Effects of Long-Term Climate Change on Global Building Energy Expenditures

Supplementary Material

1 Region Mapping

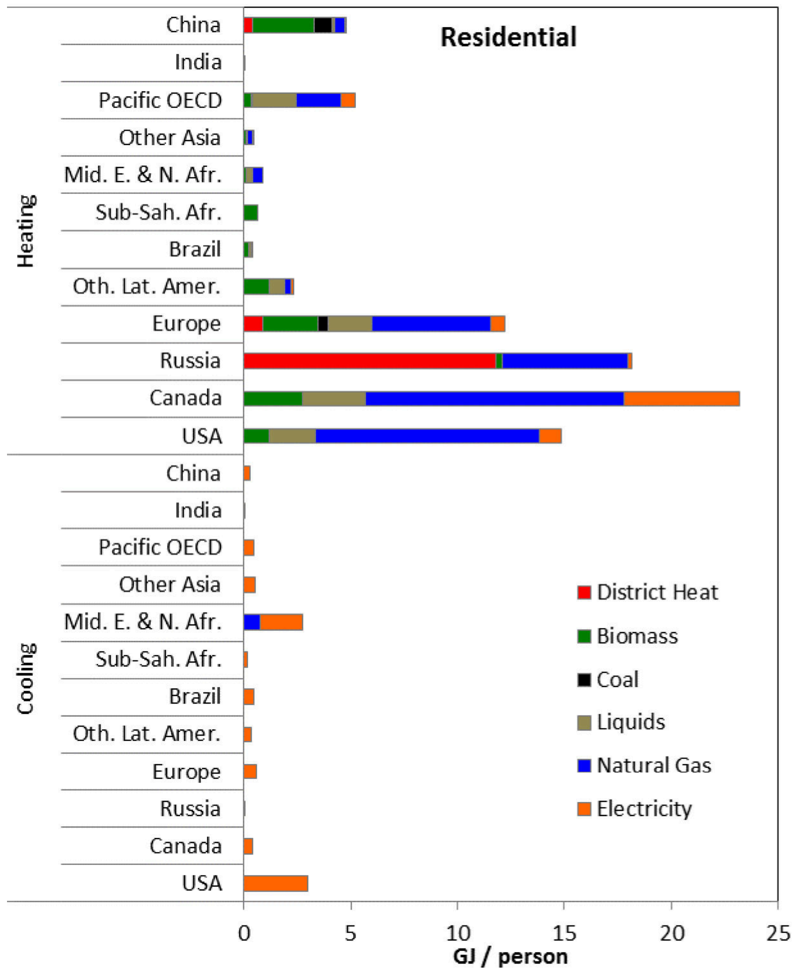
As noted in the main paper, the version of GCAM used for this project includes 32 regions. For ease in representing results throughout this paper, these 32 regions have been aggregated into a smaller set of regions as shown in Table S1.

Table S1. Mapping between regions used in this study and 32 GCAM regions

Region	GCAM region
China	China, Taiwan
India	India
Pacific OECD	Australia & New Zealand, Japan, South Korea
Other Asia	Central Asia, Indonesia, Pakistan, South Asia, Southeast Asia
Middle East and North Africa	Middle East, Northern Africa
Sub-Saharan Africa	Western Africa, Eastern Africa, Southern Africa, South Africa
Brazil	Brazil
Other Latin America	Argentina, Central America & Caribbean, Colombia, Mexico, Northern South America, Southern South America
Europe	EU-12, EU-15, Eastern Europe, European Free Trade Association, Non-EU Europe
Russia	Russia
Canada	Canada
USA	USA

2 Current Global Building Heating and Cooling Energy Use Patterns

Understanding the current pattern of building energy demand offers a useful starting point for evaluating future scenarios. Building energy demand patterns today vary substantially across the globe (Figure S1). Income levels and associated access to energy infrastructure explain much of the variation in building energy demands, with more developed countries generally having higher per capita demands than less-developed countries. Current climate also influences energy demands. Colder regions such as Canada, Russia, and Europe exhibit higher per capita heating demands than warmer regions such as India, Africa, and Other Asia. Current demands for space cooling, however, are less sensitive to climate conditions, particularly for less-developed regions, because the penetration of air conditioning is lower than that of heating.



Residential
Heating
Cooling
China
India
Pacific OECD
Other Asia
Mid. E. & N. Afr.
Sub-Sah. Afr.
Brazil
Oth. Lat. Amer.
Europe
Russia
Canada
USA
District Heat
Biomass
Coal
Liquids
Natural Gas
Electricity
0
5
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25
GJ / person

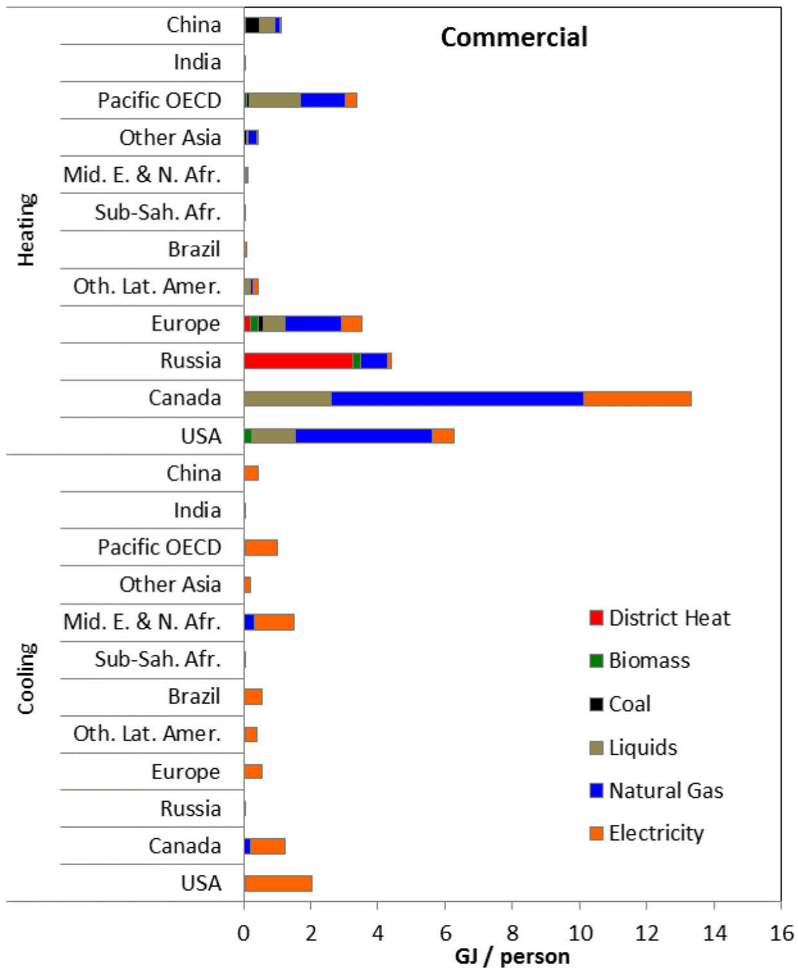

Figure S1: Per capita global energy demand in 2010 by service, region, and fuel

Space cooling relies predominantly on electricity across the globe, with little variation. In contrast, space heating is produced from a variety of fuels, ranging from direct fossil fuels (coal, oil, and natural gas) to secondary fuels (electricity and district heat) and biomass. Thus, decreased heating and increased cooling due to climate change may affect the composition of final energy demand as well as direct or indirect emissions (Wilbanks et al., 2007; Swann et al., 2010).

3 Population and GDP Assumptions

Population and GDP-related assumptions are core drivers of the scenarios in this study. Different assumptions about these socioeconomic variables would lead to different numerical results. The overall GDP and population numbers used in this study are taken from the SSP2 scenario (Fricko et al., 2016) and shown in Figure S2. Note that income and GDP are used synonymously in this paper.

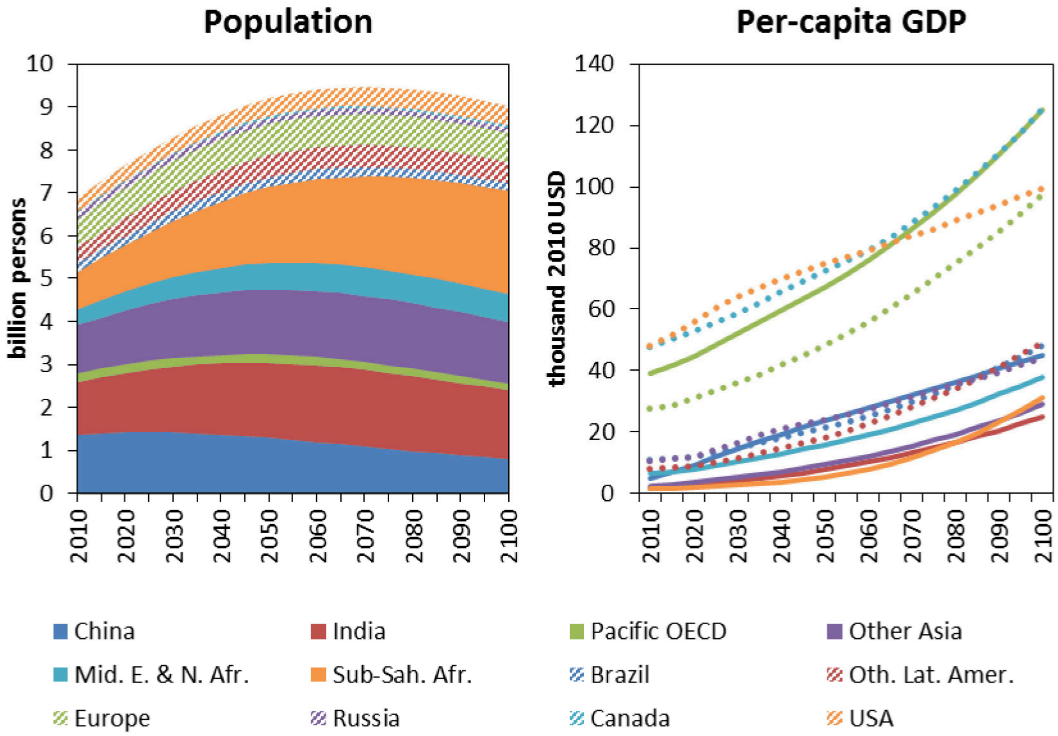

Figure S2: Population and Per-capita GDP in the scenarios

4 Building Shell and End-use Technology Assumptions

In the context of the demand decomposition shown in Equations 7 and 8 of the main paper, the assumptions for building shell conductivity are important for determining the levels of heating and cooling service demand, and the heating and cooling technologies are important for determining the average service prices, as indicated in Equations 5 and 6 of the main paper. These assumptions are also important for buildings sector energy consumption by fuel type and CO_2 emissions.

Building shells are assumed to improve over time so as to reduce the need for heating and cooling services. Specifically, the building shell conductivity, η (also referred to as U-factor), improves for all GCAM regions from current levels to significantly lower levels by the end of the 21st century. Rates of shell conductivity improvements of 0.5% per year for industrialized countries are used, based on estimates of future shell efficiency improvement in the U.S. (EIA 2007). Higher rates of improvement are assumed for developing countries. Rates of improvement vary across developing regions, but values as high as 0.8% per year are assumed. The building shell conductivities indexed to the 2005 U.S. value are shown in Figure S3. The range of values for η across GCAM regions narrows and converges over time with rising incomes of developing regions.

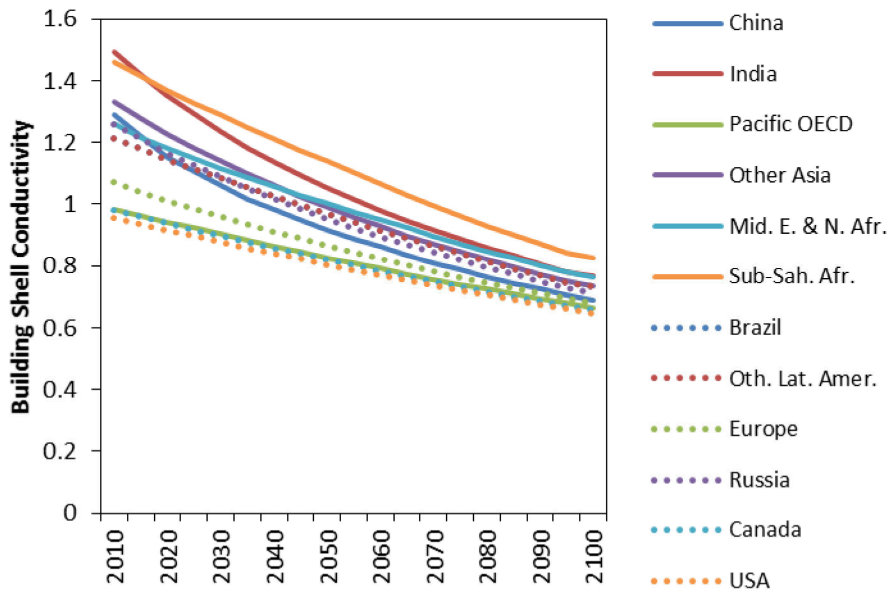

Figure S3: Trends in building shell η (or U-factor) (indexed to year-2005 USA levels)

End-use technologies for building energy services, such as air conditioners, furnaces, lighting, and other appliances, are also assumed to improve over time. Boilers and furnaces for heating services are assumed to improve from 0.1% per year in industrialized countries to as high as 0.4% per year in developing countries throughout the century. Air conditioning technologies for cooling services improve at a faster rate of 0.25% per year in industrialized countries to as high as 0.58% per year in developing countries throughout the century. Rates of heating and cooling equipment efficiency improvements, and the higher rates of improvement for cooling equipment, are consistent with EIA's estimates of improvements for the U.S. (EIA 2007). Over time, all regions are assumed to have greater access to the latest, more efficient end-use technologies and therefore, the end-use technology efficiencies converge across all regions.

Building end-use technology efficiencies in GCAM represent stock average efficiencies, so stock turnover effects are incorporated into the exogenous efficiency improvement rates described above. While there is no endogenous capacity for consumers to modify the efficiency level within any service and fuel type, for example in response to energy prices, there is endogenous competition among the different available fuels for each service. Cooling tends to be mostly provided by electricity, with a small portion provided by natural gas in some regions, but heating may have up to seven competing options, each of which has its own assigned efficiency level. In this way, the average heating and cooling efficiency pathways shown in Figure S4 are the result of the exogenous assumptions described above, and the endogenous fuel choices. Note that the efficiencies assumed for open wood fires used for space heating are relatively low; average efficiency levels below 50% in Figure S4 indicate high shares of heating services provided by open fires. Conversely, heating efficiencies approaching or exceeding 100% indicate high shares of electric heating technologies, which include heat pumps.

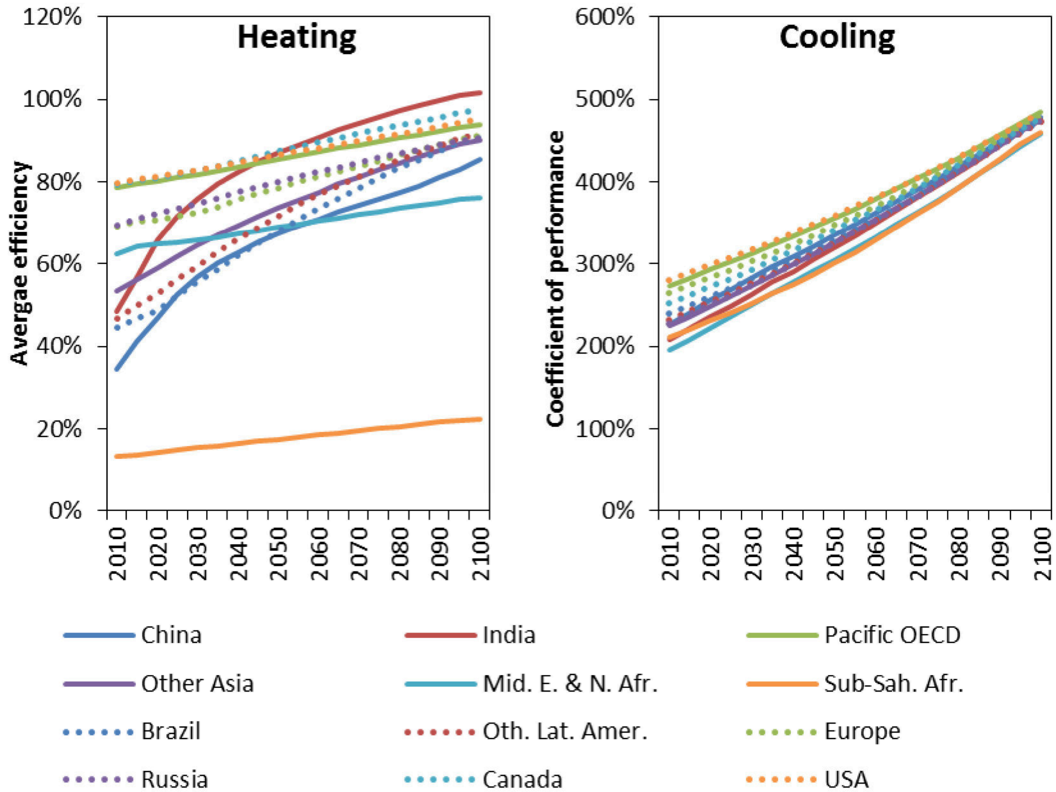

Figure S4: Trends in heating and cooling technology efficiency by region. Efficiency for air conditioners and for heat pumps refers to coefficient of performance.

5 Building Floor Space Calibration and Projection

5.1 Base-year Building Floor Space Calibration

Calibration of total commercial and residential floorspace for 2005 for all GCAM regions relies on many data sources. For the USA, the CBECS and RECS building energy consumption surveys (CBECS, 2003; RECS, 2005) are used to aggregate census and state level data of building floor space to national totals for residential and commercial floorspace. The IEA report, *30 Years of Energy Use in IEA Countries* (IEA, 2004) is utilized extensively for floorspace calibration for many GCAM regions. However, the IEA report provides historical data only through 2004, so floorspace estimates for 2005 and 2010 were estimated on a region-specific basis. For Canada, Japan, and Australia/NZ, total floorspace for 2005 is extrapolated from the 2004 historical per capita floorspace from the IEA report (IEA, 2004) and the respective 2005 population for these GCAM regions. For Western Europe, Eastern Europe and the Former Soviet Union, which are composed of multiple countries, both the IEA report (IEA, 2004) and the Odyssee database (ODYSSEE, 2011) were used to estimate the total commercial and residential floorspace for 2005. The 2004 per capita floorspace was calculated from the dataset and extrapolated to 2005 using the respective total 2005 population for these GCAM regions. For China, commercial and residential floorspace is calculated from the China Energy Databook (CEG, 2008) and building analysis by Zhou and

Lin (Zhou and Lin, 2008). For India, the commercial and residential floorspace comes from the *Housing Condition and Amenities in India 2008-2009* (NSSO, 2010) and building analysis by Chaturvedi et al. (Chaturvedi et al., 2013). For Korea, the national energy consumption survey (KEEI, 2009) is used to construct national-level commercial and residential building floorspace. Aggregated 2005 floorspace estimates for Africa, Latin America, Other Asia, and Middle East, as a whole, were not available from the literature. Estimates of 2005 residential floorspace for these GCAM regions were extrapolated using income growth and historical floorspace estimates from Malpezzi and Mayo (1997).

5.2 Building Floorspace Projection

This study assumes a simple relationship between per capita floor space and per capita income. The relationship is shown in Figure S5. In this study, the relationship was constructed to create a scenario that could be described as representing a largely urban future. Most countries evolve toward a long-term configuration that is similar to that of Europe or Japan. Both of these regions experience only limited increase in floorspace per capita. Only those countries on substantially higher trajectories of floorspace per capita, notably Canada and the U.S., are exempted from this general trend. These countries maintain their high levels of floorspace per capita, but with limited future growth.

This simple linkage between floorspace and income results in the most pronounced growth in per capita floorspace in the currently less-developed regions, such as Africa, Other Asia, India, and Latin America, where rapid income growth is expected. In contrast, the currently developed regions exhibit modest increases in per capita floorspace throughout the century.

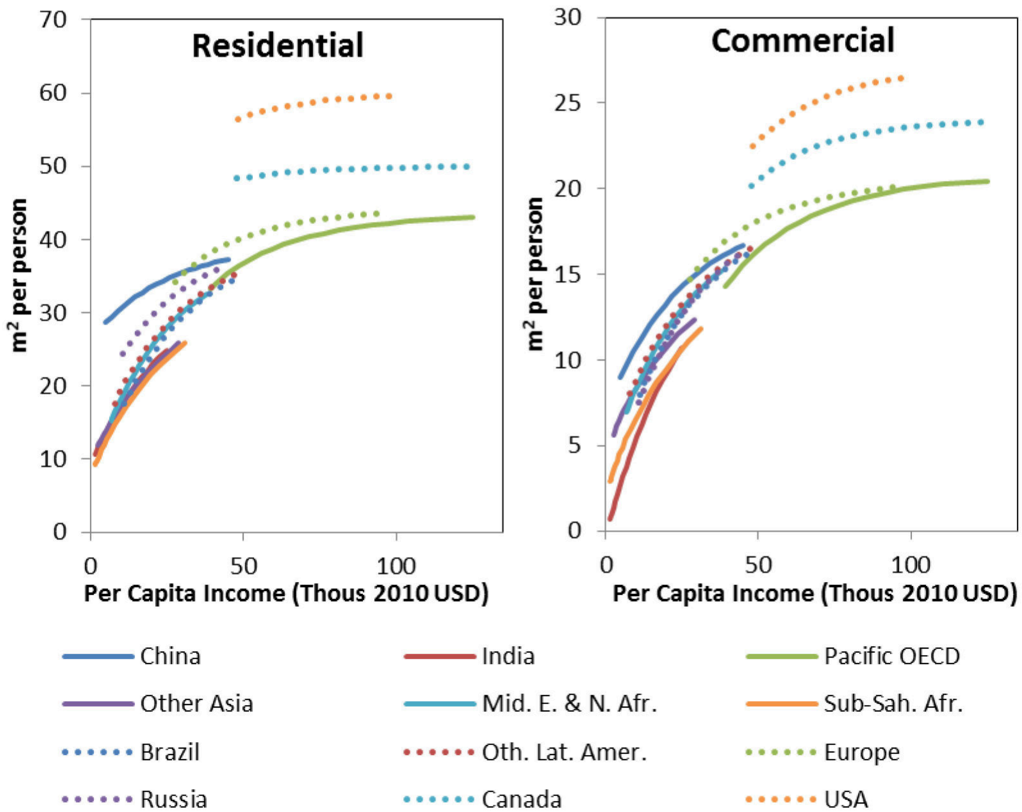

Figure S5. Per capita floor space in residential and commercial buildings as a function of per-capita income (2010-2100)

6 Energy Service Demand Calibration

Three building services —space heating, space cooling, and other — are modeled in each region for GCAM's residential and commercial buildings. This section focuses on the demands for heating and cooling services, indicated in Equations 3 and 4 of the main paper. The demand for other services, while a large and highly uncertain component of future building energy use, only influences heating and cooling demands through internal gains and fuel prices, and similarly, the changes in demand levels of these other services due to climate change would be indirect and difficult to quantify. The source of all parameters in each region in Equations 3 and 4 is described in Table S2.

Table S2. Parameters used in the building formulation

Parameter	Definition	Source
k_H, k_C	Calibration coefficients	Derived from Equations 3 and 4 and S1 and S2 to derive specified satiated demand
HDD, CDD	Heating and cooling degree days	Historical climate data and population; see Sections 2.3 and 3.1 in the main paper
η	Shell conductivity	Assumed; see Figure S3
R	Ratio of building surface area to floorspace area	Assumed; set constant in all regions and time periods
IG	Internal gain	Derived from "other" energy consumption
μ	Income level at mid-point of satiation curve	Derived from Equations 3 and 4 based on base year information, after all other parameters have been specified
i	Per-capita income	Exogenous assumption
P_H, P_C	Service price	Calculated from assumed non-fuel costs of each technology, endogenous fuel prices, and shares of each technology

Service demands for heating and cooling per unit floorspace in the base year, d_H and d_C, are calculated as the sum of service demands provided by each technology providing each service divided by the total floorspace (Figures 2 and 3). Service demands for each technology are calculated by multiplying energy consumption for each technology (Figure S1) by its efficiency (Figure S3).

There are two free, calibration parameters each in Equation 3 and in Equation 4, μ and k. The approach to calibrating these two parameters proceeds in two steps. The first step is to calculate k. Income, i, is set to infinity in Equations 3 and 4. The term in the brackets then drops out and what remains is an equation for the satiated demand – that is demand in the limit of very high income. The only calibration parameter that remains is k, because the term with μ has dropped out.

To calibrate k, it is necessary to make assumptions for the other parameters that remain (on the right side of Equation 3 and Equation 4) and for the level of satiated demand (on the left side of the abbreviated Equation 3 and Equation 4). The parameters on the right side of Equation 3 and Equation 4 are thermal conductivity, building configuration, and internal gains along with calculated CDD and HDD information. Internal gains are calculated in each region as 50% of the sum of all fuel consumption used for "other" (i.e., not heating or cooling) services. This energy quantity is then modified by a region-specific scaling factor designed to only apply the internal gain during the portion of the year in which the heating or cooling service applies. For example, in temperate regions that heat in the winter and cool in the summer, the annual cooling demand calculation is only modified by the internal gain during the summer months, and vice versa. These scaling factors are derived based on the heating and cooling degree days in each region.

The satiated demand assumptions were calculated using the USA as a benchmark. The satiation values in the USA are assumed to be 10% higher than the present demand levels in 2010, for both residential and commercial heating and cooling. In all other regions, the satiation level is assumed to be the maximum of the actual observed base-year demand levels, and the satiation level in the USA for the corresponding sector and service, modified for the HDD/CDD difference between the regions as indicated in Equations S1 and S2. It is worth noting that once the relationship between demand and climate has been estimated using the prescribed satiated demands (once k has been determined), the future satiated demands will depend on the realized HDD/CDDs, since k is essentially a constant of proportionality relating future satiated demand to future climate.

Equation S1
$$\hat{s}_{H,i} = \hat{s}_{H,USA} \cdot \left(\frac{HDD_i}{HDD_{USA}}\right)$$

Equation S2
$$\hat{s}_{C,i} = \hat{s}_{H,USA} \cdot \left(\frac{CDD_i}{CDD_{USA}}\right)$$

A plot of 2010 service levels for space heating and space cooling (labeled “Base year”) and the satiation levels (labeled “Satiation”) are shown in Figure S6. Overall, space heating demand is closer to the satiation levels than space cooling for most regions. China is an exception as their current per capita space heating service demands per unit floorspace and per heating degree day are far lower than the levels of industrialized nations. China’s current spacing heating is heavily reliant on primary solid biomass, most of which is considered to be open fires with very low space heating efficiency levels. For tropical regions, such as Africa, Latin America and Other Asia, space heating demand is minimal despite the presence of heating degree days. A small number of heating degree-days may not justify investments in heating equipment in most buildings, even at high income levels.

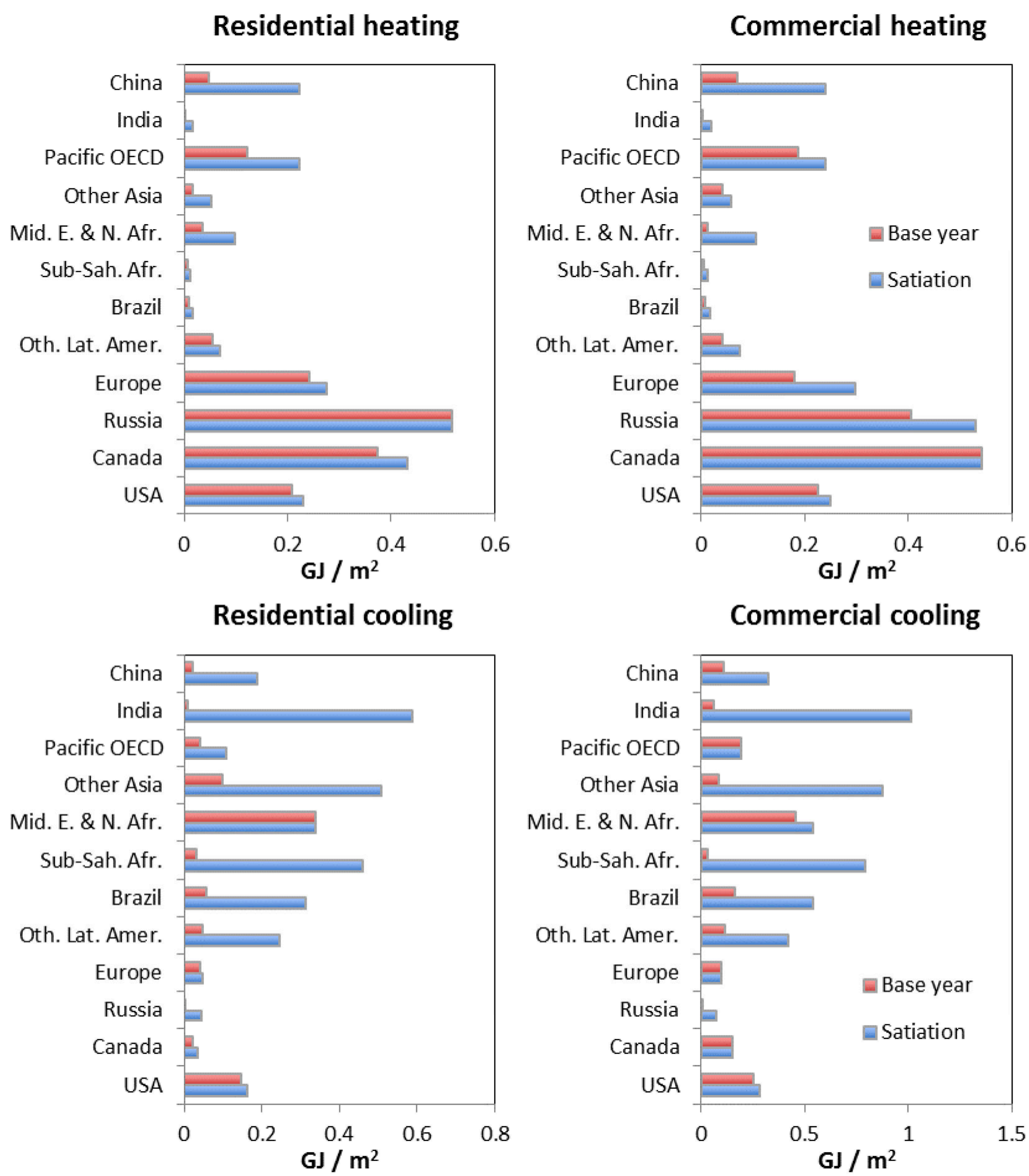

Figure S6: Base-year Actual Demands and Assumed Satiation Demands

After calculation of k, the second step in the calibration is to calculate μ. This is done by applying the actual income and service prices in the base year (on the right side of Equation 3 and Equation 4) and the actual service demand (on the left side of Equation 3 and Equation 4). μ is calculated such that the two sides of the equation are in balance.

7 Regional Energy Consumption by Service

Several long-term trends emerge in the intensity of residential and commercial building energy use in GCAM in the Fixed Climate Scenario. Figure S7 shows energy consumption by fuel per floorspace for residential and commercial heating and cooling services, in 2010, 2050, and 2100.

First, improvements to the building shell and heating technology efficiencies reduce the energy intensity of heating service over time for nearly all regions. In general, because current demands for heating service are often close to the satiation levels, heating service demands per unit floorspace do not grow substantially in the future. In addition, increasing internal gains over time from growing “other” services further contribute to the reduction in fuel consumed for space heating. The net result is that at a global level, the energy intensity of space heating decreases by 57% from 2010 to 2100.

However, the future trends in energy consumption for cooling are more complex. In developing regions, there is substantial service demand growth even in the Fixed Climate Scenario, driven by the high ratio between the satiation level and the base-year service demand (Figure S5). Growing internal gains over time further enhance these income-related increases in service demand. Taken together, these trends actually result in an increase in cooling energy intensity over time in many regions (prominently Latin America, Sub-Saharan Africa, India, China, and Other Asia), despite the assumed improvements in cooling technologies and building shells (Figures S3 and S4). In contrast, in industrialized regions, where climate-normalized base-year cooling demands are already close to the assumed satiation levels, the significant future efficiency improvements in air conditioning equipment (Figure S4) results in greater energy intensity reduction. In the Fixed Climate Scenario, the weighted global average energy intensity increases by 17% from 2010 to 2100, but again this is the net result of competing effects in different regions of the world.

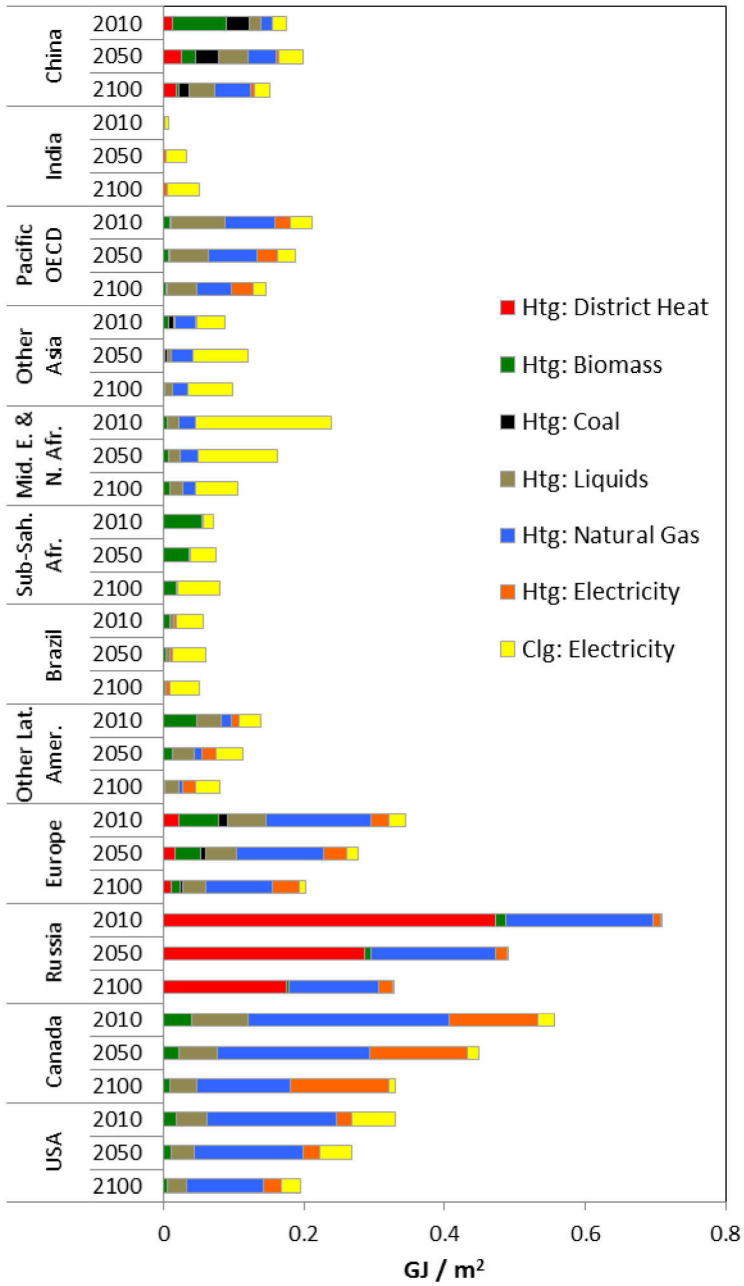

Figure S7: Building energy consumption per unit floorspace by service and fuel, from 2010-2100 in the Fixed Climate Scenario

In all regions, climate change increases electricity demands and decreases the demands for other fuels, as shown in Figure S7. This is because of the prominence of electricity in cooling and the large share of heating that is provided by other fuels, and is consistent with the literature on climate impacts on buildings energy use (Amato et al., 2005; Wilbanks et al., 2007; Chaturvedi et al., 2013). While there is virtually no global total net impact of climate change on building total final energy (a change of less than

1 EJ), primary energy consumption across the whole global economy increases by about 10 EJ, due to the additional energy used in producing electricity.

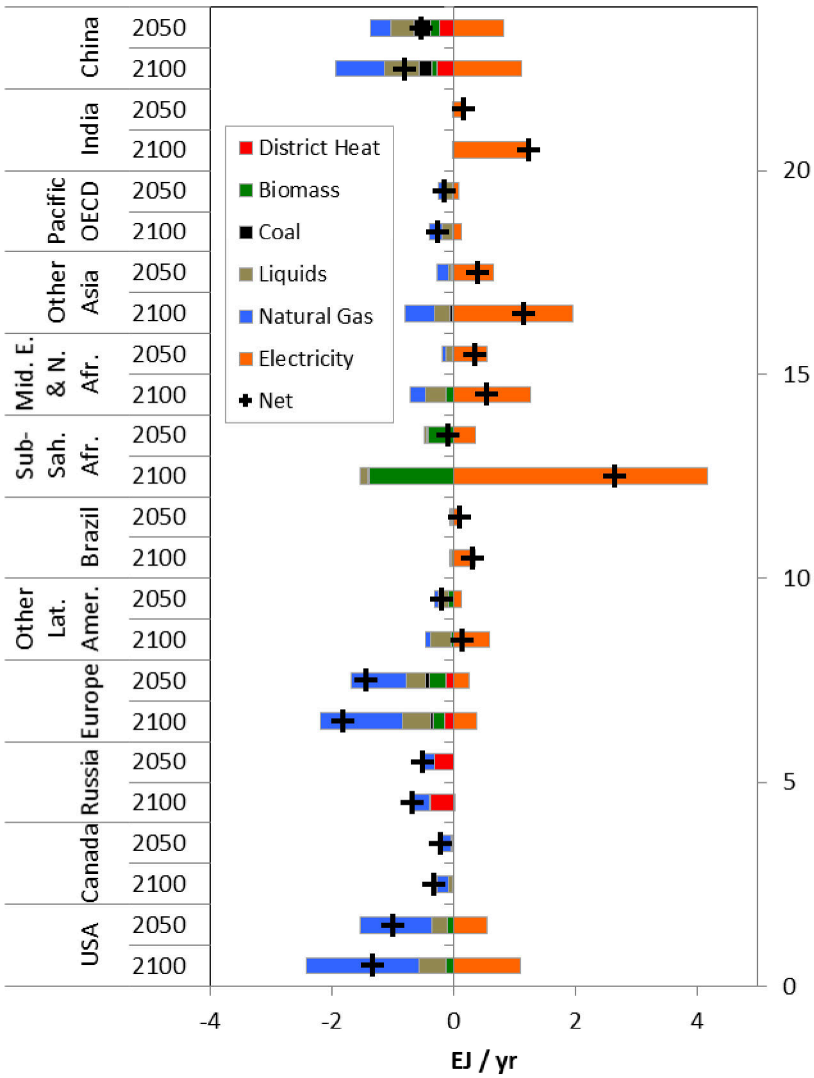

Figure S8: Change in buildings sector final energy consumption by fuel between the 8.5 Climate and Fixed Climate Scenarios, in 2050 and 2100

8 Change in Energy Expenditures Relative to Income

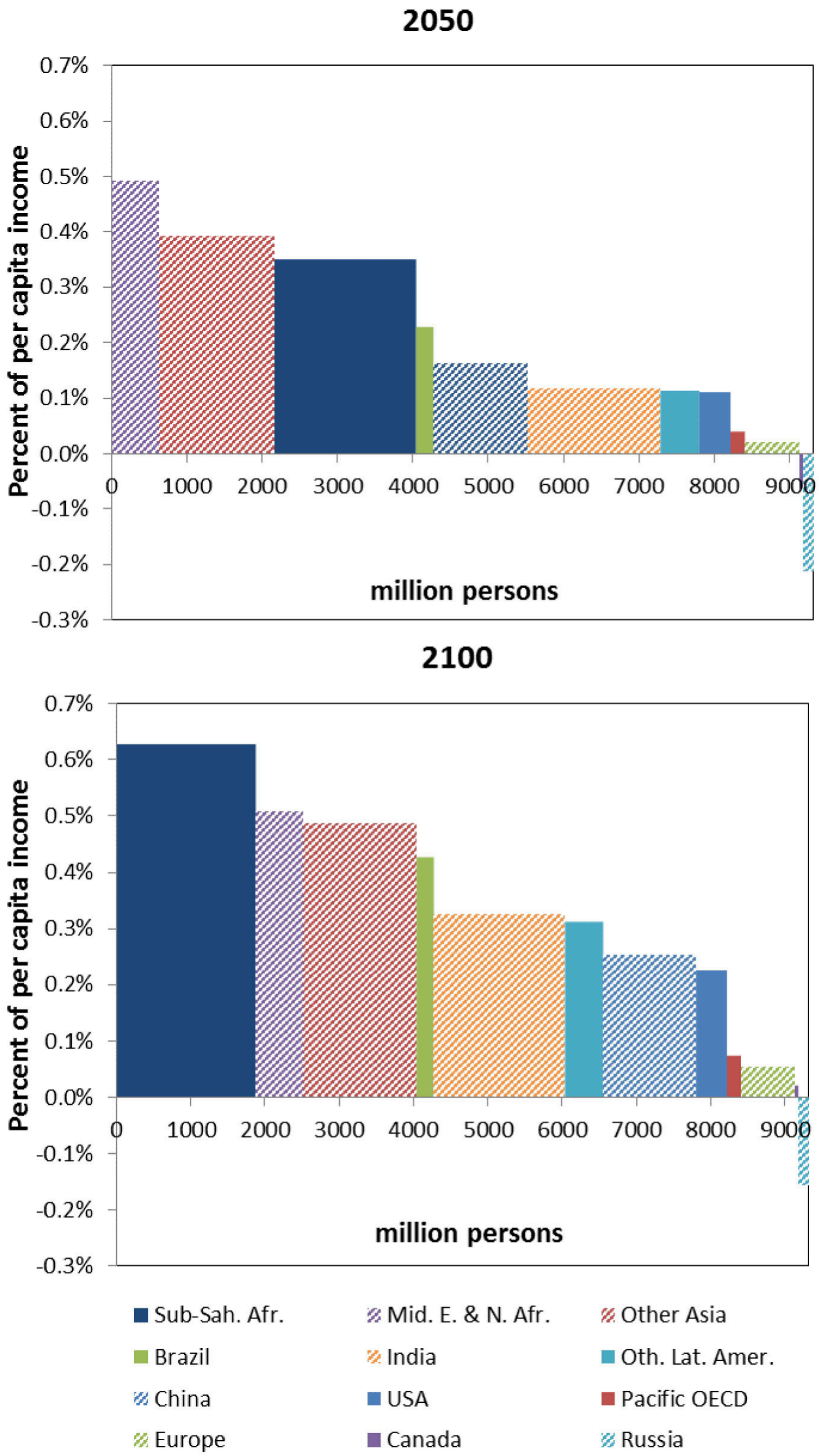

Figure S9: Net building energy expenditure changes between the 8.5 Climate and Fixed Climate Scenarios in 2050 (top) and 2100 (bottom). The height of each bar indicates the net expenditure change in percent of per capita income. The width of the bar represents the size of the population.

9 Cooling Demand Sensitivity Scenarios

9.1 Scenario Construction

The three core scenarios in this study all share socioeconomic characteristics, including the effects of future income on floorspace demand, and on utilization of heating and cooling equipment per unit floorspace and per degree day. However, many of the regions in the analysis have low present-day utilization of cooling technology despite warm climates; in the model this is represented as relatively high satiation levels for cooling demands (i.e., the cooling demands absent any financial constraints), as compared with the base-year levels. These regions, which include much of Africa, South and East Asia, and Latin America, account for much of the world's future population and economic output in the scenarios. The degree to which increases in per-capita income lead to increased floorspace, and to increased cooling demands per unit floorspace, is quite uncertain, and is important for the baseline levels of cooling service demand in the scenarios.

In addition, the effects of climate change on cooling-related expenditures are likely sensitive to baseline levels of cooling service demands. For example, Equations 7 and 8 in the main text suggest that if baseline values for per capita floorspace or demand per unit floorspace are higher, then a given change in heating or cooling degree days would have a larger effect on per capita expenditures. This section presents two demand sensitivity scenarios (LO and HI) which are run for each of the three climate scenarios in the main paper (Fixed Climate; 4.5 Climate; and 8.5 Climate). In Table S3, the specific features of the scenarios are described and compared with the Base Case (BASE), i.e., the scenarios in the main paper. The focus on cooling demands rather than heating demands is motivated by the greater uncertainty in cooling and the likelihood that the increase in cooling demands will far outpace heating demands over the century. Heating demands per unit floorspace and per heating degree day are already close to the estimated satiation levels in most model regions, in part because heating is disproportionately demanded by developed regions. In contrast, cooling is expected to be disproportionately demanded by developing countries. Note that these sensitivity cases are not intended to serve as bounding scenarios, defining the upper and lower limits of plausible future outcomes. Rather, they are provided in order to analyze the effects of perturbing several key uncertainties on the main outcomes of the study.

Table S3. Cooling Demand Sensitivity Scenarios

Feature	Base Case (BASE)	Low Case (LO)	High Case (HI)
Floorspace per capita	Each region is assigned one of five terminal (satiated) levels of per-capita floorspace. The lowest levels are 35 m2/person (residential) and 17 m2/person (commercial), and the highest are 60 m2/person (residential) and 27m2/person (commercial). See Figure S5.	Same as Base Case but use the mid-point between the present-day levels and the Base Case satiation levels as the terminal per capita floorspace demand.	Same as Base Case but use the mid-point between the highest (USA) satiation level and the currently assumed satiation level as the terminal per capita floorspace demand.
Cooling demand per unit floorspace	The satiation values in the USA are assumed to be 10% higher than the present demand levels in 2010. Other regions' satiation levels are assumed to be the maximum of the base-year levels and the satiation levels in the USA, modified for inter-regional HDD/CDD differences (see Equations 10 and 11 and Section 6 of the Supplementary Material).	Satiation levels are set to the mid-points between present-day levels and the Base Case satiation levels.	Satiation levels unchanged from Base Case but satiation is approached more rapidly by calibrating the demand function such that the income level at which 50% cooling service satiation is achieved is $15,000.

9.2 Sensitivity Scenario Results

Due to similarities between the residential and commercial sectors in both the implementation and in the outcomes of the sensitivity scenarios, the present section focuses initially on the residential sector, and concludes with analysis of the combined sectors. Figure S10 shows the evolution in floorspace demands, highlighting the differences between the baseline and the sensitivity scenarios. In high-floorspace regions such as the USA and Canada, the scenarios are not remarkably different, but in regions that have low present-day floorspace demands, and are assigned low future satiation levels in the Base Case (e.g., India, Sub-Saharan Africa, Brazil, and Other Latin America), the LO scenarios have 20% less floorspace than the baseline scenarios, and the HI scenarios have between 10% and 15% more floorspace than the baseline scenarios.

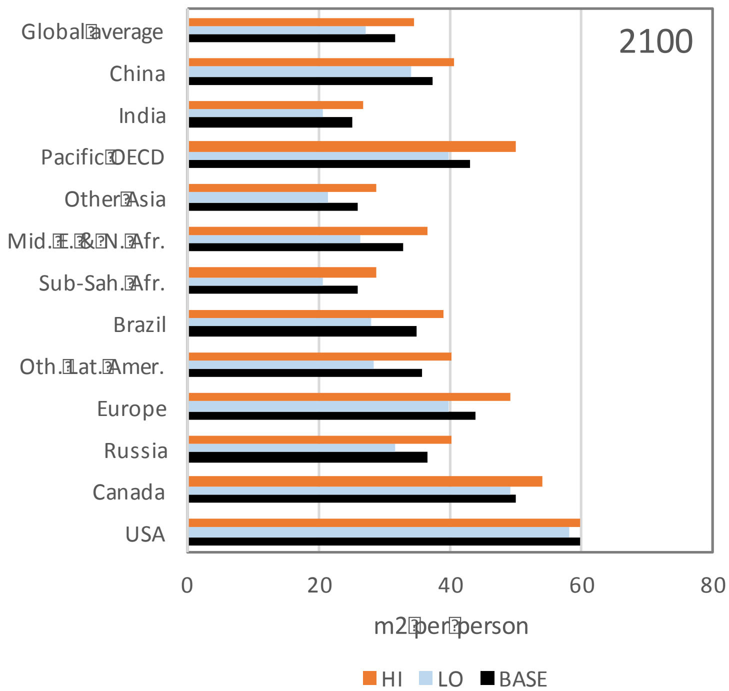

Figure S10. Residential floorspace demand per capita in 2100 for each of the three demand level sensitivities

The per-capita residential cooling demands associated with these scenarios are shown in Figure S11. Here again, regions at or near their satiation levels in the base year (e.g., the USA, Canada, and to some extent the Middle East and North Africa) do not vary considerably across this scenario set, but the regions that have low base-year demands and warm climates do show considerable variation. Global average residential cooling service demand is increased by 26% in the HI case, and reduced by 42% in the LO case, as compared with the BASE case. The remainder of this section analyzes how these increases or decreases in fundamental service demand levels affect climate change impacts on the buildings sector, globally and regionally.

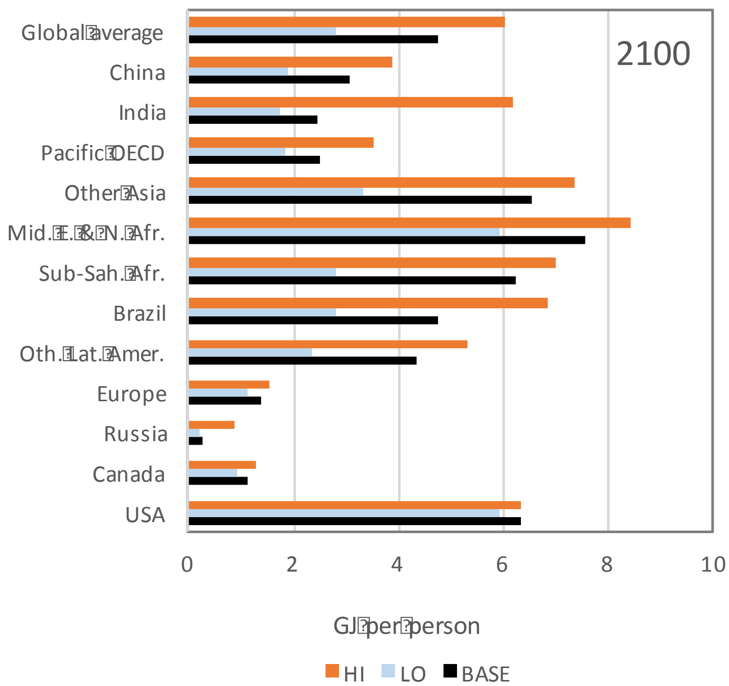

Figure S11. Residential sector cooling service demand per capita for each of the three demand level sensitivities without climate change (Fixed Climate).

The effect of the underlying building service demand levels on climate change impacts on buildings energy consumption are addressed in Figure S12. Following the approach in the main text, the climate impacts on energy consumption for each of the three demand levels are computed as the difference between total energy consumption in the 8.5 Climate and Fixed Climate Scenarios. For simplicity, Figure S12 aggregates the sectors (residential, commercial) and services (heating, cooling).

Wealthy regions whose base-year cooling demands are at or near the assumed satiation levels (USA, Canada, Europe, and the Middle East) do not show strong variation in the different future demand levels; this outcome is consistent with the degree of variation in floorspace shown in Figure S10, and in cooling service demands shown in Figure S11. In contrast, the energy consumption impacts of climate change do depend on the evolution of underlying building service demand levels in other regions, particularly developing economies with warm climates (e.g., India, Other Asia, Sub-Saharan Africa, Brazil, and Other Latin America). As shown in Figure S12, the climate impacts on energy consumption are reduced by about 40% for the LO cases, and increased by 20% to 30% for the HI cases. The divergent result for Russia—i.e., the low-demand scenario has greater climate-related impact than the baseline—is because the low-demand scenarios have lower floorspace and therefore less heating demands; with less floorspace, there is less climate change-related reduction in these heating service demands. This effect is only seen in Russia among the regions considered due to its especially high ratio of heating to cooling demands.

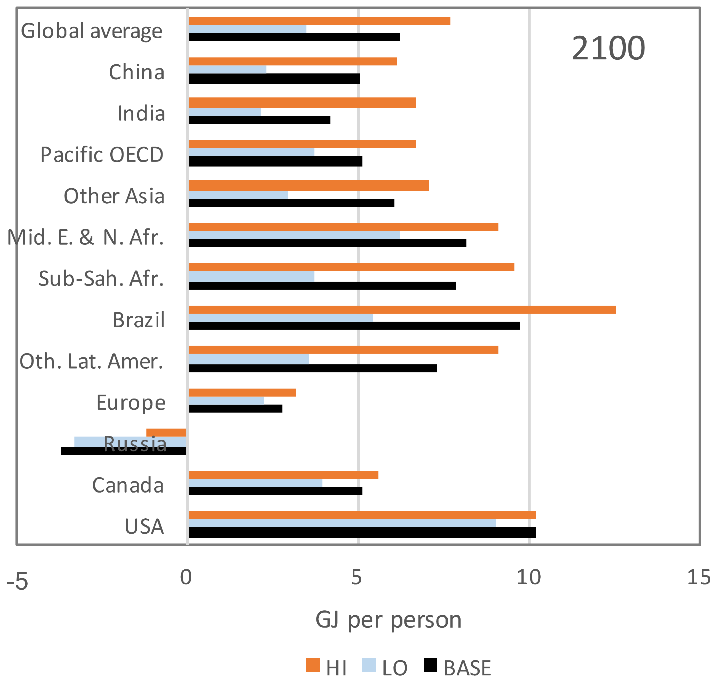

Figure S12. Change in total buildings sector energy consumption per capita between the 8.5 Climate and Fixed Climate Scenarios, for each of the three demand level sensitivities.

Finally, Figure S13 examines the effects of the changes in service demand levels for climate impacts on building heating and cooling expenditures. The results for expenditures are consistent with what was shown in Figure S12 for energy service demands. In general, the climate impacts on energy service demand and expenditures scale with the fundamental demand levels; at the global level, increasing residential cooling service demands by 26% led to increases in climate change related energy service demand of 23%, and increases in climate change related expenditures of 26%. At the regional level the numbers differ considerably, but the general effects are similar; the climate impacts on energy service demand and related expenditures generally scale with the baseline (Fixed Climate) demand levels.

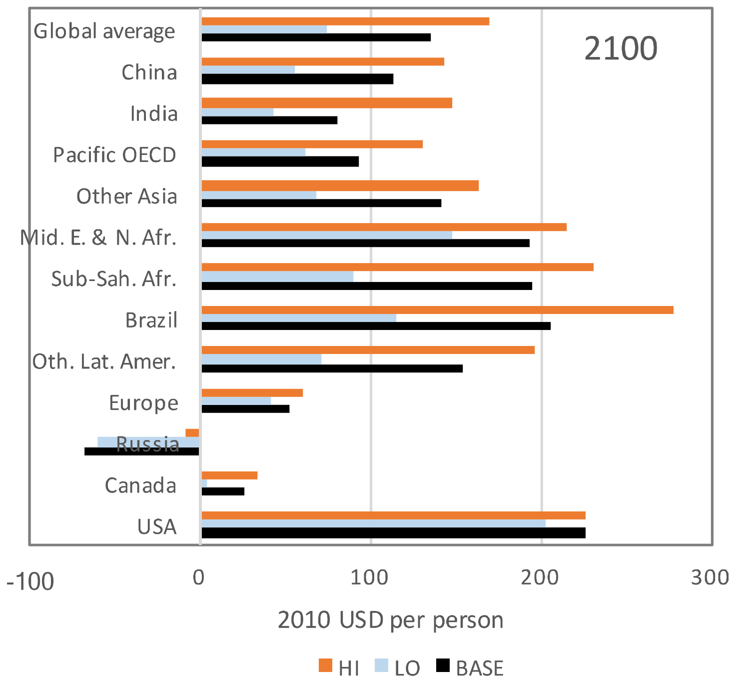

Figure S13. Change in buildings sector net heating and cooling-related expenditures in 2100 between the 8.5 Climate and Fixed Climate Scenarios, for each of the three demand level sensitivities.

10 Role of Socioeconomic Assumptions in Determining the Expenditure-Temperature Relationship

Figure 12 in the main text suggests that the net change in global building energy expenditures is an approximately linear function of global average surface temperature. Moreover, since the points derived from the 4.5 Climate Scenario trace out a path similar those traced out by the 8.5 Climate Scenario, this figure suggests that the relationship does not depend strongly on the underlying socioeconomic assumptions. Although the socioeconomic assumptions (i.e. the per capita GDP growth rates) are identical between the two climate scenarios, these scenarios achieve the same temperatures at different years and therefore at different levels of per capita income. If socioeconomic assumptions significantly affected the relationship, one would not expect the same temperature to yield the same expenditure change across scenarios, since that temperature would be associated with a different level of per capita income in each case.

Rather than conducting additional sensitivity analyses in GCAM, it is potentially more instructive to consider the underlying explanation for the observed relationship between expenditures and temperature. Equations 1 and 2 in the main text relate per capita expenditures to floorspace per capita (f) and demand per unit floorspace (d). Equations 3 and 4, in turn, express demand per unit floorspace (d) in terms of other quantities, such as the shell efficiency (η), per capita income (i) and heating or cooling degree days (*DD*). It is important to note that demand per unit floorspace (*d*) is a concave function of per capita income (*i*), while it is approximately linear in both the shell efficiency (η) and degree days (*DD*). Since per capita floorspace (*f*) is also a concave function of per capita income (*i*) as shown in Figure S5, it is plausible that the product ($d \cdot f$) would give rise to an approximately linear function in per capita income. In this case, per capita demand (and thus per capita expenditures, assuming service prices do not change significantly) would be a linear function of shell efficiency (η), per capita income (*i*) and heating or cooling degree days (*DD*). By dividing that relationship through by per capita income (*i*), one would find that expenditures as a share of income would be a linear function of shell efficiency (η) and heating or cooling degree days (*DD*). An important implication of this relationship is that the share of a region's income expended on heating and cooling of buildings is independent of the per capita income level, or put differently, that differences in per capita income trajectories (i.e. in different socioeconomic scenarios) are not likely to affect the expenditure-temperature relationship, which is consistent with the finding in Figure 12.

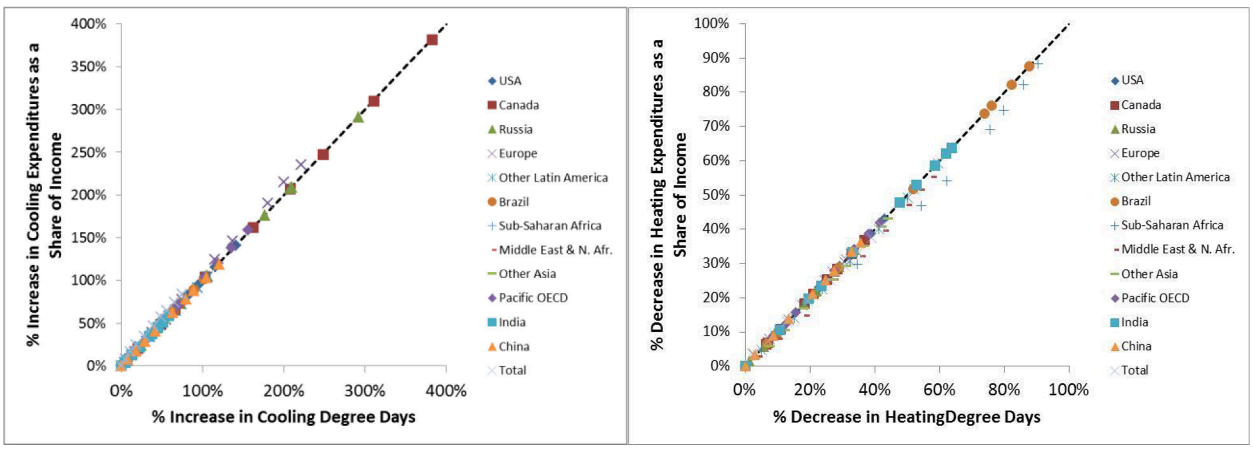

Figure S14. Percent increase in the cooling expenditures (as a share of income) as a function of the percent increase in cooling degree days (left-hand panel) and percent decrease in heating expenditures (as a share of income) as a function of the percent decrease in heating degree days (right-hand panel). Percent changes are reported with respect to the Fixed Climate Scenario. For a given region, the different data points associated with that region reflect information from different years between 2010 and 2100. The dashed line has a slope equal to one.

If expenditures as a share of income are linearly related to degree days, then the percent change in expenditures would equal the percent change in degree days. Figure S14 plots this relationship for the 8.5 Climate Scenario. An important implication of this finding is that the percent change in expenditures as a share of income can be estimated given only information about the percent change in degree days. Put differently, the additional expenditure on heating and cooling as a share of income can be estimated given only information about the baseline share of income spent on heating and cooling and the change in heating or cooling degree days.

As an example, if global cooling expenditures as a percent of income are approximately 0.6% (as they are over much of the century in the fixed climate scenario), then a 35% global increase in cooling degree days (achieved in 2050 in the 8.5 Climate Scenario when the temperature increase from preindustrial is approximately 2.5 degrees) would increase expenditures as a share of income by ~0.21%. If, at the same time, global heating expenditures as a percent of income are approximately 0.4% (as they are in 2050 in the Fixed Climate Scenario), then a 20% global decrease in heating degree days (achieved in 2050 in the 8.5 Climate Scenario) would decrease expenditures as a share of income by ~0.08%. The net effect of these two changes would be an increase in total building energy expenditures (as share of income) of ~0.13%, which is consistent with Figure 12 in the main text.

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