Climate Sensitivity by Energy Balance with Urban and Natural Warming

By Ken Gregory, P.Eng. *Version 3* *2022-07-12*

Abstract

The paper Lewis & Curry 2018 presents estimates of climate sensitivity parameters Equilibrium Climate Sensitivity (ECS) and Transient Climate Response (TCR) with uncertainty analysis. 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 urban heat island effect (UHIE) from the temperature record. This study presents corrected estimates of ECS and TCR with uncertainty estimates by including the UHIE and natural warming. The median estimate (with likely range in brackets) of ECS and TCR are estimated at 1.19 °C (0.90 - 1.57 °C) and 0.95 °C (0.74 - 1.21 °C), respectively. Global average temperatures are forecast to increase by 0.87 °C (0.70 – 1.08 °C) from 2020 to 2100, assuming the greenhouse gas concentrations in the atmosphere increase exponentially and no natural climate change. The FUND economic model, using updated temperature projections, energy impacts and CO_2 fertilization effects, calculates that a 2 °C GMST rise from 2020 would increase global wealth by 9.8% of 2020 global income by 2146, equivalent to $_{2020}$US$8.8 trillion.

Lewis & Curry 2018

The sensitivity of the Earth's climate to increasing concentrations of greenhouse gases (GHG) is the most important parameter in climate science. Climatologists Nicholas Lewis and Dr. Judith Curry published a paper in the *Journal of Climate* in 2018 (LC2018)[1] that used the observationally-based energy balance method to estimate the Equilibrium Climate Sensitivity (ECS) and the Transient Climate Response (TCR). The ECS is the global average surface temperature change due to a doubling of CO_2 after allowing the oceans to reach temperature equilibrium, which takes about 1500 years for the upper 3 km of the ocean.[2] The TCR is more relevant to climate policy as it is the global surface temperature change at the time of the CO_2 doubling assuming that the change in forcing takes place gradually over at least 70 years, which it does for the base and final periods

[1] N. Lewis and J. Curry, 2018, "The impact of recent forcing and ocean heat uptake data on estimates of climate sensitivity", *Journal of Climate*, JCLI-D-17-0667. https://niclewis.files.wordpress.com/2018/04/lewis_and_curry_jcli-d-17-0667_accepted.pdf

[2] H. Yang and J. Zhu, 2011, "Equilibrium thermal response timescale of global oceans", *Geophysical Research Letters*, Vol. 28, Issue 14. https://doi.org/10.1029/2011GL048076

used. A doubling of CO_2 at the current exponential growth rate of 0.60%/year would take 116 years.

The LC2018 paper states “The energy budget framework provides an extremely simple physically-based climate model that, given the assumptions made, follows directly from energy conservation.” The energy balance method relates the ECS and TCR to changes in the global mean surface temperature (GMST), the effective radiative forcing and the planetary radiative imbalance between a base and final period.[3] The radiative imbalance is the downward solar radiation net of albedo (reflection) less the upward longwave radiation from the surface and the atmosphere at the top of the atmosphere.

LC2018 presents two sets of climate sensitivity estimates using the surface temperature datasets HadCRUT4.5 and the infilled Had4_krig_v2 (Cowtan and Way 2014). This version 3 study presents results using the infilled Had4_krig_v2 temperature dataset. LC2018 uses the GHG forcings as estimated in the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), except for an upward revision of the methane forcing, an upward revision of the lower uncertainty bound of the aerosol forcing and updating the forcings to 2016. Earth's top-of-atmosphere radiative imbalance is necessarily equal to the total heat uptake by the climate system, which is over 90% by the oceans. The preferred base (1869-1882) and final periods (2007-2016) were chosen to avoid the period of sparse temperature data before 1869, avoid significant volcanism and to have the largest change in forcing so to give the narrowest uncertainty ranges. The long time between these periods averages out the temperature effects of short-term ocean oscillations such as the ENSO, the Atlantic Multi-decadal Oscillation and the Pacific Decadal Oscillation.

The energy balance method employed by LC2018 is deficient[4] for two reasons;

- it falsely assumes that all of the temperature change from the base period was due to anthropogenic causes (other than a small solar irradiance forcing) and,
- it doesn’t account for the urban warming contamination of the surface temperature record which exaggerates post 1970 warming.

Natural Climate Change

A paper by Gebbie and Huybers[5] used an ocean circulation model and modern and paleoceanographic observations from both the end of the 19th century and the end of the 20th

[3] Energy balance estimates of ECS and TCR use these equations: $ECS = Fco2 \cdot \Delta T/(\Delta F - \Delta N)$ and $TCR = Fco2 \cdot \Delta T/\Delta F$, 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.

[4] Perhaps the authors intentionally chose not to include natural climate change and UHIE corrections so as to match the IPCC methodology.

century to show that the deep Pacific Ocean is still cooling. The paper says “historical model simulations are biased toward overestimating ocean heat uptake when initialized at equilibrium during the Little Ice Age”. The ongoing deep ocean cooling revises Earth's overall heat budget since 1750 downward by 35%. Taking this into account would revise downward the ECS calculated by energy balance.

Solar forcing may be several times larger than just that caused by the change in the total solar irradiance (TSI) as interpreted by the IPCC. A paper Scafetta et al 2019[6] shows that the TSI increased from the 1986 minimum to the 1996 minimum by about 0.45 W/m^2 and that 2000–2002 was likely a grand solar maximum. This implies that the TSI forcing was greater than that used in LC2018. There are several estimates of TSI. One historical TSI reconstruction is presented as figure 1. Generally the TSI has been increasing through the 20th century and is significantly higher than that in 1600-1700 and 1800-1820.

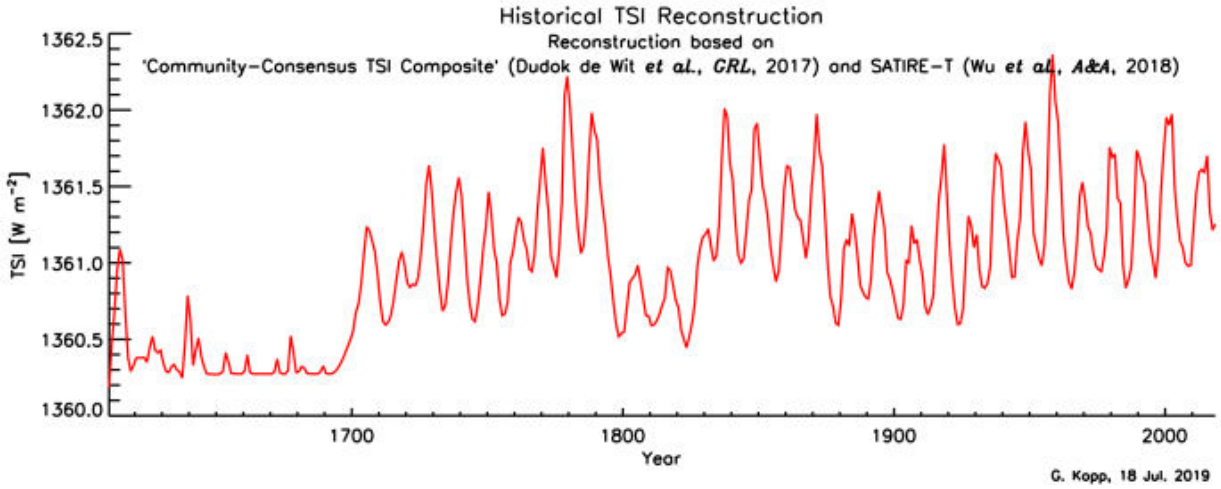

Figure 1. TSI reconstruction[7] by G. Kapp, 2019.

Numerous studies show that solar ultraviolet radiation and solar magnetic flux has caused a significant positive solar forcing from pre-industrial times to date. The large variations of solar ultraviolet radiation affect ozone in the upper atmosphere which causes a solar forcing at least as much as that of TSI. The changing solar magnetic flux carried by the solar wind repels cosmic rays which help to create cloud condensing nuclei. High solar activity reduces cosmic rays entering the atmosphere, reducing lower cloud cover and causing warming by increased incoming solar

[5] G. Gebbie and P. Huybers, 2019, “The Little Ice Age and 20th-century deep Pacific cooling”, *Science*, Vol. 363, Issue 6422. https://science.sciencemag.org/content/363/6422/70

[6] Nicolas Scafetta et al, 2019, “Modeling Quiet Solar Luminosity Variability from TSI Satellite Measurements and Proxy Models during 1980–2018”, *Remote Sensing*, Vol. 11, Issue 21. https://www.mdpi.com/2072-4292/11/21/2569/htm A summary of the paper is at https://friendsofscience.org/index.php?id=2517

[7] https://spot.colorado.edu/~koppg/TSI/

radiation. Therefore, the increasing solar activity throughout the 20th century has increased global average temperatures by three distinct mechanisms. A paper by Henrik Svensmark summarizes the known solar effects on climate.[8] It shows that over the eleven-year solar cycle the energy that enters the Earth's system is of the order of 1.0-1.5 W/m^2. A paper by Nir Shaviv compared changes in TSI with changes in sea levels, sea surface temperature and ocean heat and found that the solar signal is ~5–7 times larger than the change in solar irradiance alone.[9]

The low solar activity during the Little Ice Age (LIA) and the deep ocean cooling imply that the climate system wasn't in temperature equilibrium in the LC2018 base period 1869-1882. As it is difficult to quantify each of these forcings, temperature proxies are used to estimate the natural warming since the start of the base period by extrapolating the millennium scale temperature cycle. The surface temperature change should be revised downward to remove the natural warming from the Little Ice Age so that the temperature change used in the energy balance calculations includes only the portion that was caused by the change in anthropogenic forcing.

Adjustment for 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[10] as shown in figure 2. Human-caused GHG emissions did not cause significant temperature change to the year 1900 because cumulative CO_2 emissions to 1900 were insignificant.[11] Therefore, the changes in temperature prior to 1900 are free of anthropogenic influences.

Extrapolations of the millennium cycle from 1900 to 2010 provide an estimate of the natural component of the temperature change. The ETNH temperature reconstruction by Ljungqvist was extrapolated to 2010 using two methods. The first method is to average the absolute value of temperature trends between the minimums and maximums of the temperature oscillations as indicated by the line segments shown in figure 3. The average of the absolute natural temperature change over the four periods was 0.095 °C/century. The second method is to fit a sine curve to the

[8] Henrik Svensmark, 2019, "Force Majeure, The Sun's Role in Climate Change", *The Global Warming Policy Foundation*, report 33. https://www.thegwpf.org/content/uploads/2019/03/SvensmarkSolar2019-1.pdf
[9] Nir Shaviv, 2008, "Using the oceans as a calorimeter to quantify the solar radiative forcing", *Journal of Geophysical Research*, vol. 113.
[10] Fredrik Ljungqvist, 2010, "A New Reconstruction of Temperature Variability in the Extra-tropical Northern Hemisphere During the Last Two Millennia", Geografiska Annaler, Physical Geography, Vol. 92, No. 3. https://www.jstor.org/stable/40930999?seq=1
[11] Cumulative CO2 emission to 1900 = 45 GtCO2. Cumulative CO2 emissions to end 2018 = 1611 GtCO2.

temperature series up to 1900. The amplitude, wavelength and positions were adjusted to create the best fit to the data.

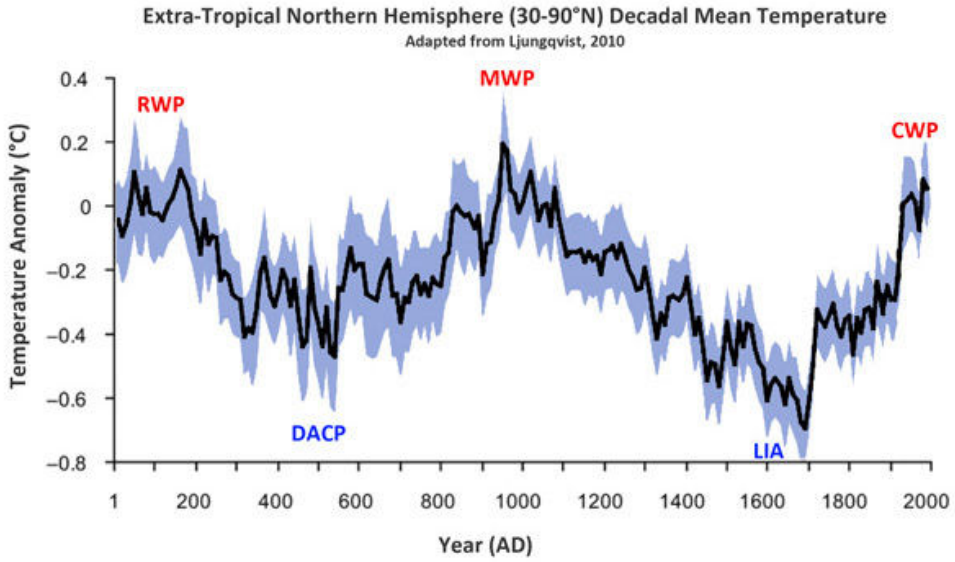

Figure 2. Extra-Tropical Northern Hemisphere temperatures utilizing many palaeo-temperature proxy records, adapted from Ljungqvist 2010. The shading represents 2 standard deviation errors. RWP = Roman Warm Period AD 1-300; DACP = Dark Age Cold Period 300-900; MWP = Medieval Warm Period 800-1300; LIA = Little Ice Age 1300-1900.

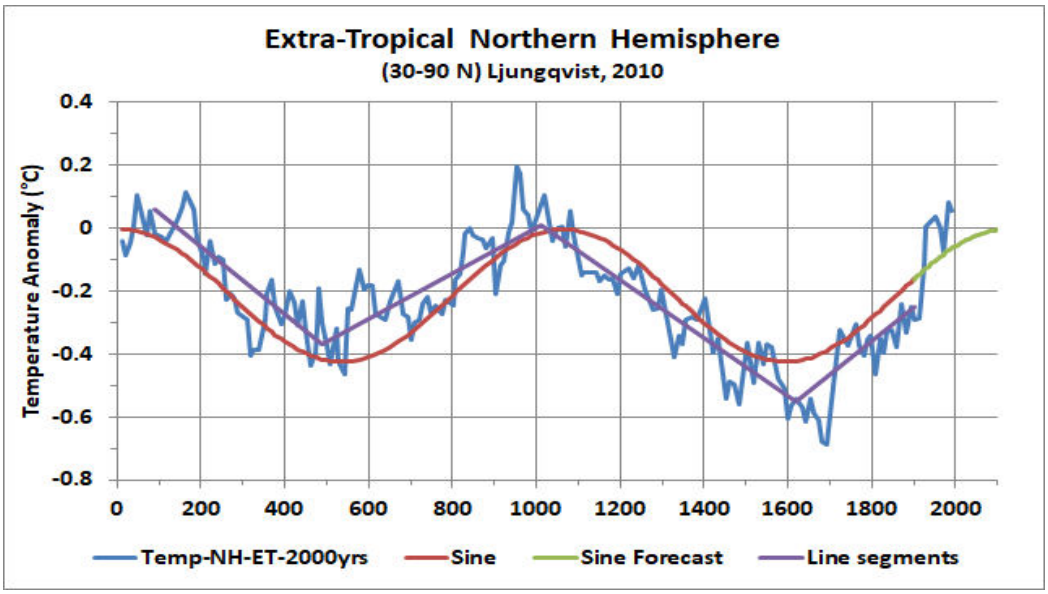

Figure 3. Extra-tropical Northern Hemisphere temperature change years 1 – 2000, adapted from Ljungqvist 2010 with line segments in purple and a sine curve in red fitted to the data up to 1900. The green curve is an extrapolation of the sine curve to 2010.

The temperature change from the center of the base to final periods of LC2018, 1875 to 2010, of the sine curve forecast was 0.107 °C/century. The estimated natural climate change over this period is the average of the two methods, being 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. The tree-ring proxies are biased toward the summer growing season. If the warming from the LIA was more pronounced during winter months than during the growing season, the estimate of the annual temperature rise would be biased too low. The large dating uncertainties of the sediment proxies have the effect of "flattening out" the temperatures so the true magnitude of the temperature change between warm and cold periods is underestimated.

The proxy temperatures did not rise as sharply during the 20th century as the thermometer record did, indicating the instrument temperature record is biased high due to the uncorrected urban heat island effect (UHIE) and/or underestimated reconstructed temperature variations from the proxies.

The annual temperatures were compared to the weighted average of the growing season months during two decades of the coldest part of the Global Historical Climate Network record[12], 1960 to 1979, and the warmest part of the record, 1995 to 2014, to determine the seasonal growing bias. The annual temperatures rose 23% more than the tree growing season temperature did, weighted by the monthly tree growth rates[13], indicating that the tree-ring proxies underestimate the temperature variability. Assuming that the seasonal temperature variability over the last century was similar to that over the last two millennia, the tree-ring proxy temperature variability should be increased by 23%. Eight of the 30 proxies have this tree-ring seasonal bias.

Ljungqvist wrote “The dating uncertainty of sediment proxies are typically +/- 160 years. The dating uncertainty of proxy records very likely results in ‘flattening out’ the values from the same climate event over several hundred years ... so they are unable to capture the true magnitude of the cold and warm periods in the reconstruction." Assuming the dating uncertainty of the 12 sediment proxies spreads the resolution over 100 years it was estimated that these proxies underestimated the temperature variability by 12%. The weighted average bias of the 30 proxies was estimated at 11%.

The southern hemisphere and tropics temperature variability is less than the northern extra-tropics due to the larger ocean area. The ratio of the global temperature change to the ETNH temperature change was calculated for a cold and a warm period of the instrument temperature record of HadCRUT4.6. From 1900-1919 to 2002-2015, the global temperatures changed by only 75% of the ETNH temperatures.

[12] Global Historical Climate Network CAMS 2m temperatures were obtained from KNMI Climate Explorer. https://climexp.knmi.nl/select.cgi?id=someone@somewhere&field=ghcn_cams_25

[13] The weighting factors were taken from an analysis of tree growth in Oregon, USA. The factors relative to June for May to September are 0.75, 1.0, 0.7,0.35 and 0.17. http://www.sciencedirect.com/science/article/pii/S0168192312003024

Table 1 summarized the calculations to determine the global natural temperature change representing the recovery from the Little Ice Age between the base and final periods of the LC2018 analysis.

Table 1. Natural Climate Change	
ETNH from proxy data	0.101 C°/century
Global adjustment factor	75%
Proxy adjustment factor	111%
Natural temperature change	0.084 C°/century

The global natural recovery from the LIA is estimated at 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 0.797 °C to 0.683 °C to account for natural climate change.

Urban Heat Island Effect

Numerous papers have shown that the UHIE contaminates the instrument temperature record. The surface-measured data has many problems. Most long-term temperature records are recorded in or near cities which have gotten warmer as they grow. Trees and shrubs are replaced by buildings, road, parking lots and airports. Poor countries have few monitoring stations and limited resources to provide maintenance and quality control. The number of operating stations dropped from 6000 in the 1970s to 2600 by 1997. Some datasets have urban adjustments whose purpose is to remove the warming effects of urbanization.

A study by Steve McIntyre shows that in the GISS temperature dataset, 45% of the UHI adjustments increase the warming trends. These wrong-way adjustments increase the urbanization effects rather than remove the effects.[14]

Dr. Roy Spencer compared the area weighted temperature trend 1973 - 2009 in the USA using data from weather stations that are located where the population density is less than 25 persons per km^2 to the corresponding trend of the Climate Research Unit temperature data (CRU). He found the low population density temperature trend is 0.09 °C/decade and the CRU trend is 0.29 °C/decade. Significantly, the warming trend where the population density is low is only 47% of

[14] See K. Gregory, "Correct the Corrections: The GISS Urban Adjustment" 2008, a summary of the audit by Steve McIntyre with a link to the original study at https://friendsofscience.org/pdf-render.html?pdf=assets/documents/CorrectCorrections.pdf

the CRUT trend. He also found that temperature trends decrease with lower population densities, so the trend with zero population density is likely about 0.08 °C/decade.[15]

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.[16] 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.[17] 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. Therefore the study shows the UHIE is 0.040 °C/decade. The results of this study and the MM2007 study are nearly identical. The average UHIE warming trends of 0.040 °C/decade from 1979 will be used to adjust the temperature rise of the LC2018 study. The temperature changes used in the LC2018 climate sensitivity calculations must be reduce by 0.133 °C to account for the UHIE from 1979. 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.

These studies are supported by numerous other studies. A study by Nicola Scafetta and Shenghui Ouyang used the divergence of the daily measured maximum and minimum temperatures to investigate the UHIE in China.[18] The study concluded that about 50% of the recorded warming since the 1940s is due to uncorrected urbanization bias. A study by Quereda et al 2016 of the

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[15] Dr. Roy Spencer, "Direct Evidence that Most U.S. Warming Since 1973 Could Be Spurious" March 2010, http://www.drroyspencer.com/2010/03/direct-evidence-that-most-u-s-warming-since-1973-could-be-spurious/

[16] Ross McKitrick, and Patrick Michaels, 2007, "Quantifying the influence of anthropogenic surface processes and inhomogeneities on gridded global climate data", *Journal of Geophysical Research-Atmospheres*, 112, D24S09, doi:10.1029/2007JD008465.
https://www.rossmckitrick.com/uploads/4/8/0/8/4808045/m_m.jgrdec07.pdf

[17] A. De Laat and A Maurellis, 2006, "Evidence of Influence of Anthropogenic surface processes on lower tropospheric and surface temperature trends", *International Journal of Climatology*, 26.
https://rmets.onlinelibrary.wiley.com/doi/epdf/10.1002/joc.1292

[18] N. Scafetta and S. Ouyang,2019, "Detection of UHI bias in China climate network using Tmin and Tmax surface temperature divergence", *Global and Planetary Change*, Volume 181, 102989.
https://www.sciencedirect.com/science/article/pii/S092181811930102X

UHIE in the Spanish Mediterranean concludes "In these Western Mediterranean cities, the UHI could account for up to 80% of the recorded warming."[19]

Summary of Climate Sensitivity Estimates

The millennium cycle natural warming and UHIE corrections reduce the temperature change between the two periods of the LC2018 analysis due to GHG by 0.114 °C and 0.133 °C, respectively. These adjustments reduce the temperature change between the base and final periods from 0.880°C to 0.633 °C. The best estimate of ECS considering the natural millennium warming cycle and the UHIE is 1.19 °C and the best estimate of TCR is 0.95 °C.

Table 2. Estimates of Equilibrium Climate Sensitivity and Transient Climate Response 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
IPCC AR5	*3.0*	1.5-4.5	1.0-*6.5*	*1.75*	1.0-2.5	*0.5*-3.0
LC2018	1.66	1.35-2.15	1.15-2.70	1.33	1.10-1.60	1.00-1.90
With Natural & Urban Warming	**1.19**	**0.90-1.57**	**0.73-1.94**	**0.95**	**0.74-1.21**	**0.61-1.44**

Table 2 summarizes the ECS and the TCR best estimate (median), likely and very likely confidence intervals (CI) for 3 cases. All forcing-based estimates use initial and final periods of 1869-1882 and 2007-2017, respectively. The IPCC and LC2018 ranges are to the nearest 0.05°C.

LC2018 discussed revising the lower bound of aerosol forcing from that used in AR5 in light of new estimates. AR5 estimated the aerosol lower bound at -1.9 W/m^2. The authors wrote "Stevens (2015) presented several observationally-based arguments that total aerosol forcing since preindustrial was weak, and could not be stronger than −1.0 Wm^{-2}." The paper noted several other studies supporting the Stevens' result. However, LC2018 chose to weaken the negative aerosol forcing only slightly to −1.7 W/m^2 which is still far lower than recommended by Stevens (2015). Using the Stevens' recommended lower bound would reduce the ECS estimates. The corrected median estimates of TCR and ECS both were reduced by 28% compared to that of LC2018.

[19] J. Quereda et al, 2016, "Significant Climate Warming (1950–2013) in the Spanish Mediterranean: Natural Trend or Urban Heat Island", *Journal of Mediterranean Meteorology & Climatology*, Tethys, 13.

Uncertainty Estimates

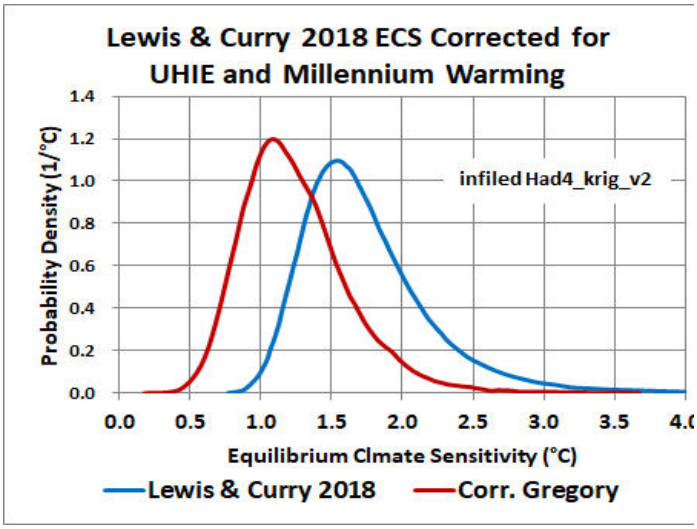

Figure 4. LC2018 ECS adjusted by UHIE and millennium warming (red), and LC2018 (blue).

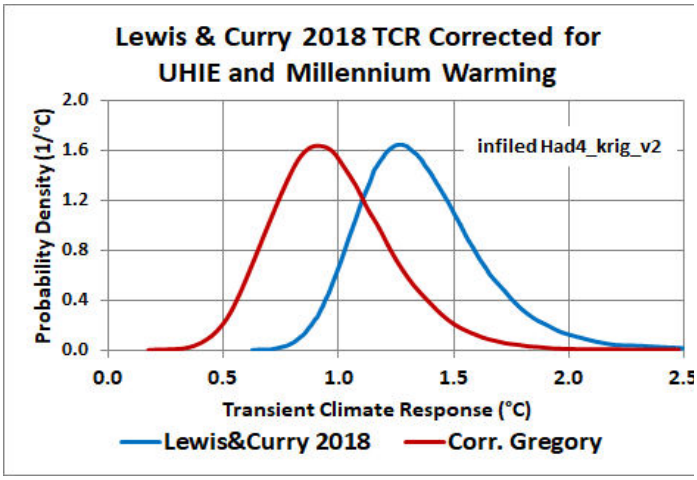

Figure 5. LC2018 TCR corrected by UHIE and millennium warming (red), and LC2018 (blue).

The LC2018 study reported best estimates (median at 50% cumulative probability), likely 17-83% confidence intervals (CI) and very likely 5-95% CIs. Using the CIs given in the paper, the probability density function (PDF) of the ECS and TCR were replicated. The forcing of a doubling of CO_2 is strongly, positively correlated with the change in GHG forcing, which reduces the uncertainty of ECS.[20]

The replicated median ECS is 1.66 °C with 17-83% CI of 1.35-2.09 °C and the replicated median TCR is 1.33 °C with 17-83% CI of 1.11-1.60 °C which agrees well with the median and rounded CI reported in LC2018.

Standard deviations and CIs were assigned to factors used to calculate the millennium cycle and UHIE adjustments to determine a PDF for the corrected ECS estimates. Figure 4 shows the LC2018 digitized ECS PDF and the corrected ECS PDF as determined by this study. While the uncertainty ranges of the corrected ECS is less than that of LC2018, the likely uncertainty as a fraction of the median of the corrected ECS is 26% larger than that of LC2018.

Figure 5 shows the LC2018 digitized TCR PDF and the corrected TCR PDF as determined by this study. While the uncertainty ranges of the corrected TCR

[20] Uncertainty estimates 5-95% of ΔT, ΔF and ΔN used to determine ECS as per footnote 3 are given in LC2018 table 2. The estimate of well mixed greenhouse gas (WMGHG) forcing is in LC2018 table 1. The Fco2 forcing uncertainty is taken as proportional to WMGHG, so Fco2 = 3.80 (3.03-4.57). The Fco2 and ΔF uncertainties were reduced by a factor 0.69 to account for the strong correlation between them.

is slightly less than that of LC2018, the likely uncertainty as a fraction of the median of the corrected TCR is 32% larger than that of LC2018.

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.

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

Forecast Greenhouse Gas Induced Temperature Rise

The best estimate TCR of 0.95 °C implies that the global temperature will increase from 2020 to 2100 by only 0.87 °C due to anthropogenic GHG emissions. Natural climate change and changes to aerosol forcings are not forecast. The forecast assumes that atmospheric CO_2 concentrations continue to increase at the current rate of 0.60%/year and that non-CO_2 GHG contribute 18% of the CO_2 forcing.[21] This estimate includes the effects of increasing GHG concentration prior to 2020, which by 2100 is 0.08 °C. The scaled difference between the ECS and TCR estimates is realized, after the period used to estimate them (i.e. 2011), according to an exponential response function.[22] Actual temperatures may rise or fall depending on natural climate change. Figure 6 shows the projected temperature response to continued exponential growth in GHG concentrations. The 2020-2100 temperature rise is 0.87 °C with a likely 17-83% range of 0.69 to 1.08 °C.

[21] GHG forcings are from the Annual Greenhouse Gas Index, NOAA's Global monitoring Laboratory, here. The non-CO2 contribution fraction (18%) is the average 2009-2019.

[22] The response function [1 - exp(-t/tau)] where t is elapsed time from the center of the final period of LC2018 and tau is a time constant. The scaling factor is GHG forced warming to date (0.71 °C)/TCR.

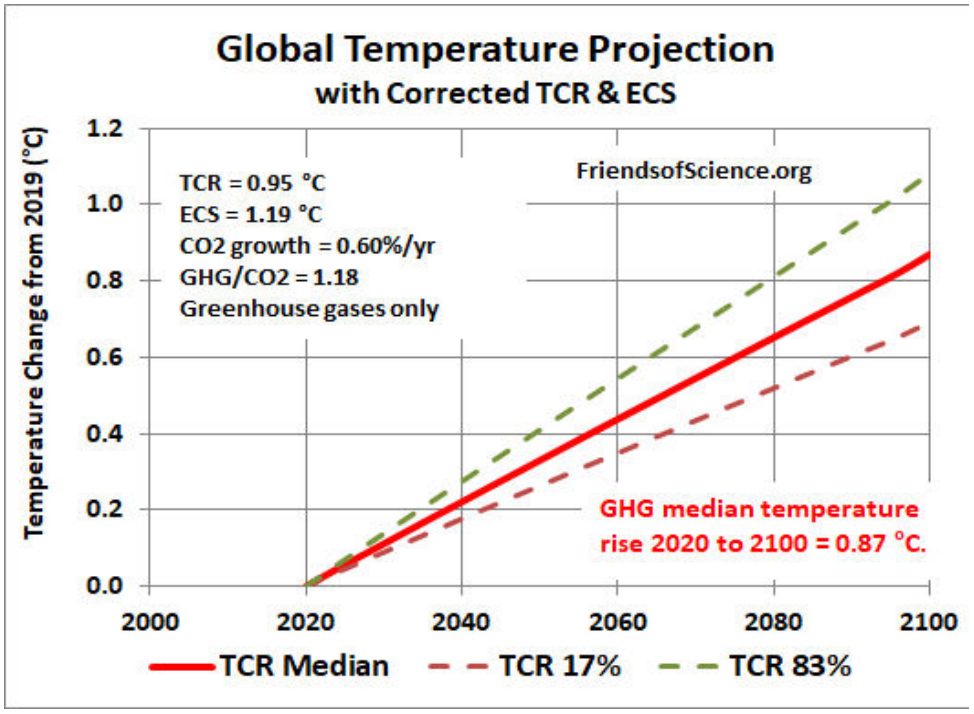

Figure 6. Global temperature projection 2020=2100 due to greenhouse gases. TCR and ECS are corrected from LC2018 to account for natural temperature change and the UHIE. The forecast include the effect of past emissions.

Note that the exponential GHG growth is offset by the logarithmic radiative forcing so that the temperature forecast is nearly a straight line.

Economic Impacts of Climate Change

A paper published in *Energies* by Peter Lang and me[23] shows that the impact of a 3 °C global temperature rise from 2000 on USA energy expenditures would have a positive impact on USA economic wealth of +0.07% of gross domestic product (GDP) whereas the FUND model projects a wealth impact of -0.80% of GDP, with non-temperature drivers held constant. A paper by me (Gregory 2020) extends the analysis to global impacts.[24] The paper finds a 3 °C global temperature increase would reduce global energy costs and increase wealth by +0.05% of gross world income (GWI) using empirical data, while FUND projects a wealth impact of -1.59% of GWI. The paper also shows using our empirical estimate of energy and using the FUND projected impacts of all

[23] Peter Lang & Ken Gregory, 2019, "Economic Impact of Energy Consumption Change Caused by Global Warming", Energies, 12(18), 3575. https://www.mdpi.com/1996-1073/12/18/3575
[24] Ken Gregory, 2020, "The Global Economic Impact of Climate Change on Energy Expenditures", https://friendsofscience.org/pdf-render.html?pdf=assets/documents/Global-Econ-Impact-CC-Energy.pdf

other impact sectors, the total impact of a 3 °C increase of global temperatures would increase global wealth by 0.2%.

A paper by Dayaratna, McKtrick & Michaels recommends that the CO_2 fertilization effect in FUND be increased by 30% due to recent studies of the effect.[25] Incorporating this change in FUND with empirical energy impacts and assuming an ECS of 1.0 °C shows that a 2 °C GMST rise from 2000 would increase global wealth by 1.45% in 2147, equivalent to $_{2019}$US$1.26 trillion.[26] The Gregory 2020 study shows that CO_2 emissions have a large social benefit, so policies to restrict CO_2 emissions are harmful and misguided.

Discussion and Conclusions

This study builds on the LC2018 study by removing the natural warming and the UHIE from the temperature change used to calculate the climate sensitivity parameters.

Numerous studies have been published that show that there was substantial climate change prior to the start of significant GHE emissions. The climate system was likely not in temperature equilibrium during the base period of LC2018. This study estimates the natural warming from the base to final period which was a continuation of the natural recovery from the LIA, the coldest period of the last 10,000 years. Natural climate change includes solar forcing that is correlated with temperature as well as internal climate variability via ocean cycles. Two studies of global UHIE were used to estimate the UHIE correction from 1979. No studies are known to estimate the effect prior to 1979 but it is likely there was significant UHIE prior to 1979 which is not accounted for in this study.

Uncertainty estimates were assigned to several parameters used to estimate the UHIE and the natural warming. Corrected estimate of ECS and TCR with uncertainty CI were calculated. Compared to LC2018, the corrected ECS and TCR median estimates were both reduced by 28%. The likely 17-83% uncertainty ranges of TCR and ECS as a fraction of the median increased by 32% and 26%, respectively, compared to LC2018 due to the considerable uncertainties of the UHIE and natural warming included in the analysis. The median (best estimate) of ECS and TCR are estimated at 1.19 °C and 0.95 °C, respectively.

Using the corrected TCR and ECS median estimates, the temperatures from 2020 to 2100 are forecast to increase by 0.87 °C, assuming the GHG concentrations in the atmosphere increases exponentially. The estimate includes “warming in the pipeline” due to past emissions.

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[25] K Dayaratna, R. McKitrick & P. Michaels, 2020, *Environmental Economics and Policy Studies*, Springer, 22. https://link.springer.com/article/10.1007/s10018-020-00263-w

[26] The gross world product is estimated in 2019 at US$86.6 trillion, http://statisticstimes.com/economy/gross-world-product.php

The policy implications of this study are substantial. If the pre-industrial global surface temperature is defined as the average of 1850 to 1900 temperatures, then warming from pre-industrial to 2019-2021 was 1.22 °C according to HadCRUT5.0. Correcting this by the estimated urban warming heat island effect of 0.16 °C gives a GHG warming of 1.06 °C to 2020. The total GHG warming from pre-industrial to 2100 is forecast at 1.93 °C. This is less than the Paris Agreement target of 2.0 °C.

Economic analysis in Gregory 2021 titled "Social Cost (Benefit) of Carbon Dioxide from FUND" shows that the FUND economic model, using updated temperature projections with a median ECS of 1.2 °C, energy impacts and CO_2 fertilization effects, a 2 °C GMST rise from 2020 would increase global income by 1.33% in 2146 (or 9.8% of 2020 global income), equivalent to $_{2020}$US$8.8 trillion. Therefore, GHG emissions are not a 21st century problem. All policies designed to reduce fossil fuel use should be repealed.

Risk analysis was performed using the Argo addin for Excel. See the Excel file for data and calculations.[27]

Acknowledgement

I thank Nic Lewis for helping me to replicate the LC0218 PDF.

Revision

Version 1 dated 2020-06-14.

Version 2, added an abstract, a paragraph about Dr. Spencer's UHIE study and an acknowledgement and removed a graph of TSI.

Version 3, Replaced the CS values of LC2018 using HadCrut4.5 with CS values using Had4_krig_v2.

[27] The Excel file is at https://friendsofscience.org/assets/files/Lewis_Curry_Gregory_ECS_TCR-C&W.xlsx . The Argo addin for Excel is available at https://github.com/boozallen/argo/wiki