Test of FUND's Temperature Response to CO_2

By Ken Gregory, P.Eng. 2020-12-15

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 CO_2 concentration to the time when it doubles. The ECS is the temperature change due to a doubling of CO_2 after allowing the oceans to reach temperature equilibrium. I want to confirm if the equilibrium temperature change in FUND due to a CO_2 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 CO_2 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 CO_2 concentration and the radiative forcings versus time, respectively, of the modified model.

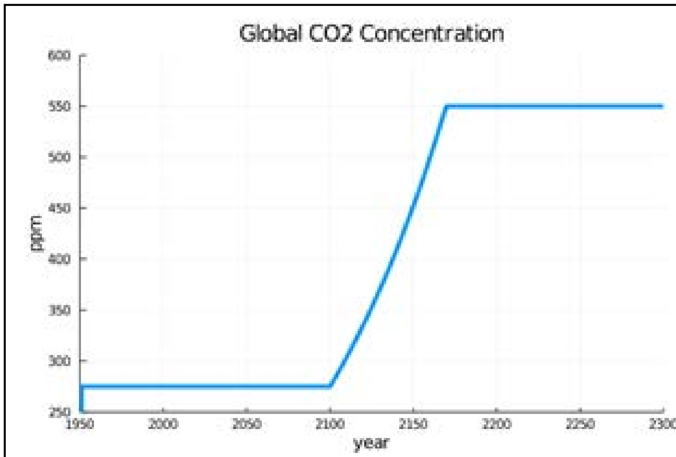

Figure 1

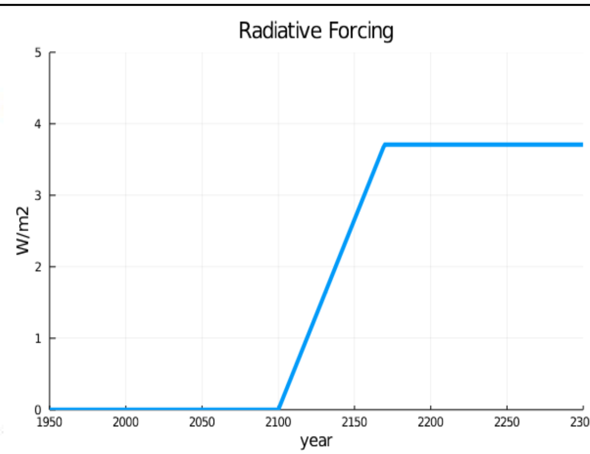

Figure 2

The CO_2 increase starts in 2100 to ensure that temperatures where stable at that time. The first graph shows the exponential increase of CO_2 at 1% per year until it doubles from 275 ppm to 550 ppm. The second graph shows only the radiative forcing of CO_2, which at a doubling is 3.708 W/m^2. The graph confirms that all other forcings were removed from the model. The CO_2 radiative forcing increases linearly over the period because the exponential increase of the CO_2 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% CO_2 concentration increase and year 70 is when the CO_2 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 CO_2 increase. The set of TCR/ECS and TCR given at the top of the graph correspond to the ECS values in the legend.

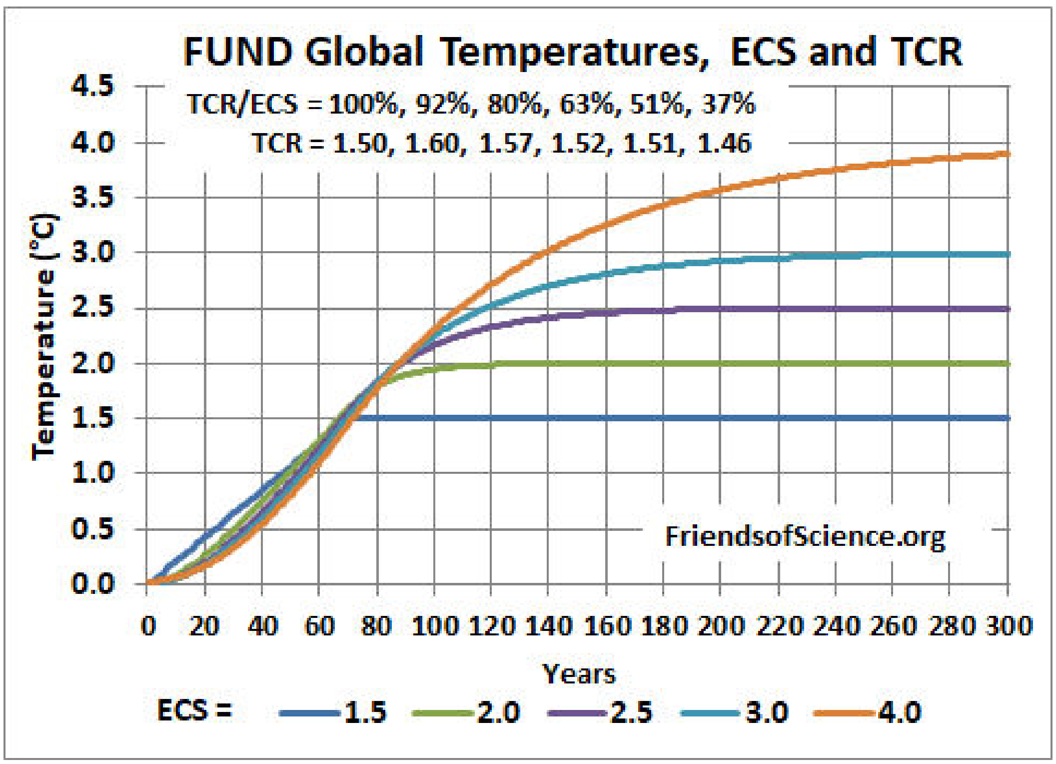

Figure 3

The model output confirms that the equilibrium temperature change due to the doubling of the CO_2 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 then end of the CO_2 increase (year 300 of the graph). At ECS = 1.5 °C, the temperature does not increase at all after the CO_2 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 CO_2 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.

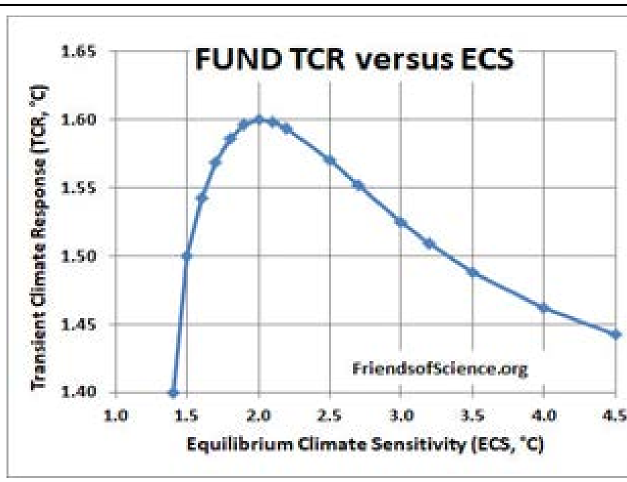

Figure 4

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 ESC and TCR of 23 climate models. These values are compared to the values calculated by the FUND model in figure 5.

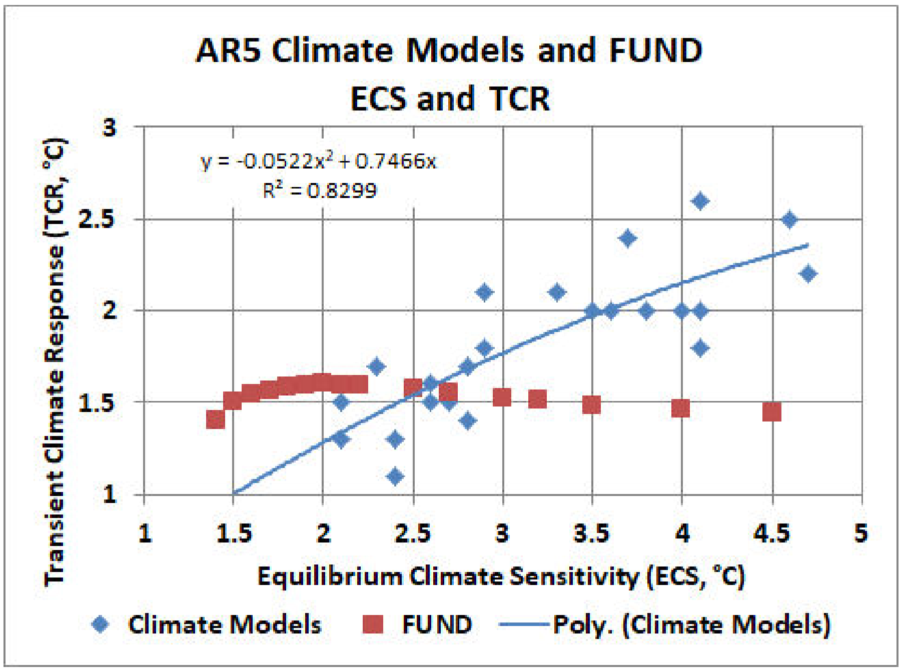

Figure 5

Figure 5 shows that FUND's TCR is too high when the ECS is less than 2.2 °C. The quadratic trend of 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 ESC after 2 °C is very wrong. It appears that the TCR and the temperature responses are reasonable only in the ESC 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 or the climate models.

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 by K. Dayaratna, R. McKitrick & P. Michaels recommends that the CO_2 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 CO_2 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 $_{2019}$US$1.26 trillion. This estimated benefit would increase if the climate response to radiative forcings were corrected.

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

The original version of this article was published Dec. 3, 2020. Figures 5 and the corresponding text of page 4 were added on December 15, 2020.

Appendix

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

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

Temps = ECS/(5.35 x 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/m^2.

Dtemp = Delaytemp x Temps x Radforc[t] – Delaytemp x 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.

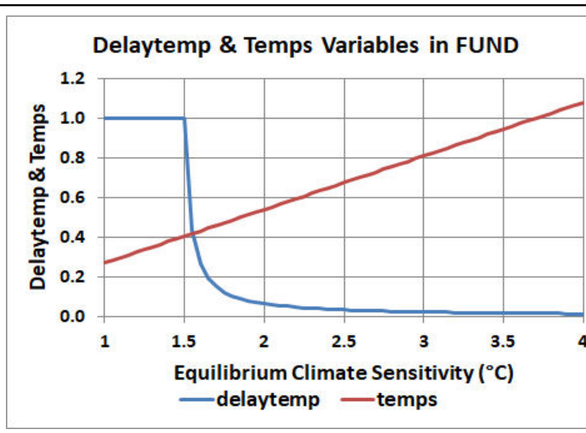

Figure A1

Temp[t] = Temp[t-1] + 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;

Dtemp = ECS/3.71 x Radforc – Temp[t-1], and

Temp[t] = ECS/3.71 x 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.