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Future proofing the accuracy of building simulations by addressing climate change projections in modified weather files

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Abstract: Complex building simulation is increasingly common in the design process of buildings in Australia. Traditionally, building simulation has been conducted using weather files constructed from typical historical weather data, but in a period of climate change the use of historical data to assess performance has been criticised as inappropriate. Modern buildings need to be efficient and comfortable today, but also into the future. This new design challenge requires adaptability and resilience to be included in building designs from the outset, and necessitates that data used for simulation is as accurate and reflective as possible of the environmental conditions in which buildings are likely to operate. This research utilises the improved imposed offset method proposed by Guan to construct a future hourly weather data file for various Australian locations that can be used in building simulation software. This approach will produce weather time series that incorporates the RCP8.5 climate change scenario while maintaining the local and realistic characteristics of the original weather file. This future weather data can then be used by designers and building engineers to assess off-axis scenarios in the simulation and address the risks of overheating during the lifetime of the building.

Keywords: Building simulation; climate change; future weather data; morphing technique.

1. Introduction

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (2014) concluded that since the 1950s many observed parameters including atmosphere and ocean temperature, snow and ice cover, and sea levels have undergone adverse and unprecedented changes. By the end of the 21st century the global mean surface temperature is projected to increase in the range of 0.3-1.7° C to 2.6-4.8° C relative to 1986-2005 baseline climate, heat waves will occur more frequently and last longer, and extreme precipitation events will become more intense and recurrent (IPCC 2014).

Buildings designed to operate in a period of climate change need to be efficient and comfortable today, but also into the future. This new design challenge requires adaptability and resilience to be incorporated into building designs from the outset, and also necessitate that data used for decision-making is as accurate and reflective as possible of the environmental conditions in which buildings are likely to operate during their lifetime. Over the last decades detailed building simulation has increasingly become part of the design process to demonstrate compliance with regulations, optimise design and building services' performance, and inform developers, building's owners and occupants of the expected efficiency of their buildings (Augenbroe 2002). Traditionally, building simulation has been conducted using weather files constructed from typical historical weather data (usually for a period of 20 to 30 years) for a particular location. However, when considering that buildings have an operational life of 50 to 100 years, the use of historical weather data to assess their performance in a changing climate has been criticised as inappropriate (Watkins et al. 2011; Gupta, & Gregg 2012; Ren et al. 2011).

Previous research has investigated a number of methods to develop weather files representative of the possible future climate that can be used in building simulation (Chow & Levermore 2007; Rimante et al. 2015; Robert & Kummert 2012; Wilby & Wigley 1997; van Paassen & Luo 2002). The objective of this paper is to use the framework proposed by Guan (2009) to construct future hourly weather data files for Sydney, Brisbane, Perth, Darwin, Melbourne, Canberra, and Adelaide to use in building simulation software. Guan's approach allows to simultaneously employ different methods, thus providing a more holistic and representative method to obtain future weather data that can be used by designers and building engineers to assess the performance of their proposed design and the risks of overheating during the lifetime of the building.

2. Climate change projections and scenarios

The Intergovernmental Panel on Climate Change (IPCC) (2014) has predicted that by the end of the 21st century the global mean surface temperature will likely increase in the range of 0.3-1.7°C to 2.6-4.8°C relative to 1986-2005 baseline climate. This prediction is the result of multiple global emissions scenarios developed by the IPCC and based on varying assumptions for future possible economic growth, resource consumption, technology implementation, social equity and global population development. The scenarios used to predict the future climate exclude targeted strategies for the mitigation of climate change, however they represent possible development pathways of human activities (Jentsch et al. 2013).

The emissions scenarios used by the IPCC to conduct the fifth Couple Model Intercomparison Project (CMIP5) are referred to as Representative Concentration Pathways (RCPs). Four RCPs have been defined based on the radiative forcing (W/m^2) associated with a particular pathway by 2100 and include: RCP8.5 (high emission scenario), RCP4.5 and 6.0 (intermediate emission scenarios), and RCP2.6 (low emission scenario). The assumptions underpinning each of these scenarios range from a future assuming very rapid economic growth with a population peak around mid-century, rapid introduction of new and more efficient technologies, substantial reduction in regional differences in per capita income, and little curbing of emissions, to a future assuming a peak in emissions around 2020 followed by their rapid decline due to very ambitious and sustained emissions reduction targets (Climate Change in Australia 2015). At this time there is no particular probability attached to any one of the proposed scenarios (Belcher et al. 2005; Holmes & Hacker 2007), however, for the purpose of this study and in order to represent a worst case scenario, RCP8.5 has been used.

3. Generation of future weather data

3.1. Methodology

The imposed offset method, also called morphing, imposes data from complex climate models on top of observed historical weather data (Belcher et al. 2005). This method involves three general operations: 1) shifting; 2) stretching; and 3) a combination of shifting and stretching. These operations are applied to the data available within historical weather files using the climate change forecast included in global circulation models (GCMs), thus producing a future weather file that preserves physically realistic weather sequences of the baseline data (Chan 2011). Due to its ability to retain the nature of the observed data and the relatively low amount of computational power required for calculation, morphing has become the most used approach for constructing future weather files for building performance simulation and is also used by the Chartered Institution of Building Services Engineers (CIBSE) in the development of their climate change weather data files (Jentsch et al. 2013).

Based on a review of the literature of the various methods available to generate future weather data, it was established that no single procedure can be considered fully robust. This paper therefore proposes to utilise a hybrid approach, whereby procedures from various methods are integrated into one. Following the process proposed by Wang et al. (2010), climate change projections in Australia have been simulated using the Climate Future Tool developed by the CSIRO. For the purpose of this study, and in order to account for the strengths and weaknesses of individual GCMs, data from a total of 26 models has been used (see Table 1). These models have been selected based on their confidence levels to predict climatic variables in Australia.

Table 1: Atmospheric-ocean general circulation models used in this research

ACCESS1-0	CESM1-CAM5	FGOALS-s2	IPSL-CM5B-LR
ACCESS1-3	CMCC-CESM	FIO-ESM	MRI-CGCM3
bcc-csm1-1-m	CMCC-CM	GFDL-CM3	MIROC5
bcc-csm1-1	CMCC-CMS	GFDL-ESM2M	MRI-ESM1
CanESM2	CCSM4	HadGEM2-CC	MPI-ESM-LR
CNRM-CM5	EC-EARTH	HadGEM2-ES	MPI-ESM-MR
CESM1-BGC		HadGEM2-AO	

The climate change projections obtained from the GCMs have then been downscaled using the framework proposed by Guan (2009) in order to develop weather files for the studied locations. Guan (2009) elaborates on the imposed offset method proposing to retain current conditions when a reliable prediction for a particular climatic parameter is not available or when there is little confidence in its accuracy, while adopting either the morphing approach or the diurnal modelling method depending on the details of projection available.

3.2. Dry bulb temperature projections

The GCMs used for this study provide predicted changes in monthly mean temperature, monthly maximum temperature, and monthly minimum temperature. Using the current IWEC data, the monthly mean daily maximum and minimum temperature are determined. The scaling factor for the stretch algorithm is then determined by Eq. (1):

$$\alpha dbt_m = \frac{\Delta TMAX_m - \Delta TMIN_m}{(dbt_{omax})_m - (dbt_{omin})_m} \quad (1)$$

Where the subscript symbol "m" stands for "monthly", αdbt_m is the scaling factor, $\Delta TMAX_m$ is the predicted change in monthly maximum temperature, $\Delta TMIN_m$ is the predicted change in monthly minimum temperature, $(dbt_{omax})_m$ is the current monthly mean daily maximum temperature and $(dbt_{omin})_m$ is the current monthly mean daily minimum temperature.

The hourly future dry bulb temperature is then given by Eq. (2):

$$dbt = dbt_o + \Delta TEMP + \alpha dbt_m \times (dbt_o - (dbt_o)_m) \tag{2}$$

Where *dbt* is the hourly future dry bulb temperature, dbt_o is the existing dry bulb temperature, $\Delta TEMP$ is the predicted monthly mean temperature rise, and $(dbt_o)_m$ is the existing monthly mean daily temperature.

3.4. Solar radiation on horizontal projections

Although the overall solar energy is not predicted to change, an increase in the surface temperature is likely to alter the Earth's cloud cover and albedo, which in turn could impact on daylight and solar gains at ground level (Jentsch et al. 2013). To calculate the projected increase in global solar radiation, a scaling factor was obtained by Eq. (3):

$$\alpha grs_m = 1 + (\frac{\Delta DSWF_m}{gsr_0}) \tag{3}$$

Where αgrs_m is the scaling factor, $\Delta DSWF_m$ is the absolute monthly change in solar radiation as projected by the GCMs, and gsr_0 is the existing monthly mean solar radiation.

The projected solar radiation is then obtained by multiplying the scaling factor by the existing hourly solar radiation using Eq. (4):

$$gsr = \alpha grs_m \times gsr_0 \tag{4}$$

3.5. Diffuse solar radiation on horizontal

Predictions for the diffuse solar radiation are not given by the GCMs used within this study and therefore, as suggested by Belcher et al. (2005) this data has been assumed to change proportionally to the global solar radiation. The equation used to calculate the projected diffuse solar radiation is given below (Eq. 5):

$$dsr = \alpha gsr_m \times dsr_0 \tag{5}$$

Where αgsr_m is given by Eq. (5) and dsr_0 is the existing diffuse solar radiation.

3.6. Air humidity projections

The humidity projection data provided by the used GCMs is given as changes in percentage, and thus the future relative humidity is given by Eq. (6):

$$RH = \left(1 + \frac{RH_m}{100}\right) \times RH_0 \tag{6}$$

Where RH is the future relative humidity, RH_m is the projected change in relative humidity, and RH_0 is the current relative humidity.

3.7. Wind patterns projections

Changes in wind direction are not provided by the utilised GMCs, therefore for the purpose of this research the future wind direction has been assumed to remain unchanged, while the future wind speed has been calculated using the morphing approach as outlined by Eq. (7):

$$ws = \left(1 + \frac{WIND_m}{100}\right) \times ws_0 \quad (7)$$

Where ws is the future wind speed, $WIND_m$ is the projected change in wind speed, and ws_0 is the current wind speed.

4. Cross correlation verification

A method of demonstrating that the morphing approach is valid and ensuring that the future weather data file has maintained the characteristics of the historic file is to evaluate whether similar relationships occur between the variables in the historic data and those in the future data.

Weather data has been found non-normally distributed, and therefore the Spearman's correlation coefficient has been used to conduct this test. This nonparametric measure of statistical dependence allows to assess how well the relationship between two variables can be described using a monotonic function, with values of +1 or -1 occurring when each of the variables is a perfect monotone function of the other. Table 2 presents the test results from the statistical analysis with correlation significance at the 0.01 level (2-tailed). These results demonstrates that the correlations within the historic data and the future data files are very similar, thus offering confidence on the utilised approach.

Table 2: Spearman's correlation coefficients

	Dry Bulb Temperature and Diffuse Radiation		Dry Bulb Temperature and Global radiation		Dry Bulb Temperature and Relative Humidity	
	Historic	Future	Historic	Future	Historic	Future
Adelaide	.413	.409	.463	.461	-.711	-.703
Brisbane	.546	.555	.565	.576	-.341	-.345
Canberra	.419	.415	.470	.467	-575	-.566
Darwin	.638	.637	.682	.685	-.509	-.526
Melbourne	.462	.453	.508	.498	-.594	-.578
Perth	.434	.432	.511	.509	-.741	-.738
Sydney	.391	.393	.421	.425	-.244	-.244

5. Results and discussion

5.1. Global Circulation Models characteristics

The variations in climate change projections for the seven studied locations are presented in Figure 1 and are relatively large due the different climate zones in which each city is located, ranging from Darwin's humid and warm climate to Canberra's cool temperate climate.

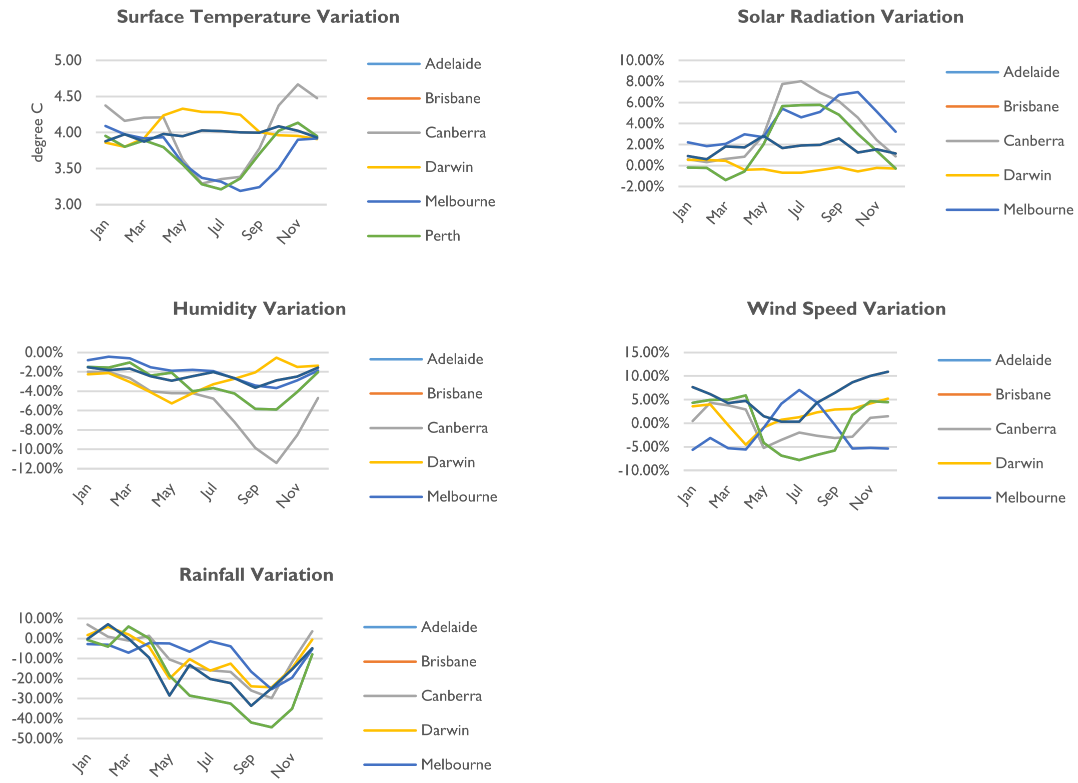

Figure 1: Mean annual variations in surface temperature, solar radiation, humidity, wind speed and rainfall for the 2090s using RCP 8.5 emissions scenario

The mean surface temperature projections obtained from the models range from 3.19° C to 4.67° C, with higher temperatures occurring during the warmer months (October to March) for Melbourne, Perth, Canberra, Adelaide, and Brisbane (see Figure 1). In Darwin, higher temperatures are projected to occur during the winter months and in Sydney, the approximate 4° C increase is projected to remain almost constant throughout the year. Solar radiation is projected to follow the opposite pattern to surface temperature, with solar radiation increasing by up to 8% during winter in Canberra, decreasing by up to 1.37% during summer in Perth, and remaining almost unchanged throughout the year in Darwin. This may be due to changes in cloud cover which will be affected by air temperature. Warmer air usually results in more evaporation, which consequentially means more water vapour and more clouds. The increase in cloud cover during summer means a reduction in solar radiation reaching the Earth's surface, but also a warming effect caused by the clouds trapping some of the heat emitted from the Earth's surface and reemitting it back towards the Earth. Humidity is projected to decrease in a similar way in all studied cities, with Canberra projected to experience a decrease of up to 11% during spring. Rainfall is likely to follow a similar pattern, with projections showing a decrease in precipitation in all cities during most of the year and only slight increases between December and April (expect for Melbourne which is projected to have no increase in rainfall). Lastly, wind speed is projected to variate between -10% and +10% with the variation pattern relatively irregular and different for all cities.

5.2. Changes to dry bulb temperature, and heating and cooling degree days

The results from the morphing process for dry bulb temperature are illustrated in Figure 2, which show the historical and projected annual variations for the studied locations. It can be seen how the projected dry bulb temperature maintains the characteristic of the historic data thus providing further confidence in the morphing approach. Moreover, these changes in dry bulb temperature are likely to have significant impacts on the performance of buildings and occupants' comfort. With the expected rise in temperature and more frequent and severe heat waves, buildings will be subject to increased cooling loads to maintain the indoor environment at thermal comfort levels. Various research has concluded that this variation in air temperature will likely increase the risk of overheating and have serious negative impacts on heating and cooling systems energy requirements (Dodoo et al. 2014; Wang et al. 2010; Williams et al. 2012).

Degree days are a simplified representation of outside air-temperature data, and provide a simplified measure of the heating and cooling required to maintain thermal comfort in the indoor environment and the consequential expected energy consumption. In this study, the changes in heating and cooling degree days in response to climate change are calculated in order to estimate the impacts that a warming climate could have on thermal comfort and energy consumption by the end of the century. Here, the heating and cooling degree days are calculated by counting the number of hours that dry bulb temperature is below 18° C (for heating) and above 25° C (for cooling).

Table 3 presents the heating and cooling degree days obtained from the historic weather data and the future (2090s) weather file. From these results it is possible to establish that the number of cooling degree days increases by between 22 and 95 degree days per annum, while the number of heating degree days decreases by between 2 and 102 degree days per annum. The effects that this variation will have on energy consumption may not be extreme, as increases in cooling energy demand will be partially absorbed by decreases in heating energy demand in most cities. However, this data further demonstrates the higher vulnerability to overheating that buildings in all studied locations are likely to face.

Table 3: Comparison of the heating and cooling degree days between the historic and future weather data

	Cooling Degree Days (above 25° C)		Heating Degree Days (below 18° C)	
	Historic	Future	Historic	Future
Adelaide	36	64	**255**	**155**
Brisbane	**69**	**164**	122	51
Canberra	16	47	286	210
Darwin	287	356	2	0
Melbourne	19	41	296	221
Perth	50	101	199	106
Sydney	29	93	**185**	**83**

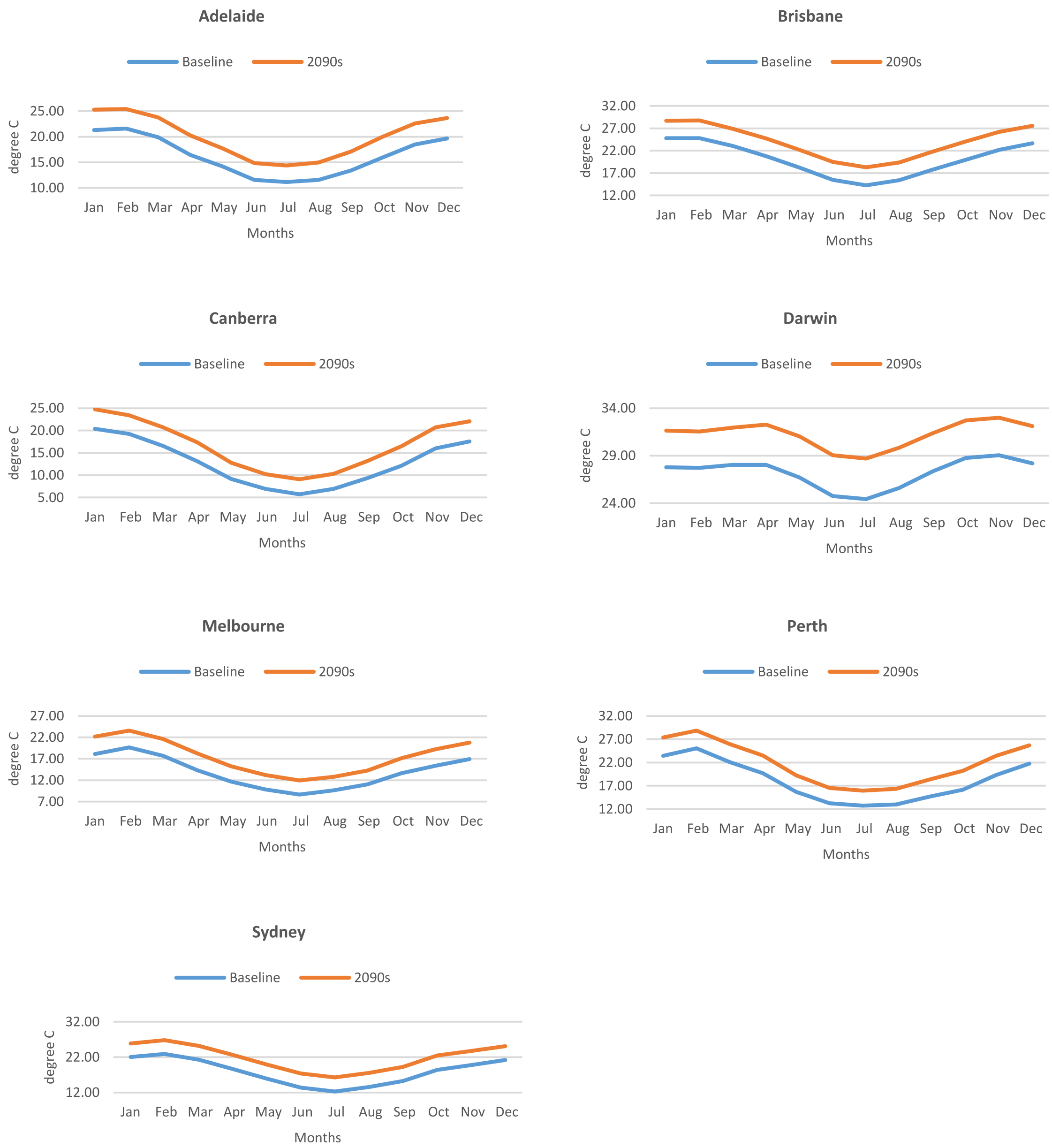

Figure 2: Mean annual historic and projected dry bulb temperature (degree C)

6. Conclusion

This research has developed predicted climate change weather data files incorporating the RCP8.5 scenario for the major Australian capital cities including Sydney, Brisbane, Perth, Darwin, Melbourne, Canberra and Adelaide, representing a diverse range of climates. The improved offset method proposed by Guan (2009) has been used for this study, and has resulted in climate change weather files that maintain the local characteristics of the historic weather data. As a way to demonstrate the accuracy of the future weather data, a cross correlation study has been conducted and demonstrated that similar relationships exist both in the historic weather file and in the future weather file.

This research shows that heating degree days are projected to decrease by 25-100% and cooling degree days projected to increase by 24-221%, depending on location. While the actual energy intensity of building may not vary by much as a result of these changes, the risk of overheating posed by higher temperatures and extended heat waves is significant. When considering that these changes are projected to occur within the lifetime of most buildings constructed today, the design and construction industry faces the new challenge of developing a built environment able to be efficient today and into the future. To achieve this task, it is important that design teams are provided with tools that empowered them to future proof their designs. In this sense, building performance simulation can be a powerful tool to evaluate the effectiveness of design solutions. Critical to the long term success of the design solutions is the ability to address climate change scenarios in the building simulation process.

This research is part A in a two part study. Part B is concerned with the testing of the future weather files generated in this study in building simulation in order to establish actual impacts on a range of buildings and evaluate mitigation strategies that can be included in the design of new buildings.

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