The effect of global climate change, population distribution, and climate mitigation on building energy use in the U.S. and China

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Abstract Climate change will affect the energy system in a number of ways, one of which is through changes in demands for heating and cooling in buildings. Understanding the potential effect of climate change on heating and cooling demands requires taking into account not only the manner in which the building sector might evolve over time, but also important uncertainty about the nature of climate change itself. In this study, we explore the uncertainty in climate change impacts on heating and cooling requirement by constructing estimates of heating and cooling degree days (HDD/CDDs) for both reference (no-policy) and 550 ppmv CO_2 concentration pathways built from three different Global Climate Models (GCMs) output and three scenarios of gridded population distribution. The implications that changing climate and population distribution might have for building energy consumption in the U.S. and China are then explored by using the results of HDD/CDDs as inputs to a detailed, building energy model, nested in the long-term global integrated assessment framework, Global Change Assessment Model (GCAM). The results across the modeled changes in climate and population distributions indicate that unabated climate change would cause building sector's final energy consumption to decrease modestly (6 % decrease or less depending on climate models) in both the U.S. and China by the end of the century as decreased heating consumption more than offsets increased cooling using primarily electricity. However, global climate change virtually has negligible effect on total CO_2 emissions in the buildings sector in both countries. The results also indicate more substantial implications for the fuel mix with increases in electricity and decreases in other fuels, which may be consistent with

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climate mitigation goals. The variation in results across all scenarios due to variation of population distribution is smaller than variation due to the use of different climate models.

1 Introduction

Integrated assessment of global climate change has traditionally focused on the greenhouse gas emissions arising from energy systems and related human activities and the associated contribution of these activities to global climate change. Yet, there is an increasing acknowledgement that a changing climate will also influence the energy system (Scott and Huang 2007; Mideksa and Kallbekken 2010; Wilbanks et al. 2007), and meaningful integrated assessment must consider these feedbacks particularly when assessment is focused at a regional, sector-specific level and over a longer time frame (Wilbanks et al. 2008).

The buildings sector is particularly susceptible to climate feedbacks because of its significant demand for space conditioning energy, which are directly related to temperature change, as well as other climatic factors. In the U.S., space conditioning energy consumption - heating and cooling energy, not including water heating and ventilation - accounts for about 49 % of all final energy in residential buildings and 44 % in commercial buildings in 2005 (Kyle et al. 2010). Final energy demand for space conditioning in China, the second biggest building energy consumer following after the U.S., is estimated to be around 30 % in residential buildings and 55 % in commercial buildings in 2005 (Eom et al. 2012). All else being equal, with increasing temperature, heating energy consumption will decrease, and cooling energy consumption will increase. Because of the two competing effects, it is not straightforward to predict whether climate change will cause net energy consumption for space conditioning to increase or decrease in the future. Further, the balance between these effects will differ across countries, because of differences in the balance of heating and cooling requirements.

To date, several analyses have addressed the long-term implications of climate change for building energy use patterns. For example, Amato et al. (2005) explored regional building energy demand responses to climate change by assessing demands for electricity and heating fuels in the Commonwealth of Massachusetts, and found notable changes in overall building energy consumption and its energy mix. Sailor (2001) related climate change to electricity consumption in eight U.S. states and drew out mixed results. Olonscheck et al. (2011) accounted for future changes in climate and building stock in Germany and projected a shift of German energy demand from primary energy toward electricity caused by decreased heating energy demand and increased cooling energy demand. Mendelsohn et al. (2000) developed a climate-impact model to generate country-specific impacts by market sector, predicting that the results vary by country. Scott and Huang summarized the effects of climate change on building energy use from approximately 20 studies that use either building energy simulation models or econometric models for energy consumption choices (Scott and Huang 2007).

These studies, however, are mostly based on historical energy consumption sensitivities to climate variations, which may obscure underlying patterns of economic growth, population growth and distribution, land use, and technological change. Representation of long-term socioeconomic transformation and energy service expansion is an important part of climate impact assessment particularly for emerging economies such as China and India. Increasing urbanization may lead to a sizeable shift in building energy mix away from very inefficient traditional fuels (Krey et al. 2011). Continued income growth and climate change might lead to different patterns of space cooling and heating energy consumption, although space cooling currently accounts for a much lower share of building energy consumption than space heating in those developing countries.

There are limited studies addressing the effect of a changing climate on building energy demands while simultaneously accounting for these important facets of evolution in the underlying human systems. One notable exception is Isaac and Van Vuuren (2009). They assessed global energy consumption for residential heating and air conditioning under climate change, based on a saturation model for heating equipment and air conditioners with socioeconomic and climate data taken from one integrated assessment model's scenarios. Based on the same climate dataset, Van Ruijven et al. (2011) employed a full residential energy use model to project household energy demand in India, and Daioglou et al. (2012) expanded the work to other developing regions. Our study follows their work by exploring the effects of climate change on building energy demands within an integrated assessment modeling framework, in this case the Global Change Assessment Model (GCAM)   (Edmonds et al. 2004).

This study distinguishes itself from previous works in two ways (Daioglou et al. 2012; Isaac and van Vuuren 2009; van Ruijven et al. 2011). First, instead of calculating the changes to heating and cooling demands independent of or soft-linked to the integrated assessment model, we employ an explicit, detailed, service-based building energy model representing urbanization, income growth, and energy service expansion, nested inside the integrated assessment framework. This allows for more explicit consideration of the underlying evolution of the building sector, and the explicit incorporation of climate change at a structural level within an integrated assessment modeling framework is an important step forward toward a new generation of integrated assessment model that will consider mitigation and impacts simultaneously. Second, this study explores two major sources of uncertainty that could potentially broaden our understanding about the impact of climate change on buildings. The first is uncertainty across climate models regarding the effects of increased greenhouse gas concentrations on climate, particularly at a regional level. The second is uncertainty about how populations may be distributed spatially in the future, as a result of migration and heterogeneous population growth. The remainder of this paper summarizes our research approach including scenario design, raw and population-weighted HDD/CDDs calculation (Section 2) and climate impacts on building energy consumption, fuel use, and CO_2 emissions in the U.S. and China (Section 3), and concludes with final remarks (Section 4).

2 Heating and cooling degree day scenarios

2.1 Overview of approach

The HDD/CDD scenarios developed for this study are constructed to explore the implications of a changing climate on HDD/CDDs in China and the U.S., with explicit consideration of three factors: (1) the nature of the global greenhouse gas concentration pathways determined by SRES emissions scenarios, (2) lack of certainty about the nature of climate change under any CO_2 concentration pathway as represented by differences in GCM outputs, and (3) the degree to which population distribution in the future might look different than it does today. A total of 18 scenarios are explored, representing permutations associated with two concentration pathways (a "reference" concentration pathway and a 550 ppmv CO_2 concentration pathway), three climate model representations of the associated climate change (CCSM3, GISS, and Hadley), and three population distribution scenarios (A2r, B1, and Fix). The entire framework of the HDD/CDDs scenario development and its nomenclature are illustrated in Fig. 1.

The first dimension is the nature of the greenhouse gas concentration pathway. The two concentration pathways explored in this study are a 550 ppmv CO_2 concentration pathways
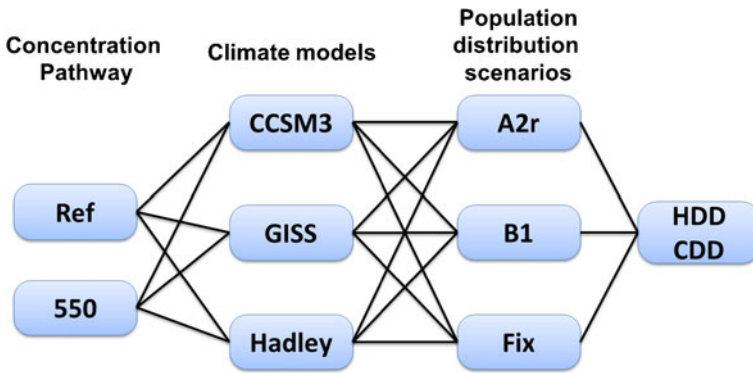
Fig. 1 The three components of scenario design: concentration pathways, climate models, and population distribution scenarios

and a "reference" concentration pathway. In the latter case, concentrations continue to rise throughout the century in a manner that would be consistent with generalized technological progress throughout the global economy leading to a more efficient energy system without any explicit measures designed to control greenhouse gas emissions. Two concentration pathways, A2 and B1, developed by Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) (IPCC 2000) were used as the basis for this analysis. We used the SRES A2 concentration pathway (about 850 ppmv in the end of 21st century) to calculate reference scenario HDD/CDDs for use in the GCAM simulations because the business-as-usual case of the version of GCAM used for this study is largely consistent with the SRES A2 marker concentration pathway (Nakicenovic et al. 2000; IPCC 2000). The SRES B1 concentration pathway was used to calculate HDD/CDDs for the 550 ppmv CO_2 GCAM simulations since this concentration pathway most clearly resembles a pathway that would lead to 550 ppmv CO_2 stabilization. Details about the A2 and B1 concentration pathways are described in **SI** 1. These two concentration pathways have been replicated by the GCAM integrated assessment framework.

The second dimension explored in this study is the nature of future climate change associated with a given global concentration pathway. The fact that GCMs provide different results for any given concentration pathway raises the question of how sensitive heating and cooling requirements might be to the choice of GCM used to conduct the analysis. The three climate models chosen for this study were CCSM3 from National Center for Atmospheric Research, USA (Collins et al. 2006), GISS from NASA/Goddard Institute for Space Studies, USA (Russell et al. 2000), and Hadley from Hadley Centre for Climate Prediction and Research/Met Office, UK (Gordon et al. 2000). The three climate models and their results are discussed further in **SI** 1.

The final dimension of the scenario design is the change in population distribution. A change in population distribution, by itself, can lead to differences in HDD/CDDs even absent changes in the climate as populations move to hotter or colder climates. To capture the potential effect of population distribution change on HDD/CDDs, not of population size, we chose three future population distribution scenarios: two gridded population scenarios (A2r and B1) developed by International Institute for Applied Systems Analysis (IIASA) in which the distribution evolves over the 21st century and one hypothetical scenario (Fix) in which population distribution in 2000 is held constant throughout the century. A2r is a revised "high-growth" scenario A2 with adjustment according to the most recent

demographic literature (Grübler et al. 2007). The three population scenarios and their differences are highlighted in **SI** 1. Note that the same total population path at regional level is assumed for all of the scenarios to control the effect of population size.

2.2 Raw HDD/CDDs

Before presenting HDD/CDDs that integrate all of the three scenario components, we show in this section how raw annual HDD/CDDs are calculated for each grid cell. Degree-days are essentially the summation of temperature differences from a human comfort level over time, and hence they capture both extremity and duration of difference between outdoor temperatures and reference temperatures (Baumert and Selman 2003; Day 2006). Degree-days are a metric that indicates building heating or cooling requirements (Büyükalaca et al. 2001). For example, a "set point" of 18 °C (65 °F) is commonly used as the reference temperature of the metric (Baumert and Selman 2003; Isaac and van Vuuren 2009), so that HDD and CDD are measured in degree-days below (HDD) and above (CDD) the set point. It is worth to note that different values of reference temperature have been used in previous studies such as 22 °C used by Giannakopoulos and Psiloglou (2006).

The challenge is that HDD/CDDs are calculated from daily temperature, whereas projected long-term temperature is generally available at monthly level. We developed a method to calculate spatially explicit HDD/CDDs using the standard deviation of daily mean temperature estimated from the historical daily data, in combination with monthly mean temperature projected by climate models. This method attempts to capture the variability in daily temperature within different months of year for temporal and spatial heterogeneities of HDD/CDDs. The method and the spatial distribution of changes in HDD/CDDs across the global are detailed in **SI** 2.

2.3 Population-weighted HDD/CDDs

What matters for heating and cooling requirements in buildings is not just what the distribution of HDD/CDDs is in an abstract sense, but also who is living where. In this study, we calculated the population-weighted HDD/CDDs for 14 regions defined by GCAM. The method of and resulting temporal change in population-weighted HDD/CDDs (henceforth, HDD/CDDs will refer to population-weighted HDD/CDDs) are discussed at the global level in **SI** 3.

The impact analysis on the buildings sector in this study focuses on China and the U.S. The trends in the HDD/CDDs in these two study regions support three important points (Fig. 2). First, all of the global trends are maintained: HDDs decrease over the century and CDDs increase; and the reference concentration pathway exhibits a more pronounced effect than the 550 ppmv CO_2 concentration pathway. Second, although the U.S. continues to have higher HDDs and lower CDDs than China, the two regions broadly agree in terms of the rates of changes in HDD/CDDs over the century particularly in the reference concentration pathway with Fix population distribution. This potentially allows for the examination of how the two countries at different stages of development might play out in response to similar climate change impacts, a topic we will take up in Section 3. Third, the effect of the shift in population distribution on HDD/CDDs is much more pronounced in China than in the U.S., and the effects operate in opposite directions. This is because the population scenarios project that, in China, population re-distribution mainly occurs between areas with steep temperature gradient, generally from colder (or 'less-hot') areas to warmer (or 'less-cold') areas mostly concentrated in the eastern urban areas, accelerating the decrease in HDDs and
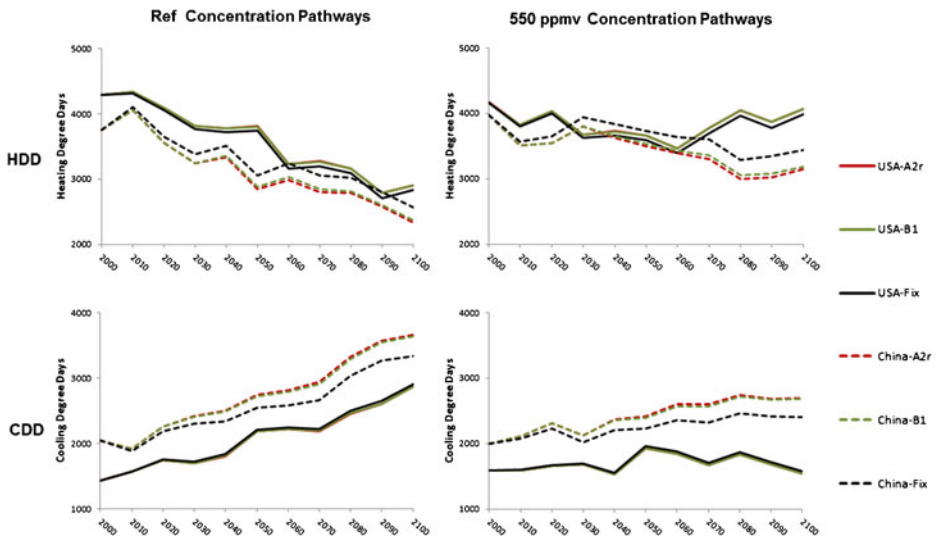
Fig. 2 Population-weighted HDD/CDDs (CCSM3) for the U.S. and China in the reference and the 550 ppmv concentration pathways

the increase in CDDs (see **SI Fig**. 1). In the U.S., however, the impact is relatively small and even reversed because urbanization and urban sprawls occur in relatively small areas evenly distributed across the country.

3 Modeling building energy consumption in GCAM

This section explores how changing HDD/CDDs might interact with energy demands in the buildings sector and the energy system as whole in China and the U.S. by using technologically-detailed, service-based building energy models for both China and the U.S. (Eom et al. 2012; Kyle et al. 2010), nested in the long-term, global, integrated assessment framework, GCAM (Edmonds et al. 2004). The model allows for countries in different development stages demanding different heating and cooling services even under the same set of HDD/CDDs. The description about the building models can be found in **SI** 4.

There are several advantages of implementing such a detailed buildings model within an integrated assessment framework for the cases of the U.S. and China. First, as an integrated assessment model, it allows for proper representation of technology substitution driven by the change in relative energy prices and the likely effects of climate mitigation policy on energy prices and attendant energy service demand. Second, aside from the two countries' significance in global energy consumption, they have relatively large geographical coverage that could potentially make the effects of global climate change and population distribution more pronounced, providing more broadly applicable insights. Third, the cases of the U.S. and China provide a useful comparison because they are relatively similar in terms of the balance between HDD and CDD but are in drastically different status of economic development, technology, and fuel choice. This allows us to gain insights into how the two different countries might react to global climate change and also to policy measures to mitigate the change.

   The 18 different pathways of HDD/CDDs described in Section 2 were used as inputs to the building energy model embedded in GCAM. One necessary condition for linking HDD/CDDs estimated based on the two concentration pathways with the GCAM building energy model is to ensure that GCAM is run under emissions constraints that lead to the same concentrations as those in the two pathways. The process of establishing the consistency is detailed in **SI** 5.

3.1 Building energy consumption in the U.S. and China

Buildings in the U.S. and in China, in particular, will experience increasing share of electricity during the 21st century even without a climate policy (Fig. 3). The increased role of electricity in building energy demand occurs because of the penetration of electricity-based services such as space cooling and appliances and, to a lesser extent, service-level substitution toward electricity away from other fuels occurring over the century. The penetration of electricity-based services occurs much faster in China than in the U.S. because China is further away from its saturation point and also experiences faster income growth and urbanization over the century. This resulted in per capita energy demand continuing to increase in China over the century, which is different from the steadily decreasing per capita energy demand in the U.S. due to its relatively modest income effect dominated by the improvement of technology efficiencies. The results also indicate that the overall development of fuel mix in the buildings sectors between the two countries will continue to be very different. While the U.S. buildings sector depends on several major modern fuels (electricity, gas, and oil) with relatively stable shares, the Chinese buildings sector continues to demand various fuels, and its fuel shares change rapidly even in the absence of carbon mitigation policy, although the carbon policy accelerates the transition (Eom et al. 2012). This distinctive behavior in China buildings can be explained by the different growth rates of individual service demands, service-level fuel substitution, and increasingly less use of traditional energy[1] associated with urbanization. Note that these two dynamics occur irrespective of a changing climate.
   Climate change interacts with these dynamics. The results indicate that a changing climate causes both the U.S. and China buildings to reduce their final energy consumption. This is because the increase in cooling energy use is less than the decrease in heating energy use. The demand for electricity, by which nearly all of cooling service is delivered, increases with the climate change, whereas the demand for other major heating fuels, such as gas in the U.S. and district heat and coal in China, decreases with the climate change (Fig. 3). Note that, at a primary energy level, the effect is somewhat different, as we will discuss later.
   We now return to the broader set of climate change, climate policy, and population distribution scenarios laid out in Section 2.1. Although the level of reduction in building final energy demand varies across the climate models, in the reference emissions scenarios, it is about 6 % or less by the century-end in both of the countries in comparison to the case without climate change feedback (**SI Fig**. 5). The reduction becomes almost negligible in the 550 ppmv CO_2 scenario, regardless of the climate models, largely because the mitigation policy leads to less global warming—a slower increase in CDDs and a slower decrease in HDDs.

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[1] Traditional energy refers to unsustainable use of wood, charcoal, agricultural residues, and animal dung for cooking and heating in the residential sector (Edenhofer et al. 2011). Its typical conversion efficiency is substantially lower than other commercial fuels.
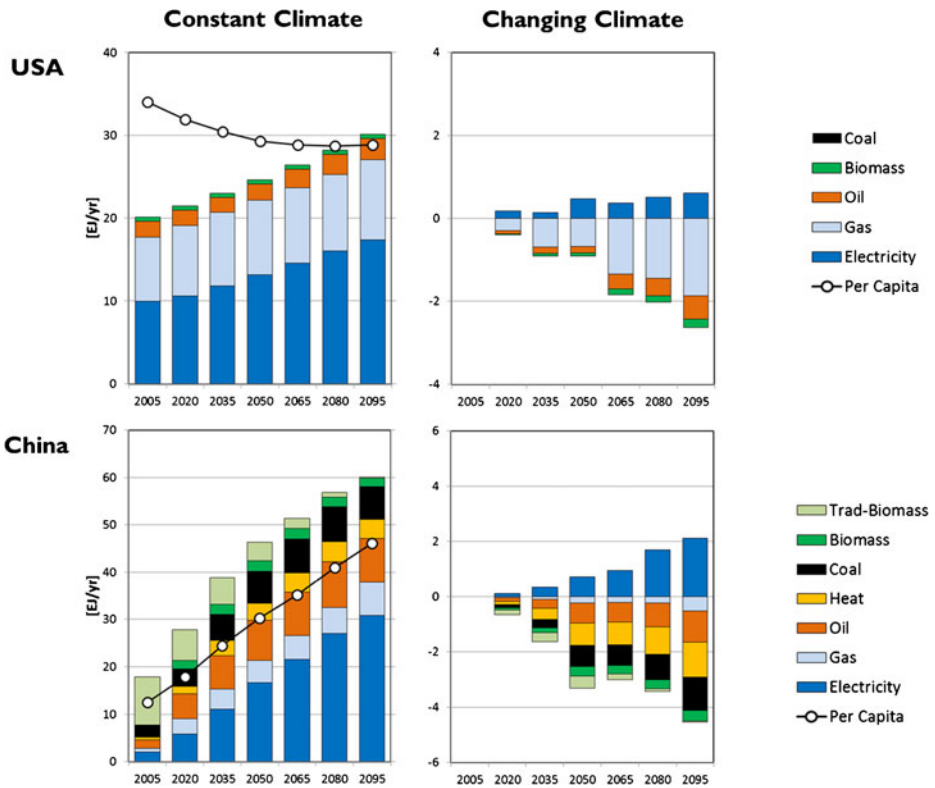
Fig. 3 Absolute and per capita building energy demand by fuel in the U.S. and China in GCAM reference emissions scenario with constant and changing climate (CCSM3 and Fix population distribution)

Overall, the effect of climate change on building energy demand is not substantial. This is because heating and cooling energy uses, which collectively account for less than half of total building energy consumption in both countries, shift in the opposite direction, balancing out each other. The impact on heating and cooling energy demands tend to increase over time with the net impact remaining negative during the century. A similar result emerges when heating and cooling energy demands are examined from a century-long, cumulative perspective (Fig. 4).[2] It is important to note that the lack of a major effect at the aggregate level does not necessarily mean that the magnitude and characteristics of the impacts are also small at the sub-regional level. For example, some parts of the U.S. may experience extreme heating events requiring sustained expansion in electricity supply, while many other parts may experience only a modest decline in heating energy consumption. This is a limitation of aggregate-level energy analysis, such as the analysis conducted in this study.

A major uncertainty in the effect of anthropogenic emissions on building energy demands is uncertainty about the nature of climate change associated with any long-term emissions pathway. Although runs from multiple climate models may not necessarily constitute a full

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[2] A similar trend was observed when we compare cumulative heating and cooling energy demands through 2050, a time horizon that policy makers might have on their agenda, although the net impact is smaller than the century-long cumulative value.
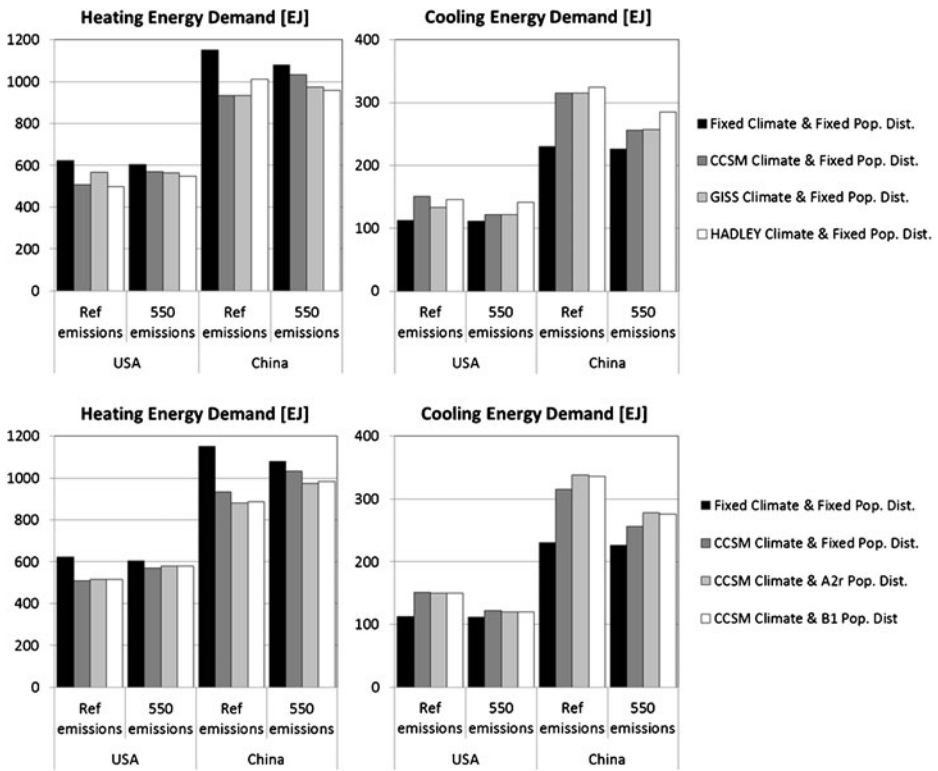
Fig. 4 Cumulative final energy demand for heating and cooling in the U.S. and China buildings by GCAM emissions scenarios by climate model (all Fix population distribution) (*top*) and by population distribution (all CCSM3) (*bottom*)

spanning of uncertainty space, the results indicate that choice of climate model represents a major uncertainty with respect to building energy demand and the general trends are consistent across the models (Fig. 4). In the reference scenario, climate change generally results in a larger increase of cooling energy use in China than in the U.S., while the decrease in heating energy use is about the same in both countries. Depending on the climate models, the U.S. has a 20–35 % increase in cooling energy use and 9–20 % savings in heating energy use, whereas China has a 37–41 % increase in cooling energy use and 12–19 % savings in heating energy use (Fig. 4). This is interesting result because, in the reference scenario, HDDs and CDDs change roughly at the same rates in the two countries. The reason for the asymmetric energy response is that different from heating service, cooling service is far less ubiquitous in China than in the U.S.; when increased CDDs induced by the climate change is combined with China's rapid income growth, cooling service and associated cooling energy use will grow faster in China than that in the U.S. during the 21st century. With abated emissions (i.e., 550 ppmv scenario), however, the trends in heating and cooling energy uses are not noticeably different between the two countries as the magnitude of the impacts becomes relatively small in both countries.

Changes in the distribution of population between colder and hotter regions can also alter building energy demands. However, the three different population distribution scenarios (Fix, A2r, and B1) did not results in meaningfully different impacts on heating and cooling

energy use (Fig. 4). Still it is interesting to note that changing population distribution itself may have qualitatively different implications for heating and cooling energy consumption. With the increased population density in 'less-cold' areas relative to the Fix population distribution case, the China buildings sector demands less heating energy and more cooling energy; but the effect is modestly reversed in the U.S. buildings sector. This is supported by the findings about HDD/CDDs that the change in population distribution accelerates the decrease in HDDs and the increase in CDDs in China; but in the U.S., while not significant, the effect slows down the decrease in HDDs and the increase in CDDs (Fig. 2). Note that the minor impact of the change in population distribution is a direct result of the population distribution scenarios used in this study. A range of alternative scenarios with greater population movements than the current scenarios could be explored. .

3.2 Fuel consumption and CO_2 emissions

Global climate change and the associated shift in heating and cooling energy use also have important implications for fuel mix. Because of the changing climate, electricity consumption increases in the buildings sector, whereas the consumption of all other direct fossil fuels decreases (Fig. 5). This is because cooling service is almost entirely delivered by electricity, whereas heating service is delivered by various primary or secondary fuels. Given that the choice of population distribution scenarios is less important than the other sources of uncertainties for the analysis of climate impacts on buildings, we now focus on the sensitivities to climate models and concentration pathways.

The fuel composition of heating energy savings is, however, vastly different between the two countries. Savings in heating energy in the U.S. buildings sector imply less use of several major fuels (gas, oil, biomass, and electricity), predominantly delivered gas, whereas savings in the China buildings sector come from more diverse, more evenly distributed sources, ranging from direct fossil fuels (coal, oil, and gas) to secondary fuels (district heat) and carbonaceous fuels (commercial and traditional biomass). This suggests that global climate change itself may help decarbonize the sector by reducing on-site fossil-fuel use for
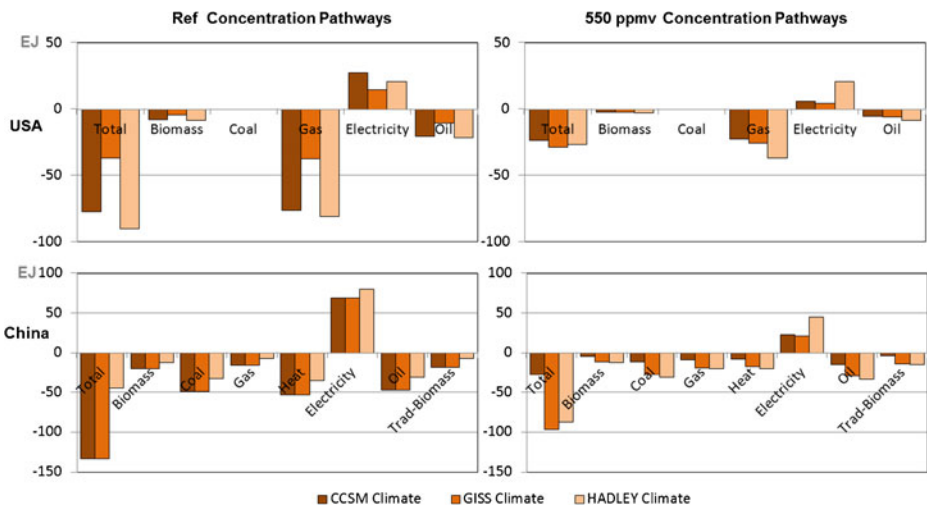

Fig. 5 Climate change effects on the U.S. and China buildings' cumulative fuel consumption (Fix population distribution)

space heating, and that the effect would be more pronounced in China than that in the U.S. (Fig. 6a). Note also that the direct effect of a climate policy is noticeable only in China, which is much more carbon-intensive than the U.S.

Treatment of emissions only at the end use, however, neglects the emission that result in the production of electricity. It is therefore useful to look at the effect of global climate change not simply at the direct emissions levels, but also at the level of total CO_2 emissions that account for power sector emissions attributable to building energy demand. When emissions from the electricity sector are also taken into account, global climate change virtually has negligible effect on CO_2 emissions in the buildings sector in both countries (Fig. 6b). The reason is that the emissions reduction due to savings in direct use of heating fuels is offset by the emissions increase due to increased electricity use by air conditioning. This is because power generation will continue to be fossil-fuel intensive, particularly coal intensive, in both countries without any carbon policy. Note, however, that climate policy required to achieve 550 ppmv pathway now plays a major role in reducing total CO_2 emissions in the sector in both countries by promoting increased use of progressively decarbonized electricity. This is because the carbon policy leads to increased deployment of low-carbon technologies including nuclear power, fossil energy installed with CCS, bioenergy, and non-biomass renewable energy such as wind power and solar power. This rapid de-carbonization of the power sector is a well-known dynamic in previous mitigation studies (Edmonds et al. 2006). The effect of abated climate change itself under 550 scenario remains much smaller than the effect under reference scenarios or the effect of the carbon policy in terms of both direct and total emissions.[3]

4 Conclusions

This study has explored the influence of a changing climate on building energy demands and associated CO_2 emissions in China and the U.S. by coupling a range of possible pathways of population-weighted HDD/CDDs with the detailed, service-based building energy model nested in the GCAM integrated assessment framework. The influence has been examined in the context of three factors: the degree of climate mitigation, limitations in our knowledge about climate science as expressed in differences in global climate change across climate models, and change of population distribution over time.

In general, the results confirm intuition and previous studies in several areas. They confirm that global climate change will cause an increase in CDDs and a decrease in HDDs both at the global and regional levels. In countries such as China and the U.S. with relatively balanced requirements for heating and cooling, the climate change has a modest effect on total building energy consumption (6 % decrease or less depending on climate models) as decreased heating more than offset increased cooling, and the effect becomes even smaller in emissions mitigation scenarios. However, a changing global climate does have a pronounced effect on the mix of energy carriers in the buildings sector with a movement toward electricity. It is also found that although HDD/CDDs trends are similar in the two countries, their effects on heating and cooling energy demands vary because the countries are currently at different stages of development, resulting in differences in the expansion of cooling demand over the century and its interaction with the climate change.

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[3] Abated climate change (550 ppmv) decreases cumulative direct CO_2 emissions (2005–2095) by 2–3 %, compared to the effect of full climate change of around 11 % in both countries. The numbers become much smaller in terms of cumulative total emissions.
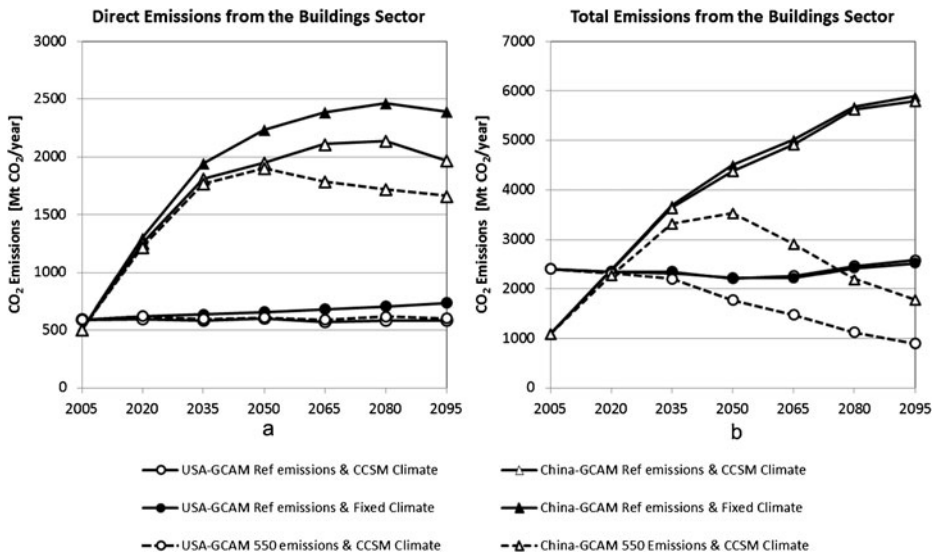
Fig. 6 Direct (**a**) and total (**b**) CO_2 emissions from the U.S. and China buildings sector under the GCAM reference emissions scenario using constant and changing HDD/CDDs and under the GCAM 550 emissions scenario using changing HDD/CDDs (Fix population distribution)

The results also confirm that our incomplete understanding about climate science exacerbate the uncertainty in the effect of a changing climate on building energy demands. Yet, the climate change effect is clearly discernible across all selected climate models and population distribution scenarios. However, there are two caveats. First, the model projections that were used to represent climate change do not effectively represent a full range of uncertainty in climate change, so the true effects could be either larger or smaller than in this study. Second, more importantly, the scenarios of population distribution over time, although coming from the only established set of long-term scenarios in the literature, were developed using relatively simple methods, for which further improvement is also needed. Nonetheless, as a first comparison of these two effects, the results do tend to indicate that climate change is the larger of the two effects.

Last, even without mitigation policy, climate change would reduce direct fossil-fuel use for space heating, helping decarbonize the buildings sector in terms of on-site emissions, although emissions from electricity use would increase at the same time. When emissions from the electricity sector are also taken into account, global climate change may have little effect on the total CO_2 emissions. This implies that building CO_2 emissions in the U.S. and China often projected by conventional integrated assessment models may not necessarily over- or under-estimate the entire dynamics that takes into account climate change impact.

The progress in building energy modeling in this study has been made at the expense of several limitations. Most notably, we employed a set of average buildings located in an average climate region to analyze the climate impact on building energy demand at the national level. Disaggregating the buildings sector, for instance, into several distinct climate sub-regions exhibiting different pathways of HDD/CDDs, may offer more useful insights into local energy system planning. Second, as discussed above, we chose only three sets of population distribution scenarios. However, this dataset may not capture the likely characteristics of climate-driven migration within or beyond the country level, which might be

important drivers of migration particularly for rapidly urbanizing countries with large geographical coverage. Third, the study examined the effect of changing climate on gross energy consumption, not on the temporal and spatial characteristics of heating and cooling load. For instance, heat waves would increase peak load, resulting in different technology investment profiles and CO_2 emissions. Together with the urbanization-induced population redistribution, such events might have even larger impact on building energy use, additional investment requirement, energy price, and human health. Although the potential impact of extreme events on building energy use have been explored using mostly bottom-up models at the hourly or daily temporal resolution (Xu et al. 2009), its interaction with the nature of socioeconomic development, such as urbanization and demographic transition, has been paid little attention. Improvements in climate model data, population movement, and more detailed representation of electricity demand would greatly improve the modeling and thus help gain more comprehensive insights.

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