Social Cost (Benefit) of Carbon Dioxide from FUND
with Corrected Temperatures, Energy and CO_2 Fertilization

By Ken Gregory, P.Eng. **May 26, 2021; modified June 11, 2021***

Climate policies such as carbon taxes are set by governments using social cost of carbon (SCC) values calculated by a set of economic computer programs called integrated assessment models (IAM). The USA government used modified versions of three IAM, called PAGE, DICE and FUND. Neither PAGE nor DICE includes significant CO_2 fertilization benefits. Dr. Pat Michaels wrote "By including the results of IAMs that do not include known processes that have a significant impact on the end product must disqualify them from contributing to the final result" and "The sea level rise module used by the IWG2013/2015 in the DICE model produces future sea level rise values that far exceed mainstream projections and are unsupported by the best available science." Therefore, this article discusses the FUND model.

FUND is the most complex of the IAMs which links scenarios and simple models of population, technology, economics, emissions, atmospheric chemistry, climate, sea level, and impacts. FUND distinguishes 16 major world regions. It is the only model used by the US Government that includes benefits of warming and CO_2 fertilization. Unfortunately, the climate component of FUND that determines temperature is flawed as it assumes that the deep oceans are instantly in temperature equilibrium with the atmosphere, without any time delay, when the equilibrium climate sensitivity (ECS) is 1.5 °C or less. The transient climate response (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. If CO_2 concentrations are then held constant, temperatures would continue to increase to the ECS as the oceans reach temperature equilibrium with the surface, which can take hundreds to more than a thousand years depending on the value of the ECS. The FUND temperature response at an ECS of 1.5 °C shows the TCR is equal to the ECS, also 1.5 °C, which is impossible. Comparing the average of two climate models which each have ECSs equal to 2.1 °C, the FUND model runs 0.43 °C too warm in 2100 using the RCP4.5 emissions scenario.

The FUND model uses a default ECS of 3.0 °C based on the average of climate models that over warm the lower air temperatures by a factor of two compared to global temperature measurements as shown by this graph. This article shows the climate models warm the sea surface at twice the rate of the measured temperatures. The models on average over warm the tropical bulk atmosphere by a factor of 2.7. The models produce too much warming because they attribute natural warming caused by high solar activity and ocean cycles to greenhouse gas warming and they fail to account for the urban heat island effect (UHIE) that contaminate the government temperature datasets.

The ECS can only be estimated using the energy balance method that compares the climate forcings to historical temperature records. The paper Lewis & Curry 2018 presents estimates of ECS with uncertainty analysis. The authors estimated the median ECS at 1.50 °C with a likely (17%-83%) range of 1.20 - 1.95 °C using the HadCRUT4.5 temperature dataset. The probability distribution is shown as the blue curve of figure 1. The 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 UHIE from the temperature record. There exists a huge body of literature that shows the UHIE is a large part of the warming in government datasets and that the natural millennium cycle of warming from the Little Ice Age affects current temperatures so it is incorrect to ignore these effects. Making these adjustments, the likely range of ECS based on energy balance calculations using actual historical temperatures is 0.76 - 1.39 °C with a best estimate of 1.04 °C. The red line of figure 1 is the corrected ECS probability distribution used to calculate the SCC.

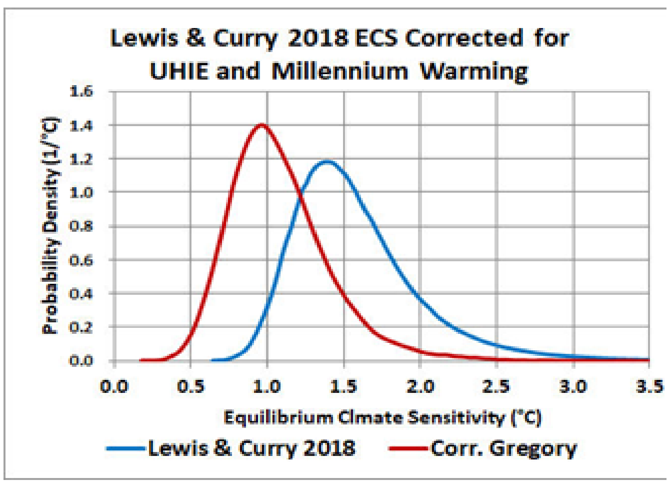

Figure 1

The energy impact components of FUND are very flawed. The energy impacts are for space heating and cooling expenditures. In FUND, the expenditures depend on temperature anomalies relative to 1900, but expenditures actually depend of the actual temperatures where people live. The change of expenditures with temperatures does not correspond to expenditure data published for the USA states. A paper by Peter Lang and me shows that a 3 °C temperature rise would decrease energy expenditures in the USA by 0.07% of gross domestic product (GDP) but FUND projects an increase of expenditures of 0.80% of GDP with non-temperature drivers held constant. The analysis is based on extensive energy consumption surveys in the USA.

The FUND energy cost projections show very bizarre results. For example, when average temperatures in China reach 12.5 °C, China is forecast to spend over 38% of its GDP on space cooling with non-temperature drivers held constant at 2010 values, whereas when the USA reaches the same temperature they are forecast to spend less than 0.5% of its GDP on space cooling. Figure 2 shows the impacts on GDP percent of heating expenditure changes due to temperature change. In China when average temperature are 5 °C, space heating expenditure decrease by 1.8% of GDP per °C of temperature change, again with non-temperature drivers held constant at 2010 values, whereas in Canada with temperatures less than 5 °C, space heating expenditure decrease by 0.006% of GDP per °C of temperature change.

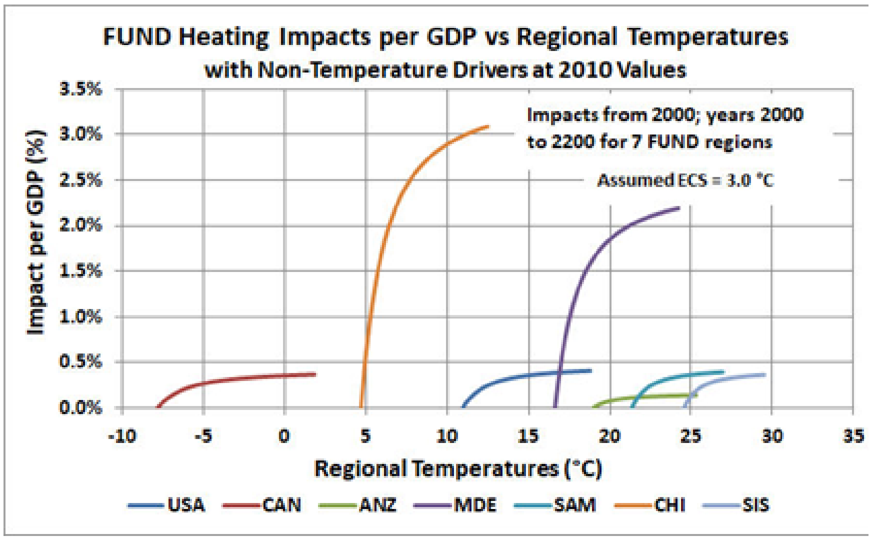

Figure 2

A study by Dayaratna, McKitrick and Michaels (D, M & M 2020) of the CO_2 fertilization effect and the FUND agricultural component shows that the FUND CO_2 fertilization effect should be increased by 30%. The study says “New compilations of satellite and experimental evidence suggest larger agricultural productivity gains due to CO_2 growth are being experienced than are reflected in FUND parameterization. … For numerous crop types around the world, CO_2 fertilization more than offsets negative effects of climate change on crop water productivity, with some of the largest gains likely in arid and tropical regions”.

I have created a modified version of FUND which incorporates a 2-box ocean climate model that is tuned to closely match the temperature profile of climate models. A 2-box ocean energy balance model can very well replicate the temperature rise of climate models. A blog post by Dr. Isaac Held provides a set of equations and information about this model. The top 70 m of the oceans are well mixed and in near temperature equilibrium with the surface. Heat flow from this layer to the deeper ocean acts as a negative feedback, inhibiting the surface temperature rise. The results are shown figure 3. The global temperature profile of two climate models that each have an ECS of 2.1 °C are shown. The blue line is their average. The purple line is the FUND temperature profile with ECS set at 2.1 °C. The 2-box energy balance model is the orange line which well matches the model average blue line. All models use the RCP4.5 emissions scenario. Nic Lewis published an article that shows both the FUND and DICE climate modules are mis-specified. He calls the DICE climate module a "trillion dollar error".

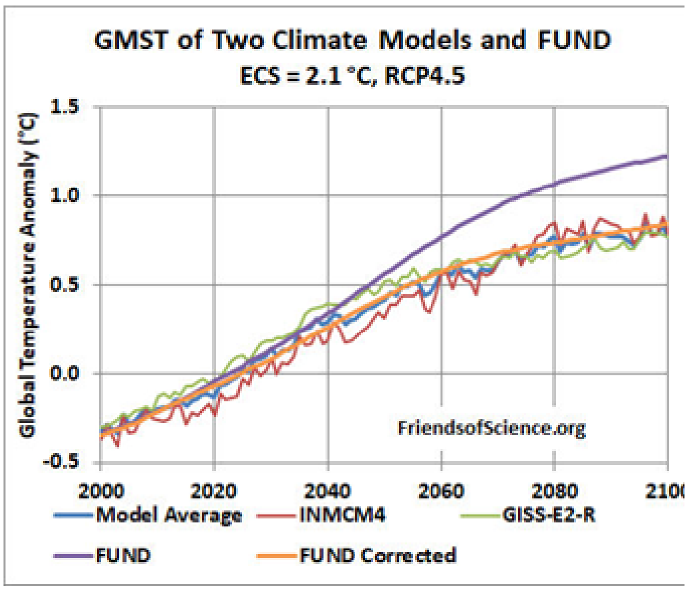

Figure 3

I have replaced the flawed space heating and cooling components with new components to match the empirical heating and cooling USA data. The model assumes that when other regions reach the wealth per person of the USA in 2010, adjusted for the same energy efficiency and temperature, they will have similar space heating and cooling costs per capita as that in the USA. I also increased the FUND CO_2 fertilization effect by 30% as recommended by D, M & M 2020. This allows me to calculate the realistic social net benefit of CO_2 emissions using all impact sectors, weighted by the energy balance based ECS probability distribution.

The table below shows the SCC (negative means CO_2 emissions are net beneficial) for emissions in 2020 in US and Canadian 2020 dollars, using 3% and 5% discount rates, with and without the CO_2 fertilization update using the modified FUND. The Can$ to US$ exchange rate of 0.83 was used. The results show the net benefits of CO_2 emissions range from 6 to 12 US$/t$CO_2$ (7 to 14 Can$/t$CO_2$) depending on the discount rate used.

$/t$CO_2$	US$ 2020		Can$ 2020	
Discount Rate	3%	5%	3%	5%
Corrected Energy	-8.48	-4.43	-10.22	-5.33
Corrected Energy & CO_2 Fertilization	-11.78	-6.17	-14.19	-7.44

The data show that climate change with CO_2 fertilization effect is quite beneficial, so policies costing trillions of dollars to reduce CO_2 emissions are misguided. Bjorn Lomborg estimates reducing global temperatures by 0.35 °C in 2100 would cost US$18 trillion. At the 3% discount rate, the 30% increase of the CO_2 fertilization effect increases the benefits of emissions by US$3.30/t$CO_2$.

The social cost (benefit) of CO_2 is a marginal concept. It represents the difference of a base case of a forecast global wealth changes with CO_2 emissions without any emissions control policies and the case with a pulse of CO_2 emissions added in the year 2020, discounted to the year of the pulse, divided by the pulse size, giving the wealth impact in dollars per tonne of CO_2. In FUND, the pulse size is 10 megatonnes (Mt) of CO_2. If the SCC is positive, a tax may be imposed on CO_2 emission equal or less than the SCC only after all other non-tax policies designed to reduce fossil fuel use are removed and all other taxes which are greater than that imposed on other factors of production are removed. Since this study shows that the SCC is negative, the optimum policy would be to subsidize CO_2 emissions equal to the calculated net benefits.

Figure 4 compares the temperature forecasts by FUND and the 2-box climate model, both using FUND's default emissions scenario with ECS = 1.1 °C. FUND's climate component causes too much warming.

The figures 5, 6 and 7 below show the empirical space heating and cooling impacts for 7 selected regions versus the regional temperatures, from 2000 to 2200, with non-temperature drivers held constant at 2010 values. I do this to show only the impacts of the temperature change. The regions are Canada, USA, Australia & New Zealand, North Africa, South America, China & near countries and Small Island States. The ECS probabilistic distribution gives a mean SCC equal to that calculated using ECS of 1.13 °C, so the ECS is set to 1.1 °C for the following graphs and discussion.

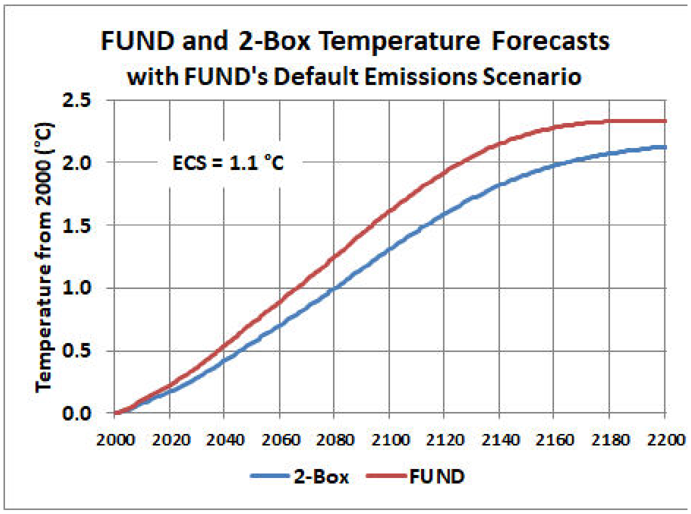

Figure 4

Figure 5 shows the energy impacts which are the sum of the space heating and cooling impacts. A decrease in space heating cost due to a temperature rise results in an increase in GDP as people are left with more cash to spend on other things.

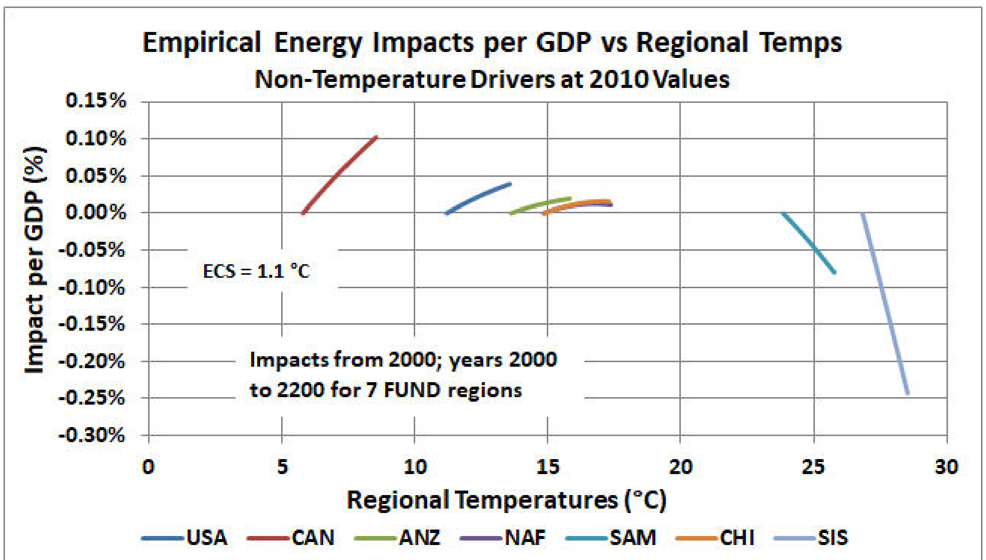

Figure 5

The impacts are positive for cold countries and negative for warm regions. Canada's temperature in 2000 is much warmer than that shown in the FUND graph, figure 2, because I use the temperature at the population centroid latitude, not the geographical center of the country as used by FUND. Figure 6 shows the heating impacts. Small Island States (SIS) have no impact because their average temperature is above 26 °C so no heating is required.

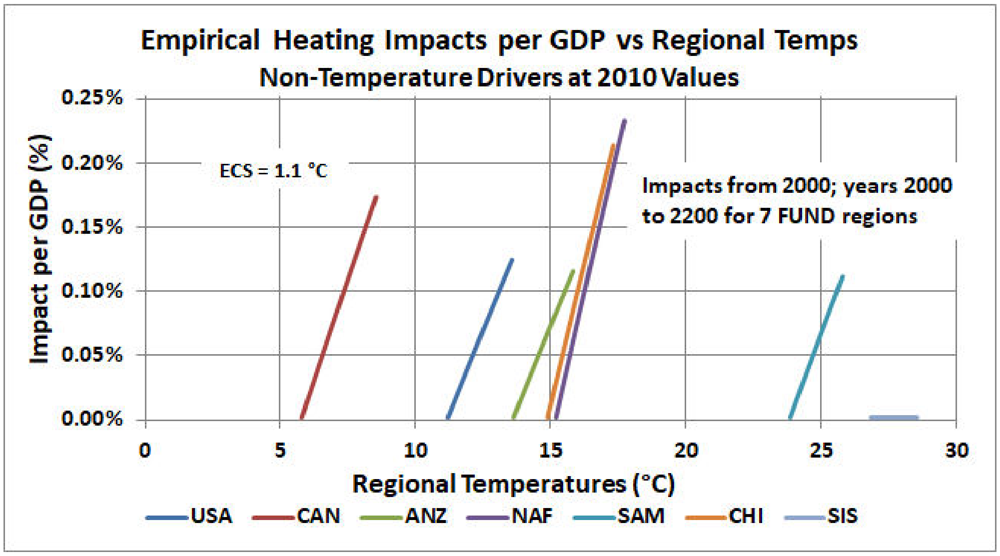

Figure 6

Figure 7 shows the cooling impacts. An increase of cooling costs with temperatures decreases wealth.

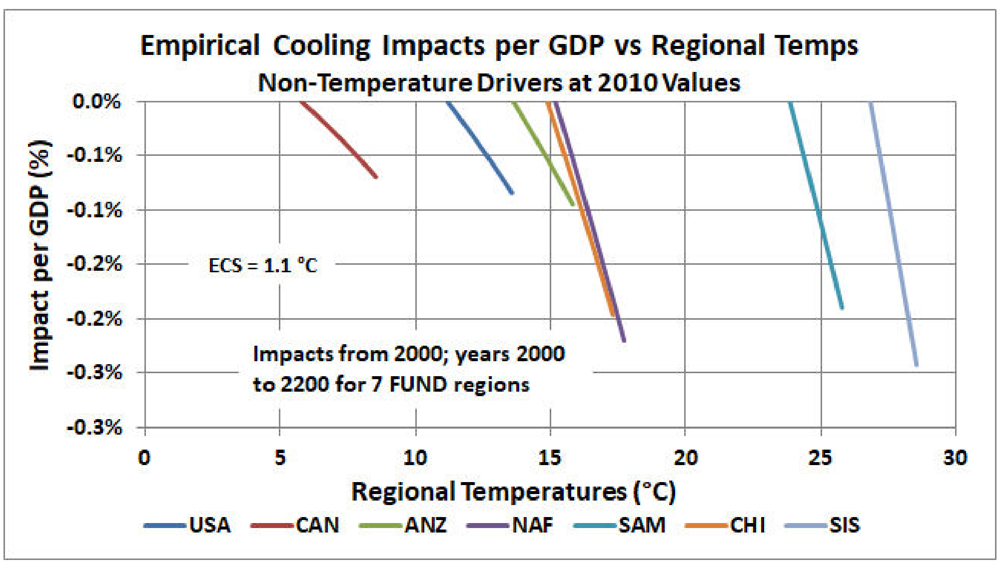

Figure 7

Figure 8 shows the global energy, heating and cooling impact, again with non-temperature drivers held constant at 2010 values. Note that the temperature impacts on space energy (heating plus cooling) reduce expenditures and increase global wealth. The blue line shows that 2 °C of global warming would **increase** global wealth by 0.029%. By contrast, the default FUND parameters forecast that 2 °C of global warming would **decrease** global wealth by 0.37%.

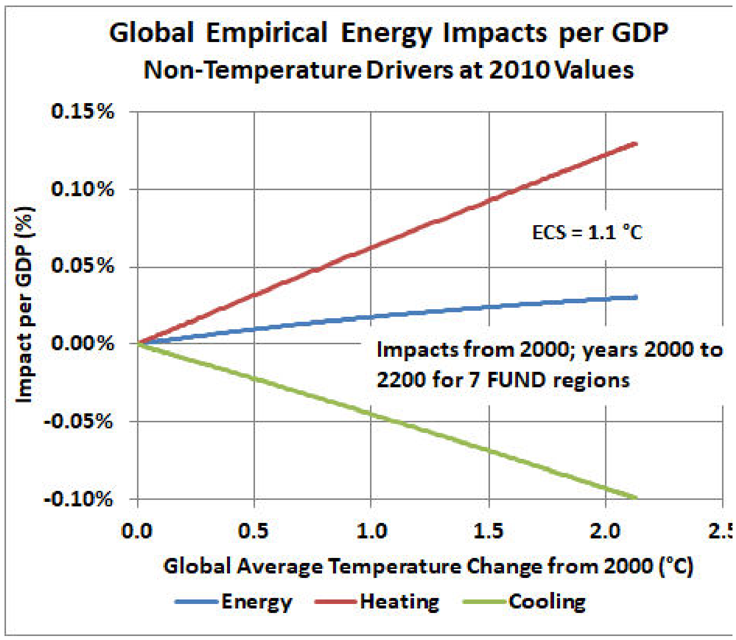

Figure 8

Figure 9 show the global impacts per GDP of seven impact sectors and the total impacts, with non-temperature drivers changing with time.

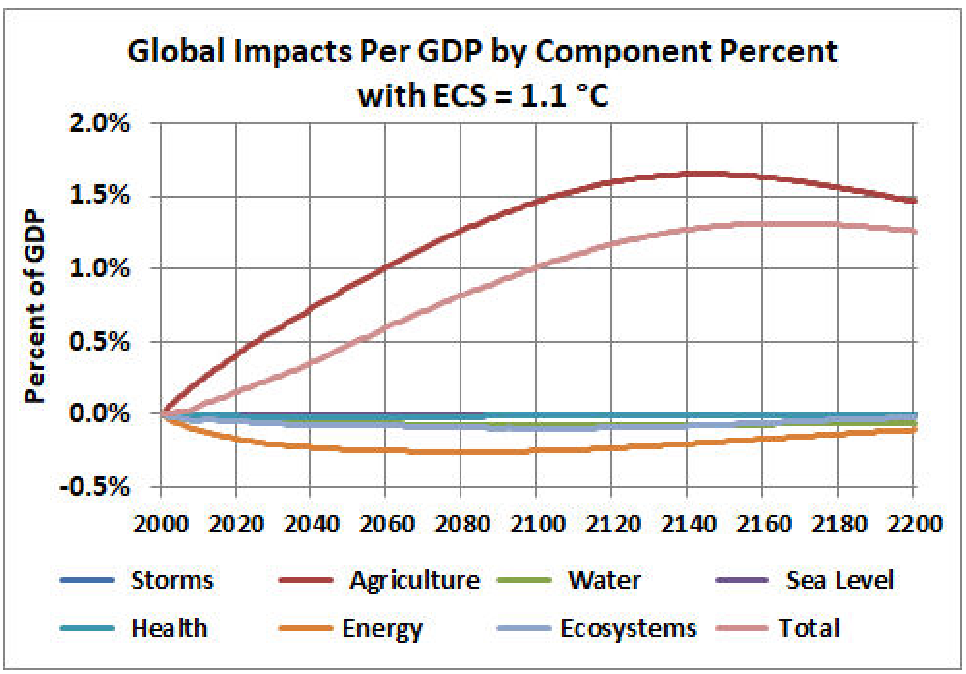

Figure 9

The non-temperature drivers of energy, including population and GDP per capita growth, have a large effect on the forecast. The large income growth caused the forecast of energy (mostly heating) expenditure to increase from 2000 to 2040 despite increasing temperatures resulting in a reduction of wealth per GDP. Figure 8 by contrast shows that global energy impacts are always positive with non-temperature drivers held constant.

To get a better understanding how temperatures affect the seven impact sectors, the calculated SCC values can be parsed by impact sector. Figures 10 and 11 show the percent contribution of each impact sector at 3% and 5% discount rates,

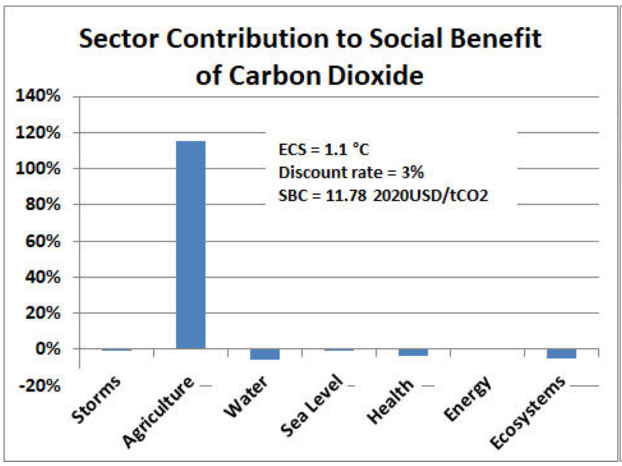

Figure 10

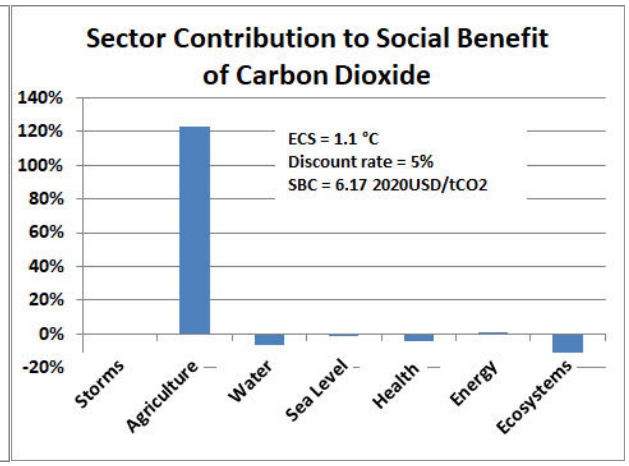

Figure 11

respectively. Agriculture dominates the SCC values. At 3% discount rate, agriculture represents 115.3% of the US$11.78/t$CO_2$ net benefit. Water resources is the next largest at -6.0%. The mainstream media is fixated on storms and sea level rise which are insignificant. Sea level rise damages are kept in check by protection expenditures which are included by cost-benefit optimization. At 5% discount rate, agriculture increases to 122.9% and ecosystems is the next largest at -11.1% of the US$6.17/t$CO_2$ net benefit.

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An Excel file with all the data and calculations is here. [3,373 KB]
The FUND model can be downloaded and installed from here.
The IJulia notebook used to modify and run the FUND model in the html format is here. [1,713 KB]
*Corrected a computing error.