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Economic impact of energy consumption change caused by global warming

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This paper tests the hypothesis that global warming would be detrimental to the global economy this century. It compares empirical data of energy expenditure and average temperatures of the US states and census divisions against projections using the FUND [1] energy impact functions holding time-dependent parameters, except temperature, constant at 2010 values. It finds that energy expenditure reduces as temperatures increase. This suggests that global warming, by itself, would reduce, not increase, US energy expenditure and so would have a positive, not a negative, impact on US economic growth. Next, these findings are compared against FUND energy expenditure projections for the world for the 21st century. The findings suggest that warming, by itself, would also reduce global energy expenditure. If these findings are correct, and if FUND projections of the non-energy impact sectors are valid, warming would benefit the global economy up to around 4˚C increase in average global temperature from 1900. If this is true, the hypothesis is false. In this case, greenhouse gas mitigation policies are detrimental to the global economy. The analysis and conclusions warrant further investigation. We recommend the FUND energy impact functions be modified and recalibrated against empirical data.

Economic impact of energy consumption change caused by global warming

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This paper tests the hypothesis that global warming would be detrimental to the global economy this century. It compares empirical data of energy expenditure and average temperatures of the US states and census divisions against projections using the FUND [1] energy impact functions holding time-dependent parameters, except temperature, constant at 2010 values. It finds that energy expenditure reduces as temperatures increase. This suggests that global warming, by itself, would reduce, not increase, US energy expenditure and so would have a positive, not a negative, impact on US economic growth. Next, these findings are compared against FUND energy expenditure projections for the world for the 21st century. The findings suggest that warming, by itself, would also reduce global energy expenditure. If these findings are correct, and if FUND projections of the non-energy impact sectors are valid, warming would benefit the global economy up to around 4°C increase in average global temperature from 1900. If this is true, the hypothesis is false. In this case, greenhouse gas mitigation policies are detrimental to the global economy. The analysis and conclusions warrant further investigation. We recommend the FUND energy impact functions be modified and recalibrated against empirical data.

Keywords: Economic impacts; global warming; climate change; energy consumption; empirical evidence; impact function; damage function.

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1 Introduction

There is a scientific hypothesis and political acceptance [2] that global warming of 2°C or more would have a negative impact on global economic growth. This hypothesis is supported by economic models, which rely on impact functions and many assumptions. However, the data needed to calibrate the impact functions is sparse and the uncertainties in the modelling results are large [3,4]. The negative overall impact projected by at least one of the main models [1] is mostly due to the one impact sector – energy consumption. However, this seems to be at odds with empirical evidence. If this paper's findings from the empirical energy consumption data are correct, and the impact functions for the non-energy sectors are correct, then the overall economic impact of global warming would be beneficial. This paper tests the energy consumption impact projections.

Integrated Assessment Models (IAM) approximately reproduce the projections from the Global Climate Models (GCM) and apply impact functions to estimate the biophysical and economic impacts of global warming. The impact functions are derived from and calibrated to what the researchers assess are the most suitable studies of the impacts. The impact functions require many assumptions; for example, they require projections of population, gross domestic product (GDP), GDP per capita, energy efficiency improvement rates, energy prices and elasticities. The analysis presented here provides a validity check, which avoids the need for these projections and assumptions.

Climate Framework for Uncertainty, Negotiation and Distribution (FUND) [1] is one of the three most cited IAMs; Bonen et al. (2014) [5], National Research Council (2010) [6] and The National Academies (2017) [4] compare them. FUND is the most complex. FUND disaggregates by sixteen world regions and eight main impact sectors (agriculture, forestry, water resources, sea level rise, ecosystems, health, extreme weather, and energy consumption). This enables analysts to conduct sensitivity analyses and to separately test the validity of individual impact functions.

Tol (2013) [7] estimated the economic impact of global warming for these sectors from 1900 to 2000 using historical data, and used FUND to project impacts from 2000 to 2100. This is an important study because it estimates the positive and negative impacts for the most significant impact sectors, globally and by region. It also estimates the total impact on all sectors. Tol (2013) Figure 3 shows the projected economic impact of global warming on these sectors; it is copied in Figure 1.
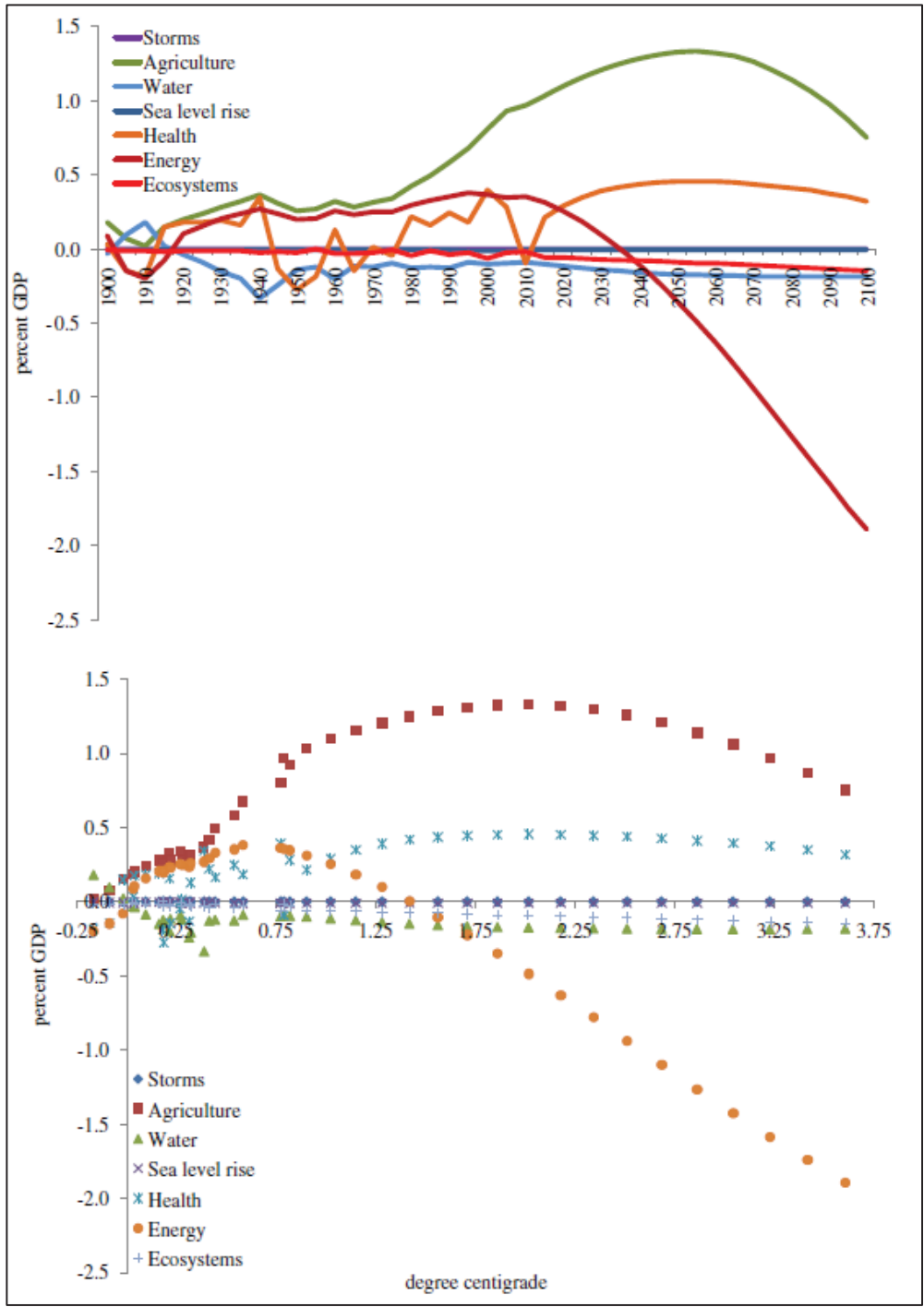
Figure 1: Copy of Tol (2013) Figure 3 [7]. "The global average sectoral economic impact of climate change in the 20th and 21st century as a function of time (top panel) and temperature (bottom panel)." [Reprinted by permission from Springer Climate Change.]

The bottom panel of Figure 1 shows that an increase of around 4°C Global Mean Surface Temperature (GMST) relative to 1900, would be beneficial for the total of all sectors, if energy consumption is excluded. Energy consumption is projected to have a substantial

negative impact during the 21ˢᵗ century; in fact, its negative impact exceeds the total impact of all other sectors, which is positive, from about 2080.

The change in the energy impact at the turn of the century is striking. The trend was positive as GMST increased by 0.75°C during the 20th century (Tol 2013) [7], but FUND projects it will be substantially negative for the 21ˢᵗ century as GMST is projected to increase further. That is, the empirical data for 1900 to 2000 shows global warming is associated with increased economic growth whereas FUND projects continued global warming would substantially reduce economic growth.

Contrary to the FUND projection for the period 2000 to 2100, the US Energy Information Administration (EIA) [8,9] empirical data appears to indicate that global warming would reduce energy expenditure and, therefore, deliver positive economic impacts.

If this is true, its significance for climate policy is substantial. If the sectoral projections in Tol (2013), other than for energy consumption, are correct and the economic impact of energy is near zero or positive, global warming would be beneficial up to around 4°C GMST increase relative to 1900. Therefore, the economic impact of energy consumption projected in Tol (2013) [7] warrants investigation if FUND is to be used for policy.

This paper examines empirical data to investigate whether the impact of global warming on energy consumption would reduce or increase economic growth. Section 2 reviews some relevant literature. Section 3 describes the methodology, assumptions and data sources. Section 4 presents the results and discussion, and suggests modifications to the FUND energy impact equations. Section 5 presents the conclusions.

2   Literature review

FUND projects the economic impact of changes in space heating and space cooling energy consumption caused by projected global warming. Comparison of FUND projections with empirical data requires the latter be in units of expenditure. The EIA provides space heating and space cooling data for the US in suitable units. Before discussing the EIA data, it is informative to review other studies that report space heating and space cooling energy consumption (as distinct from expenditure, which is not readily available for most countries) by country and region. Fourteen studies and reports are discussed in this section.

FUND Documentation [10] states: "The parameters [used in the energy impact equations] are from calibrating FUND to the results of Downing et al. (1995, 1996). Savings on space heating are assumed to saturate. [Space cooling is assumed to be more than linear in temperature because cooling demand accelerates as it gets warmer.] The income elasticity of heating [and cooling] demand is taken from Hodgson and Miller (1995, cited in Downing et al., 1996), and estimated for the UK. Space heating [and cooling] demand is linear in the number of people for want of scenarios of number of households and house sizes. Energy efficiency improvements in space heating [and

cooling] are assumed to be equal to the average energy efficiency improvements in the economy."

Downing et al. (1996) [11] conclude (p. 26): "The increased cooling demand is much less than the heating benefits, implying that the aggregate cost of climate change on energy demand would be positive." This conclusion seems at odds with the large negative economic impact projected in Tol (2013). Downing et al. also say:
- "Space heating demand is not expected to be very dependent on GNP. … Reasonable comfort levels are a basic necessity and overheating has negative utility. Income elasticities are therefore low."
- "Space cooling demand is expected to be far more dependent on GNP than space heating demand. Space cooling is closer to a luxury than a basic necessity. This implies that the related energy demand can be very income sensitive at some stages of development".
- The analyses rely on many assumptions.

These statements are relevant to attributing the heating and cooling demand responses to global warming as distinct from increasing income per capita over time.

Hodgson and Miller (1995) [12] is a comprehensive analysis of UK energy demand data, and provides income elasticities for heating and cooling demand. However, FUND uses these data to calibrate the energy impact functions for all regions. This raises the question of the suitability of the UK data for this purpose.

Bessec and Fouquau (2008) [13] analyse the non-linear response of electricity consumption to warming and cooling in 15 European countries for 1985 to 2000. The average temperature of these countries for this period ranged from 2˚C to 16˚C. The analysis is an advance on previous studies. However, it has limitations. While residential, commercial and industrial consumption responses to temperature change are included, the study analyses electricity only and so does not capture the full heating cost from all fuels.

Fazeli et al. (2016) [14] review the recent literature on models of energy demand responses to temperature change. However, most of the studies reviewed focus on residential, not commercial and industrial use; on consumption not expenditure; on electricity rather than all energy carriers (gas, oil, coal, biofuel, district heating); and on energy demand responses to short-term weather changes rather than to change in average annual temperature. Those studies that do analyse the response to changes in average annual temperature do so over an extended period, which brings other drivers of energy consumption change into play. To investigate the temperature sensitivity of energy consumption, the effects of the other drivers need to be removed.

Ürge-Vorsatz et al. (2014) [15] project that, between 2010 and 2050, energy consumption in buildings will increase, except in Europe and Pacific OECD countries. However, this increase is not due to global warming. The drivers of the increase are changes in the "number of households, persons per household, floor space per capita, and

specific energy consumption for residential heating and cooling; and GDP, floor space per GDP, and specific energy consumption for commercial buildings". Although this study does not investigate the effect of increasing ambient temperatures, it is relevant because it analyses the non-warming drivers.

International Energy Agency (IEA) (2012) [16] Figures 1 and 2, show space heating and space cooling energy consumption in residential and commercial buildings in US, EU, Japan, China and India. (Some data is not available for some of the countries.) It is worth highlighting that, where both space heating and space cooling are included, the charts show that energy consumption for space heating is two to four times higher than for space cooling. This IEA data is for consumption, not expenditure, so it is not in a form readily usable for estimating the change in energy expenditure per degree of temperature change.

IEA (2016) [17] summarises information on end-use energy consumption in IEA member countries. It provides total energy consumption in the residential sector, and the proportions used for space heating and space cooling; the data is not in units of expenditure, and data for commercial buildings and industry is not included. The IEA figures for the residential sector show that energy consumption for space cooling is small to negligible compared with space heating in the high income countries reported. Table 1 presents data for selected countries.

Table 1: Space heating and space cooling share of 2013 residential energy consumption petajoule (PJ) in selected IEA member countries.

Country	Consumption, PJ	Heating, %	Cooling, %
US	11,792	45	6
Canada	1426	62	1
UK	1670	63	0
Sweden	338	62	0
France	1761	68	0.1
Germany	2558	69	0
Italy	1258	72	2
Spain	639	46	1
Japan	1970	25	2
S Korea	839	43	1
Australia	410	35	5

The **European Environment Agency (EEA) (2016)** [18] expects no significant economic impact from changes in energy consumption as a result of projected global warming over the 21st Century. EEA states (edited): "population-weighted heating degree days (HDD) in Europe decreased by 9.9 per year (0.45% p.a.) on average between 1981 and 2014. Over the same period population-weighted cooling degree days (CDD) increased by 1.2 per year (1.9% p.a.). While HDD are projected to decrease more than CDD increase over the 21st century, in economic terms they are expected to be about equal in Europe because cooling is generally more expensive than heating."

National Oceanic and Atmospheric Administration (NOAA) (2014) [19] says that, since 1990, the increase in cooling needs is greater than the decrease in heating needs. As temperatures warm, NOAA predicts "Warmer winters will decrease energy demands for heating, but on average, people living in the contiguous United States are not likely to see a net energy saving". This is similar to the EEA statement for Europe, i.e. little economic impact of global warming on heating and cooling energy use.

Natural Resources Canada (2016) [20] says: "63% of Canada's residential energy use was for space heating and only 1% for space cooling in 2013. […] However, there are multiple influences apart from change in annual average temperatures". With a 63:1 ratio of space heating to space cooling energy consumption, it seems unlikely that increasing ambient temperatures would cause increases in space cooling to exceed reductions in space heating expenditures in Canada. EIA data for the US indicates the cost per unit of energy consumed for cooling is about three times higher than that for space heating. Converting from consumption to expenditure units, changes the ratio from 63:1 to 63:3, or 21:1. This also does not appear to support the energy projections in Tol (2013).

Réseau de Transport d'Électricité (RTE) (2015) [21] says the "report illustrates, once again, how sensitive power consumption is to climate conditions. In 2014, the hottest year on record since the beginning of the 20th century according to Météo France, gross power consumption contracted by 6% versus 2013 and ended the year at … the lowest level since 2002. … This decline was attributable in large part to weather conditions" (p.2). The report says: "The temperature sensitivity of power demand … is estimated at about 2,400 MW per degree Celsius in winter on average" (p.12). However, the RTE report is for electricity only. Consumption of other fuels used for heating would also decrease with warmer temperatures, further reducing annual heating energy consumption.

National Academies of Sciences, Engineering and Medicine (2017) [4] says FUND needs further justification for "the damage formulations for heating demand, cooling demand, […], the assumptions underlying adaptation in the different sectors, the regional distribution of damages, and the parametric uncertainties overall" (p.261).

Tol (2018) [22] "reviews estimates of the total economic impact of climate change and the distribution of those impacts around the world, and discusses the interactions between economic development and climate change, …". Tol finds the relative impacts of climate change decline as per capita income rises. Tol says "the impact of climate change on numerous important issues — …, space cooling, … — has not received sufficient attention; there is either very little solid evidence, no conclusive evidence, or no quantification of welfare impacts". However, the paper does not disaggregate by impact sector, and so doesn't provide new information that is of use in the current paper.

The above studies mostly appear to be at odds with the negative economic impact of global warming on energy consumption projected in Tol (2013).

EIA data also seems contrary to the NOAA and EEA statements. The analysis of the EIA data is presented below.

3   Materials and methods

This section explains the methods, assumptions and data sources used to:

- Find relationships, using empirical data for the US, between average annual temperature, per capita space heating and space cooling energy expenditure, and economic impact

- From these relationships, estimate the economic impact of a 3˚C GMST increase on US energy expenditure

- Compare the economic impacts estimated using US empirical data with impacts projected by FUND for the US

- Compare the US energy impacts with the world energy impacts projected by FUND.

3.1   US energy expenditure versus temperature

This section explains the method used to analyse space heating and space cooling consumption and expenditure data for the US, and how these vary by latitude, to determine a relationship between per capita energy expenditures and average annual temperature, and to estimate the economic impact of temperature change.

The method uses data from single year surveys, conducted in 2009 and 2012. This has the advantage of holding constant most of the time-dependent drivers of change in energy expenditure. Adaptation to historical average temperatures is effectively included, because regions have adapted to their climates, but adaptation to other time-dependent parameters, such as changes in incomes, are effectively excluded.

Ürge-Vorsatz et al. (2014) [15] point out there are many drivers of change in energy consumption other than temperature change. To investigate the relationship between temperature change and energy expenditure change, the effects of the other variables need to be removed. Using empirical data for one country, the US, for one year has a number of advantages for checking the validity of the energy projection in Tol (2013) [7] and of the FUND energy impact functions. Advantages include:

- During a short period of time, such as a year, most of the drivers of change in energy consumption and expenditure are relatively constant. Drivers include: number of buildings, age of buildings, area heated, area cooled, persons per building, floor space per capita, energy consumption per floor area and per capita,

GDP, average annual income per capita, temperature, energy efficiency, and energy prices.

- The effects of adaptation to the local climate – such as behavioural responses and decisions about purchases or replacements of durable products – are effectively included because buildings and behaviours are adapted for its climate.
- The US has a relatively uniform standard of living, compared with regions comprising multiple countries, so we can relate per capita energy expenditure to latitude and temperature with less need to adjust for differences in, for example, wealth, standard of living, and country specific energy regulations, subsidies, penalties, and other market distortions.
- The US data includes space heating and space cooling energy consumption and expenditure by state (for residential buildings) and energy consumption and fuel prices per census region and division (for residential and commercial buildings); these provide sufficient data points to regress per capita expenditure by latitude, and by temperature.
- The contiguous states of the US span the latitudes where most of the world's GDP is produced; in 2010, 84% of the world's GDP [23] was produced in the FUND regions (FUND3.9 Tables [10], Table R) with population centroids between latitudes 30˚N and 50˚N; the regions are US, Canada, Western Europe, Eastern Europe, Former Soviet Union, China plus, Japan and South Korea, Middle East and North Africa. The relationship between the economic impact of energy expenditure and average temperature in the US provides a means to check the Tol (2013) [7] and FUND [24] projections for the regions where most of the world's GDP is produced and, by extension, for the world.

EIA publishes energy consumption and expenditure data for US residential and commercial buildings. The residential data is from the 2009 Residential Energy Consumption Survey (RECS) [8]; it includes space heating and space cooling energy consumption and expenditures by US census region and division, and by state for the larger states and by groups of smaller states. The commercial buildings data is from the 2012 Commercial Buildings Energy Consumption Survey (CBECS) [9]; it includes space heating and space cooling energy consumption by fuel by census region and division (but not expenditure and not by state). We convert from consumption to expenditure using 2012 fuel prices calculated from consumption and expenditure per fuel, per division [9]. These fuel prices are the full-year average for all uses in commercial buildings. They are not segregated by use, such as for heating and cooling.

Economic impacts and GMST change are relative to 2000. GDP and expenditures are in 2010 US dollars.

The average annual temperatures [25] are for years 2009 for residential and 2012 for commercial buildings. These apply at the area centroid (geographic centre) of each state. However, since energy is consumed where people live, the heating and cooling energy consumption and expenditure should be assigned to the population centroid [26] rather than to the area centroid [27]. Therefore, we convert temperature at the area centroids to temperature at the population centroids. We do this by regressing the temperature per

degree latitude at the area centroids of the US states and census divisions, then applying the corresponding slopes to convert temperatures at the latitude of the area centroids to that at the latitude of the population centroids. This applies the relevant slope for the conversion of each state and census division. The 2010 population and coordinates of the population centroid [26], and the area and coordinates of the area centroid, for each state are published by the US Census Bureau [27].

The methodology used for analysing the EIA data is as follows:

1. Calculate per capita space heating and space cooling energy expenditure by state for large states and by groups of smaller states (27 in total) for residential buildings, and by US census division (9 in total) for both residential and commercial buildings. Expenditures are converted to 2010 US$.

2. Get the area and the area centroid latitude [27], and the population and the population centroid latitude [26], of each state. Calculate the latitude of the area centroid and population centroid of each state group and each census division.

3. Regress per capita energy expenditure per state and state group (for residential) and per census division (for commercial) against the population centroid latitudes.

4. Get the 2009 and 2012 average temperature for each state [25]. Calculate the area-weighted temperature for each state group and census division. Regress temperature against area centroid latitude.

5. Apply the slopes to convert the temperatures at the area centroid latitudes to the temperatures at the population centroid latitudes. Regress temperature against population centroid latitude.

6. Regress per capita expenditure against temperature at the population centroids.

7. Regress the regional temperature conversion factor (RTCF) of the FUND regions (FUND3.9 Tables, Table RT [10]) against their area centroid latitudes. Apply the slope to calculate the temperature at the population centroid latitude, for each US state, state group and census division, at a 3˚C GMST increase relative to 2000.

8. Calculate per capita expenditure versus temperature at the population centroid latitudes at 3˚C GMST increase.

9. Calculate per capita expenditure change per degree of temperature change at the population centroid latitudes, at a 3˚C GMST increase.

10. Convert per capita expenditure change to total US expenditure change ($ billions), and to the economic impact as a percent of US GDP.

A linear regression model is fitted to all data sets. Other models showed some slight improvements in fit but they are not sufficient to warrant using more complex models.

3.2 Reproduction of Tol (2013) energy impact projection

To compare the EIA data for the US with the Tol (2013) energy impact projection, we need to reproduce the Tol (2013) projection for the world, then project the impact for the US using the same impact functions.

We attempted to reproduce the Tol (2013) energy projection using the energy impact functions and the input parameter values documented in the FUND3.6 documentation and tables [10], as well as input parameter values and results for 1990 and 2000 published at Harvard Dataverse [28]. However, not all the required input data and results are published. Also, Tol used the national version of FUND3.6, version 3.6n, which is not published. Tol (2013) [7] says this version "only covers the impacts of climate change – while population etc. are as observed for the 20th century and exogenous for the 21st century". Tol also says "The continental version of FUND is a fully integrated model, including scenarios of population, economy, energy use, and emissions; a carbon cycle and simple climate model; and a range of impact models". In short, these factors are endogenous in the continental version. The recent FUND versions are developments from the continental version. Consequently, we were unable to reproduce the Tol (2013) projection.

We investigated FUND3.9, Julia version [24] (which is still in development) and found it uses more recent data, and includes some changes. The energy impact projection in the Julia FUND version is significantly different from that in Tol (2013) [7]. Input parameter data and results can be exported from Julia FUND3.9. For these reasons we have used impact functions, input data and results from Julia FUND3.9 for the comparisons with the EIA empirical data.

3.3 Comparison of FUND projections with EIA data

This section explains the method used to compare the economic impact of global warming on energy expenditure interpreted from the EIA data, with the FUND3.9 energy impact projections for the US.

The energy impact functions are explained in FUND3.9 Documentation [10], pp.9-10. The parameter data are provided in FUND3.9 Tables [10]. However, as noted above, some changes have been made in Julia FUND. Where the data is different we have used data downloaded from Julia FUND. Where base years are changed, we have modified the documented impact equations to be consistent with Julia FUND.

Since the empirical data we use is from the EIA 2009 residential survey [8], the EIA 2012 commercial buildings survey [9], and the 2010 US census data [26], to do a proper

comparison between the EIA data and the FUND projections we need to project the energy impacts with time-dependent parameters held constant at their 2010 values. We built an Excel spreadsheet, and verified that it correctly reproduces the Julia FUND3.9 energy impact projections. With this, we can hold the time-dependent parameters constant to project impacts with GMST as the only variable. This method implicitly changes temperature instantaneously in 2010. It also assumes buildings, durable products and behaviours adapt instantaneously to be the same as those at the latitude where the temperature existed before the instantaneous temperature increase.

The Tol (2013) temperature and energy impact projections for the 21st century were obtained by digitising from the Tol (2013) [7] Figures 1 and 3 respectively. The Julia FUND3.9 energy impact projections were produced by the version of Julia FUND3.9 downloaded on 5 January 2018. The default parameter values are used for all analyses.

3.4 FUND projections for world regions

The Tol (2013) projections are for the world, whereas the EIA data are for the US only. For comparison, analysis of the projections for the US economy therefore need to be extended to the world economy. This section explains the method used to analyse Julia FUND3.9 projections of the regional economic impact of a 3˚C GMST increase on heating and cooling energy expenditure by latitude and by temperature.

The countries included in each region are listed in FUND3.9 Tables [10], Table R, and shown in Figure 2 (copied from FUND Home [1]).

Figure 2: FUND regions. Source: FUND Home [1]

The change in the average temperature of a region in response to a change in GMST is assigned to the area centroid. However, as noted in Section 3.1, the distribution of heating and cooling energy expenditure within a region relates to the population distribution within the region and so should be assigned to the population centroid. The steps needed to convert the temperature change at the area centroid latitude to the temperature change at the population centroid latitude of the world regions are:

1. Calculate the latitude of the area centroid [29,30] and population centroid [31,32] for each region.

2. Regress RTCF, (FUND3.9 Tables, Table RT [10]), for each region against its area centroid latitude. Apply the slope to calculate the RTCF at the population centroid latitude for each region.

3. Calculate the temperature change at each region's population centroid for a 3˚C GMST increase.

4. Get the FUND3.9 projected heating and cooling impacts for each region. Regress the heating and cooling impacts for each region against its population centroid latitude.

5. Regress the heating and cooling impacts for each region against the temperature change at its population centroid latitude, for a 3˚C GMST increase.

4   Results and discussion

4.1 US energy expenditure versus temperature

This section analyses the US EIA data of space heating and space cooling, and how these vary by latitude, to determine relationships between energy expenditures and temperature, and between economic impact and temperature.

Figures 3 to 6 are charts for the main steps described in Method (Section 3.1) for the residential buildings data, by state and state group. Figures 7 and 8 are the equivalent of Figures 3 and 6, but with both residential and commercial buildings data, by census division. Table 2 presents the total US economic impact estimated from the 2009 residential data and the 2012 commercial buildings data. (Refer to Appendix A, Table A.1 for the Figures 3 and 5 data, and Table A.2 for the Figure 7 data. Temperature and latitude of the area and population centroids, and temperature change at the population centroid at 3˚C GMST increase, are in Table A.3 (by state and state group) and Table A.4 (by division). Appendix B summarises and discusses the statistical analyses and data issues.)

The impacts calculated from the residential heating and cooling data are less uncertain than the impacts calculated from the commercial buildings data. Whereas EIA publishes residential heating and cooling expenditures, commercial buildings expenditures have to be calculated from consumption and fuel prices, both of which are incomplete, and some have as few as one significant figure. The commercial buildings data do not breakdown fuel prices for heating and cooling. The prices are full-year averages; these may be biased low for heating and cooling (see Appendix B). Consequently, the impacts of temperature increase may be underestimated for commercial buildings. Further, the residential data has more data points and span a wider latitude band than the commercial buildings data, so the regression results have higher statistical significance. However, commercial buildings impacts comprise only 35% of the total impact (from Table 2).
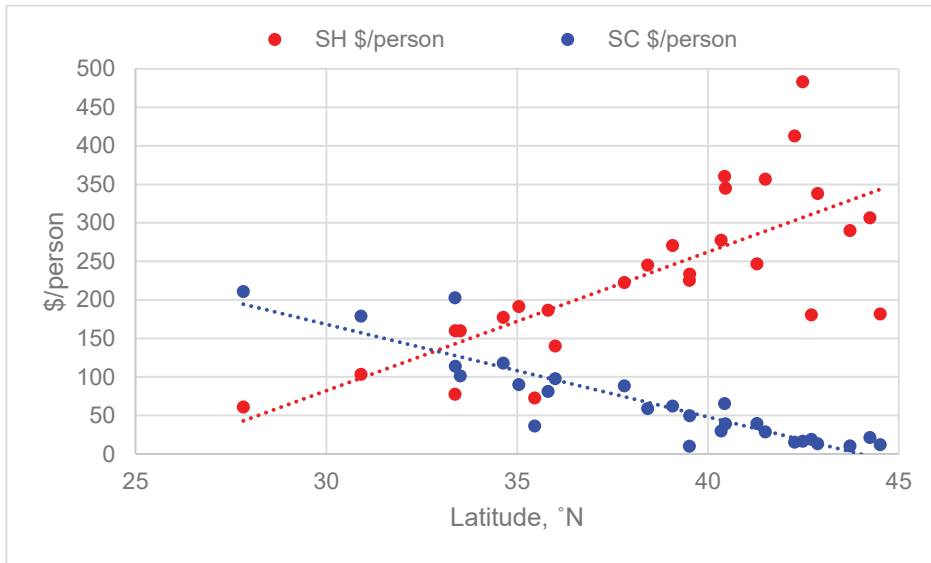
Figure 3: Residential per capita space heating (SH) and space cooling (SC) expenditure versus population centroid latitude, for the 27 states and state groups.

Figure 4 plots temperature against population centroid latitude of each state and state group at: Present (2009), 3˚C GMST increase, and the change.
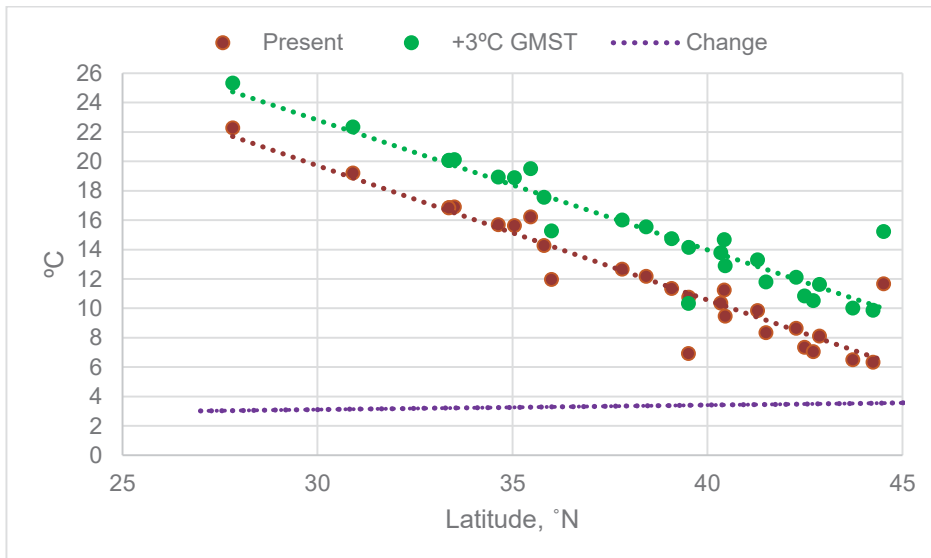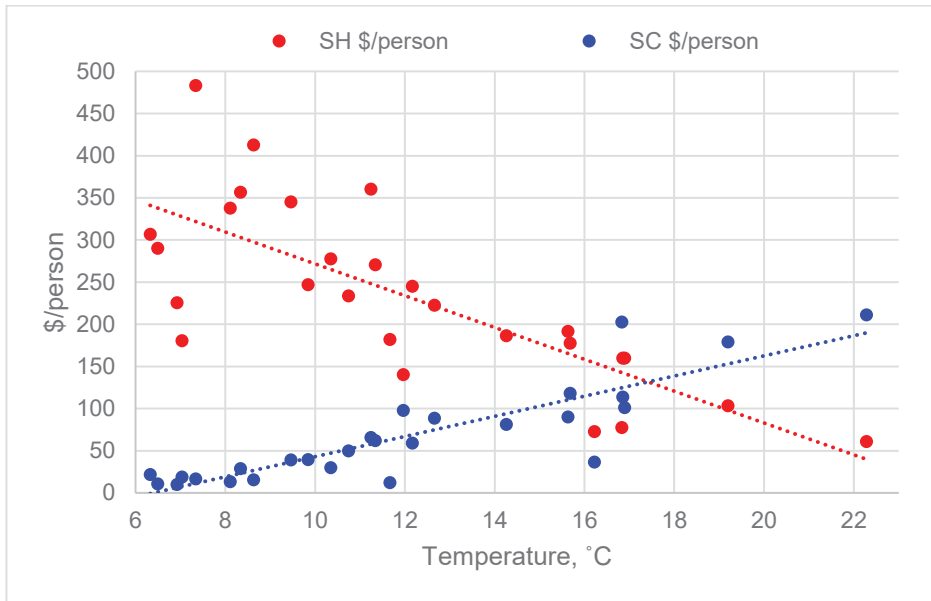

Figure 4: Average temperature versus population centroid latitude of the US states and state groups: Present (2009), at 3˚C GMST increase, and the change. [3]

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[3] The high data point at latitude 44.5˚N is state group 'Alaska, Hawaii, Oregon and Washington'; it is high due to moderation of temperatures caused by the oceanic influence. The low data point at latitude 39.5˚N is Colorado; it is low due to its relatively high elevation compared with other states at similar latitude.

Figure 5: Residential per capita space heating and space cooling expenditure versus temperature at the population centroid, for the 27 states and state groups.

Figure 5 shows that the trends are approximately linear over the range 6° to 23°C, and projects to $0 expenditure at average annual temperatures above 24.4°C for heating and below 6.4°C for cooling. We infer that energy consumption for heating flattens across the tropics.
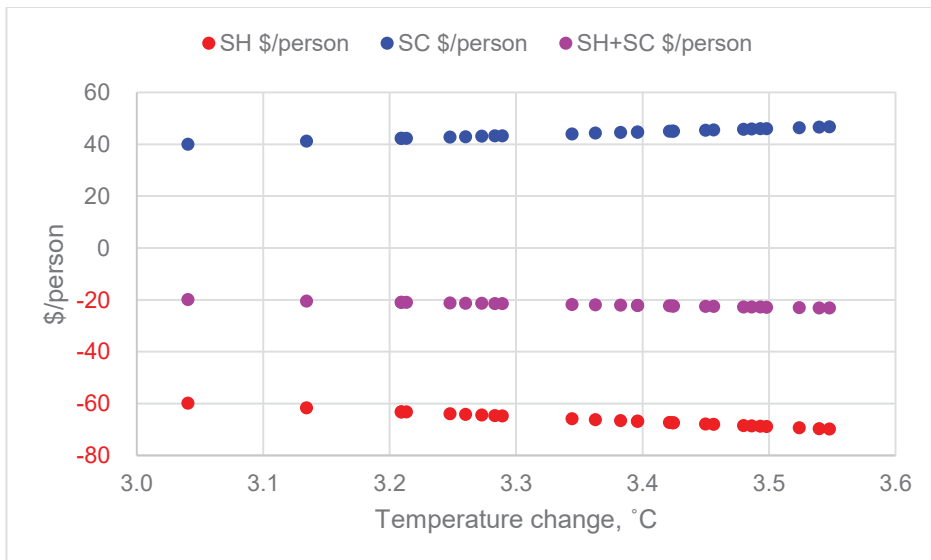

Figure 6: Residential per capita space heating and space cooling expenditure change versus temperature change at 3°C GMST increase, for the 27 states and state groups.

Figure 6 shows per capita residential space heating plus space cooling expenditure would reduce by around $21 per person per year in response to a 3°C GMST increase, and that the savings increase as temperature change increases.

The same method is applied to estimate the per capita expenditure change in commercial buildings for the nine census divisions. Figures 7 shows the residential expenditure changes (same as Figure 3) and the commercial buildings expenditure changes, by latitude by census division.
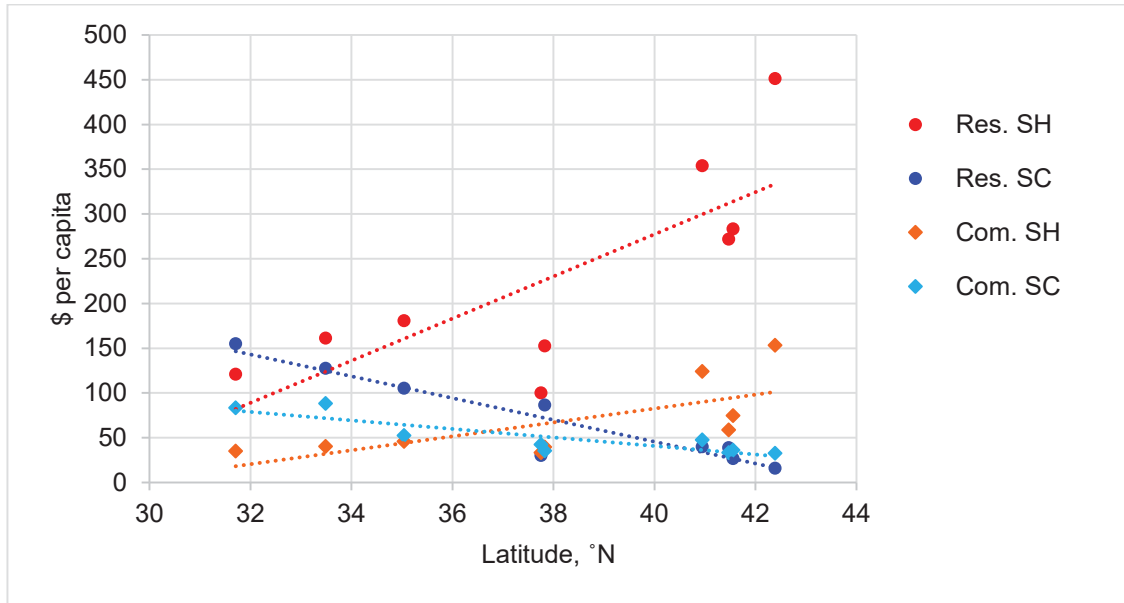

Figure 7: Residential and commercial buildings per capita space heating and space cooling expenditure versus population centroid latitude, for the nine census divisions.
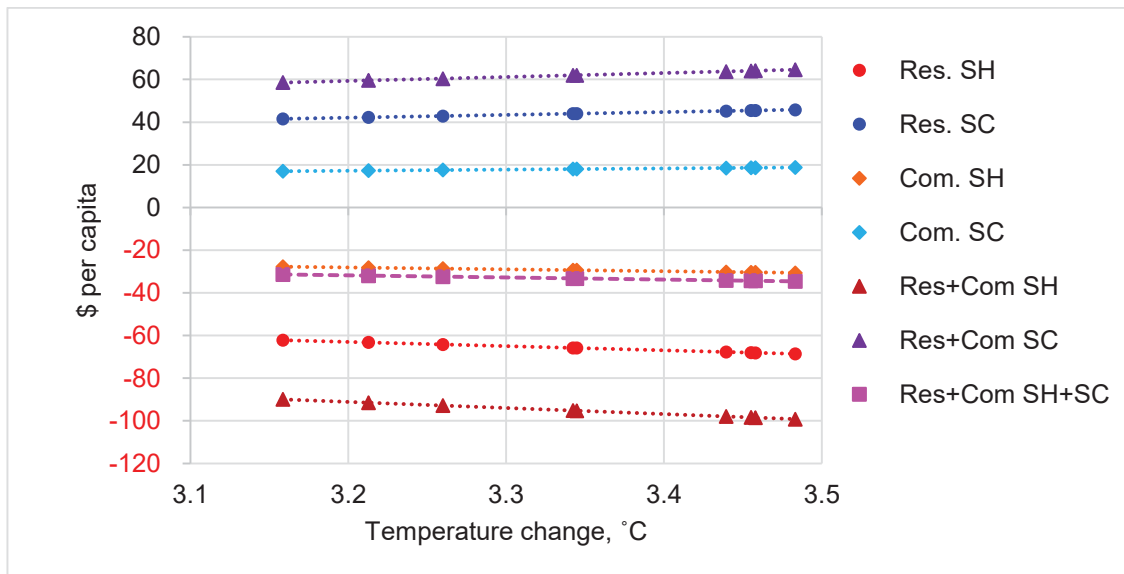

Figure 8: Residential and commercial buildings per capita space heating and space cooling expenditure change versus temperature change at 3°C GMST increase.

Figure 8 shows the total of space heating and space cooling for both residential and commercial buildings (pink) would result in savings of $31 to $35 per person per year at a 3°C GMST increase; further, the savings increase as the temperature change increases.

Table 2 presents the total US economic impact of a 3˚C GMST increase calculated from the residential and commercial buildings space heating and space cooling data.

Table 2: Impact of a 3˚C GMST increase on US annual space heating and space cooling expenditure, 2010 US$ billion (negative values are savings).

	Units	Res. SH	Res. SC	Com. SH	Com. SC	Total
Residential & Commercial	$ bn	-20.28	13.55	-9.05	5.54	-10.24

In summary, the EIA empirical data indicates that a 3˚C GMST increase (relative to 2000) would reduce US energy expenditure by around $10 billion per year; that is, a positive impact on GDP, not negative as projected in Tol (2013) and FUND3.9.

4.2 Comparison of Tol and FUND global projections

Figure 9 compares the Tol (2013) and Julia FUND3.9 projections for the world. The space heating and space cooling components are also shown for the Julia FUND3.9 projections. GMST change and economic impact (percent of GDP) are relative to 2000 values.
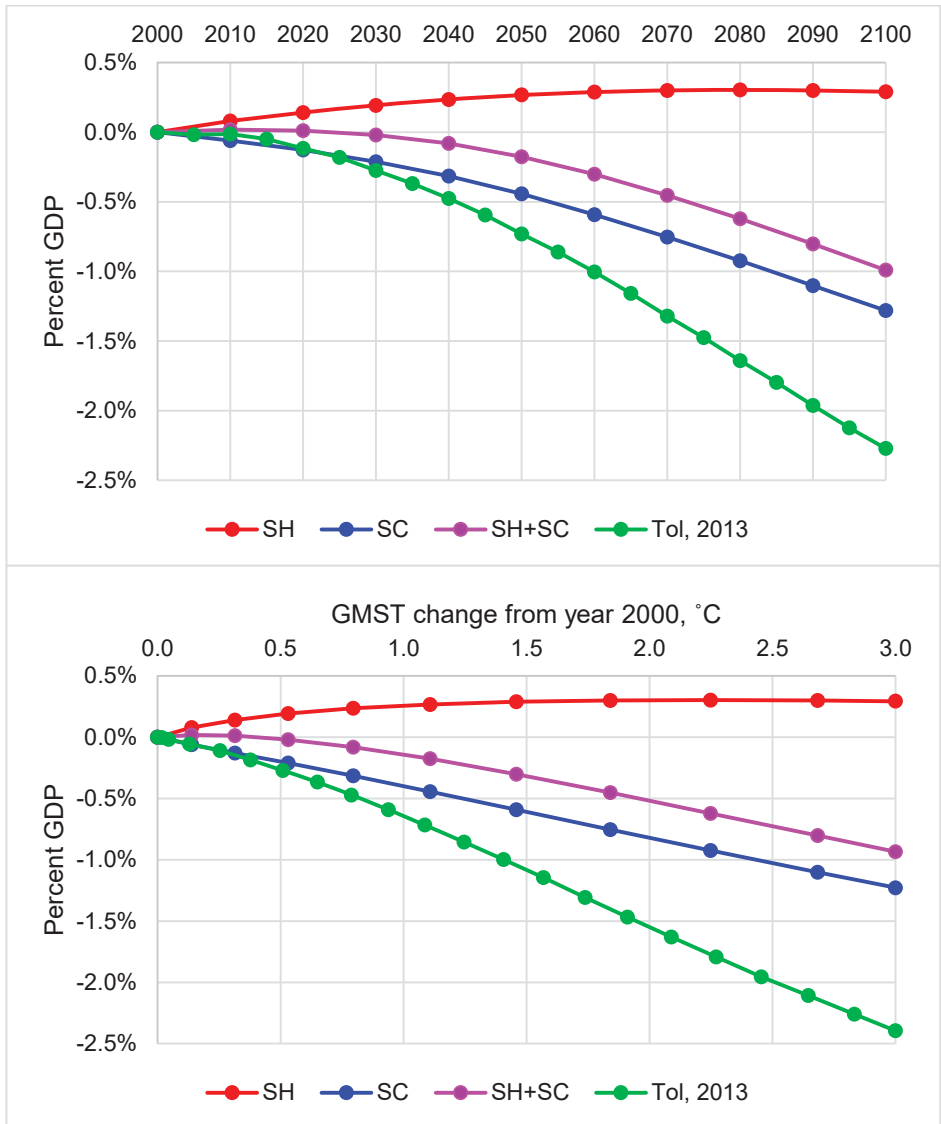
Figure 9: Comparison of Julia FUND3.9 projections and Tol (2013), Figure 3. The projections show the economic impact of global warming on global energy expenditure for the period 2000 to 2100 as a function of time (top panel) and temperature (bottom panel). The space heating (SH) and space cooling (SC) components are also shown for the Julia FUND3.9 projections.

Figure 9, top and bottom charts, show there is a substantial difference between the Tol (2013) (green) and Julia FUND3.9 (pink) projections. Table 3 compares the percentage change in global GDP in 2100, and at 3˚C GMST increase from 2000, projected by Tol (2013) and Julia FUND 3.9.

Table 3: Tol (2013) and Julia FUND3.9 projected percentage change in world GDP in 2100, and at 3˚C GMST increase from 2000.

	2100	**+3˚C GMST**
Tol (2013)	-2.27%	-2.41%
Julia FUND3.9	-0.99%	-0.94%

Figure 9 (bottom panel) shows that, whereas the rate (percent of GDP versus GMST change) of cooling is near-linear, the rate for heating increases to a peak at +0.3% percent of GDP at +2.25°C (in 2080); thereafter, the rate slows. These are at odds with the results from the US EIA data. The EIA space heating data does not display the curved trend, and the total impact of space heating and space cooling is positive, not negative.

4.3 Comparison of FUND projections with EIA data

This section compares the US energy expenditure impacts projected without and with the time-dependent parameters held constant at 2010 values, and the impacts calculated from the EIA empirical data (Figure 10).
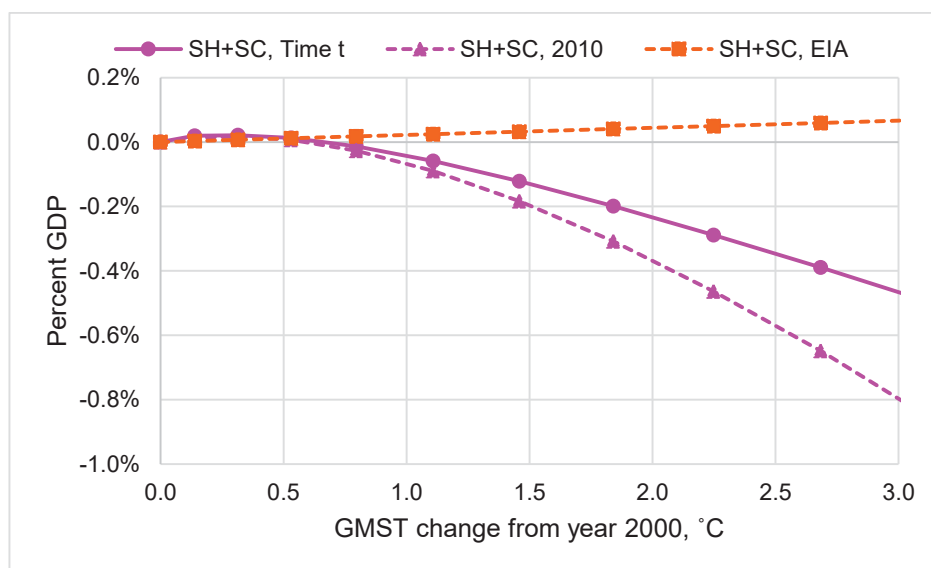

Figure 10: US energy expenditure economic impact as a function of GMST change, from 2000. Pink solid line is Julia FUND3.9 projection. Pink dashed line is the projection with time-dependent parameters, other than GMST change, held constant at their 2010 values. The orange dashed line is estimated from the EIA data.

The orange line is the trend calculated from EIA empirical data; the pink lines are the projections with the FUND3.9 impact functions. The pink solid line is Julia FUND3.9 projection with values for population, GDP, GDP per capita, and energy efficiency as a function of time. The pink dashed line is the projection with the time-dependent parameters held constant at their 2010 values; this is required for a fair comparison with the EIA data, which are from the 2009 and 2012 EIA surveys, and the 2010 US Census data. Figure 10 shows that the FUND projections are not consistent with the EIA empirical data.

Table 4 compares the FUND projections for the US with time-dependent parameters held constant at 2010 values, against the estimates from the EIA data. The projections are at 3°C GMST increase (relative to 2000).

Table 4: Economic impact of 3˚C GMST increase, from 2000, on US space heating and space cooling energy expenditure in residential and commercial buildings. Projections are with time-dependent parameters constant at 2010 values.

	Units	Heating	Cooling	Total
US GDP, 2010	US$ bn			15,318.74
SH + SC expenditure, FUND projection	US$ bn	-53.04	175.22	122.18
SH + SC expenditure, EIA data	US$ bn	-29.32	19.09	-10.24
GDP %, FUND projection	% GDP	0.35%	-1.14%	-0.80%
GDP %, EIA data, Res+Com	% GDP	0.19%	-0.12%	0.07%

Table 4 shows that the FUND energy impact functions, with time-dependent parameters constant at 2010 values, project the impact on the US economy would be -0.80% of GDP, whereas the analysis of the EIA empirical data finds +0.07%. These results are opposite in sign and the difference is 0.87% of GDP; that is, the FUND impact functions project that the impacts would be about twelve times worse than the empirical data indicates. The cooling component contributes most of the difference. These differences suggest the FUND energy impact functions may be mis-specified. Possible reasons for these differences are discussed in Section 4.5.

4.4 FUND projections for world regions

This section discusses the FUND projections of the regional economic impact of global warming on heating and cooling energy expenditure by latitude and by temperature. The economic impact results presented in this section are Julia FUND projections at 3˚C GMST increase. The population centroid latitude, RTCFs and temperature change data for each region are listed in Table 5 (FUND RTCF is at the area centroid).

Table 5: FUND RTCF, latitude of area and population centroids, RTCF at population centroid, and temperature change at the population centroid at 3˚C GMST increase, for each region.

Region	Code	RTCF FUND	Centroid latitude (˚) Area	Centroid latitude (˚) Pop.	RTCF at Pop. centroid	Temp. change (˚C)
USA	USA	1.1941	44.97	37.36	1.1173	3.35
Canada	CAN	1.4712	64.31	46.39	1.2902	3.87
Western Europe	WEU	1.1248	51.32	47.94	1.0907	3.27
Japan and South Korea	JPK	1.0555	36.21	35.88	1.0522	3.16
Australia and New Zealand	ANZ	0.9676	-27.46	-33.99	0.9017	2.71
Central and Eastern Europe	EEU	1.1676	47.18	47.77	1.1736	3.52
Former Soviet Union	FSU	1.2866	56.80	49.58	1.2136	3.64
Middle East	MDE	1.1546	28.49	32.35	1.1936	3.58
Central America	CAM	0.8804	20.99	18.87	0.8590	2.58
South America	SAM	0.8504	-13.39	-13.88	0.8454	2.54
South Asia	SAS	0.9074	23.63	23.61	0.9071	2.72
Southeast Asia	SEA	0.7098	5.48	6.03	0.7153	2.15
China plus	CHI	1.1847	36.56	32.33	1.1420	3.43
North Africa	NAF	1.1430	27.25	32.07	1.1917	3.57
Sub-Saharan Africa	SSA	0.8780	1.48	0.86	0.8717	2.62
Small Island States	SIS	0.7517	10.10	15.49	0.8062	2.42

Figure 11 shows that FUND projects the economic impact would be negative for all regions, except the Middle East, Japan-South Korea, and Australia-NZ; the largest negative impacts would occur in the North Africa and China plus regions.
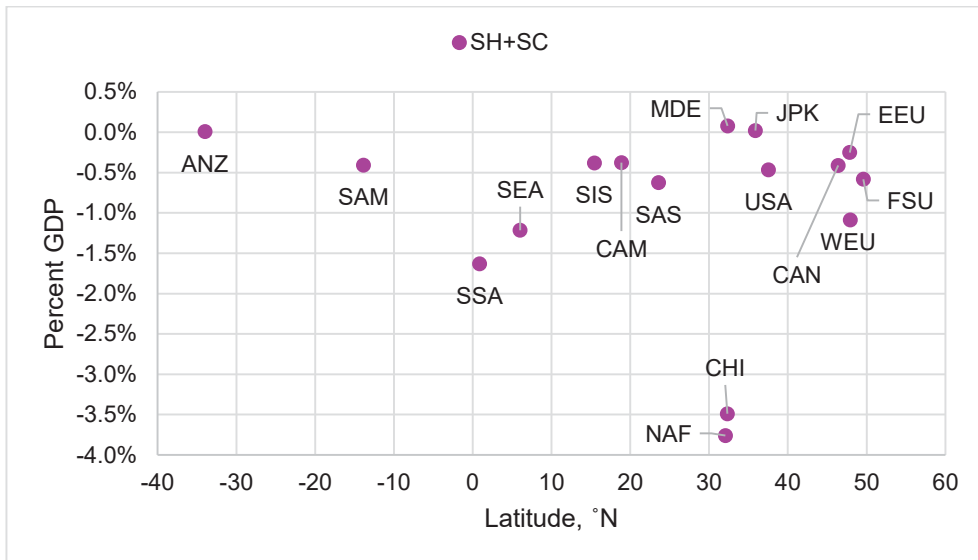

Figure 11: Economic impact of 3˚C GMST increase on energy expenditure for FUND regions, plotted against the latitude of the population centroid for each region.

Figure 12 separates the regional economic impacts shown in Figure 11, into their space heating and space cooling components.
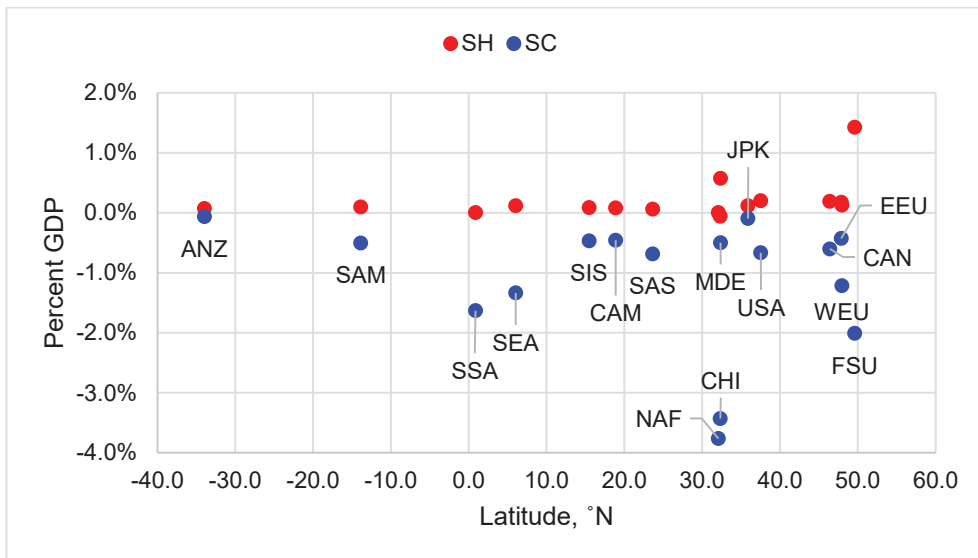

Figure 12: Data points in Figure 11 separated into space heating and space cooling components

Figure 12 shows that the projected negative impact of space cooling (expenditure increase) is substantially greater than the positive impact of space heating (expenditure decrease). Heating expenditures do not decrease significantly, even at high latitudes for

most regions, whereas space cooling expenditures increase significantly at all latitudes, for most regions. These trends are contrary to the trends shown by the EIA data for the US. This suggests the FUND energy impact functions may be mis-specified.

Figures 13 and 14 plot the percent of GDP data points in Figures 11 and 12 respectively against the temperature change, for a 3˚C GMST increase, at each region's population centroid.
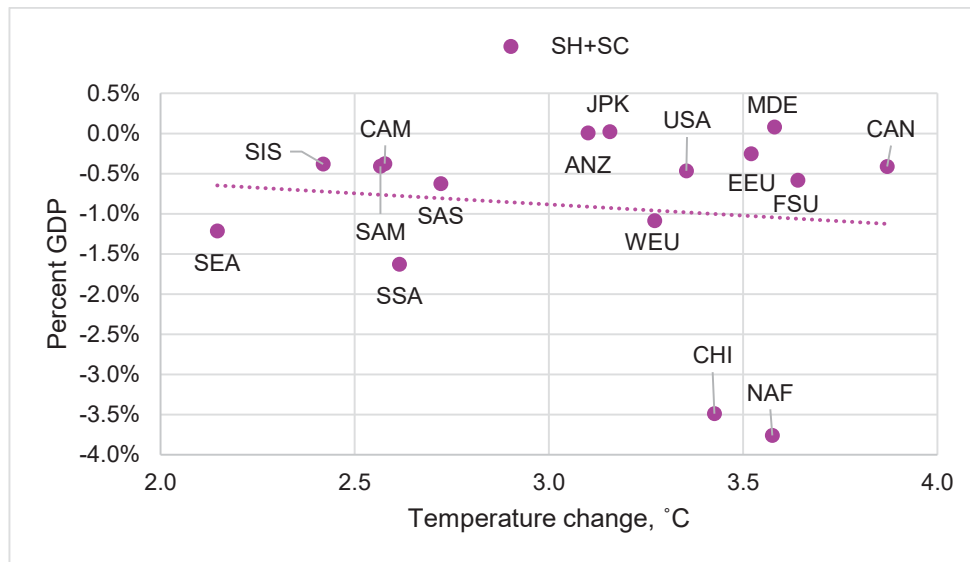

Figure 13: Economic impact of 3˚C GMST increase on energy expenditure for FUND regions, plotted against temperature change at the latitude of each region's population centroid.
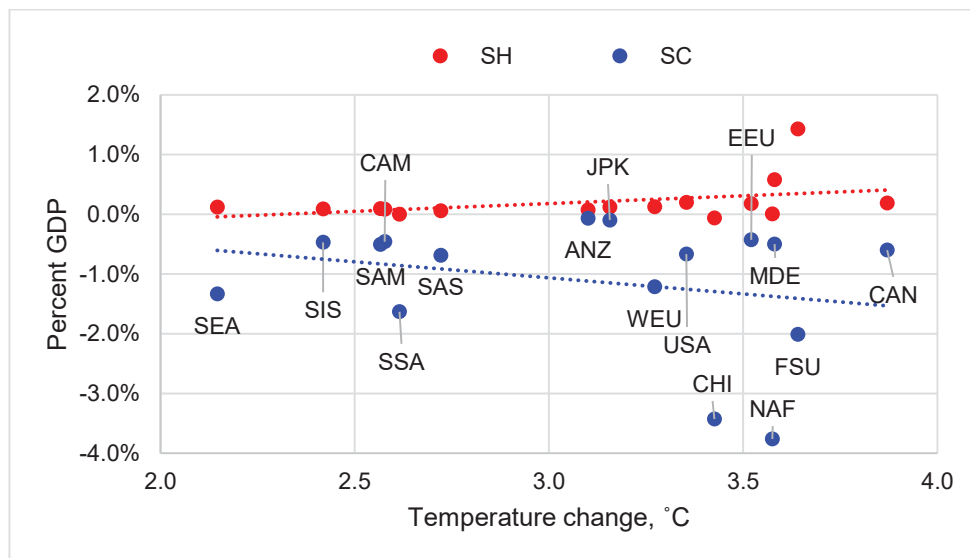

Figure 14: Data points in Figure 13 separated into space heating and space cooling components

The trendline in Figure 13 shows FUND projects the economic impact of warming on energy expenditure is negative, and the negative impact increases as temperature change increases. This is contrary to what the EIA data shows for the US (compare Figure 8)[4].

The trendlines in Figure 14 show FUND projects that the negative economic impact of warming on space cooling is greater than the positive impact on space heating. This too is contrary to the findings from the EIA empirical data for the US (see Figure 8).

4.5 Reasons for differences between FUND projections and EIA data

As noted above, Downing et al. (1996) [11] say heating demand is relatively income insensitive, whereas cooling demand can be very income sensitive at some stages of development. The differences between the cooling impacts found from the EIA data and those projected by the FUND energy impact functions, with time-dependent parameters held constant at 2010 values, might be because most of the projected increased cooling cost is due to increasing per capita income rather than to increasing temperature.

To test this, we compare the FUND projections of heating and cooling energy expenditure impacts for the USA and China plus (CHI) regions. These two regions are at different stages of development, having substantially different levels of income per capita, and income per capita growth rates. However, they have similar areas, and their population centroids are at similar latitudes. The projected increase in the average temperature of the two regions is also similar; for a 3°C GMST increase, they are 3.35°C for the US and 3.43°C for CHI (Table 5).

Given the similar geographic area, latitude band, and temperature response to GMST change, we might expect the economic impact, attributable to temperature change alone, would be similar in the two regions if they had similar per capita income levels and all else being equal.

Figures 15 and 16 compare the economic impact of heating and cooling energy expenditure in the US and CHI as a function of GMST change relative to 2000. Figure 15 is with time-dependent parameters as a function of time. Figure 16 is with time-dependent parameters, except GMST, held constant at their 2010 values. [5]

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[4] Note that Figure 8 is in units of expenditure change per capita whereas Figures 13 and 14 are in units of percent of GDP; positive expenditure change has a negative impact on GDP)

[5] Note that the y-axis scale in Figure 16 is four times that in Figure 15.
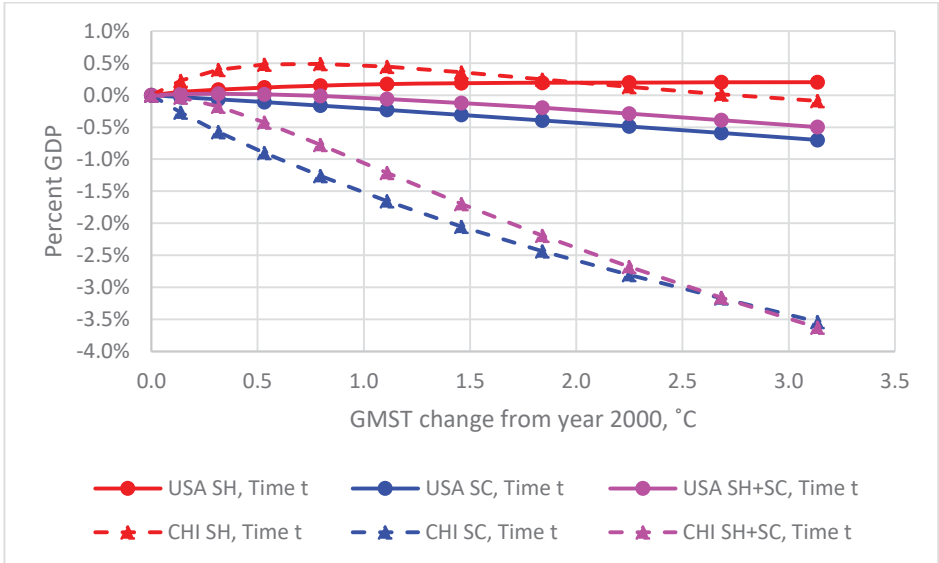
Figure 15: US and CHI, heating, cooling and total %GDP v GMST, change from 2000, with time-dependent parameters a function of time.
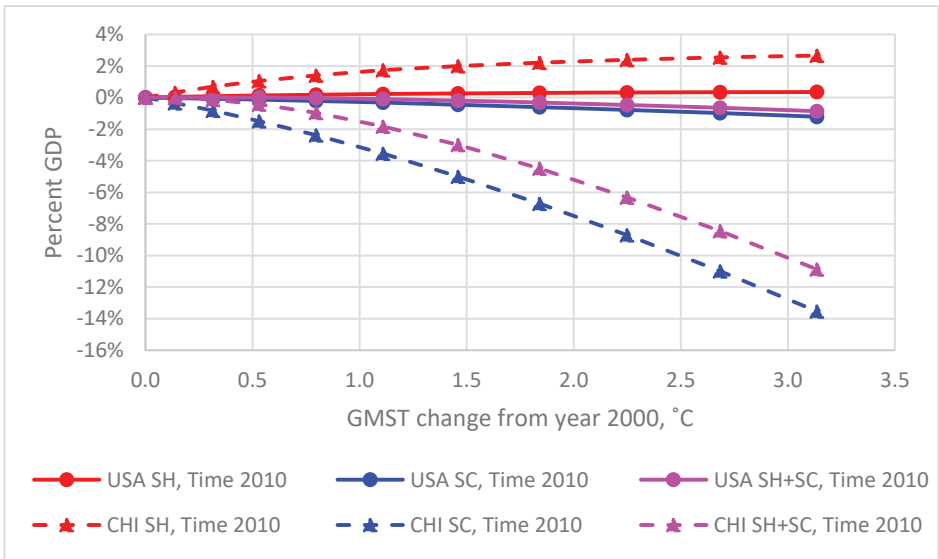

Figure 16: US and CHI, heating, cooling and total %GDP v GMST, change from 2000, with time-dependent parameters held constant at their 2010 values.

Table 6 summarises the values in Figures 15 and 16 at 3˚C GMST increase from 2000, and the ratios of the changes.

Table 6: USA and CHI economic impact (in percent GDP) of heating and cooling for a 3°C GMST increase from 2000, for two scenarios: time-dependent parameters are 1) a function of time, and 2) held constant at their 2010 values. Bottom rows are possible causative factors: factor change in per capita income, and parameters Alpha (heat) and Alpha (cool). The CHI/US ratio is in the last column.

	USA	CHI	CHI/USA
Time-dependent parameters as a function of time:			
SH, Time *t*	0.20%	-0.06%	-0.3
SC, Time *t*	-0.67%	-3.43%	5.1
SH+SC, Time *t*	-0.47%	-3.49%	7.5
Time-dependent parameters, except GMST change, held constant at 2010 values:			
SH, 2010	0.35%	2.63%	7.6
SC, 2010	-1.14%	-12.78%	11.2
SH+SC, 2010	-0.80%	-10.15%	12.7
Possible causative factors:			
Per capita income change (from 2000 to 2097):	3.65	17.05	4.7
Alpha (heat)	0.00429	0.03971	9.3
Alpha (cool)	-0.00212	-0.02891	13.6

Table 6 (top section) shows that, for a 3°C GMST increase, FUND projects that heating and cooling impacts would be substantially more negative in CHI than in the USA. Figure 15 and Table 6 show that FUND projects heating impacts in CHI would be negative. This means that FUND projects heating expenditure in CHI would increase, not decrease, as temperature increases. Clearly, the increase in heating expenditure projected by FUND is due to factors other than temperature increase. FUND projects the cooling impact increase is 5.1 times more in CHI than in the US, while per capita income increase is 4.7 times more in CHI than in the US. The 7.5 times greater increase in heating plus cooling impacts in CHI compared with the US might be due to the 4.7 times greater per capita income increase in CHI compared with the US, and the 9.3 and 13.6 times larger Alphas[6] [10], rather than to temperature changes.

Doing a similar comparison, with all time-dependent parameters except GMST change held constant at their 2010 values, enables us to investigate the projected impacts caused by temperature changes and adaptation only. The results of this comparison are shown in the middle section of Table 6. Contrary to expectation, for the same temperature increase, the heating impact is projected to be 7.6 times more and the cooling impact 11.2 times more in CHI than in the US. These differences are clearly due to factors other than temperature change.

In short, most of the differences between the projected impacts for CHI and the US may be due to differences in projected per capita income increases, and to the values of Alpha, rather than to temperature change.

Other causes of the differences may be inferred from the comparison of the FUND projections, and the EIA empirical data for the US. First, the EIA data does not support

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[6] Alpha is a parameter that relates temperature change to the space heating/cooling impact.

the substantial 'saturation' effect of heating energy expenditure projected by FUND. Figure 5 shows US residential energy expenditure per capita for heating is near linear over the range 6° to 22°C, and projects to $0 per capita at 24.4°C. Since there is little demand for heating in the tropics, the slope flattens at low latitudes. We infer that the slope flattens over the approximate range 22°C to 26°C. The term 'atan (T)/atan (1.0)' in the FUND heating impact equation appears to overestimate the saturation of the heating impact at average temperatures below about 22°C.

Second, the heating and cooling expenditure changes projected by the FUND impact equations are substantially more than the EIA data shows. Figure 17 plots the heating and cooling energy expenditure per capita derived from the EIA residential plus commercial buildings data (Figure 8) and compares these with the projections from the FUND energy impact equations for the US with time-dependent parameters held constant at 2010 values.
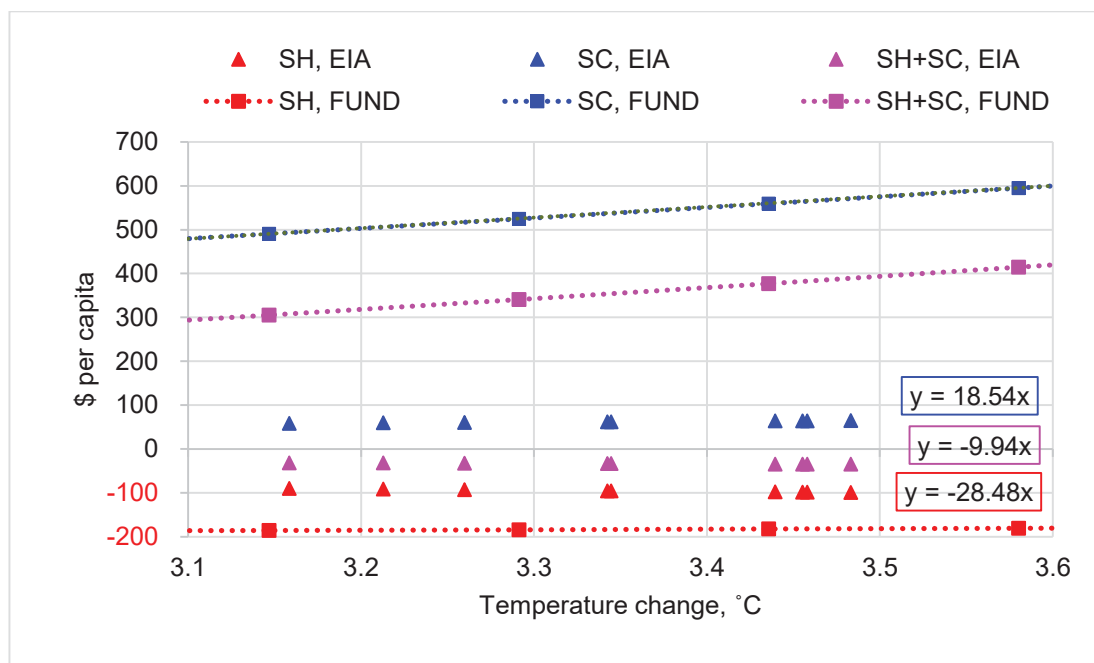

Figure 17: Impact of 3°C GMST increase on US space heating and space cooling energy expenditure per capita; from the analysis of the EIA data, and from the FUND energy impact equations with time-dependent parameters held constant at 2010 values.

The cooling expenditure increase projected by the FUND impact equations is about nine times more, and the heating expenditure decrease is about two times more, than the EIA data shows. A likely cause of the differences is attribution of most of the change to increasing per capita income rather than to temperature change, as discussed above.

It is worth noting that Figure 17 shows that FUND projects per capita heating savings decrease as temperature change increases, from $185 per capita per year at 3.15°C change to $180 at 3.58°C. This is not consistent with the EIA data, nor with expectation.

4.6 Suggested modifications to energy impact functions

Here we suggest a modified energy impact function for the linear regressions of the 2010 US data. It includes RTCF as a separate parameter and does not include per capita income change. The impact of temperature change on total US residential and commercial heating and cooling expenditure, with all time-dependent parameters except GMST held constant at their 2010 values, is given by the equation:

Impact (energy expenditure change, \$) = $\alpha \cdot T \cdot F \cdot P$

Where:

α (heat) = -28.48 (\$/capita/°C change at the population centroid)

α (cool) = 18.54 (\$/capita/°C change at the population centroid)

T = GMST change (from 2000)

F = RTCF (at the population centroid)

P = Population

α (heat) and α (cool) are the slopes of the EIA heating and cooling trendlines in Figure 17.

This energy impact equation and the parameter values are for the US only (population centroid latitudes 28° to 45°N). It needs to be generalised to be applicable for all regions, latitudes and projection periods.

We suggest:

- The FUND energy impact functions and parameters be updated using best available empirical evidence.

- RTCF be included as an explicit user-definable input parameter in the energy impact equations.

- FUND be modified to allow user input of parameters, including RTCF, so that users can test the calibration, and conduct sensitivity analyses, of the impacts of each of the parameters.

5 Conclusions

The analysis of the EIA heating and cooling energy data presented here finds that, contrary to the Tol (2013) and FUND3.9 projections, global warming would reduce US energy expenditure and, therefore, would have a positive impact on US economic growth. The analysis also finds that this conclusion may be valid for the impact of global warming on the regions that produced 84% of the world's GDP in 2010 and, therefore, on the world economy.

The significance of these findings for climate policy is substantial. If the sectoral economic impact projections, other than energy, in Tol (2013) and by FUND3.9 are correct, and the projected economic impact of energy should actually be near zero or positive, global warming of up to around 4˚C relative to 1900 would be economically beneficial, not detrimental.

In this case, the hypothesis that global warming would be harmful to the world economy this century is false, and policies to mitigate greenhouse gas emissions are not justified on an economically rational basis.

Our analysis and conclusions warrant further investigation.

Authors' contributions

Peter Lang designed the research, analysed the data, and wrote the paper. Ken Gregory interrogated Julia FUND3.9, and contributed to the data analysis and to writing the paper.

Acknowledgements

Abbreviations

˚C – Degree Celsius
CBECS – Commercial Buildings Energy Consumption Survey
CDD – Cooling degree- days
EEA – European Environment Agency
EIA – US Energy Information Administration
FUND – Climate Framework for Uncertainty, Negotiation and Distribution (FUND)
GCM – Global Climate Model
GDP – Gross Domestic Product

GMST – Global Mean Surface Temperature
HDD – Heating degree-days
IAM – Integrated Assessment Model
IEA – International Energy Agency
NAS – National Academies of Sciences, Engineering and Medicine
NOAA – National Oceanic and Atmosphere Administration
NRC – National Research Council
OECD – Organisation of Economic Cooperation and Development
PJ – Petajoule
RECS – Residential Energy Consumption Survey
RTCF – Regional Temperature Conversion Factor
RTE – Réseau de Transport d'Électricité
SH – Space heating
SC – Space cooling

Appendix A: Data plotted in Figures 3, 4, 5 and 7

Table A1: Space heating and space cooling energy expenditure per person, in 2010 US$, by US state and state group, for residential consumers, and the calculated latitude and average temperature of the population centroid for each.

State and state groups	Lat, ºN	Temp, ºC	Res. SH, $	Res. SC, $
Massachusetts	42.3	8.6	413	15
CT, ME, NH, RI, VT	42.5	7.3	483	17
New York	41.5	8.3	357	29
Pennsylvania	40.5	9.5	345	39
New Jersey	40.4	11.2	360	66
Illinois	41.3	9.8	247	39
Michigan	42.9	8.1	338	13
Wisconsin	43.7	6.5	290	11
Indiana, Ohio	40.3	10.4	277	30
Missouri	38.4	12.2	245	59
IA, MN, ND,SD	44.2	6.3	307	22
Kansas, Nebraska	39.5	10.7	234	50
Virginia	37.8	12.7	223	89
Georgia	33.4	16.9	160	114
Florida	27.8	22.3	61	211
DC, DE, MD, WV	39.1	11.3	271	62
North Carolina, South Carolina	35.0	15.6	192	90
Tennessee	35.8	14.3	187	81
Alabama, Kentucky, Mississippi	34.6	15.7	178	118
Texas	30.9	19.2	103	179
Arkansas, Louisiana, Oklahoma	33.5	16.9	160	101
Colorado	39.5	6.9	225	10
Idaho, Montana, Utah, Wyoming	42.7	7.0	181	19
Arizona	33.4	16.8	78	203
New Mexico, Nevada	36.0	12.0	140	98
California	35.5	16.2	73	36
Alaska, Hawaii, Oregon, Washington	44.5	11.7	182	12

Table A2: Space heating and space cooling energy expenditure per person, in 2010 US$, by US census region, for residential and commercial buildings, and the calculated latitude of the population centroid for each.

Census region	Lat, ºN	Res. SH, $	Res. SC, $	Com. SH, $	Com. SC, $
New England	42.4	451	16	154	33
Middle Atlantic	40.9	354	40	124	48
East North Central	41.6	283	27	75	36
West North Central	41.5	272	39	59	33
South Atlantic	33.5	161	128	40	88
East South Central	35.0	181	105	46	53
West South Central	31.7	121	155	35	84
Mountain	37.8	153	87	40	36
Pacific	37.8	100	30	33	43

Table A3: Latitude and 2009 temperature at the area and population centroids, and temperature change at the population centroids for a 3ºC GMST increase, by states and state groups.

US states and state groups	Area centroid		Pop. centroid		Temp change
	Lat ºN	Temp ºC	Lat ºN	Temp ºC	ºC
Massachusetts	42.16	8.72	42.27	8.63	3.48
CT, ME, NH, RI, VT	44.48	5.76	42.48	7.34	3.49
New York	42.91	7.22	41.50	8.34	3.46
Pennsylvania	40.90	9.11	40.46	9.46	3.42
New Jersey	40.11	11.50	40.43	11.24	3.42
Illinois	40.10	10.78	41.29	9.84	3.45
Michigan	44.84	6.56	42.87	8.11	3.50
Wisconsin	44.63	5.78	43.72	6.49	3.52
Indiana, Ohio	40.19	10.48	40.35	10.35	3.42
Missouri	38.35	12.22	38.42	12.16	3.36
IA, MN, ND,SD	45.28	5.51	44.24	6.33	3.54
Kansas, Nebraska	39.97	10.38	39.52	10.74	3.40
Virginia	37.52	12.89	37.81	12.66	3.34
Georgia	32.63	17.44	33.38	16.85	3.21
Florida	28.46	21.78	27.82	22.28	3.04
DC, DE, MD, WV	38.76	11.59	39.08	11.34	3.38
North Carolina, South Carolina	34.92	15.73	35.05	15.63	3.26
Tennessee	35.86	14.22	35.81	14.26	3.28
Alabama, Kentucky, Mississippi	34.09	16.11	34.63	15.68	3.25
Texas	31.43	18.78	30.91	19.20	3.13
Arkansas, Louisiana, Oklahoma	33.97	16.53	33.51	16.90	3.21
Colorado	38.99	7.33	39.51	6.92	3.40
Idaho, Montana, Utah, Wyoming	43.95	6.05	42.71	7.03	3.49
Arizona	34.21	16.17	33.37	16.83	3.21
New Mexico, Nevada	36.77	11.36	36.00	11.96	3.29
California	37.15	14.89	35.46	16.22	3.27
Alaska, Hawaii, Oregon, Washington	59.19	0.06	44.51	11.67	3.55

Table A4: Latitude and 2012 temperature at the area and population centroids, and temperature change at the population centroids for a 3ºC GMST increase, by census division.

US census divisions	Area centroid		Pop. centroid		Temp change
	Lat ºN	Temp ºC	Lat ºN	Temp ºC	ºC
New England	44.14	8.02	42.39	9.35	3.48
Middle Atlantic	41.84	10.35	40.95	11.03	3.44
East North Central	42.63	10.69	41.56	11.51	3.46
West North Central	42.72	10.75	41.47	11.71	3.46
South Atlantic	33.90	17.48	33.49	17.79	3.21
East South Central	34.50	17.01	35.04	16.60	3.26
West South Central	32.44	19.27	31.71	19.82	3.16
Mountain	40.14	10.35	37.83	12.10	3.34
Pacific	55.61	1.74	37.75	15.29	3.34

Appendix B: Regression results and data issues

A linear model provides near the best fit over the range of latitudes and temperatures spanned by the data points for the USA; other models showed some slight improvements in fit for some regressions, but not sufficient to warrant substituting more complicated models. Table B.1 summarises the results of regression analyses of Table 5 (RTCF versus latitude for the area centroids of the 16 FUND regions), and the figures with regressions.

Table B.1: Summary of the regression analyses results

		slope	intercept	df	2-sided p-value
Table 5	RTCF v area centroid latitude	0.0101	0.7316	14	1.1E-06
Figure 3	SH ($/person) v latitude	18.00	-457.94	25	9.7E-06
	SC ($/person) v latitude	-12.03	529.13	25	1.2E-10
Figure 4	Present temp v latitude	-0.91	47.14	25	2.7E-13
	Temp at +3ºC GMST v latitude	-0.88	49.33	25	5.8E-13
Figure 5	SH $/person v present temp	-18.88	460.48	25	7.8E-06
	SC $/person v present temp	11.96	-76.57	25	1.7E-09
Figure 6	SH $/person v temp change	-19.69	0.00		
	SC $/person v temp change	13.16	0.00		
	SH+SC ($/person) v temp change	-6.54	0.00		
Figure 7	Res. SH ($/person) v present temp.	23.54	-664.42	7	1.3E-02
	Res. SC ($/person) v present temp.	-12.18	532.94	7	1.5E-04
	Com. SH ($/person) v present temp.	7.77	-228.12	7	3.5E-02
	Com SC ($/person) v present temp	-4.76	231.20	7	2.4E-03
Figure 8	Res. SH $/person v temp change	-19.69	0.00		
	Res. SC $/person v temp change	13.16	0.00		
	Com. SH $/person v temp change	-8.79	0.00		
	Com. SC $/person v temp change	5.38	0.00		
	Res+Com SH $/pers v temp change	-28.48	0.00		
	Res+Com SC $/pers v temp change	18.54	0.00		
	Res+Com SH+SC $/pers v temp chg	-9.94	0.00		
Figure 13	SH+SC %GDP v temp change	-0.0028	0.0059	14	8.3E-01
Figure 14	SH %GDP v temp change	0.0026	0.0017	14	3.3E-02
	SC %GDP v temp change	-0.0054	0.0055	14	3.6E-01
Figure 17	SH, EIA $/person v temp change	-28.48	0.00		
	SC, EIA $/person v temp change	18.54	0.00		
	SH+SC, EIA $/person v temp change	-9.94	0.00		
	SH, FUND $/person v temp change	11.24	-220.63	4	4.3E-06
	SC, FUND $/person v temp change	241.52	-269.48	4	2.3E-08
	SH+SC, FUND $/pers v temp change	252.76	-490.11	4	3.6E-08

The slopes of the linear regressions of the residential expenditure data (Figures 3, 4 and 5) are significant at the 1% level, and of the commercial buildings data (Figure 7) space cooling at the 1% level and space heating at the 5% level. The negative intercept for heating in Figures 3, 5 and 7, and the $0 expenditure for cooling below 6.4˚C, are explained after Figure 5.

The slopes of the linear regressions in Figures 13 and 14 are not significantly different from zero. However, they are not used in any calculations; the regression lines are shown on the charts for illustrative purposes.

The slopes of the linear regressions of the FUND projections in Figure 17 are highly significant over the range 3.0° to 3.7°C of temperature change.

Explanation of increasing residuals with decreasing temperature

Figures 3, 5 and 7 show that the magnitude (absolute value) of residuals increase as temperature decreases. These are due to a number of causes, including: climate effects (relatively colder winters and nights in continental and mountain climates than in coastal climates, at similar average annual temperature), and differences in proportions and prices of fuels (electricity, natural gas, propane/LPG, and heating oil) used for heating in different states.

Figure B.1 plots residential per capita heating expenditure by fuel and 2009 average temperature, by state and state group. Expenditure is at 2009 state average fuel prices.
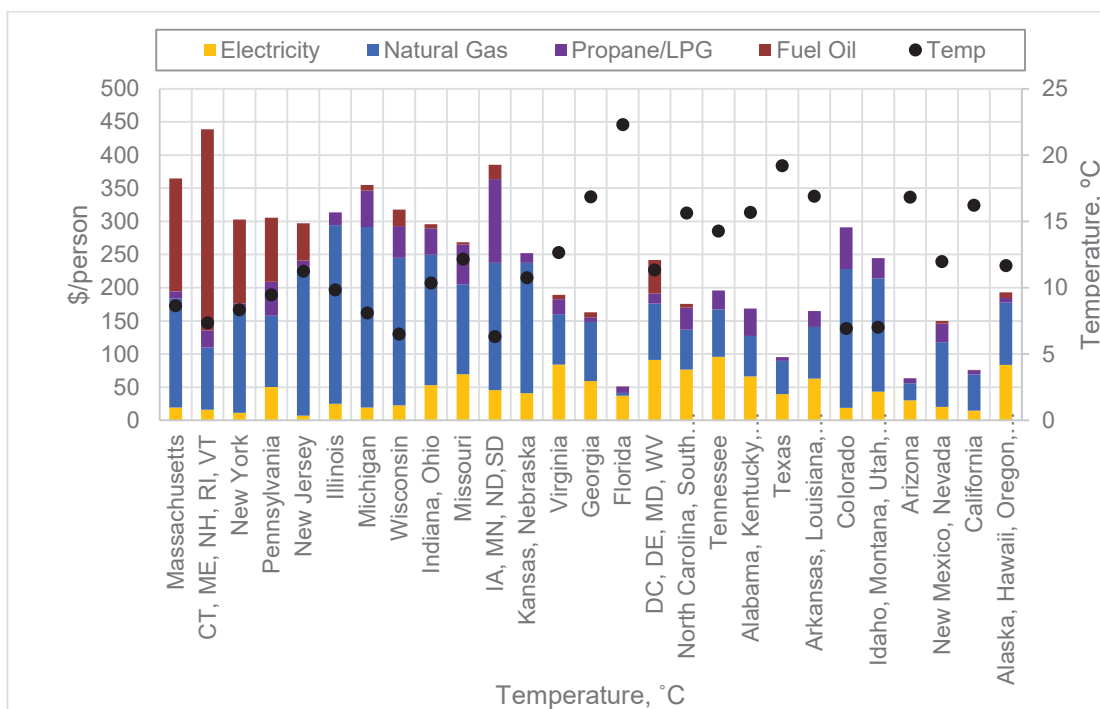

Figure B.1: Residential per capita heating expenditure by fuel, and 2009 temperature, by state.

Figure B.2 plots residential per capita heating expenditure by fuel against 2009 temperature.
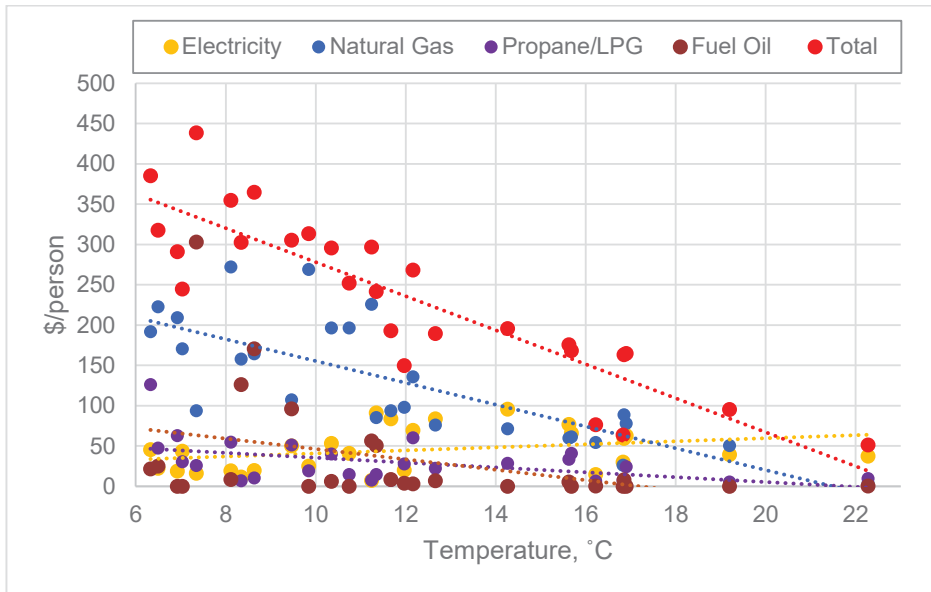
Figure B.2: Residential per capita heating expenditure, at state fuel prices, against temperature.

We test the magnitude of the effects of different fuel proportions and prices by:
- substituting natural gas prices for propane/LPG and fuel oil prices – this removes the effect of different proportions of these fuels being used in different states.
- substituting US average prices for state prices – this removes the effect of fuel price differences between states.

The test results are numbered 1 to 4 in Table B.2. The projections with time-dependent parameters held constant at 2010 values, and the impacts calculated from the EIA data, and summarised in Table 2, are included for comparison.

Table B.2: Comparison of the effect of different fuel consumption proportions and fuel prices in different states on the economic impact of 3°C GMST increase, relative to 2000, on US space-heating and space cooling energy consumption. The projections are included for comparison.

	Economic impact (US $bn)		
Expenditure data sources and calculations	**Heating**	**Cooling**	**Total**
Projections (relative to 2000)	-53.04	175.22	122.18
As per Table 2	-29.32	19.09	-10.24
1. Consumption x fuel prices, fuels at state fuel prices	-29.21	19.09	-10.12
2. All fuels at US average prices	-30.27	21.00	-9.27
3. Propane/LPG and heating oil at state natural gas prices	-24.27	19.09	-5.18
4. Electricity at US average price, propane/LPG and heating oil at US average natural gas price	-24.33	21.00	-3.32
	Economic impact (% GDP)		
Expenditure data sources and calculations	**Heating**	**Cooling**	**Total**
Projections (relative to 2000)	0.35%	-1.14%	-0.80%
As per Table 2	0.19%	-0.12%	0.07%
1. Consumption x fuel prices, fuels at state fuel prices	0.19%	-0.12%	0.07%
2. All fuels at US average prices	0.20%	-0.14%	0.06%
3. Propane/LPG and heating oil at state natural gas prices	0.16%	-0.12%	0.07%
4. Electricity at US average price, propane/LPG and heating oil at US average natural gas price	0.16%	-0.14%	0.02%

The total impacts calculated using the different fuel consumption proportions and prices are opposite in sign to the projections with time-dependent parameters constant at 2010 values. The difference, relative to the results from the empirical data, is about a factor of 12.

Data deficiencies

There are deficiencies in the EIA consumption and fuel price data, which we have attempted to compensate for by our calculations.

- Some fuel price and consumption data are not included in the tables. We have compensated by infilling missing data by differences and proportions from the available data.

- There are as few as one significant figure for some consumption data for some fuels in some states, state groups and divisions, which increases uncertainty. Since fuel prices are calculated from total expenditure and total consumption per fuel, fuel prices are also uncertain. We have partly compensated by using fuel prices per physical units which have more significant figures.

Fuel prices for commercial buildings are not provided by use category, such as for space heating and space cooling. The prices are the average per fuel for all uses, including water heating, refrigeration, computers, etc. The actual prices of fuels for heating and cooling (electricity, natural gas, fuel oil and district heat) may be higher or lower than the average.

The commercial buildings expenditures may be understated because the fuel prices are full-year averages, which are generally below the winter prices for heating fuels and the summer prices for cooling energy (electricity).

The residential expenditures for tests 1 to 4 in Table B.2, are also calculated from fuel prices and consumption data, which are incomplete; we have partly compensated as we have done for the commercial buildings data.

Other sources of uncertainty

A source of uncertainty in the US energy expenditure versus temperature analyses is the RTCF at the population centroid of each US state. We do not have these data. We estimated the RTCF at the population centroids by applying the slope of RTCF of the world regions against their area centroid latitudes to the difference between the latitudes of the area and population centroids of each US state and census division. Residential impacts at 3°C GMST increase differ by 18% when calculated by state and state group or by region. We interpret this as being due to differences between the slope of RTCF

against latitude for US states and census divisions compared with the average slope of RTCF versus latitude for all world regions. The difference may also be attributed to differences between slopes of different states and divisions within the US.

Another potential source of uncertainty is the temperature at the population centroid of each state. We estimated these by applying the slope of temperature against area centroid latitudes of all US states to the difference in latitude of the area and population centroids of each state. This assumes the same slope applies to all states, which ignores influences such as distance from oceans and large water bodies, altitude, etc.

The residential data is for year 2009 and the commercial data is for year 2012. Average temperatures were higher in 2012 than in 2009, and fuel prices were different. Thus, adding uncertainty to the calculated impacts for residential and commercial buildings.

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