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

By Ken Gregory, P.Eng. **June 19, 2021**

Climate policies such as carbon taxes are set by governments using social cost (benefit) of carbon dioxide (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[1] 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[2] 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[3] 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[4] 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[5]. The models on average over warm[6] 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[7] Lewis & Curry 2018 (L&C 2018) presents estimates of ECS with uncertainty analysis. The preferred base and final period used to determine the forcing and temperature changes were 1868-1882 and 2007-2016, respectively. The authors estimated the ECS and the TCR using the HadCRUT4.5 and the infilled Had4-krig-v2 temperature dataset.[8] The best estimate, or median, ECS estimate using the infilled dataset is 0.16 °C higher than that using HadCRUT4.5 dataset. This analysis uses the infilled Had4-krig-v2 dataset.

The median ECS was estimated at 1.66 °C with a likely (17%-83%) range of 1.35 – 2.15 °C. 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.

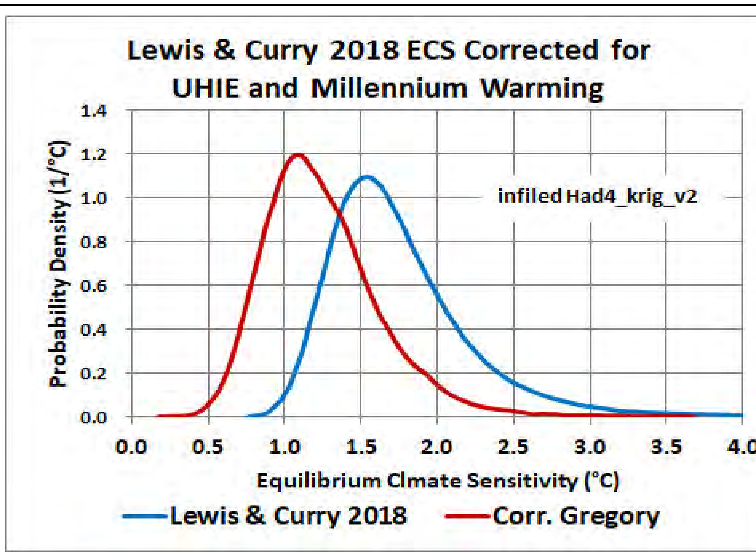

Figure 1

Making adjustments for the UHIE and the millennium cycle, the likely (17%-83%) range of ECS based on energy balance calculations[9] using actual historical temperatures is 0.90 - 1.57 °C with a best estimate of 1.19 °C. The UHIE reduces the median ECS by 0.22 °C and the millennium cycle reduces it by 0.25 °C. See Appendix 1 for details on these adjustments. The red line of figure 1 is the corrected ECS probability distribution used to calculate the SCC. It is determined comparing the greenhouse gas forcings to only the temperature change that was caused by those forcings.

Table 1 below compares the best estimate and uncertainty ranges of the LC 2018 result and the corrected results of this study.

Table 1. Estimates of ECS and TCR with Uncertainty Ranges

Case	ECS Best Estimate	ECS 17-83% range °C	ECS 5-95% range °C	TCR Best Estimate	TCR 17-83% range °C	TCR 5-95% range °C
LC 2018	1.66	1.35 – 2.15	1.15 – 2.70	1.33	1.10 – 1.60	1.00 – 1.90
This Study	1.19	0.90 – 1.57	0.73 – 1.94	0.95	0.74 – 1.21	0.61 – 1.44

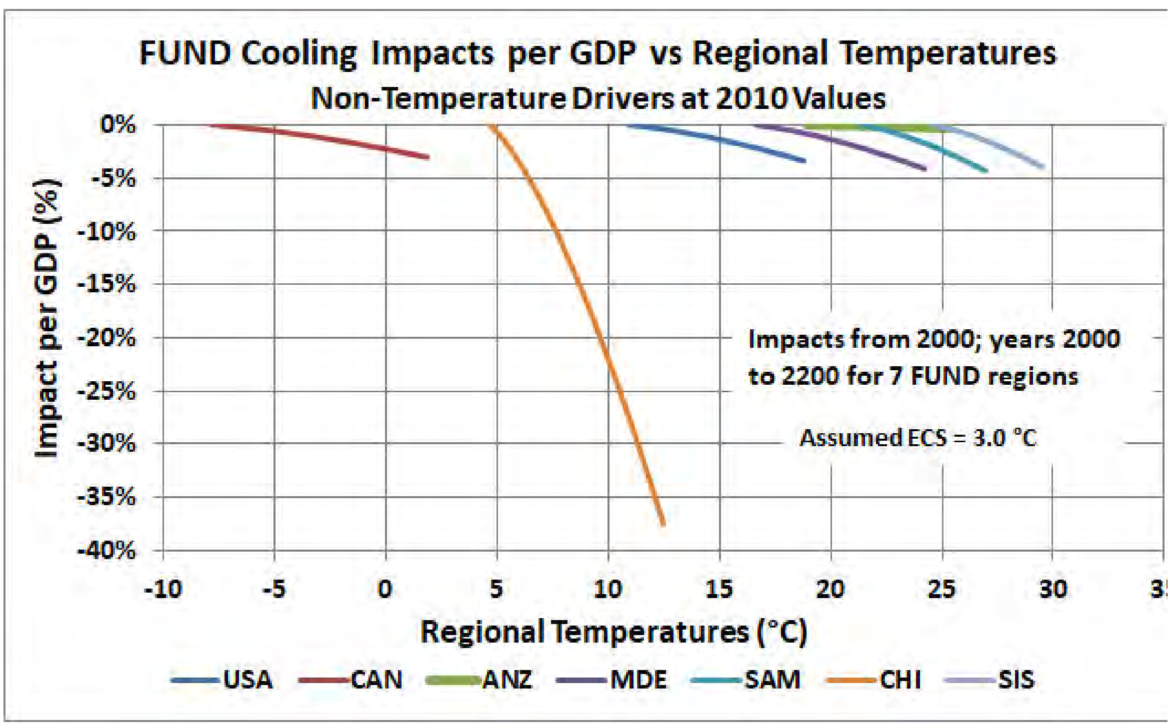

Figure 2

The energy impact components of FUND for space heating and cooling expenditures are very flawed[10]. In FUND, the expenditures depend on temperature anomalies relative to 1900, but expenditures actually depend of the temperatures where people live. The change of expenditures with temperatures does not correspond to expenditure data published for the USA states.

A paper[11] 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.

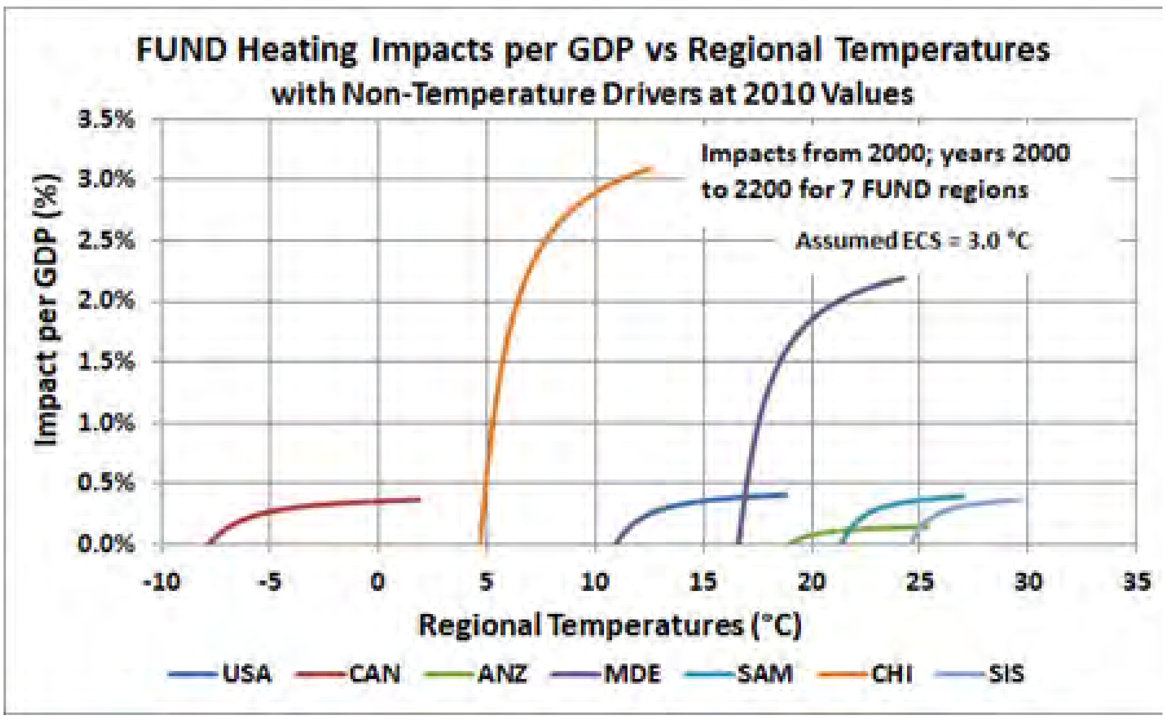

Figure 3

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 as shown in figure 2. Figure 3 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.

A study[12] 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[13] 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 4. 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

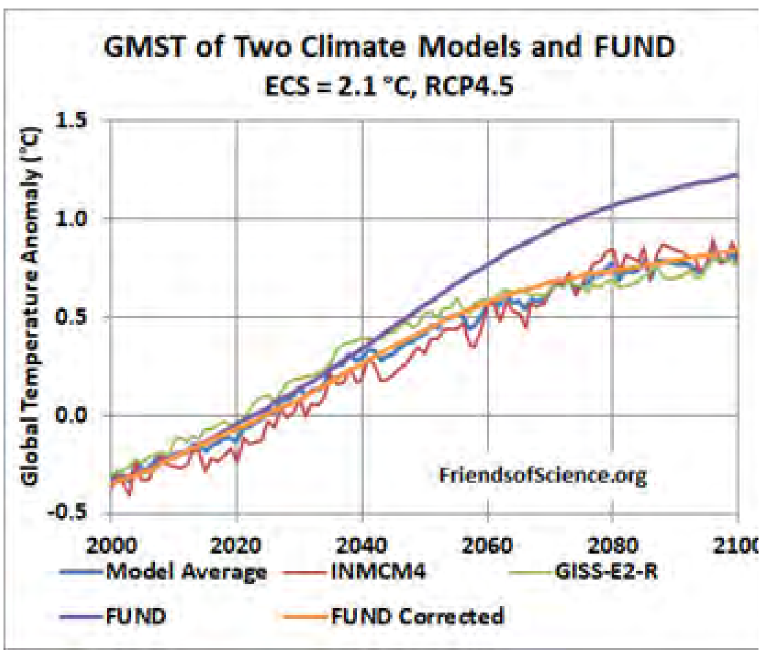

Figure 4

RCP4.5 emissions scenario. Nic Lewis published an article[14] that shows both the FUND and DICE climate modules are mis-specified. He calls the DICE climate module a "trillion dollar error".

Figure 5 compares the temperature forecasts by FUND and the 2-box climate model, both using FUND's default emissions scenario with ECS = 1.3 °C. FUND's climate component causes too much warming.

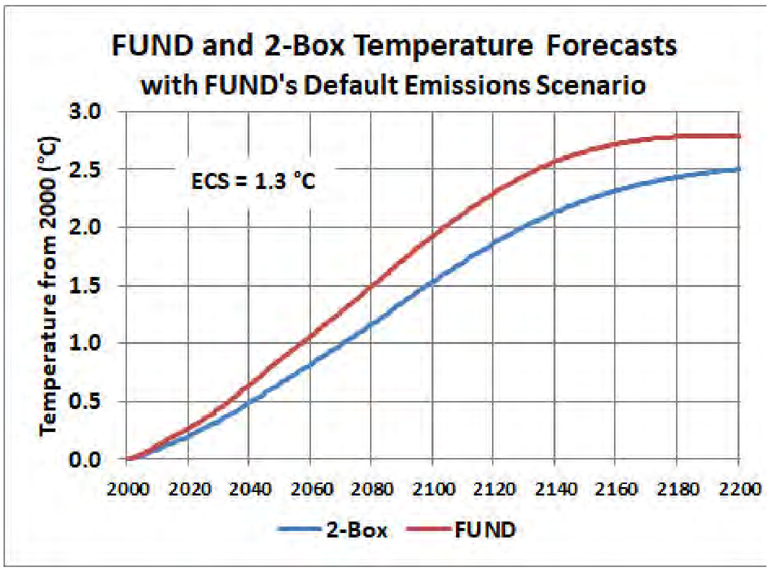

Figure 5

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.

Table 2. Social Cost (Benefit) of CO_2 Emissions in 2020				
\$/tCO_2	US\$ 2020		Can\$ 2020	
Discount Rate	3%	5%	3%	5%
Corrected Energy	-7.97	-4.20	-9.60	-5.06
Corrected Energy & CO_2 Fertilization	-11.26	-5.95	-13.57	-7.17

Table 2 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 11 US$/t$CO_2$ (7 to 14 Can$/t$CO_2$) depending on the discount rate used.

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[15] 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$3.29/t$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 loss in dollars per tonne of CO_2. In FUND, the pulse size is 10 megatonnes (Mt) of CO_2. See Appendix 2 for more details on the SCC calculation.

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.

The figures 6, 7 and 8 below show the empirical space heating, cooling and energy 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 regional temperatures are calculated at the population centroids of each region. 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 1.28 °C, so the ECS is set to 1.3 °C for the following graphs and discussion.

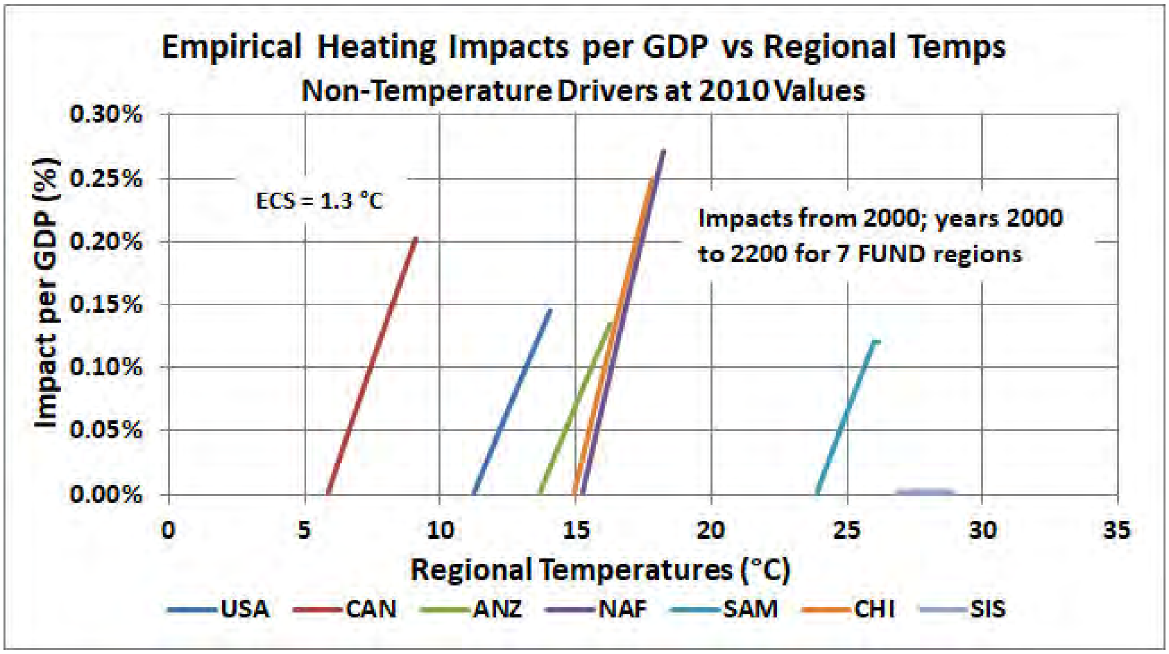

Figure 6

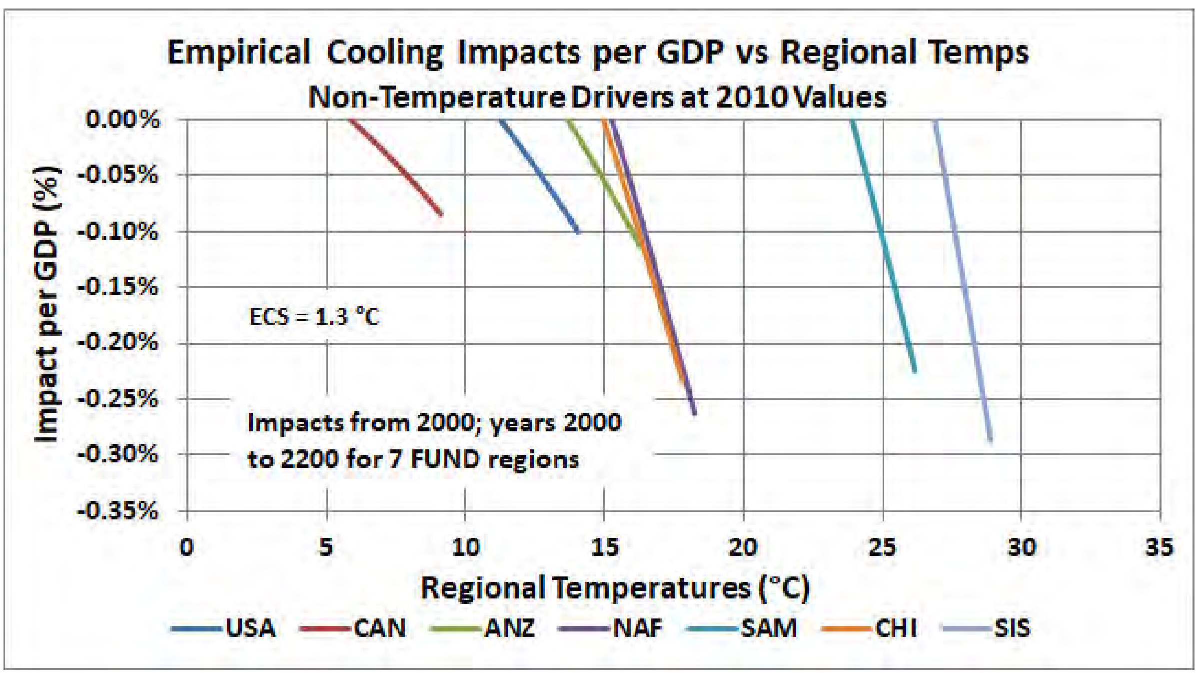

Figure 7

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 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.

Canada's temperature in 2000 is much warmer than that shown in the FUND graphs, figures 2 and 3, because I use the temperature at the population centroid latitude, not the geographical center of the country as is used by FUND.

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

Figure 8 shows the energy impacts which are the sum of the space heating and cooling impacts. The impacts are positive for cold countries and negative for warm regions.

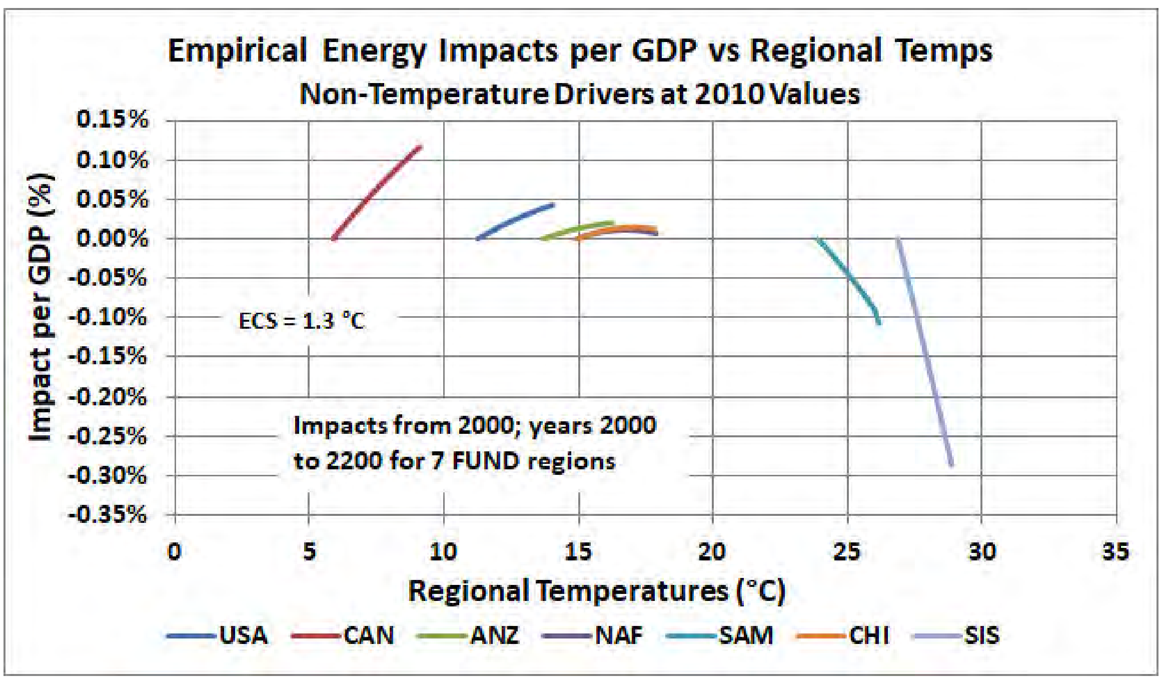

Figure 8

Figure 9 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%.

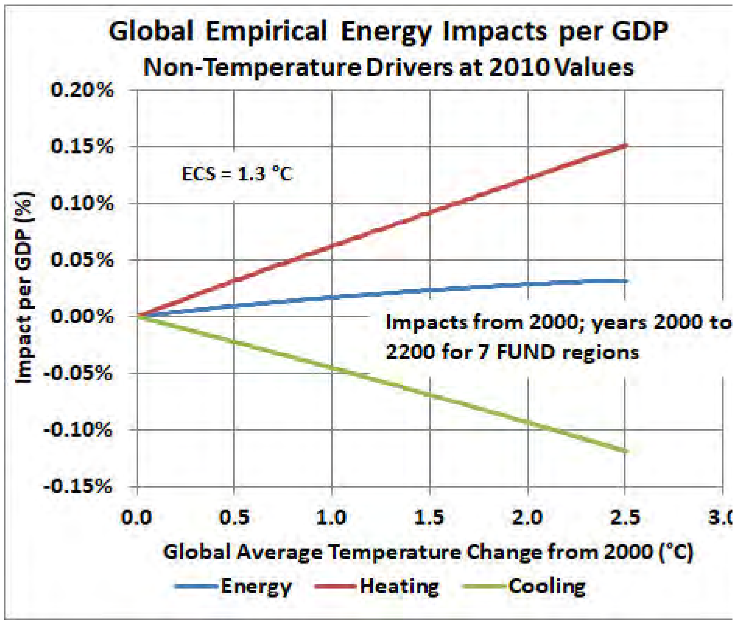

Figure 9

Figure 10 show the global impacts per GDP of seven impact sectors and the total impacts, with non-temperature drivers changing with time. I have group similar impacts calculated by FUND into 7 impact sectors for convenient presentation purposes. FUND actually calculates 5 impact components of sea level rise, being loss of wetland, loss of dry lands, protection costs and the costs of people entering and leaving each region. The health sector includes the social costs of deaths and morbidity.

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. To be clear, the energy valve at 2040 (-0.23%) is the world change of space heating and cooling energy expenditures divided by the world GDP in 2040. Figure 9 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 11 and 12 show the percent contribution of each impact sector at 3% and 5% discount rates, respectively. Agriculture dominates the SCC values. At 3% discount rate, agriculture represents 118% of the US$11.22/t$CO_2$ net benefit. Water resources is the next largest at -7.3%.

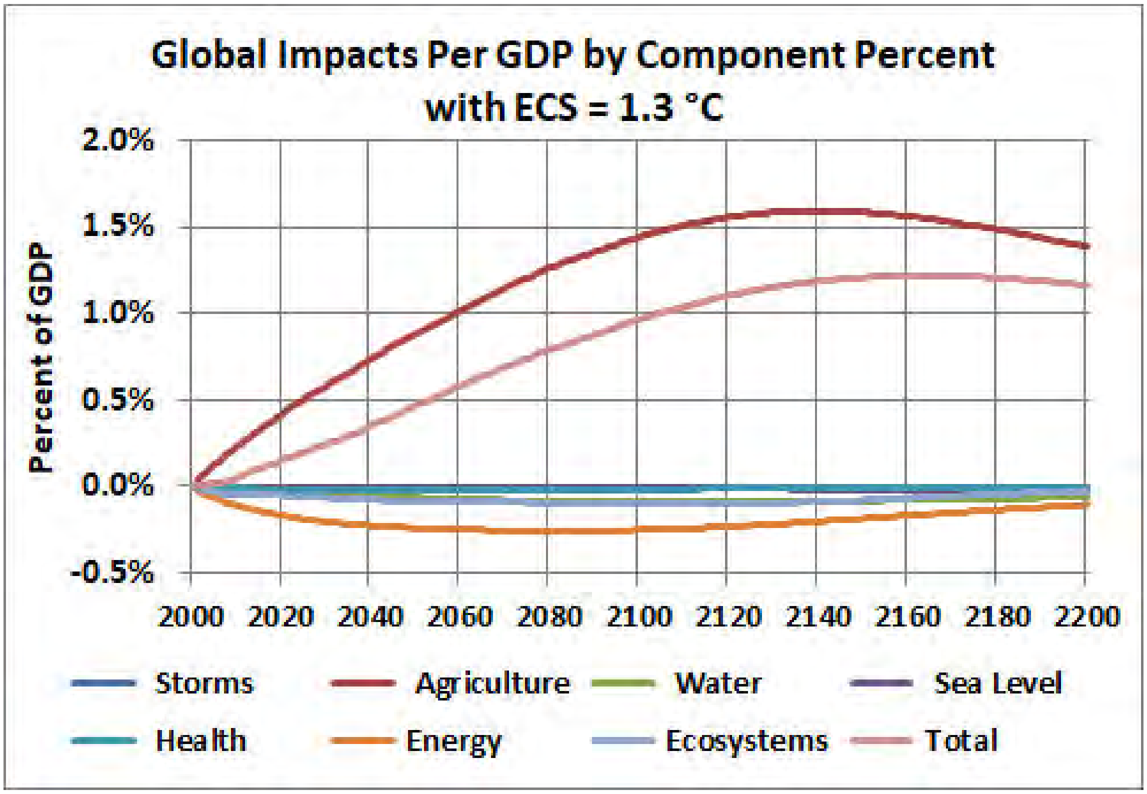

Figure 10

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 126% and ecosystems is the next largest at -12% of the US$5.91/t$CO_2$ net benefit. See Appendix 3 for the regional (USA and Canada) SCC.

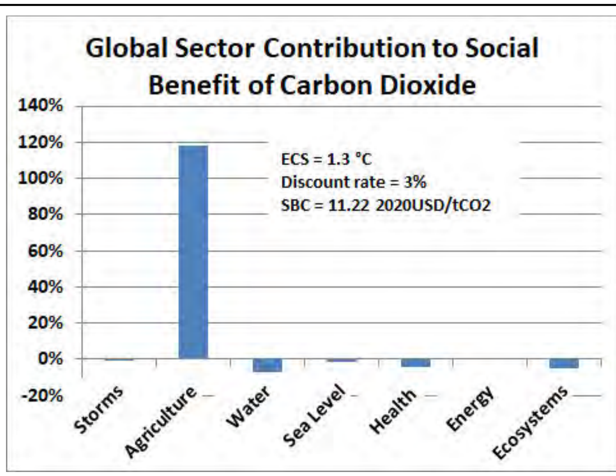

Figure 11

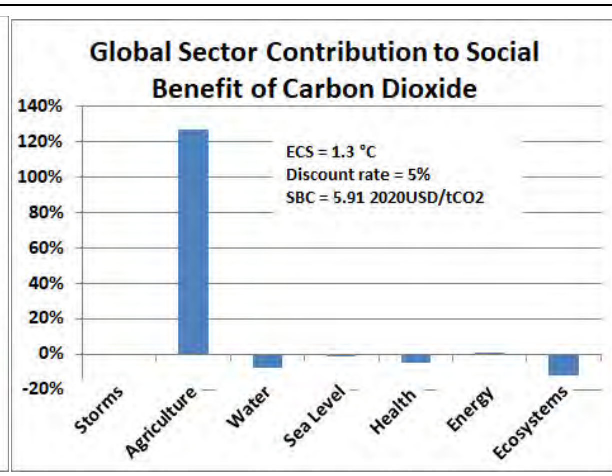

Figure 12

Appendix 1

Urban and Natural Millennium Cycle Warming Adjustments

The sensitivity of the climate to greenhouse gas additions to the atmosphere is the most important input to IAMs used to estimate the SCC. The L&C 2018 study determined the ECS and TCR assuming that there are no UHIE or millennium cycles.

Urban Heat Island Effect

A study by McKitrick and Michaels 2007 (MM2007) showed that about half of the warming over land since 1980 in instrument data sets is due to the UHIE. The authors compared the pattern of warming over the Earth's land surface to local economic conditions. They found a statistically significant correlation between the adjusted temperature data and economic development, meaning that the adjustments are not adequate to remove the urban heat island effects. The UHIE in the datasets over land is about 0.14 °C/decade. The global land area is 29.2%, so the UHIE on a global basis is 0.041 °C/decade.

A paper by De Latt and Maurellis 2005 (DM2005) gives evidence of strong influences of urban activity and other surface processes on measured temperature trends in both the surface dataset by the Climate Research Unit and the satellite lower troposphere datasets. The gridded emissions of CO_2 are used as a proxy of urbanization. The analysis is done by spatial-thresholding and binning techniques. The analysis finds that surface and satellite-measured temperature trends are higher in the vicinity of industrialized regions while this is not found in climate model simulations. The measured global mean temperature trend 1979 – 2001 is 0.169 °C/decade, while the trend without urbanization is 0.129 °C/decade. The trend difference indicates that the UHIE is 0.040 °C/decade.

The average UHIE trend from 1979 was used reduce the temperature change of the L&C 2018 study of 0.880 °C by 0.133 °C to account for the UHIE. No UHIE adjustment is made prior to 1979 due to a lack of studies. Considering that it is likely that there was UHIEs prior to 1979, this adjustment is considered conservative.

There are numerous other studies that support these results.[16]

Millennium Cyclic Warming

The analysis by Lewis and Curry does not account for the long-term natural warming from the LIA. The temperature history shows an obvious millennium scale temperature oscillation, indicating that natural climate change accounts for a significant portion of the temperature recovery since the LIA. Fredrik Ljungqvist prepared a temperature reconstruction of the Extra-Tropical Northern Hemisphere (ETNH) during the last two millennia with decadal resolution using 30 temperature proxies as shown in figure A1.[17]

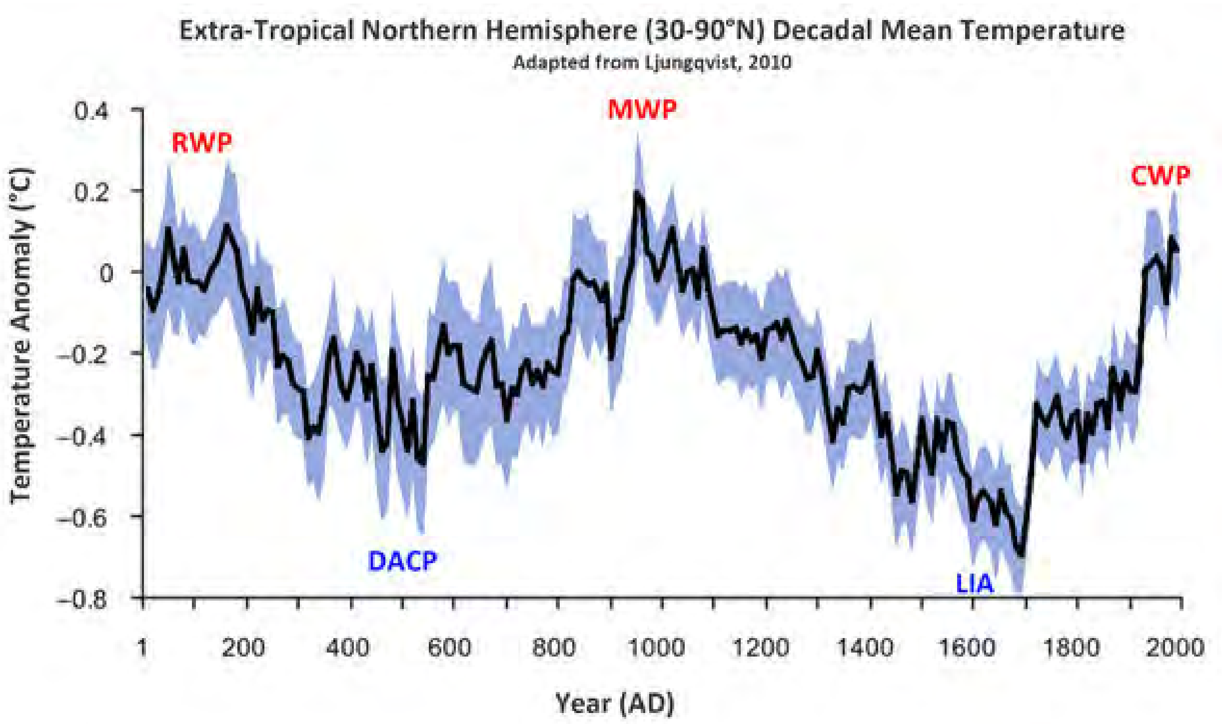

Figure A1

MWP = Medieval Warm Period 800-1300; LIA = Little Ice Age 1300-1900. Human-caused GHG emissions did not cause significant temperature change to the year 1900 because cumulative CO_2 emissions to 1900 were insignificant.[18] The proxy temperature data was analyzed by fitting a sine curve and line segments to the data up to 1900. Extrapolations of the millennium cycle from 1900 to 2010 provide an estimate of the natural component of the temperature change.

The estimated natural climate change of the ETNH from the Ljungqvist reconstruction over the period 1900 to 2010 is 0.101 °C/century.

The Ljungqvist 2010 paper gives several reasons why the reconstruction likely "seriously underestimates" the temperature variability but does not make any corrections to his reconstruction. Tree-rings respond to summer season temperature, but annual temperature have increased more than summer temperature, so the 8 tree-ring proxies are biased low. The 12 sediment proxies are also biased low due to large dating uncertainties that "results in flattening out the values form the same climate event over several hundred years … so they are unable to capture the true magnitude of the cold and warm periods." However, the paper gives sufficient information to correct for the biases. The ETNH temperature changes should be increased by 11% to account for these biases.

The ratio of the global temperature change to the ETNH temperature change was calculated from HadCRUT4.6 for 1900-1919 to 2002-2015. The global temperatures changed by 75% of the ETNH temperatures. The global natural warming is the ETNH warming rate of 0.101 °C/century times the 1.11 bias correction times 0.75, giving 0.084 °C/century.

The period between the centers of the base and final period is 136 years. Therefore, the temperature changes used in the climate sensitivity calculations must be reduce by 0.114 °C from 0.880 °C to 0.766 °C to account for natural climate change.

Uncertainties

Uncertainty estimates of factors used to determine ECS of L&C 2018 are given in table 2 of that study.

The uncertainty intervals for the UHIE was not provided in MM2007 but the DM2005 study did provide 1-sigma uncertainty estimates which were used in this study.

Table 3 gives the mean, standard deviations and 5-95% CIs for factors used to calculate the UHIE and millennium adjustments. All input factors used to calculate the UHIE and millennium adjustments were assigned normal distributions. However, note that the PDFs of both the TRC and ECS estimates are skewed distributions. Also see endnote 8.

Table 3. Uncertainty Analysis			
Trends in °C/decade	Mean	5-95% CI	Std. deviation
GMST without UHIE trend	0.129	0.094-0.164	0.021
GMST trend	0.169	0.124-0.213	0.027
DM2005 UHIE trend	0.040	-0.017-0.096	0.034
Ave. UHIE trend	0.040	0.0-0.080	0.024
ETNH Millennium trend	0.101	0.068-0.134	0.020
Global adjustment	0.754	0.63-0.88	0.076
Proxy adjustment	1.11	1.08-1.14	0.018
Global Millennium trend	0.084	0.053-0.116	0.019

The forcing of a doubling of CO_2 is strongly, positively correlated with the change in greenhouse gas forcing, which reduces the uncertainty of ECS. The forcing of double CO_2 and change of greenhouse gas forcings uncertainties were reduced by a factor 0.69 to account for the strong correlation between them. A comparison of the L&C 2019 ECS probability distribution and my replication of it are shown in figure A2. Then the temperature change over the analysis period was reduced by the urban and natural warming adjustments and the simulations where rerun to determine the corrected ECS and TCR with uncertainty ranges. Risk analysis was performed using the Argo addin for Excel.[19] Monte Carlo simulations with 20,000 trials were used.

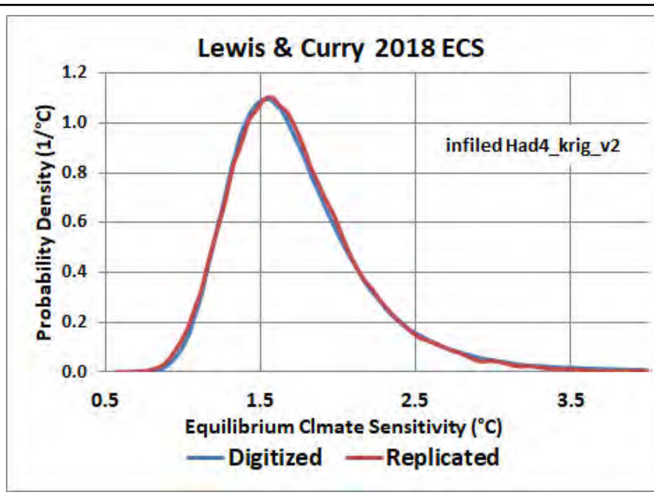

Figure A2

Appendix 2

Social Cost (Benefit) of CO_2

The SCC can be a confusing concept for those who are nor familiar with incremental economics. FUND produces forecasts of global and regional temperatures, sea level rise, population growth, income growth, energy efficiency and impacts. The non-temperature variables affect the impacts more than temperature change so the SCC is determined by subtracting a base forecast from a base plus a CO_2 pulse forecast at the given year. This incremental result is discounted to the year of the CO_2 pulse then divided by the pulse size to arrive at the cost (benefit) per metric tonne of CO_2.

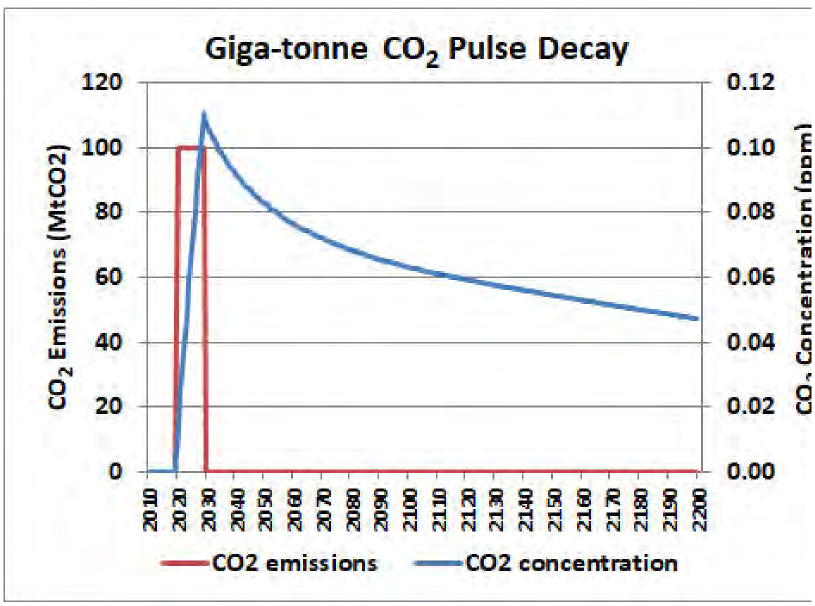

Figure A3

The results are demonstrated by the following graphs. Figure A3 shows a gigatonne pulse of CO_2 from 2020 to 2029 (red line) and the resulting change in the CO_2 concentration in the air. The CO_2 concentration decays to 50% of the maximum concentration after 115 years as the CO_2 is absorbed by plants and the oceans.

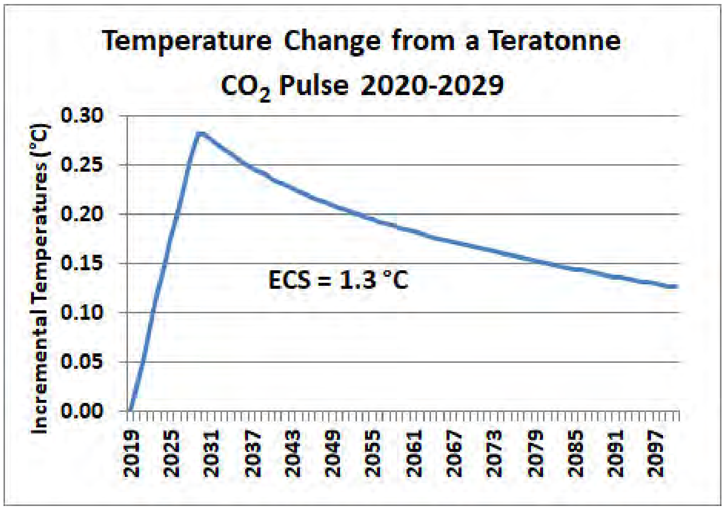

Figure A4

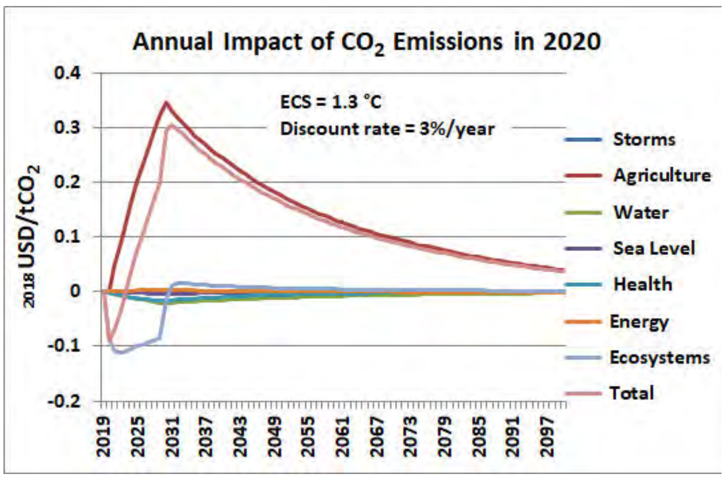

Figure A5

Figure A4 shows the temperature response of the CO_2 increase and decay to a teratonne CO_2 pulse. The maximum temperature response to a gigatonne pulse would be 1000 times less or 0.000282 °C. The temperature declines to 50% of the maximum temperature response after 58 years.

Figure A5 shows the annual impact of CO_2 fertilization and the temperature change due to one tonne of CO_2, discounted to 2020 at 3% per year. The SCC value is the sum of the discounted annual values, from 2020 to 2600. Limiting the time period to 2200 would reduce the social net benefits of CO_2 emission by 8 ¢/tonne for the 3% discount rate case, from 11.26 to 11.18 US$/t$CO_2$.

Appendix 3

Regional (USA & Canada) SCC

The values of the SCC presented are based on total global impacts, which are the sum of the impacts of 16 regions in FUND. The SCC can also be determined at a regional level, which may be defined as the social cost (benefit) incurred in a region per tonne of global CO_2 emitted divided by the region's percentage share of current global emissions.[20] The impacts by impact sector and the regional SCC may be significantly different that the global average impacts.

The CO_2 fossil emissions in 2019 of the USA and Canada and the resulting SCC are given in the table below using ECS of 1.3 °C. Values at 3% and 5% discount rates are in $_{2020}$US\$/tCO_2.

Region	Discount	Global	USA	Canada
CO_2 emissions share		100%	13.434%	1.538%
Social Cost (Benefit) of CO_2	3%	-11.22	-0.77	-2.82
Social Cost (Benefit) of CO_2	5%	-5.91	+0.31	-1.27

Figures A6 and A7 show the impact sector contributions for USA and Canada, respectively. The social net benefit of CO2 (SBC) is positive in these charts.

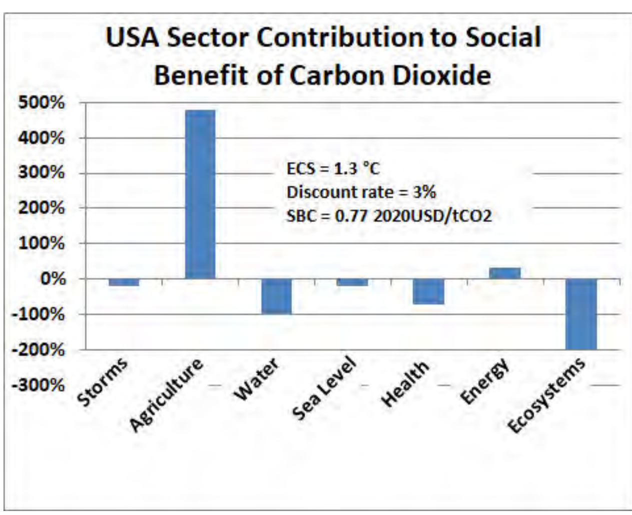

Figure A6

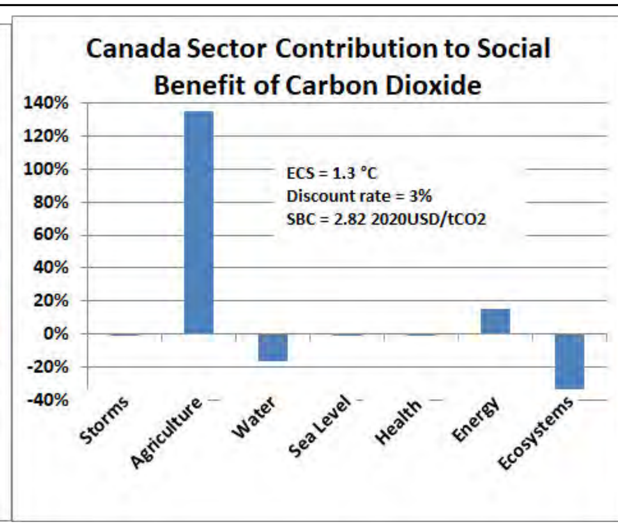

Figure A7

Data

An Excel file with all the data and calculations is here. [7,503 KB]
Monte Carlo simulation was performed using the Argo addon for Excel, note 19.
The FUND model can be downloaded and installed from here.
The Jupyter notebook used to modify and run the FUND model in the html format is here. [1,996 KB]

References and Notes

[1] "Statement of Patrick J. Michaels, Hearing on an Analysis of the Obama Administration's Social Cost of Carbon before the US House of Representatives Committee on Natural Resources", 2020-07-22. [LINK]

[2] FUND means Climate **F**ramework for **U**ncertainty, **N**egotiation and **D**istribution. It is developed by Dr. Richard Tol and Dr. David Anthoff. [LINK]

[3] "Test of FUND's Temperature Response to CO_2", Ken Gregory, P.Eng., 2020-12-15. [LINK]

[4] "Equilibrium Thermal Response Timescale of Global Oceans", Haijun Yang and Jhu, Geophysical Research Letters, Vol 39, Issue 14, 2011-07-29. [LINK]

[5] "Global Lower Troposphere Temperatures", University of Alabama in Huntsville, Friends of Science.org. [LINK] The model trend is 198% of the measurements.

[6] "Examination of Space-based Bulk Atmospheric Temperatures Used in Climate Research", John R. Christy et al, International Journal of Remote Sensing, Vol 39, Issue 11, 2018-03-08. [LINK]

[7] "The Impact of Recent Forcing and Ocean Heat Uptake Data on Estimates of Climate Sensitivity", Nicholas Lewis and Judith Curry, Journal of Climate, Vol. 31, Issue 15, 2018-04-12 [LINK at Nic Lewis] [LINK at Journal of Climate]

[8] Energy balance estimates of ECS and TCR use these equations: ECS = Fco2 ·ΔT/(ΔF – ΔN) and TCR = Fco2 ·ΔT/ΔF, where Fco2 is the forcing from a doubling of CO2, ΔT is the change in surface temperatures between the base and final periods, ΔF is the change in forcing and ΔN is the top-of-atmosphere radiative imbalance, which is equal to the heat uptake by the climate system.

[9] "Climate Sensitivity by Energy Balance with Urban and Natural Warming", Ken Gregory, P.Eng., 2020-09-07. [LINK] This article presents ESC and TCR estimates corrected for urban and natural warming based on the L&C 2018 climate sensitivities using the HadCRUT4.5 dataset. It gives more details on the UHIE and natural millennium warming corrections.

[10] "The Global Economic Impact of Climate Change on Energy Expenditures", Ken Gregory, P.Eng., 2020-05-30. [LINK] This article shows the global economic impact on energy expenditures using the FUND default ECS of 3.0 °C.

[11] "Economic Impact of Energy Consumption Change Caused by Global Warming", Peter Lang and Ken Gregory, Journal Energies, Vol. 12, Issue 18, 2019-09-19. [LINK]

[12] "Climate Sensitivity, Agricultural Productivity and the Social Cost of Carbon in FUND", K. Dayaratna, R. McKitrick and P. Michaels, Environmental Economics and Policy Studies, Vol. 22, 2020-01-18. [LINK]

[13] "Transient vs Equilibrium Climate Responses", Isaac Held at Geophysical Fluid Dynamics Laboratory, 2011-03-11. [LINK]

[14] "Abnormal Climate Response of the DICE IAM – a Trillion Dollar Error?", Nicholas Lewis, 2016-08-15. [LINK]

[15] "Welfare in the 21st Century: Increasing Development, Reducing Inequality, the Impact of Climate Change, and the Cost of Climate Policies", Technological Forecasting and Social Change, Vol. 156, 2020-04-24. [LINK]

[16] See FriendsofScience.org >> Climate Science >> Urban Heat Island Effect [LINK]

[17] "A New Reconstruction of Temperature Variability in the Extra-Tropical Northern Hemisphere During the Last Two Millennia", Fredrik C. Ljungqvist, Geografiska Annaler, Vol. 92, Issue 3, 2010-09-06. [LINK]

[18] Cumulative CO_2 emission to 1900 = 45 $GtCO_2$. Cumulative CO_2 emissions to end 2018 = 1611 $GtCO_2$.

[19] The Argo addin for Excel is available at https://github.com/boozallen/argo/wiki

[20] At ECS = 1.3 °C and 3% discount rate, the USA portion of the global SCC per tonne of global CO_2 emissions is -0.10 US$/t$CO_2$. The USA regional SCC is -0.10 US$/t$CO_2$ divided by the USA share of emissions of 13.434% give -0.77 US$/t$CO_2$. This is what the global SCC would be if all regions proportionally emitted as much CO2 as the USA. Even in this case, the emissions are net beneficial as indicated by the negative sign.