CREATING WEATHER FILES FOR CLIMATE CHANGE AND URBANIZATION IMPACTS ANALYSIS

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ABSTRACT

Over the past 15 years, much scientific work has been published on the potential human impacts on climates. For the Third Assessment Report published by the United Nations International Program on Climate Change in 2001, a series of economic development scenarios were created and four major general circulation models (GCM) were used to estimate the anthropogenesis-forced climate change. These GCMs produce worldwide grids of predicted monthly temperature, cloud, and precipitation deviations from the period of 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 island (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 pattern. This paper presents the methodology used to create weather files which represent climate change scenarios in 2100 and heat island impacts today and present the typical climatic patterns resulting for 20 climate regions worldwide.

KEYWORDS

Climate change, weather data, urban heat island, historical weather

INTRODUCTION

Over the past 15 years, the international scientific community [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 GCM predict climate at a relatively high level of spatial resolution (5 x 5 degrees latitude and longitude or several hundred kilometers). The four major GCM are HadCM3 (United Kingdom) which includes a finer spatial resolution for the British Isles, CSIRO2 (Australia), CGCM2 (Canada), and PCM (USA) (IPCC 2001).

When combined within the GCM, the scenarios represent a range of potential climate impact defined by IPCC—16 combinations of scenario and climate prediction. The range of potential annual average global temperature changes predicted by the GCM using the scenarios is shown in Figure 1.

But climate change may not be the only change affecting our built environment. Over the past 30 years, there has been a significant trend towards increasingly larger urban areas. This concentration of transportation infrastructure and buildings often results in urban heat islands—increasing the cooling loads on buildings. For example, London Heathrow, Los Angeles, and Phoenix have all seen average temperature increases of at least 1°C over the past 30 years.

This papers describes the method for selecting 25 weather locations to support analysis of potential impacts of climate change scenarios and urban heat island on building performance (Crawley 2007). This paper also describes how the base set of weather data was modified to represent climate change scenarios and urban heat island.

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 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 (ASHRAE 2001) worldwide. The TMY2, CWEC, and IWEC typical weather years contain more solar radiation and illumination data than some that the typical month method used to select data

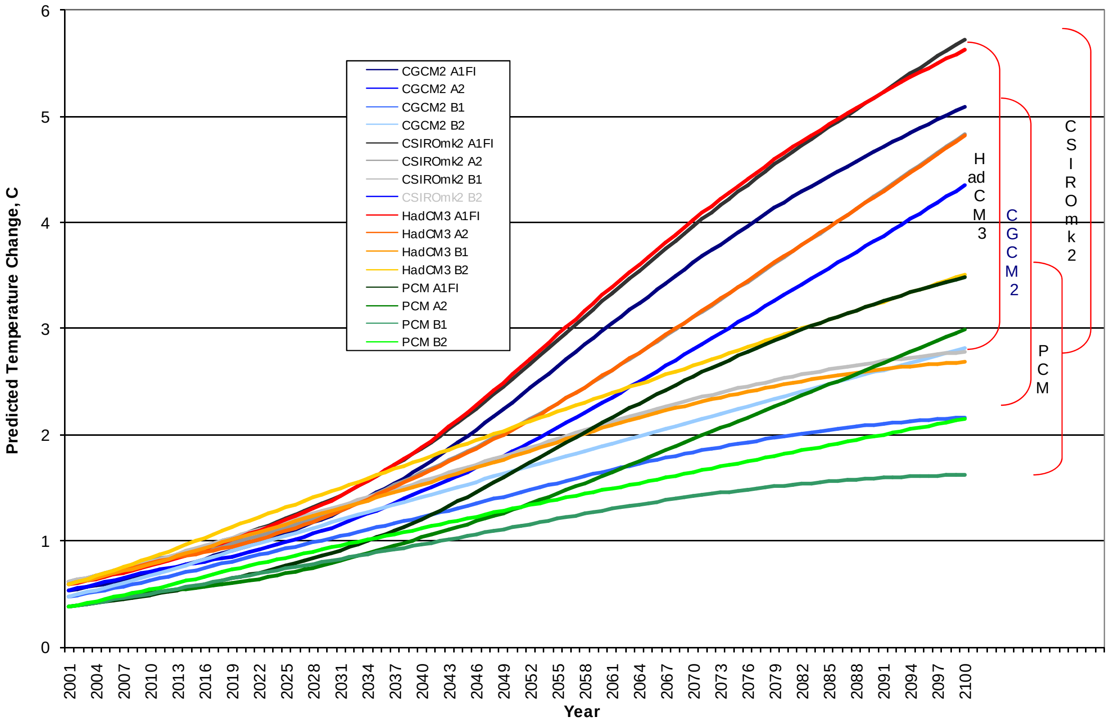

Figure 1. Global Annual Average Temperature Change Predicted by Four Major Global Climate Models

for these data sets fits the long-term climate patterns better.

First consideration was that the locations should have a reasonable source period of record—on the order of 15 years—to make this work possible. The TMY2/SAMSON/NSRDB and CWEC/CWEEDS have more than 30 years for all their locations. IWEC locations have up to 19 years. But the periods of record vary—TMY2/SAMSON/NSRDB covers 1961-2005 while CWEC/CWEEDS covers ~1950-1999, and IWEC covers 1982-1999. Despite these differences, TMY2, CWEC, and IWEC were the most robust climatic data sources from which to select the range of climate regions for this work.

Climate Classification

Early in the 20th 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 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

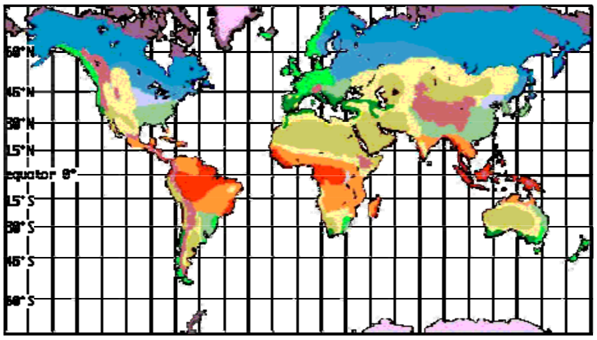

Figure 2 Map of Köppen Climate Classes

These six major climate types are further subdivided into hot/cold and dry/wet—creating 20 regions which represent the range climatic conditions worldwide. See the description of each class in Table 1 and a world map of the classes above in Figure 2.

The first step was to determine which Köppen climate class that the available TMY2, CWEC, and IWEC locations best fit. As a second step, the population rank of the cities was added, based on Brinkhoff (2007). The goal was to select at least one location within each climate region to represent that region. Generally, from the equator to approximately 40-50º latitude, the location within the TMY2/CWEC/IWEC data sets with the highest population was selected. Ten of the 25 locations are in the top 25 largest population centers. (Note that for colder climates—where no city rank is shown—there are not many cities with large populations.)

Table 1. Köppen Climate Classification System

Climate	Description
Af	Tropical wet (no dry season, rainforest, hot all year, lat. < 10°)
Am	Tropical monsoonal or tradewind-coastal (short dry season, lat. 5-25°)
Aw	Tropical savanna (pronounced wet & 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

For 5 Köppen climate regions where there were both major developed and emerging country locations, a second location was selected—part of a test of developed versus emerging building design practice. The twenty-five locations selected and their Köppen and a few other major climatology attributes based on the typical files (TMY2, CWEC, and IWEC) are shown in Table 2 below.

Selecting Climate Years for Simulation

Rather than attempting to run up to 45 years of weather data for each location plus the possible climate scenarios, a more efficient way was to attempt to determine the years which would produce the highest and lowest energy use. Initially this was thought to be something as simple as a combination of highest and lowest heating and cooling degree days for each weather year might be sufficient to select the years producing the highest and lowest energy years. To test this, a prototype small office building was simulated using the EnergyPlus building energy simulation model (Crawley et al. 1999). Three locations—an extreme cold location (Resolute, Nunavut, Canada), a mid-latitude location (Washington, DC—Sterling VA, USA), and a tropical location (San Juan, Puerto Rico)—were selected to represent a wide range of climate conditions. These three locations are part of the TMY2 and CWEC data sets, which have longer available period of record (45 and 49, respectively). Thus, for Resolute, the same prototype was simulated in all the available years—sized using the ASHRAE 2005 Fundamentals design conditions—from 1963 through 1999 plus the CWEC typical year data.

Starting with the results for the Washington-Dulles Airport, VA, USA (Sterling, VA, USA) climate and energy calculations in Figure 3, all 45 years in the TMY2/SAMSON/NSRDB data set for Washington, DC are ranked from coolest to warmest based on the combination of heating and cooling degree days, base 18 and 10 C, respectively. From Figure 3, one might presume that 1969 might result in the combination of highest cooling and lowest heating while 1990 resulted 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 to not be the case. As shown in Figure 4, while 1990 had the next to lowest energy use, 2001 resulted in 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. A similar comparison is shown in Figures 5 through 8 for Resolute, Nunavut, Canada and San Juan, Puerto Rico. As shown in Figure 5, for Resolute the lowest heating degree days (there were no cooling degree days for Resolute) was for 1998 and the highest heating degree days was for 1972. Figure 6 shows that the 1998 data result in the 3rd lowest energy use and 1972 does result in the highest annual energy use. In Figures 7 and 8, similar results are shown for San Juan, Puerto Rico. In this case, 1961 is the coolest year 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 weather data based on single, simple climate descriptors such as degree days would not guarantee the lowest or highest energy for the period of record. There are too many contributing variables such as solar radiation and humidity that were significantly impacting energy use. The only reasonable way to select the cool and warm years for the climate change scenario tests was to run the prototype office through the complete set of years (707 simulations).

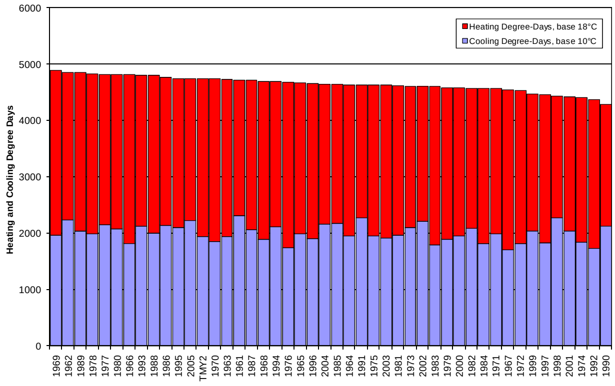

Figure 3 Washington, DC Heating and Cooling Degree Days Ranked from Highest to Lowest

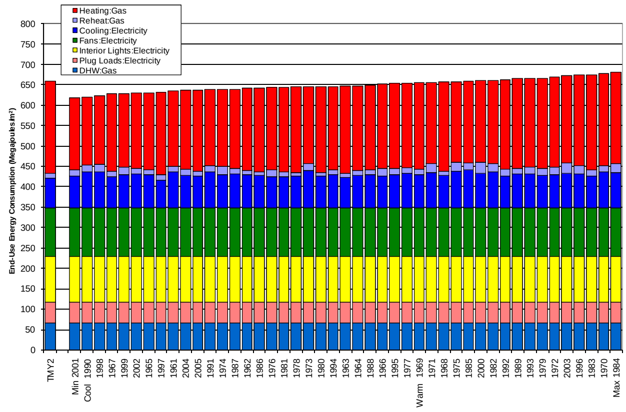

Figure 4 Washington, DC Energy End-use Consumption for 550 m^2 Office Building

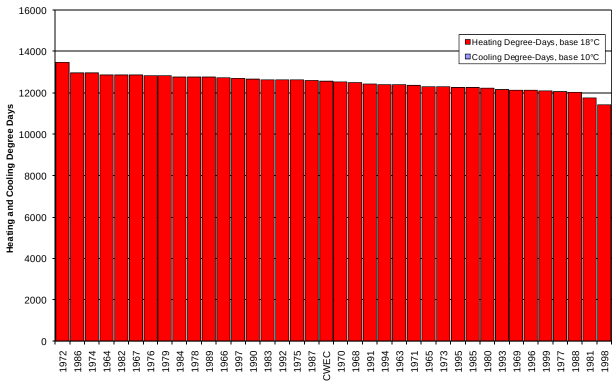

Figure 5 Resolute, Nunavut, Canada Heating Degree Days Ranked from Highest to Lowest

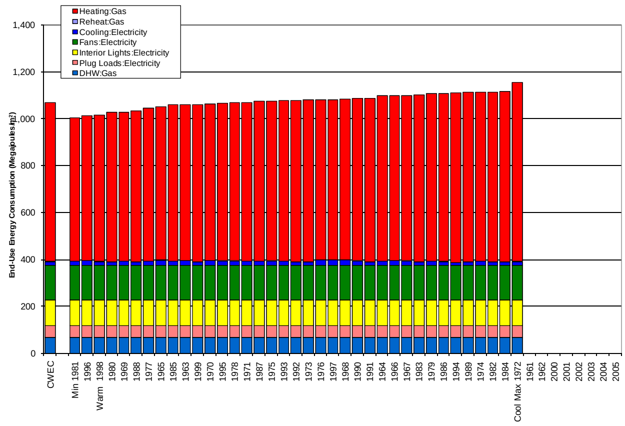

Figure 6 Resolute, Nunavut, Canada, Energy End-use Consumption for 550 m^2 Office Building

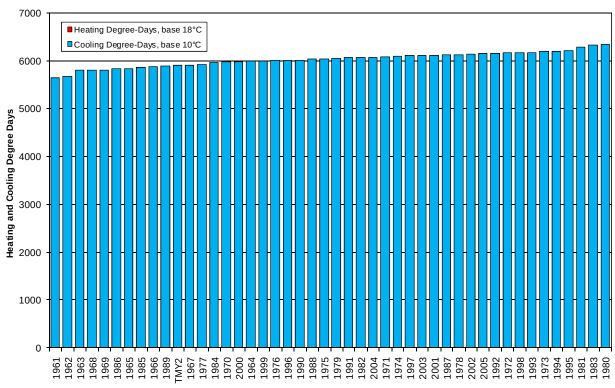

Figure 7 San Juan, Puerto Rico, Cooling Degree Days Ranked from Lowest to Highest

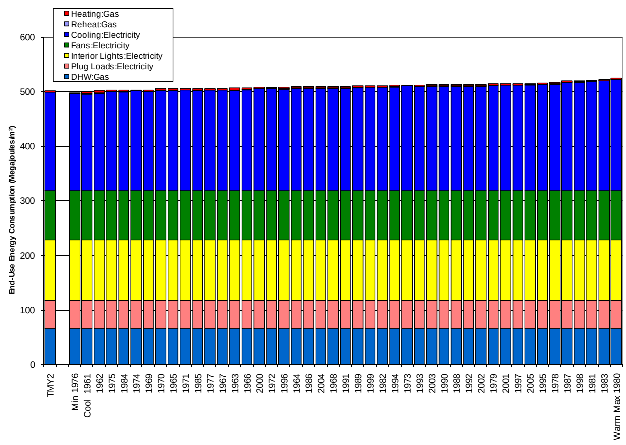

Figure 8 San Juan, Puerto Rico, Energy End-Use Consumption for 550 m^2 Office Building

REPRESENTING THE CLIMATE SCENARIOS

As described 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 emissions scenarios from the storylines–A1FI, A2, B1, and B2–cover the range of potential climate impacts as defined by the IPCC:

- A1: rapid economic and population growth, three groups of alternative energy system change: fossil intensive, non-fossil sources, or balance among sources.
- A2: continuous population growth, but fragmented economic growth.
- B1: population peaks in mid- 21st 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.

Mitchell (2003) created a dataset with a higher resolution of 0.5 x 0.5 degrees latitude and longitude. These data are monthly grids for the period 2001-2100. Five climatic variables are provided: cloud cover, diurnal temperature range, precipitation, temperature, and vapour pressure. In the data set, there are 16 climate change scenarios—the four GCM 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 was selected to represent the four climate scenarios because, as seen in Figure 1, it provides a broadest range of predicted global average temperature change among the four GCM. Since Mitchell reanalyzed the data to create a denser global grid, the predicted monthly change for a weather variable could be simply looked up. As noted above, Mitchell's data includes cloud cover, diurnal temperature range, precipitation, temperature, and vapor pressure. As the weather data used by EnergyPlus (and most energy simulation programs) does not include precipitation, these data were not included in modified weather data files. Since the change in vapor pressure indicated by Mitchell in this data set was quite small, it was also not included.

The existing weather files were modified to account for changes in diurnal temperature range, dry bulb temperature, and cloud cover. Solar radiation was recalculated based on the modified cloud cover. A program was created to read in the existing weather file and GCM monthly delta values, recalculate the hourly dry bulb temperature based on both the temperature change and the reduced diurnal temperature range, recalculate the humidity ratio based on relative humidity, and recalculate the hourly global, direct normal, and diffuse horizontal solar radiation based on the cloud cover. Figure 9 shows an example of the average hourly temperatures for January in Washington, DC. Note that there is almost imperceptible compression of the diurnal temperature range for Scenarios B1 and B2, while for Scenarios A1FI and A2 there is no difference from the baseline TMY2 weather.

REPRESENTING THE URBAN HEAT ISLAND

That urban conditions are different from rural has been recorded for more than 2,000 years. As Neuman (1979) found in a historical review of heat island, the air pollution and temperature differences in Rome from the countryside was noted in the odes of Quintus Horatius Flaccus in 24 B.C. From the Middle Ages, London was known for its pollution. King Edward I banned the burning of sea coal in 1306; Queen Elizabeth I banned the burning of coal during sessions of Parliament.

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 center 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 3.70º *warmer* and day 0.34º *cooler* in the city than in the country," recognizing what today is called the heat island effect.

More recently, Mitchell (1953, 1961) and other researchers have measured the heat island phenomenon. Oke and Runnells (1988, 2000) developed a diagram to explain the diurnal patterns of heat island. Their diagram is consistent with measured data such as Streuker (2003) and Morris and Simmonds (2000). Streuker's measurements reinforced Oke's findings (1973) that heat island intensity depends on a number of factors including urban density (population density), vegetation and surface albedo.

The US Environmental Protection Agency (EPA) estimates that the heat island effect is in the range of 2-10ºF (1-5ºC) (EPA 2007). But this is a range of potential impacts, not an annual, monthly or even a daily average. Most discussions in the heat island literature focus on mitigating the effects through green roofs, increased vegetation, light roof colors, and reduction of hard surfaces. Little attention has been given to the measurement of the resultant air temperatures and how they impact building operating performance.

In reviewing the measured data, one could see that heat islands could be represented as a change to the diurnal temperature patterns. This was implemented in the same program used for the climate change scenarios. For heat islands, the program modifies dry bulb temperatures and recalculates the humidity ratio in an existing weather file. An example for the hourly average dry bulb temperatures in April is shown in Figure 10. Because the EPA estimates that the heat island effect is in the range of 1 to 5ºC, these values were selected to represent the range of heat island modification except for colder climates (>48 degress latitude) where the climates would be represented by 1 and 3 ºC. 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.

CONCLUSION

This paper describes the development of a set of modified typical and high-low energy weather years to represent four scenarios of climate change and two cases of urban heat island. Examples of the resulting climate change scenarios and urban heat island cases are shown in Figures 9 and 10.

This set of 525 weather files were then used in subsequent work to examine the simulated impacts of climate change and UHI on a small office building designed to current practice, good energy standards, and low energy practice.

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Figure 9 Hourly Average TMY2 and Climate Change Scenario Dry Bulb Temperatures for January in Washington, DC

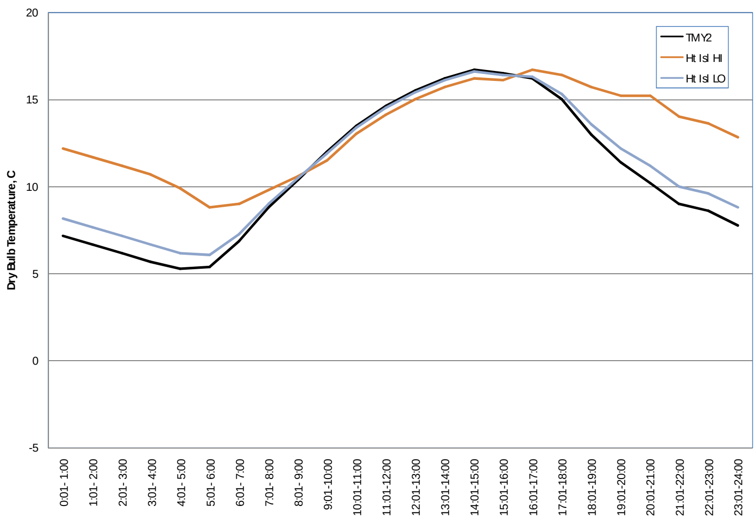

Figure 10 Hourly Average TMY2 and Heat Island Dry Bulb Temperatures for April in Washington, DC

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]			Annual CDD, base 10°C	Annual HDD, base 18°C
								Heating DB 99.6%, °C	Cooling DB 0.4%, °C	Cooling 0.4% MCWB, °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

[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)
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).
[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.