The Impacts of Climate Change on Building Design Conditions

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Abstract

The Impacts of Climate Change on Building Design Conditions

by Gesangyangji

Buildings are designed to function within local climate conditions. As such, building designers rely on climate metrics that are not always common in meteorology, such as upper and lower 1% dew point temperature, and heating/cooling degree days and hours. Currently, these standards are calculated from historical climate conditions, but for new buildings under design, it is important to include impacts of climate change to adapt the design and performance of buildings for future climate conditions.

This study uses the climate design chart (2013 edition) produced by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) as starting point for future climate analysis, and has successfully reproduced AHSRAE's temperature and precipitation metrics for Madison, WI. In both temperature and precipitation metrics, several discrepancies appeared between our and ASHRAE's results, which are more likely to be caused due to the way to deal with missing values instead of calculation methods. ASHRAE's precipitation show strange drops in May and June, which are the main differences.

We also produced four ASHRAE-equivalent future design charts under RCP 4.5 and RCP 8.5 for mid- and late- century. The ASHRAE metrics related to extreme events, which can be a challenging to capture in archived climate data due to requirements of realistic variance. This issue is addressed by our new downscaled dataset, the University of Wisconsin

Probabilistic Downscaled (UWPD) data. UWPD data is a probabilistic statistical downscaled data assuming large-scale climate can only determine the likelihood of local-scale climate instead of a specific value of local-scale climate. This dataset gives probabilistic density functions of variables, which captures realistic variances at the local scale. ASHRAE's calculations are based on hourly basis, to be consistent to ASHRAE's methods, we rescaled historical hourly observations to future hourly data by using UWPD projection.

By analyzing absolute and percentage difference, we found the metric for degree days and hours is more sensitive to global warming than other metrics. The sensitivity is higher in the spring and fall, and when the threshold temperature is higher. Furthermore, we examined the trend of cooling degree hours (CDHs) with base temperature 23.3°C throughout the 21st century under RCP 4.5 and RCP 8.5, and we found CDHs are expected to increase under both scenarios. In Madison, CDHs will double by 2050 and fivefold by 2090 under RCP 8.5. The increase is significantly greater than the increase under RCP 4.5. Our results show that under moderate emissions scenario (RCP 4.5) Madison will be similar to St. Louis, Missouri by 2090; and under high emissions scenario (RCP 8.5), Madison will resemble Birmingham, Alabama by 2070.

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Abbreviations

ASCII	American Standard Code for Information Interchange
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
CDFs	Cumulative Distribution Functions
CDD	Cooling Degree Day
CDH	Cooling Degree Hours
CMIP	The Climate Model Inter-comparison Project
CMIP5	The fifth phase of Climate Model Inter-comparison Project
GCMs	General Circulation Models
GHCN	The Global Historical Climatology Network
GHG	Greenhouse Gas
NCDC	The National Climate Data Center
HDD	Heating Degree Day
IECC	The International Energy Conservation Code
IPCC	The intergovernmental Panel on Climate Change
ISD	The Integrated Surface Database
km	kilometer
mm	millimeter
PDFs	Probability density functions

RCP Representative Concentration Pathway

UWPD The University of Wisconsin Probabilistic Downscaled data

Symbols

W humidity ratio/mixing ratio

p_w partial pressure of water vapor

p pressure

h enthalpy

t^* wet-bulb temperature

Ws^* humidity ratio by wet-bulb temperature

Chapter 1

Introduction

Buildings must be designed for local weather and climate. Meteorological parameters including temperature, humidity, wind, precipitation, and solar irradiance are not only critical factors for selecting building materials (roofing, window, etc.) and design tools, but also the basis for building energy use through indoor heating, ventilating, air conditioning and refrigerating (HVAC&R) systems. This study calculates building design metrics based on future climate model projections, in a manner consistent with The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

1.1 Building Design Conditions

To provide recognizable weather information for building design teams, climatic design conditions are developed from meteorological elements. ASHRAE is an association that has been working on converting meteorological elements to building design information. ASHRAE has published Climatic Design Conditions in Chapter 14 of the 2013 ASHRAE Handbook - Fundamentals (HOF) (ASHRAE, 2013a).

Climatic design elements in ASHRAE's table can be broadly defined as 1) annual heating and humidification design conditions, 2) annual cooling and dehumidification design conditions, 3) extreme annual design conditions, and 4) monthly climate design conditions, which cover temperature, degree-days and hours, dry-bulb and wet-bulb temperature at various frequency of occurrence, mean daily temperature range, and clear sky solar irradiance (ASHRAE, 2013b). The 2013 edition of ASHRAE climate design standard is calculated for 6443 locations around the world, and it uses a period of record from 1986 to 2010. The 2013 ASHRAE Climatic Design Conditions for Madison is provided in the Appendix Section. A.1 and a simple description for all variables is provided in Appendix A.2.

The design variables in the ASHRAE tables are calculated from typical weather variables but are not common for traditional meteorological analysis. Cooling and heating degree days are calculated from hourly temperature and are related to the amount of energy used to operate heating or cooling systems. Degree-day measurement is the difference in temperature between the mean outdoor temperature over a 24-hour period and a given threshold temperature for a building space, typically 65 °F in the U.S. (Baechler et al., 2015). Monthly cooling degree days (CDDs) are defined as the sum of the differences between daily temperature and the threshold temperature when the differences are positive in a given month. While daily temperature exceeds the threshold temperature, air conditioning often needs to be used to cool the buildings, so CDDs often reflect the amount of energy that is used for operating the cooling system.

Building designers rely on such metrics to adapt the design of buildings and energy systems. Figure 1.1 shows ASHRAE's climate zone map (ASHRAE, 2017). These climate zones are defined based on average temperature, heating and/or cooling degree days, and annual precipitation amount (ASHRAE, 2017), which are covered in the ASHRAE table. Pérez-Lombard et al., 2011 shows that HVAC systems serving multiple zones may waste a great amount of energy in conditioning all zones when only a few are occupied (Pérez-Lombard et al., 2011). With correct information of average temperature, heating and/or cooling degree days, and annual precipitation amount, designers can find the right climate zone and adjust their building design to minimize energy waste. For example, the climate of the tropical climate zone (Zone 1) including Hawaii, Puerto Rico, and the Virgin Islands is uniquely constant at high temperatures throughout the year, so traditional HVAC&R installation found in buildings outside of the tropical environment, like heating systems, may not be needed (IECC, 2015). Thus, materials and energy used for installing and utilizing the heating system can be saved.

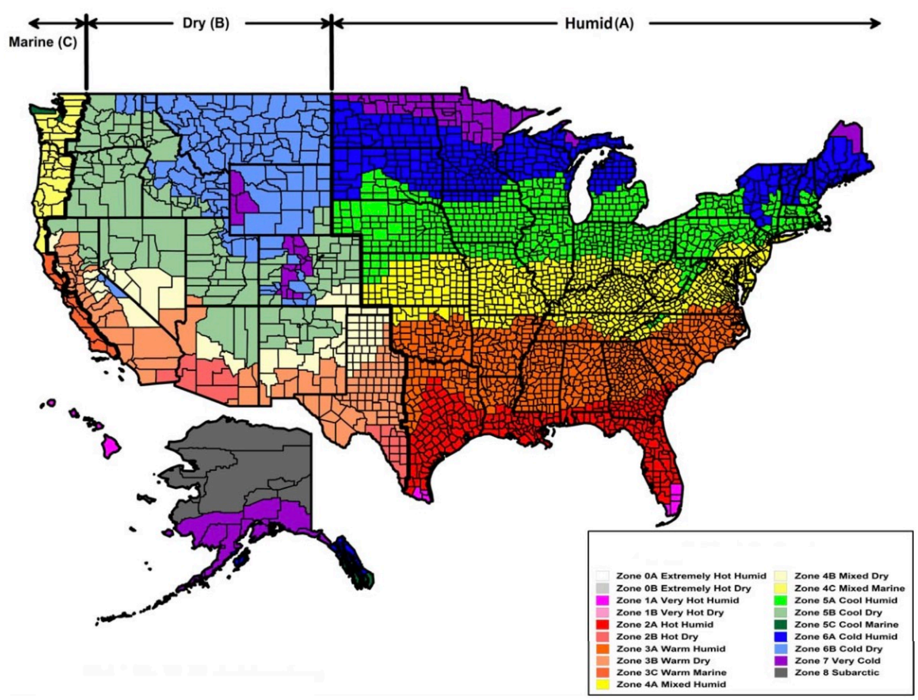

Figure 1.1 ASHRAE's Climate Zone Map (ASHRAE, 2017).

1.2 Interaction between Buildings and Climate Change

The intergovernmental Panel on Climate Change (IPCC) has reported that global warming is likely to reach 1.5 °C between 2030 and 2052 above pre-industrial levels at the current increase rate. Human activities are estimated to have caused about 0.8°C to 1.2 °C of warming thus far (IPCC, 2018). Potential impacts and associated risks of climate change include an increase in mean temperature, extremes heat, heavy precipitation, and the probability of drought and precipitation deficits in some regions (IPCC, 2018). Heatwaves in Europe and North America are likely to become more intense and longer-lasting in the second half of the 21st century (Meehl & Tebaldi, 2004). With the increase in temperature, more precipitation occurs as rain instead of snow, and snow melts earlier. This results in increased runoff and risk of flooding in early spring and increased risk of drought in summer with greater surface evaporation due to warming (Trenberth, 2011).

Many studies have linked the effects of rising temperatures on building energy use. Due to the higher temperatures, the U.S. national CDDs are expected to rise by 540 to 670 degree days (32% to 43%) during the period of 2005 to 2050 (McFarland et al., 2015). This requires greater electricity supply for buildings to operate space cooling systems. Studies show a uniformly higher electricity demand in the future to meet the increased need for air conditioning (Hadley et al., 2006; Rosenthal et al., 1995). Under a scenario with global temperatures rising by 1.7 °C from 2005 to 2050, US electricity demand in 2050 is 1.6% to 6.5% higher than a control scenario with global temperature rising by 0 °C (McFarland et al., 2015). When similar studies were done at the state level, the impacts of high temperatures on building energy are even more significant (Huang & Gurney, 2016). High relative humidity in conjunction with high temperature, also affects electricity demand because the perceived temperature can be higher in such meteorological conditions and, as a consequence, the use of air cooling appliances increase (Apadula et al., 2012).

On the other hand, building emissions contribute to global warming through two main pathways. The first is the "operational carbon emissions" that comes from day-to-day energy use, including HVAC&R systems and powering lighting (Diana, 2019). Operating HVAC&R systems contribute to greenhouse gas (GHG) emissions through direct refrigerant emissions and indirect CO_2 emissions (Ashrae, 2018). The second pathway is the "embodied carbon of a building", referring to the amount of carbon generated during building construction. This pathway also considers the fate of building materials after disposal. Examples include manufacturing and transporting building materials, as well as the disposal of construction waste (Diana, 2019). In 2010 buildings accounted for 32% of total global final energy use, 19% of energy-related GHG emissions, and approximately one-third of black carbon emissions (Ürge-Vorsatz et al., 2014). In the United States, buildings and their construction together account for 40% of energy consumption (Diana, 2019).

Overall, building HVAC&R systems use are a big source of GHG emissions and are contributing to global warming. Rising temperature as a result of global warming in turn affect building emissions by changing the usage of HVAC&R. With the growing frequency of extreme weather events due to climate change, new buildings designed for the present climate will be unsuitable and vulnerable for the future climate and therefore affect the usage of HVAC&R negatively. The cycle can be broken if new buildings are well-adapted for the right future climate. Building suitable for the local climate can minimize indoor energy usage and optimize energy efficiency by making full use of natural resources. For example, natural ventilation can be driven by local conditions without using mechanical systems if designers know and take advantage of air pressure and airflow around the building. Energy-efficiency measures, like improving roof and wall insulation, upgrading the water-cooled chillers, and installing ventilation energy recovery wheels, can also reduce the cooling and heating loads during hot summers and cold winter by reducing the amount of energy used for cooling and heating equipment (Schuetter et al., 2014). Thus, it is important to consider the effects of climate change when calculating building design conditions from weather elements. The first step of adapting the new buildings for the future climate is to understanding climate change.

1.3 Climate Models

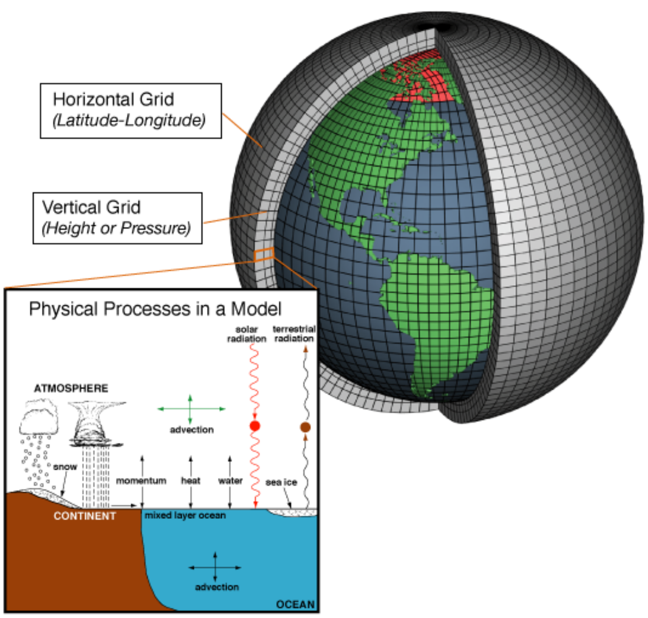

Figure 1.2 the concepts used in climate models (NOAA, 2007).

Climate models, also known as General Circulation Models (GCMs), are computer-based simulations that use quantitative methods to simulate the interaction of the important climate drivers including the atmosphere, ocean, land surface and sea ice. Figure 1.2 shows the concepts used in climate models. To run a model, scientists divide the planet into thousands of 3-dimensional grid cells. Each of these grid cells can be represented by equations based on fundamental laws of physics, fluid motion, and chemistry (NOAA, 2007). Atmospheric models calculate winds, heat transfer, radiation, relative humidity, and surface hydrology with each grid and evaluate interactions with neighboring points (NOAA, 2007). The Coupled Model Intercomparison Project (CMIP) studies the output of coupled GCMs and assesses their strengths and weaknesses to improve future models. The fifth phase of CMIP (CMIP5) is the most current and extensive version, offering a multi-model perspective of simulated climate change and climate variability and providing a freely available state-of-the-art multi-model dataset (Taylor et al., 2012).

A set of scenarios known as Representative Concentration Pathway (RCPs) is GHG concentration trajectory adopted by the IPCC to provide a range of possible future for atmospheric compositions (R. Moss et al., 2008; R. H. Moss et al., 2010). Four main pathways including RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 were used by the IPCC Fifth Assessment Report (AR5) for climate modeling and research (IPCC, 2014). These four GHG concentration-dependent pathways are labeled after a possible range of radiative forcing values in 2100 (2.6, 4.5, 6.0 and 8.5 W/m2, respectively). Each pathway provides a different estimation for global-mean surface temperature increases, from 1.5°C for RCP 2.6 to 4.5°C for RCP8.5, relative to pre-industrial levels (Meinshausen et al., 2011).

The resolution of GCMs participating the fifth IPCC ranges from 2.8° by 2.8° to 0.5° by 0.5° (Vavrus et al., 2011; Zhao et al., 2009), which is not sufficient for regional climate processes of 10-15km (1° near the equator is equivalent to about 111 km). Regional extremes are often muted by GCMs due to their relatively coarse resolution (Sillmann et al., 2013). Downscaling methods can solve this issue by extracting high-resolution information from GCMs. Downscaling methods can be characterized as dynamical or statistical: dynamical downscaling methods use a higher resolution model that is forced by the large-scale GCMs (Giorgi, 2006), while statistical downscaling develops large- and small-scale relationship from historical data and applies this relationship to adjust large-scale data down to local scale. Downscaling methods provide high-resolution data for researchers to better study regional climate processes.

1.4 Focus of the Study

Where ASHRAE climate design conditions are calculated based on historical weather observations, buildings designed today are subjected to the climate of the future. Thus, it is important and necessary to update ASHRAE climate design conditions by including the effects of climate change so the design and performance of buildings can adapt to future climate. In other words, one can use ASHRAE's calculation methods but replace historical weather data with future weather data to produce a future design standard. AHSRAE's calculation is provided on an hourly basis, which is challenging for many model products because 1) the data volume would be overwhelming (Taylor et al., 2012), and 2) it is difficult to capture realistic variance when downscaling large-scale climate data to local-scale. This study will address the issue of getting future hourly data by using a new probabilistic downscaled data set and a novel rescaling method.

One goal of this study is to produce climate-based design standards for ongoing UW campus building constructions, so the new UW buildings can be well-adapted for the future climate in Wisconsin. This work in turn developed a meteorology that maybe directly applied to cities in the Eastern U.S. and extended to cities around world.

In this study, ASHRAE-equivalent climate design conditions were produced for the mid- and late- century under alternative emission scenarios (RCP4.5 and RCP 8.4). These further metrics were calculated to answer the following questions:

- What are the meteorological based metrics most sensitive to climate change?
- How do cooling degree days change with time throughout the 21st century?
- How will the trend of cooling degree days change under different emission scenarios?

This study involves four major tasks, including 1) reproducing ASHRAE's climate condition chart, 2) developing future climate conditions on hourly basis, 3) rescaling ASHRAE chart for future climate conditions, and 4) analyzing future metrics. Descriptions of observed and downscaled datasets, and rescaling and calculation methodologies are discussed in Chapter 2. All results are presented in Chapter 3. Chapter 4 gives conclusions of this study.

Chapter 2

Data and Methodology

To complete our work of producing ASHRAE-equivalent climate conditions for the future, we took three steps.

The first step is to recalculate the 2013 ASHRAE Climatic Design Conditions for the Madison/Dane County station, over the period from 1986 to 2010. The goal of this step is to make sure we understand ASHRAE's calculation methods correctly.

The second step is to develop hourly downscaled data. In this step we will rescale downscaled data to hourly basis to ensure the consistency with ASHRAE's calculation.

In the third step, we replace the historical meteorological data that ASHRAE used with a downscaled data to obtain a climate design conditions for the future. To further study future climate design conditions, we evaluate the results to assess what metrics are most sensitive to climate and how building design will adapt to the 21st century.

2.1 Reproducing ASHRAE Climate Design Conditions

2.1.1 Temperature Metrics

Data Source

The Integrated Surface Data (ISD) is used for the temperature metrics in 2013 ASHRAE Climatic Design Conditions. The ISD data, produced by the National Climate Data Center

(NCDC), consists of global hourly and synoptic observations compiled from numerous sources into a common American Standard Code for Information Interchange (ASCII) format (NOAA, 2020). In ASHRAE's work, all temperature metrics are calculated on an hourly basis. For this study, hourly temperature, wind magnitude and wind direction data were acquired for the Madison/Dane County station over a period from 1986 to 2010. One missing year (1996) for this station is omitted, since ASHRAE has not given specific information on how to address the missing year for the Madison/Dane county. However, ASHRAE's handbook mentions that while the calculation period in most cases is 25 years, the actual number of years for a given station can be as little as 8 years.

Table 2.1 shows the basic information of the Madison/Dane County station in the ISD dataset. To make sure all the data we used would be valid, suspicious and erroneous data indicating by quality code of 2, 3, 6, or 7 (NCDC, 2015) and a missing value of 9999 and/or 999 were replaced by a linear interpolation to provide the most complete time series possible. Duplicating times were all replaced by the average of duplicated times. Finally, all data were linearly interpolated in time to the nearest hour. Further details of data quality check and screen criteria in ASHRAE's work (ASHRAE, 2013a) are provided in the Appendix A.3.

Table 2.1 Madison Station Information from ISD

STATION	NAME	STATE	CALL_SIGN	LATITUDE	LONGITUDE	ELEVATION
72641014837	MADISON DANE CO REGIONAL AIRPORT	WI	MSN	43.1405	-89.3452	264 (meter)

Mathematical Equations for ASHRAE variables

The same methods as described in the 2013 ASHRAE Climate Conditions were used to recalculate ASHRAE metrics. Basic meteorological variables including dry-bulb temperature, dew point temperature, wind speed, wind direction, and elevation were directly taken from the ISD dataset. Depending on dry-bulb temperature, dew point temperature and elevation, other heating/cooling and humidification/dehumidification variables were calculated. The following equations are used for the variables directly included in ASHRAE's chart. There are some variables used during calculation that are not contained in ASHRAE's chart; the mathematical equations to calculate these variables are provided in the Appendix Section. A.4.

Humidity ratio/mixing ratio (W) is calculated based on the partial pressure of water vapor as variable p_w, and the pressure, expressed as a variable p. Equations for calculating p_w and p are included in the Appendix Section. A.4.

$$W = 0.621945 * \frac{p_w}{p - p_w} \tag{2.1}$$

Enthalpy (h) is calculated based on humidity ratio (W) and dry-bulb temperature (t) with a unit of kJ/kg:

$$h = 0.240 * t + W * (1061 + 0.444 * t) \tag{2.2}$$

The calculation of wet-bulb temperature (t*) is more complicated since it involves nonlinear equations. The equations we used to calculate t* are based on humidity ratio W and humidity ratio by wet-bulb temperature Ws*, where Ws* is dependent on t* itself. In this case, we solved t* numerically by subtracting equation 2.1 (a function of known parameters) from 2.3 or 2.4 (a function of t*) and setting the result equation to zero. The zero crossing the resulting function is solved by using the *fzero()* function in MATLAB (R2015a). It should be noted that t* calculated by this equation is in units of °F, while t* in the chart is in units of °C. Unit conversion equations are also included in Appendix Section. A.4.

For temperature <32 °*F*:

$$W = \frac{(1220-0.04*t^{*})Ws^{*}-0.240*(temp-t^{*})}{1220+0.444*temp-0.48*t^{*}} \tag{2.3}$$

For temperature >32 °*F*:

$$W = \frac{(1093-0.556*t^{*})Ws^{*}-0.240*(temp-t^{*})}{1093+0.444*temp-t^{*}} \tag{2.4}$$

Monthly heating degree days (HDD) and cooling degree days (CDD) are calculated as the sum of the differences between daily average temperature and the base temperature in a given month. N in equations (2.5) and (2.6) indicates the number of days in the month. T_{base} is the reference temperature (10.0°C and 18.3°C), and $\overline{T}_i$ is the daily mean temperature, calculated by averaging the maximum and minimum temperature of the day.

$$HDD = \sum_{i=1}^{N}(T_{base} - \overline{T}_i) \tag{2.5}$$

$$CDD = \sum_{i=1}^{N}(\overline{T}_i - T_{base}) \tag{2.6}$$

Monthly cooling degree hours (CDH) are calculated as the sum of the differences between hourly temperature and the base temperature in a given month. N in the equation

(2.7) is the number of hours in the month. T_{base} is the reference temperature (23.3°C and 26.7°C), and T_i is the hourly temperature in the day.

$$CDH = \sum_{i=1}^{N}(T_i - T_{base}) \tag{2.7}$$

Threshold exceedance calculation method

Many variables are presented corresponding to different percentages of annual cumulative frequency of occurrence: 0.4, 1.0, and 2.0% for warm conditions and 99.0 and 99.6% for cold conditions. For the simple threshold exceedance calculations, ASHRAE binned hourly data into frequency vectors, then derived from the binned data the design condition with the probability of being exceeded a certain percentage of the time. In this study, we used the same method and sorted all hourly data in descending order to obtain the exceed value in terms of different thresholds. For the more complicated case of mean coincident values, we first find all hours for which the exceedances exist, and then average the mean coincident variables at those time. For example, to calculate annual mean coincident dry-bulb temperature at 99.6% dew point temperature, we first find the threshold dew point temperature corresponding to 99.6% annual cumulative frequency of occurrence (-26°C), and then find all times for which dew point temperatures exceed -26°C, and average dry-bulb temperatures for these times.

2.1.2 Precipitation Metrics

Several sources of data, including surface data and model data, were used by ASHRAE for precipitation metrics calculations. Among these sources, surface data were used whenever possible and compensated with other sources when surface data was unavailable

(ASHRAE, 2013b). According to ASHRAE'S data selection criteria, we used the Global Historical Climatology Network (GHCN) data for precipitation metrics. Monthly precipitation is directly retrieved from version 2 of GHCN monthly data.

The GHCN dataset is an integrated database of climate summaries from ground-based stations across the globe and it is obtained from more than 20 sources. This data set includes both 'adjusted' and 'unadjusted' data. The adjusted set consists of data where adjustments were made by scientists to account for large inhomogeneities discovered in the unadjusted datasets (ASHRAE, 2013b). ASHRAE used the adjusted GHCN data whenever possible, as it is considered to be the best available for calculating climate design conditions. As a result, we used adjusted GHCN monthly data in our work.

The precipitation metric contains annual and monthly average precipitation, standard deviation, and maximum and minimum values. As mentioned before, monthly values are directly retrieved from GHCN data and annual values and other statistical variables are calculated based on monthly values.

2.2 Producing Future Climate Design Conditions

2.2.1 Climate Projection

The University of Wisconsin Probabilistic Downscaled (UWPD) Data (Lorenz, 2015) is used in our work. The UWPD data is constructed using a probabilistic approach, meaning the large-scale climate model quantifies a range of local-scale variables that could occur, instead of the precise value of the downscaled variables. The UWPD method uses a generalized linear model to predict the parameters of the underlying probability distribution of station-based observations, using large-scale climate variables as predictors. Thus, the effective result of the UWPD downscaling routine is daily varying probability density functions (PDFs) of the variables (KIRCHMEIER-YOUNG et al., 2016). By using this method, the UWPD produced the monthly cumulative distribution functions (CDFs) for daily station maximum and minimum temperature and precipitation over the eastern U.S. (east of Rockies) as well as some of southern Canada. The resulting distributions are interpolated to spatial resolution of 0.1° by 0.1°, and continuous monthly resolution from 1950 to 2100. To be noted, because the distributions are interpolated instead of actual values, they still represent point-based station data, and are thus very well suited to be used for the analysis in this study.

The UWPD dataset was selected because 1) it was downscaled from more than 20 GCMs and avoided the bias from one single model, and 2) it outputs the likelihood of local variables to preserve realistic extremes. In this study, the monthly UWPD CDFs which represent daily values are used to rescale ISD historical hourly observations (1986-2010) to the mid- (2040 to 2060) and late- (2080 to 2100) century, under high (RCP 8.5) and moderate (RCP4.5) emission scenarios.

2.2.2 Data Rescaling

Since ASHRAE calculations are based on historical hourly data, we need to rescale historical data so that it represents future climate conditions. The rescaling process consists of four steps, 1) obtaining daily maximum/minimum temperature from historical (ISD) hourly observations and computing the historical fractional relationship between hourly temperature and daily maxima/minima, 2) obtaining the UWPD data that is appropriate for a particular day of the years, 3) rescaling the historical daily maximum/minimum values to future daily maxima/minima by using the UWPD CDFs, and 4) applying the historical diurnal cycle fraction obtained from step 1 into the future daily maximum/minimum temperature obtained from step 2 to compute the future hourly data.

Step 1. Obtaining a historical relationship between the hourly and daily value

ISD hourly observations were adjusted with respect to standard time (UTC) to local time by subtracting 6 hours from each time stamp. Next, the daily maximum and minimum temperature were obtained for each day (midnight to 11pm local time). Then, equation (2.8) was used to calculate the fractional relationship between hourly and daily maximum/minimum temperature for each day. The relationship is indicated by parameter a in equation (2.8), which varies for each hour.

$$a_{ihour} = (T_{ihour} - Tmin_{iday})/(Tmax_{iday} - Tmin_{iday}) \tag{2.8}$$

The idea behind this equation is shown in Figure 2.1. The relationship between every single hour in a given day and the minimum temperature for that day can be represented by some fractions of the difference between the maximum and minimum temperature for that day. This means we can produce the observed diurnal cycle, which will be more realistic than a modeled diurnal cycle.

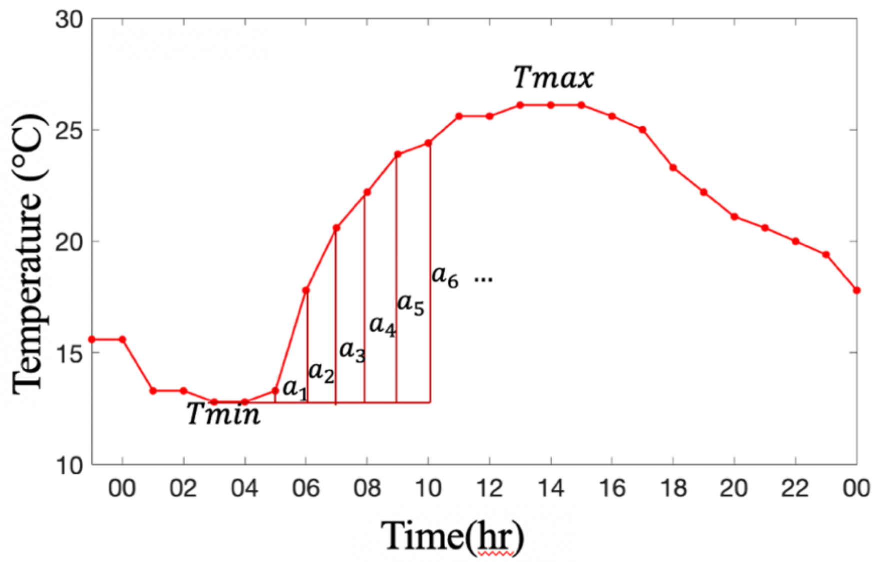

Figure 2.1 Hourly temperature and the diurnal cycle fractions for July 1st, 1986.

Step 2. Obtaining the UWPD CDFs for a given calendar day

The UWPD dataset contributes CDFs of daily maximum and minimum temperature for a particular time period, and for a particular calendar month. Thus, for the historical (1981-2010) period, the UWPD dataset contributes 24 individual PDFs, one for each variable (maximum and minimum temperature) and one for each calendar month. It is important to remember, though, that the CDFs themselves represent the distribution of daily maximum and minimum temperature, and as such retain the full variance (including extremes) of the underlying daily data.

In this step, we adjust the calendar-month UWPD CDFs so that they are representative of a given calendar day. This step avoids abrupt jumps in the CDF that would occur near the ends of the month, say, from September 30th to October 1st. The adjustment from mid-month to calendar day CDFs was accomplished via linearly interpolating the calendar month CDF (which is representative of mid-month conditions) to the particular calendar day via (2.9):

$$CDF_{iday} = b_{iday} \times CDF_{imonth} + (1 - b_{iday}) \times CDF_{jmonth} \tag{2.9}$$

Where the parameter b is the temporal fractional scaling for each day. This function means that CDF for a certain day (CDF_{iday}) is determined by 1) the CDF of the current month (CDF_{imonth}), 2) the adjacent month that is closest to the given day (CDF_{jmonth}, where j=i-1 if *iday* falls before the middle of month i, and j=i+1 if *iday* falls after the middle of month i), and 3) the temporal scaling (b_{iday}) for this day. For example, if we want to get CDF of the maximum temperature for August 10, we take the weighted average of the monthly CDFs of August and July, since July is closer to this day than September. If we want the CDF of the maximum temperature for August 25, then we would compute a weighted average of the monthly CDFs of August and September. The weighting b equals to 1 for the days which are exactly in the middle of the month, like Aug 16th, and approach b equals to 0.5 at the beginning and end of the month. Thus, we have a unique and smoothly varying CDF for each calendar day. This weighted average is applied separately to CDFs of maximum and minimum temperature.

Step 3. Rescaling historical values to future values by using UWPD CDFs

We use a CDF rescaling to obtain future maximum and minimum temperature from historical data. The whole process in this step can be explained by the example shown in Figure 2.2. Figure 2.2 is the UWPD CDFs for maximum temperature in one month. Two CDFs represent historical (1986-2010) and future (2041-2060) scenarios, respectively. Assuming a historical maximum temperature of -10°C on a given day, our first step is to find the exceedance probability (blue line) for this temperature, and this process is represented by the red dashed line on the historical CDF. We maintained exceedance probability and shift it from the historical CDF parallel to the future CDF. Finally, we obtain the corresponding future maximum temperature for the day based on the exceedance temperature for the maintained exceedance probability, this process is denoted by the blue dashed line. The rescaling process is exactly same for the minimum temperature, except we use the minimum temperature CDFs.

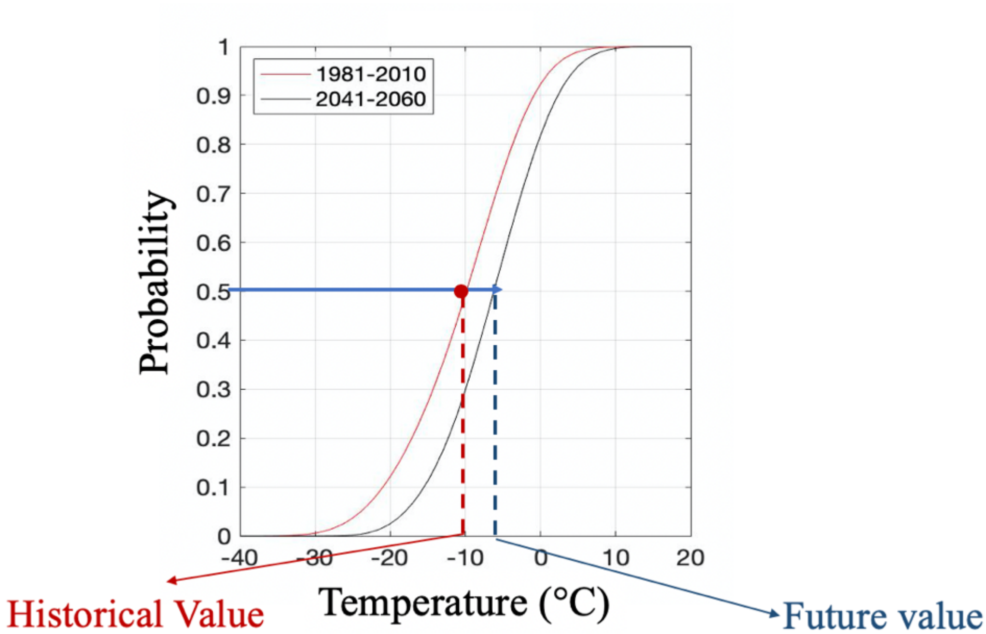

Figure 2.2 UWPD CDF of daily maximum temperature for historical (red lines) and future (black lines) scenarios.

Step 4. Obtaining future hourly values

Knowing the future daily maximum/minimum temperature and assuming that the observed diurnal cycle fractions will remain the same, we can transform the equation in 2.8 to another form (2.10), in which the future hourly temperature can be calculated.

$$T_{ihour} = a_{ihour} * Tmax_{iday} + (1 - a_{ihour}) * Tmin_{iday} \tag{2.10}$$

Where a_{ihour}, the diurnal fraction between hourly and daily maximum/minimum temperature for each day, is obtained from the historical data.

2.2.3 Calculating Future Climate Design Conditions

Finally, we have the future hourly data in the same format as the historical hourly data. Figure 2.3 shows the time series of historical hourly temperature (blue line), and the mid-century hourly temperature (red line) that is rescaled from the historical temperature for a given year. This is an example result of our rescaling work under RCP 4.5 scenario. With climate change, hourly temperatures rise during the year in the future, but the historical annual fraction has retained in the future. The blue line represents the hourly temperatures used by ASHRAE, and we will replace them the future hourly temperature represented by the red line. With the future hourly data and the methods that were utilized in Step 1(Section. 2.2.2), we produced future climate design metrics for the mid- and late- century under high (RCP 8.5) and moderate (RCP 4.5) emissions scenarios. The GCMs that are used for different scenarios (24 models for RCP 8.5 and 22 models for RCP 8.5) are listed in Table 2.2.

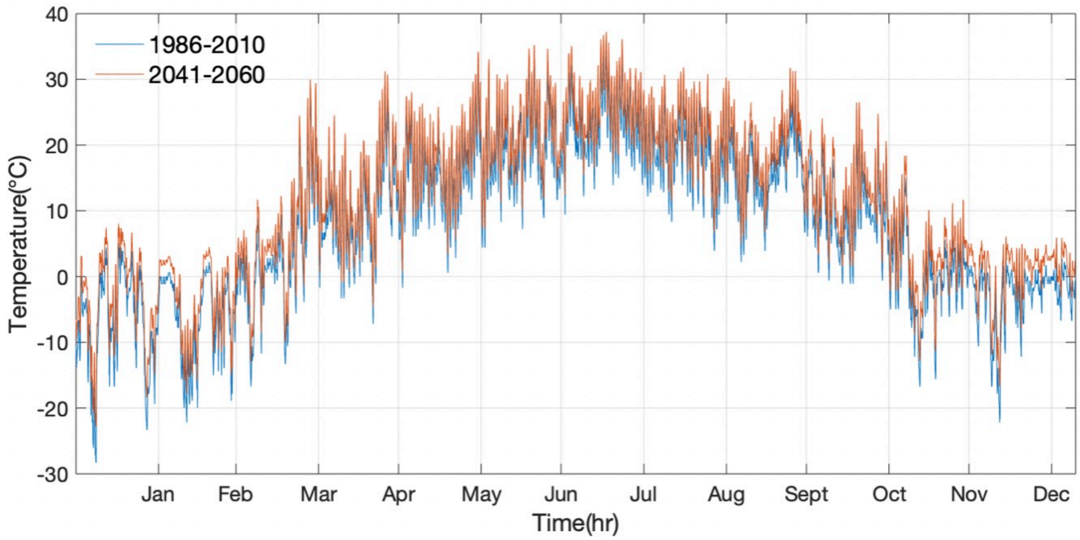

Figure 2.3 Time series of historical (blue line) and future (red line) hourly temperature for a year.

Table 2.2 List of Models used for difference emission scenarios

Model Name	RCP 4.5	RCP 8.5	Reference
ACCESS1-0	X	X	(Ackerley & Dommenget, 2016; Collier & Uhe, 2012)
ACCESS1-3	X	X	(Collier & Uhe, 2012)
CMCC-CESM		X	(Vichi et al., 2011)
CMCC-CM	X	X	(Scoccimarro et al., 2011)
CMCC-CMS	X	X	(Scoccimarro et al., 2011)
CNRM-CM5	X	X	(Voldoire et al., 2013)
CSIRO-Mk3-6-0	X	X	(Collier et al., 2011)
CanESM2	X	X	(Chylek et al., 2011)
GFDL-CM3	X	X	(Donner et al., 2011)
GFDL-ESM2G	X	X	(Dunne et al., 2012)
GFDL-ESM2M	X	X	(Dunne et al., 2012)
HadGEM2-CC	X	X	(Collins et al., 2011)
IPSL-CM5A-LR	X	X	(Dufresne et al., 2013)
IPSL-CM5A-MR	X	X	(Dufresne et al., 2013)

IPSL-CM5B-LR	X	X	(Dufresne et al., 2013)
MIROC-ESM	X	X	(S. Watanabe et al., 2011)
MIROC-ESM-CHEM	X	X	(S. Watanabe et al., 2011)
MIROC5	X	X	(M. Watanabe et al., 2010)
MPI-ESM-LR	X	X	(Block & Mauritsen, 2013)
MPI-ESM-MR	X	X	(Block & Mauritsen, 2013)
MRI-CGCM3	X	X	(Yukimoto et al., 2012)
MRI-ESM1		X	(Yukimoto et al., 2011)
NorESM1-M	X	X	(Bentsen et al., 2013)
inmcm4	X	X	(Volodin et al., 2010)

2.3 Further Analysis on Future Climate Design Conditions

2.3.1 Sensitivity Analysis

To better study how climate change will make differences in building design variables in the 21st century, we compared building metrics calculated from past data (1986-2010) and from projected data (2081-2100) to assess what metrics are most sensitive to climate change. Two standards, absolute change and percentage change, will be used for the evaluation due to the various magnitude of the variables.

Percent difference is used for degree days and hours, and precipitation metrics, and the actual difference is used for the rest of the metrics. The reason that we use different criteria is that the order of values in the degree days and hours metric, which ranges from 0 to 10^4, is much greater than the order of values in other metrics, which ranges from 1 to 10. Thus, using the same standard for all metrics will not accurately show the sensitivity of the metrics. Further, temperature metrics are not zero-based, which make percent differences meaningless to interpret (e.g. any change from 0°C would be an infinite percent difference, which makes no sense; changing to Fahrenheit scale does not alleviate the problem, and a Kelvin scale would be meaningless in practice).

Overall, the absolute and percentage differences were calculated between building metrics in the past and in the late century. Although the results will be presented in different formats (absolute value and percent value), we will still be able to understand the level of change in different metrics due to climate change and learn what metrics are most sensitive.

2.3.2 Trend of Design Variables under Different Emission Scenario

We will also show how sensitive metrics change with time under different emission scenarios. In this study, cooling degree days (CDD) with a threshold temperature of 23.3°C was examined. CDD by decades was calculated from 2020 to 2100 and averaged from 10 years before and after the year. For example, the value for 2020 is the mean of values from 2010 to 2030, and the value for 2030 is the mean of values from 2020 to 2040. This part of the study shows the pattern of change of CDD throughout the 21st century under different emission scenarios.

Chapter 3

Results

3.1 Reproducing ASHRAE Climate Design Conditions

The first result of this work is the recalculated the 2013 ASHRAE Climatic Design Conditions for the Madison/Dane County station from 1986 to 2010. A comparison between our work and ASHRAE's are shown and analyzed below.

Absolute and percent difference are used to examine the consistency between ASHRAE's and our results. Percentage difference is used for degree days and hours, and precipitation metrics, and the actual difference is used for the rest of the metrics for the same reason described in Section. 2.3.1. To be noted, absolute and percent difference were used twice in this study. First for testing our reproducing work, which compares our results and ASHRAE'S, and then for sensitivity analysis, where we compare past and future results.

3.1.1 Temperature metrics

Table 3.1 is a color-coded table showing the comparison of ASHRAE's and our temperature metrics. The colors blue and green refer to the actual difference and percent difference, respectively. The light blue shows difference between 0.5°C and 1°C, and the dark blue shows differences greater than 1°C. For the percent difference criteria, the light and dark green shows a difference between 1% and 5% and greater than 5%, respectively. The color yellow highlights where the difference is smaller than 0.5 °C or 1% or where there is no difference. In general, Table 3.1 shows remarkable agreement between our calculation and ASHRAE's. Some differences are discussed below.

Among all variables, degree days and hours are the metric with the more non-yellow color, but this does not necessarily indicate less consistency for this metric. Some of these gaps are caused by a small order of the base number instead of an incorrect calculation. For example, there are five variables in dark green, indicating that our results differ from ASHRAE's work by more than 5%. This sounds like a large discrepancy, but in reality, our heating/cooling degree days or hours are only 1°C more or less than ASHRAE's result. Thus, a large percentage does not necessarily mean there is a problem in the data or calculation methods. In general, our method does tend to slightly overestimate CDD and CDH during summer months, but only by a few Degree Celsius.

Other metrics show more consistency than degree days and hours, with only 12 variables showing some gaps. The largest difference, 1.3°C, occurred for a 99.6% mean coincident dry- bulb temperature and a minimum value of 50-year minimum return period value of extreme dry-bulb temperature. Other differences are all smaller than 1°C. Interestingly, for the extreme annual design conditions (the 4th metric in Table 3.1), relatively large differences occur for minimum n-year return period values of extreme dry-bulb temperature. For the monthly design conditions, differences are occurred for wet-bulb temperature or mean coincident wet-bulb temperature.

By using the same dataset and same calculation methods, we expected to see identical results to ASHRAE (all yellow color), but unexpected discrepancies appeared in some metrics. A possible explanation may be the way we dealt with the missing year. Since

ASHRAE only gives a general instruction for all sites instead of specific information for each station, we are not sure about how they dealt with 1996 (the missing year) over Madison. It

Annual Heating and Humidification Design Condition

Coldest Month	Heating DB		Humidification DP/MCDB and HR						Coldest month WS/MWDB				MCWS/PCWD to 99.6% DB	
			99.60%			99%			0.40%		1%			
	99.60%	99%	DP	HR	MCDB	DP	HR	MCDB	WS	MCDB	WS	MCDB	MCWS	PCWD
Jan	-21.7	-18.6	-26.9	0.3	-21.1	-23.7	0.5	-18	11.6	-4.6	10.6	-5.9	3	290
Jan	-21.1	-18.3	-26.4	0.3	-19.8	-23.4	0.5	-18	11.3	-4.5	10.3	-5.1	3.1	276

Annual Cooling and Dehumidification, and Enthalpy Design Condition

Hottest Month	Hottest Month DB Range	Cooling DB/MCWB						Evaporation WB/MCDB						MCWS/PCWD to 0.4% DB	
		0.40%		1%		2%		0.40%		1%		2%			
		DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD
July	10.9	32	23.4	30.4	22.6	28.8	21.7	25	30.1	23.9	28.5	22.9	27.3	4.9	180
July	10.8	32	23.5	30.6	22.6	28.9	21.7	25	30.1	23.8	28.6	22.8	27.5	5.03	215

Dehumidification DP/MCDB and HR									Enthalpy/MCDB						Hours 8 to 4 and 12.8/20.6
0.40%			1%			2%			0.40%		1%		2%		
DP	HR	MCDB	DP	HR	MCDB	DP	HR	MCDB	Enth	MUDB	Enth	MCDB	Enth	MCDB	
23.3	18.6	28.3	22.3	17.6	27	21.4	16.5	25.7	77.3	29.9	72.7	28.7	68.9	27.4	634
23.3	18.7	28.5	22.2	17.5	27	21.3	16.5	25.4	76.7	29.5	72.2	28.7	68.5	27	625

Extreme Annual Design Conditions

Extreme Annual Design Conditions			Extreme Max WB	Extreme Annual DB				n-Year Return Period Values of Extreme DB							
				Mean		Standard deviation		n=5 years		n=10 years		n=20 years		n=50 years	
1%	2.5%	5%		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
10.1	8.8	8	29.3	-25.5	34.4	3.4	1.9	-27.9	35.7	-29.9	36.8	-31.8	37.8	-34.3	39.2
9.8	8.8	8	29.3	-25.1	34.4	3.1	1.9	-27.3	35.8	-29.1	36.9	-30.8	37.9	-33	39.3

Monthly Climate Design Conditions

		Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature Degree-Days and Degree-Hours	Tavg	8.5	-6.6	-4.6	1.5	8.5	14.4	19.9	22	20.9	16.5	9.7	2.8	-4.3
	Tavg	8.5	-6.5	-4.6	1.6	8.6	14.6	20	22	20.9	16.5	9.7	3	-4.3
	Sd		6.59	6.15	6.03	5.27	4.64	3.92	3.22	3.43	4.41	4.96	5.29	6.07
	Sd		6.58	5.93	6	5.25	4.6	3.93	3.22	3.47	4.43	4.98	5.21	6.1
	HDD 10	2033	515	409	272	89	11	0	0	0	3	68	223	444
	HDD 10	2019	512	410	269	88	11	0	0	0	4	68	217	442
	HDD 18.3	3947	773	642	521	299	139	28	6	13	86	272	466	702
	HDD 18.3	3919	769	643	517	295	135	28	5	13	85	271	459	699
	CDD 10	1472	0	0	9	43	149	298	373	337	198	58	7	1
	CDD 10	1482	0	0	9	44	152	299	377	338	199	58	7	1
	CDD 18.3	344	0	0	0	3	18	77	121	92	31	3	0	0
	CDD 18.3	353	0	0	0	3	19	78	124	94	31	3	0	0
	CDH 23.3	3178	0	0	2	36	197	758	1111	776	264	34	0	0
	CDH 23.3	3262	0	0	3	37	202	771	1151	793	270	36	0	0
	CDH 26.7	936	0	0	0	6	43	237	363	223	58	5	0	0
	CDH 26.7	941	0	0	0	5	43	234	370	226	58	5	0	0

Monthly Climate Design Conditions

			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly Design Dry Bulb and Mean Coincident Wet Bulb Temperature	0.40%	DB	8.8	12	22.2	27.5	30.1	33.6	34.3	33.7	30.9	27.3	19.4	13
		DB	8.9	12	22.2	27.7	30	33.9	34.4	33.9	31	27.2	19.4	13
		MCWB	5.8	8.7	15.3	17.1	20.7	22.7	24.6	24.8	21.7	19.8	13.7	11.7
		MCWB	6.5	7.8	15.8	17.7	20.7	22.5	24.2	25.4	21.5	19.7	13.7	12.1
	2%	DB	5.4	8.1	17.6	23.4	27.8	31.2	32.2	31.1	28.3	23.6	16.1	8.5
		DB	5.6	8.2	17.8	23.4	27.8	31.1	32.2	31.1	28.3	23.8	16.1	8.8
		MCWB	3	5	12.1	15.3	19.7	22.3	23.9	23.6	20.7	17.1	12.2	6
		MCWB	3	5	12.1	15.5	19.4	22.5	24	23.5	20.8	17.4	12	6
	5%	DB	3.3	5.6	13.9	20.6	25.6	29.3	30.4	29	26.4	21	13.5	5.6
		DB	3.3	5.6	13.9	20.6	25.6	29.4	30.6	29	26.6	21	13.7	5.7
		MCWB	1.8	3.1	10.1	13.4	18	21.3	23	22.7	19.3	15.4	10.2	3.5
		MCWB	1.8	3	10.1	13.6	18	21.5	23	22.7	19.4	15.5	10.4	3.6
	10%	DB	2	3.2	10.5	17.6	23.1	27.6	28.6	27.4	24.4	18.2	11.1	3.3
		DB	2	3.2	10.6	17.8	23.3	27.8	28.8	27.3	24.4	18.3	11.1	3.3
		MCWB	0.7	1.3	6.7	11.6	16.4	20.4	22.1	21.4	18.6	13.8	8	1.5
		MCWB	0.5	1.5	6.7	11.8	16.6	20.4	22.2	21.3	18.6	13.7	8	1.5

Monthly Climate Design Conditions

			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly Design Wet Bulb and Mean Coincident Dry Bulb Temperature	0.40%	WB	6.9	8.6	16.2	18.6	22.9	24	26.9	26.1	23.7	20.7	15.2	11.8
		WB	6.7	8.6	16.3	18.7	22.9	25	26.9	26.1	23.7	20.8	15.2	11.8
		MCDB	7.9	11.1	21.1	25.6	28.4	30.7	32.1	31.4	27.9	25.5	18.3	13.1
		MCDB	7.7	10.7	20.9	25.5	28.8	30.7	32	31.8	28.2	25.7	18	13.2
	2%	WB	3.4	5.2	13.4	16.5	21	23.7	25.4	24.7	22	18.4	13	6.4
		WB	3.4	5.2	13.5	16.5	21	23.6	25.3	24.6	22	18.5	13	6.5
		MCDB	4.9	8.1	16.5	21.9	25.6	29.1	30.6	29.4	26.1	22	15.3	8.1
		MCDB	5.3	8	16.3	22.2	25.6	29.4	30.8	29.7	26.3	22.2	15.5	8.2
	5%	WB	1.9	3.1	10.1	14.7	19.4	22.7	24	23.6	20.8	16.3	10.8	3.6
		WB	1.9	3	10.2	14.8	19.3	22.6	24	23.6	20.9	16.4	11	3.7
		MCDB	3.1	5.2	14	19.5	23.8	27.8	28.5	27.9	24.6	20.1	12.7	5.4
		MCDB	3.2	5.3	14.3	19.6	23.6	27.8	28.6	28.1	24.7	20.3	13	5.7
	10%	WB	0.7	1.4	6.9	12.2	17.7	21.5	22.9	22.5	19.7	14.3	8.1	1.7
		WB	0.8	1.4	7	12.3	17.7	21.4	22.9	22.5	19.7	14.3	8.3	1.7
		MCDB	1.8	3	9.9	16.7	21.8	26.1	27.1	26.3	23.3	17.9	10.6	3
		MCDB	1.9	3	10.1	16.8	22	25.9	27.5	26.5	23.6	18.1	10.8	3.1

Monthly Climate Design Conditions

			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Daily Temperature Range		MDBR	8.1	8.6	9.9	11.4	11.8	11.5	10.9	10.7	11.6	10.8	8.6	7.6
		MDBR	8	8.5	9.8	11.4	11.8	11.5	10.9	10.7	11.6	10.7	8.6	7.7
	5% DB	MCDBR	8.6	10.8	14.4	15.2	14.2	13.4	12.3	11.8	13.5	14.1	12.2	9.3
		MCDBR	8.4	10.8	14.4	15.1	14.4	13.5	12.5	11.8	13.2	14.4	12.3	9.5
		MCWBR	7.3	8.1	9.5	8.7	7.5	6.5	5.8	5.7	6.8	8.5	9.2	7.7
		MCWBR	7.2	8.2	9.4	8.6	7.5	6.4	5.8	5.6	6.5	8.6	9.1	7.8
	5% WB	MCDBR	8	10.1	13.1	13.5	12.1	11.3	10.6	10.3	11.1	12.1	11.3	8.9
		MCDBR	8	10.3	13.3	13.6	12.2	11.5	10.7	10.3	11	12.1	11.3	8.9
		MCWBR	7	7.9	9.4	8.5	7.1	6.5	5.9	5.6	6.8	8.5	9.2	7.7
		MCWBR	7.1	8	9.3	8.5	7	6.6	6	5.4	6.6	8.3	9.7	7.7

Table 3.1 Comparison of temperature design conditions by ASHRAE (black) and by UW (red).

is possible that ASHRAE substituted the year using alternative datasets or performed a special integration. This might cause discrepancies between our work and ASHRAE's since we omitted the missing year. Another possibility is that ISD might have upgraded their observations since 2013 when ASHRAE used their data. Overall, we were able to successfully reproduce temperature metrics with most variables that are remarkably consistent with ASHRAE's results.

3.1.2 Precipitation metrics

The precipitation metric calculated by ASHRAE (black), UW-Madison/GHCN (red), and their percentage difference (purple) are shown in Table 3.2. As with the temperature metrics, the yellow color indicates overall consistency with a difference smaller than 20%. The light and the dark green highlight where the differences range from 20% to 50%, and where the differences are greater than 50%, respectively.

The mean precipitation for an individual month is directly derived from GHCN data. Although our results are slightly different from ASHRAE's, the differences are smaller than 20%. The discrepancies for standard deviation in February, March, May, July, and September are within 50%. Significant bias greater than 50%, occurred for extreme values, especially for the minimum precipitation metric. Nine months in this metric show a large percentage difference, with six of them larger than 50%. While it may appear that this metric inconsistent, the order of values made a big difference. Although they are highlighted in dark blue and show a difference of up to 80%, the real differences in the minimum precipitation from January to March are only 4, 2, and 5 mm for each month, respectively. Considering the average precipitation in these months is around 30 to 50 mm, differences smaller than 5 mm can be ignored. For other dark green cells in the minimum and maximum precipitation metric, the real differences are also significant. For the maximum precipitation in May and November in particular, the amount of rainfall by GHCN (275 and 190 mm) is as twice much as what ASHRAE provided (159 and 100 mm).

The results for reproducing precipitation metrics are not as consistent as temperature metrics. According to the ASHRAE handbook, the ground based GHCN data is most recommended, so we used version 2 monthly GHCN data for Madison's precipitation metrics calculation. As mentioned before, the monthly precipitation is directly retrieved from GHCN monthly data without any additional processing. However, we see the amount of precipitation differs for reasons that may be similar to the temperature metrics. While ASHRAE has multiple data sources for precipitation, we elected to use the recommended ground based GHCN dataset. However, even the monthly precipitation from GHCN is different from ASHRAE.

Precipitation Conditions															
			Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation	Avg	ASHRAE	784	27	27	55	73	80	93	86	103	86	55	53	47
		GHCN	867	31	32	57	84	88	106	103	101	83	61	55	44
			10.6	14.8	18.5	3.6	15.1	10	14	19.8	-1.9	-3.5	10.9	3.8	-6.4
	Max	ASHRAE	941	62	66	128	181	159	253	168	241	234	140	100	92
		GHCN	1104	64	84	157	176	275	278	237	194	173	136	190	104
			17.3	3.2	27.3	22.7	-2.8	73	9.9	41.1	-19.5	-26.1	-2.9	90	13
	Min	ASHRAE	535	5	4	7	34	25	21	37	24	3	2	3	6
		GHCN	620	9	2	12	43	23	30	49	22	23	17	10	7
			15.9	80	-50	71.4	26.5	-8	42.9	32.4	-8.3	666.7	750	233.3	16.7
	SD	ASHRAE	125.5	16.6	15.5	31.5	34.9	40.3	67.5	36.2	57.9	73.4	35.3	24.4	23.3
		GHCN	146	16.8	22.3	38.9	36.4	58.6	67.7	45.5	48.1	43	31	39.6	27.1
			16.3	1.2	43.9	23.5	4.3	45.4	0.3	25.7	-16.9	-41.4	-12.2	62.3	16.3

Table 3.2 Comparison of precipitation design conditions by ASHRAE (black), by GHCN (red), and their percentage difference (purple).

To better study the precipitation inconsistency, we compared observed monthly mean, maximum and minimum precipitation data from GHCN and ASHRAE with estimates from realizations from the UWPD. Note that in addition to the CDFs, the UWPD includes 14 precipitation "realizations" for each of model simulations (22 for RCP 4.5 and 24 for RCP 8.5 scenario), yielding a sample of 308 (RCP 4.5) and 336 (RCP 8.5) to draw from. These realizations allow us to characterize the expected spread of precipitation metrics.

Figure 3.1 shows mean, maximum and minimum precipitation from ASHRAE (blue line), GHCN (red), averaged UWPD (black line), and a range of UWPD realizations (boxplot). A boxplot is a standardized way of displaying the distribution of data. Two whiskers represent the maximum and minimum values, and the first quartile (Q1) and the third quartile (Q3) are the 25th and 75th percentiles, respectively. The red bar is the median, and the red points are drawn as outliers that are larger that Q3 + 1.5*(Q3-Q1) or smaller than Q1 - 1.5*(Q3-Q1). The default value 1.5 represents the length of the maximum whisker, and it corresponds to approximately +/- 2.7 sigma and 99.3 coverage if the data are normally distributed.

Monthly mean precipitation from three sources are consistent from January to March as well as from August to December. There are some biases that occurred from April to July, but all differences are within the range of UWPD realizations. GHCN and averaged UWPD are largely consistent with each other, while the value from ASHRAE shows a sudden drop in July.

Maximum and minimum precipitation are, by nature, more variable and demonstrate less consistency among these three sources. The maximum precipitation from three sources is consistent from January to April. However, precipitation from three sources becomes very different after April. GHCN and UWPD both show an inverted "U" shape. GHCN monthly maximum precipitation peaks in June, and then starts falling in the following months with a second peak in November. UWPD precipitation peaks in July/August, and there is no second peak. ASHRAE's precipitation, however, is more variable. It shows a sudden drop in April and peaks in June, followed by a sharp drop in July. Overall, GHCN and UWPD agree with each other more than ASHRAE in terms of maximum precipitation. Still, both ASHRAE and GHCN largely fall within the expected spread from the UWPD realizations.

The situation is somewhat different for minimum precipitation. Minimum precipitation from GHCN and ASHRAE show a similar "M" shape. They both have two peaks, in April and July respectively, and a large drop between the two peaks, but the value from ASHRAE falls faster than from GHCN after August. The amount of minimum precipitation from September to November is lower than 10 mm from ASHRAE's calculation, but higher than 10 mm from GHCN. UWPD shows a smoother inverted "U" shape, with a peak in June. In summary, ASHRAE and GHCN agree more with each other, though again, estimates fall within the spread of expected values from the UWPD realizations.

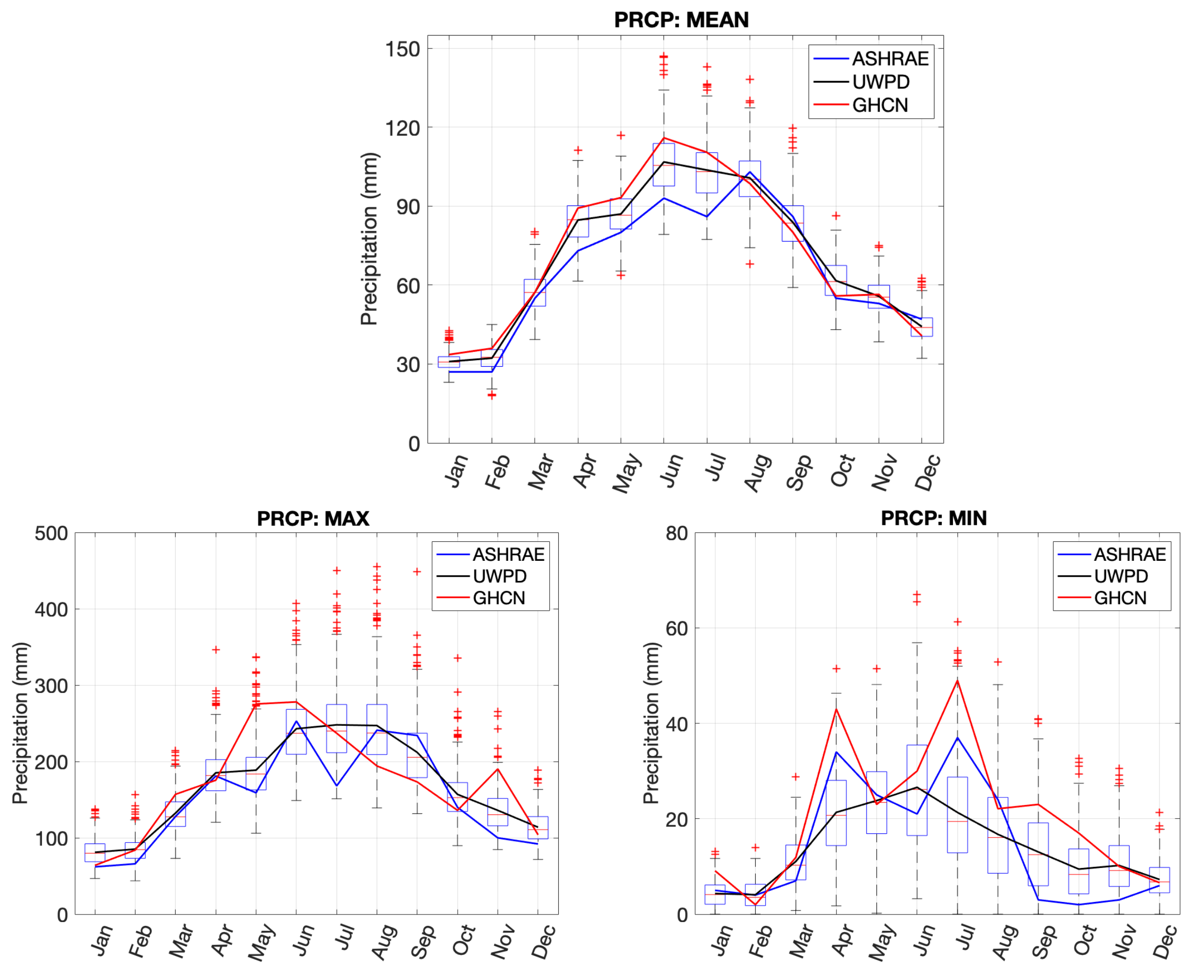

Figure 3.1 Comparison of monthly precipitation design conditions by ASHRAE (blue), GHCN (red), and UWPD (black) for Madison, WI. Lines are the mean values and box plots refer to the UWPD realizations.

Overall, Figure 3.1 shows that monthly precipitation from ASHRAE is fluctuating with a drop in July for mean value, drops in May and July for maximum value, and a drop in June for minimum value. Two drops in ASHRAE monthly maximum precipitation, especially the one in July, may be the main reason for the inconsistency between mean precipitation from ASHRAE and the other two sources. Further study is needed to figure out why ASHRAE presents a drier July.

3.2 Producing Future Climate Design Conditions

After we reproduced the ASHRAE's calculations (more than 90% climate design variables are reproduced), we calculated ASHRAE-equivalent temperature and precipitation metrics for Madison, Wisconsin, for the mid-century (2041-2060) and the late-century (2081-2100) using the rescaled hourly data. Four complete charts are provided in Appendix B.

3.2.1 Sensitivity of temperature metrics

A simple sensitivity analysis was done for climate design variables under a high emission scenario (RCP 8.5). Table 3.3 shows the change in variables from the present (1986-2010) to the late century (2081-2100) and how much they would change with a changing climate. Percentage change is used for degree days and hours, and absolute change is used for the rest of the variables because the order of value in the degree days and hours metric is much larger than the order of value in other metrics. Using different standards might not give details for the change of variables, but we can still see a general sensitivity of metrics.

Although all metrics depend on temperature, different metrics exhibit different levels of sensitivity to global warming. Among the metrics, heating and cooling degree days and hours show a higher sensitivity which varies by month. A higher sensitivity can be seen in the spring (March to May) and fall (September to November), highlighted by darker green or orange color. Degree days and hours defined as the number of hours that the temperature exceeds a base threshold. It quantifies the demand for energy needed to heat or cool buildings. Due to global warming, the need for cooling will increase and the need for heating will decrease. This change can be seen in Table 3.3, with the positive percentage change for CDD and hour, and a negative percentage change for HDD.

Climate Design Conditions in Madison/Dane County, WI, USA (WMO: 726410)

Lat: 43.14N, Long: 89.34W, Elev: 264m, StdP: 98.19, Time zone:-6.00, Period: 2081-2100

Annual Heating and Humidification Design Conditions

Coldest Month	Heating DB		Humidification DP/MCDB and HR						Coldest month WS/MWDB				MCWS/PCWD to 99.6% DB		
			99.60%			99%			0.40%		1%				
	99.60%	99%	DP	HR	MCDB	DP	HR	MCDB	WS	MCDB	WS	MCDB	MCWS	PCWD	
Jan	-11.9	-9.7	-17.5	0.9	-10.6	-15.2	1.1	-8.6	11.3	2.4	10.2	1.9	3	276	

Annual Cooling, Dehumidification, and Enthalpy Design Conditions

Hottest Month	Hottest Month DB Range	Cooling DB/MCWB						Evaporation WB/MCDB						MCWS/PCWD to 0.4% DB	
		0.40%		1%		2%		0.40%		1%		2%			
		DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD
July	9.7	38.1	28.5	36.5	27.7	34.9	26.9	30.6	35.6	29.6	34	28.6	32.9	5	215.8

Dehumidification DP/MCDB and HR									Enthalpy/MCDB						Hours 8 to 4 and 12.8/20.6
0.40%			1%			2%			0.40%		1%		2%		
DP	HR	MCDB	DP	HR	MCDB	DP	HR	MCDB	Enth	MCDB	Enth	MCDB	Enth	MCDB	
29.5	27.5	33.9	28.5	25.9	32.7	27.6	24.5	31.6	104.7	35.4	99.2	34.1	94.4	32.8	566

Extreme Annual Desig Conditions

Extreme Annual WS			Extreme Max WB	Extreme Annual DB				n-Year Return Period Values of Extreme DB							
				Mean		Sd		n=5 years		n=10 years		n=20 years		n=50 years	
1%	2.5%	5%		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
9.8	8.8	7.7	35.3	-15.2	40.6	2.6	2	-17.1	42	-18.6	43.2	-20	44.3	-21.9	45.7

Monthly Climate Design Conditions

			Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature Degree-Days and Degree-Hours		Tavg	14.7	0.6	1.5	7	14.2	20.8	26	28.2	27.2	23.1	16.2	9.5	2.7
		Sd		5.7	5.1	5.7	5.4	4.7	4	3.3	3.4	4.4	5.1	5.2	5.5
		HDD 10	1004	293	242	132	21	0	0	0	0	0	8	73	234
		HDD 18.3	547	471	354	148	31	2	0	0	13	107	269	484	484
		CDD 10	2762	3	4	39	147	334	481	564	532	393	200	57	8
		CDD 18.3	1155	0	0	4	25	107	234	306	275	157	42	4	0
		CDH 23.3	14595	0	0	51	323	1288	3022	4113	3465	1821	477	35	0
		CDH 26.7	7344	0	0	16	122	570	1593	2230	1770	843	192	8	0
Monthly Design Dry Bulb and Mean Wet Bulb Temperature	0.40%	DB		15.1	16.9	27.9	33.6	36.7	39.8	40.2	39.7	37.4	34.4	26.6	19.8
		MCWB		11.5	12.6	20.1	22	26	27.5	29.3	30.2	27	25.8	19.6	17.9
	2%	DB		11.7	13.4	23.2	29.6	34.2	37.2	37.9	37	34.9	30.8	23	15.1
		MCWB		9	9.7	16.7	20.1	24.7	27.5	29.1	28.7	26.4	23.1	18.3	12.1
	5%	DB		9.7	10.9	19.4	26.7	32	35.4	36.2	35	33	27.9	20.4	12.2
		MCWB		7.8	7.9	14.8	18.3	23.2	26.5	28.1	28	25.1	21.4	16.3	9.8
	10%	DB		8.3	8.5	16	23.8	29.6	33.7	34.4	33.4	31	25.2	17.9	9.9
		MCWB		6.9	6.3	11.5	16.4	21.9	25.6	27.3	26.8	24.4	19.8	14.1	7.6
Monthly Design Wet Bulb and Mean Dry Bulb Temperature	0.40%	WB		12.7	13.5	21.3	24	28.7	30.4	32.6	31.8	29.9	27.2	21.8	18.3
		MCDB		13.7	16	26.2	31	34.6	36	37.3	36.8	34.2	32	25	19.8
	2%	WB		9.4	10	18.5	22	26.9	29.2	30.8	30.3	28.2	25	19.5	12.8
		MCDB		10.9	13	21.7	26.6	31.4	34.4	36	34.8	31.8	28.8	21.9	14.1
	5%	WB		8	8	14.8	20	25.2	28.2	29.6	29.3	27	22.7	17.3	9.8
		MCDB		9.5	10.6	19.2	25.7	29.5	33.5	33.9	33.4	30.8	26.8	19.9	12.1
	10%	WB		6.9	6.5	11.8	17.5	23.5	27.1	28.5	28.3	25.9	20.6	14.4	8
		MCDB		8.3	8.2	15.1	22.4	27.9	31.8	32.5	31.9	29.6	24.5	17.1	9.7
Mean Daily Temperature Range		MDBR		6.9	7.9	10.3	12.2	11.9	11.2	9.7	9.7	11.7	11.7	9.5	7.1
	5% DB	MCDBR		8.1	10.5	15.1	15.6	14.4	13.3	11.6	11	13.3	15.4	13.3	9.6
		MCWBR		6.5	7.4	9.4	8.4	6.9	5.9	4.9	4.7	6	8.7	9.6	7.6
	5% WB	MCDBR		7	9.7	13.3	13.7	11.7	11	9.6	9.3	10.6	12.7	12.1	8.8
		MCWBR		6.2	7.3	9.4	8.6	6.7	6.1	5.2	4.7	6.3	8.8	10.5	7.7

Change by (°C)
0~1
1~5
5~10
10~20
>20

Change by %
> 480
240~480
120~240
60~120
30~60
-30~30
-30~-60
-60~-120
-120~-240
-240~-480
> -480

Table 3.3 Sensitivity analysis for design variables in the late century (2081-2100), under high emission (RCP 8.5) scenario.

Apart from the seasonal variability, the sensitivity of degree days and hours also change with different base/threshold temperature. A higher sensitivity to temperature increase can be seen for a higher threshold temperature. We can see this in Table 3.3, where the orange for the row of CDD and CDH with base temperature 18.3°C and 26.7°C is darker

than the row of CDD and CDH with base temperature 10°C and 23.3°C, respectively. Table 3.4 shows a clearer comparison of CDD and CDH between the present (blue), the mid (black), and the late (red) century, under high emission (RCP 8.5). From the present to the late-century, CDD will double when the base temperature is 10°C and triple when the base temperature is 18.3°C. The change is more significant for CDH. CDH with a base temperature 23.3°C increases by a factor of 5. While when the base temperature is increased to 26.7°C, CDD in the late century is increased eightfold from the present value.

Monthly Climate Design Conditions														
		Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature Degree-Days and Degree-Hours	CDD 10	1482	0	0	9	44	152	299	377	338	199	58	7	1
		2064	0	1	20	84	235	388	470	435	290	116	22	2
		2762	3	4	39	147	334	481	564	532	393	200	57	8
	CDD 18.3	353	0	0	0	3	19	78	124	94	31	3	0	0
		695	0	0	1	9	49	148	213	181	79	14	1	0
		1155	0	0	4	25	107	234	306	275	157	42	4	0
	CDH 23.3	3262	0	0	3	37	202	771	1151	793	270	36	0	0
		7508	0	0	16	116	543	1655	2381	1847	791	155	4	0
		14595	0	0	51	323	1288	3022	4113	3465	1821	477	35	0
	CDH 26.7	941	0	0	0	5	43	234	370	226	58	5	0	0
		2983	0	0	3	32	184	700	1024	727	269	43	0	0
		7344	0	0	16	122	570	1593	2230	1770	843	192	8	0

Table 3.4. Comparison of cooling degree days (CDD) and cooling degree hours (CDH) for present (blue), 2041-2060 (black) and 2081-2100 (red) century.

3.2.2 Trend of Cooling Degree Hours by Decades

To better understand how much more time in the future building will need cooling and how a change in GHG emissions impact the time needed for cooling, we examined the trend of annual CDH by decades under moderate (RCP 4.5) and high (RCP 8.5) emission scenarios. Estimates are calculated for each of the 22 and 24 models (see Table 2.2) contributing to the UWPD RCP 4.5 and RCP 8.5 archives and shown as box plots in Figure 3.2. The left figure is under RCP 4.5 scenario and the right one is under RCP 8.5 scenario. The red line is the current value in Madison, WI as claimed by ASHRAE, and the pink dashed line and the blue dashed line represent the current CDH value in St.Louis, Missouri and Birmingham, Alabama, respectively.

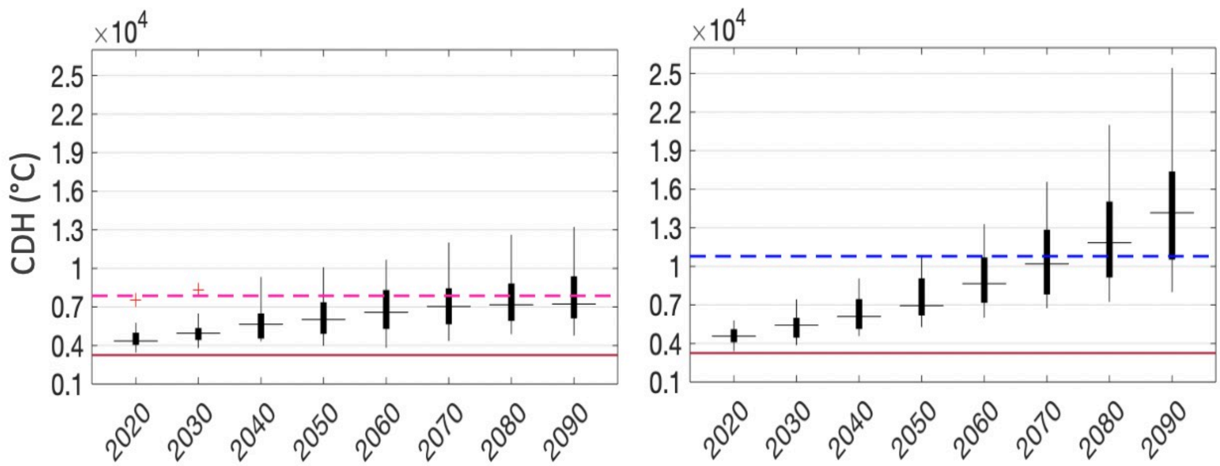

Figure 3.2 Trend of cooling degree hours (CDH) with a base temperature of 23.3 °C, under moderate emission PRC 4.5 (left) and high emission RCP 8.5 (right) for Madison WI.

Under both scenarios, the CDH increased and its range spreads out with time, meaning a higher uncertainty. Both the increase and the uncertainty are more noticeable with higher emissions. The initial values of CDH for 2020 are about the same under the two scenarios, but the value under RCP 8.5 increases significantly faster than the value under RCP 4.5, and in 2090, the former become as twice higher as the latter. This indicates that GHG emissions will make a substantial difference to CDH and, therefore, to our demand for indoor energy used for cooling buildings. By comparing the trend of CDH in Madison with current CDH in St. Louis, MO and Birmingham, AL, we found that under moderate emissions, Madison will be similar to St. Louis, Missouri, by 2090, and under high emissions, Madison will resemble Birmingham, Alabama, by 2070.

Chapter 4

Conclusions

This work has used the ASHRAE climate design chart 2013 edition as a starting point and has estimated and evaluated how building climate design conditions are expected to change with global warming.

As discussed in Section. 3.1, by using exactly the same dataset, ISD hourly temperature and GHCN adjusted monthly precipitation, we have successfully reproduced most of ASHRAE's temperature and precipitation metrics for the same period of 1986-2010 over Madison. Ninety percent of our calculations are nicely consistent with ASHRAE's with no difference, or difference smaller than 0.5°C and 1% for temperature metrics and smaller than 20% for precipitation metrics.

Some discrepancies were seen in 12 temperature related variables, with the largest difference of 1.3°C in 99.6% mean coincident dry-bulb temperature and the minimum value of 50-year return period value of extreme dry-bulb temperature. Other differences are smaller than 1°C or 1%. In precipitation metrics, significant differences occurred in extreme metrics, especially for the maximum precipitation in May and November where the amount of rainfall by GHCN (275 mm and 190 mm) is twice as much as ASHRAE's value (159mm and 100mm). These differences may be due to the methods to address the missing year (1996) of observed data over Madison.

Using the same ASHRAE calculations, four equivalent future design tables under RCP 4.5 and RCP 8.5 for the mid- and late- century have been produced. These tables can provide good estimates of the future climate impacts on building design metrics over Madison. Our calculations for these future metrics were based on hourly future data rescaled from UWPD projection. The UWPD dataset was downscaled from more than twenty GCMs, which avoid bias from one single climate model. This dataset also preserves local realistic variance by giving PDFs of local-scale variables instead of the precise values, which are keys for calculating the extreme metrics in ASHRAE table.

To study the impacts of climate change on building design conditions, we analyzed the sensitivity of multiple meteorological metrics and found the metric of cooling degree days (CDDs) and hours (CDHs) to be most sensitive to global warming. Our findings also show the sensitivity of degree days and hours demonstrate seasonal variability, with a higher sensitivity in the spring and fall. The sensitivity also varies when the threshold temperature changes. A higher sensitivity can be seen for a higher threshold temperature.

Furthermore, we examined CDHs with a base temperature of 23.3°C over decades. The result shows that under both high and moderate emission scenarios, CDHs increase with time. The increase is much faster under high emissions, with the value of CDH in 2090 under high emission is twice as high as the value expected under moderate emission. When comparing the CDH in Madison with CDH in select southern cities, we found that under moderate emissions, Madison will be similar to St. Louis, MO, by 2090; under high emissions, CDHs in Madison will double by 2050 and fivefold by 2090, and Madison will resemble Birmingham, AL, by 2070.

Based on these results, we answered research questions in Section. 1.4:

- **What are the meteorological based metrics most sensitive to climate change?**

Degree days and hours are more sensitive than other metrics.

- **How do cooling degree days change with time throughout the 21th century?**

  In Madison, cooling degree days increase through the 21th century under both RCP 4.5 and RCP 8.5 scenario. Under RCP 8.5, cooling degree days will be 1.4 and 2 times greater than now by 2050, and 2 and 3.3 times by 2090, when the threshold temperature is 10°C and 18.3°C, respectively.

- **How the trend of cooling degree days change under different emission scenarios?**

  Although the value of cooling degree days increases under both scenarios, it increases much faster when emission is high. In Madison, cooling degree days under RCP 4.5 and RCP 8.5 are almost the same in 2020, but in2090, the value under RCP 8.5 is twice as greater than the value under RCP 4.5.

In conclusion, our study considers the effects of CDDs, HDDs on demand for using cooling and heating systems, and indoor energy usage, and shows general consistency with other studies that have been done on CDD/HDD metrics and HVAC&R usage (McFarland et al., 2015; Hadley et al., 2006; Rosenthal et al., 1995; Huang & Gurney, 2016). In particular, McFarland et al., 2015 has shown the U.S. national CDDs are expected to rise from 32% to 42% by 2050 (McFarland et al., 2015), and Huang & Gurney, 2016 has shown the change is greater at the state level (Huang & Gurney, 2016). Our study, taking Madison as an example, extends to city level, and the results show even larger changes in CDDs metric, doubling by 2050 under RCP 8.5. This highlights the importance of taking a local approach to understand changes of building design conditions. The updated design conditions in this study can be used for new building construction in Madison, and the methods of data rescaling in this study provides a novel perspective of how to include information of climate change in building constructions.

Appendix A:

A.1 2013 edition ASHRAE Climate Design Conditions for Madison, WI (ASHRAE, 2020)

Climate Design Conditions in Madison/Dean County, WI, USA (WMO: 726410)

Lat: 43.14N, Long: 89.34W, Elev: 264m, StdP: 98.19, Time zone:-6.00, Period: 1986-2010

Annual Heating and Humidification Design Conditions

Clodest Month	Heating DB		Humidification DP/MCDB and HR						Coldest month WS/MWDB				MCWS/PCWD to 99.6% DB		
			99.60%			99%			0.40%		1%				
	99.60%	99%	DP	HR	MCDB	DP	HR	MCDB	WS	MCDB	WS	MCDB	MCWS	PCWD	
Jan	**-21.7**	**-18.6**	**-26.9**	**0.3**	**-21.1**	**-23.7**	**0.5**	**-18**	**11.6**	**-4.6**	**10.6**	**-5.9**	**3**	**290**	

Annual Cooling, Dehumidification, and Enthalpy Design Conditions

Hottest Month	Hottest Month DB Range	Cooling DB/MCWB						Evaporation WB/MCDB						MCWS/PCWD to 0.4% DB	
		0.40%		1%		2%		0.40%		1%		2%			
		DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD
July	**10.9**	**32**	**23.4**	**30.4**	**22.6**	**28.8**	**21.7**	**25**	**30.1**	**23.9**	**28.5**	**22.9**	**27.3**	**4.9**	**180**

Dehumidification DP/MCDB and HR									Enthalpy/MCDB						Hours 8 to 4 and 12.8/20.6
0.40%			1%			2%			0.40%		1%		2%		
DP	HR	MCDB	DP	HR	MCDB	DP	HR	MCDB	Enth	MCDB	Enth	MCDB	Enth	MCDB	
23.3	**18.6**	**28.3**	**22.3**	**17.6**	**27**	**21.4**	**16.5**	**25.7**	**77.3**	**29.9**	**72.7**	**28.7**	**68.9**	**27.4**	**634**

Extreme Annual Desig Conditions

Extreme Annual WS			Extreme Max WB	Extreme Annual DB				n-Year Return Period Values of Extreme DB							
				Mean		Standard deviation		n=5 years		n=10 years		n=20 years		n=50 years	
1%	2.5%	5%		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
10.1	**8.8**	**8**	**29.3**	**-25.5**	**34.4**	**3.4**	**1.9**	**-27.9**	**35.7**	**-29.9**	**36.8**	**-31.8**	**37.8**	**-34.3**	**39.2**

Monthly Climate Design Conditions

			Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature Degree-Days and Degree-Hours		Tavg	**8.5**	**-6.6**	**-4.6**	**1.5**	**8.5**	**14.4**	**19.9**	**22**	**20.9**	**16.5**	**9.7**	**2.8**	**-4.3**
		Sd		**6.59**	**6.15**	**6.03**	**5.27**	**4.64**	**3.92**	**3.22**	**3.43**	**4.41**	**4.96**	**5.29**	**6.07**
		HDD 10	**2033**	**515**	**409**	**272**	**89**	**11**	**0**	**0**	**0**	**3**	**68**	**223**	**444**
		HDD 18.3	**3947**	**773**	**642**	**521**	**299**	**139**	**28**	**6**	**13**	**86**	**272**	**466**	**702**
		CDD 10	**1472**	**0**	**0**	**9**	**43**	**149**	**298**	**373**	**337**	**198**	**58**	**7**	**1**
		CDD 18.3	**344**	**0**	**0**	**0**	**3**	**18**	**77**	**121**	**92**	**31**	**3**	**0**	**0**
		CDH 23.3	**3178**	**0**	**0**	**2**	**36**	**197**	**758**	**1111**	**776**	**264**	**34**	**0**	**0**
		CDH 26.7	**936**	**0**	**0**	**0**	**6**	**43**	**237**	**363**	**223**	**58**	**5**	**0**	**0**
Precipitation		PrecAvg	**784**	**27**	**27**	**55**	**73**	**80**	**93**	**86**	**103**	**86**	**55**	**53**	**47**
		PrecMax	**941**	**62**	**66**	**128**	**181**	**159**	**253**	**168**	**241**	**234**	**140**	**100**	**92**
		PrecMin	**535**	**5**	**4**	**7**	**34**	**25**	**21**	**37**	**24**	**3**	**2**	**3**	**6**
		PrecSD	**125.5**	**16.6**	**15.5**	**31.5**	**34.9**	**40.3**	**67.5**	**36.2**	**57.9**	**73.4**	**35.3**	**24.4**	**23.3**
Monthly Design Dry Bulb and Mean Wet Bulb Temperature	0.40%	DB	**8.8**	**12**	**22.2**	**27.5**	**30.1**	**33.6**	**34.3**	**33.7**	**30.9**	**27.3**	**19.4**	**13**	
		MCWB	**5.8**	**8.7**	**15.3**	**17.1**	**20.7**	**22.7**	**24.6**	**24.8**	**21.7**	**19.8**	**13.7**	**11.7**	
	2%	DB	**5.4**	**8.1**	**17.6**	**23.4**	**27.8**	**31.2**	**32.2**	**31.1**	**28.3**	**23.6**	**16.1**	**8.5**	
		MCWB	**3**	**5**	**12.1**	**15.3**	**19.7**	**22.3**	**23.9**	**23.6**	**20.7**	**17.1**	**12.2**	**6**	
	5%	DB	**3.3**	**5.6**	**13.9**	**20.6**	**25.6**	**29.3**	**30.4**	**29**	**26.4**	**21**	**13.5**	**5.6**	
		MCWB	**1.8**	**3.1**	**10.1**	**13.4**	**18**	**21.3**	**23**	**22.7**	**19.3**	**15.4**	**10.2**	**3.5**	
	10%	DB	**2**	**3.2**	**10.5**	**17.6**	**23.1**	**27.6**	**28.6**	**27.4**	**24.4**	**18.2**	**11.1**	**3.3**	
		MCWB	**0.7**	**1.3**	**6.7**	**11.6**	**16.4**	**20.4**	**22.1**	**21.4**	**18.6**	**13.8**	**8**	**1.5**	
Monthly Design Wet Bulb and Mean Dry Bulb Temperature	0.40%	WB	**6.9**	**8.6**	**16.2**	**18.6**	**22.9**	**24**	**26.9**	**26.1**	**23.7**	**20.7**	**15.2**	**11.8**	
		MCDB	**7.9**	**11.1**	**21.1**	**25.6**	**28.4**	**30.7**	**32.1**	**31.4**	**27.9**	**25.5**	**18.3**	**13.1**	
	2%	WB	**3.4**	**5.2**	**13.4**	**16.5**	**21**	**23.7**	**25.4**	**24.7**	**22**	**18.4**	**13**	**6.4**	
		MCDB	**4.9**	**8.1**	**16.5**	**21.9**	**25.6**	**29.1**	**30.6**	**29.4**	**26.1**	**22**	**15.3**	**8.1**	
	5%	WB	**1.9**	**3.1**	**10.1**	**14.7**	**19.4**	**22.7**	**24**	**23.6**	**20.8**	**16.3**	**10.8**	**3.6**	
		MCDB	**3.1**	**5.2**	**14**	**19.5**	**23.8**	**27.8**	**28.5**	**27.9**	**24.6**	**20.1**	**12.7**	**5.4**	
	10%	WB	**0.7**	**1.4**	**6.9**	**12.2**	**17.7**	**21.5**	**22.9**	**22.5**	**19.7**	**14.3**	**8.1**	**1.7**	
		MCDB	**1.8**	**3**	**9.9**	**16.7**	**21.8**	**26.1**	**27.1**	**26.3**	**23.3**	**17.9**	**10.6**	**3**	
Mean Daily Temperature Range		MDBR	**8.1**	**8.6**	**9.9**	**11.4**	**11.8**	**11.5**	**10.9**	**10.7**	**11.6**	**10.8**	**8.6**	**7.6**	
	5% DB	MCDBR	**8.6**	**10.8**	**14.4**	**15.2**	**14.2**	**13.4**	**12.3**	**11.8**	**13.5**	**14.1**	**12.2**	**9.3**	
		MCWBR	**7.3**	**8.1**	**9.5**	**8.7**	**7.5**	**6.5**	**5.8**	**5.7**	**6.8**	**8.5**	**9.2**	**7.7**	
	5% WB	MCDBR	**8**	**10.1**	**13.1**	**13.5**	**12.1**	**11.3**	**10.6**	**10.3**	**11.1**	**12.1**	**11.3**	**8.9**	
		MCWBR	**7**	**7.9**	**9.4**	**8.5**	**7.1**	**6.5**	**5.9**	**5.6**	**6.8**	**8.5**	**9.2**	**7.7**	

A.2 Variables typically calculated by ASHRAE (ASHRAE, 2013a)

Annual Design Conditions

Annual Heating and Humidification Design Conditions.

- Coldest month (i.e., month with lowest average dry-bulb temperature; 1 = January, 12 = December).
- Dry-bulb temperature corresponding to 99.6 and 99.0% annual cumulative frequency of occurrence (cold conditions), °C.
- Dew-point temperature corresponding to 99.6 and 99.0% annual cumulative frequency of occurrence, °C; corresponding humidity ratio, calculated at standard atmospheric pressure at elevation of station, grams of moisture per kg of dry air; mean coincident dry bulb temperature, °C.
- Wind speed corresponding to 0.4 and 1.0% cumulative frequency of occurrence for coldest month, m/s; mean coincident dry-bulb temperature, °C.
- Mean wind speed coincident with 99.6% dry-bulb temperature, m/s; corresponding most frequent wind direction, degrees from north (east = 90°).

Annual Cooling, Dehumidification, and Enthalpy Design Conditions.

- Hottest month (i.e., month with highest average dry-bulb temperature; 1 = January, 12 = December).
- Daily temperature range for hottest month, °C [defined as mean of the difference between daily maximum and daily minimum dry bulb temperatures for hottest month].
- Dry-bulb temperature corresponding to 0.4, 1.0, and 2.0% annual cumulative frequency of occurrence (warm conditions), B°C; mean coincident wet-bulb temperature, °C.
- Wet-bulb temperature corresponding to 0.4, 1.0, and 2.0% annual cumulative frequency of occurrence, °C; mean coincident dry bulb temperature, °C.
- Mean wind speed coincident with 0.4% dry-bulb temperature, m/s; corresponding most frequent wind direction, degrees true from north (east = 90°).
- Dew-point temperature corresponding to 0.4, 1.0, and 2.0% annual cumulative frequency of occurrence, °C; corresponding humidity ratio, calculated at the standard atmospheric pressure at elevation of station, grams of moisture per kg of dry air; mean coincident dry-bulb temperature, °C.
- Enthalpy corresponding to 0.4, 1.0, and 2.0% annual cumulative frequency of occurrence, kJ/kg; mean coincident dry-bulb temperature, °C.

- Number of hours between 8 AM and 4 PM (inclusive) with dry-bulb temperature between 12.8 and 20.6°C.

Extreme Annual Design Conditions.

- Wind speed corresponding to 1.0, 2.5, and 5.0% annual cumulative frequency of occurrence, m/s.
- Extreme maximum wet-bulb temperature, °C.
- Mean and standard deviation of extreme annual minimum and maximum dry-bulb temperature, °C.
- 5-, 10-, 20-, and 50-year return period values for minimum and maximum extreme dry-bulb temperature, °C.

Monthly Design Conditions

Temperatures, Degree-Days, and Degree-Hours.

- Average temperature, °C. This parameter is a prime indicator of climate and is also useful to calculate heating and cooling degree days to any base.
- Standard deviation of average daily temperature, °C. This parameter is useful to calculate heating and cooling degree-days to any base. Its use is explained in the section on Estimation of Degree-Days.
- Heating and cooling degree-days (bases 10 and 18.3°C). These parameters are useful in energy estimating methods. They are also used to classify locations into climate zones in ASHRAE Standard 169.
- Cooling degree-hours (bases 23.3 and 26.7°C). These are used in various standards, such as Standard 90.2-2004.

Monthly Design Dry-Bulb, Wet-Bulb, and Mean Coincident Temperatures.

- Dry-bulb temperature corresponding to 0.4, 2.0, 5.0, and 10.0% cumulative frequency of occurrence for indicated month, °C; mean coincident wet-bulb temperature, °C.
- Wet-bulb temperature corresponding to 0.4, 2.0, 5.0, and 10.0% cumulative frequency of occurrence for indicated month, °C; mean coincident dry-bulb temperature, °C.

Mean Daily Temperature Range.

- Mean daily temperature range for month indicated, B°C (defined as mean of difference between daily maximum and minimum dry bulb temperatures).

- Mean daily dry- and wet-bulb temperature ranges coincident with the 5% monthly design dry-bulb temperature. This is the difference between daily maximum and minimum dry- or wet-bulb temperatures, respectively, averaged over all days where the maximum daily dry-bulb temperature exceeds the 5% monthly design dry-bulb temperature.
- Mean daily dry- and wet-bulb temperature ranges coincident with the 5% monthly design wet-bulb temperature. This is the difference between daily maximum and minimum dry- or wet-bulb temperatures, respectively, averaged over all days where the maximum daily wet-bulb temperature exceeds the 5% monthly design wet-bulb temperature.

A.3 Data quality check and screen criteria (ASHRAE, 2013a)

In according to ASHRAE's work, the minimum number of years of data required to process a station was set to 8 years. This was derived from a previous study which showed that a minimum of 8 years of data would provide reliable design calculation for most stations. In some cases, several stations may be combined into one single station processing. In terms of missing data, gaps up to 6h were filled by linear interpolation. When data were not recorded at the beginning of the hour, missing data at exact hour were replaced by data up to 0.5h before or after.

Annual cumulative frequency distribution was constructed from relative frequency distribution complied for each month, so after missing data filled by interpolation, the individual month need to meet following screening criteria for completeness and unbiased distribution: 1) The number of dry-bulb temp values for the month had to be at least 85% of total hours for the month. For example: a month with 31 days has 31*24=744 hours in total, will be included in calculation if the number of dry-bulb temp values for this month exceed 744*85%=633 hours. 2) The difference between the number of day and nighttime dry-bulb temp had to be less than 60. In addition, a station's dry-bulb temp design conditions were calculated only if there were data from at least 8 months that met the quality control and screening criteria.

Dew point, wet-bulb and enthalpy were calculated for a given month only if the number of these values were greater than 85% of the minimum number of dry-bulb temp value. For example, a month will be included in calculation of dew point only if dew point was present for at least 85% of 633 hours, which was 538 hours.

Annual dry-bulb extremes were calculated only for years that were 85% complete. At least 8 annual extremes are required to calculate the mean and standard deviation of extreme values. Daily max and min dry-bulb temp were calculated only for complete days, so were daily ranges and mean coincident temp ranges

A.4 Mathematical Equations for standard meteorological variables calculated by ASHRAE (ASHRAE, 2013a)

Dry bulb temperature: t (°C), Dew point temperature: td (°C) and Elevation: Z (ft) are given in the ISD data.	
Unit conversion: Temperature relating variables in the design table are all presented by unit [°C], but unit of [°F] and [°R] are involved in the calculation of p_w, $p_{ws}{}^*$ and t*. [°R] = [°F] + *459.67;* [°F] = [°C] * 1.8 + 32	
p barometric pressure (psia).	$\mathbf{p} = 14.696(1 - 6.8754 \times 10^{-6} Z)^{5.2559}$
$\mathbf{p_w}$ partial pressure of water vapor. (psia) *td is in [°R].* *temp is in [°F]*	For temp<32: $\ln(p_w)$ = c1/td + c2 + c3*td + c4*td^2 + c5*td^3 + c6*td^4 + c7*log(td); For 32<temp: $\ln(p_w)$ = c8/td + c9 + c10*td + c11*td^2 + c12*td^3 + c13*log(td); c1 = -1.0214165*10^{4}; c2 = -4.8932428*10^{0}; c3 = -5.3765794*10^{-3}; c4 = 1.9202377*10^{-7}; c5 = 3.5575832*10^{-10}; c6 = -9.0344688*10^{-14}; c7 = 4.1635019*10^{0}; c8 = -1.0440397*10^{4}; c9 = -1.1294650*10^{1}; c10 = -2.7022355*10^{-2}; c11 = 1.2890360*10^{-5}; c12 = -2.4780681*10^{-9}; c13 = 6.5459673*10^{0};
W humidity ratio/mixing ratio ($\mathrm{gr_{moisture}/lb_{dry\ air}}$)	$\mathrm{W} = 0.621945 * \frac{p_w}{p - p_w}$
h enthalpy (Btu/lb)	$\mathrm{h} = 0.240 * \mathrm{t} + \mathrm{W} * (1061 + 0.444 * \mathrm{t})$

$p_{ws}{}^{*}$ saturation pressure by wet bulb temperature (psia). *t* is in [°R].* *temp is in [°F].*	For temp<32: $\ln(p_{ws}{}^{*}:\ ) = c1/t^* + c2 + c3{*}t^* + c4{*}t^{*}\hat{}2 + c5{*}t^{*}\hat{}3 + c6{*}t^{*}\hat{}4 + c7{*}\log(t^*);$ For 32<temp: $\ln(p_{ws}{}^{*}:\ ) = c8/t^* + c9 + c10{*}t^* + c11{*}t^{*}\hat{}2 + c12{*}t^{*}\hat{}3 + c13{*}\log(t^*);$ c1-c13 are the same with pw calculation.
Ws* humidity ratio by wet bulb temperature $(gr_{moisture}/lb_{dry\ air})$	$Ws^* = 0.621945 * \frac{p_{ws}{}^{*}}{p - p_{ws}{}^{*}}$
t* wet-bulb temp (°*F*) *temp is in [°F].* *t* we get here is also in [°F], so need to convert to [°C] when present in chart.*	For temp<32: $W = \frac{(1220 - 0.04 * t^*)Ws^* - 0.240 * (temp - t^*)}{1220 + 0.444 * temp - 0.48 * t^*}$ For 32<temp: $W = \frac{(1093 - 0.556 * t^*)Ws^* - 0.240 * (temp - t^*)}{1093 + 0.444 * temp - t^*}$
Hottest/Coldest Month	Month with highest/lowest dry-bulb temperature
Daily Temperature	Mean of the difference between daily maximum and daily minimum dry-bulb temperature for hottest month
Mean daily temp range	Mean daily difference between max and min.

Extreme conditions calculation	Extreme annual wind speed
	Extreme Max: the highest value over the entire period of record.
	The mean / Standard deviation of annual max and min: Avg(daily max/min), Sd(daily max/min) from hourly data.
	N-year return period value of extreme DB (describe the probability of the condition occurring at all in any year): $$\mathrm{Tn} = \mathrm{M} + \mathrm{I} * \mathrm{F} * \mathrm{s}$$ Tn: n years return value of extreme (Max/Min). M: mean of annual extreme (Max/Min) s: standard deviation of annual extreme (Max/Min) I= 1 for Max and -1 for Min
Monthly average and standard deviation of daily average	$\frac{\sum_{i=1}^{N} \frac{Timax+Timin}{2}}{N}$ for each complete day N: The number of days in the month
Monthly Heating degree days (HDD)/ Cooling degree days (CDD)	$$\mathrm{HDD} = \sum_{i=1}^{N} (\mathrm{T_{base}} - \overline{\mathrm{T}}_i) \qquad \mathrm{CDD} = \sum_{i=1}^{N} (\overline{\mathrm{T}}_i - \mathrm{T_{base}})$$ T_{base}=10 or 18.3 $\overline{T} = \frac{\max + \min}{2}$ N: the number of days in the month)
Monthly Cooling degree hours (CDH)	$$\mathrm{CDH} = \sum_{i=1}^{N} (\overline{\mathrm{T}}_i - \mathrm{T_{base}})$$ T_{base}=23.3 or 26.7 $\overline{T}$ = Hourly dry bulb temperature N: the number of hours in the month).
Annual HDD/CDD/ CDH	The sum of monthly HDD/CDD/CDH

Appendix B:

Updated Climate Design Conditions

Climate Design Conditions in Madison/Dean County, WI, USA (WMO: 726410)															
Lat: 43.14N,			*Long: 89.34W,*			*Elev: 264m,*			*StdP: 98.19,*			*Time zone:-6.00,*		*Period: 2041-2060*	
Annual Heating and Humidification Design Conditions															
Coldest Month	Heating DB		Humidification DP/MCDB and HR						Coldest month WS/MWDB				MCWS/PCWD to 99.6% DB		
			99.60%			99%			0.40%		1%				
	99.60%	99%	DP	HR	MCDB	DP	HR	MCDB	WS	MCDB	WS	MCDB	MCWS	PCWD	
Jan	**-14.5**	**-14.5**	**-22.4**	**0.5**	**-16.2**	**-19.7**	**0.7**	**-13.6**	**11.3**	**-1.6**	**10.3**	**-2.2**	**3**	**274.9**	
Annual Cooling, Dehumidification, and Enthalpy Design Conditions															
Hottest Month	Hottest Month DB Range	Cooling DB/MCWB						Evaporation WB/MCDB						MCWS/PCWD to 0.4% DB	
		0.40%		1%		2%		0.40%		1%		2%			
		DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD
July	**10.5**	**34.2**	**25.3**	**32.7**	**24.5**	**31.1**	**23.7**	**27**	**32.1**	**26**	**30.6**	**25.1**	**29.4**	**5**	**215.5**
Dehumidification DP/MCDB and HR									Enthalpy/MCDB						Hours 8 to 4 and 12.8/20.6
0.40%			1%			2%			0.40%		1%		2%		
DP	HR	MCDB	DP	HR	MCDB	DP	HR	MCDB	Enth	MCDB	Enth	MCDB	Enth	MCDB	
25.6	**21.6**	**30.3**	**24.7**	**20.4**	**29**	**23.8**	**19.3**	**27.9**	**86.3**	**32.1**	**81.5**	**30.5**	**77.6**	**29.4**	**606.8**
Extreme Annual Desig Conditions															
Extreme Annual WS			Extreme Max WB	Extreme Annual DB				n-Year Return Period Values of Extreme DB							
				Mean		Standard deviation		n=5 years		n=10 years		n=20 years		n=50 years	
1%	2.5%	5%		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
9.8	**8.8**	**7.7**	**31.3**	**-20.7**	**36.6**	**2.8**	**1.9**	**-22.7**	**38**	**-24.3**	**39.1**	**-25.9**	**40.1**	**-27.9**	**41.5**
Monthly Climate Design Conditions															
			Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature Degree-Days and Degree-Hours		Tavg	**11**	**-3.5**	**-2.3**	**4**	**10.8**	**17**	**22.3**	**24.4**	**23.3**	**19.1**	**12.1**	**5.6**	**-1.2**
		Sd		**6.08**	**5.53**	**5.82**	**5.2**	**4.61**	**3.89**	**3.19**	**3.39**	**4.47**	**5.04**	**5.12**	**5.69**
		HDD 10	**1554**	**418**	**345**	**204**	**51**	**3**	**0**	**0**	**0**	**1**	**35**	**149**	**349**
		HDD 18.3	**3259**	**675**	**577**	**446**	**232**	**82**	**11**	**1**	**4**	**45**	**202**	**380**	**605**
		CDD 10	**1935**	**0**	**1**	**17**	**75**	**220**	**368**	**448**	**412**	**275**	**101**	**18**	**1**
		CDD 18.3	**611**	**0**	**0**	**1**	**7**	**42**	**130**	**191**	**158**	**70**	**11**	**0**	**0**
		CDH 23.3	**6372**	**0**	**0**	**11**	**95**	**464**	**1412**	**2042**	**1542**	**681**	**123**	**3**	**0**
		CDH 26.7	**2394**	**0**	**0**	**2**	**25**	**148**	**562**	**833**	**571**	**220**	**33**	**0**	**0**
Precipitation		PrecAvg	**881**	**35**	**35**	**63**	**93**	**91**	**107**	**102**	**104**	**82**	**64**	**59**	**46**
		PrecMax	**1210**	**91**	**91**	**137**	**194**	**193**	**236**	**237**	**251**	**206**	**158**	**146**	**107**
		PrecMin	**590**	**6**	**5**	**15**	**27**	**27**	**26**	**20**	**20**	**12**	**11**	**11**	**11**
		PrecSD	**164**	**23**	**23**	**33**	**44**	**44**	**56**	**59**	**63**	**52**	**39**	**37**	**26**
Monthly Design Dry Bulb and Mean Wet Bulb Temperature		0.40%	DB	**11.4**	**13.7**	**24.4**	**29.9**	**32.7**	**36**	**36.5**	**35.9**	**33.6**	**30.2**	**22.2**	**15.9**
			MCWB	**8.3**	**10**	**17.2**	**19.3**	**22.6**	**24.5**	**26.2**	**27.1**	**23.7**	**22.4**	**16**	**14.4**
		2%	DB	**7.9**	**10.2**	**19.9**	**25.8**	**30.2**	**33.4**	**34.3**	**33.3**	**31**	**26.5**	**18.8**	**11.4**
			MCWB	**5.5**	**6.9**	**13.8**	**17.3**	**21.5**	**24.4**	**25.8**	**25.5**	**23.2**	**19.7**	**14.6**	**8.8**
		5%	DB	**5.9**	**7.6**	**16.2**	**22.9**	**28.1**	**31.6**	**32.7**	**31.3**	**29.2**	**23.6**	**16.3**	**8.4**
			MCWB	**4.3**	**4.9**	**12.1**	**15.4**	**19.9**	**23.4**	**25**	**24.7**	**21.8**	**17.8**	**12.7**	**6.3**
		10%	DB	**4.5**	**5.1**	**12.9**	**20.1**	**25.7**	**29.9**	**30.9**	**29.7**	**27.1**	**20.9**	**13.9**	**6.1**
			MCWB	**3.3**	**3.2**	**8.9**	**13.5**	**18.6**	**22.3**	**24.1**	**23.5**	**21**	**16.1**	**10.6**	**4.1**
Monthly Design Wet Bulb and Mean Dry Bulb Temperature		0.40%	WB	**9.2**	**10.6**	**18.2**	**20.8**	**25.1**	**26.9**	**29**	**28.2**	**26.3**	**23.5**	**17.9**	**14.6**
			MCDB	**10.3**	**13.2**	**22.8**	**27.6**	**31**	**32.7**	**34.2**	**33.6**	**30.6**	**28.4**	**20.9**	**15.9**
		2%	WB	**5.8**	**7.1**	**15.5**	**18.6**	**23.2**	**25.7**	**27.4**	**26.8**	**24.6**	**21.1**	**15.6**	**9.2**
			MCDB	**7.6**	**9.9**	**18.5**	**23.6**	**27.7**	**31.2**	**32.7**	**31.6**	**28.4**	**24.7**	**17.9**	**10.5**
		5%	WB	**4.4**	**5**	**12**	**16.8**	**21.6**	**24.7**	**26.1**	**25.7**	**23.4**	**18.9**	**13.5**	**6.3**
			MCDB	**5.8**	**7.3**	**16.3**	**22.1**	**25.8**	**30**	**30.6**	**30**	**27.2**	**22.7**	**15.7**	**8.3**
		10%	WB	**3.3**	**3.3**	**9.1**	**14.3**	**20**	**23.6**	**25.1**	**24.7**	**22.2**	**16.7**	**10.8**	**4.4**
			MCDB	**4.5**	**4.9**	**12.1**	**19**	**24.2**	**28.1**	**29.2**	**28.4**	**26**	**20.6**	**13.4**	**5.9**
Mean Daily Temperature Range			MDBR	**7.4**	**8.2**	**10.1**	**11.8**	**11.9**	**11.4**	**10.5**	**10.4**	**11.8**	**11.2**	**9**	**7.3**
		5% DB	MCDBR	**8.4**	**10.8**	**14.7**	**15.3**	**14.4**	**13.4**	**12.2**	**11.6**	**13.5**	**14.9**	**12.7**	**9.5**
			MCWBR	**6.9**	**7.9**	**9.4**	**8.5**	**7.3**	**6.2**	**5.4**	**5.3**	**6.4**	**8.8**	**9.3**	**7.7**
		5% WB	MCDBR	**7.4**	**10.2**	**13.2**	**13.6**	**12**	**11.3**	**10.3**	**10.1**	**11**	**12.5**	**11.6**	**8.9**
			MCWBR	**6.5**	**7.8**	**9.3**	**8.5**	**6.9**	**6.3**	**5.7**	**5.2**	**6.6**	**8.7**	**10**	**7.7**

*Under RCP 4.5 scenario, averaged form 22 models presented in Table 2.2

Climate Design Conditions in Madison/Dean County, WI, USA (WMO: 726410)																
Lat: 43.14N,			*Long: 89.34W,*			*Elev: 264m,*			*StdP: 98.19,*			*Time zone:-6.00,*			*Period: 2081-2100*	
Annual Heating and Humidification Design Conditions																
Coldest Month	Heating DB		Humidification DP/MCDB and HR						Coldest month WS/MWDB				MCWS/PCWD to 99.6% DB			
			99.60%			99%			0.40%		1%					
	99.60%	99%	DP	HR	MCDB	DP	HR	MCDB	WS	MCDB	WS	MCDB	MCWS	PCWD		
Jan	**-15.7**	**-13.1**	**-21**	**0.6**	**-14.6**	**-18.5**	**0.8**	**-12.3**	**11.3**	**-0.6**	**10.2**	**-1.1**	**3**	**275.9**		
Annual Cooling, Dehumidification, and Enthalpy Design Conditions																
Hottest Month	Hottest Month DB Range	Cooling DB/MCWB						Evaporation WB/MCDB						MCWS/PCWD to 0.4% DB		
		0.40%		1%		2%		0.40%		1%		2%				
		DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD	
July	**10.4**	**35.1**	**26.1**	**33.6**	**25.2**	**32**	**24.4**	**27.9**	**33**	**26.8**	**31.4**	**25.9**	**30.2**	**4.9**	**216.7**	
Dehumidification DP/MCDB and HR									Enthalpy/MCDB						Hours 8 to 4 and 12.8/20.6	
0.40%			1%			2%			0.40%		1%		2%			
DP	HR	MCDB	DP	HR	MCDB	DP	HR	MCDB	Enth	MCDB	Enth	MCDB	Enth	MCDB		
26.5	**22.9**	**31.2**	**25.6**	**21.6**	**29.9**	**24.7**	**20.4**	**28.8**	**90.3**	**32.9**	**85.4**	**31.4**	**81.2**	**30.3**	**598.5**	
Extreme Annual Desig Conditions																
Extreme Annual WS			Extreme Max WB	Extreme Annual DB				n-Year Return Period Values of Extreme DB								
				Mean		Standard deviation		n=5 years		n=10 years		n=20 years		n=50 years		
1%	2.5%	5%		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	
9.8	**8.8**	**7.7**	**32.1**	**-19.2**	**37.6**	**2.8**	**1.9**	**-21.2**	**39**	**-22.8**	**40.1**	**-24.4**	**41.2**	**-26.4**	**42.6**	

Monthly Climate Design Conditions

			Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature Degree-Days and Degree-Hours	Tavg		**11.9**	**-2.5**	**-1.1**	**4.7**	**11.7**	**17.8**	**23.1**	**25.3**	**24.2**	**20**	**13.2**	**6.7**	**-0.2**
	Sd			**5.96**	**5.36**	**5.74**	**5.17**	**4.6**	**3.94**	**3.2**	**3.43**	**4.4**	**5.01**	**5.14**	**5.65**
	HDD 10		**1393**	**387**	**311**	**183**	**40**	**2**	**0**	**0**	**0**	**0**	**25**	**126**	**318**
	HDD 18.3		**3027**	**644**	**543**	**422**	**208**	**67**	**8**	**0**	**2**	**35**	**175**	**350**	**573**
	CDD 10		**2115**	**0**	**1**	**20**	**91**	**245**	**393**	**475**	**439**	**299**	**123**	**26**	**2**
	CDD 18.3		**720**	**0**	**0**	**1**	**10**	**53**	**152**	**218**	**184**	**85**	**16**	**1**	**0**
	CDH 23.3		**7913**	**0**	**0**	**17**	**128**	**602**	**1731**	**2477**	**1918**	**860**	**174**	**6**	**0**
	CDH 26.7		**3233**	**0**	**0**	**3**	**37**	**212**	**753**	**1096**	**774**	**304**	**52**	**1**	**0**
Precipitation	PrecAvg		**896**	**37**	**39**	**65**	**94**	**91**	**106**	**106**	**102**	**81**	**66**	**62**	**48**
	PrecMax		**1247**	**95**	**97**	**138**	**193**	**196**	**247**	**246**	**255**	**209**	**158**	**151**	**116**
	PrecMin		**608**	**7**	**5**	**16**	**26**	**24**	**24**	**23**	**17**	**11**	**11**	**11**	**9**
	PrecSD		**167**	**24**	**25**	**33**	**44**	**46**	**59**	**60**	**64**	**54**	**40**	**38**	**29**
Monthly Design Dry Bulb and Mean Wet Bulb Temperature	0.40%	DB		**12.3**	**14.6**	**25.2**	**30.7**	**33.6**	**36.9**	**37.4**	**36.9**	**34.3**	**31.1**	**23.3**	**17**
		MCWB		**9.3**	**10.6**	**17.7**	**19.9**	**23.5**	**25.4**	**26.9**	**27.9**	**24.4**	**23**	**16.8**	**15.4**
	2%	DB		**8.9**	**11.1**	**20.6**	**26.6**	**31.2**	**34.3**	**35.2**	**34.2**	**31.8**	**27.4**	**20**	**12.4**
		MCWB		**6.4**	**7.7**	**14.5**	**17.8**	**22.2**	**25.1**	**26.6**	**26.3**	**23.8**	**20.4**	**15.7**	**9.7**
	5%	DB		**6.8**	**8.6**	**17**	**23.8**	**28.9**	**32.5**	**33.5**	**32.2**	**29.9**	**24.6**	**17.4**	**9.5**
		MCWB		**5.1**	**5.9**	**12.7**	**16**	**20.6**	**24.1**	**25.8**	**25.5**	**22.4**	**18.6**	**13.8**	**7.3**
	10%	DB		**5.4**	**6.1**	**13.6**	**21**	**26.6**	**30.8**	**31.8**	**30.5**	**27.9**	**21.9**	**15**	**7.1**
		MCWB		**4.1**	**4.1**	**9.5**	**14.2**	**19.4**	**23.1**	**24.9**	**24.3**	**21.6**	**16.9**	**11.5**	**5.1**
Monthly Design Wet Bulb and Mean Dry Bulb Temperature	0.40%	WB		**10.1**	**11.4**	**19**	**21.5**	**26**	**27.7**	**29.9**	**29**	**27**	**24.2**	**18.9**	**15.6**
		MCDB		**11.2**	**13.8**	**23.7**	**28.2**	**31.9**	**33.6**	**35**	**34.4**	**31.2**	**29.1**	**21.9**	**17**
	2%	WB		**6.7**	**8**	**16.2**	**19.4**	**24.1**	**26.6**	**28.2**	**27.6**	**25.3**	**22**	**16.6**	**10.2**
		MCDB		**8.5**	**10.9**	**19.3**	**24.3**	**28.7**	**32.1**	**33.5**	**32.4**	**29**	**25.6**	**18.9**	**11.5**
	5%	WB		**5.2**	**5.9**	**12.7**	**17.5**	**22.4**	**25.5**	**27**	**26.6**	**24.1**	**19.7**	**14.6**	**7.3**
		MCDB		**6.6**	**8.3**	**17**	**23**	**26.7**	**30.9**	**31.4**	**30.8**	**28**	**23.8**	**16.8**	**9.3**
	10%	WB		**4.1**	**4.3**	**9.7**	**15**	**20.8**	**24.4**	**25.9**	**25.5**	**22.9**	**17.6**	**11.7**	**5.3**
		MCDB		**5.4**	**5.9**	**12.9**	**19.9**	**25**	**29**	**30**	**29.3**	**26.7**	**21.4**	**14.5**	**6.9**
Mean Daily Temperature Range		MDBR		**7.2**	**8.1**	**10.1**	**11.9**	**12**	**11.4**	**10.4**	**10.3**	**11.8**	**11.4**	**9.2**	**7.3**
	5% DB	MCDBR		**8.4**	**10.6**	**14.8**	**15.4**	**14.4**	**13.5**	**12.2**	**11.6**	**13.5**	**15.1**	**12.9**	**9.6**
		MCWBR		**6.9**	**7.7**	**9.4**	**8.5**	**7.2**	**6.2**	**5.3**	**5.1**	**6.3**	**8.8**	**9.4**	**7.7**
	5% WB	MCDBR		**7.4**	**10**	**13.2**	**13.6**	**12**	**11.3**	**10.3**	**10**	**10.9**	**12.7**	**11.8**	**8.9**
		MCWBR		**6.5**	**7.6**	**9.3**	**8.6**	**6.9**	**6.3**	**5.6**	**5.1**	**6.6**	**8.8**	**10.2**	**7.7**

*Under RCP 4.5 scenario, averaged form 22 models presented in Table 2.2

Climate Design Conditions in Madison/Dean County, WI, USA (WMO: 726410)

Lat: 43.14N, Long: 89.34W, Elev: 264m, StdP: 98.19, Time zone:-6.00, Period: 2041-2060

Annual Heating and Humidification Design Conditions

Coldest Month	Heating DB		Humidification DP/MCDB and HR						Coldest month WS/MWDB				MCWS/PCWD to 99.6% DB		
			99.60%			99%			0.40%		1%				
	99.60%	99%	DP	HR	MCDB	DP	HR	MCDB	WS	MCDB	WS	MCDB	MCWS	PCWD	
Jan	**-16.5**	**-13.9**	**-21.8**	**0.6**	**-15.6**	**-19.2**	**0.7**	**-13.1**	**11.3**	**-1**	**10.3**	**-1.6**	**3**	**275**	

Annual Cooling, Dehumidification, and Enthalpy Design Conditions

Hottest Month	Hottest Month DB Range	Cooling DB/MCWB						Evaporation WB/MCDB						MCWS/PCWD to 0.4% DB	
		0.40%		1%		2%		0.40%		1%		2%			
		DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD
July	**10.3**	**35**	**26**	**33.4**	**25.1**	**31.8**	**24.4**	**27.7**	**32.8**	**26.7**	**31.2**	**25.8**	**30.1**	**4.9**	**216**

Dehumidification DP/MCDB and HR									Enthalpy/MCDB						Hours 8 to 4 and 12.8/20.6
0.40%			1%			2%			0.40%		1%		2%		
DP	HR	MCDB	DP	HR	MCDB	DP	HR	MCDB	Enth	MCDB	Enth	MCDB	Enth	MCDB	
26.4	**22.7**	**31.1**	**25.5**	**21.4**	**29.7**	**24.6**	**20.2**	**28.6**	**89.6**	**32.8**	**84.7**	**31.2**	**80.6**	**30**	**596**

Extreme Annual Desig Conditions

Extreme Annual WS			Extreme Max WB	Extreme Annual DB				n-Year Return Period Values of Extreme DB							
				Mean		Standard deviation		n=5 years		n=10 years		n=20 years		n=50 years	
1%	2.5%	5%		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
9.8	**8.8**	**7.7**	**32**	**-20.1**	**37.4**	**2.8**	**1.9**	**-22.1**	**38.8**	**-23.8**	**39.9**	**-25.4**	**41**	**-27.4**	**42.4**

Monthly Climate Design Conditions

			Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature Degree-Days and Degree-Hours		Tavg	**11.6**	**-2.9**	**-1.8**	**4.4**	**11.3**	**17.5**	**22.9**	**25.2**	**24**	**19.7**	**12.8**	**6.2**	**-0.5**
		Sd		**6.1**	**5.5**	**5.9**	**5.3**	**4.7**	**4**	**3.2**	**3.5**	**4.5**	**5.1**	**5.1**	**5.7**
		HDD 10	**1468**	**401**	**331**	**193**	**46**	**3**	**0**	**0**	**0**	**1**	**28**	**136**	**329**
		HDD 18.3	**3129**	**658**	**563**	**432**	**220**	**73**	**9**	**0**	**2**	**39**	**184**	**364**	**584**
		CDD 10	**2064**	**0**	**1**	**20**	**84**	**235**	**388**	**470**	**435**	**290**	**116**	**22**	**2**
		CDD 18.3	**695**	**0**	**0**	**1**	**9**	**49**	**148**	**213**	**181**	**79**	**14**	**1**	**0**
		CDH 23.3	**7508**	**0**	**0**	**16**	**116**	**543**	**1655**	**2381**	**1847**	**791**	**155**	**4**	**0**
		CDH 26.7	**2983**	**0**	**0**	**3**	**32**	**184**	**700**	**1024**	**727**	**269**	**43**	**0**	**0**
Precipitation		PrecAvg	**892**	**35**	**39**	**66**	**93**	**91**	**107**	**100**	**104**	**83**	**65**	**60**	**48**
		PrecMax	**1218**	**91**	**97**	**153**	**193**	**196**	**244**	**243**	**257**	**216**	**164**	**146**	**118**
		PrecMin	**602**	**6**	**6**	**14**	**26**	**26**	**23**	**18**	**19**	**13**	**12**	**11**	**9**
		PrecSD	**163**	**22.6**	**24.9**	**36.8**	**44.6**	**45.3**	**58.6**	**59.6**	**63.6**	**53.6**	**40.7**	**36.9**	**29.5**
Monthly Design Dry Bulb and Mean Wet Bulb Temperature	0.40%	DB	**11.9**	**14.3**	**25.1**	**30.4**	**33.3**	**36.8**	**37.2**	**36.7**	**34.2**	**30.8**	**23**	**16.4**	
		MCWB	**8.8**	**10.4**	**17.7**	**19.6**	**23.2**	**25.1**	**26.8**	**27.7**	**24.2**	**22.8**	**16.6**	**14.8**	
	2%	DB	**8.5**	**10.7**	**20.4**	**26.4**	**30.8**	**34.2**	**35**	**34**	**31.6**	**27.2**	**19.5**	**12**	
		MCWB	**6.1**	**7.4**	**14.5**	**17.6**	**21.9**	**25**	**26.5**	**26.1**	**23.7**	**20.2**	**15.2**	**9.3**	
	5%	DB	**6.4**	**8.1**	**16.7**	**23.5**	**28.6**	**32.3**	**33.4**	**32**	**29.7**	**24.4**	**16.9**	**9**	
		MCWB	**4.8**	**5.3**	**12.5**	**15.7**	**20.4**	**24**	**25.7**	**25.3**	**22.3**	**18.4**	**13.2**	**6.9**	
	10%	DB	**5.1**	**5.6**	**13.4**	**20.6**	**26.2**	**30.7**	**31.6**	**30.4**	**27.7**	**21.7**	**14.4**	**6.7**	
		MCWB	**3.8**	**3.6**	**9.2**	**13.9**	**19.1**	**23**	**24.7**	**24.2**	**21.5**	**16.7**	**11**	**4.7**	
Monthly Design Wet Bulb and Mean Dry Bulb Temperature	0.40%	WB	**9.7**	**11.1**	**18.9**	**21.2**	**25.7**	**27.6**	**29.7**	**28.9**	**26.8**	**24**	**18.5**	**15.1**	
		MCDB	**10.8**	**13.7**	**23.4**	**28**	**31.5**	**33.4**	**34.9**	**34.2**	**31**	**28.8**	**21.6**	**16.4**	
	2%	WB	**6.3**	**7.6**	**16**	**19.1**	**23.8**	**26.4**	**28.1**	**27.5**	**25.1**	**21.7**	**16.2**	**9.7**	
		MCDB	**8**	**10.4**	**19**	**24**	**28.4**	**31.9**	**33.4**	**32.2**	**28.9**	**25.4**	**18.5**	**11.1**	
	5%	WB	**4.9**	**5.4**	**12.5**	**17.3**	**22.2**	**25.4**	**26.8**	**26.5**	**23.9**	**19.5**	**14.1**	**6.9**	
		MCDB	**6.3**	**7.8**	**16.8**	**22.7**	**26.4**	**30.8**	**31.2**	**30.6**	**27.7**	**23.5**	**16.3**	**8.9**	
	10%	WB	**3.8**	**3.8**	**9.5**	**14.8**	**20.5**	**24.3**	**25.8**	**25.4**	**22.8**	**17.4**	**11.3**	**5**	
		MCDB	**5.1**	**5.3**	**12.7**	**19.6**	**24.7**	**28.8**	**29.9**	**29.1**	**26.5**	**21.2**	**13.9**	**6.5**	
Mean Daily Temperature Range		MDBR	**7.3**	**8**	**9.9**	**11.7**	**11.8**	**11.3**	**10.3**	**10.2**	**11.7**	**11.3**	**9**	**7.2**	
	5% DB	MCDBR	**8.3**	**10.6**	**14.6**	**15.3**	**14.3**	**13.3**	**12.1**	**11.4**	**13.3**	**15**	**12.8**	**9.4**	
		MCWBR	**6.8**	**7.7**	**9.3**	**8.4**	**7.1**	**6.1**	**5.2**	**5**	**6.3**	**8.7**	**9.3**	**7.6**	
	5% WB	MCDBR	**7.4**	**10.1**	**13.1**	**13.6**	**11.8**	**11.2**	**10.1**	**9.8**	**10.8**	**12.6**	**11.6**	**8.8**	
		MCWBR	**6.5**	**7.7**	**9.2**	**8.5**	**6.8**	**6.2**	**5.5**	**5**	**6.4**	**8.7**	**10**	**7.6**	

*Under RCP 8.5 scenario, averaged form 22 models presented in Table 2.2

Climate Design Conditions in Madison/Dean County, WI, USA (WMO: 726410)

Lat: 43.14N, Long: 89.34W, Elev: 264m, StdP: 98.19, Time zone:-6.00, Period: 2081-2100

Annual Heating and Humidification Design Conditions

Coldest Month	Heating DB		Humidification DP/MCDB and HR						Coldest month WS/MWDB				MCWS/PCWD to 99.6% DB	
			99.60%			99%			0.40%		1%			
	99.60%	99%	DP	HR	MCDB	DP	HR	MCDB	WS	MCDB	WS	MCDB	MCWS	PCWD
Jan	**-11.9**	**-9.7**	**-17.5**	**0.9**	**-10.6**	**-15.2**	**1.1**	**-8.6**	**11.3**	**2.4**	**10.2**	**1.9**	**3**	**276**

Annual Cooling, Dehumidification, and Enthalpy Design Conditions

Hottest Month	Hottest Month DB Range	Cooling DB/MCWB						Evaporation WB/MCDB						MCWS/PCWD to 0.4% DB	
		0.40%		1%		2%		0.40%		1%		2%			
		DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD
July	**9.7**	**38.1**	**28.5**	**36.5**	**27.7**	**34.9**	**26.9**	**30.6**	**35.6**	**29.6**	**34**	**28.6**	**32.9**	**5**	**215.8**

Dehumidification DP/MCDB and HR									Enthalpy/MCDB						Hours 8 to 4 and 12.8/20.6
0.40%			1%			2%			0.40%		1%		2%		
DP	HR	MCDB	DP	HR	MCDB	DP	HR	MCDB	Enth	MCDB	Enth	MCDB	Enth	MCDB	
29.5	**27.5**	**33.9**	**28.5**	**25.9**	**32.7**	**27.6**	**24.5**	**31.6**	**104.7**	**35.4**	**99.2**	**34.1**	**94.4**	**32.8**	**566**

Extreme Annual Desig Conditions

Extreme Annual WS			Extreme Max WB	Extreme Annual DB				n-Year Return Period Values of Extreme DB							
				Mean		Standard deviation		n=5 years		n=10 years		n=20 years		n=50 years	
1%	2.5%	5%		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
9.8	**8.8**	**7.7**	**35.3**	**-15.2**	**40.6**	**2.6**	**2**	**-17.1**	**42**	**-18.6**	**43.2**	**-20**	**44.3**	**-21.9**	**45.7**

Monthly Climate Design Conditions

			Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature Degree-Days and Degree-Hours	Tavg		**14.7**	**0.6**	**1.5**	**7**	**14.2**	**20.8**	**26**	**28.2**	**27.2**	**23.1**	**16.2**	**9.5**	**2.7**
	Sd		**0**	**5.7**	**5.1**	**5.7**	**5.4**	**4.7**	**4**	**3.3**	**3.4**	**4.4**	**5.1**	**5.2**	**5.5**
	HDD 10		**1004**	**293**	**242**	**132**	**21**	**0**	**0**	**0**	**0**	**0**	**8**	**73**	**234**
	HDD 18.3		**547**	**471**	**354**	**148**	**31**	**2**	**0**	**0**	**13**	**107**	**269**	**484**	**484**
	CDD 10		**2762**	**3**	**4**	**39**	**147**	**334**	**481**	**564**	**532**	**393**	**200**	**57**	**8**
	CDD 18.3		**1155**	**0**	**0**	**4**	**25**	**107**	**234**	**306**	**275**	**157**	**42**	**4**	**0**
	CDH 23.3		**14595**	**0**	**0**	**51**	**323**	**1288**	**3022**	**4113**	**3465**	**1821**	**477**	**35**	**0**
	CDH 26.7		**7344**	**0**	**0**	**16**	**122**	**570**	**1593**	**2230**	**1770**	**843**	**192**	**8**	**0**
Precipitation	PrecAvg		**892**	**35**	**39**	**66**	**93**	**91**	**107**	**100**	**104**	**83**	**65**	**60**	**48**
	PrecMax		**1300**	**104**	**107**	**154**	**214**	**209**	**251**	**256**	**272**	**228**	**171**	**164**	**138**
	PrecMin		**623**	**7**	**7**	**16**	**29**	**24**	**22**	**17**	**14**	**10**	**12**	**9**	**9**
	PrecSD		**180**	**26.1**	**27.1**	**36.2**	**48.9**	**49.3**	**61.1**	**65**	**70**	**58.7**	**43.1**	**42.6**	**34.4**
Monthly Design Dry Bulb and Mean Wet Bulb Temperature	0.40%	DB	**15.1**	**16.9**	**27.9**	**33.6**	**36.7**	**39.8**	**40.2**	**39.7**	**37.4**	**34.4**	**26.6**	**19.8**	
		MCWB	**11.5**	**12.6**	**20.1**	**22**	**26**	**27.5**	**29.3**	**30.2**	**27**	**25.8**	**19.6**	**17.9**	
	2%	DB	**11.7**	**13.4**	**23.2**	**29.6**	**34.2**	**37.2**	**37.9**	**37**	**34.9**	**30.8**	**23**	**15.1**	
		MCWB	**9**	**9.7**	**16.7**	**20.1**	**24.7**	**27.5**	**29.1**	**28.7**	**26.4**	**23.1**	**18.3**	**12.1**	
	5%	DB	**9.7**	**10.9**	**19.4**	**26.7**	**32**	**35.4**	**36.2**	**35**	**33**	**27.9**	**20.4**	**12.2**	
		MCWB	**7.8**	**7.9**	**14.8**	**18.3**	**23.2**	**26.5**	**28.1**	**28**	**25.1**	**21.4**	**16.3**	**9.8**	
	10%	DB	**8.3**	**8.5**	**16**	**23.8**	**29.6**	**33.7**	**34.4**	**33.4**	**31**	**25.2**	**17.9**	**9.9**	
		MCWB	**6.9**	**6.3**	**11.5**	**16.4**	**21.9**	**25.6**	**27.3**	**26.8**	**24.4**	**19.8**	**14.1**	**7.6**	
Monthly Design Wet Bulb and Mean Dry Bulb Temperature	0.40%	WB	**12.7**	**13.5**	**21.3**	**24**	**28.7**	**30.4**	**32.6**	**31.8**	**29.9**	**27.2**	**21.8**	**18.3**	
		MCDB	**13.7**	**16**	**26.2**	**31**	**34.6**	**36**	**37.3**	**36.8**	**34.2**	**32**	**25**	**19.8**	
	2%	WB	**9.4**	**10**	**18.5**	**22**	**26.9**	**29.2**	**30.8**	**30.3**	**28.2**	**25**	**19.5**	**12.8**	
		MCDB	**10.9**	**13**	**21.7**	**26.6**	**31.4**	**34.4**	**36**	**34.8**	**31.8**	**28.8**	**21.9**	**14.1**	
	5%	WB	**8**	**8**	**14.8**	**20**	**25.2**	**28.2**	**29.6**	**29.3**	**27**	**22.7**	**17.3**	**9.8**	
		MCDB	**9.5**	**10.6**	**19.2**	**25.7**	**29.5**	**33.5**	**33.9**	**33.4**	**30.8**	**26.8**	**19.9**	**12.1**	
	10%	WB	**6.9**	**6.5**	**11.8**	**17.5**	**23.5**	**27.1**	**28.5**	**28.3**	**25.9**	**20.6**	**14.4**	**8**	
		MCDB	**8.3**	**8.2**	**15.1**	**22.4**	**27.9**	**31.8**	**32.5**	**31.9**	**29.6**	**24.5**	**17.1**	**9.7**	
Mean Daily Temperature Range		MDBR	**6.9**	**7.9**	**10.3**	**12.2**	**11.9**	**11.2**	**9.7**	**9.7**	**11.7**	**11.7**	**9.5**	**7.1**	
	5% DB	MCDBR	**8.1**	**10.5**	**15.1**	**15.6**	**14.4**	**13.3**	**11.6**	**11**	**13.3**	**15.4**	**13.3**	**9.6**	
		MCWBR	**6.5**	**7.4**	**9.4**	**8.4**	**6.9**	**5.9**	**4.9**	**4.7**	**6**	**8.7**	**9.6**	**7.6**	
	5% WB	MCDBR	**7**	**9.7**	**13.3**	**13.7**	**11.7**	**11**	**9.6**	**9.3**	**10.6**	**12.7**	**12.1**	**8.8**	
		MCWBR	**6.2**	**7.3**	**9.4**	**8.6**	**6.7**	**6.1**	**5.2**	**4.7**	**6.3**	**8.8**	**10.5**	**7.7**	

*Under RCP 8.5 scenario, averaged form 22 models presented in Table 2.2

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