GENERATING FUTURE WEATHER FILES FOR RESILIENCE

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ABSTRACT: Weather files provide hourly times series of weather variables for a typical year based on historical observations, and are widely used for modeling energy use and human comfort in the built environment. However, since they are based on historical data, they are increasingly inaccurate tools for estimating the future performance of buildings and communities, especially those with lifetimes exceeding 30 years. A "morphing" technique [1] has been used to transform historical time series based on projected changes in the monthly averages of several climatic variables. Since future values of these variables are uncertain, especially at local scales, changes in the monthly mean value of each of the variables, or offsets, have been calculated for an ensemble of climate projections generated by models from the Coupled Model Intercomparison Project Phase 5 (CMIP5). These models were run for the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment (AR5). The offsets were calculated for several future time periods during the 21st century for both the 4.5 and 8.5 Representative Concentration Pathways (RCPs). For each combination of time period and RCP, a cumulative frequency distribution (CFD) of the offset in mean monthly temperature was constructed based on the percentile rankings of the projections in the ensemble. The association between the mean monthly temperature and the other variables for each model is maintained, providing a consistent and physically plausible set of inputs to the morphing algorithm for each point on the CFD. The Weather File Module of the WeatherShift™ tool provides an intuitive user interface that allows the user to select a location, emissions scenario, future time period and point on the CFD to obtain a projected weather file reflecting a plausible future climate.

Keywords: Weather Files, Climate Change, Future, Resiliency

INTRODUCTION

Nearly all of the $8.7 trillion of global construction volume makes use of climate data (i.e. time averaged weather data) in order to size building and infrastructure services or gauge the cost effective performance of alternative systems and designs [2]. However, it is widely known that the data used as a basis for these decisions is, at best, inaccurate and, more likely, insufficient given the changes in the climate predicted in the coming decades. More alarmingly, much of the historic data being used by engineers, architects, and planners is already outdated by a quarter-century or more and may not be appropriate for use in the present or the future. This unnerving reality was the motivation for the creation of projected future weather files that would better reflect current conditions and a range of plausible futures based on scientific consensus and the ensemble of global climate models used for the International Panel on Climate Change (IPCC) Fifth Assessment (AR5) [3]. The research team believes that it is timely and appropriate to translate climate science into building design practice in order to design appropriate buildings and fulfill the fiduciary responsibility of professionally licensed designers to their clients. The effort required is surprisingly small given that the projected weather data can easily be substituted into existing modeling software.

The WeatherShift tool is a platform intended to provide access to projected future weather and climate data for use in building, urban environment, and infrastructure design. The Weather File Module (WFM) is the first application to be made available.

The files that are widely used for representing the weather data used in building energy simulation, the "morphing" technique for transforming weather time series based on changes in climatic conditions, and the climate offset distributions used to provide inputs for the transformations, are all described briefly in the following section. This is followed by examples in the building industry that have used the projected weather files.

AN OVERVIEW OF THE WEATHER FILE MODULE

There are a number of types of weather file formats that have been developed for the purpose of building energy simulation. EnergyPlus Weather files (EPW files) were developed initially for use with the EnergyPlus building energy simulation engine and utilize the most modern text file format for weather data currently in use [4]. The format is independent of data source and has become widely used for other energy simulation and weather analysis platforms as well, making it an ideal vehicle for the WeatherShift tool. EPW files provide 8760 hourly values for a year for weather variables including temperature, humidity, wind speed, and solar irradiance.

First generation Typical Meteorological Year (TMY) data was collected from 1948 to 1980, TMY2 data from 1961 to 1990, and TMY3 data either from 1976 to 2005 or from 1991 to 2005, depending on data availability for a particular location. All TMY data is derived by concatenating twelve "typical" months to create a "typical" year for a given location [5]. Typical months are chosen based on the best statistical fit of several weather variables to the thirty year statistics for that month, with the heaviest weighting being assigned to solar radiation.

During early project stages, weather data may be used for climatic analysis to determine the feasibility of envelope and mechanical strategies, although it is important to remember that they do not represent either average or extreme weather because of the way in which the files have been constructed. In later project stages the same weather data are used in energy simulations of the strategies determined to have merit and to weigh them on an energy and lifecycle basis.

The approach to generating projected future weather files is based on the method of Belcher et al [1], with some refinements. Belcher et al refer to their method as "morphing" weather variable time series, which is characterized by several relatively simple transformations applied to those time series, depending on the nature of the particular variable. Because the projected weather data is based on historical weather data, it is meteorologically realistic. However, since most of the transformations preserve historical variability, the projected files may understate changes in future extremes.

The fundamental premise is to preserve the hour-to-hour variability of each of the time series comprising the weather files while transforming their monthly mean values consistent with future climate projections. (Monthly means are used since the weather files in question are assembled from "typical" months.) As described later in this section, changes in monthly means, or offsets, are calculated for selected weather variables for each member of an ensemble of global climate models for a future period compared to a baseline period. Then these offsets are used to morph the weather variable time series that collectively comprise the weather file.

Several types of transformations are used depending on the nature of the weather variable in question. For example, atmospheric pressure uses the simplest transformation, an additive shift. The offset for each month is simply added to the pressure time series values for that month. A scaling transformation, or multiplicative shift, is used for several variables including solar irradiance and wind speed. In this case, the monthly time series values change by a fraction equal to the ratio of the monthly offset to the mean value of the variable for that month.

The transformation for relative humidity is a bit more complex, since by definition it is bounded by 0 and 100%. To simplify the transformation, the relative humidity is represented as a decimal fraction, r, rather than a percentage, bounded by 0 and 1. The changes in the monthly time series values can be expressed as $r_i(1-r_i)$, where r_i is the current day relative humidity in the i^{th} hour of the month, multiplied by the ratio of of the monthly offset to the mean value $r_i(1-r_i)$ for that month. Since the value of $r_i(1-r_i)$ is 0 if r_i is either 0 or 1, the transformed values will be bounded by 0 and 1 by construction.

A similar transformation is used for dry bulb temperature, but modified to take advantage of the fact that offsets are available for mean daily temperature, minimum daily temperature, and maximum daily temperature. The temperature time series values are normalized for each day of the month to their relative position between the minimum and maximum temperature for that day and a transformation applied of the form described for relative humidity.

The monthly offsets for the following variables were calculated using 14 of the models run for AR5 for three future time periods (2026-2045, 2056-2075 and 2081-2100), relative to a baseline period (1976-2005), for 259 cities around the globe:

- Mean daily temperature
- Maximum daily temperature
- Minimum daily temperature
- Relative humidity
- Daily total solar irradiance
- Wind speed
- Atmospheric pressure
- Precipitation

The offsets were computed using bilinear interpolation between the four model grid points nearest each city. They were calculated for representative concentration pathways (RCP) 4.5 and 8.5, both of which were mandatory for AR5. Roughly speaking, RCP 8.5 represents a business as usual scenario and RCP 4.5 represents a moderately aggressive emissions mitigation scenario.

The results of these calculations can be thought of as a matrix for each calendar month with a column for each variable and a row for each model with the rows arranged in ascending order of the mean daily temperature offset. A cumulative distribution function (CDF) is constructed for each variable using linear interpolation between the model values. Because the offset values for each model remain linked with each other, a physically consistent relationship between the values of the variables is maintained.

The user of the WFM can specify the point on the mean daily temperature offset distribution they would like to select for the offsets used to transform the weather file for the location of interest to them. Table 1 shows an example subset of the offsets at the percentile values of 5, 50, and 95 for Chicago in August for 2056-2075 for RCP 8.5.

Table 1: Sample Offsets for Chicago, 2056-2075, RCP 8.5

	5%	50%	95%
mean temperature K	2.96	4.20	6.55
max temperature K	2.95	4.46	7.05
min temperature K	3.01	4.06	6.10
relative humidity %	-2.24	-1.10	-4.68
solar irradiance W m-2	-8.13	4.41	19.81
wind speed m s-1	0.31	-0.19	-0.27
pressure Pa	-31.64	-57.16	-63.50
precipitation mm/day	0.18	0.03	0.11

WEATHERSHIFT WEBSITE

The WeatherShift website has been built to allow users to view summary data from a projected weather file without cost, with an option to purchase the full weather file for use in commercial projects (not yet implemented on the website). This online interface allows engineers and designers to demonstrate to their clients and peers how significant the effects of climate change can be

The site provides the user with basic information about the WFM in help text so that a layman can understand the terminology and options available.

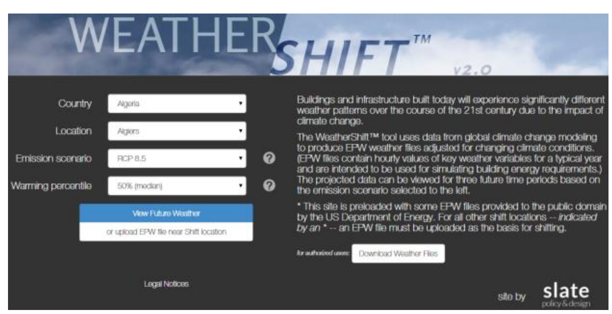

Figure 1: WeatherShift Homepage

The user can select a city by first choosing the country, and then the city. Some cities are marked with an asterisk (*) that indicates that the required baseline weather files are not freely available from the US Department of Energy, and therefore have not been preloaded. If a user wishes to perform an analysis at one of these locations, a user supplied weather file in EPW format can be uploaded. Next, the user can select either the RCP 4.5 or 8.5 emission scenario, and one of the standard warming percentile values.

The "View Future Weather" button loads visualizations of the summary data based on the input selections. The first three graphs allow the users to view several variables either monthly, seasonally, or as a histogram.

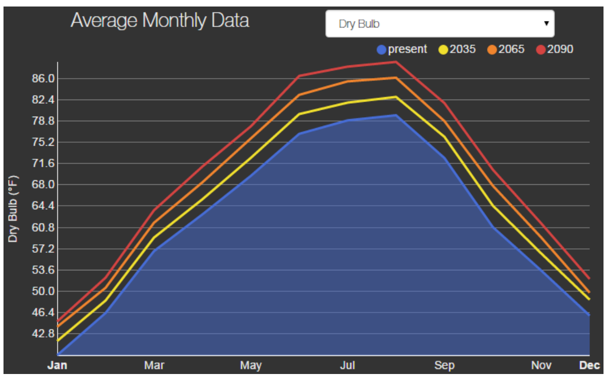

Figure 2: Monthly Data Visualization

The user can also view all of the variables in an annual time series with the ability to zoom in on specific periods of time.

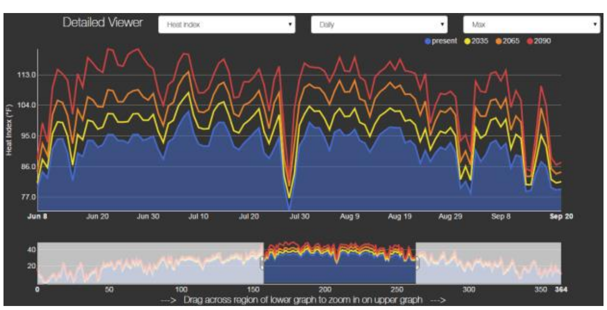

Figure 3: Time Series Data Visualization

APPLICATIONS OF THE WEATHERSHIFT WEATHER FILES

The usefulness of the projected weather files lies in their implications for building and infrastructure design. Several projects have already used this data, providing examples of its applications. All of the analyses described below assumed the 50th warming percentile for the projected weather files used.

2015 ASHRAE Energy Modeling Competition: During the 2015 SimBuild conference the team from Integrated Environmental Solutions designed and modeled a net zero office building in Boulder, CO. Various strategies were used to achieve this including natural ventilation. The team performed a future typical weather analysis using WeatherShift files to ensure performance throughout the building's lifetime.

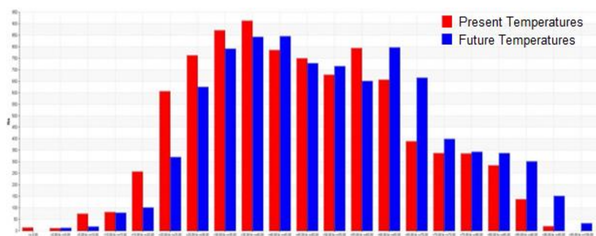

Figure 4: Future Weather Comparison for Boulder, CO

Figure 4shows a comparison of the histogram for mean daily temperature in 2035 compared to current day conditions. Due to the large amount of heating currently needed in this location, the warmer future climate actually showed a reduction in annual energy usage due to reduced heating requirements. However, the future simulations also suggested that the summer operating conditions would be somewhat out of comfort range since the design was based on natural ventilation and had no mechanical cooling. The team rectified this with an evaporative cooling system, thereby accounting for the future heat without requiring any mechanical cooling.

California Campus Plan

For an unconditioned warehouse-like structure in California, the energy analysis revealed that the ambient temperatures will likely be too cool for part of the year, due to a lack of solar gains. A WeatherShift study showed, however, that this issue will lessen over time, and as long as the present design provides enough passive heating for the current situation, the facility will likely remain comfortable in the future. If the space were to be conditioned, the energy usage would remain similar over time, but the heating needs would decrease and the cooling needs increase, as shown in Figure 5.

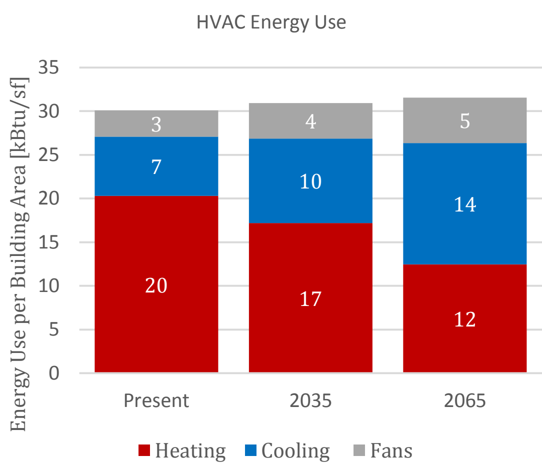

Figure 5: HVAC Energy Use for CA Campus

California Campus Rainfall

The precipitation offsets were used to estimate the change in rainfall in 2050 for a building intended to have a 100 year life span. The project looked at the feasibility of a net zero water approach to the building system designs and needed to ensure that the storage tanks were sized adequately to support that objective. Since in that location the projected change in monthly rainfall is less than a tenth of an inch, the design team and client concluded that the proposed system sizing would not be of sufficient capacity in future years.

Mesa City Center

A microclimate study for a city center building built in Mesa Arizona made use of WeatherShift files in order to ensure that the design would be resilient with respect to heat stress in the future. The climate is already fairly hot, so even small increases in temperature can have drastic effects. The analysis suggested an increase in typical monthly mean daily air temperatures of between 3-4°F over the next 40 years. More importantly, the incidence of dangerous levels heat stress is projected to increase at a fairly alarming rate, as shown in Figure 6.

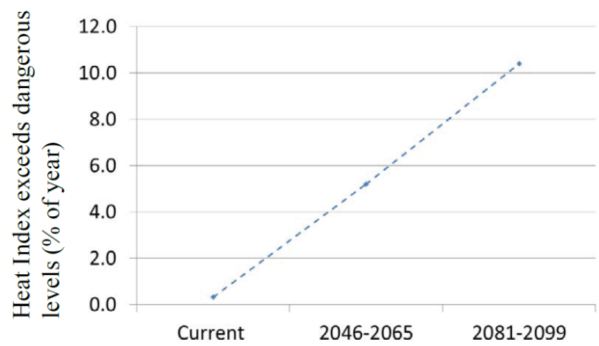

Figure 6: Heat Index Trends for Mesa Arizona

At present the area experiences dangerous heat stress less than 1% of the year, but by 2055 this is expected to increase to 5%, making exterior passive design strategies even more critical. This analysis helped influence the design team's decisions to mitigate future heat stress. It should be noted that these projections actually represent a lower bound, since they are based on typical weather data that does not fully incorporate increases in future extremes.

University Campus Towers

For new towers on a campus in Massachusetts, the design team conducted a weather sensitivity analysis to be sure that the system topology and size was sufficient to be resilient to future conditions.

Even though the design team slightly increased the capacity of the cooling system to account for increasing summer temperatures, the expected energy usage actually decreases due to the increased heat, because the winter heating requires far more energy than the summer cooling, similar to the Boulder example. However, this heating energy is generally cheaper, so even though the energy usage will likely decrease, its cost will increase.

New York Museum Competition

An analysis using weather data near Central Park in New York City predicted many changes in the future that were suggested to a client during a design competition. These suggestions ranged from the requirement of detailed study on passive ventilation strategies to ensure comfortable operation during warmer climates, possible increased cooling system capacities or dedicated space allocation for future resiliency, or potential reduction in heating capacity that would likely not be needed in the near future.

CONCLUSIONS

This paper has described a method of projecting future typical weather data. Several project case studies have also been discussed, illustrating ways in which this type of data can be used to make building and infrastructure designs more resilient to future climatic conditions. The authors suggest that the engineering community make a standard practice of considering the impacts of climate change on all future projects, from the standpoints of resource utilization, comfort, and safety.

ACKNOWLEDGMENT

This work was supported by funding from Arup and Argos Analytics.

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