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Exploring Alternatives to the "Typical Meteorological Year" for Incorporating Climate Change into Building Design

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ABSTRACT

Typical climate conditions of the 20th century may not provide adequate design parameters for the built environment of the 21st century due to changing climate. The conventional practice in the engineering community is to use past climate observations to provide climate input for building design to function into the middle of the 21st century. Recent studies have used global climate models together with statistical downscaling techniques to develop site-specific climates for future energy demands on buildings. An alternative method is to use "dynamical" downscaling by use of regional climate models as is being done under the North American Regional Climate Change Assessment Program (NARCCAP). This technique uses results of global climate models to drive regional climate models which give higher resolution results over specific locations, thereby more robustly representing features such as mountains, coastal areas, and fine scale dynamical processes of the atmosphere that create regionally unique climates. We use seven global/regional climate model combinations in conjunction with the solar radiation analyses method of Wilcox and Marion to produce scenarios of future typical meteorological years for the middle of the 21st century for Mason City, IA. Our method goes beyond previous results in that (1) we use dynamical downscaling rather than statistical downscaling, (2) our results are applicable to all US locations available in the TMY3 database, and (3) our use of multiple global and multiple regional models enables us to present strong evidence that, for our test location, the magnitude of climate change in meteorological variables of high importance to building energy considerations by the middle of the 21st century will be of greater magnitude than both the natural variation in these variables during last three decades of the 20th century and the inter-model variation of the model combinations used to project this change. In future work these results will be used in building design and building energy modeling, starting with the U.S. DOE Commercial Reference Buildings.

INTRODUCTION

Typical climate conditions for the 20th century may not provide adequate design parameters for the built environment of the 21st century. Huang (2006) (as reported by Xu et al., 2009) used results of four global climate model (GCM) future climate scenarios to estimate that net energy use by residential and commercial buildings in Los Angeles will increase by 25 - 28% by 2100 due to increase in atmospheric greenhouse gases. Furthermore, he noted that the frequency, duration and intensity of heat waves will increase peak energy demand significantly under these climate scenarios.

The conventional practice in the engineering community for determining normal climate is to use the time-honored method developed by the World Meteorological Organization (WMO) and the National Oceanic and Atmospheric Administration (NOAA). This method uses the most recent three completed decades as the definition of "normal climate".

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Currently the observed weather conditions are averaged from 1981-2010 to produce a location's "normal climate". However, Livezey et al. (2007) assert that the WMO-recommended 30-yr normals are no longer useful for many applications such as building design. Use of such data for estimating future natural gas send-out by utility firms, for example, leads to serious over-estimates of consumer demand in locations such as Chicago where winters are becoming much milder. Alternative methods such as those explored by Huang (2006) and Xu et al. (2009) are needed to better represent continuing climate trends that are outside the range of means of past observations, while concurrently allowing for high levels of interannual variability and extreme events as suggested by Huang (2006).

Wilcox and Marion (2008) have developed and described the current version of the typical meteorological year (TMY3) for use by building designers and others for modeling renewable energy conversion systems at a wide range of locations across the US. The database uses observed conditions from the National Solar Radiation Data Base (NSRDB) and from 1020 locations in the U.S. and its territories and meteorological data from the National Climatic Data Center. This TMY3 database enjoys wide use in building design and alternative energy applications, although other weather databases also are used, such as the Weather Year for Energy Calculations (WYEC), the Test Reference Year (TRY), Canadian Weather for Energy Calculations (CWEC) for Canada, and the California Thermal Zones (CTZ2) for California. Crawley and Huang (1997) provide discussion on characteristics and uses such of alternative climate databases.

The currently accepted method for assessing impacts of climate change is to "downscale" climate change information produced by GCMs for particular locations and add these "changes" to the current (20th century) climate to produced a refined estimate of future climate. This downscaling can be performed with statistical methods as was done in the most recent assessment of impacts for the U.S. (Karl et al., 2009) and by Xu et al. (2009) for California. Crawley (2008) used GCMs with statistical downscaling to represent four scenarios of climate change and two cases of urban heat islands for 25 locations worldwide. Overall, the impacts of climate change were projected to reduce energy use for cold climates by around 10%, increase energy use in tropical climates by more than 20%, and change energy use from heating to cooling for the mid-latitudes. The study states that unless significant changes are made to buildings, "building owners will experience substantial operating cost increases and possible disruptions in an already strained energy supply system."

Guan (2009) reviewed a variety of methods including the extrapolating statistics method, the imposed offset method, the stochastic weather model and GCMs. The study declared that the extrapolating statistics method was too simple, and the stochastic weather model was too complex. GCMs were said to be useful for generating average changes but perhaps not local changes. That left the imposed offset method as the best overall method of those considered but left open the prospect of improving GCMs to better represent regional changes.

An alternative method to that used by Karl et al. (2009), Xu et al. (2009), Crawley (2008), and Guan (2009) is to use "dynamical" downscaling by use of regional climate models (RCMs) as is discussed in Chapter 11 of IPCC (2007) and as is being done under the North American Regional Climate Change Assessment Program (NARCCAP, 2010). This technique uses results of GCMs to drive RCMs, which give higher resolution results over specific locations, thereby more robustly representing features such as mountains, coastal areas, and fine scale dynamical processes of the atmosphere that create regionally unique climates. Xu et al. (2009) recommended that this method be used as a refinement to their statistically downscaled results when the dynamically downscaled results become available.

Our study combined the solar radiation analyses method as described by Wilcox and Marion (2008) together with dynamically downscaled climate change information generated under NARCCAP to produce scenarios of future typical meteorological years for the middle of the 21st century. Dynamical downscaling consists of using a high-resolution RCM driven at lateral boundaries (in our case place well beyond the borders and coasts of the US) by results of a GCM. The GCM therefore provides the global climate conditions but the RCM provides finer scale regional refinements by dynamical methods based on the laws of motion and thermodynamics. Under this method the GCM/RCM combined models determine the changes in monthly climate, which are then added to the TMY3 values, so that the advantages of the TMY3 cumulative frequency distributions are preserved in the future climate datasets. It is important to note that this method preserves the method to account for daily extremes that has been used in the TMY3. RCMs produce regional climate refinements not simulated in global models. Our method builds on, but also extends, previous efforts to incorporate future climate

information into building design in that (1) we use dynamical downscaling (suggested by Xu et al. 2009) rather than statistical downscaling, (2) our results are applicable to all US locations available in the TMY3 database and not just California, and (3) our use of multiple global and multiple regional models enables us to quantify the range of uncertainty in our future climate projections. One limitation is that the NARCCAP data do not take account of future (unknown) volcanic activity that would have impact on global and regional solar radiation at the Earth's surface.

DATA

Three different datasets were used for comparisons in this study. The TMY3 dataset is widely used in building design and alternative energy applications, and as such is the standard against which our comparisons will be made. We use observations taken from the National Climatic Data Center (NCDC) to assess how the TMY3 data compare with averages of long-term climate and to make comparisons with RCM model output. Modeled data were taken from the NARCCAP database where a total of seven global-regional model combinations were available and used. Mason City, Iowa was chosen as the first city to study due to its rural environment and its extended weather records. Mason City is a Class I TMY3 station, with a full 24-year period of record. NCDC data was available for Mason City for the full period, and the closest grid point to Mason City was found for each NARCCAP model. Seven variables considered as important meteorological inputs to building design were chosen to evaluate. These include total sky cover, dry-bulb temperature, dew-point temperature, relative humidity, absolute humidity, pressure, and wind speed. Most of these variables were available directly, but those that were not were derived from the available data.

TYPICAL METEOROLOGICAL YEAR

The TMY3 database provides designers and other users with a reasonably sized annual dataset consisting of hourly meteorological values that typify conditions at a specific location over a longer period of time, such as 30 years. For our study, we examined the most current version of the typical meteorological year, TMY3, as developed by Wilcox and Marion (2008). This dataset is based on more recent and accurate data and has a greater geographical coverage than the TMY2 dataset. Although not designed to provide meteorological extremes events, TMY3 data have natural diurnal and seasonal variations for each location and thereby represent a year of site-specific typical climatic conditions. The TMY3 data should not be used to predict weather for a particular period of time, nor are they an appropriate basis for evaluating real-time energy production or verifying efficiencies for building design applications or solar conversion systems.

The TMY3 dataset consists of 12 typical meteorological months (January through December), with individual months selected from different years of the period of record. For example, in the case of the NSRDB that contains 30 years of data, all 30 Januarys are examined, and the one judged most typical is selected to be included in the TMY3. The other months of the year are treated in a like manner, and then the 12 selected typical months are concatenated to form a complete year. These monthly datasets contain actual time series of meteorological measurements and modeled solar values, although some hourly records may contain filled or interpolated data for periods when original observations are missing from the data archive. Also, since adjacent months in the TMY3 may be selected from different years, discontinuities at the month interfaces are smoothed for 6 hours on each side.

TMY3 datasets are derived from the 1991-2005 NSRDB update for 1020 locations in the United States and its territories. The TMY3 dataset consists of hourly values of solar radiation and meteorological elements for a 1-year period. The meteorological data used in this dataset are provided by NCDC from its Integrated Surface Database (ISD).

The 12 selected typical months for each station were chosen using statistics determined by considering five elements: global horizontal radiation, direct normal radiation, dry-bulb temperature, dew-point temperature, and wind speed. These elements are considered the most important for simulating solar energy conversion systems and building systems. Final selection of a month includes consideration of the monthly mean and median and the persistence of weather patterns.

OBSERVATIONS

The observed data were extracted from the NCDC ISD for the years 1976 to 2005 in order to overlap the TMY3 period of record for Mason City. Months that may have been influenced by volcanic activity were eliminated. Large volcanoes create global reductions in solar energy that render meteorological conditions to be atypical. These months included May 1982 – December 1984 (32 months) and June 1991 – December 1994 (43 months). So, a total of 75 months were eliminated (6 years, 3 months). This leaves approximately 24 years of data, depending on the month.

NARCCAP MODEL SIMULATIONS

NARCCAP is an international program focused on using RCMs driven by GCMs to produce high-resolution climate change simulations. The model domain covers the conterminous United States and most of Canada, and the spatial resolution of the RCMs is 50 km. The GCMs are forced with the SRES A2 emissions scenario for the 21st century.

NARCCAP model output for scenarios created by GCMs is available for the current period, defined as 1971-2000, and the future period, 2041-2070. Also, the RCMs are driven with NCEP/NCAR Reanalysis II data for the period of 1979-2004 (Kalnay et al., 1996) so that evaluation of their performance against observations of the recent past may be undertaken. Volcano months were eliminated from the reanalysis and the current data, as with the observed data. Not all models incorporate the influence of volcanic aerosols, but these months were eliminated in all models for the sake of continuity. Four different GCMs were explored, including the Community Climate System Model (CCSM), the Third Generation Coupled Global Climate Model (CGCM3), the Hadley Centre Coupled Model version 3 (HadCM3), and the Geophysical Fluid Dynamics Laboratory GCM (GFDL). Model output from five different RCMs was available and used in our study, including the Canadian Regional Climate Model (CRCM), the Hadley Regional Model 3 (HRM3), the PSU/NCAR Mesoscale Model (MM5I), the Regional Cimate Model, version 3 (RCM3), and the Weather Research & Forecasting Model (WRFG). This resulted in a total of seven different RCM-GCM combinations, including the CRCM-CCSM, CRCM-CGCM3, HRM3-HADCM3, MM5I-CCSM, RCM3-CGCM3, RCM3-GFDL, and the WRFG-CCSM.

The magnitude of climate change for each weather variable from each RCM at each NARCCAP grid point over North America is calculated as the difference (2041-2070 values minus 1971-2000 values) of the monthly mean 3-hourly values. The models are not bias-corrected, but subtracting simulated contemporary values from simulated future scenario values minimizes impact of bias in the simulated magnitude of climate change (i.e, it is commonly assumed that bias in simulated future weather variables is similar to bias in contemporary variables and hence the biases cancel in the subtraction).

TMY3 EVALUATION

The process used in this project involved several steps. First, the "typicalness" of the TMY3 derived by Wilcox and Marion (2008) was evaluated for seven variables - total sky cover, dry-bulb temperature, dew-point temperature, relative humidity, absolute humidity, pressure, and wind speed. Averages of these variables were compared between the TMY3 months and the 1976-2005 base period of observations (in which volcano months were eliminated).

Although TMY3 data were not intended to match 30-year average climates at their specific sites, it is instructive to make this comparison with the observations of that time period. Differences between the TMY3 monthly averages and the observed monthly averages were computed for all seven variables. Results (not shown) revealed that the differences were generally quite small - less than the monthly standard deviation in all months and all variables except for relative humidity and pressure. The TMY3 months were evaluated on an hourly basis as well, and again the results showed the data to be representative of (except for relative humidity and pressure) the 30-year observed conditions.

MODEL EVALUATION

The second step was to evaluate the skill of individual RCMs to reproduce TMY3 data. Data for the seven variables mentioned previously were extracted from the NARCCAP archives for reanalysis-driven runs of the five RCMs for which complete data were available. Data were compared with the TMY3 months through both monthly and 3-hourly averages.

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All models have biases, so comparing data in this way clearly shows the bias structure for each model. For instance, the HRM3 regional climate model appears to have a consistent warm bias in the dry-bulb temperatures, with largest values in January, February, and August, as shown in Figure 1. Other models and other variables (not shown) each have their own unique bias structure. Our method of correcting for model biases as previously described minimizes this source of uncertainty, and analysis of model-specific bias structure provides a deeper understanding of the models being used.

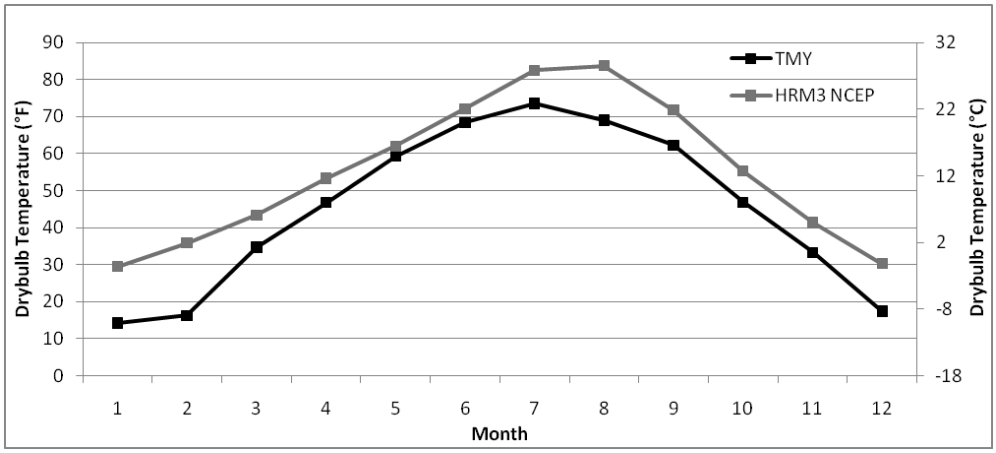

Figure 1 *Comparison of TMY3 and HRM3-NCEP average monthly dry-bulb temperature for Mason City, Iowa. The comparison shows a consistent warm bias in the dry-bulb temperature for the HRM3 regional climate model.*

MODEL PROJECTED CHANGE

Climate sets for Mason City, Iowa were extracted from the NARCCAP archive for the seven GCM/RCM model combinations for both the contemporary (1971-2000) and future (2041-2070) time periods. Differences of the monthly averages of these datasets for each variable were then added to the hourly TMY3 data to produce a future typical meteorological year analogous to the TMY3 for the middle of the 21st century.

The standard deviations (SDs) of the 20th century observed climate variables provide a measure of natural variations. Simply put, if the projected magnitudes of climate change in variables important to building energy consumption are less than the natural variations of the current climate, then there is little incentive to evaluate impact of climate change on building design. Table 1 lists the computed climate change in seven variables for seven model combinations as well as the seven-model average. Comparison of the bottom three rows of Table 1 for each variable shows that models produce climate change values exceeding both natural variability of the 20th century and inter-model variability in projected climate change for dry-bulb temperature, dew-point temperature, and absolute humidity, but not for cloud cover, relative humidity, and surface pressure. For wind speed the projected change is slightly larger than the SDs of the models but far less than 20th century variability. Dry-bulb temperature, dew-point temperature, and absolute humidity (which of course is determined from the previous two and pressure) are all important factors in energy calculations for buildings. We therefore conclude that the TMY3 database should be modified for use in estimating energy requirements of building functioning in the middle of the 21st century.

Table 1. NARCCAP Average Projected Climate Change (for Mason City, Iowa)

Model	Totcld (tenths)	Drybulb (°F/ K)	Dewpoint (°F / K)	Rhum (%)	Ahum (g cm^{-3})	Pressure (in Hg / mbar)	Wspd (mph / m s^{-1})
CRCM-CCSM	-0.03	5.18 / 2.88	5.67 / 3.15	2.05	1.49	0.014 / 0.48	-0.09 / -0.04
CRCM-CGCM3	-0.11	5.85 / 3.25	4.54 / 2.52	-2.15	1.20	0.003 / 0.09	-0.04 / -0.02
HRM3-HadCM3	-0.25	4.80 / 2.67	3.37 / 1.87	-2.84	0.92	-0.022 / -0.73	-0.02 / -0.01
MM5I-CCSM	N/A	3.67 / 2.04	4.15 / 2.30	1.12	1.02	0.013 / 0.45	-0.10 / -0.04
RCM3-CGCM3	N/A	4.61 / 2.56	4.27 / 2.37	-0.04	1.07	0.004 / 0.14	-0.17 / -0.08
RCM3-GFDL	N/A	4.01 / 2.23	3.70 / 2.05	-0.05	0.88	0.015 / 0.51	-0.08 / -0.04
WRFG-CCSM	0.16	4.87 / 2.71	5.19 / 2.88	1.19	1.03	0.020 / 0.68	-0.18 / -0.08
Mean projected change	-0.06*	4.71 / 2.62	4.41 / 2.45	-0.10	1.09	0.007 / 0.23	-0.10 / -0.04
SD of models' change	0.17*	0.72 / 0.40	0.80 / 0.45	1.80	0.20	0.014 / 0.48	0.06 / 0.03
SD of 20th C obs	0.83	1.66 / 0.92	2.11 / 1.17	3.21	0.42	0.016/ 0.54	0.54 / 0.24

* only four models used in calculation

SEASONAL AND DIURNAL CHANGES

Projected changes in climate at seasonal and diurnal scales provide additional insight on the details of climate change. For instance, the models show an average expected increase in summertime dry-bulb temperatures of about 5°F (3K) and

Table 2. Model-Averaged NARCCAP Projected Climate Change by Month (for Mason City, Iowa)

Month	Totcld (tenths)	Drybulb (°F / K)	Dewpoint (°F / K)	Rhum (%)	Ahum (g cm^{-3})	Pressure (in Hg / mbar)	Wspd (mph / m s^{-1})
1	0.15	6.23 / 3.46	6.39 / 3.55	1.20	0.55	0.010 / 0.34	-0.27 / -0.12
2	-0.11	4.77 / 2.65	4.40 / 2.44	-0.22	0.41	0.018 / 0.61	-0.64 / -0.28
3	-0.14	3.73 / 2.07	3.45 / 1.92	-0.22	0.49	0.007 / 0.23	0.05 / 0.02
4	0.06	3.68 / 2.04	3.65 / 2.03	0.30	0.83	0.025 / 0.84	-0.37 / -0.17
5	0.03	3.24 / 1.80	3.67 / 2.04	1.03	1.20	0.003 / 0.12	0.18 / 0.08
6	-0.26	4.70 / 2.61	4.37 / 2.43	-0.54	1.97	0.025 / 0.83	-0.16 / -0.07
7	-0.51	5.28 / 2.94	4.04 / 2.25	-2.18	2.06	0.007 / 0.23	-0.04 / -0.02
8	-0.30	5.73 / 3.18	3.93 / 2.18	-2.74	1.83	0.004 / 0.13	-0.09 / -0.04
9	0.01	5.33 / 2.96	4.61 / 2.56	-0.70	1.45	-0.009 / -0.30	0.10 / 0.05
10	0.12	4.16 / 2.31	4.65 / 2.58	1.49	1.06	0.004 / 0.13	-0.20 / -0.09
11	-0.02	4.29 / 2.38	4.07 / 2.26	-0.19	0.65	-0.004 / -0.14	0.11 / 0.05
12	0.28	5.38 / 2.99	5.72 / 3.18	1.51	0.56	-0.007 / -0.24	0.18 / 0.08

an increase in summertime dew-point temperature of about 4°F (2K). These values are about twice as large or more as the natural variation over the last 30 years as shown by the SD in the bottom row in Table 1. Some individual models simulate larger increases in these variables. For instance, the CRCM-CCSM model combination predicts an increase of about 7°F (4K) in the dry-bulb temperature and 8°F (4K) in the dew-point temperature for January as shown in Figure 2, giving an increase in relative humidity of about 4%. For July, the CRCM-CCSM model produces a dry-bulb temperature increase of about 7°F (4K), but an increase of only 5°F (3K) in dew-point temperature. The larger increase in dry-bulb temperature in this case produces a *decrease* in relative humidity of about 2% to 6% depending on the time of day. This seasonal reversal of change in relative humidity is also generally shown in the other models. Absolute humidity (or dew-point temperature),

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which increases in all months, is a better indicator than relative humidity of change in building energy requirements.

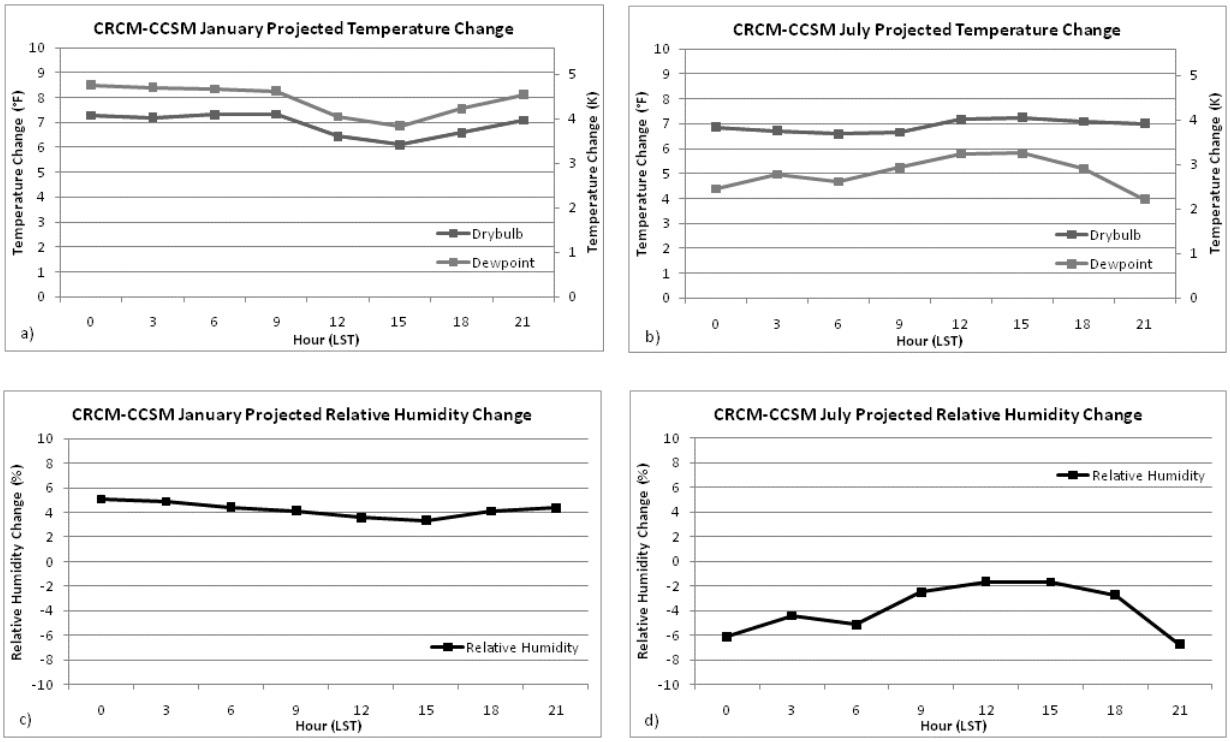

Figure 2 *Seasonal changes in the diurnal patterns of temperature and humidity for the CRCM-CCSM model for Mason City, Iowa. (a) January temperature changes project an increase in relative humidity. (b) July temperature changes project a decrease in relative humidity. Projected July temperature changes are more than twice the standard deviation (natural variability) of the last 30 years.*

PROJECTED IMPACT ON BUILDING ENERGY CONSUMPTION

Building energy consumption is influenced by many design and operational factors, but weather data plays a major role. As Huang (2006) points out, multiple researchers have taken a variety of approaches in the past twenty years to estimate potential impacts of changing climate. Using advances in climate science, climate modeling as well as energy modeling and simulations Crawley (2003) was among the first to create modified hourly weather files from gridded global climate results as input files for energy simulation software for 25 global locations. Huang (2006) followed using the same method for 18 US climate zones and prototypical residential and commercial buildings, while Xu et al (2009) focused on the impact on the state of California finding increases in cooling loads for 2100 of about 50% for the worst case IPCC carbon emission scenario (A1F1) and still 25% with the most likely carbon scenario (A2). Heating loads would decrease significantly under all scenarios leaving the overall annual aggregated energy consumption only slightly higher than today. But the implications for building systems and electrical power supply would be significant and therefore further research and verification are necessary.

CONCLUSION

We have extended the work of past researchers on the impact of climate change on building energy demand by using multiple global models and multiple regional models to evaluate site-specific climate change. Our method goes beyond

previous results in that (1) we use dynamical downscaling (suggested by Xu et al. 2009) rather than statistical downscaling, (2) our results are applicable to all US locations available in the TMY3 database, and (3) *our use of multiple global and multiple regional models enables us to present strong evidence that, for our test location, the magnitude of climate change in meteorological variables of high importance to building energy considerations by the middle of the 21st century will be of greater magnitude than both the natural variation in these variables during last three decades of the 20th century and the inter-model variation of the model combinations used to project this change*. By interpolation of mid-21st century results back to the current climate, our methodology can be used to derive future typical meteorological year databases for each decade of the first half of the 21st century.

FURTHER WORK

This study is currently being expanded to include more locations. With a grant from the Center for Global and Regional Environmental Research (CGRER) we will examine the 16 different climate zones used in the creation of the U.S. Department of Energy (DOE) reference buildings. Also, energy performance simulations will be conducted to evaluate the impact of projected changes in climate on a selection of these 16 buildings that represent about 60% of the U.S. commercial building stock. For those regions having significant changes in energy consumption and patterns, future typical meteorological year data can be prepared for risk analysis of a changing climate.

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