Journal of Building Performance Simulation
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t787187009

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Online Publication Date: 01 June 2008

To cite this Article Crawley, Drury B.(2008)'Estimating the impacts of climate change and urbanization on building performance',Journal of Building Performance Simulation,1:2,91 — 115

To link to this Article: DOI: 10.1080/19401490802182079

URL: http://dx.doi.org/10.1080/19401490802182079

Journal of Building Performance Simulation
Vol. 1, No. 2, June 2008, 91–115

Estimating the impacts of climate change and urbanization on building performance

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(*Received 23 October 2007; final version received 6 May 2008*)

Over the past 15 years, much scientific work has been published on the potential human impacts on climates. For their Third Assessment Report in 2001, the United Nations International Programme on Climate Change developed a set of economic development scenarios, which were then run with the four major general circulation models (GCM) to estimate the anthropogenesis-forced climate change. These GCMs produce worldwide grids of predicted monthly temperature, cloud, and precipitation deviations from the period 1961–1990. As this period is the same used for several major typical meteorological year data sets, these typical data sets can be used as a starting point for modifying weather files to represent predicted climate change. Over the past 50 years, studies of urban heat islands (UHI) or urbanization have provided detailed measurements of the diurnal and seasonal patterns and differences between urban and rural climatic conditions. While heat islands have been shown to be a function of both population and microclimatic and site conditions, they can be generalized into a predictable diurnal and seasonal pattern. Although the scientific literature is full of studies looking at the impact of climate change driven by human activity, there is very little research on the impact of climate change or urban heat islands on building operation and performance across the world. This article presents the methodology used to create weather files which represent climate change scenarios in 2100 and heat island impacts today. For this study, typical and extreme meteorological weather data were created for 25 locations (20 climate regions) to represent a range of predicted climate change and heat island scenarios for building simulation. Then prototypical small office buildings were created to represent typical, good, and low-energy practices around the world. The simulation results for these prototype buildings provide a snapshot view of the potential impacts of the set of climate scenarios on building performance. This includes location-specific building response, such as fuel swapping as heating and cooling ratios change, impacts on environmental emissions, impacts on equipment use and longevity comfort issues, and how low-energy building design incorporating renewables can significantly mitigate any potential climate variation. In this article, examples of how heat island and climate change scenarios affect diurnal patterns are presented as well as the annual energy performance impacts for three of the 25 locations. In cold climates, the net change to annual energy use due to climate change will be positive – reducing energy use on the order of 10% or more. For tropical climates, buildings will see an increase in overall energy use due to climate change, with some months increasing by more than 20% from current conditions. Temperate, mid-latitude climates will see the largest change but it will be a swapping from heating to cooling, including a significant reduction of 25% or more in heating energy and up to 15% increase in cooling energy. Buildings which are built to current standards such as ASHRAE/IESNA Standard 90.1-2004 will still see significant increases in energy demand over the twenty-first century. Low-energy buildings designed to minimize energy use will be the least affected, with impacts in the range of 5–10%. Unless the way buildings are designed, built, and operated changes significantly over the next decades, buildings will see substantial operating cost increases and possible disruptions in an already strained energy supply system.

Keywords: climate change; urban heat island; future simulation; weather data; historical weather

1. Introduction

Over the past 15 years, the international scientific community [as organized through the Intergovernmental Panel on Climate Change (IPCC)] has focused significant effort to characterize the potential impacts of greenhouse gas emissions from human activities (anthropogenic) on the complex interactions of our global climate. IPCC Working Group I focused on creating atmosphere–ocean general circulation models (GCM), similar to models used to predict the weather, in which the physics of atmospheric motion are translated into equations which can be solved on supercomputers. The GCMs predict climate at a relatively high level of spatial resolution ($5 \times 5^\circ$ latitude and longitude or several hundred kilometres). The four major GCMs are HadCM3 (United Kingdom), which includes a finer spatial resolution for the British Isles, CSIRO2 (Australia), CGCM2 (Canada), and PCM (USA) (IPCC 2001). In 2007, the IPCC released the fourth assessment report (AR4) (IPCC 2007). Rather than creating a new series of economic development scenarios or revising the results from the

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ISSN 1940-1493 print/ISSN 1940-1507 online

DOI: 10.1080/19401490802182079
http://www.informaworld.com

GCMs, the IPCC instead focused on the impacts of climate change, providing the strongest consensus to date on the potential impacts of climate change: 'the net effect of human activities since 1750 has been one of warming'. In this same report, the IPCC identifies buildings as the sector with the highest economic mitigation potential of any other energy sector.

The scenarios developed by the experts of the IPCC in 2001 represent the range of continued carbon dioxide and other pollutants based on specific economic and political conditions (described later). When these scenarios are then simulated within the four major GCMs, they result in 16 combinations of scenario and climate prediction. The range of potential annual average global temperature changes predicted by the GCMs using the scenarios – from 1.5 to nearly 6°C – is shown in Figure 1.

Human-induced warming at the global scale is not the only change affecting our built environment. Over the past 50 years, there has been a worldwide trend towards increasingly larger urban areas. This concentration of transportation infrastructure and buildings often results in a phenomenon labelled urban heat islands, where the average temperature within an urban area can be several degrees warmer than the surrounding, undeveloped countryside. For example, the average temperatures at London Heathrow, Los Angeles, and Phoenix have all increased by at least 1°C over the past 30 years.

For this study, typical and extreme meteorological weather data were created for 25 locations (20 climate regions) to represent a range of predicted climate change and heat island scenarios for building simulation. Then prototypical buildings were created to represent typical, good, and low-energy practices around the world. When these prototype buildings were simulated, the results provided a snapshot view of the impact of the set of climate scenarios on building performance. These include location-specific responses of the prototype buildings, including impacts on equipment use and longevity, fuel swapping as heating and cooling ratios change, impacts on environmental emissions, comfort issues, and how low-energy building design incorporating renewables can significantly mitigate any potential climate variation.

2. What are the potential impacts on the built environment?

Even with all the scientific study, little of it has pursued the potential impact of climate change on the operating

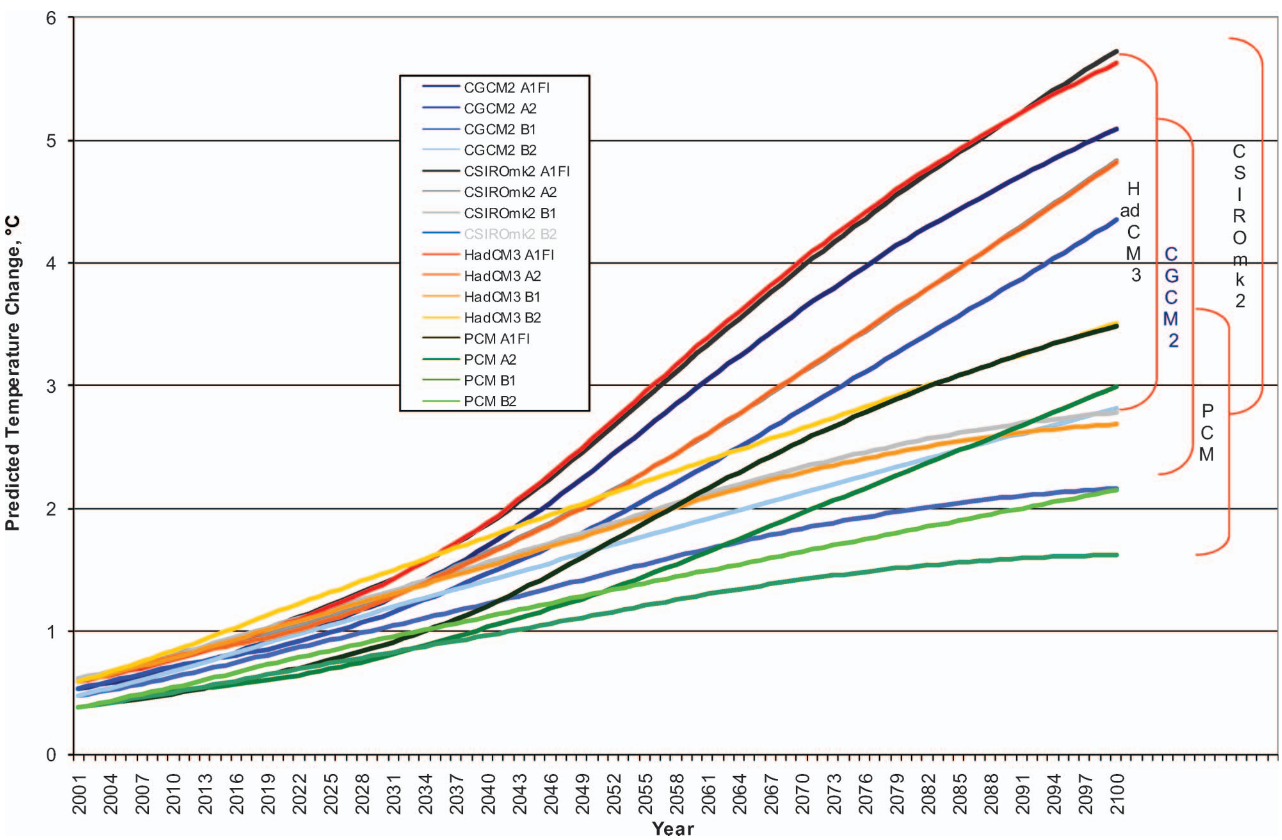

Figure 1. Global annual average temperature change predicted by four major global climate models.

performance of buildings. The IPCC's Third Assessment Report (IPCC 2001) summarizes the impact on the built environment simply as 'increased electric cooling demand and reduced energy supply reliability'. This is essentially a top-down view of the entire building sector, which ignores the variability in climatic response seen among buildings from the poles to the equator. Buildings respond to their environments in complex ways – with time-varying interactions of local weather conditions with internal loads (people, lights, equipment, and appliances) and heating, ventilating, and cooling systems (natural or forced). This is seen in Figure 2, comparing energy end-uses of commercial buildings in the United States and Europe, where typical European buildings use little or no cooling whereas cooling is a significant portion of commercial building energy performance in the United States.

In the Third Assessment Report, Working Group II states:

> ... The basis of research evidence is very limited for human settlements, energy, and industry. Energy has been regarded mainly as an issue for Working Group III, related more to causes of climate change than to impacts ... Impacts of climate change on human settlements are hard to forecast, at least partly because the ability to project climate change at an urban or smaller scale has been so limited. As a result, more research is needed on impacts and adaptations in human settlements (IPCC 2001).

From this, one might ask a number of questions about the impact of climate change or urbanization on the performance of buildings:

- What might be the potential impacts of climate change or urbanization on buildings?
- Will the changes predicted by the climate models and recent measurable temperature changes due to urbanization significantly change building energy use patterns and peak demand or cause cost shocks?
- Will increased demands on building heating and cooling equipment decrease life?
- What are the potential impacts on comfort?
- What other building performance impacts might be seen?

3. Building simulation as a tool for evaluating climate change

Building energy and environmental performance simulation programs have the capability to evaluate a wide range of responses to external stimulus and have been in use (and development) for more than 40 years (Clark 2001). Typically, these software tools are used by practitioners evaluating an individual building design or retrofit. Other uses for building simulation include overheating prediction, heating and cooling equipment design, evaluating alternative technologies (energy efficiency and renewable energy), regulatory compliance, or more recently, integrated performance views.

But simulation does have another equally powerful use when coupled with building models that represent a range of building types and locations. Simulation can be used to represent a portion of (existing or new, offices or hospitals, large, medium or small) or the entire building stock. In this article, building energy simulation is used to answer questions such as those above for a small office building. This work is a portion of a broader study currently under way on the value of building simulation as a policy tool – while presenting some answers to the questions above. Specifically, how building energy and environmental simulation can be used to answer policy questions such as the potential impacts of climate change or urbanization on building performance.

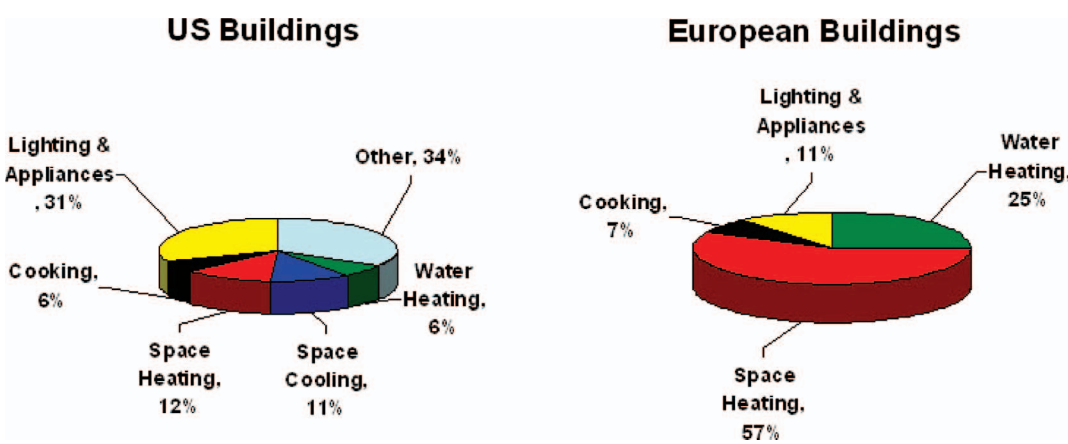

Figure 2. Commercial building energy end-uses in the United States (EIA 2002) and Europe (EC 2000).

The following process was tested:

- Translate scenarios [such as the IPCC Special Report on Emissions Scenarios (SRES) mentioned above or urban heat islands] into temporal climatic change based on a reference period.
- Define a building (or set of buildings) prototype to represent the building stock.
- Define a series of simulation cases to represent the range and combinations of scenarios and building response and evaluate the results.

This article next describes how a set of baseline climate regions were developed, and how the climate change and heat island scenarios were translated into modified climate data which could be used within building simulation software. Finally, a series of building energy simulations of a small office building are run and the thousands of megabytes of sub-hourly data were analysed.

4. Selecting weather sources, climate regions and locations

All of the widely used building simulation programs use some representation of weather conditions to simulate the response of a building. These data are often 'typical' data derived from hourly observations recorded at a specific location by the national weather service or meteorological office. Examples of these typical data include TMY2 (NREL 1995) in the United States, CWEC (WATSUN Simulation Laboratory 1992) in Canada, TRY (CEC 1985) in Europe, and IWEC (American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) 2001) worldwide. The TMY2, CWEC and IWEC typical weather years contain more detailed solar radiation and illumination data than some older typical meteorological year data sets. Crawley (1998) showed that assembling months which are most typical of the period of record but that may be from different years (the typical month method used in the TMY2, CWEC and IWEC data sets) results in synthetic weather years that better fit the long-term climate patterns.

For the work described here, a number of locations were needed to represent the range of climatic conditions around the world. Also, it was clear that the locations should have data with a reasonable source period of record – on the order of 15 years. Both the TMY2 and CWEC were derived from at least 30 years of weather data for all their locations, whereas IWEC locations have up to 19 years. But the periods of record vary – TMY2[1] covers 1961–2005 whereas CWEC[2] covers ~ 1950–1999, and IWEC covers 1982–1999. Despite these varying periods of record, TMY2, CWEC and IWEC were the most robust climatic data sources from which to select the range of climate regions for this work.

4.1. Climate classification

Early in the twentieth century, Vladimir Köppen (1918) proposed categorizing the climate regions of the world with a relatively straightforward schema, originally intended for agricultural use. Over the past 90 years, this schema has been expanded to include polar and highland climates but remains much as Köppen originally proposed. The major Köppen climate classes are:

A – Tropical humid climates
B – Hot dry climates
C – Mild mid-latitude climates
D – Cold mid-latitude climates
E – Polar climates
H – Highland climates

These six major climate types are further subdivided into hot/cold and dry/wet – creating 20 regions which represent the range of climatic conditions worldwide. Table 1 has a description of each class and a world map of the classes is shown in Figure 3.

Table 1. Köppen climate classification system.

Climate	Description
Af	Tropical wet (no dry season, rainforest, hot all year, lat. < 10°)
Am	Tropical monsoonal or trade wind-coastal (short dry season, lat. 5–25°)
Aw	Tropical savanna (pronounced wet and dry seasons, lat. 15–20°)
BSh	Hot subtropical steppe (lat. 15–30°N)
BSk	Mid-latitude dry semiarid (e.g. Great Plains of USA, lat. 15–60°N)
BWh	Subtropical hot desert (lat. 15–25°N)°
Cfa	Humid subtropical (mild with no dry season, hot summer, lat. 20–35°N)
Cfb	Marine west coastal (warm summer, mild winter, rain all year, lat. 35–60°N)
Cfc	Marine west coastal (mild summer, cool winter, no dry season, lat. 35–60°S)
Csa	Mediterranean climate (dry hot summer, mild winter, lat. 30–45°S)
Csb	Mediterranean climate (dry warm summer, mild winter, lat. 30–45°S)
Dfa	Humid continental (hot summer, cold winter, no dry season, lat. 30–60°N)
Dfb	Moist continental (warm summer, cold winter, no dry season, lat. 30–60°N)
Dfc	Subarctic (cool summer, severe winter, no dry season, lat. 50–70°N)
Dwa	Humid continental (hot winter, cold dry winter, lat. 30–60°N)
Dwb	Moist continental (warm summer, dry severe winter, lat. 30–60°N)
Dwc	Subarctic (cool summer, dry severe winter, lat. 50–70°N)
Dwd	Subarctic (cool summer, severely cold dry winter, lat. 50–70°N)
ET	Polar (tundra, no true summer, latitude 60–75°)
H	Severely cold high altitude climate

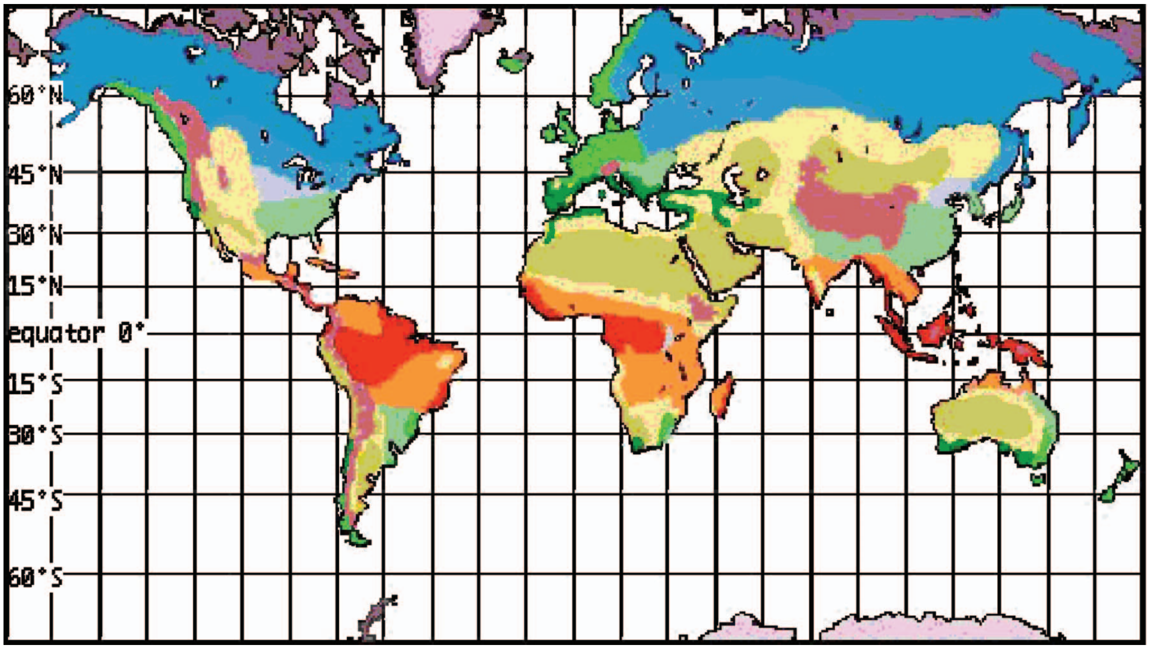

Figure 3. Map of Köppen climate classes.

To select locations for this work, the TMY2, CWEC and IWEC locations were first categorized into Köppen climate regions. Then the rank of the cities based on population was added, derived from Brinkhoff (2007). Using this information, at least one location was selected within each climate class to represent that region. Generally, from the equator to ~40–50° latitude, the location within the TMY2, CWEC, or IWEC data set with the largest population was selected. For five Köppen climate regions where there were both major developed and emerging economy locations, a second location was selected. Ten of the 25 locations are among the top 25 largest population centres. (For colder climates where no city rank is shown, there are not many cities with large populations.) The 25 locations selected, their Köppen climate classes, and a few major climatological attributes based on the TMY2, CWEC and IWEC typical files are shown in Table 2.

4.2. Selecting climate years for simulation

As Crawley (1998) showed, when using a range of actual weather years, the annual energy consumption as predicted by building simulation software could vary as much as ± 11%. It was important to capture this normal variation in climatic conditions in this study. Thus, in addition to the typical year from the TMY2, CWEC, or IWEC data sets, additional years of data from the period of records were needed to cover the range of climatic conditions such as hottest/coldest.

But rather than attempting the brute force method of simulating up to 45 years of weather data for each location plus the possible climate scenarios, a more efficient way would be to determine which years result in the highest and lowest energy use. Initially, it was thought that a simple combination of climatic variables, such as highest and lowest heating and cooling degree days for each weather year, might be sufficient to pinpoint which years result in the highest and lowest energy. To test this, a prototype small office building was simulated using the EnergyPlus building energy simulation model (US Department of Energy (USDOE) 2007) in three locations – an extreme cold, high latitude location (Resolute, Nunavut, Canada), a mid-latitude temperate location (Washington, DC–Sterling, VA), and a tropical location (San Juan, Puerto Rico) – selected to represent a wide range of climate conditions. These three locations are part of the TMY2 and CWEC data sets with periods of record of 45 and 36 years, respectively. For each location, the same prototype was simulated using weather data for each of the available years – from 1961 through 2005 for Washington and San Juan and from 1963 through 1999 for Resolute. HVAC equipment and systems were automatically sized using the ASHRAE 2005 fundamentals design conditions (ASHRAE 2005).

Figure 4 shows all 45 years in the TMY2/SAMSON/NSRDB data set for Washington, DC, ranking each year from coolest to warmest based on the combination of heating and cooling degree days, base 18 and 10°C, respectively. From Figure 4, one

Table 2. Selected locations and climate characteristics arranged by Köppen climate type.

Köppen climate	City rank[1], D/E[2]	Location	Data source[3] and period of record	Latitude	Longitude	Time zone[4]	Elevation (m)	Design conditions[5] Heating DB 99.6%,°C	Cooling DB 0.4%,°C	Cooling 0.4% MCWB,°C	Annual CDD, base 10°C	Annual HDD, base 18°C
Af	65, D	Singapore, SGP	IWEC, 1982–1999	N 1° 22′	E 103° 58′	8	16	22.8	33	25.9	6374	0
Am	139, D	San Juan, PRI	TMY2, 1961–2005	N 18° 25′	W 66° 0′	− 4	19	20.3	33.2	25	5904	0
Aw	57, D	Miami, FL, USA	TMY2, 1961–2005	N 25° 47′	W 80° 16′	− 5	2	7.6	32.8	25.2	5225	64
BSh	12,E	Cairo, EGY	IWEC, 1982–1999	N 30° 7′	E 31° 23′	2	74	7	38	20.3	4276	390
BSk	145, D	Boulder, CO, USA	TMY2, 1961–2005	N 40° 1′	W 105° 15′	− 7	1634	− 19.7	33.8	15.3	1493	3322
BSk	3, E	Mexico City, MEX	IWEC, 1982–1993	N 19° 25′	W 99° 4′	− 6	2234	4	29	13.8	2503	547
BWh	6, E	New Delhi, IND	IWEC, 1982–1999	N 28° 34′	E 77° 11′	5.5	216	6.6	41.7	22	5279	321
Cfa	1, D	Tokyo, JPN	IWEC, 1982–1999	N 36° 10′	E 140° 25′	9	35	− 7	31.8	25.4	1911	2311
Cfa	7, E	Sao Paulo, BRA	IWEC, 1982–1999	S 23° 37′	W 46° 39′	− 3	803	8.8	31.9	20.3	3607	252
Cfb	22,D	London (Gatwick), GBR	IWEC, 1982–1997	N 51° 9′	W 0° 10′	0	62	− 5.6	26.4	18.4	864	2866
Cfb	38,E	Johannesburg, ZAF	IWEC, 1982–1999	S 26° 7′	E 28° 13′	2	1700	1	29	15.6	2216	1052
Cfc	–, E	Punta Arenas, CHL	IWEC, 1982–1999	S 53° 0′	W 70° 50′	−4	37	−5	17.8	12.5	96	4273
Csa	17, E	Buenos Aires, ARG	IWEC, 1982–1999	S 34° 49′	W 58° 31′	−3	20	−0.7	33.9	22.8	2524	1189
Csb	9, D	Los Angeles, CA, USA	TMY2, 1961–2005	N 33° 55′	W 118° 24′	−8	32	6.2	29.2	17.7	2433	720
Csb	48, E	Santiago, CHL	IWEC, 1982–1999	S 33° 22′	W 70° 46′	−4	476	−1.4	31.9	18.4	1784	1570
Dfa	35,D	Washington-Dulles, VA, USA	TMY2, 1961–2005	N 38° 57′	W 77° 26′	−5	82	−12.8	33.7	23.9	1939	2795
Dfb	60, D	Toronto, ON, CAN	CWEC, 1961–1999	N 43° 40′	W 79° 37′	−5	173	−19.9	30.3	21.8	1172	4089
Dfb	18, E	Moscow, RUS	IWEC, 1982–1999	N 55° 45′	E 37° 37′	3	156	−23.1	27.6	19.3	862	4655
Dfc	–, D	Whitehorse, YT, CAN	CWEC, 1961–1999	N 60° 43′	W 135° 4′	−8	703	−36.8	25	13.8	271	6946
Dwa	19, E	Beijing, CHN	IWEC, 1982–1999	N 39° 47′	E 116° 28′	8	32	−10.4	34.2	21.9	2321	2750
Dwb	–, D	The Pas, MB, CAN	CWEC, 1961–1999	N 53° 58′	W 101° 5′	−6	271	−35.3	28.1	18.6	790	6443
Dwc	–, D	Fairbanks, AK, USA	TMY2, 1961–2005	N 64° 49′	W 147° 52′	−9	138	−44	27.1	15.8	510	7715
Dwd	–,E	Yakutsk, RUS	IWEC, 1982–1999	N 62° 4′	E 129° 45′	9	103	−51.9	29.4	18.7	685	10032
ET	–, D	Resolute, NU, CAN	CWEC, 1963–1999	N 74° 43′	W 94° 58′	−6	67	−40.9	10.2	7.3	0	12571
H	224, E	La Paz, BOL	IWEC, 1982–1999	S 16° 31′	W 68° 10′	−4	4042	−4	17.3	6.6	6	4015

TMY2, Typical Meteorological Year 2 (NREL 1993), 1961–1990 period of record SAMSON (NCDC 1993), 1991–2005 period of record NSRDB (NREL 2007). CWEC, Canadian Weather for Energy Calculations (WATSUN Simulation Laboratory 1992), 1950–1999, here an intersecting portion of 1961–1999 used, CWEEDS [Environment Canada (2001)].

[1]Rank of cities with population greater than 1 million. (Brinkhoff 2007).

[2]D = Developed economy, E = Emerging economy.

[3]IWEC, International Weather for Energy Calculations, 1982–1999, (ASHRAE 2001).

[4]Hours from universal coordinated time.

[5]ASHRAE *Handbook of fundamentals* (ASHRAE 2005). DB, dry-bulb temperature; MCWB, mean coincident wet-bulb temperature; HDD, heating degree days; CDD, cooling degree days.

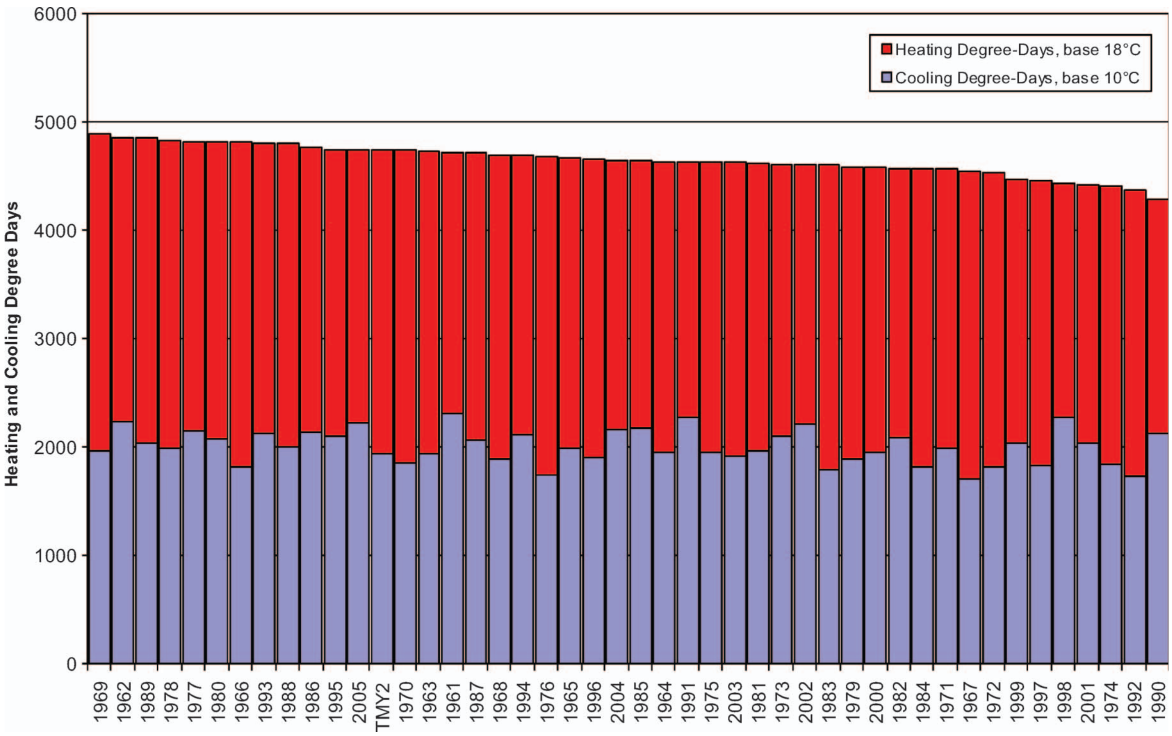

Figure 4. Washington, DC, heating and cooling degree days ranked from highest to lowest.

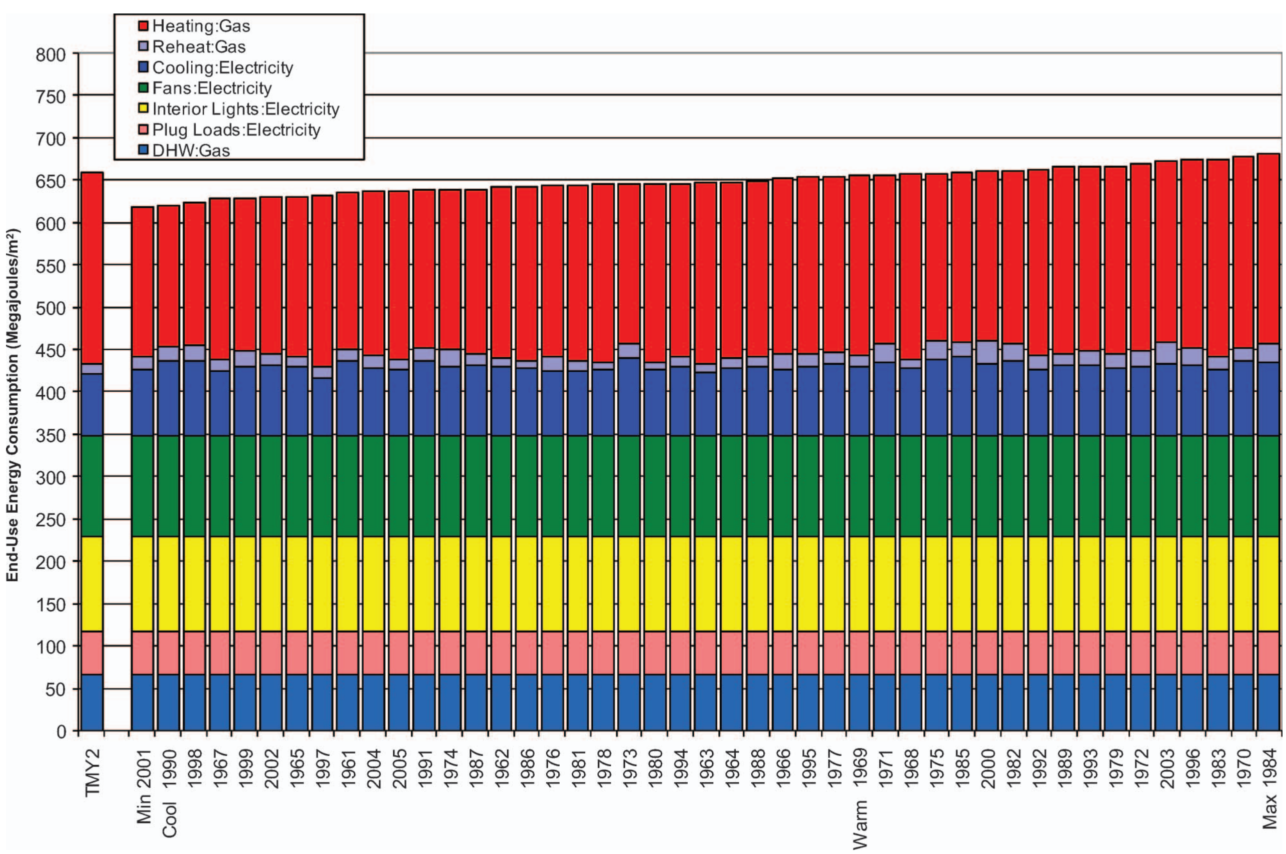

Figure 5. Washington, DC, energy end-use consumption for 550 m^2 office building.

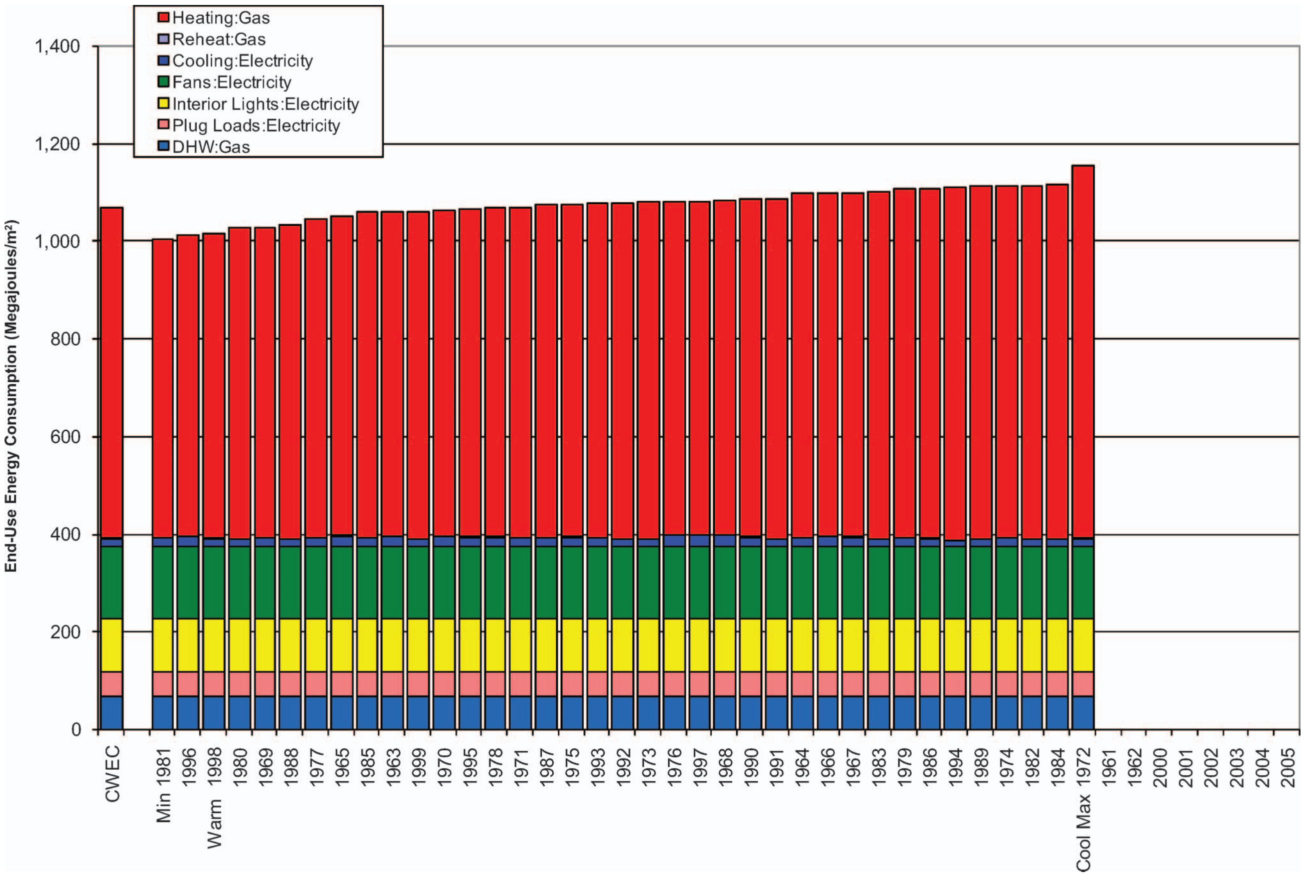

Figure 6. Resolute, Nunavut, Canada, energy end-use consumption for 550 m^2 office building.

might presume that 1969 might result in the combination of highest cooling and lowest heating while 1990 would result in the combination of lowest cooling and highest heating in terms of energy. Yet when the energy end-use results for these 46 annual simulations were assembled, this proved not to be the case, as shown in Figure 5. 1990 had the next to lowest energy use but 2001 had the lowest energy use overall of the 45 simulated years and a full third of the years yielded a higher annual energy consumption than 1969. Similar comparisons are shown in Figures 6 and 7 for Resolute, Nunavut, Canada, and San Juan, Puerto Rico. Figure 6 shows for Resolute that the year with the lowest heating degree days (there were no cooling degree days for Resolute) was 1998 (warm) and the year with highest heating degree days was 1972 (cool). But the 1998 data result only in the third lowest energy use but 1972 does result in the highest annual energy use. Figure 7 shows that 1961 is the coolest year for San Juan, Puerto Rico, and the second lowest energy use while 1980 is both the warmest year and highest energy use.

From this test case of three locations, one can conclude that selecting a year of weather data based on a single, simple climate descriptor such as degree days would not guarantee the lowest or highest energy for the period of record. Too many other variables such as solar radiation and humidity significantly impact how buildings perform and the resulting energy use. Thus, the most robust means of selecting years that result in high and low energy use was to run the prototype office through the complete set of years available for the 25 locations (a total of 707 simulations). The years which resulted in the highest and lowest energy use were then used in further analysis described below.

5. Representing the climate scenarios

As mentioned above, the four major storylines developed by IPCC WG III represent a potential range of different demographic, social, economic, technological and environmental developments (IPCC 2000). Four of the storyline scenarios cover the range of annual average global temperature changes predicted by the GCMs:

- A1: rapid economic and population growth, three groups of alternative energy system change:

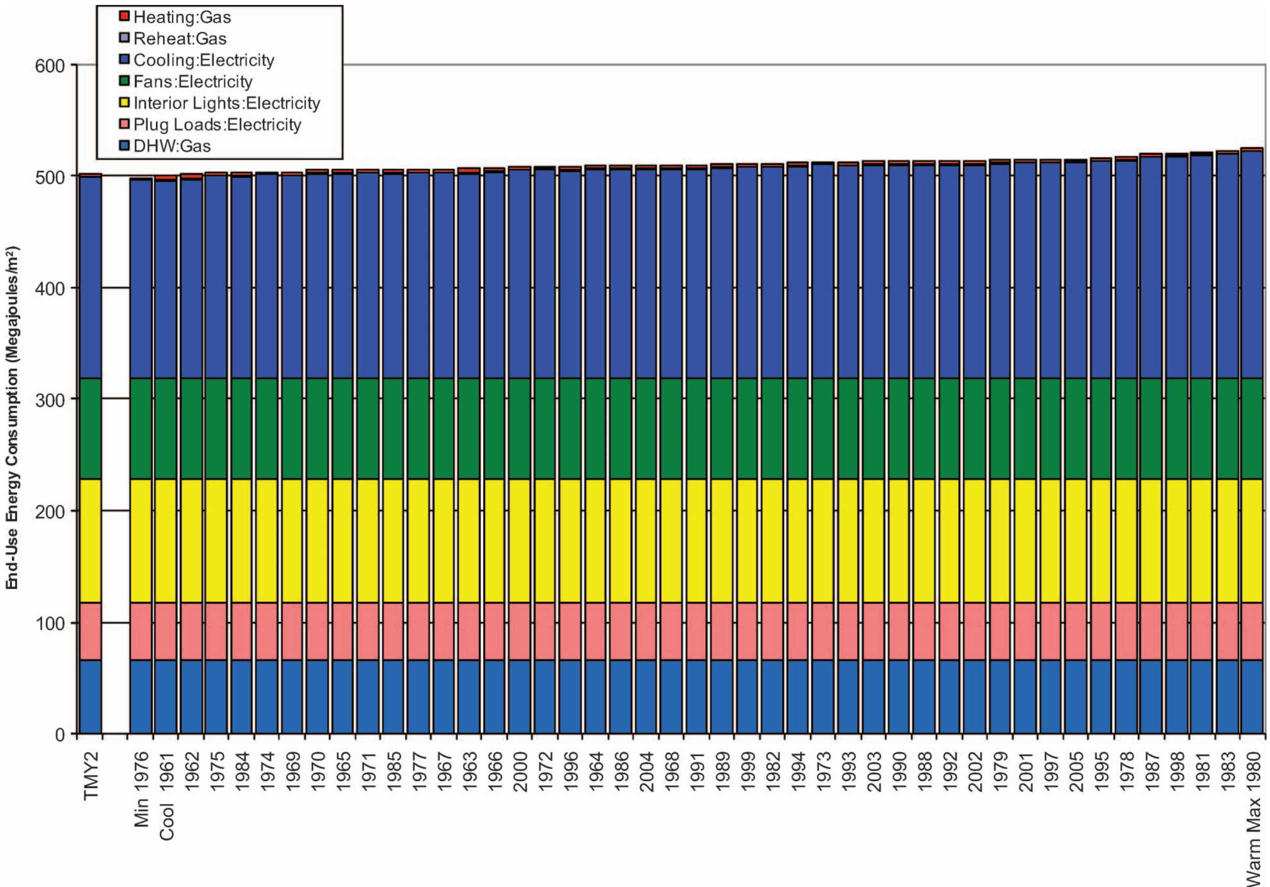

Figure 7. San Juan, Puerto Rico, energy end-use consumption for 550 m^2 office building.

fossil intensive, non-fossil sources, or balance among sources.

- A2: continuous population growth, but fragmented economic growth.
- B1: population peaks in mid-twenty-first century; economic change towards service and information economy, clean and resource-efficient technologies at global level.
- B2: local solutions to economic, social, and environmental sustainability; intermediate population and economic development.

The GCMs work with a three-dimensional grid of latitude and longitude, which varies by model. For example, the Hadley CM3 GCM uses a grid of 2.5° latitude by 3.75° longitude – up to 60 km – fairly coarse resolution when working with local climatic conditions. Through reanalysis of the data sets, Mitchell (2003) created a data set with a higher resolution of 0.5° × 0.5° latitude and longitude. These data are monthly grids of latitude and longitude covering the period 2001 through 2100. Five climatic variables from the larger IPCC data set were reanalysed: cloud cover, diurnal temperature range, precipitation, temperature, and vapour pressure. In the data set, there are 16 climate change scenarios – the four GCMs with four SRES emissions scenarios each (A1FI, A2, B2, B1). Between them, the 16 scenarios cover 93% of the possible range of future global warming estimated by the IPCC in their Third Assessment Report (2001). The Hadley CM3 GCM data were selected to represent the four climate scenarios because, as seen in Figure 1, they provide the broadest range of predicted global average temperature change among the four GCMs.

With Mitchell's denser global grid of the data, the predicted monthly change for a weather variable in a particular location could simply be looked up. Because the weather data used by EnergyPlus (and most energy simulation programs) does not include precipitation, these data were not used to modify existing weather data. Also, because Mitchell calculated the change in vapour pressure in this data set to be quite small, it was also excluded.

The next step was to modify the existing weather data (typical as well as highest and lowest energy years) to account for the monthly predicted changes in diurnal temperature range, drybulb temperature, and cloud cover effects on solar radiation. A program was

Figure 8. Hourly average TMY2 and climate change scenario drybulb temperatures for January in Washington, DC.

created to read in the existing weather file and GCM monthly change in the variable. It then recalculated the hourly dry bulb temperature based on both the temperature change and the reduced diurnal temperature range, recalculated the humidity ratio based on relative humidity, and recalculated the hourly global, direct normal, and diffuse horizontal solar radiation based on the change in cloud cover. The equations for modifying the drybulb temperature, dew point temperature, and relative humidity are shown below.

Modify drybulb temperature:

If $(DB + \Delta DB) > (DB_{dailyave} + \Delta DB)$ then

$$DB_{mod} = DB + \Delta DB + 0.5 \times \Delta DB_{diurnal}. \quad (1)$$

If $(DB + \Delta DB) \leq (DB_{dailyave} + \Delta DB)$ then

$$DB_{mod} = DB + \Delta DB - 0.5 \times \Delta DB_{diurnal}, \quad (2)$$

where
DB = drybulb temperature
ΔDB = change in drybulb temperature from the climate change scenario
$DB_{dailyave}$ = daily average drybulb temperature
DB_{mod} = modified drybulb temperature
$\Delta DB_{diurnal}$ = change in diurnal drybulb temperature from the climate change scenario

Modify dew point temperature:

If $(DB + \Delta DB) > (DB_{dailyave} + \Delta DB)$ then

$$DP_{mod} = DP + \Delta DB + 0.5 \times \Delta DB_{diurnal}. \quad (3)$$

If $(DB + \Delta DB) \leq (DB_{dailyave} + \Delta DB)$ then

$$DP_{mod} = DP + \Delta DB - 0.5 \times \Delta DB_{diurnal}, \quad (4)$$

where
DB = drybulb temperature
ΔDB = change in drybulb temperature from the climate change scenario
$DB_{dailyave}$ = daily average drybulb temperature
DP_{mod} = modified dew point temperature
$\Delta DB_{diurnal}$ = change in diurnal drybulb temperature from the climate change scenario

Modify relative humidity:

$$RH_{mod} = RH + \Delta RH. \quad (5)$$

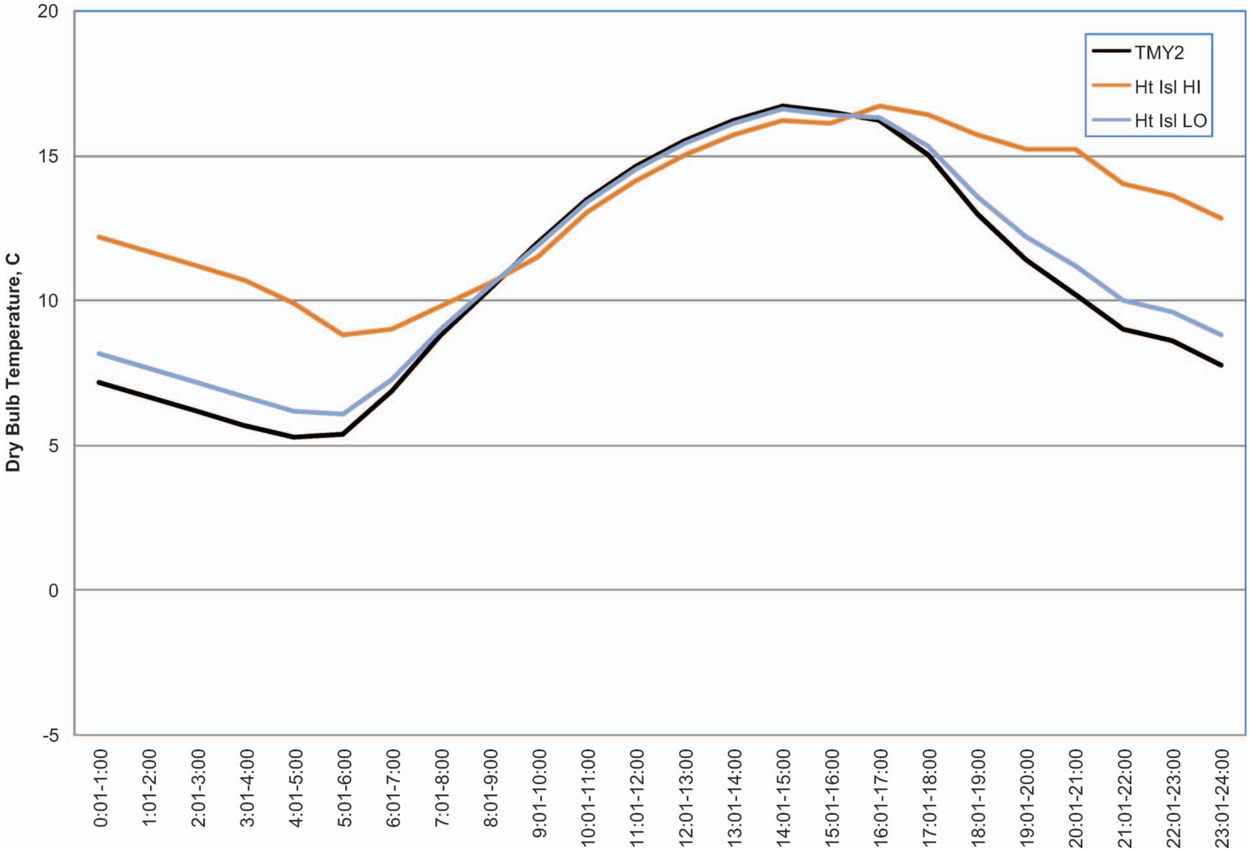

Figure 9. Hourly average TMY2 and heat island drybulb temperatures for April in Washington, DC.

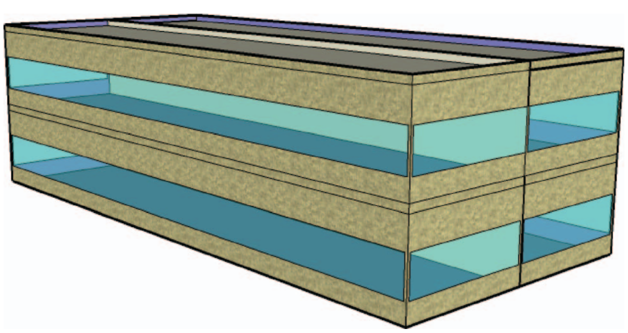

Figure 10. Schematic of small office building.

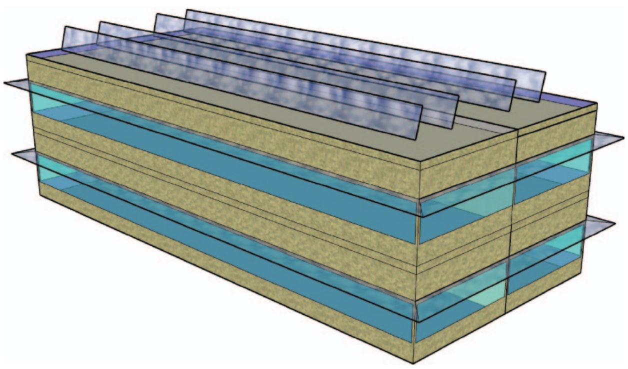

Figure 11. Schematic of low-energy building.

where
RH = relative humidity
ΔRH = change in relative humidity from the climate change scenario
RH_{mod} = modified relative humidity

Then the humidity ratio and wetbulb temperature were recalculated using standard psychrometric equations based on the modified drybulb temperature, dew point temperature, and relative humidity.

To estimate the effects of changes in solar radiation, solar radiation was recalculated twice using the Zhang/Huang solar models – once for the existing cloud cover and a second time using the modified cloud cover. The modified cloud cover is simply adding the monthly change in cloud cover from the climate change scenarios to the existing hourly cloud cover. To determine the modified solar radiation, the existing solar radiation data was multiplied by the ratio between the recalculated solar radiation with the modified cloud cover and the existing solar radiation

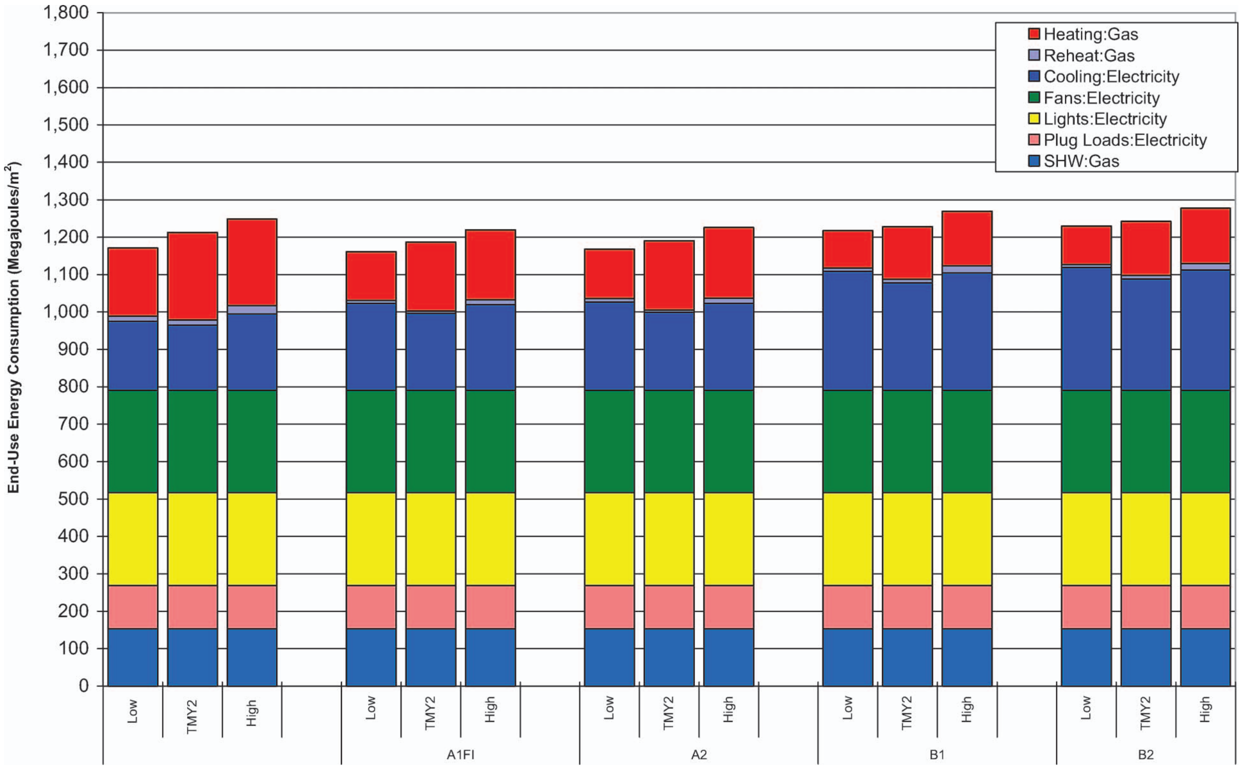

Figure 12. Predicted annual source energy energy-use consumption, in MJ/m^2, in Washington, DC, USA for standard and four climate change scenarios.

with the existing cloud cover. (One note – the cloud cover change in the IPPC climate change scenarios was often little changed – resulting in little change in the solar radiation.)

Figure 8 shows an example of the average hourly temperatures for January in Washington, DC. Note that for this one day, the diurnal temperature range is slightly compressed for Scenarios B1 and B2 (almost imperceptible in Figure 8). For this location in January, there are no differences among Scenarios A1FI and A2 and the baseline TMY2 weather and the lines for A1FI, A2 and TMY2 fall exactly on top of each other.

6. Representing the urban heat island

That urban conditions are different from rural has been recorded for more than 2000 years. In Neuman's historical review of heat islands (1979), he notes that the effects of pollution and heat islands have been known for thousands of years. That the air pollution and temperature in Rome differed from the countryside was noted in the odes of Quintus Horatius Flaccus in 24 BC. From the Middle Ages, larger cities such as London were known for their often health-threatening pollution. King Edward I banned the burning of sea coal in 1306; two centuries later, Queen Elizabeth I banned the burning of coal during sessions of Parliament. Even in the nineteenth and twentieth centuries, people of means left for the countryside to escape city summer heat.

In the early 1800s, Luke Howard first described the altered meteorological conditions caused by pollution in London as 'city fog' (Howard 1833). Howard also measured the temperature differences between the urban centre and the countryside for a number of years, publishing his initial findings in 1820. In a footnote to his table of mean monthly temperature differences, Howard wrote 'night is 3.70° *warmer* and day 0.34° *cooler* in the city than in the country', recognizing what today we call the heat island effect.

More recently, Mitchell (1953, 1961) measured the extent and intensity of the heat island phenomenon. Oke (1988) and Runnalls and Oke (2000) were the first to develop diagrams to explain the diurnal and seasonal patterns of heat islands. Their diagrams were confirmed by the temperature measurements by Streutker (2003) and Morris and Simmonds (2000).

Specifically, Streuker's measurements reinforced Oke's findings (1973) that heat island intensity depends on urban concentration (population density), vegetation and surface albedo.

The US Environmental Protection Agency (USEPA) Heat Island Reduction Initiative estimates that the heat island effect is in the range of 2–10°F (1–5°C) (USEPA 2007). But this is a range of potential impacts, not an annual, monthly or even a daily average. Rather than focus on the impacts, most discussions in the literature focus on mitigating heat island effects through green roofs, increased vegetation, light roof colours, and reduction of hard surfaces. Some research has focused on measuring the resultant air temperatures, but there is little (or no) documentation of how urban heat islands impact building operating performance.

In reviewing the measured data and Oke's diagrams, one can see that heat islands could be represented as a change to the diurnal temperature patterns. Using Oke's diagram as a starting point, this diurnal pattern of heat islands was implemented in the same program used for the climate change scenarios. The equations used in the program are shown below. For heat islands, this includes modifying only drybulb temperatures and recalculating the humidity ratio in an existing weather file.

If sun is down:

$$DB_{mod} = DB + \Delta DB. \qquad (6)$$

If hour is first or last hour of daylight:

$$DB_{mod} = DB + 0.5 \times \Delta DB. \qquad (7)$$

If hour is second or next to last hour of daylight:

$$DB_{mod} = DB + 0.25 \times \Delta DB. \qquad (8)$$

If hour is third or second to last hour of daylight:

$$DB_{mod} = DB + 0.0755 \times \Delta DB. \qquad (9)$$

All other hours when sun is up:

$$DB_{mod} = DB - 0.1 \times \Delta DB. \qquad (10)$$

where
DB = drybulb temperature
ΔDB = change in drybulb temperature for heat island
DB_{mod} = modified drybulb temperature

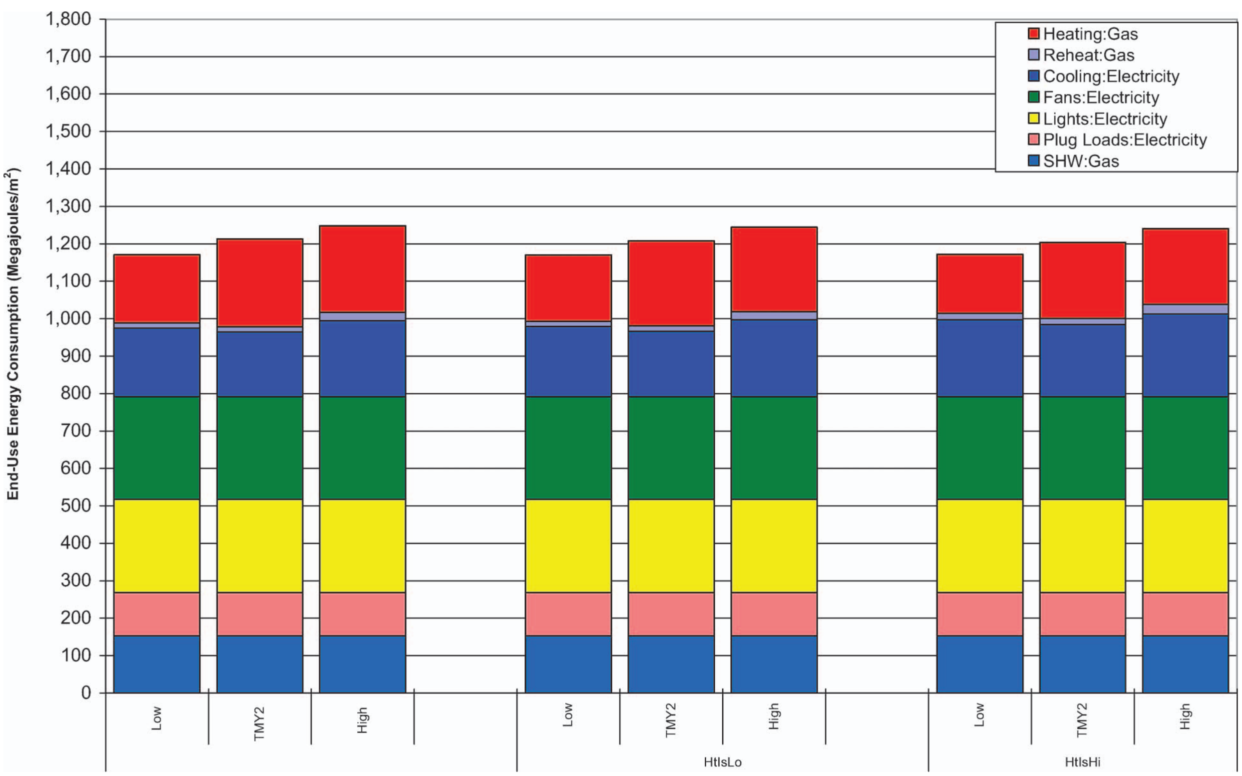

Figure 13. Predicted annual source energy energy-use consumption, in MJ/m^2, in Washington, DC, USA, for standard and high and low heat island cases.

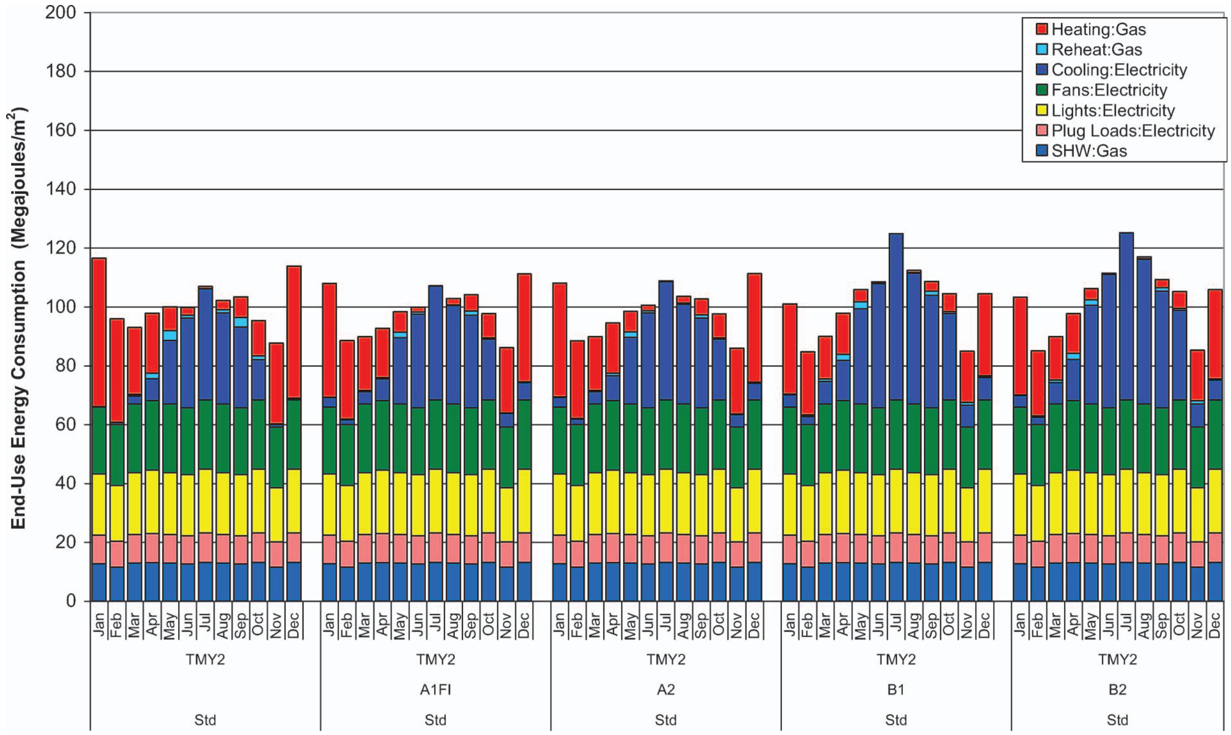

Figure 14. Predicted monthly source energy energy-use consumption, in MJ/m^2, in Washington, DC, USA, for standard and four climate change scenarios.

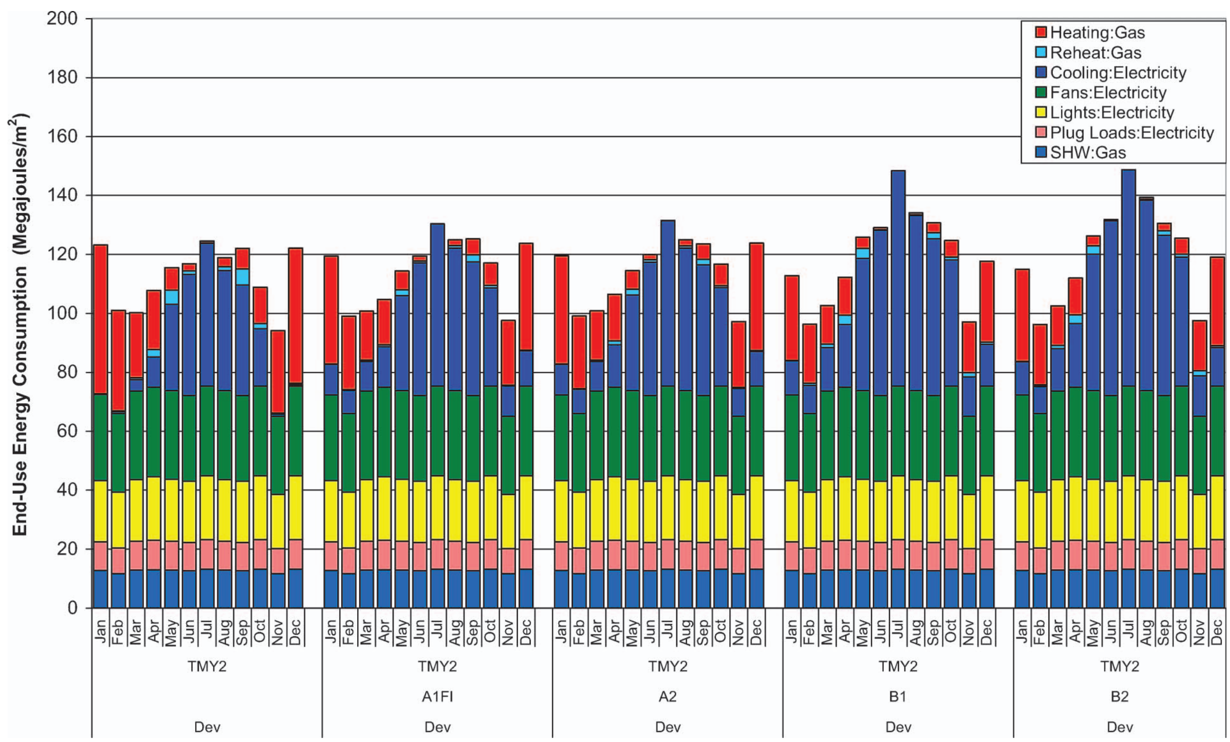

Figure 15. Predicted monthly source energy energy-use consumption, in MJ/m^2, in Washington, DC, USA, for developing and four climate change scenarios.

An example for the hourly average drybulb temperatures in April is shown in Figure 9. Because the USEPA estimates that the heat island effect is in the range of 1–5°C, these values were selected to represent the range of heat island modification – except for colder climates (>48° latitude) where lower populations limit the heat islands, here represented by a range of 1–3°C. The result was a set of new weather files representing a range of heat island impacts based on the typical weather file and the high and low energy years for each of the 25 locations described above.

7. Calculating the impact on a small office building

To represent smaller office buildings, a simulation model was created based on the Commercial Building Energy Consumption Survey (EIA 2002). From the survey data, a two-storey building of 550 m^2 was the median size for buildings in the floor area quartile with the smallest buildings – thus it is representative of ~25% of US office buildings. The small office building model has the following characteristics (see the schematic in Figure 10):

- 550 m^2 (5918 ft^2).
- Two storeys.
- 14 m^2/person.
- Typical office occupancy schedules.
- Office equipment at 8 W/m^2.
- Natural gas heating and hot water.
- Packaged rooftop electric DX cooling units.
- Lighting power at 11 W/m^2, opaque building envelope and windows and equipment efficiencies equivalent to current minimum regulations. [Standard 90.1-2004 (ASHRAE 2004)]

Two other models with the same shape and floor area were also created:

- Low-energy building which includes photovoltaic power cells on the roof as well as the shading overhangs (see Figure 11), using less than 50% of

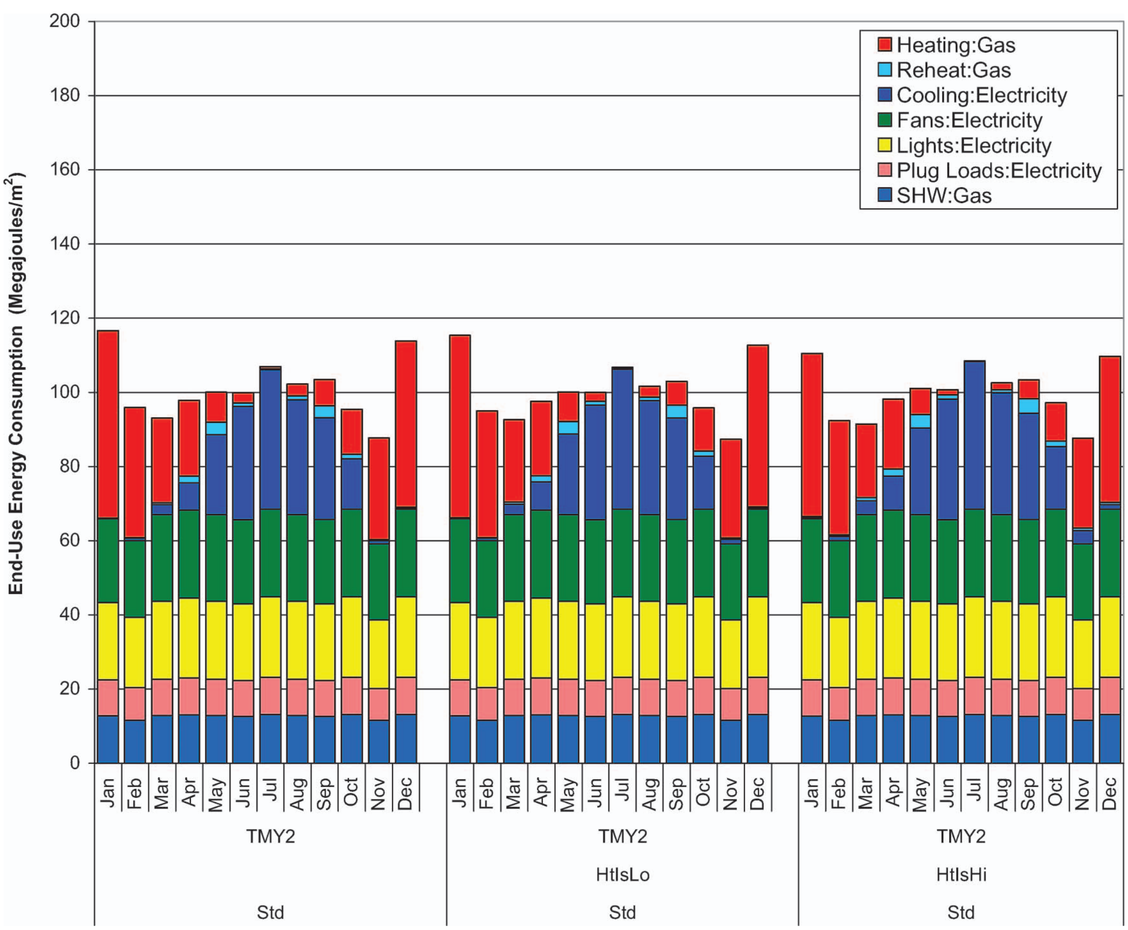

Figure 16. Predicted monthly source energy energy-use consumption, in MJ/m^2, in Washington, DC, USA, for standard and high and low heat island cases.

the energy of the base small office building model.

- Building similar to the base building which has thermophysical characteristics more typical of locations without an energy code or developing economies, hereafter called the developing case.

As described above, 25 locations were selected to represent the range of climatic conditions worldwide (shown in Table 2). For each location, a combination of typical year data (TMY2, CWEC or IWEC) and high and low energy weather years were selected. Then, for each of these (typical/high/low), weather files were created to represent four IPCC climate change scenarios (A1FI, A2, B1 and B2) and two levels of heat island (1 and 5°C or 1 and 3°C in high latitude locations). Design conditions from Chapter 28 of the *Handbook of fundamentals* (ASHRAE 2005) were used in all cases – essentially using 2005 design conditions for HVAC equipment and system sizing. EnergyPlus (USDOE 2007) was used to calculate building thermal flows given the varying weather data sets. For each simulation, results available from the annual simulations include:

- Surface temperature and conduction and radiation through the building envelope.
- Zone sensible, latent, convective, and radiant heating gains and losses.
- Zone air and mean radiant temperature, relative humidity, and humidity ratio.
- HVAC equipment runtime fraction, heating and cooling rates, part-load ratios, and temperature and humidity.
- Energy consumption and demand by zone, system, and plant equipment.
- Energy end-uses, consumption and demand by energy source.
- Atmospheric emissions by pollutant type and equivalent carbon.

A few summary energy performance results from the EnergyPlus simulation of the climate change scenarios and heat islands for Washington, DC, San

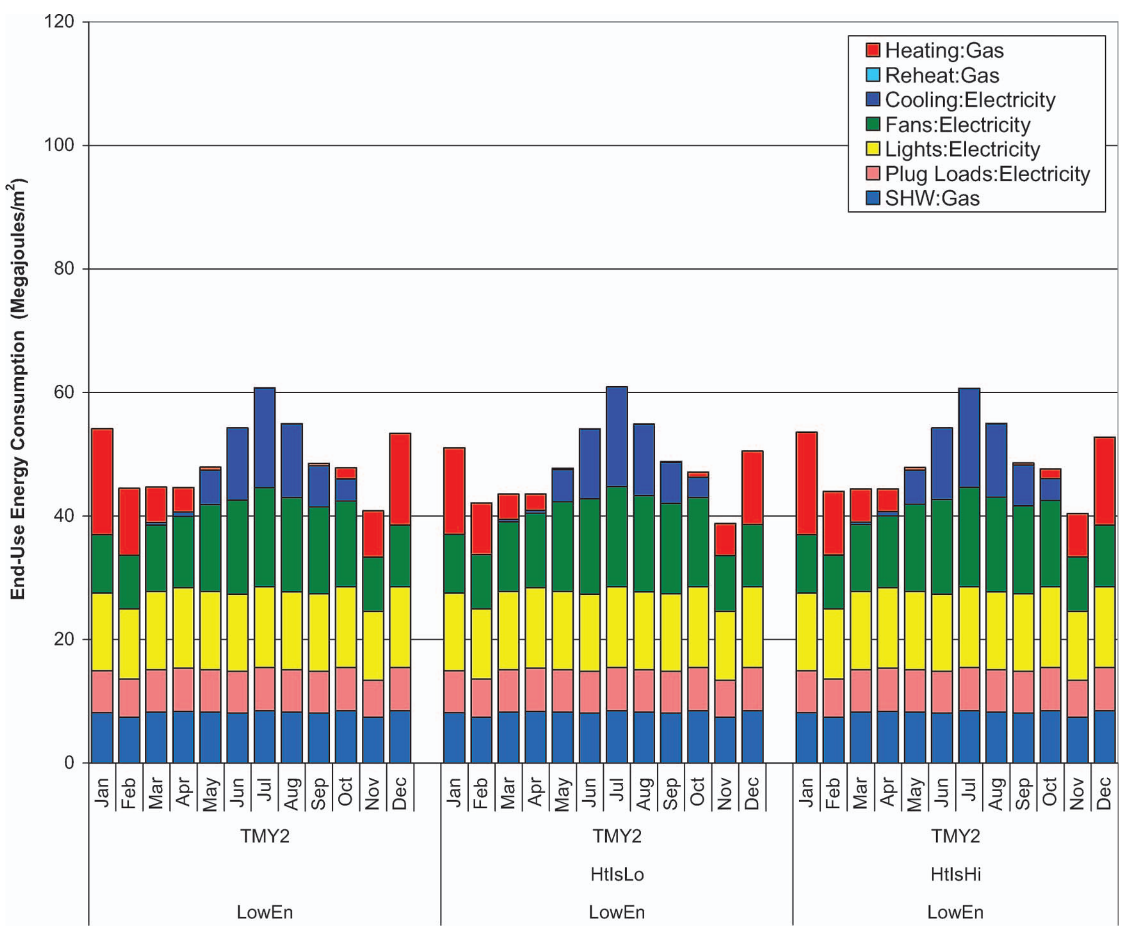

Figure 17. Predicted monthly source energy energy-use consumption, in MJ/m^2, in Washington, DC, USA, for low energy and high and low heat island cases.

Juan, Puerto Rico, and Resolute, Nunavut, Canada, are described in the following figures. Figures 12 and 13 show the annual energy consumption for the small office building in Washington, DC, USA (Köppen region Dfa, wet all seasons, hot summer). These figures each have three columns for each case – low, TMY2, and high. The low and high cases are the years from the period of record that result in the lowest and highest energy use; TMY2 is the typical year weather file. Figure 12 compares the results for the standard small office building with the four climate change scenarios (A1FI, A2, B1, and B2) using source energy – taking into account the energy flows back at the power plants. Note that all the remaining figures use source energy, which approximates both costs and environmental impacts of the various energy sources. Figure 13 compares the results of the standard building with those of the two heat island cases (1 and 5°C), again with source energy. Figures 14 through 18 show similar results, but for monthly source energy end-use of only the typical (TMY2) weather file for Washington, DC, for the heat island and climate change scenarios.

Although not shown here, total site energy consumption – what is measured by utilities at the building site – for the small office in Washington, DC, declines slightly over the range of scenarios and for the two heat island cases, despite the predicted increase in temperature. This is due to significant decreases in less-efficient natural gas-fired heating, whereas the more efficient electric cooling increases slightly. This fuel swapping results in roughly equivalent total site energy consumption over the range of scenarios. A striking example of the swapping between heating and cooling can be seen in the monthly data presented in Figures 14 and 15 for Washington, DC. For the base weather data, the substantial portion of the cooling occurs primarily between May and September. With the climate change scnearios, the cooling season is extended throughout the year, with substantial cooling from March through October.

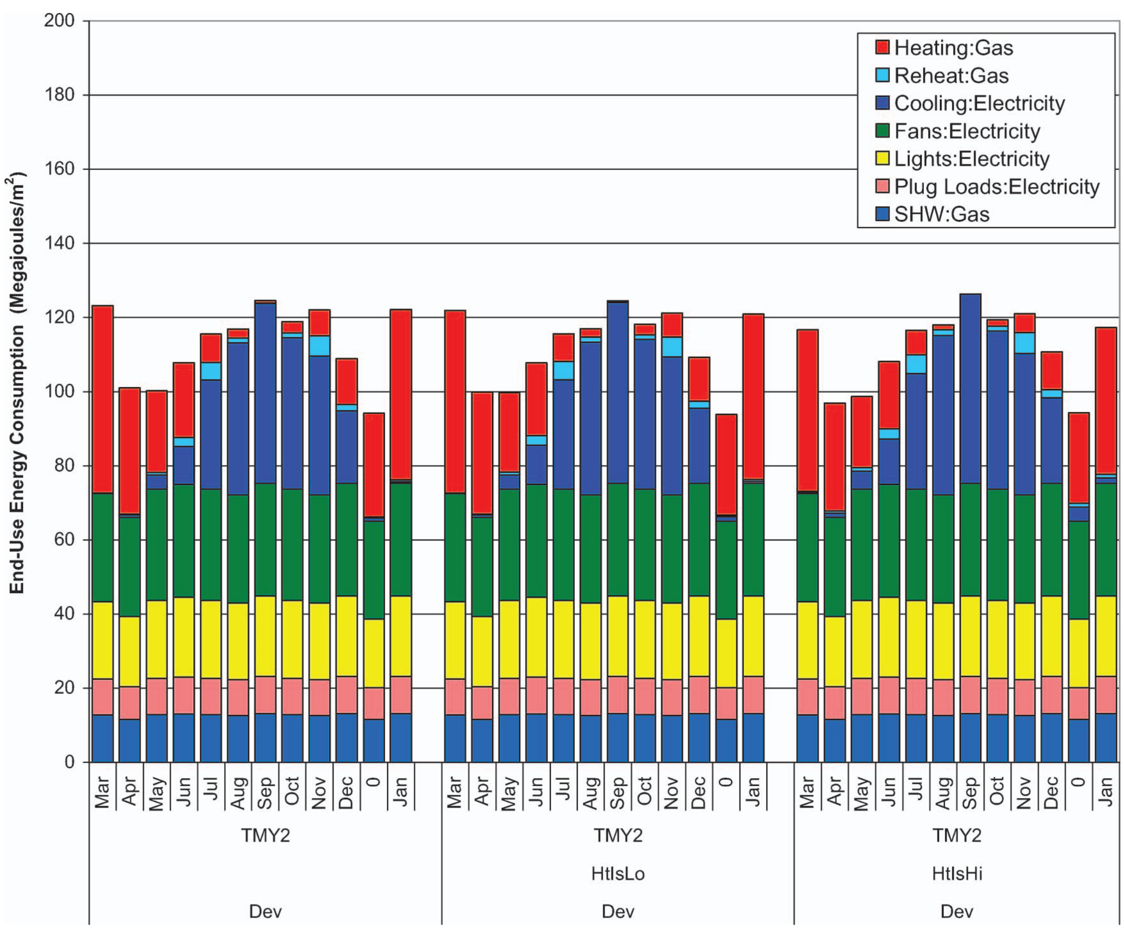

Figure 18. Predicted monthly source energy energy-use consumption, in MJ/m^2, in Washington, DC, USA, for developing and high and low heat island cases.

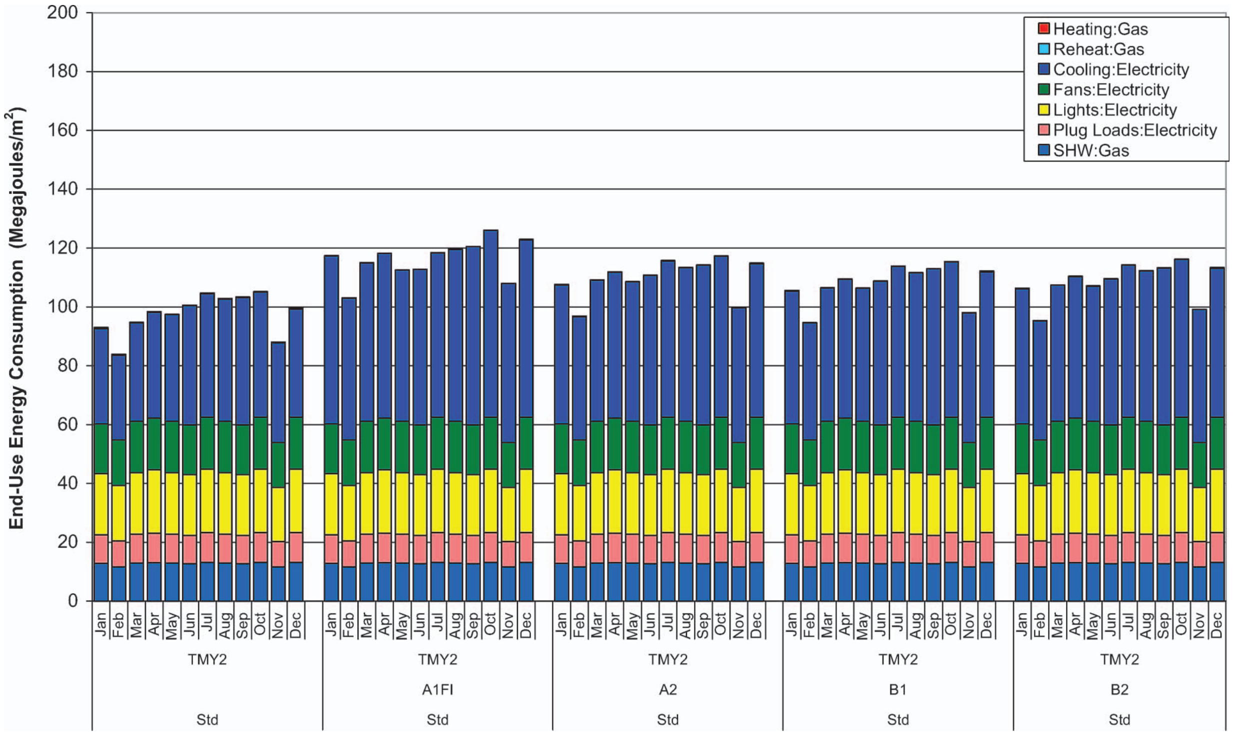

Figure 19. Predicted monthly source energy energy-use consumption, in MJ/m^2, in San Juan, Puerto Rico, for standard and four climate change scenarios.

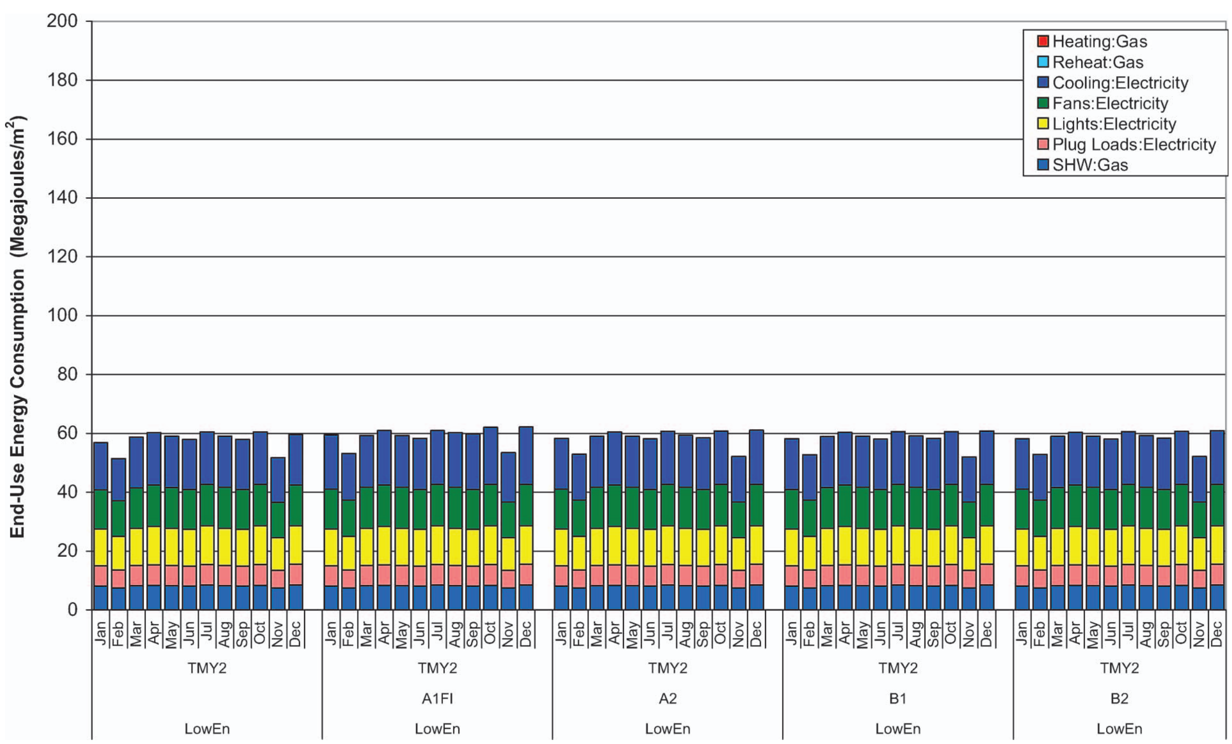

Figure 20. Predicted monthly source energy energy-use consumption, in MJ/m^2, in San Juan, Puerto Rico, for low energy and four climate change scenarios.

For Figures 12 and 13, which show source energy performance, there is only a slight increase to a small decrease in energy use across the various scenarios. Figures 14 and 15 show the monthly source energy end-use consumption for the low-energy office building. The difference for the low-energy office building is that the variation between the baseline and the climate change scenarios or heat island cases is significantly less. For the small office building built to the energy standard, the largest difference is 7%, whereas for the low-energy office building, the largest difference is 5%. Similar reduction in the spread of results is seen (but not included in this article) among the high, low, and typical cases included for the low-energy office building. This suggests that the low-energy office building, while already significantly reducing energy consumption by 50% over the baseline energy standard, also reduces the variation in energy performance due to year-to-year variation in climatic conditions. Although the results for the developing case (with no energy standards or codes enforced) are not shown in this article, the climate scenarios result in more than a 15% change in a monthly energy performance for a few cases – much higher than either the standard or low-energy buildings.

A few other observations (for which data are not shown in this article): locations which were heating dominated (little or no cooling – such as Resolute) or that had a balance of heating and cooling energy usually saw decreases in annual energy consumption when the climate change scenarios were applied; warmer regions with significantly less heating, such as New Delhi or Singapore, showed significant overall increases in total site energy consumption. Heating consumption in these cooling-dominated regions, reductions which might have offset the increased cooling energy, was small to begin with. In addition, locations with a relative balance between heating and cooling show significant swapping of cooling for heating – especially in winter and spring/autumn

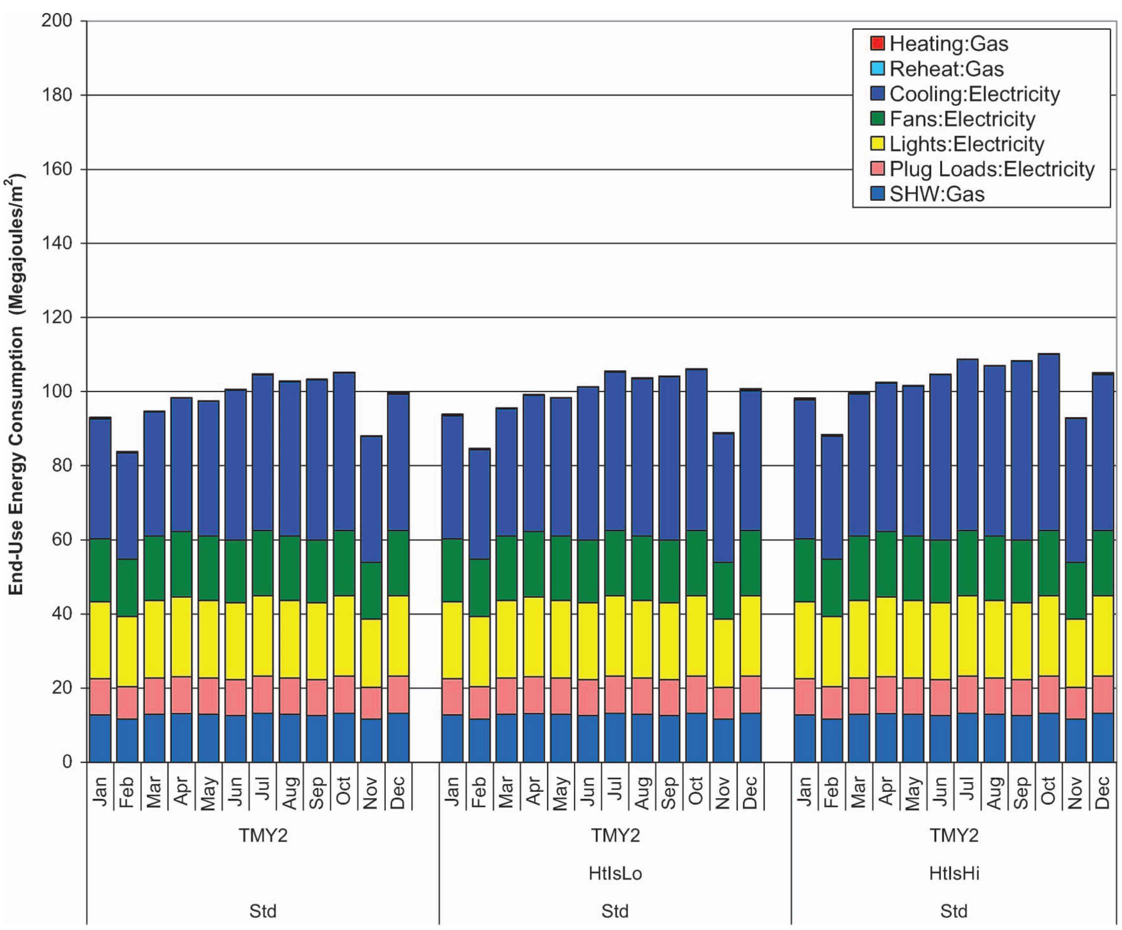

Figure 21. Predicted monthly source energy energy-use consumption, in MJ/m^2, in San Juan, Puerto Rico, for standard and high and low heat island cases.

months. For example, Boulder, CO, which has relatively cold winters, shows significant decreases in heating energy and cooling energy appears in autumn and spring months where there was previously no cooling required. The developing case with the least effective building envelope and least efficient HVAC equipment is the most sensitive to normal climate variation or to climate change.

In Washington, DC, the annual energy for the developing case small office building varied by 9.2% between the years with the highest and lowest energy use, with the typical year falling roughly in the middle of the range. For the standard case, the variation between the highest and lowest energy years was smaller at 8.8%. But the low-energy building had a similar pattern for the base year-to-year variation in weather patterns, with a range of variation from high to low of less than 9.1%. Interestingly, for the results in Washington, DC, the ranges were slightly less for the extreme climate change scenario (A1FI): 7.5%, 9.4% and 5.8%, respectively, for the developing, standard, and low-energy cases.

Results for the heat island cases are somewhat different due to the different diurnal temperature patterns, extending high daytime temperatures in the evening hours and depressing daytime temperatures till later in the day. For Washington, DC, the range of variation among years for the low (1°C) urban heat island case was similar to the baseline weather years: 9.1%, 8.3%, and 4.9%, respectively, for the developing, standard, and low-energy building cases. When the high (5°C) urban heat island cases are applied in Washington, DC, the variation is compressed somewhat: 8.7%, 8.2% and 4.3% between the years with the highest and lowest energy use, respectively again, for the developing, standard, and low-energy building models. In all cases, the energy performance of the low-energy building model was the least affected by year-to-year variation, predicted climatic changes for 2100, or urban heat islands.

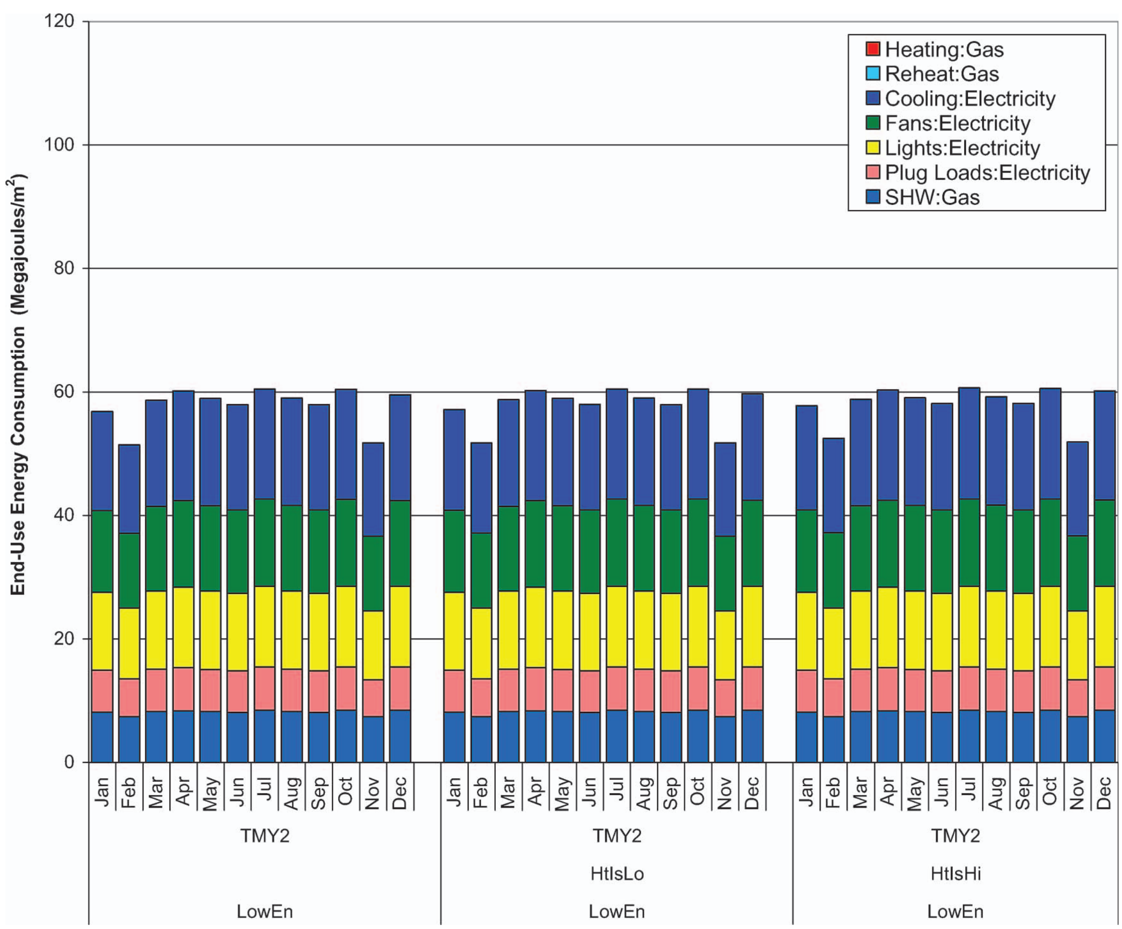

Figure 22. Predicted monthly source energy energy-use consumption, in MJ/m^2, in San Juan, Puerto Rico, for low energy and high and low heat island cases.

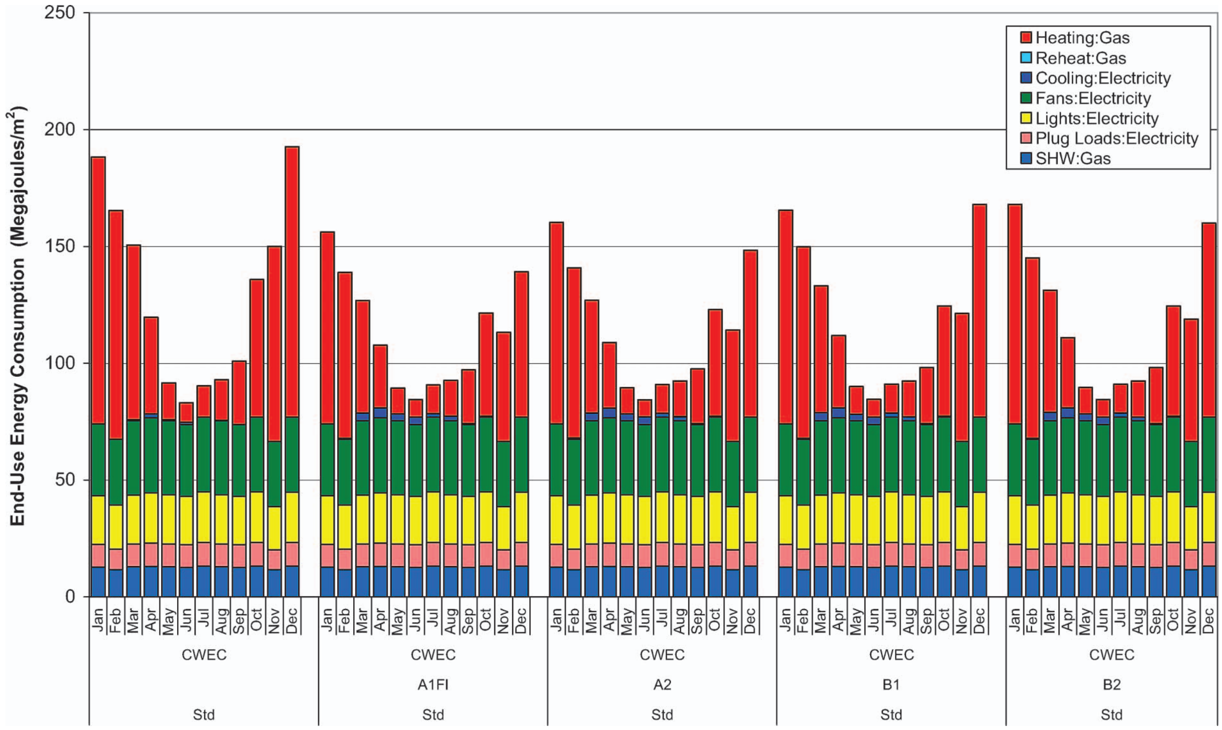

Figure 23. Predicted monthly source energy energy-use consumption, in MJ/m^2, in Resolute, Nunavut, Canada, for standard and four climate change scenarios.

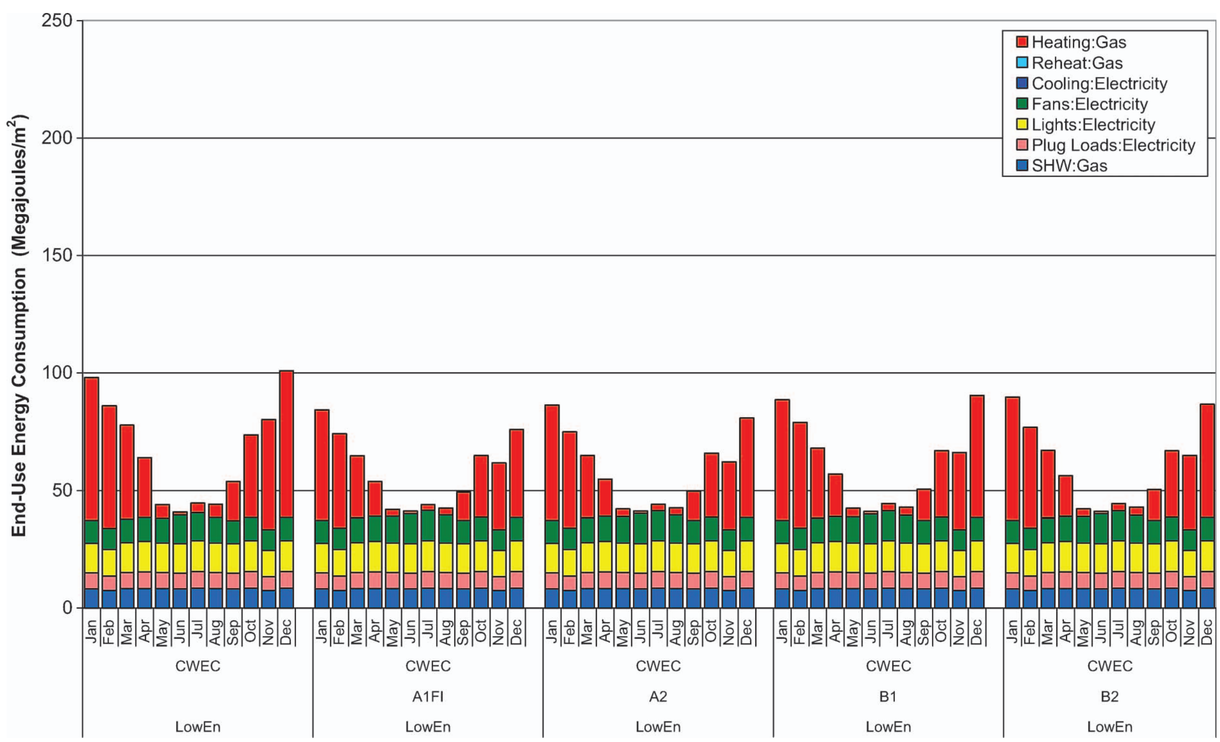

Figure 24. Predicted monthly source energy energy-use consumption, in MJ/m^2, in Resolute, Nunavut, Canada, for low energy and four climate change scenarios.

The remaining figures show monthly source end-use energy consumption of the standard and low-energy versions of the small office building for San Juan (Figures 19 through 22) and Resolute (Figures 23 through 25). Only the monthly energy consumption is shown here as it reveals more about the changes in energy use patterns for these two locations than does the annual energy performance data. Table 3 compares the ranges of decreases and increases for four cases – the base weather years, the A1FI climate change case, and the two urban heat island cases – 1°C (low) and 5°C (high). For Washington, DC, and San Juan, the range of energy performance between the years with lowest and highest energy use decreases for all the modified climate cases. For Resolute, the ranges increase slightly for the developing building model, between 0.1 and 1%, but decrease slightly for the standard and low-energy models.

For San Juan, a similar pattern to Washington, DC, emerges – increases in cooling causing an overall increase in energy use due to the climate scenarios. But as with Washington, DC, the low-energy building case (Figures 20 and 22) show the least impacts due to either the climate change scenarios or the heat island cases. On the other hand, the developing building case (not shown in this article) shows significant increases in monthly energy consumption – in some cases approaching 20% or more.

The annual energy use in San Juan for the developing case small office building ranged 4.7% between the years with the highest and lowest energy use, lower than either the Washington, DC, or Resolute results. For the standard case, the variation between the highest and lowest energy years was a bit larger at 5.3%. But the low-energy building was almost insensitive to the year-to-year variation in climate conditions, with a range from low to high of only 0.5%. In San Juan, the ranges decreased slightly for the standard building under the extreme climate change scenario (A1FI), whereas the developing and

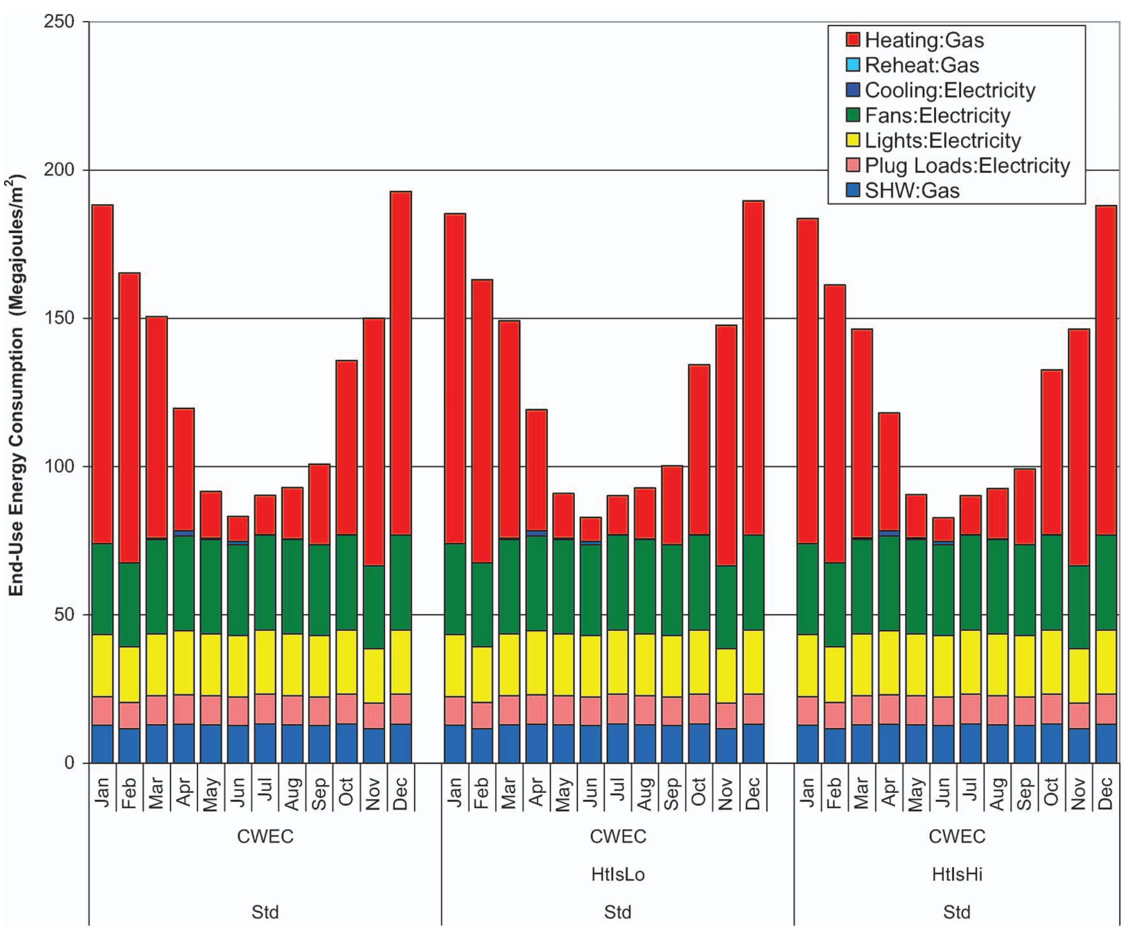

Figure 25. Predicted monthly source energy energy-use consumption, in MJ/m^2, in Resolute, Nunavut, Canada, for standard and high and low heat island cases.

low-energy models increased: 4.9%, 4.8% and 2.1%, respectively, for the developing, standard, and low-energy cases.

Results for the heat island cases in San Juan are similar to the base weather data despite the change in diurnal temperature patterns. The range of variation among years for the low (1°C) urban heat island case was similar to the baseline weather years: 4.8%, 5.3%, and 0.4%, respectively, for the developing, standard, and low-energy building cases, with similar results for the high (5°C) urban heat island cases: 4.9%, 5.1% and 0.4% between the years with the highest and lowest energy use. In all cases, the energy performance of the low-energy building model was again the least affected by year-to-year variation, predicted climatic changes for 2100, or urban heat islands.

For Resolute, a similar pattern but a different result – significant reductions in heating due to the climate scenarios – but with almost no cooling load, the results are significant overall decreases in energy use. As with San Juan and Washington, DC, the low-energy buildings (Figures 24 and 26) see almost no impacts for the climate scenarios while the developing building case sees monthly energy use and variability twice as large.

Resolute demonstrates the greatest variability of the locations shown in this article, generally around 10% from the high to low years among all the cases. The annual energy performance for the developing model varied by 11.5% between the highest and lowest energy use years. For the standard case, the variation between the highest and lowest energy years was similar at 11.2%, but the low-energy building had a slightly lower range of energy use for the base year-to-year variations of 9.71%. For Resolute, the results for the extreme climate change scenario (A1FI) all saw increased ranges of variability: 12.4%, 11.0%, and 11.2%, respectively, for the developing, standard, and low-energy cases.

Results for the heat island cases are close to the base weather data results, with only the standard model reducing the range of variation slightly (11.2–11.0%). For Resolute, the range of variation among years for both the low (1°C) and high (3°C) urban heat island cases is almost unchanged from the standard

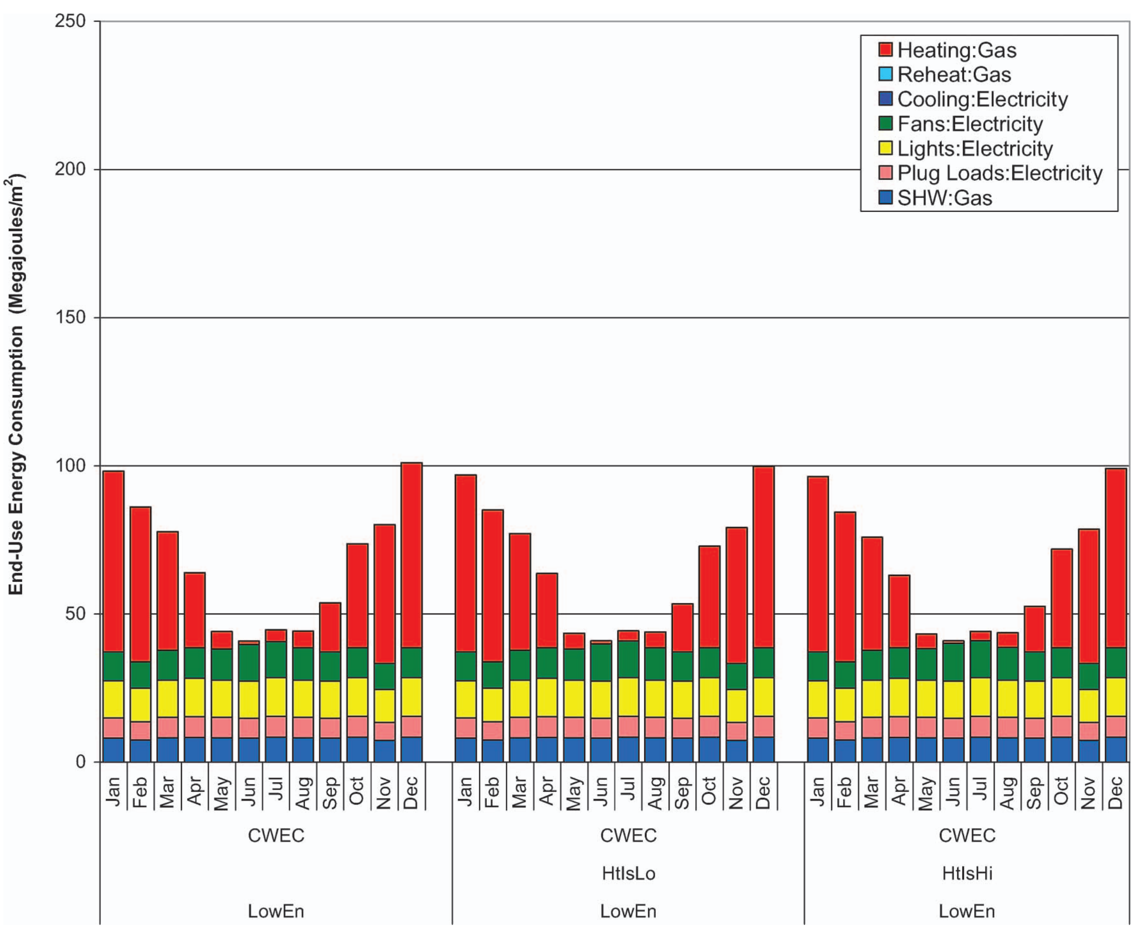

Figure 26. Predicted monthly source energy energy-use consumption, in MJ/m^2, in Resolute, Nunavut, Canada, for low energy and high and low heat island cases.

Table 3. Ranges of percentage change of energy performance for the low and high energy years in comparison with typical weather data.

Location	Building model	Base weather data (1961–1990 and typical	Climate change scenario A1FI	Low urban heat island	High urban heat island
Washington, DC	Standard	−6.3 to +2.5	−5.6 to +2.8	−5.9 to +2.4	−5.3 to +2.9
	Developing	−5.5 to +3.7	−4.5 to +3.0	−5.2 to +3.9	−4.5 to +4.2
	Low-energy	−6.3 to +2.8	−5.6 to +0.2	−6.3 to −1.4	−5.5 to −1.2
Resolute,	Standard	−4.6 to +6.6	−4.1 to +6.9	−4.5 to +6.5	−4.5 to +6.5
Nunavut,	Developing	−5.0 to +6.5	−4.9 to +7.5	−4.9 to +6.6	−4.9 to +6.6
Canada	Low-energy	−4.1 to +5.6	−4.7 to +6.5	−3.9 to +5.6	−3.9 to +5.6
San Juan,	Standard	−0.9 to +4.4	−0.6 to +4.2	−0.9 to +4.4	−0.9 to +4.2
Puerto Rico	Developing	−0.7 to +4.0	−0.6 to +4.3	−0.8 to +4.0	−1.0 to +3.9
	Low-energy	+0.0 to +0.5	−0.2 to +1.9	+0.0 to +0.4	−0.1 to +0.3

weather data: 11.5%, 11.0%, and 9.5%, respectively, for developing, standard, and low-energy building models.

In general, the low-energy building model shows the least change in energy performance in response to the variation in climatic conditions. It also usually results in annual energy performance ∼ 50–60% less than the standard model. In contrast, the developing building model shows a substantial increase (around 10–20%) in annual energy performance over that of the standard building. The climate change scenarios can increase that by another 10%. Interestingly, as described above, the significant switchover from heating to cooling in Resolute results in a reduction in annual energy use due to the climate scenarios. At the other extreme, in the data shown here for San Juan, the developing building model changes from being 13% higher than the standard model to more than 33% higher in the A1FI climate change scenario.

8. Conclusions

This article first describes the development of a set of modified typical and high and low energy weather years to represent four scenarios of climate change and two cases of urban heat islands in 25 locations throughout the world. Example days showing how the climate change scenarios and urban heat islands affect the diurnal drybulb temperatures were also presented. This set of 525 weather files were then used in building simulation models of a small office building to examine the range of potential impacts of climate change and UHI on building operating performance. How heat island and climate change scenarios affect annual source energy performance are presented for three of the 25 locations. In cold climates, the net change to annual energy use due to climate change will be positive – reducing energy use on the order of 10% or more. For tropical climates, buildings will see an increase in overall energy use due to climate change, with some months increasing by more than 20% from current conditions. Temperate, mid-latitude climates will see the largest change but it will be a swapping from heating to cooling, including a significant reduction of 25% or more in heating energy and up to 15% increase in cooling energy. Buildings which are built to current standards such as ASHRAE/IESNA Standard 90.1-2004 will still see significant increases in energy demand over the twenty-first century. Low-energy buildings designed to minimize energy use will be the least affected, with impacts in the range of 5–10%. Unless the way buildings are designed, built, and operated changes significantly over the next decades, building owners will experience substantial operating cost increases and possible disruptions in an already strained energy supply system.

The analysis of the small office building prototype showed that building performance simulation can be used to answer policy questions such as:

- Location-specific responses to potential scenarios.
- Impacts on equipment use and longevity.
- Fuel swapping as heating and cooling change.
- Emissions impacts.
- Comfort.
- Means to improve building energy efficiency and incorporate renewable energy while mitigating potential changes.

This article presents only a small fraction of the building performance data available from this study. Today's building energy performance simulation tools provide data at a variety of time slices – from annual, monthly, weekly, daily, and hourly down to the time step (10 min for this study) for all surfaces, components, spaces, zones, equipment, spaces, and systems within the building.

8.1. Further work

The author will be drawing additional data from the available results over the next few months. Some of the work includes:

- More results for the entire range of 25 locations.
- Adding results from a high and low energy version of the small office building.
- Evaluating the results from the high and low energy weather data years.
- Substantially greater depth of time-dependent resolution.

Notes

1. The source data for the TMY2 was the SAMSON data set (NCDC 1993) with a period of record of 1961–1990 for 239 locations. The newer NSRDB data set (NREL 2007) has a period of record of 1991 through 2005 for more than 1450 locations in the United States.
2. The source data for the CWEC was the CWEEDS data set (Environment Canada 2001) with a period of record of 1953–1999. Subsequent to the work described here, the CWEEDS data set was updated through 2005.

References

ASHRAE, 2001. *International weather for energy calculations (IWEC weather files)*. [User's manual and CD-ROM.] Atlanta: ASHRAE.

ASHRAE, 2004. ANSI/ASHRAE/IESNA Standard 90.1–2004. *Energy efficient design of new buildings except low-rise residential buildings*. Atlanta: ASHRAE.

ASHRAE, 2005. *Handbook of fundamentals*. Atlanta: ASHRAE.

Brinkhoff, Thomas., 2007. *City population* [online]. Available from: http://www.citypopulation.de/.

CEC, 1985. *Test reference years, weather data sets for computer simulations of solar energy systems and energy consumption in buildings, CEC, DG XII*. Brussels: Commission of the European Community.

Clark, J.A., 2001. *Energy simulation in building design*. 2nd ed. London: Butterworth-Heinemann.

Crawley, D.B., 1998. Which weather data should you use for energy simulations of commercial buildings? *In*: *ASHRAE Transactions*. Atlanta: ASHRAE, 104 (Pt. 2).

Energy Information Administration, 2002. *Commercial buildings energy consumption survey – commercial buildings characteristics*. Washington: Energy Information Administration, US Department of Energy.

Environment Canada, 2001. *Canadian weather energy and engineering data sets (CWEEDS files)*. Downsview, Ontario: Meteorological Service of Canada, Environment Canada.

European Commission, 2000. *Green paper – towards a European strategy for the security of energy supply*. Brussels: European Commission. Technical document.

Howard, L., 1833. *Climate of London deduced from meteorological observations*. 3rd ed. London: Harvey & Darton.

IPPC, 2000. *Emissions scenarios*, IPCC Special Report. Cambridge: Cambridge University Press.

IPPC, 2001. *Climate change 2001: Impacts, adaptation and vulnerability*. Cambridge: Cambridge University Press.

IPPC, 2007. *Climate change 2007: Synthesis report*. Cambridge University Press.

Köppen, W., 1918. Klassifikation der Klimate nach Temperatur, Niederschlag und Jahreslauf. *Petermanns Mitt*, 64, 193–203

Mitchell, J.M., 1961. The temperature of cities. *Weatherwise*, 14, 224–229, 258.

Mitchell, J.M., 1953. On the causes of instrumentally observed secular temperature trends. *Journal of Meteorology*, 10, 244–261.

Mitchell, T.D., 2003. *A comprehensive set of climate scenarios for Europe and the globe*. Tyndall Centre for Climate Change Research.

Morris, C.J.G. and Simmonds, I., 2000. Associations between varying magnitudes of the urban heat island and the synoptic climatology in Melbourne, Australia. *International Journal of Climatology*, 20, 1931–1954.

NCDC, 1993. *Solar and meteorological surface observation network, 1961–1990*. Asheville, North Carolina: National Climatic Data Center, US Department of Commerce. Version 1.0, September 1993.

Neumann, J., 1979. Air pollution in ancient Rome. *Bulletin of the American Meteorological Society*, 60, 1097.

NREL, 1995. *User's manual for TMY2s (typical meteorological years. NREL/SP-463-7668, and TMY2s, Typical meteorological years derived from the 1961–1990 national solar radiation database*, June 1995 [CD-ROM]. Golden, Colorado: National Renewable Energy Laboratory.

NREL, 2007. *User's manual, national solar radiation database, 1991–2005 update*. Asheville, North Carolina: National Climatic Data Center, US Department of Commerce.

Oke, T.R., 1973. *City size and the urban heat island. Atmospheric Environment*, 7, 769–779.

Oke, T.R., 1987. *Boundary layer climates*. New York: Routledge.

Runnalls, K.E. and Oke, T.R., 2000. Dynamics and controls of the near-surface heat island of Vancouver, British Columbia. *Physical Geography*, 21 (4), 283–304.

Streutker, D.R., 2003. *A study of the urban heat island of Houston, Texas*. Thesis (PhD), May 2003, Rice University, Houston, TX.

WATSUN Simulation Laboratory, 1992. *WYEC2/CWEC user's manual, engineering data sets of hourly weather observations in WYEC2 format and Canadian weather for energy calculations (CWEC files)*. Waterloo, Ontario: WATSUN Simulation Laboratory, University of Waterloo.

USDOE, 2007. *EnergyPlus Version 2.0*. www.energyplus.gov.

USEPA, 2007. *Heat island effect* [online]. Available from: http://www.epa.gov/heatisland/.