Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 169 (2016) 316 – 323

Procedia Engineering

www.elsevier.com/locate/procedia

4th International Conference on Countermeasures to Urban Heat Island (UHI) 2016

Assessment of Heatwave Impacts

Gertrud Hatvani-Kovacs[a] *, Martin Belusko [b], John Pockett [b], John Boland [c]

[a] *School of Information Technology & Mathematical Sciences, University of South Australia, Mawson Lakes, 5095, South Australia*
[b] *Barbara hardy Institute, University of South Australia, , Mawson Lakes, 5095, South Australia*
[c] *Centre for Industrial and Applied Mathematics, University of South Australia, Mawson Lakes,5095, South Australia*

Abstract

The frequency and intensity of urban heatwaves (UHWs) have been growing worldwide due to climate change and the exacerbating effects of urban heat islands (UHIEs). UHWs have many negative impacts, including excess negative health outcomes (e.g. morbidity), energy (consumption and peak demand) and water consumption. Most studies have evaluated these impacts separately even though there is an interplay between them. The study assessed the daily excess morbidity, energy demand and consumption, and water supply in the Adelaide metropolitan region during heatwaves, between January 2008 and March 2014. The assessment quantifies the thresholds and the increase in each impact relative to temperature increase. The demonstrated negative impacts on public health, and energy and water resources, potentially exacerbated by UHIEs, justify the importance of interdisciplinary research and integrated policy changes on the mitigation of and adaptation to heatwaves.

Peer-review under responsibility of the organizing committee of the 4th IC2UHI2016

Keywords: Heatwave; Electricity demand; Water supply; Morbidity; Resilience.

1. Literature about the Negative Impacts of Heatwaves

Heatwaves have received a growing interest in research on climate change, public health, the built environment and social life recently. The increasing level of attention has been attracted by the media-reported, high number of heat-related fatalities. Heatwaves account for more deaths than all other natural hazards combined in Australia [1].

* Corresponding author. Tel.: +61 8 8302 3789; fax: +61 8 8302 5785
E-mail address: gertrud.hatvani-kovacs@mymail.unisa.edu.au

Peer-review under responsibility of the organizing committee of the 4th IC2UHI2016
doi:10.1016/j.proeng.2016.10.039

Meanwhile, fewer studies have been concerned with other negative impacts of heatwaves such as electricity and water demand. Power outages are triggered by the disproportionally high electricity demand due to air-conditioning during heatwaves. The normalised peak electricity demand is the highest in South Australia (SA) from amongst the Australian States, where the top 30% of electricity demand occurs in less than 2% of the time [2]. During peak demand, the generation costs can rise from a normal \$30/MWh to \$12,000/MWh in the electricity market [3]. Rising electricity prices lead to energy poverty, describing the householders' financial inability to heat or cool their homes to an appropriate level [4]. Extensive air-conditioning by others exacerbates UHIEs and the increasing dependence on air-conditioning raises further concerns based on the assumption that air-conditioning can become addictive [5].

Excess water use due to heatwaves can be detrimental in cities suffering from water scarcity [6], especially in the context of climate change. SA is exposed to water scarcity, facing water management issues now and increasingly in the future [7]. Nonetheless, to our knowledge no study has yet been undertaken about the association between excess water use and heatwaves.

In general, an interdisciplinary approach has been missing from research into heatwaves. This study argues for the importance of understanding the magnitude of heatwave impacts collectively, particularly since morbidity, excess electricity demand and water use are intertwined. For instance, the excess electricity use for air-conditioning has been acknowledged in the literature as a preventative measure against morbidity [8]. Cooling demand can be ameliorated, meanwhile, by the increased irrigation of green spaces resulting in the decrease of urban air temperatures. Such an integrative assessment of negative impacts would be the essential first step towards a more comprehensive evaluation of heat stress resilience. Furthermore, there is a need for predictive capability of heatwave impacts to more efficiently utilise scarce resources. This paper aims to analyse: (1) which weather parameters best predict the magnitude of heatwave impacts and (2) how the sensitivities and thresholds of the impacts are related to heatwaves.

Adelaide, with a population of almost 1.3 million [9] is the capital city of SA. The climate is temperate with hot and dry summer months [10]. The highest normalised heat-related mortality within Australia has occurred in SA since the middle of 19th century [1]. As a city suffering from regular severe heatwaves, the Adelaide metropolitan region was selected for the data analysis.

2. Data Sources and Analyses

The Adelaide metropolitan region was defined according to the current Australian Statistical Geography Standard (Australian Bureau of Statistics 2015b). The water and electricity datasets, therefore, include energy and water used by the built environment during operation and construction, infrastructure, industry and urban agriculture.

The daily number of ambulance call-outs and water supply were obtained from the SA Department for Health and Ageing and the SA Water, respectively, for the time period between 1st January 2008 and 31st March 2014. Research ethics approvals have been granted from the University of SA and the SA Department for Health and Ageing. The electricity demand data at thirty-minute intervals were obtained from the SA Power Network for each substation in the Adelaide metropolitan region and aggregated to calendar days within the same time period. The daily consumption figures were calculated from the half-hourly power demand data, assuming that the demand was constant in that half an hour. The daily weather parameters, collected at the Kent Town station, SA, were obtained from the Australian Bureau of Meteorology. Kent Town station has been widely used as a representative weather station for Adelaide in earlier studies [11,12].

The original daily datasets were decomposed using an additive model comprising of exponential smoothing to eliminate the seasonal changes and longitudinal trends, and Fourier series to deduct the weekly cycles detected. A more elaborate description of the method is available in an earlier study [13]. National public holidays were excluded from the analyses of electricity demand and morbidity because of the significant differences found between public holidays compared to normal days presumably due to the changes in population.

The predictive powers of different weather parameters – daily maximum and mean temperatures (DMaxTs and DMTs) and excess heat factors (EHFs) – were probed and compared in case of the four heatwave impacts, including daily morbidity, electricity demand and consumption, and water supply. The EHF is a metric for heatwave intensity, devised by Nairn et al. [11] and proved to be a better indicator of excess morbidity than other widely used weather parameters in Adelaide [13]. Linear regression with linear and polynomial models, scatterplot, bar and linear diagrams were applied for the analyses. The p values of the regression analyses were statistically significant at $p<0.05$ in the reported results unless specified otherwise. Three different heatwave definitions were tested to show their predictive powers in differentiating heatwave days with excess impacts from normal days. The definitions included; days with positive EHFs, days with DMaxTs above 35°C and three days in a row with DMaxTs above 35°C. Based on the associations found, the magnitudes of excess impacts were calculated. The sensitivity of electricity consumption and peak demand and water supply were derived from the regression relationships as undertaken in earlier studies [14,15].

3. Heatwave Intensities and Impacts

3.1. Longitudinal and seasonal changes in heatwave impacts

Adelaide has long and hot summers with 45.7°C as the maximum temperature that has been recorded at the Kent Town station since its opening in 1977. On average, 16 heatwave days (calculated as days with positive EHFs) and 28 days with DMaxTs above 35°C occurred annually within the investigated time period. The winters are relatively mild, with an average daily mean temperature of 11.98°C.

The close link between electricity load and climate is acknowledged in the literature [16,17]. The local climate pattern is reflected in the electricity demand and consumption. The summer is the critical period in terms of peak electricity demand because of the cooling demand. Meanwhile, the daily total electricity consumption in winter months very slightly overtakes the consumption in summer months because of heating (Fig. 1).

Investigating the changes across years within the studied period, both the highest annual average of daily electricity peak demand and mean consumption were encountered in 2009 with a decline since then. The decrease in peak demand can be partially attributed to the gradual penetration of solar panels since 2006. The normalised operation demand curve graphed for Adelaide between 2008 and 2013 showed a slightly better case than the curve for whole SA reported earlier for the financial year 2010-11 [18]. Approximately the top 22% of the peak electricity demand was used in 2% of the time in Adelaide, compared to the reported top 30% of the peak electricity load used in 2% of the year in SA [18]. The associations between annual averages of daily electricity demand, consumption and weather parameters are not visible, even though local weather influences electricity use.

Similar to the electricity demand, the annual average daily water supply significantly changed during the investigated period. A gradual decrease has occurred since 2003 thanks to the permanent water restrictions introduced in SA to manage the Australian Millennium Drought [7]. The restrictions applied for the Adelaide metropolitan region between 1 July 2003 and 1 December 2010 resulted in more than 30% reduction in water consumption per household from 2003 to 2008 [7]. In 2010, the more lenient, yet permanent Water Wise Measures replaced the earlier water restrictions. Regardless of these external factors, the annual average of daily water supply is strongly related to weather parameters, particularly to the annual average of DMaxTs. Consequently, water supply peaks in January and is the lowest in June and July.

An increase was found within the investigated time period in the annual average of daily number of ambulance call-outs that can be attributed to changes in population, such as the ageing and growing of population. No apparent associations exist between annual average of daily morbidity and weather. Compared to countries in colder climates,

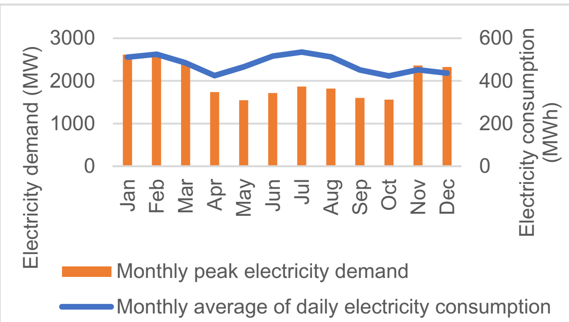

Fig. 1. Monthly changes in peak electricity demand with electricity consumption superimposed

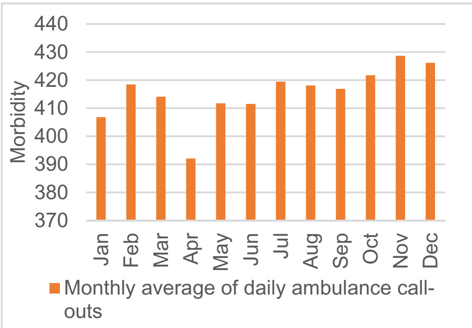

Fig. 2. Monthly changes in morbidity

the inter-season peak in Adelaide occurs in early summer, with a secondary hump in the middle of winter (Fig. 2). The relatively low number of ambulance call-outs occurring in January can be attributed to the holiday season in Australia.

3.2. Associations between heatwave impacts and weather

A very weak association exists between daily morbidities and weather parameters considering all days of the investigated years, with the strongest significant connection found with DMaxTs (adjusted $R^2 = 0.04$). In contrast with morbidity, daily electricity power and water supply showed strong relationships with DMaxTs (adjusted $R^2 = 0.63$, and 0.78, Fig. 3 and Fig. 4 respectively). The associations were the same or weaker with DMTs and EHFs, particularly when only heatwave days were investigated. The daily electricity consumption was most closely related to the DMTs (adjusted $R^2 = 0.55$).

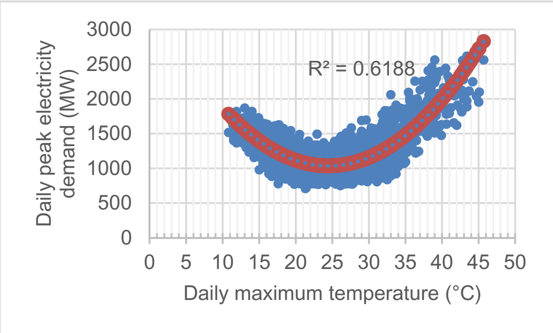

Fig. 3. Daily peak electricity demand plotted against daily maximum air temperatures

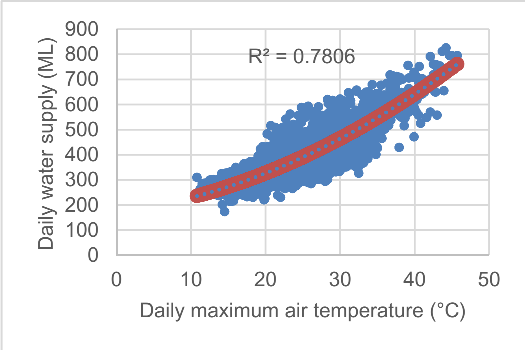

Fig. 4. Daily water supply plotted against daily maximum air temperatures

The excess demand in electricity and supply in water were calculated based on the strong associations found with daily temperatures. The daily maximum electricity demand was grouped by the DMaxTs in 2°C intervals (Fig. 5). Heatwave days comprised 6.61% of the days between 2008 and 2013, considering heatwave days as days with DMaxTs above 35°C. More than one-fifth (21.18%) of peak demand occurred only on heatwave days. If we compare this result with the earlier reported normalised operational demand curve, heatwaves seem to account for only a part of the top of annual peak demand. However, this result might also show that DMaxTs cannot perfectly differentiate days with excess electricity demand due to heatwaves from normal summer days. To our knowledge, no study has presented before the excess electricity demand due to heatwaves at an urban scale in Australia, even though many studies have been undertaken globally [19]. The average increase in electricity demand and in consumption were 6.35% and 5.62% per one-degree increase in daily maximum and mean temperatures, respectively. The electricity penalty in electricity demand for the whole city is higher than any reported in a recent international literature review, while in electricity consumption it is in the middle range of the reported figures [19]. This corresponds to a penalty in peak demand of 50.87 W per degree of temperature rise per person. The comparison demonstrates, how much the disproportionate peak electricity demand in Adelaide is above the worldwide average.

Changes in daily water supply per 2°C were graphed as the next step (Fig. 6). Almost one-fifth (19.18%) of peak water supply occurs only on heatwave days. The penalty in water supply for the whole city was 5.13% for each one-degree increase in daily maximum temperatures, compared to the baseline consumption in July. Although this penalty is similar to the figures related to the electricity demand and consumption, this negative aspect of heatwaves has not yet been covered by the literature. Nevertheless, note that peak demand management is much easier in case of water than electricity.

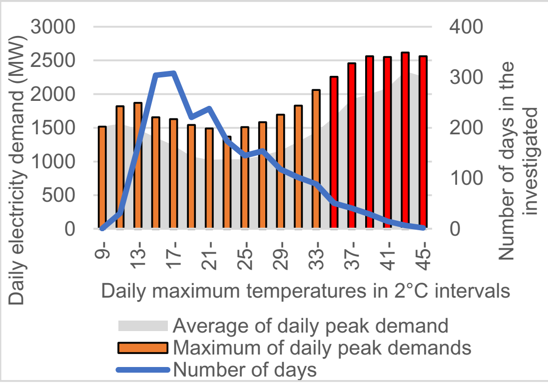

Fig. 5. Daily peak electricity demand grouped in 2°C intervals with the number of days superimposed for different daily maximum temperatures

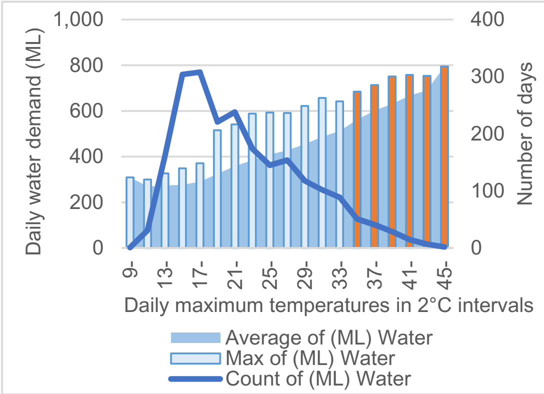

Fig. 6. Daily water supply grouped in 2°C intervals with the number of days superimposed

3.3. Associations between daily anomalies and weather

After the decomposition of the original datasets, the association between the resultant daily anomalies and weather parameters were analysed. The EHF was found to be a significantly better indicator of excess morbidity than DMaxT or DMT in an earlier study [13]. The predictive power of EHFs was the best (adjusted $R^2 = 0.77$) on days with EHFs above 40°C^2, however weaker on all days with positive EHFs (adjusted $R^2 = 0.36$) [13]. In contrast, anomalies in daily electricity demand and water supply were the strongest associated with DMaxTs on days with positive EHFs (adjusted $R^2 = 0.75$, Fig.7 and 0.58, Fig. 8 respectively). Note that only the association with anomalies in electricity demand is stronger than the association with the original datasets before decomposition. The explanation for this result is that most of the inter-season variability were modelled and eliminated by the exponential smoothing. It is important to note that exponential smoothing could capture only the climate-triggered changes, while residuals reflect the variability triggered by extreme weather events such as heatwaves. To analyse the impacts of heatwaves and not the climate, anomalies seem to be more suitable.

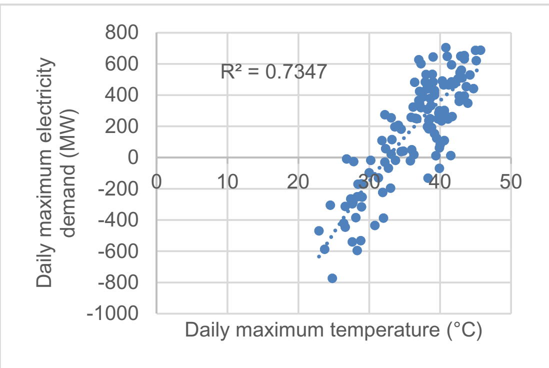

Fig. 7. Scatter plot diagram of daily anomalies in peak electricity demand plotted against daily maximum air temperatures on days with excess heat factor above zero.

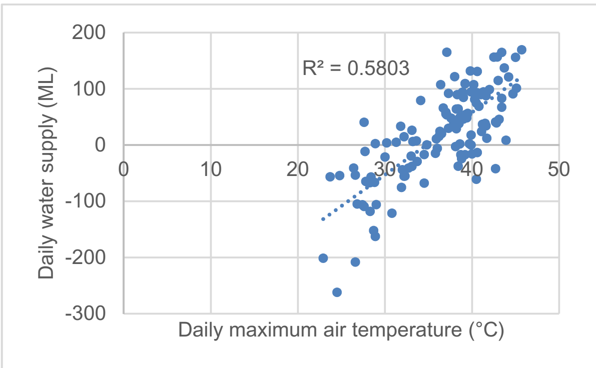

Fig. 8. Scatter plot diagram of daily anomalies in water supply plotted against daily maximum air temperatures on days with excess heat factor above zero.

The relatively poor performance of EHFs in predicting the excess electricity demand and water supply could be expected on the basis that the EHF was devised to predict excess health incidences. The question still remains why positive EHFs better differentiate days with excess electricity demand and water supply due to heatwaves than the DMaxT threshold. Note, that the EHF accounts for the period of time available for acclimatisation and the amplified impact of the lengths of heatwaves on human body. Acclimatisation refers to both the biological acclimatisation of the body and the extended time necessary for adaptation, reflected in the acclimatisation index [11]. The EHF is the product of the acclimatisation and the significance indices, where the later reflects the long-term weather anomalies compared to the climate [11]. Both indices are based on the mean temperature of a three-day-long period. Consequently, they affect the differentiation of heatwave days from normal summer days. For example, three consecutive days above the DMaxT threshold would be out-of-phase with days with positive EHFs. Since both electricity power, driven by the cooling demand, and water use are important sources for adaptation, they might coincide with positive EHF values, even if not with their magnitudes. This result reflects earlier studies on electricity and water use and temperature, where temperatures of preceding days affected the consumption on the designated day [14,16,20].

3.4. Thresholds of heatwave impacts

As the next step, temperature thresholds of heatwave impacts were calculated. An earlier study showed that the positive EHFs better differentiated heatwave days with excess morbidities from non-heatwave days than DMaxTs and also better predicted excess morbidities [13]. The DMaxT was, nevertheless, used in this paper to make the anomalies in morbidity comparable with anomalies in the other two investigated impacts. Warmer months between 1 October and 31 March were considered in the analyses as in an earlier study about excess morbidity in Adelaide [12].

In excess morbidity, daily anomalies shifted from negative to positive at 28°C (Fig. 9). An earlier study from Adelaide reported 26°C, daily maximum temperature, as a turning point for excess ambulance call-outs, with notable excess morbidity occurring only above 28°C [12]. Fig. 10 and Fig. 11 demonstrate that peak demand shifted from negative to positive at 30°C followed by the electricity consumption at 32°C.

The anomalies in daily water supply approached zero on days with DMaxT at 28°C with a notable positive excess anomalies appearing at and above 30°C (Fig. 12).

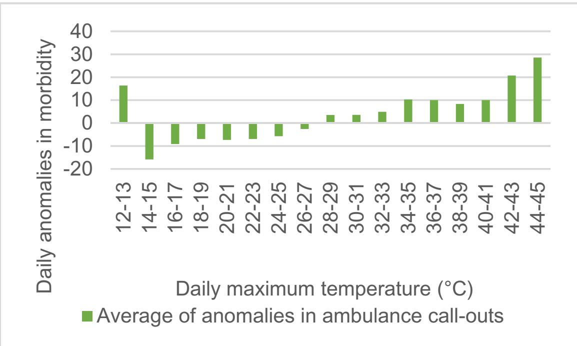

Fig. 9. Average daily anomalies in morbidity grouped in 2°C intervals

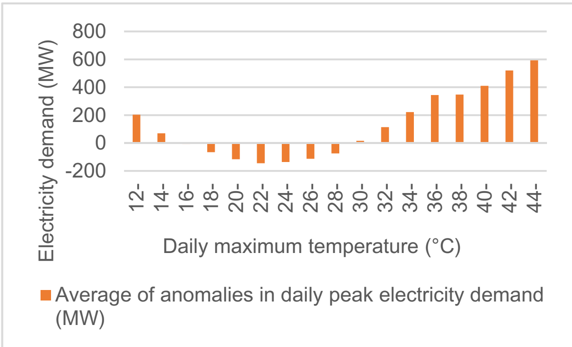

Fig. 10. Average daily anomalies in peak electricity demand grouped in 2°C intervals

To summarise, the anomalies in the number of excess ambulance call-outs and water supply shift from negative to positive at 28°C, followed by the electricity demand at 30°C and electricity consumption at 32°C. These results can be interpreted that among the two sources of adaptation, excess water use occurs slightly sooner than excess electricity use at a metropolitan scale. The found adaptation thresholds between 28°C and 32°C coincide with a recent empirical study from Adelaide [21], in which the changes in outdoor behaviour occurred above the threshold of apparent temperature between 28°C and 32°C. Note that apparent temperatures, considering wind speed and relative humidity, can differ from air temperatures by 0.6°C on average between 24°C and 34°C in the climate of Adelaide.

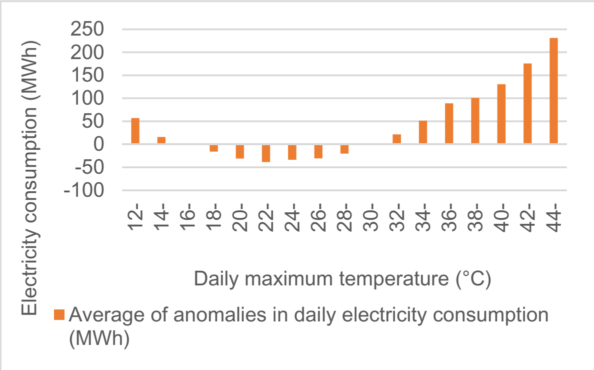

Fig. 11. Average daily anomalies in electricity consumption grouped in 2 °C intervals

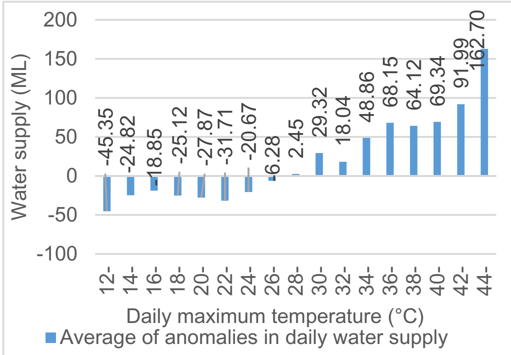

Fig. 12. Average daily anomalies in water supply grouped in 2 °C intervals

4. The Interplay of Heatwave Impacts

The interplay between heatwave impacts and weather parameters were investigated. Different weather parameters were found to better predict different heatwave impacts. Electricity demand and water supply can be best predicted by DMaxTs, while EHFs better predict excess morbidity. Consequently, for the time being, there is no one weather parameter that could be used to measure the negative impacts of heatwaves and to evaluate comprehensively the heat stress resilience of a city. The analysis demonstrated that although energy demand and water supply are more dependent on weather than morbidity, the associations are weaker on the most extreme heatwave days. This difference can be attributed to the fact that both energy and water use are capped by institutional deterrents and bans (water restrictions, industrial heatwave management) and structural inhibitors (power outages).

While the daily energy and water supply peak simultaneously with the daily maximum temperatures, heat-related morbidity lags behind by one or two days. One of the explanations is that adaptation using additional electricity and water help to avoid or minimise excess morbidity. Future research should attempt to discover the changes in heatwave impacts according to the heatwave intensities at a household scale and exclude the changes in industrial energy and water use.

Differing turning points from negative to positive were found in the daily anomalies of different heatwave impacts. Adaptation using excess energy and water became notable between 28 and 32°C at the city scale, only following to the first excess morbidity cases occurring at 28°C.

This paper demonstrates the critical role of heatwaves in urban facility design and management. Heatwaves were found to be responsible for more than and almost one fifth of the yearly electricity demand and water supply, respectively. These findings demonstrate that heatwaves put a great pressure on the infrastructure of not just electricity but also water. The development of heat stress resistant built environments and water-sensitive urban design would be necessary to counteract the negative impacts of heatwaves and to create heat stress resilient cities.

Acknowledgement

This study was supported by a grant from the Cooperative Research Centre for Low Carbon Living as part of the project, called Urban Micro Climates: Comparative Study of Major Contributors to the Urban Heat Island (UHI) in three Australian cities; Sydney, Melbourne and Adelaide.

References

[1] L. Coates, K. Haynes, J. O'Brien, J. McAneney, F.D. De Oliveira, Exploring 167 years of vulnerability: An examination of extreme heat events in Australia 1844–2010, Environ. Sci. Policy. 42 (2014) 33–44.

[2] Energy Networks Association, Demand Management Regulatory & Policy Framework, (2008). http://www.aemc.gov.au/getattachment/01a161b5-7185-411d-80a0-3893e2ebba25/Energy-Networks-Association-(1).aspx (accessed January 14, 2016).

[3] R.R. Dickinson, J.J. Parham, G.G. Nathan, H. Adelaide, Responding to Peak Electricity Loads Using Renewable Fuel, in: CHEMECA, Adelaide, Australia, 2010: pp. 26–29. https://digital.library.adelaide.edu.au/dspace/handle/2440/61550.

[4] M. Santamouris, D. Kolokotsa, On the impact of urban overheating and extreme climatic conditions on housing, energy, comfort and environmental quality of vulnerable population in Europe, Energy Build. 98 (2014) 125–133. doi:10.1016/j.enbuild.2014.08.050.

[5] C. Cândido, R. de Dear, R. Lamberts, L. Bittencourt, Cooling exposure in hot humid climates: are occupants "addicted"?, Archit. Sci. Rev. 53 (2010) 59–64. doi:10.3763/asre.2009.0100.

[6] N. Tapper, Adapting Urban Environments to Climate Change: A Case Study of Melbourne Australia, in: Sch. Sustain. Dev., Springer, 2012: pp. 185–198.

[7] Government of South Australia, Water for good- A plan to ensure our water future to 2050, (2010) 194. http://www.google.com.au/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=0ahUKEwjVzITbv6PKAhXHHaYKHb1OBYIQFggnMAE&url=http%3A%2F%2Fwww.environment.sa.gov.au%2Ffiles%2Fsharedassets%2Fpublic%2Fwater%2Fwater-for-good-full-plan.pdf&usg=AFQjCNFu_fT4Fo7GeruJWRh9RT (accessed January 5, 2016).

[8] J. a. Patz, H. Frumkin, T. Holloway, D.J. Vimont, A. Haines, Climate Change Challenges and opportunities for global health, Jama. 312 (2014) 1565. doi:10.1001/jama.2014.13186.

[9] Australian Bureau of Statistics, Population trends and estimates, Commonwealth of Australia, (2015). http://www.abs.gov.au/ausstats/abs@.nsf/ViewContent?readform&view=productsbyCatalogue&Action=Expand&Num=3.2 (accessed April 16, 2015).

[10] M.C. Peel, B.L. Finlayson, T.A. McMahon, Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci. 11 (2007) 1633–1644. http://www.scopus.com/inward/record.url?eid=2-s2.0-35348859178&partnerID=tZOtx3y1.

[11] J.R. Nairn, R.G. Fawcett, The excess heat factor: a metric for heatwave intensity and its use in classifying heatwave severity., Int. J. Environ. Res. Public Health. 12 (2015) 227–53. doi:10.3390/ijerph120100227.

[12] S. Williams, M. Nitschke, T. Sullivan, G.R. Tucker, P. Weinstein, D. Pisaniello, et al., Heat and health in Adelaide, South Australia: Assessment of heat thresholds and temperature relationships, Sci. Total Environ. 414 (2012) 126–133. http://www.sciencedirect.com/science/article/pii/S0048969711013520.

[13] G. Hatvani-Kovacs, M. Belusko, J. Pockett, J. Boland, Can the Excess Heat Factor indicate heatwave-related morbidity? A case study in Adelaide, South Australia, Ecohealth. 13(1) (2015) 100–110. doi:0.1007/s10393-015-1085-5.

[14] A.F. Colombo, D. Etkin, B.W. Karney, Climate variability and the frequency of extreme temperature events for nine sites across Canada: Implications for power usage, J. Clim. 12 (1999) 2490–2502. doi:10.1175/1520-0442(1999)012<2490:CVATFO>2.0.CO;2.

[15] S.J. Parkpoom, G.P. Harrison, Analyzing the Impact of Climate Change on Future Electricity Demand in Thailand, Power Syst. IEEE Trans. 23 (2008) 1441–1448. doi:10.1109/TPWRS.2008.922254.

[16] A. Pardo, V. Meneu, E. Valor, Temperature and seasonality influences on Spanish electricity load, Energy Econ. 24 (2002) 55–70. doi:10.1016/S0140-9883(01)00082-2.

[17] L. Magnano, J.W. Boland, Generation of synthetic sequences of electricity demand: Application in South Australia, Energy. 32 (2007) 2230–2243. doi:10.1016/j.energy.2007.04.001.

[18] Australian Electricity Market Operator, Electricity Statement of Opportunities 2011-Complete document, (2011) 1–323. http://www.aemo.com.au/Electricity/Planning/Archive-of-previous-Planning-reports/Electricity-Statement-of-Opportunities-2011 (accessed January 16, 2016).

[19] M. Santamouris, C. Cartalis, A. Synnefa, D. Kolokotsa, On The Impact of urban heat island and global warming on the power demand and electricity consumption of buildings–a review, Energy Build. 98 (2015) 119–124. doi:10.1016/j.enbuild.2014.09.052.

[20] S.L. Zhou, T. a. McMahon, A. Walton, J. Lewis, Forecasting daily urban water demand: A case study of Melbourne, J. Hydrol. 236 (2000) 153–164. doi:10.1016/S0022-1694(00)00287-0.

[21] E. Sharifi, A. Sivam, J. Boland, Resilience to heat in public space : a case study of Adelaide, South Australia, J. Environ. Plan. Manag. (2015). doi:10.1080/09640568.2015.1091294.