# Effects of long-term climate change on global building energy expenditures

Leon Clarke [a,*], Jiyong Eom [a,1], Elke Hodson Marten [b], Russell Horowitz [a], Page Kyle [a],
Robert Link [a], Bryan K. Mignone [c], Anupriya Mundra [a,2], Yuyu Zhou [a,3]

[a] Joint Global Change Research Institute and Pacific Northwest National Laboratory, College Park, MD 20740, United States
[b] U.S. Department of Energy, Office of Energy Policy and Systems Analysis, Washington, DC 20585, United States
[c] ExxonMobil Research and Engineering Company, Annandale, NJ 08801, United States

## ARTICLE INFO

## ABSTRACT

This paper explores potential future implications of climate change on building energy expenditures around the globe. Increasing expenditures result from increased electricity use for cooling, and are offset to varying degrees, depending on the region, by decreased energy consumption for heating. The analysis is conducted using a model of the global buildings sector within the GCAM integrated assessment model. The integrated assessment framework is valuable because it represents socioeconomic and energy system changes that will be important for understanding building energy expenditures in the future. Results indicate that changes in net expenditures are not uniform across the globe. Net expenditures decrease in some regions, such as Canada and Russia, where heating demands currently dominate, and increase the most in areas with less demand for space heating and greater demand for space cooling. We explain these results in terms of the basic drivers that link building energy expenditures to regional climate.
© 2018 Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

Climate change will primarily affect building energy consumption through changes in heating and cooling demands. These changes will also alter the mix of fuels used in buildings, increasing the use of electricity for cooling while decreasing the use of natural gas and other fuels used for heating. These changes, in turn, will alter the amount of money that individuals and businesses spend to heat and cool their buildings, with the net effect depending on whether the increase in cooling expenditures outweighs the decrease in heating expenditures, or vice versa. This research explores the potential impact of climate change on building energy expenditures and energy consumption at global and regional levels over the 21st century.

The existing literature on this subject has generally adopted one of two approaches. One group of studies has employed statistical or econometric relationships between major climate variables—most commonly, the statistics of temperatures—and energy demand. This group includes studies exploring future demand for electricity and heating fuels in Massachusetts (Amato et al., 2005), electricity consumption in eight

U.S. states (Sailor, 2001), cooling energy demand in 12 U.S. cities (Sailor and Pavlova, 2003), total building energy consumption in five Chinese cities (Wan et al., 2011), heating and cooling energy demand in Greece (Cartalis et al., 2001), and heating and cooling energy demands and energy expenditures in various U.S. locations (Rosenthal et al., 1995). Additional studies using econometric approaches include research on the impacts of climate change on fuel choice, energy consumption, and energy expenditures in the U.S. (Mansur et al., 2008), on electricity demand in Europe (Eskeland and Mideksa, 2009), on the constant utility cost of living in 88 different countries based on a household production function framework (Maddison, 2003), and on the value of amenities in more than two thousand U.S. regions based on a hedonic method (Albouy et al., 2013).

This general approach based on historical data in a given region or set of regions is limited in its ability to explore the implications of longer-term socioeconomic and energy system transformation. Representation of such transformation is particularly important for emerging economies because continued income growth may lead to very different patterns of building energy consumption than those observed in historical data. For example, space cooling currently accounts for a much lower share of building energy consumption than space heating (Zhou et al., 2013), and increasing urbanization may lead to a sizeable shift in the building energy mix away from traditional fuels (Eom et al., 2012b; Krey et al., 2012).

Due to these limitations, a second approach attempts to incorporate the implications of longer-term transformation by employing building-

---

* Corresponding author.
  E-mail address: leon.clarke@pnnl.gov (L. Clarke).
[1] Eom is currently affiliated with Korea Advanced Institute of Science and Technology (KAIST).
[2] Mundra is currently affiliated with Columbia University.
[3] Zhou is currently affiliated with the Department of Geological and Atmospheric Sciences, Iowa State University.

specific energy simulation models of varying levels of detail. Isaac and van Vuuren (2009) assessed global energy consumption for residential heating and air conditioning under climate change using a saturation model for heating intensity and air conditioners. Zhou et al. (2013) explored the effects of various climate scenarios on building energy demands in China and the U.S. within the GCAM integrated assessment framework (Edmonds et al., 2004). Several energy modeling studies have been conducted for developed economies as well. Scott et al. (2007) provided estimates of the impacts of climate change on U.S. building energy consumption and associated energy expenditures and their interaction with buildings energy-efficiency programs, based on a detailed representation of all U.S. building types and stock nested in two linked models. Hadley et al. (2006) projected changes in U.S. energy demand based on a modified version of the National Energy Modeling System (NEMS). Olonscheck et al. (2011) analyzed the combined effect of future changes in climate, building stock, renovation measures, and heating energy systems on residential energy demand in Germany based on a simple building energy system model.

This paper builds on this second approach in three ways. First, the study assesses building impacts at a global level, providing an alternate perspective to Isaac and van Vuuren (2009). Second, it does so using a detailed, service-based building energy model nested within a state-of-the-art integrated assessment model (GCAM) (Edmonds and Reilly, 1985; Edmonds et al., 2004). The nested model is thus capable of representing the evolution of the global building energy system within the context of socioeconomic development, technological change, and climate change, providing a consistent assessment framework. Our building energy model extends the regional energy models developed by Eom et al. (2012a, 2012b) and Zhou et al. (2013) to the global level. Finally, the focus of this study differs from previous efforts using simulation models in that it is specifically addressed at understanding and unpacking impacts on building energy expenditures and how these may vary over time and across regions.

The remainder of the paper is structured as follows. Section 2 presents the core structure of the buildings model and discusses other methodological issues associated with the scenarios in this paper. Section 3 discusses key results regarding the effect of climate change on building energy expenditures. Section 4 provides concluding remarks.

## 2. Methodology

### 2.1. The global change assessment model

Assessing the combined impacts of socioeconomic changes, technological changes, climate change, and other factors on the global buildings sector requires an internally consistent framework that can account for these factors simultaneously. For this reason, the global building energy model used in this study has been constructed within the Global Change Assessment Model (GCAM).[4] GCAM is a dynamic-recursive market equilibrium model. It combines models of the global energy system (Edmonds et al., 2004), global land use (Wise and Calvin, 2011), and a reduced-form representation of the carbon cycle and climate (Hartin et al., 2015). GCAM represents supplies of and demands for energy and agricultural products in each of 32 geopolitical regions, aggregated post-hoc in this study to 12 aggregate regions in order to facilitate inter-regional comparisons (see Supplementary Material section 1). Demands are linked to region-specific assumptions of population growth, labor participation rates, and labor productivity growth. Other important inputs include technology cost

and performance information, fossil and other resource information, and climate or other policies. The model is solved by finding a set of prices in all markets at which supplies match demands. For this study, GCAM is run in five-year time steps from 2010 to 2100.

A distinctive feature of GCAM relevant for this study is the logit specification used to determine market shares of technologies, notably heating and cooling technologies (Clarke and Edmonds, 1993). The logit approach has a long history in the economics of decision-making (McFadden, 1980; Train, 1993). It is used to represent decision-making among competing options when only some characteristics of the options can be observed or modeled. A key feature of this approach is that not all decision-makers will choose the same technology option simply because the average price is lower than all competing technologies; even higher-priced options may take some market share due to price heterogeneity and unobserved factors. Because of the logit specification, GCAM does not exhibit "winner-take-all" behavior in technology choice.

### 2.2. Modeling global building energy consumption and expenditures in GCAM

This study builds on the technologically-detailed, service-based building energy modeling approach implemented previously for China, India, and the U.S. in GCAM (Eom et al., 2012b; Chaturvedi et al., 2013; Zhou et al., 2013), simplifying its detail and applying it to all regions (Fig. 1). The basic structure of the model can be understood by reading Fig. 1 from left to right. Underlying socioeconomic drivers – population and income – drive the demand for floorspace in representative residential and commercial buildings in each of GCAM's 32 regions. There are three types of energy service demands associated with this floorspace: space heating, space cooling, and "other" services, which includes services such as appliances, lighting, and water heating. The change in demand for these per unit of floorspace is related to the change in affordability of the energy services (the ratio of per capita income to the price of the service) and to heating and cooling degree days. The latter dependence allows the model to represent the impact of climate change on service demands (Eom et al., 2012b), and hence on energy expenditures. Services can be provided by several end use technologies using a variety of different fuels, depending on the type of technology (see Supplementary Material Section 4).

This paper focuses on the effect of climate change on per capita expenditures for space heating and cooling in buildings ($E_H$ and $E_C$). In the modeling framework used for this study, per capita building expenditures for heating and cooling are the product of the price of these services ($P_H$, $Pc$) and the per-capita consumption of these services ($D_H$, $D_C$). Note that service prices include fuel costs as well as levelized equipment capital costs, and fixed and variable non-fuel operating and maintenance costs. For convenience, it is useful to decompose total per capita consumption of services into floorspace per capita ($f$) and consumption per unit of floorspace ($d_H$, $d_C$). This leads to the fundamental equations for determining expenditures in the model:

$$E_H = D_H P_H = f d_H P_H \tag{1}$$

$$E_C = D_C P_C = f d_C P_C \tag{2}$$

The remainder of this subsection discusses each of the three terms on the right side of Eqs. (1) and (2). For this study, we assume that per capita floorspace rises with per capita income toward a pre-specified level for every region. (See Supplementary Material section 5; all scenarios in this study have the same future floorspace trajectories for a given region and sector.)

For this study, consumption of heating and cooling services per unit of floorspace is based on the demand expression proposed by Eom

---

[4] As a full global integrated assessment model, it is not possible to fully document GCAM in this paper. However, extensive documentation on GCAM can be found at http://www.globalchange.umd.edu/models/gcam/. A copy of the model can also be downloaded from this website.
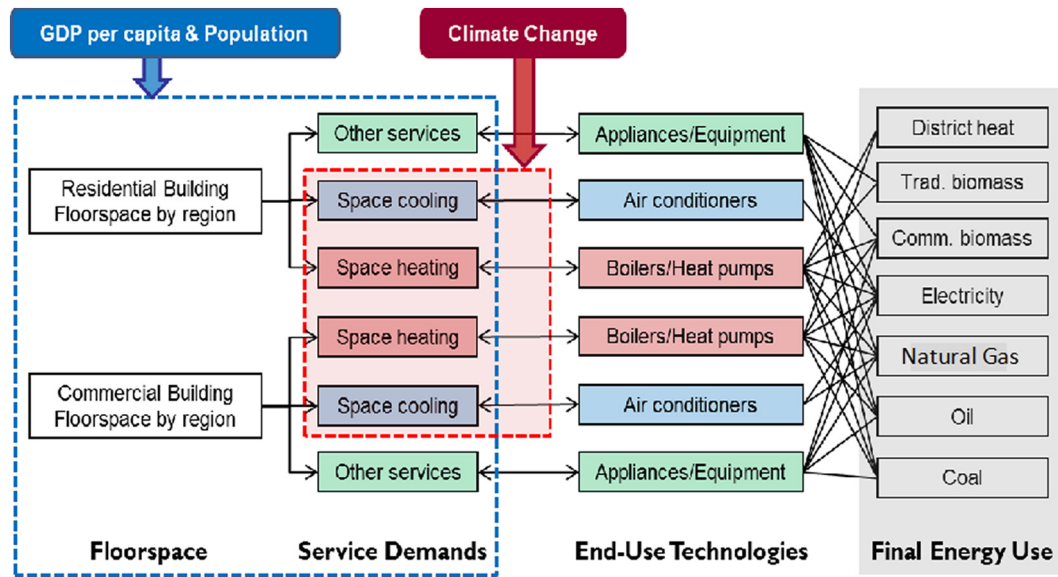
**Fig. 1.** The structure of energy demand and supply in the buildings energy model used for all GCAM regions.

et al. (2012a, 2012b). Consumers demand more energy services as the services become more affordable, until energy service "satiation" is reached. Specifically, the demands for heating and cooling services per unit of floorspace [GJ-out/m$^2$] are given as follows:

$$d_H = k_H(HDD \cdot \eta \cdot R - IG)\left[1 - exp\left(-\frac{\ln 2}{\mu_H}\frac{i}{P_H}\right)\right] \quad (3)$$

$$d_C = k_C(CDD \cdot \eta \cdot R + IG)\left[1 - exp\left(-\frac{\ln 2}{\mu_C}\frac{i}{P_C}\right)\right] \quad (4)$$

Working from left to right, the demand for energy services per unit of floorspace consists of three parts. (Note that we will utilize an approximation of this formulation when we decompose the results into component terms in the next section.) First, $k_i$ is a unitless calibration coefficient. Second, the terms in parentheses are the satiated levels of heating and cooling services—that is, services required to maintain a reference indoor temperature year round. $HDD$ and $CDD$ are heating and cooling degree days [units of day °C], respectively. Annual HDDs (CDDs) measure the amount that the temperature was below (above) a given balance point (18 °C in this study) and for how long.[5] Hence, climate change affects heating and cooling service demands through changes in $HDD$ and $CDD$. $\eta$ represents the thermal conductance (or U-factor) of the building envelope as a whole [GJ/m$^2$ day °C], and $R$ is the unitless average surface-to-floor area ratio that translates floorspace into the total surface of a building that is in contact with the ambient atmosphere. $IG$ is the internal gain [GJ/m$^2$] from heat released by equipment operating in the building, calculated endogenously in the model based on the demand for other building services.

The third term, in brackets, captures the effects of price and income on behavior. This term indicates the fraction of the satiated demand that is actually met, which increases with the affordability of the services, $i/P_H$ and $i/P_C$— where $i$ is per-capita income. The parameter $\mu_i$, determines the degree of demand satiation given a particular level of affordability of the service. It captures region- and sector-specific behavior of demand satiation. Regions with different preferences may exhibit varying service levels even under the same economic and climate conditions, as determined by calibration.[6]

The total price of providing each service is constructed from the cost of providing the service from each of the individual technologies that are used to provide the service. For example, multiple technologies can provide heating services. Each technology is characterized by its own capital and operating costs, efficiencies, and fuel requirements. These vary among technologies, leading to different costs for providing heating and cooling services using different technologies. This means that the prices for heating and cooling are a weighted average of the costs from all heating and cooling technologies, or.

$$P_H = \frac{\sum_j P_{H,j} d_{H,j}}{d_H} \quad (5)$$

$$P_C = \frac{\sum_j P_{C,j} d_{C,j}}{d_C} \quad (6)$$

where $j$ represents the different technologies that can provide the service.

### 2.3. Scenarios explored in this study

This study develops three different scenarios to explore the impacts of climate change on building energy service demands and expenditures (Table 1). The 4.5 Climate Scenario uses spatially explicit gridded temperature profiles from the Community Earth System Model (CESM) run fulfilling the RCP 4.5 concentration pathway, and the 8.5 Climate Scenario uses the same information from the CESM model run fulfilling the RCP 8.5 concentration pathway (Meehl et al., 2006). CESM was one of several models that contributed to the 5th Coupled Model

---

[5] HDD (CCD) can be viewed as the integral over all the times that temperature is below (above) the balance point over a full year. In this study, a standard simplification was used in which HDD and CDD were calculated on a daily basis, using average daily temperatures.

[6] See the Supplementary Material section 6 for information on calibration procedures.

**Table 1**
Overview of scenarios in this study.

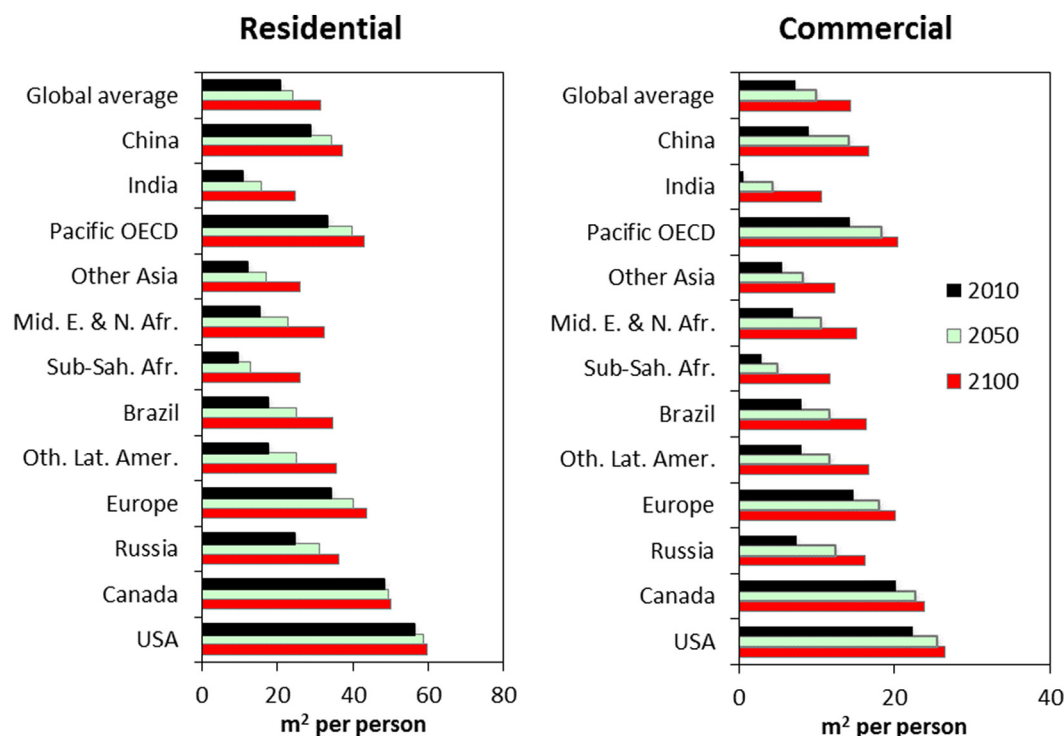| Scenario name | Climate assumption |
|---|---|
| Fixed climate | Today's climate – no change over time |
| 4.5 climate | Climate change associated with an RCP 4.5 Wm$^{-2}$ pathway |
| 8.5 climate | Climate change associated with an RCP 8.5 Wm$^{-2}$ pathway |

**Fig. 2.** Building per-capita floorspace (f) by region.

Intercomparison Project (CMIP5).[7] The names "4.5" and "8.5" refer to the radiative forcing levels in 2100 in Wm$^{-2}$. The Fixed Climate Scenario assumes that there is no change in HDD/CDD from today in order to provide a counterfactual reference case against which to compare the other scenarios.

To reflect the impact of climate change on heating and cooling requirements associated with these three scenarios, heating and cooling degree days (HDD/CDDs) were estimated at the grid level and then aggregated to GCAM regions for each of the three climate scenarios. Country-, region-, and macro-region-level HDD and CDD are population-weighted, as detailed by Zhou et al. (Zhou et al., 2013), but assume a static sub-national population distribution over time.

To facilitate the discussion of results, we focus primarily on the difference between the 8.5 Climate Scenario and the Fixed Climate Scenario, quantifying the impact of climate change on space heating and cooling demands and expenditures in a world with comparatively high greenhouse gas emissions. This choice also allows us to understand the impact on net building energy expenditures as a function of temperature across a wider domain of potential temperature change. Note that none of the scenarios includes changes in the energy system that would result from policies to reduce greenhouse gas emissions, because the purpose of this study is to quantify the potential effects of climate change on global building energy service demand and expenditures, all else equal. As such, the specification of these scenarios only differs in the way that climate change affects building energy service demands.

Due to the importance of baseline levels of air conditioning utilization for the study results, we also supplement these three core scenarios with sensitivity scenarios of low and high cooling service demand. Implementation details and results from these scenarios are documented in the Supplementary Material section 9.

# 3. Results

## 3.1. Fixed climate scenario

Any future scenario must ultimately be constructed by making assumptions about a wide range of uncertain factors. Following a common approach for scenario-based analyses, we posit a set of driving factors and then use the resulting "reference scenario" as a baseline from which to start impact assessments. For this study, our reference scenario is the Fixed Climate Scenario. It is based on the core set of socio-economic and technological assumptions used throughout the analysis, and it also assumes that there is no change in country-level heating and cooling degree days from 2010 to 2100. This is a counterfactual scenario in the sense that even the lowest plausible scenarios are projected to experience increases in global average surface temperatures over this time interval. However, this scenario is useful as a benchmark against which other scenarios can be compared.

### 3.1.1. Core drivers: population, economic growth, and technology

Among the most important drivers of the baseline scenario are assumptions about fundamental socioeconomic trends – roughly captured in the representation of population and per capita income – along with the characteristics and improvement of building technologies. Global population and per-capita income are input assumptions to the scenarios employed in this study, and they are the same across all the scenarios (see the Supplementary Material section 3). The population and GDP assumptions follow the Shared Socioeconomic Pathways (SSPs), and SSP2 in particular (Fricko et al., 2016).[8] Global population is assumed to peak in 2070 and then decline to about 9 billion people by the end of the century, with the growth occurring mostly in a subset of the developing regions. This falls within the range of current estimates in the integrated assessment community as surveyed by the IPCC, and it

---

[7] We compared CESM output to 12 other models that participated in CMIP5. The temperature response in CESM was close to the ensemble mean for both the RCP 4.5 and RCP 8.5 scenarios. The realized temperature changes in CESM in 2050 and 2100 (compared to the 1850–1870 average) were 2.05 and 2.87 degrees C, respectively, under RCP 4.5, and 2.59 and 4.97 degrees C, respectively under RCP 8.5.

[8] We use the terms GDP and income interchangeably in this paper.

sits slightly below the U.N. median estimate (Clarke et al., 2014). Population remains nearly unchanged in the currently industrialized regions.

Global economic growth is substantial, reflecting an optimistic outlook in which the developed regions continue to grow at roughly historical rates. Income per capita in the developing regions slowly converges toward the developed region level. This means that the weight of economic output shifts toward the developing regions in this scenario, with implications for where the largest total building energy demands will be.

Building technologies are assumed to improve over time in the scenarios in this study (see the Supplementary Material section 4). Improvements to building shell efficiencies reduce the heating and cooling required to keep buildings at any particular temperature, while improvements in heating and cooling equipment decrease the energy required to supply these heating and cooling services. Improvement paths are specified for the USA by technology type, and these pathways then serve as the basis for improvements in other regions.
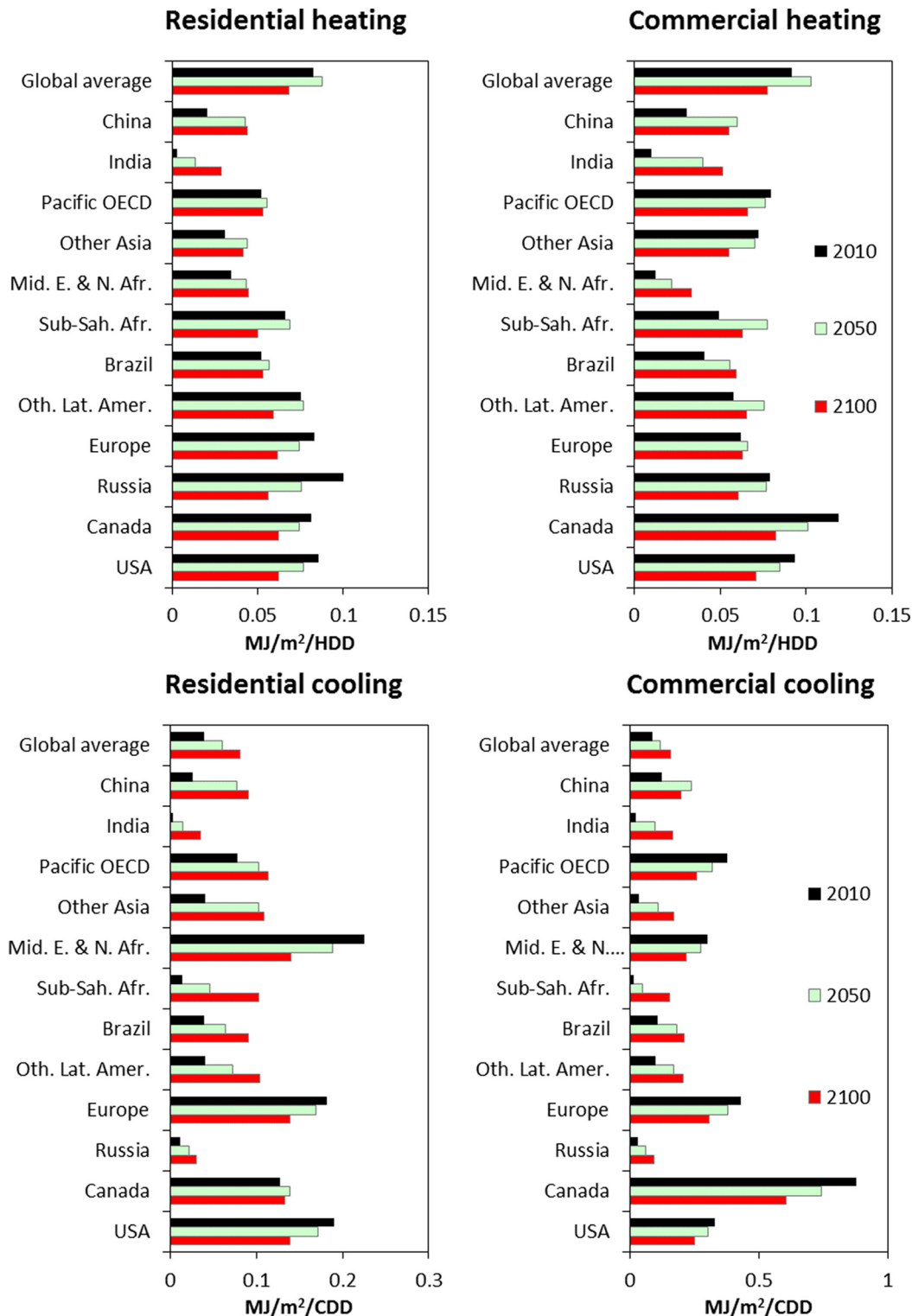


**Fig. 3.** Heating and cooling service demand per unit floorspace per degree day (B) in the Fixed Climate Scenario.
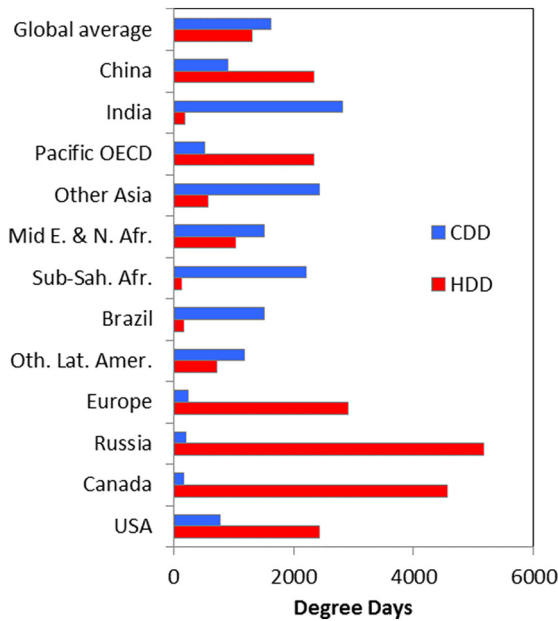
**Fig. 4.** Heating degree days (HDD) and cooling degree days (CDD) in 2010. Degrees indicate degrees Celsius.

*3.1.2. Fixed climate scenario building energy expenditures*

As a means to understand both heating and cooling expenditures in the Fixed Climate Scenario and changes in these expenditures with climate change, we will henceforth employ an approximate decomposition of Eqs. (1) and (2) into four components:

$$E_H = D_H P_H = f d_H P_H \approx f[B_H \cdot HDD]P_H \qquad (7)$$

$$E_C = D_C P_C = f d_C P_C \approx f[B_C \cdot CDD]P_C \qquad (8)$$

The fundamental change from Eqs. (1) and (2) is that service demands per unit of floorspace, $d_C$ and $d_H$, have been decomposed into two terms. The first term in brackets, $B_C$ or $B_H$, is a behavioral term that captures per capita energy service demand per unit of HDD and CDD (and per unit of floorspace). The second term is simply the HDD or CDD. Note that this decomposition is an approximation of the relationship between HDD and CDD and energy expenditures; HDD and CDD do not enter in the demand equation in a purely multiplicative fashion because of internal gains (see Eqs. (3) and (4)). Nonetheless, this approximation is useful because changes in HDD and CDD are the primary means by which climate affects building energy demands and thus expenditures.

Working from left to right in Eqs. (7) and (8), it is possible to express expenditures in the Fixed Climate Scenario using this decomposition. Consistent with the income growth profile discussed above and the relationship described earlier, per-capita building floorspace (f) increases over the century from current global average estimates of about 21 and 7 m$^2$ per capita in residential and commercial sectors to 32 and 14 m$^2$, respectively (Fig. 2). This floorspace growth is most pronounced in currently less-developed regions, particularly India and Other Asia. In contrast, currently developed regions exhibit only modest increases over the century despite also having substantial income growth.

The second term, B, can be approximated by normalizing energy service demands by HDD and CDD in the Fixed Climate Scenario (Fig. 3). It characterizes how much more (or less) individuals and businesses use heating and cooling equipment as HDD and CDD increase (or decrease). In warm regions such as India and Africa with low present-day use of air conditioners, these normalized cooling service demands grow substantially by 2050 and 2100 due to income-related increases in air conditioner adoption. In developed

regions, in contrast, the base year normalized service demands tend to be high, as most buildings are equipped with heating and/or cooling technologies, and future normalized demands decrease due to improvements in shell efficiencies. Increases in internal gains over time will also tend to reduce normalized heating energy service demands and increase cooling energy service demands.

The third term in Eqs. (7) and (8) is HDD and CDD, shown by region for 2010 in Fig. 4. The significant regional variation hints at the very different impacts of climate change across different regions, a topic that will be addressed further in Section 3.2.

Taken together, these first three terms largely determine the scale of per-capita heating and cooling service demands in the Fixed Climate Scenario. The result shown in Fig. 5 is the per-capita demand for heating and cooling services, $D_H$ and $D_C$, for both the residential and commercial buildings sectors. Whereas the per-capita service demands for space heating tend to stay close to their base year levels in most regions, as shell efficiency improvements and increased internal gains balance the growth in per-capita floorspace, the service demands for cooling do not. With the exception of temperate and developed regions (e.g., Europe, USA, Canada), cooling service demands grow substantially as higher incomes lead to greater adoption of air conditioning equipment. This is especially pronounced in India and Sub-Saharan Africa, each of which has a hot climate and very low present day adoption of air conditioners.

The final component of expenditures from Eqs. (7) and (8) is service prices. Although there is inter-regional variation, it is not especially significant and nearly all regions follow a similar trajectory (Fig. 6). Heating service prices tend to stay relatively flat, representing the competing effects of moderately increasing fossil fuel prices and improving technology. Cooling service prices decrease by 24% and 30% from 2010 to 2100 in the residential and commercial sectors, respectively, driven by technology improvements in air conditioners that both reduce costs and improve efficiencies, and also by price decreases in electric power generation arising from technological improvements in that sector. This decrease in cooling service prices further encourages the use of cooling services in addition to income-related demand increases in future periods.

Trends in energy service demands and service prices collectively determine building energy expenditures (Eqs. (1) and (2)), which are the focus of this study. At the regional level, per capita expenditures for heating and cooling are roughly constant or modestly decreasing in the developed regions, but they increase substantially in developing regions (Fig. 7). The regional expenditure increases are driven by rapid increases in per capita floorspace along with increased demand (per unit floorspace) for space cooling associated with a higher standard of living. These increases in cooling service demands in developing nations are consistent with a broad increase in building services, many of which use electricity, resulting in approximately ten-fold increases in building sector electricity demand from 2010 to 2100 in a number of regions in which large shares of the present day populations live in rural, non-electrified dwellings.

*3.2. The effect of climate change on building energy service demands and expenditures*

We can now use the decomposition in Eqs. (7) and (8) as a basis to understand the implications of climate change for building energy expenditures. Working from left to right, the first term, *f*, for floorspace, is assumed to be invariant to climate change. The second term, $B_C$ or $B_H$, could change with climate change, because, as noted earlier, the decomposition is approximate due to the additive term in Eqs. (3) and (4) for internal gains. Nonetheless, inspection of output suggests that this effect is negligible, and the time paths of $B_C$ and $B_H$ can be considered identical between the two scenarios as well.
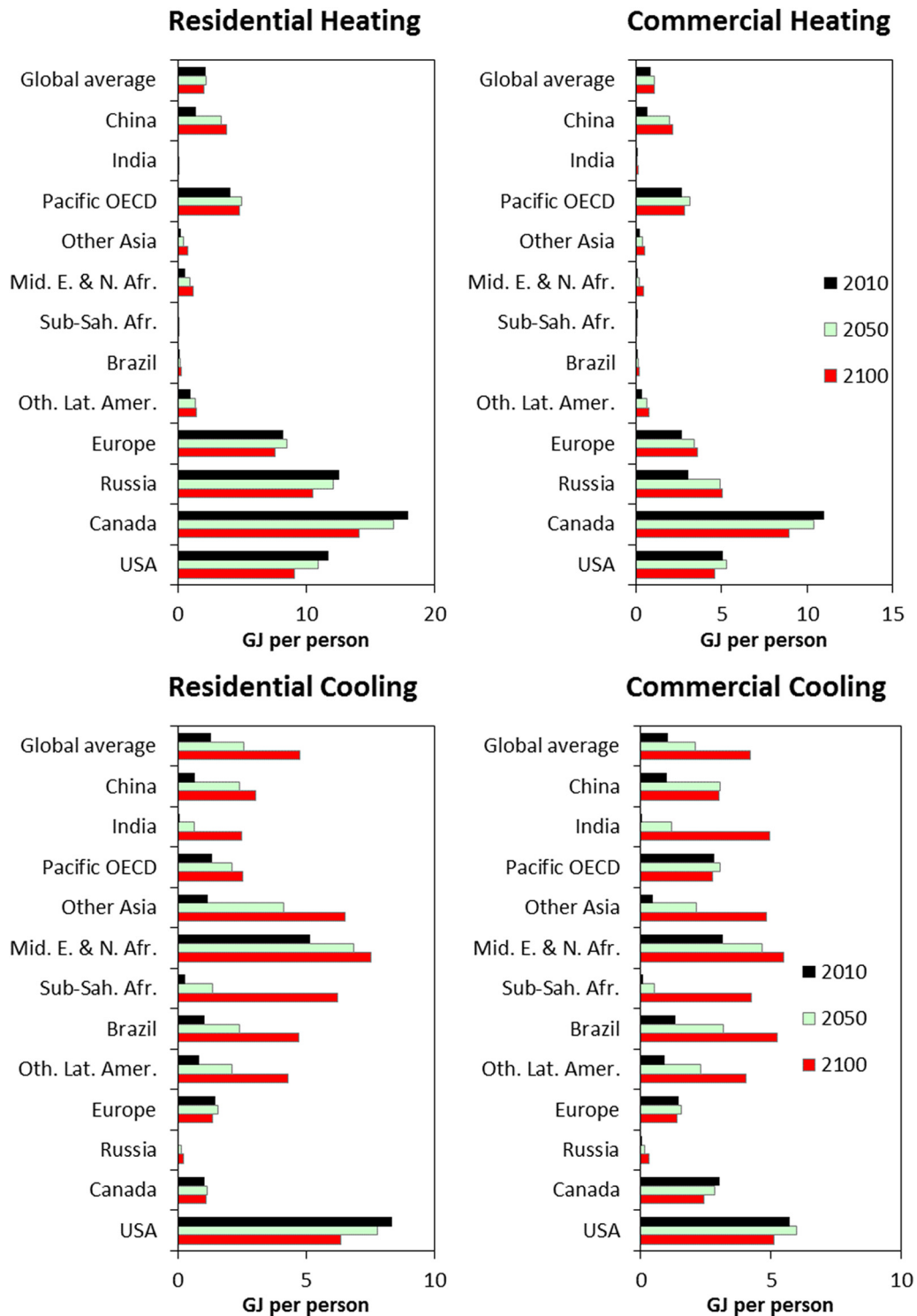
**Fig. 5.** Per-Capita Heating and Cooling Service Demands (D) in the Fixed Climate Scenario.

The third term is HDD (CDD), which decrease (increase) in all regions and time periods in this study, respectively. The magnitude of the effect of climate change on HDD and CDD varies among regions, although the effect continues to increase from 2050 to 2100 regardless of the region (Fig. 8). Temperate regions, such as the USA and China, experience approximately the same increase in CDDs as decrease in HDDs. Boreal regions, such as Canada and Russia, experience a greater decrease in HDDs than increase in CDDs. Regions encompassing more of the tropics, such as Latin America and Other Asia, experience a greater increase in CDDs than decrease in HDDs.

The combined effect of climate change on the first three terms in Eqs. (7) and (8) is the effect on energy service demand per capita. In most regions, there is a larger change in energy service demand for cooling than for heating (Fig. 9). This is because $B_C$ is generally larger than $B_H$ (Fig. 3), so that, even for the same change in HDD and CDD, cooling service demand responds more than heating service demand in most regions. As an example, CDDs and HDDs change by a similar amount, but in opposite directions, in the U.S. over the 21st century; however, the increase in per capita cooling service demand in the U.S. is greater than the decrease in per capita heating service demand.
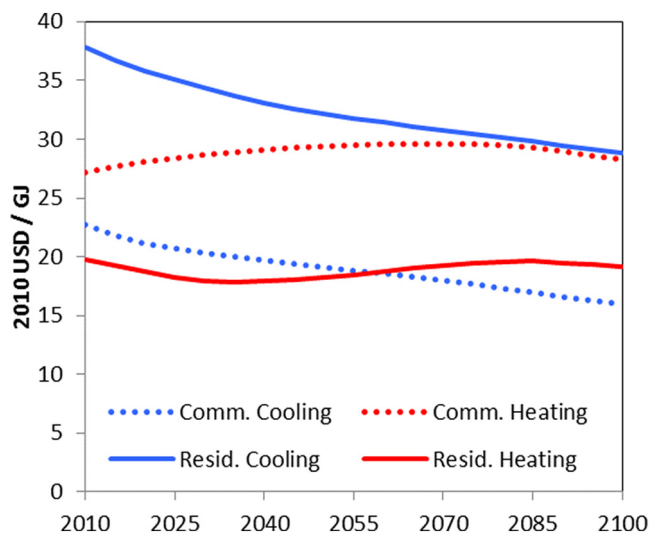
Fig. 6. Global average service price (P) for residential and commercial heating and cooling services in the Fixed Climate Scenario.

Now we move to the fourth term in the decomposition in Eqs. (7) and (8), $P_H$ and $P_C$. In general, although the results for each region indicate decreased heating service price and increased cooling service price from climate change, the magnitudes of these effects are small. This suggests a relatively elastic long-term supply in the energy system represented by GCAM, when the only aspects of climate change represented are the changes in heating and cooling degree days. An important implication of this result is that the economic impacts of climate change on consumers (i.e. changes in expenditures) are largely embodied in the first-order effect on HDD and CDD and the subsequent changes in service demands.

Combining all four terms gives the effect on energy expenditures (Fig. 10). Temperate regions such as the USA and China experience greater increases in cooling expenditures than decreases in heating expenditures, even though the changes in CDDs and HDDs are similar in magnitude, due to higher behavioral response (B) for cooling, as well as higher service prices for residential cooling. In boreal regions such as Canada and Russia, increases in cooling expenditures are roughly balanced by decreases in heating expenditures, because the decrease in HDD is much larger than the increase in CDD, offsetting differences in behavioral response and service prices. Finally, in regions encompassing more of the tropics, such as Latin America and Other Asia, increases in cooling expenditures are significantly larger than decreases in heating expenditures. To put the changes in expenditures in context, the values in Fig. 10 can be compared to the relevant Fixed Climate expenditures or to the 2010 expenditures in Fig. 7. For example, in the USA region, cooling expenditures in 2050 in the 8.5 Climate Scenario increase by 48% relative to the Fixed Climate Scenario, and cooling expenditures in 2100 increase by 141%.

Thus far, we have focused on the impact of climate change on per capita buildings energy expenditures. Another important metric is the impact on total buildings energy expenditures, which reflect differences in regional populations (Fig. 11). The results indicate that the impact on total expenditures is larger in the second half of the century than in the first half of the century, due to more significant changes in climate in the second half of the century and greater energy service demands in developing regions.

### 3.3. Sensitivity of net building energy expenditures to the level of temperature change

By combining the results of the 4.5 Climate Scenario with those of the 8.5 Climate Scenario, it is possible to plot the net increase in global
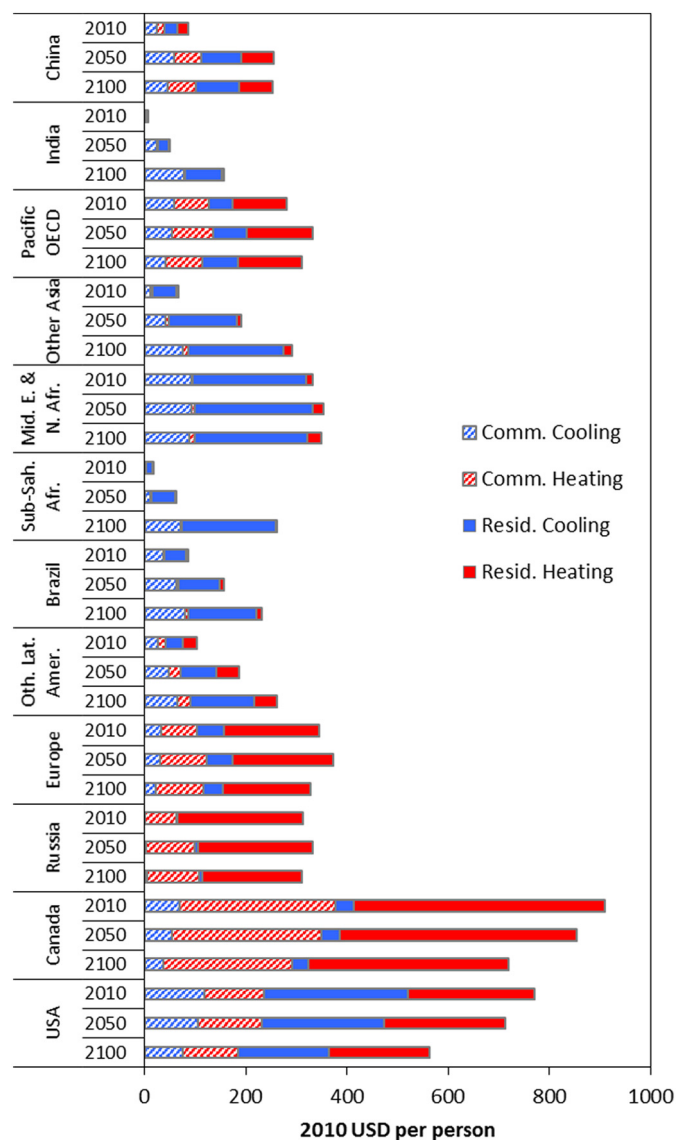


Fig. 7. Per capita expenditures on space heating and cooling (E) in the Fixed Climate Scenario.

building energy expenditures versus the rise in global average surface temperature change (Fig. 12). To put these expenditures into context, it is constructive to compare them to the overall level of income.

At a global level, the resulting relationship indicates that warming from pre-industrial temperatures on the order of 2 °C (3 °C, 1.5 °C) would lead to net increases in building energy expenditures that are about 0.10% (0.15%, 0.05%) of global income. It is interesting to note that, at the global level, the dependence is approximately linear in temperature for the scenarios considered here. This result follows from the fact that HDD and CDD changes are approximately linear in temperature and that the effect on energy prices is rather small. If the relationship between temperature and demand were nonlinear, or if there were effects on prices in addition to the effect on demand, then the dependence could be nonlinear. It is also worth noting that the results from the 4.5 Climate Scenario and 8.5 Climate Scenario approximately lie along the same line. As discussed further in the Supplementary Material section 10, this finding suggests that the dependence of expenditures per income on temperature is largely invariant to socioeconomic assumptions.

In Fig. 12, the global average results mask significant differences across regions. The maximum and minimum values in Fig. 12 illustrate that the expenditure changes relative to income in particular regions can
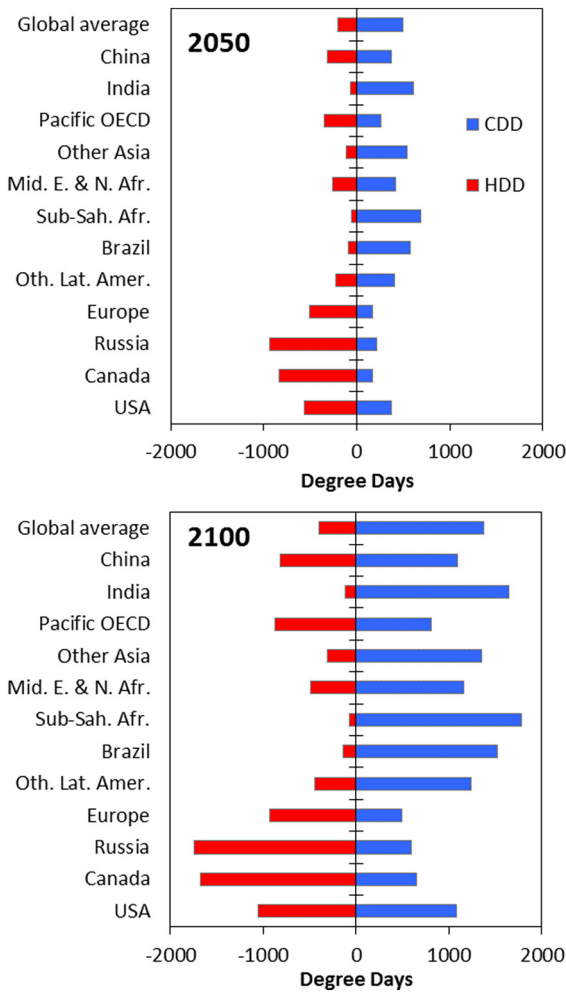
**Fig. 8.** Change in CDDs and HDDs (Celsius) between the 8.5 Climate and Fixed Climate Scenarios.



**Fig. 9.** Change in per capita service demand (D) between the 8.5 Climate and Fixed Climate Scenarios for residential and commercial heating and cooling services.

be much different than the global average. These variations arise in part due to variations in latitude, which largely determine the relative importance of heating and cooling. The net effects on tropical countries are noticeably higher than those on temperate-to-high latitude countries, because tropical countries experience minimal savings from decreased heating and tend to significantly increase cooling in response to climate change. In addition, a given increase (decrease) in cooling (heating) expenditures will account for a larger share of income in countries with lower overall income, all else equal. For both of these reasons, changes in total expenditures relative to total income in the non-OECD countries (generally lower latitudes and lower income) are substantially higher than in the OECD countries (generally higher latitudes and higher income) as shown in Fig. 13. This study does not disentangle the relative effect of income and latitude but notes that there is significant variation across different world regions.

## 4. Conclusions

In addition to illustrating methodological advances, the study has contributed to the literature by exploring the impact of climate change on building heating and cooling service demand and expenditures at a global level. The core contribution of the study has been to provide estimates of changes in building heating and cooling service demands and expenditures due to several possible levels of future climate change. Although these represent only one set of possible estimates and follow
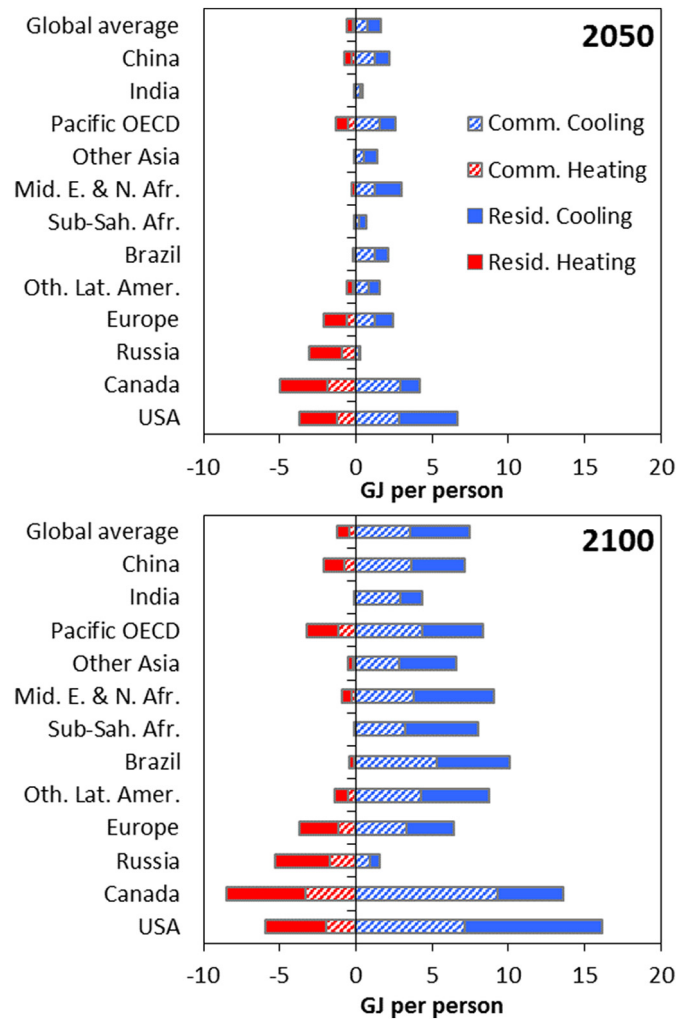
from the particular assumptions and modeling approach used in this study, they are nonetheless useful in trying to understand the implications of a changing climate.

In the scenarios explored in this study, net global building energy expenditures increase on the order of 0.1% of global economic output for a 2 °C increase in global mean surface temperature. This increase captures the additional income that would be necessary to hold the level of comfort derived from heating and cooling services approximately constant in aggregate as temperatures increase. Climate change increases net buildings energy expenditures in nearly all regions, as increased expenditures from increased cooling demands outweigh the savings from reduced heating demands, but the effects are not uniform across the globe. The largest increases in expenditures tend to occur in low-latitude countries whose present-day space heating demands are very low, but whose future demand for space cooling could grow substantially. These results hold true across a range of future sensitivities of building service demand levels to income growth.

The estimates of energy expenditure changes in this paper could be improved through several enhancements to the current analysis. Here we propose three areas for future research. First, the results in this paper depend on existing data for building energy consumption by service, for which surveys are only available in selected nations, and even in these instances face issues of consistency in definitions and methods. Collection of stronger service-level global building energy data would enhance future study of global heating and cooling demands. Second, this study has been conducted using only a small
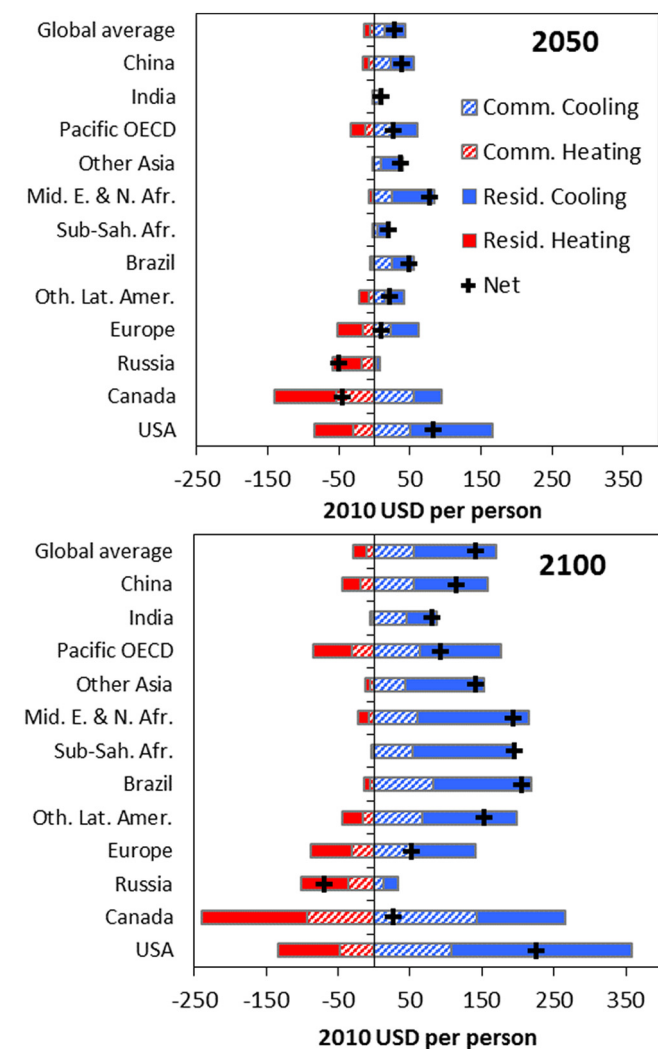
**Fig. 10.** Change in per capita buildings energy expenditures (E) between the 8.5 Climate and Fixed Climate Scenarios for residential and commercial heating and cooling services.

set of future socioeconomic, urbanization, and energy system scenarios and only one climate model. Future research could explore a broader range of possible future socioeconomic, urbanization, technological development and climate scenarios to capture various uncertainties. Finally, the simplified representation of buildings in this study may not effectively capture the full suite of options for making technology or building shell adjustments in response to climate change. More options would tend to decrease the effects of climate change on energy expenditures.

## Acknowledgments

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2018.01.003.
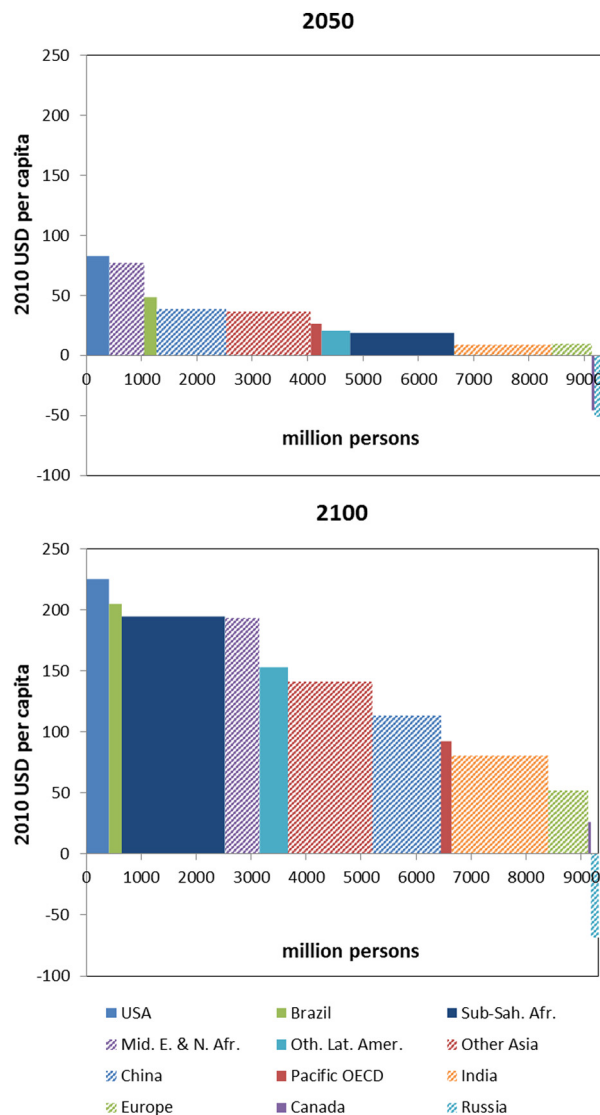


**Fig. 11.** Net building energy expenditure changes between the 8.5 Climate and Fixed Climate Scenarios in 2050 (top) and 2100 (bottom). The height of each bar indicates the per capita net expenditure change (in dollars per person). Since the width of the bar is population, the area of each bar indicates total net expenditure change (in dollars). Section 8 in the Supplementary Material includes an alternative figure in which the y-axis is net per capita expenditure change divided by per capita income.
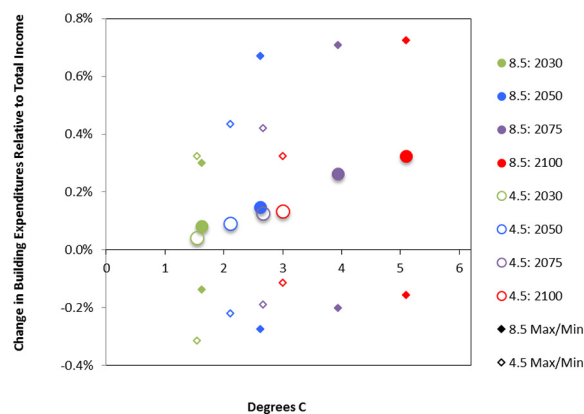


**Fig. 12.** Net increase in global building energy expenditures relative to total global income at different levels of increase in global average surface temperature relative to the 1850–1860 average as reported by CESM. The max and min symbols represent the highest and lowest values across GCAM regions.
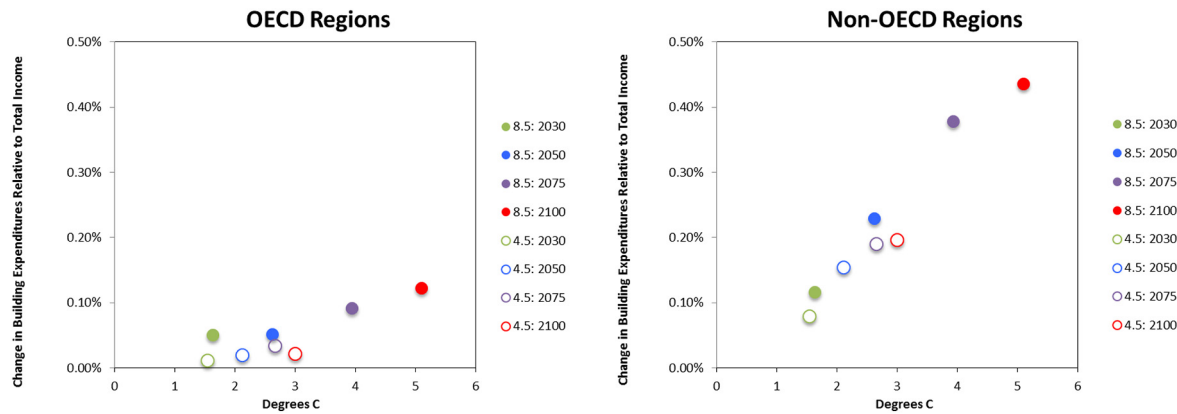
**Fig. 13.** Net increase in OECD and non-OECD average building energy expenditures relative to total income at different levels of increase in global average surface temperature relative to the 1850–1860 average as reported by CESM.

## References

Albouy, D., Graf, W.F., Kellogg, R., Wolff, H., 2013. Climate Amenities, Climate Change, and American Quality of Life.

Amato, A.D., Ruth, M., Kirshen, P., Horwitz, J., 2005. Regional energy demand responses to climate change: methodology and application to the commonwealth of Massachusetts. Clim. Chang. 71, 175–201.

Cartalis, C., Synodinou, A., Proedrou, M., Tsangrassoulis, A., Santamouris, M., 2001. Modifications in energy demand in urban areas as a result of climate changes: an assessment for the southeast Mediterranean region. Energy Convers. Manag. 42, 1647–1656.

Chaturvedi, V., Eom, J., Clarke, L., Shukla, P., 2013. Long-term Building Energy Demand for India: Disaggregating End Use Energy Services in an Integrated Assessment Modeling Framework. Energy Policy 64, 226–242.

Clarke, J.F., Edmonds, J.A., 1993. Modelling energy technologies in a competitive market. Energy Econ. 123–129.

Clarke, L., Jiang, K., et al., 2014. Assessing transformation pathways. Working Group III - Mitigation of Climate Change. Intergovernmental Panel on Climate Change.

Edmonds, J., Reilly, J., 1985. Global Energy: Assessing the Future. Oxford University Press, Oxford, New York.

Edmonds, J., Clarke, J., Dooley, J., Kim, S.H., Smith, S.J., 2004. Stabilization of CO2 in a B2 world: insights on the roles of carbon capture and disposal, hydrogen, and transportation technologies. Energy Econ. 26, 517–537.

Eom, J., Calvin, K., Clarke, L., Edmonds, J., Kim, S., Kopp, R., Kyle, P., Luckow, P., Moss, R., Patel, P., Wise, M., 2012a. Exploring the future role of Asia utilizing a Scenario Matrix Architecture and Shared Socio-economic Pathways. Energy Econ. 34 (Supplement 3), S325–S338.

Eom, J., Clarke, L., Kim, S., Kyle, P., Patel, P., 2012b. China's building energy demand: long-term implications from a detailed assessment. Energy 46, 405–419.

Eskeland, G.S., Mideksa, T.K., 2009. Climate Change and Residential Electricity Demand in Europe.

Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., Amann, M., Ermolieva, T., Forsell, N., Herrero, M., Heyes, C., Kindermann, G., Krey, V., McCollum, D.L., Obersteiner, M., Pachauri, S., Rao, S., Schmid, E., Schoepp, W., Riahi, K., 2016. The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. Glob. Environ. Chang. 42, 251–267.

Hadley, S.W., Erickson, D.J., Hernandez, J.L., Broniak, C.T., Blasing, T.J., 2006. Responses of energy use to climate change: a climate modeling study. Geophys. Res. Lett. 33, 1–4.

Hartin, C.A., Patel, P., Schwarber, A., Link, R.P., Bond-Lamberty, B.P., 2015. A simple object-oriented and open-source model for scientific and policy analyses of the global climate system–Hector v1. 0. Geosci. Model Dev. 8 (4), 939–955.

Isaac, M., van Vuuren, D.P., 2009. Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. Energy Policy 37, 507–521.

Krey, V., O'Neill, B., van Ruijven, B., Chaturvedi, V., Daioglou, V., Eom, J., Jiang, L., Nagai, Y., Pachauri, S., Ren, X., 2012. Urban and rural energy use and carbon dioxide emissions in Asia. Energy Econ. 34, S272–S283.

Maddison, D.J., 2003. The amenity value of the climate: the household production function approach. Resour. Energy Econ. 25, 155–175.

Mansur, E.T., Mendelsohn, R., Morrison, W., 2008. Climate change adaptation: a study of fuel choice and consumption in the US energy sector. J. Environ. Econ. Manag. 55, 175–193.

McFadden, D., 1980. Econometric models for probabilistic choice among products. J. Bus. 53, S13–S29.

Meehl, G.A., Washington, W.M., Santer, B.D., Collins, W.D., Arblaster, J.M., Hu, A., Lawrence, D., Teng, H., Buja, L.E., Strand, W.G., 2006. Climate change projections for the twenty-first century and climate change commitment in the CCSM3. J. Clim. 19, 2597–2616.

Olonscheck, M., Holsten, A., Kropp, J.P., 2011. Heating and cooling energy demand and related emissions of the German residential building stock under climate change. Energ. Policy 39, 4795–4806.

Rosenthal, D.H., Gruenspecht, H.K., Moran, E.A., 1995. Effects of global warming on energy use for space heating and cooling in the United States. Energy J. 16, 77–96.

Sailor, D.J., 2001. Relating residential and commercial sector electricity loads to climate — evaluating state level sensitivities and vulnerabilities. Energy 26, 645–657.

Sailor, D., Pavlova, A.A., 2003. Air conditioning market saturation and long-term response of residential cooling energy demand to climate change. Energy 28, 941–951.

Scott, M.J., Dirks, J.a., Cort, K.a., 2007. The value of energy efficiency programs for US residential and commercial buildings in a warmer world. Mitig. Adapt. Strateg. Glob. Chang. 13, 307–339.

Train, K., 1993. Qualitative Choice Analysis: Theory, Econometrics, and an Application to Automobile Demand. MIT Press.

Wan, K.K.W., Li, D.H.W., Liu, D., Lam, J.C., 2011. Future trends of building heating and cooling loads and energy consumption in different climates. Build. Environ. 46, 223–234.

Wise, M., Calvin, K., 2011. GCAM 3.0 Agriculture and Land Use: Technical Description of Modeling Approach.

Zhou, Y., Eom, J., Clarke, L., 2013. The effect of global climate change, population distribution, and climate mitigation on building energy use in the U.S. and China. Clim. Chang. 119, 979–992.