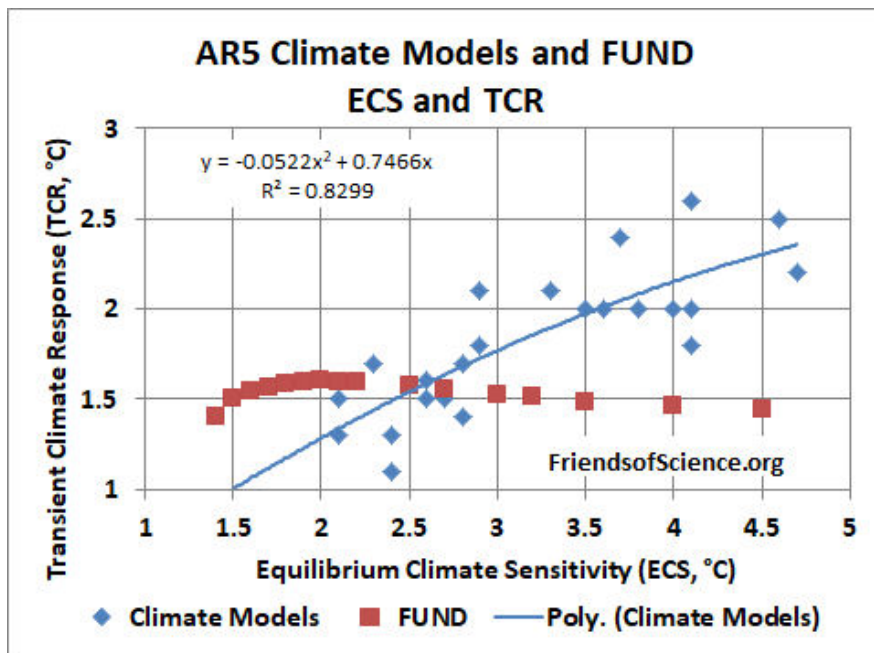


Figure 5

Figure 5 shows that FUND's TCR is too high when the ECS is less than 2.2 °C. The quadratic trend of the TCR versus ECS of the climate models with the intercept set to zero, the blue line, shows that generally the TCR should increase with increasing ECS. It is obvious that FUND's declining TCR with increasing ECS after 2 °C is very wrong. It appears that the TCR and the temperature responses are reasonable only in the ECS range of 2.2 to 2.8 °C. The TCR is too high when ECS is less than 2.2 °C. FUND's climate dynamics component fails to emulate the behavior of the climate models.

The Figure 6 compares the global mean surface temperature (GMST) anomaly profiles of the average of two climate models, NMCM4 of Russia and GISS-E2-R of USA, to FUND's temperature forecast where all are forced by the RCP4.5 scenario air concentrations of CO₂, CH₄ and N₂O. The RCP4.5 air concentrations of the three greenhouse gases and the corresponding GMST of the two climate models were obtained from [Climate Explorer](#). The two climate models were determined to have ECS of 2.1 °C and FUND's ECS was set to 2.1 °C. The FUND average temperature anomaly of the years 1998-2002 was aligned to equal that of the climate models' average. From 2000 to 2040

the FUND temperatures (purple line) closely match the average of the two climate models (blue line), but the FUND model runs too hot compared to the climate models after 2040 and is 0.43 °C too high at 2100. The temperature profile of FUND would match that of the climate models' average if FUND's climate dynamics component was calibrated properly as the greenhouse gas concentrations and ECS are the same.

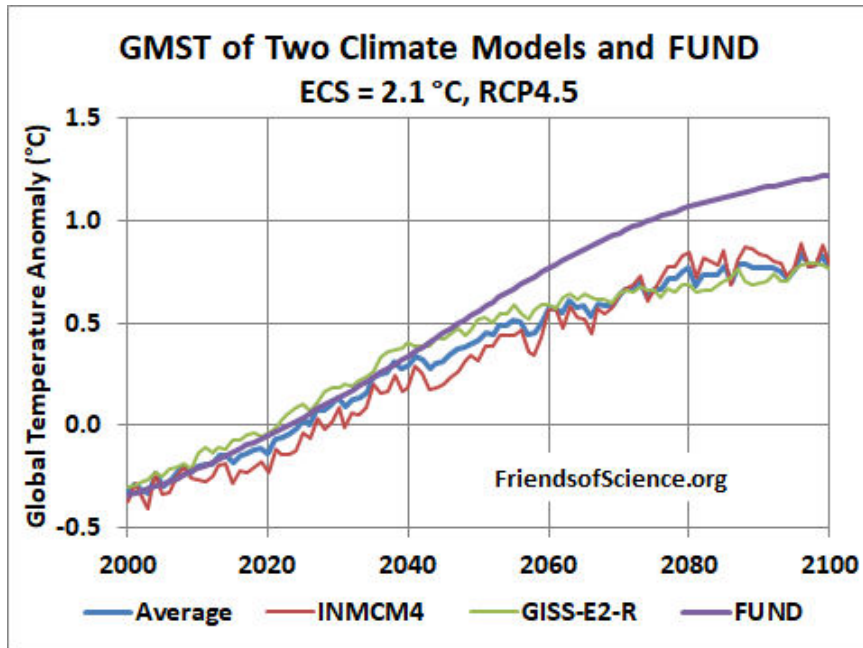


Figure 6.

I used temperature anomalies rather than the actual temperatures to focus on the temperature changes over time. The climate models are notorious for simulating significantly different actual temperatures for a given year. For the 5-year average 1998 to 2002, centered on the year 2000, the INMCM4 model gives 13.8 °C while the average of 5 runs of the GISS-E2-R model gives 15.8 °C, a difference of 2.0 °C. FUND gives a temperature anomaly of 0.284 above 1950, or approximately 13.3 °C which is 2.5 °C less than the GISS-E2-R model.

A [study](#) by Peter Lang and me published in *Energies* shows that shows that the impact of a 3 °C temperature rise on USA energy expenditures would have a positive impact on USA economic wealth whereas the FUND model projects a negative impact on wealth. A [paper](#) by me extends the analysis to global impacts. [This paper](#) recommends that the CO₂ fertilization effect in FUND be increased by 30% due to recent studies of the effect.

The FUND model using its default emissions and greenhouse gas concentrations, updated energy impacts and CO₂ fertilization effects and assuming an ECS of 1.0 °C, calculates that a 2 °C GMST

rise from 2000 would increase global wealth by 1.45% by 2147, equivalent to ₂₀₁₉US\$1.26 trillion. This estimated benefit would change if the climate response to radiative forcings were corrected.

The appendix gives the formulas of FUND's climate dynamics component.

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Appendix

The "climate dynamics" component of FUND converts the radiative forcings to a temperature forecast using a simple set of equations as follows;

$\text{Delaytemp} = 1/(A + B \times \text{ECS} + C \times \text{ECS}^2)$ to a maximum of 1.0, where A, B and C are constants. This is a quadratic equation of ECS.

$\text{Temps} = \text{ECS}/(5.35 \times \ln(2))$, where \ln means natural logarithm. Readers may recognized the '5.35 x $\ln(2)$ ' term as the radiative forcing of a doubling of CO₂, or 3.71 W/m².

$\text{Dtemp} = \text{Delaytemp} \times \text{Temps} \times \text{Radforc}[t] - \text{Delaytemp} \times \text{Temp}[t-1]$, where Dtemp is the global temperature increase in a year, Radforc[t] is the radiative forcing and Temp[t-1] is the global temperature of the previous year.

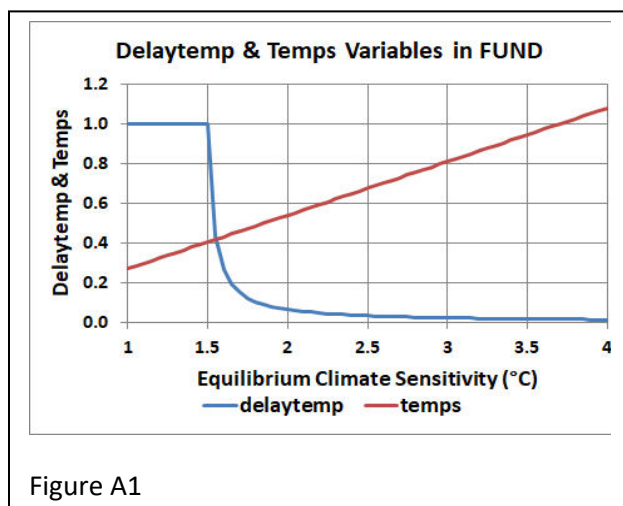


Figure A1

$$\text{Temp}[t] = \text{Temp}[t-1] + \text{Dtemp}$$

Figure A1 shows the values of Delaytemp and Temps versus ECS.

For ECS values of less than or equal to 1.5 °C, Delaytemp is 1.0, so Dtemp simplifies to;

$$\text{Dtemp} = \text{ECS}/3.71 \times \text{Radforc} - \text{Temp}[t-1], \text{ and}$$

$$\text{Temp}[t] = \text{ECS}/3.71 \times \text{Radforc}[t]$$

That is, for ECS of less than or equal to 1.5 °C, the model forecast the global average surface temperature increasing linearly with radiative forcing without any time delay.