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Concept Paper

Retrofitting Precincts for Heatwave Resilience: Challenges and Barriers in Australian Context

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Abstract: As the frequency and intensity of heatwaves are growing in Australia, strategies to combat heat are becoming more vital. Cities are exposed to urban heat islands (UHIs) due to excess urbanisation. In this study, a definition of urban heatwave (UHW) is conceptualised to investigate the combined impacts of heatwaves and UHIs. To quantify the negative impacts of UHW, indicators—such as excess morbidity, electricity and water consumption—are considered. The intensity of UHWs is calculated using the unit of excess heat factor (EHF), developed by the Australian Bureau of Meteorology. EHF enables the comparability of UHWs in different geographical locations. Using the indicators and the intensity of UHWs, a calculation method to quantify heatwave resilience at a precincts scale is proposed. The study summarises the assumed influential factors of precinct heatwave resilience based on the existing literature and propose a "cool retrofitting toolkit" (CRT). CRT creates the framework to assess the adaptation to and mitigation of UHWs available to retrofit existing precincts, and to evaluate potential retrofitting strategies in terms of energy and carbon efficiency, financial affordability and perceived acceptability by population. This study illuminates the importance of climate, function, built environment and population characteristics-conscious retrofitting.

Keywords: urban heatwave indicators; retrofitting toolkit; heatwave resilience; heatwave perception; precinct; adaptation; mitigation; adverse health outcome; Australian cities

1. Introduction

The "Fifth Assessment Report" of the Intergovernmental Panel on Climate Change noted the continuous increase of global mean surface temperatures since the late 19th century [1]. The risk of climatic extremes is also growing as a consequence of increased greenhouse gas emissions caused by human activities [2]. These emissions will potentially raise the overall temperature in Australian cities by up to 1.2 ℃ by 2030, up to 2.2 ℃ by 2050 and up to 3.4 ℃ or more by 2070 [3].

As a result of dramatic worldwide urbanisation, 50.5 per cent of the global population lived in cities in 2010; it is predicted that 70 per cent of people will be urban residents by 2050 [4]. Urbanisation has negative impacts that reduce significantly both the efficiency and liveability of cities. The urban heat island (UHI) is one of the adverse impacts caused by urbanisation and is defined in the discernible temperature difference between urban and rural areas [5]. The phenomenon is ascribed to the combination of inappropriate use of building and urban materials, urban morphology, the lack of urban vegetation, the extensive coverage of the stormwater sewage network, anthropogenic heat generation, altered wind patterns and increased air pollution in cities [5,6].

Both global warming and UHIs contribute to the development of urban heatwaves (UHWs). The inhabitants of urbanised areas suffer from heatwaves more than their rural counterparts due to the urban heat island effect and the lack of adaptive opportunities in urban environment [7]. People living in cities are dependent on the civilised world's facilities, such as air-conditioning, cooled water, artificial lighting in shaded offices and the reliance on private car use. However, by using these technologies, citizens increase significantly the generation of anthropogenic waste heat and carbon emissions; all of these contribute to the urban heat island [5] and global warming. Since citizens not only contribute to, but are also the victims of, UHIs, they are at the centre of a feedback loop; as more energy and water are consumed, even more waste heat and air pollution are generated [8]. Therefore, human beings play a major role in this cycle.

In particular, Australia is exposed to UHWs due to its high-degree of urbanisation; in 2014, 89 per cent of Australians lived in cities [9]. Moreover, in Australia, heatwaves were responsible for more deaths than all the other natural hazards combined [10]. The mortality rate related to heatwaves is predicted to double in the next forty years [11]. The detrimental impacts of heatwaves on cities and their inhabitants have been researched widely in regard to mortality rate increases and health impacts [12,13]. Fewer studies have been conducted on the severe, but not fatal, risks of heatwaves—segregation, reduced public space usage and crime [14]. The interplay of socioeconomic factors and UHWs is a new and emerging topic of research.

Since heatwaves vary with climate and latitude, a globally congruent definition has not been accepted [15,16]. However, heatwaves can be generally defined as a period of consecutive days with extremely high temperature. As an example, in Adelaide, the term heatwave refers to five consecutive days with at least 35 ℃ or above, or three consecutive days at least 40 ℃ or above [17] A globally adaptable definition of heatwaves and a new unit called excess heat factor (EHF) have been introduced recently by Nairn and Fawcett [15,16]. According to their study, an alarming rise in the frequency, magnitude and length of heatwaves is predicted [15]. As a result, mitigation techniques for and human adaptation to extreme weather conditions, in the built environment, are increasingly a subject of concern.

The ultimate goal of this paper is to summarise the principles of an evaluation tool for potential retrofitting techniques against heatwaves at precinct scale, considering cost—and energy efficiency and the location—and precinct-specific characteristics. As the first step, a framework is proposed to quantify precinct heatwave resilience, and to identify the subject of concern, such as resilience in energy, water or health. The paper also aims to summarise the most important precinct characteristics influencing heatwave resilience. The knowledge of heatwave resilience and its main drivers enable the creation of an evaluation tool for different retrofitting strategies.

2. Literature Review on Urban Heatwave Resilience

2.1. Urban Heatwaves; Causes, Consequences and Measures

The frequency and intensity of heatwaves in Australia and internationally are rising [15,18]. During summer, heat stress is exacerbated in cities because urbanisation plays an important role in global warming and the development of urban heat islands [19,20]. Consequently, weather-related health problems and costs are arising from increased energy and water demand, endangered ecosystem and social life are of growing concern (see Figure 1), [21].

Urban heat islands are attributed primarily to a lack of vegetation and permeable surfaces, the widespread use of building materials with low albedo value (low reflectivity), changes of land use patterns, disadvantageous urban form, high urban density, air pollution, and altered wind patterns [5]. While the contribution of these factors to urban heat islands is established, its degree of influence in the creation of UHIs is still under discussion due to differences in climatic, geographic and urban characteristics across the world [22–24]. Furthermore, mitigation techniques, such as green and cool roofs, can not only counteract the climatic effect of cities but also decrease the impacts of global warming [24], hence consequently the frequency and intensity of heatwaves.

Therefore neither the causes nor the consequences of UHIs can be investigated separately from heatwaves. Heatwaves pose heat stress on cities; while urban heat islands exacerbate conditions in urbanised areas. Therefore, the impacts of UHIs and heatwaves will be handled together in this study as the impacts of UHWs (see Figure 1). The negative consequences can be classified in three main groups, namely the endangered ecosystem, urban system and social life.

To measure the intensity of UHW, EHF is applied. The definition of a heatwave varies across Australia and around the world due to climate differences. Consequently, no globally accepted definition exists at the time of writing [15,25]. Despite the diverse definitions of heatwaves, in the different Australian cities, a clear interpretation was applied at the beginning of the research. A new unit named “excess heat factor” was introduced by Nairn and Fawcett (2013) to stipulate the intensity of heatwaves. The unit depends on the following two variables: “excess heat” and “heat stress” (see Equation 1).

$$EHF = EHIsig \cdot \max(1, EHIaccl) \tag{1}$$

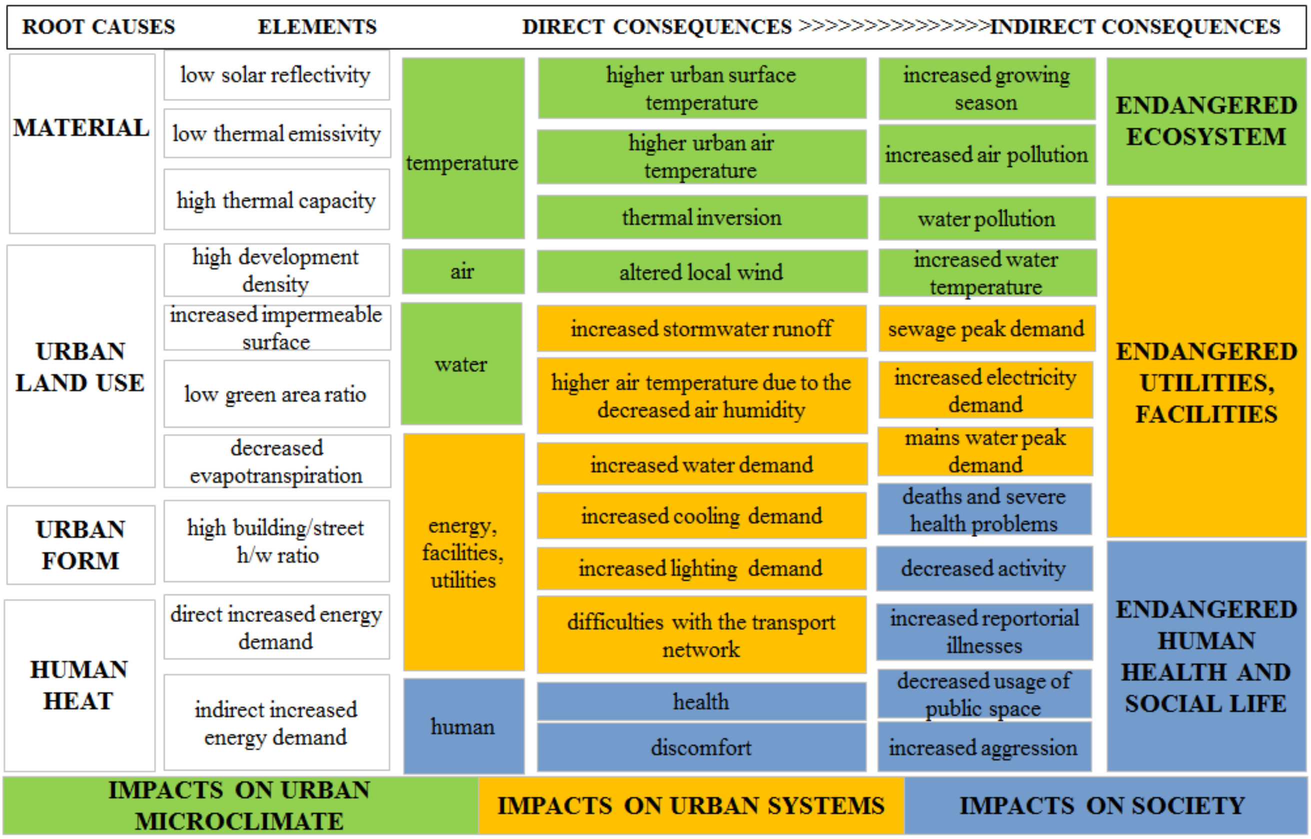

Figure 1. The indicators and impacts of urban heatwaves (UHWs).

Here EHF refers to the "excess heat factor", EHI_{sig} is the "excess heat", and EHI_{accl} is the "heat stress". "Excess heat" means the daily mean temperature (DTM) during a heatwave compared to the average value for that particular climate. "Heat stress" determines the ratio of the three-day DMT during heatwaves compared to the preceding 30 days, while "excess heat" is the ratio of the three-day DMT during heatwaves compared to the 95th percentile of the preceding 30 years. The function of "heat stress" provides the opportunity to consider the adaptation capacity of people, while "excess heat"—accounting for the people's acclimatisation level—creates a relative heatwave intensity compared to the local climate. Although any result above zero indicates a heatwave [16], a severe heatwave occurs only when the EHF threshold is significantly exceeded [15]. The application of the daily mean temperatures instead of the daily maximum temperatures highlights the importance of daily minimum temperatures during heatwaves, which are assumed to be key indicators of the mortality and morbidity rates. The calculation is proven through the direct correlation presented between EHF index changes and mortality rates during the heatwaves in South Australia in 2009 [16] and globally [15]. The EHF opens new opportunities for studies in the field of heatwave vulnerability. Since the explicit interpretation of heatwaves in recent vulnerability studies, such as studies from Phoenix and Athens [25,26] are quite rare and so far limited their comparability.

2.2. Social Interplay of Heatwaves

The formation and consequences of UHWs, as presented in Figure 1, shows how people are both indicators of and effected by the development of urban heat islands. The urban population is an important contributor to UHIs through waste heat generation. The primary catalysts of waste heat are attributed to increased traffic and the air-conditioned buildings [27]. Air-conditioning significantly raises not only cooling energy consumption [28]—for instance nearly doubling the cooling demand of a simulated reference building in the centre of Athens compared with the result if the same building was located in the suburban region—but also the urban mean air temperature [27]. Another study conducted about office buildings in Adelaide central business district (CBD), demonstrated that the cooling demand increased by between 20% and 48% during a heatwave event in 2009, compared to the reference weeks before and after the heatwave days [29]. The risks of UHWs to people include detrimental impacts on social life, health issues, excessive dependence on fossil fuels, and increased strain on public urban infrastructure. For example, peak electricity demand during summertime causing electricity blackout [14]. Despite the obvious human role in the creation of UHWs the majority of ongoing relevant research neglects socioeconomic variables and human behaviour factors. Due to the complex interplay between urban microclimates, built environment and their inhabitants a multi-disciplinary approach is needed to assess the indirect risks of UHWs [30].

2.2.1. Population Related to Suburban and City Centre Urban Heat Islands

The first UHI research to address the socioeconomic characteristics integrated the size and density of urban population as anthropogenic heat indicator. Relevant studies have acknowledged widely the correlation between size and density of population and UHIs [5,23,31]. Oke claimed that a notable UHI, of at least 1–3 °C temperature difference between urban and rural areas, can develop only in cities with a minimum population of one million inhabitants [32]. In contrast, Torok noted that significant UHI effects still occurred in smaller Australian towns with populations of less than 10,000 residents. In all cases, the approximate increase of UHIs was in proportion with the logarithm of urban populations [33].

As a direct consequence of population density and urban density, the relevant research agrees that the intensity of UHIs is higher in the city centre than in the suburbs (see Figure 2).

However, this statement is not valid for all cities. For instance, the magnitude and intensity of UHIs in Australian cities, such as Sydney are greatly influenced by the sea breeze [34], the relatively low population density and the local climatic condition, because of the immense extension of the metropolitan region. Furthermore, with the inclusion of human variables, such as heatwave perception and social vulnerability that hypothesis is also debatable in two respects. Firstly, an UHI is characterised by a double-humped graph. The first peak is the maximum surface temperature reached in the early afternoon. The second peak is the maximum air temperature that occurs in the late evening [32] or the early morning depending on the climate and weather. Therefore, during the second peak hours of an UHI, inhabitants are located mainly in the suburbs instead of the CBD. Secondly, most socially vulnerable people tend to live outside of the CBD in Australia, indicating often the suburban districts" higher susceptibility to heat stress [13]. The above argument about suburban heatwave vulnerability has been addressed, internationally only in the last decade. Also the highest number of emergency calls due to heatwaves occurred in the CBD of Chicago and its vicinity between 2003 and 2006. However, health-related dispatches were not restricted to the CBD but were also scattered in the suburbs [35]. Another study from Detroit, Michigan, US demonstrated that finer scale local weather data would foster a better prediction of heatwaves and the associated morbidity [36], due to the detectable temperature differences across the metropolitan region. Furthermore, the varying distribution of the population in different Australian cities [31] and the Australian suburban city centres with high population densities implies detectable UHI intensity in the suburbs. Therefore, further UHI research focusing on the suburbs local climatic factors and calculating with the density of population exposed indeed to the heatwave is warranted.

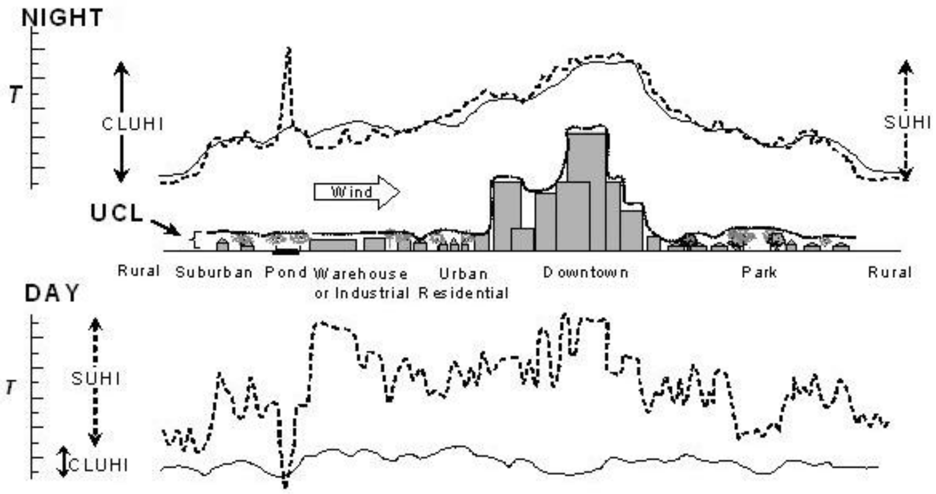

Figure 2. Theoretical magnitude of an urban heat island (UHI) on a city section adopted from Voogt [37].

2.2.2. The Risk of Vulnerability to Heatwaves

The risks associated with climate disasters are classified as event risk and outcome risk. The first investigates the frequency of climate extremity, such as heatwaves. The second covers the frequency of social and economic impacts of weather extremes. Comparing the two, event risks are relatively quantifiable; whereas, outcome risks are influenced by miscellaneous circumstances. To define outcome risks it is necessary first to determine the vulnerability threshold [38].

Vulnerability is the likelihood of being adversely affected [39]. The risk of vulnerability depends on the likelihood and the severity of the event [38] and is also influenced by social, historical and economic factors [39]. The mortality rate is the most widely used tool to evaluate the vulnerability of the urban population. In Australia, heatwaves between the early 1880s and 1990s caused almost twice the number of deaths—more than 4287—than the second most damaging climatic extreme, tropical cyclone [10]. However, only a small number of heatwaves causes death or severe health problems [15]. In mortality data for heatwaves between 1993 and 2004, there was no detectable increase found in the Adelaide metropolitan region [40]. Therefore, the morbidity, such as hospital emergency admissions and number of ambulance call-outs, seems to yield more reliable information on vulnerability than the mortality rate [40].

Several demographic and socioeconomic factors are assumed to exacerbate vulnerability to heatwaves. Firstly, vulnerability increases with age and is higher among older people [41] and young children [10]. Socially isolated residents are exposed to higher risk and include: people living alone, those who have immigrated recently, or who have moved interstate [13]. Diagnosed, pre-existing health conditions and disability also increase people's sensitivity to extreme heat. Further characteristics that influence vulnerability adversely include: lower income neighbourhoods with higher rates of ethnicity, crime and unsafe building and transport conditions [10,14]. Gender discrepancies are highly debated as the current findings are contradictory [10,21]. Furthermore, the types and locations of activities undertaken during heatwaves have a detectable effect on vulnerability [10]. For instance, Hansen *et al*., in 2011 found the highest number of ambulance calls in industrial areas within the Adelaide metropolitan region that may indicate the vulnerability of workers during heatwaves. Also an unexpected high number of events occurred near to the beaches and that underpins the importance of real daytime population data [42].

In recent years two different approaches have emerged to depict the spatial distribution of vulnerability mapping. The first approach investigates the link between socioeconomic factors and surface or air temperature [43–45]. It is commonly believed that disadvantaged groups live in hotter areas of the city because they are more likely to live in higher density areas and cannot afford the maintenance of green spaces [46]. The second uses socioeconomic factors to highlight the correlation between the mortality or morbidity rate and surface or air temperature [26,47].

The fundamental assumption in most vulnerability mapping studies is that urban surface temperatures can be applied to identify the hot spots in the urban area. However, the usage of surface temperature derived from satellite imagery is questionable because the vertical surface temperature, which can be absolutely relevant to human heat perception, is excluded in satellite imagery and rooftops dominate the thermal imagery. Therefore, the resulting mean surface temperature does not reflect the air temperature in the built environment [5] and its impact on human heatwave perception is less informative than air temperature's. Other vulnerability studies used minimum and maximum surface near air temperature [45], daily mean temperature and apparent temperature [13]. However, these studies still calculated with one station's dataset in the CBD, overlooking the significant temperature difference across the metropolitan regions. The importance of location-specific weather data in relation to accurate building energy modelling was also demonstrated by a study conducted in London [48].

These findings imply that vulnerability mapping needs to incorporate further to the demographic and urban characteristics, location-specific air temperature data and characteristics of the built environment in cities to help with the creation of reliable heatwave mitigation and prevention plans.

2.2.3. Thermal Perception in Terms of Physical, Physiological and Psychological Factors

Human vulnerability to heatwaves is influenced not only by physical factors, such as ambient air temperature, wind chill and humidity, but by physiological and psychological characteristics. Two methods are applied widely for the calculation of human heat balance: predicted mean vote (PMV) according to ISO 7730, and physiological equivalent temperature (PET) [49]. Both provide a description of the human thermal model and integrate physical and physiological factors that have been tested in a controlled climate chamber. A wide body of scholarship has pointed out the dissimilarity of the results between the laboratory heat balance model and the real world experience [7,50,51]. The deviation of the two models stems from real physiological variables, such as heat distribution in a room or metabolic rates because of mental stress and other psychological factors [51,52]. For example, when the predicted numbers of people unsatisfied with their thermal environment, based on the PMV, was compared with the number of on the spot reports of unsatisfied people, the actual mean vote (AMV), a significant deviation was found. That difference implies the detectable role of human adaptation in thermal perception [53]. The effect of psychological adaptation on thermal comfort is significant [51,52]. Psychological adaptation is described by the following parameters:

- perceived control, such as the unpleasant experience of waiting for someone to arrive,
- past experience, such as the weather in summer time,
- the time of exposure,
- naturalness—natural building materials help with thermal acceptance,environmental stimulation—people coming outside to enjoy the sunshine can bear heat for considerably longer periods than their counterparts, and
- expectation, such as the weather forecast [52,54].

Although wide research exists about psychological factors of thermal perception, there is no accepted method for their quantifications. For this reason, the definition of heatwave by Nairn *et al.*, is novel [16,55]. The created EHF, integrates the effect of the local acclimatisation in the long-term and the human adaptation in the short term on people's heatwave perception [15]. Compared to the daily mean and maximum temperature the EHF can indicate more accurately the impact of heatwaves on mortality [15]. Nevertheless, there are physical influential factors related to the intensity of heatwaves, beyond EHF, such as: humidity, wind, solar radiation. Unfortunately, at this stage these cannot be accounted for in a globally adaptable way.

2.2.4. Mitigation Techniques to Provide Adaptation Opportunities

The terminology of adaptation represents people's capabilities to change their close environments or to modify their relationship with the environment to decrease the effect of exposure to the existing environmental conditions [52]. Indoors, the perceived temperature is influenced by three aspects: climate conditions, building adaptive opportunities, and personal adaptation [7]. Brager *et al.*, rank adaptation methods in three categories: behaviour adjustment, physiological and psychological adaptation. Behaviour adjustment includes personal aspects, such as clothing, drinking and posture. Technological feedback as another opportunity for behaviour adjustment constitutes the opening of windows and the usage of heating, ventilation and air-conditioning (HVAC) systems. An example of behaviour adjustment based on cultural feedback is the siesta. Acclimatization, even over generations, is ranked with physiological adaptations. Expectation and habituation are responsible for psychological reactions [51].

Expectation is important because it realises the significant difference between people's thermal sensations at home and at work [56]. That deduction coincides with the results from Brager *et al.*, about human neutral temperature zones in the real-world compared to the calculated zones. The difference between the presumed and the measured values are significantly bigger innaturally-ventilated buildings than in air-conditioned ones [51]. These finding indicate that natural ventilation supports people's resilience; while air-conditioned buildings raise people's comfort expectations and their sensitivity. The limitations of the study by Brager *et al.*, is the assumption that the buildings had centrally controlled ventilation and were not able to be individually adjusted [51]. Nevertheless, there is a real concern about the building energy modelling practice as it considers climate and building characteristics only and excludes several physical and psychological adaptation measures [7]. The result corresponds with Humphrey's study in 1975 where the tracked variation of human neutral temperature was 20 ℃ outdoors, while only 13 ℃ indoors. Furthermore, Nicol *et al.*, found a much higher span of neutral temperature, between 15.7 ℃ in winter and 26.4 ℃ in summer, measured in a naturally ventilated building in Pakistan [51]. The research findings about adaptive comfort was implemented into the ASHRAE standards in the form of an adaptive model [57]. While adaptation opportunities can extend human thermal comfort in a strictly controlled building, the neutral zone is narrowed down. Moreover, over-controlled buildings can result in "sick building syndrome" because the utilisation of adaptive capacity is essential for human beings [7].

As the above examples show, human adaptation opportunities depend on personal adjustments and the buildings' inbuilt adaptive opportunities. In other words, buildings can be characterised by the number of inbuilt adaptive opportunities [7] even though the real application of these opportunities is decided by the users [58]. The literature on heatwaves and UHIEs handles adaptation and mitigation separately. Adaptation refers to the endeavour of the population to cope better with heatwaves, while mitigation focuses on the attenuation of heatwaves and UHIs. For instance, heatwave plans are typical adaptation methods, while the decrease of waste heat generation via energy-efficient cooling fosters the mitigation of UHIs. In contrast, the notion of inbuilt adaptive opportunities blurs the border between adaptation and mitigation. The building user is the link between adaptation and mitigation. For example, recent studies showed that user behaviour plays a significant role in building energy performance [59]. In this study mitigation and adaptation will be investigated together. Furthermore, since urban population spends most of the time within buildings, emphasis is laid on the characteristics of built environment related to heatwave resilience. For instance, a recent study demonstrated a higher influence of dwellings' thermal characteristics on overheating in London than the intensity of the UHI [60].

2.3. Precinct Retrofitting for Heatwave Resilience

"Resilience is often presented as an antonym of vulnerability, but in fact, the relationship is somehow more complex" [61]. "Yet, the enduring discursive appeal of the term resilience is in the connotations of dealing with uncertainties, disturbances, shocks and crises that cannot be adequately prevented or avoided" [62].

Resilience can also be seen as the missing link between mitigation and adaptation [62]. The resilience of urban inhabitants can be increased and human vulnerability decreased with the implementation of UHI mitigation techniques and more adaptation opportunities.

Kleerekoper *et al.*, classified the UHI mitigation opportunities into the following four groups: materials, water, vegetation, and urban form [63]. Anthropogenic heat is missing from among these scopes. Figure 3 summarises the most important mitigation techniques identified from the literature review.

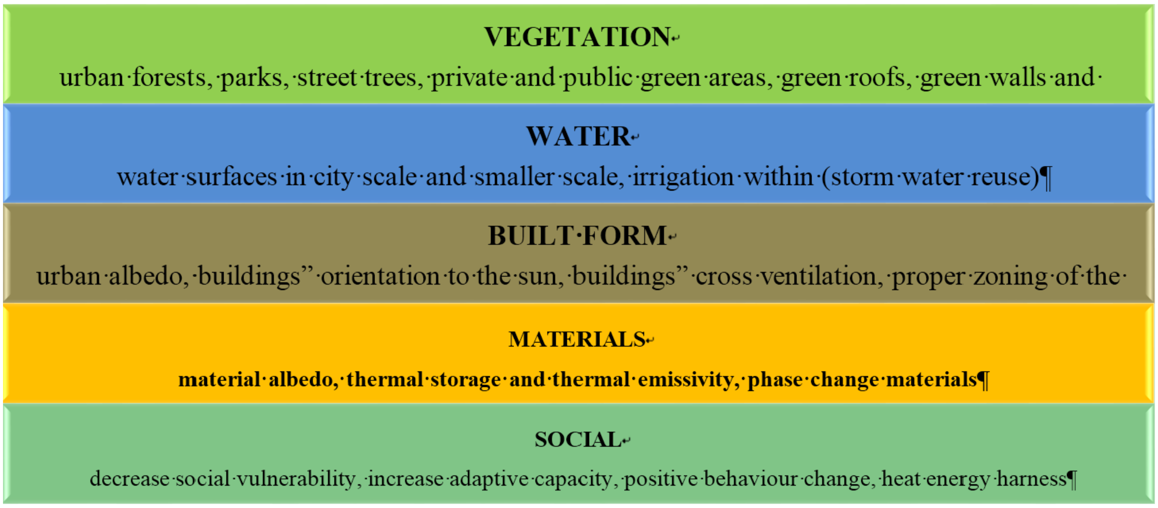

Figure 3. The five categories of UHI mitigation and adaptation strategies [63].

Retrofitting for UHI mitigation is important for two reasons. Firstly, the Australian building stock, particularly in the suburban areas, is outdated. Retrofitting the existing precincts for heatwave resilience is beneficial because of both the lower energy consumption during operation and the decreased maintenance costs of buildings, urban materials and, urban utilities [5]. Secondly, retrofitting leads to the overall less consumption of energy during the whole lifecycle of the building when compared to the higher construction and inbuilt energy needs of a brand-new development [64].

Energy-independence is important during the evaluation of retrofitting solutions. The worldwide increase in the use of air-conditioning has several negative consequences. One of the detrimental effects of air-conditioning is the indirect acceleration of global warming through increased energy consumption [58]. Artificial cooling also raises significantly the air temperatures in the built environment [65]. Moreover, human heat sensitivity is detectably higher in air-conditioned buildings than in naturally ventilated ones [66]. Human dependence on the HVAC system also raises concerns [8]. Due to significant energy price increases, in Australia in recent years, the use of air-conditioning has become unaffordable for financially disadvantaged social groups [67]. Conversely, tree canopy is one of the most effective mitigation techniques that also has miscellaneous positive benefits, such as cooling, shading, aesthetic value and the capability to generate breeze [65].

Several natural mitigation and adaptation means exist in vernacular building design. However, humans have lost their knowledge of these opportunities. One of the lost opportunities is the "cool retreat" where the internal building zones are reorganised, in residential buildings, to utilise natural cooling opportunities during heatwaves [66]. However, this solution requires a willingness to change on the part of the residents [68]. Bennetts *et al.*, have identified a further solution that requires behavioural change. Air-conditioning is limited to selected zones in residential buildings during heatwaves and insulation, and external shading and, double glazing are applied only to the selected zones [67].

Instead of adopting a comprehensive approach to the integration of mitigation solutions, the wide research on mitigation techniques focuses mainly on one of the five aspects listed in Figure 4. Comprehensive studies on the assessment of different retrofitting techniques, such as a retrofitting toolkit from UK [69] are few in number. The efficiency of mitigation techniques is rarely compared across different climates, despite the importance of climate specific design [23]. Furthermore, the scholarship tends to tackle the day-time and the night-time UHI together, despite its different characteristics and key contributors. In conclusion, for a better understanding of UHI mitigation it is essential to conduct an overarching evaluation of the different techniques that are presumed to create microclimatic and social improvements.

3. Results and Discussion

3.1. Key Aspects to Quantify and Improve Precinct Heatwave Resilience

Existing building stock is a major and not managed burden on sustainable built environment. Hence, retrofitting has to be explored in association with UHWs, both in terms of mitigation of and adaptation to UHWs. The presented literature review demonstrates that the users of the built environment create the link between adaptation and mitigation. Besides, because of the differences in climate, built environment and population, there is no one retrofitting technique that fit for all. Four main aspects should be considered during the evaluation of retrofitting techniques.

- Australian cities are low in density and their microclimates are influenced by the sea breeze; therefore the typical UHI pattern peaking in CBDs are not always traceable [70,71]. In addition, Australian cities are highly sprawled; hence the climatic condition differences across the metropolitan regions can be immense. Hence, research on UHWs should not overlook suburban areas and the use of finer-scale location-specific weather data is essential.
- Researchers tend to interpret the UHIs in terms of daily mean temperature. The characteristics of the day-time and the night-time UHIs and therefore UHWs are divergent due to location and magnitude differences across time. Consequently, in UHW resilience studies the function of the precinct should be accounted for and real population size should be used instead of the residential address based population size.
- Neither the findings of socioeconomic vulnerability nor real-world thermal perception have been integrated in the evaluation of retrofitting techniques. However, to increase heatwave resilience the knowledge of the heatwave vulnerability and perception of the local population is crucial.
- UHI literature exists on city, building, public space or canyon-scales. Since the indoor and outdoor environment temperature is closely related, only precinct analysis provides the opportunity to examine the relationship between indoor and outdoor air temperature, considering also the population’s characteristics.

The implication of these research aspects is the climate and function conscious retrofitting of Australian precincts considering the characteristics of the local population and built environment.

3.2. Implementation of the Key Aspects for Heatwave Resilient Precincts

3.2.1. Quantify Precinct Heatwave Resilience

To quantify precinct heatwave resilience risk analysis is suggested to determine the outcome risks of heatwaves. During the risk analysis, Crichton’s risk triangle is followed, where the risk is triggered by the presence of a hazard, vulnerability and exposure [72]. The hazard is gauged via the intensity of

UHWs, namely EHF. The vulnerability refers to the population vulnerability to heatwaves, while exposure is influenced primarily by the built environment both indoors and outdoors.

The first step in risk analysis is to identify the value at risk [38]. The risk is identified and quantified in this study via the impact indicators. Following the indirect consequences of UHWs—listed under Section 2.1.—the following indicators were considered:

- excess energy use during UHWs
- excess water use during UHWs
- excess morbidity and mortality during UHWs
- the perception of population of UHWs
- excess traffic to "cool pools" during UHWs, where cool pools are mainly air conditioned community spaces, acclaimed as a cool retreat during heatwaves, such as a local library or swimming pool.

Further possible indicators, covered by the literature are the higher absenteeism from work, lower efficiency, and the increased crime rate due to the increased aggressiveness [14]. However, the connection between these impact indicators and UHWs is less established so far in the research.

Each and every listed indicator captures different aspects of the impacts of UHWs on precinct and depends on UHWs only indirectly, influenced by several other variables. Because each indicator has different independent variables; they correlate with EHF expectedly at different extents. Given the deviations between precincts, their resilience level in terms of energy, water, morbidity, social perception and traffic use can be defined and ranked. This information helps to define the measures should be taken in association with energy, water and morbidity.

Based on the impact indicators and the intensity of the UHWs a calculation method for precincts heatwave resilience is proposed. Precinct resilience is a measure to the level to which a population within a neighbourhood can ignore heatwaves. The precinct specific resilient value is estimated from the data of several heatwave days. The vulnerability calculation method by Luers *et al.*, is adopted, where wellbeing is changed to the UHW impact indicator and the temperature stressor to the EHF [73], (see Figure 4). The points of UHW impact indicators with the respective EHFs for each day shape the graph of precinct resilience. The shape of the graph characterises the resilience of each precinct.

The value of the precinct heatwave resilience (Rpr), (see Equation 2.) is the function of the systems' sensitivity and the deviation between the particular impact indicator and the threshold of impact indicator for each precinct. The threshold (Mo) is defined by the calculated average impact indicator for the whole year.

$$Rpr = \int \left[|\Delta M : \Delta EHF| : \frac{M}{Mo} \right] \cdot dEHF \quad (2)$$

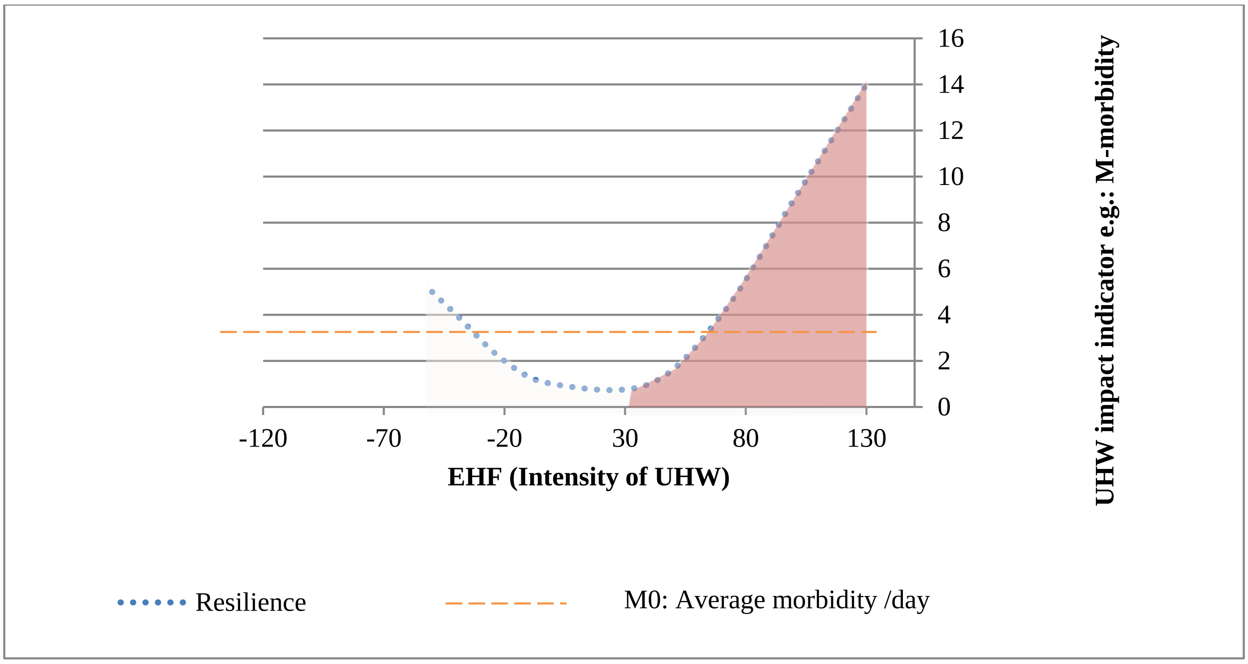

Figure 4. A hypothetical graph about precinct resilience.

This mathematical depiction of Rpr is supported by studies, assuming that the correlation of mortality rates during heatwaves with daily mean temperatures is presumed to form a graph with an upside down U or V shape [74], just as the electricity peak demand and consumption versus the ambient temperature [75,76]. Nairn *et al.*, also noted that the biggest heatwaves in recent decades, around the world with similar EHF values, caused different mortality rates because of the different vulnerabilities of the cities involved [15].

The gauged Rpr can be used to compare precincts across different climates, just as the same precinct before and after the implemented retrofitting strategies.

3.2.2. Influential Factors of Rpr

The quantification of Rpr is important to weight the different influential factors. Precinct resilience is influenced by the population vulnerability to the risk of UHWs, the level of exposure to the risk in the built environment and UHI countermeasures, namely the implemented mitigation (see Figure 5). Population vulnerability refers to the inhabitants' demographic characteristics that influence their capability to cope with extreme heat spells. The exposure to heatwave in the built environment is influenced by the number of adaptive opportunities available in the built environment, such as shading or air-conditioning. UHI countermeasures refer to the existing characteristics of urban environment, such as urban morphology and green ratio. These characteristics influence the intensity of UHIs and therefore indirectly the intensity of UHWs. Hence in this study the impact of UHIs countermeasures are already accounted for in the value of EHF. Nevertheless, correlation analysis between mitigation measures and the experienced EHF in different suburbs could illuminate the impact of mitigations on UHWs.

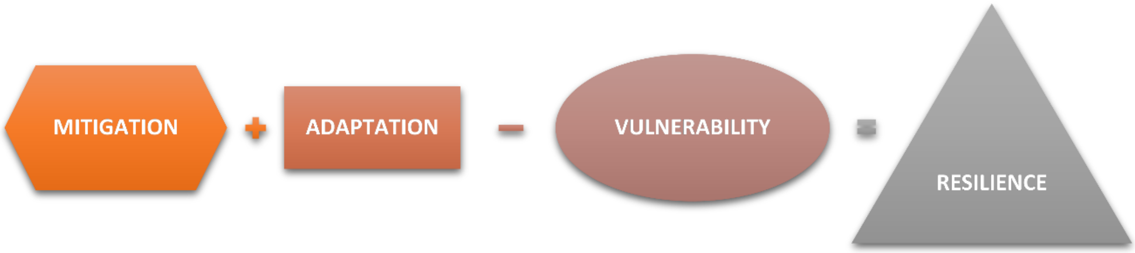

Figure 5. The influential factors of precinct resilience.

The exposure to heatwave depends on both the characteristics of the built environment—for example energy performance of the building envelope—and the population—for example the income level. Moreover, some of the built environment characteristics have an indirect influence on the microclimate, such as air-conditioning. However it has to remain a limitation of this study. The following summary table (see Table 1) entails all variables considered based on the literature review. During the classification of the variables into the three groups of mitigation, adaptation and vulnerability, special emphasis was laid on considering heatwave relevance. For instance, income level [13] and crime rate [14] are ranked under vulnerability by the literature. In contrast, this paper lists both as potential adaptation opportunities, since higher income level enables more energy-efficient building while a low income community faces various burdens of energy poverty [77]. Meanwhile, a neighbourhood with lower crime rate fosters night-time natural ventilation as a potential adaptation. Population density is ranked under mitigation as a primary urban design relevant indicator of UHIs (see Section 2.2.1).

The correlation between the independent variables and the quantified precinct resilience, leads to the best precinct specific retrofitting techniques.

Table 1. Independent variables of precinct resilience.

Mitigation as UHI Indicators	Adaptation as Population Exposure	Population Vulnerability
urban albedo/sky view factor (SVF)/frontal area index (FAI)	INDOORS	age above 65 and under 4
--	energy performance of the buildings envelope	--
green space ratio	air-conditioning coverage	the level of isolation (single household)
green intensity ratio	natural ventilation opportunity	pre-existing health conditions
water surface ratio	OUTDOORS	qualification
permeable surface rate	outdoor shadow coverage	hours spent at home: unemployment rate and people who work at home

Table 1. *Cont.*

Mitigation as UHI Indicators	Adaptation as Population Exposure	Population Vulnerability
Materials' average albedo	cool pool availability	ethnicity- length of residence, born here or offshore
population density	POPULATION CHARACTERISTICS	emergency service availability
Materials' thermal storage capacity	outdoor activity and confined spaces	electricity price
traffic type (eg.:electric cars), intensity	activity level	--
walkability	income level	--
energy-efficient building stock	crime rate (people unlikely to use public space and leave the window open at night)	--

3.2.3. The Retrofitting Toolkit

Following the key aspects for heatwave resilient precincts (see Section 3.1), the following characteristics of each precinct have to be evaluated; population, function, climate and existing built environment.

It is important to assess the mitigation techniques in terms of their impacts on their direct and indirect environment at a precinct scale. For example, even though air-conditioning is the prevalent protecting measure currently in Australia [78] they have two-fold negative effect on their environment. Firstly, they pump heat from indoors to outdoors, raising the outdoor air temperature [79]. Secondly, they use fossil fuels, increasing the population dependency on electricity grid and hence on carbon positive technology in most countries.

Related to population, retrofitting techniques vary widely in terms of their scope of benefit and scope of responsibility [8]. For instance, while external shading installed on a private house has benefit primary only for the occupants of that particular building, a green space located in public area demands responsibility on a community level with multiple benefits on the microclimate. Also their inbuilt costs and secondary maintenance costs along with their lifetime can differ, making it more or less available for a less affluent community. Furthermore, the event risks can be avoided generally by mitigation; while adaptation is used for the outcomes risks, such as heatwaves [38]. However, in regard to heatwaves the border between mitigation and adaptation is more ambiguous. Mitigation techniques, such as external shadings or individual thermostat settings provide greater opportunities for people to adapt. Therefore, retrofitting techniques have to consider and link both mitigation and adaptation techniques. Unfortunately, the likelihood of the population using adaptation options varies widely [51]. The uncertainty highlights the importance of the mitigation techniques' social and economic feasibility. For this purpose, the integration of a survey on local population's willingness to retrofit and their implemented mitigation and adaptation strategies is essential.

In regard to precinct function, exposure to and the intensity of heatwaves are a hazard that changes fundamentally between day, and night-time. Demographic factors are the key indicators of vulnerability and can be obtained easily from the residential address directory. However, during diurnal hours most people are not at home but are at work, often in another district or even in another town. Consequently, to avoid using flawed data the risk assessment has to calculate with the actual population of the precinct according to its primary function on that particular heatwave days. This difference is relevant in association with the retrofitting strategies. For example, water body behaves as a cooling element in the urban area during the day-time, while at night-time the reverse effect is detectable (see Figure 1). That phenomenon challenges the implementation of water surfaces in residential areas.

Energy efficiency of the implemented retrofitting techniques must be evaluated, accounting for the climate variables and whether the location is more cooling or heating orientated. Beyond potential energy and carbon saving, initial and lifetime-long maintenance costs are important evaluation criteria, especially for the low income population [77]. Not only the total electricity consumption, but the decrease of peak electricity demand can help in the reduction of the electricity bills, hence in the decrease of population vulnerability. The expected benefit can be more significant on precinct scale retrofitting, such as the benefit of the increase of green space intensity in public spaces. Nevertheless, green space requires higher maintenance costs, community level management and local council involvement. Population vulnerability can be decreased not only via mitigation but adaptation methods too, for instance via welfare calls on a regular basis to older people [80]. Apart from the knowledge of local demography, inhabitants' willingness to retrofit is a vital part of any intervention, especially in residential areas. Particular types of adaptation techniques, such as natural material use indoors and in public spaces, can be measured only via the adaptive increment. The adaptive increment shows the additional temperature—beyond the standard calculated neutral zone—that can be bearable by the occupants due to the implementation of adaptive behaviour and adaptation techniques [7]. A comprehensive list of these evaluation viewpoints are gathered in the proposed cool retrofitting toolkit (CRT) (see Table 2).

The proposed cool retrofitting toolkit would serve the work of policy makers, architects, urban designers and relevant practitioners.

Table 2. Cool retrofitting toolkit.

Scope of Responsibility	**The Mitigation Technique is Implementable by Individuals or Only by Community, Public Service.**
Spatial scope of benefit	It is beneficial for a smaller or bigger community.
Effect on the time distribution	Depends on the function of the building.
Effect on population vulnerability	Private green roofs and any green space can be more effective for affluent populations, who can afford to irrigate more than a less affluent one.
Cost	The initial construction and planning costs.
Willingness to retrofit and use the implemented opportunities	Investigate the common acceptance of the mitigation techniques.

Table 2. *Cont.*

Scope of Responsibility	The Mitigation Technique is Implementable by Individuals or Only by Community, Public Service.
Lifetime	The lifetime of a tree is expected to be much longer than external shading.
Maintenance	All additional cost related to the mitigation techniques' maintenance.
"Adaptive increment" (where applicable), increase of neutral thermal zone	The additional temperature beyond the standard based neutral zone which can be bearable by the users due to the implementation of adaptive behaviour and adaptation techniques [7]. Solutions with impact on heat perception, such as increased use of natural materials applicable.
Savings in annual energy and carbon emission	The findings of building energy modelling will be included.
Peak demand	Foster the decrease of peak demand in energy, water, ambulance service.
Level of independency from fossil fuels	Reduce the precincts' dependency on fossil fuels and raise inhabitants' resilience.
Positive impact on psychological perception via information distribution	For instance, inbuilt weather-forecast information spot in office buildings' foyers.

4. Conclusions

This paper illuminates the importance of a more profound knowledge of heatwave resilience. Heatwave resilience has to be evaluable and comparable across precincts and differentiable in terms of the subject of concern, such as energy, water and morbidity. The quantification of heatwave resilience can help the understanding of the focus areas of future urban and infrastructure developments, and enable efficient heatwave plans. Furthermore, via the assessment of heatwave resilience, the effectivity of different retrofitting techniques can be gauged. A cross-disciplinary approach is warranted to evaluate retrofitting techniques, considering the characteristics of local climate, existing urban design, built environment and population vulnerability. Moreover, the resilience capacity of the population and their attitude to retrofitting, are also essential to account both for adaptation and mitigation. Future research has to be taken to testify the calculation method of heatwave resilience and provide assessments for suggested retrofitting strategies. The unit of heatwave resilience will support the work of city councils, urban designers and disaster managers. The cool retrofitting toolkit can be used by policy makers, architects and urban designers.

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Author Contributions

The work is a product of the intellectual environment of the authors; both authors have contributed to the conception and design, the drafting and the critical revisions of the article. Also both authors approved the final version of the article to be published.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Stocker, T.F.; Qin, D.; Plattner, G.-K.; Tignor, M.; Allen, S.K.; Boschung, J.; Nauels, A.; Xia, Y.; Bex, V.; and Midgley P.M. IPPC Climate Change 2013: The physical science basis. In *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: New York, NY, USA, 2013; p. 1535.
2. Frich, P.; Alexander, L.V; Della-Marta, P.; Gleason, B.; Haylock, M.; Klein Tank, A.M.; Peterson, T. Observed coherent changes in climatic extremes during the second half of the twentieth century. *Clim. Res.* **2002**, *19*, 193–212.
3. Climate change in Australia-Technical Report—Chapter 5.—Appendix A: Annual Temperature Changes and Annual and Seasonal Precipitation Changes. Available online: http://www.climatechange inaustralia.gov.au/technical_report.php (accessed on 13 January 2014).
4. UN-HABITAT Hidden cities. Unmasking and Overcoming Health Inequities in Urban Settings. Available online: http://www.who.int/kobe_centre/publications/hiddencities_media/who_un_habitat _hidden_cities_web.pdf?ua=1 (accessed on 13 January 2015).
5. Gartland, L. *Heat Islands: Understanding and Mitigating Heat in Urban Areas*; Earthscan: London, UK, 2008.
6. The Effect of the Urban Built-up Density and the Land Cover Types on the Radiated Temperature-Author's Own Translation. Available online: http://www.google.com.au/url?sa=t&rct= j&q=&esrc=s&frm=1&source=web&cd=1&ved=0CCUQFjAA&url=http://phd.lib.unicorvinus.hu /639/2/Olah_Andras_thu.pdf&ei=ZVOJUsW5OIPJiAeRtYGABQ&usg=AFQjCNHCscaMBGO9 A-7V0JE0B1k1mtIUnQ&bvm=bv.56643336,d.aGc (accessed on 13 January 2015).
7. Baker, N.; Standeven, M. Thermal comfort for free-running buildings. *Energy Build.* **1996**, *23*, 175–182.
8. Ichinose, T.; Matsumoto, F.; Kataoka, K. Counteracting urban heat islands in Japan. In *Urban Energy Transition–From Fossil Fuels to Renewable Power*; Droege, P., Ed.; Elsevier: Amsterdam, The Netherlands, 2008; pp. 365–380.
9. UN DESA Population Division World urbanization prospects, the 2014 revision. File 1: Population of Urban and Rural Areas at Mid-Year (thousands) and Percentage Urban, 2014. Available online: http://esa.un.org/unpd/wup/cD-rom/ (accessed on 13 January 2015).
10. Coates, L. An overview of fatalities from some natural hazards in Australia. In *Conference on Natural Disaster Reduction 1996: Conference Proceedings*; Institution of Engineers: Gold Coast, Australia, 1996; pp. 49–54.

11. Major Cities Unit. State of Australian Cities 2013. Available online: https://www.infrastructure.gov.au/infrastructure/pab/soac/files/2013_01_INFRA1782_MCU_SOAC_PRELIMINARIES_WEB_FA.pdf (accessed on 15 December 2014).
12. Wolf, T.; McGregor, G.; Analitis, A. Performance assessment of a heat wave vulnerability index for Greater London, United Kingdom. *Weather. Clim. Soc.* **2014**, *6*, 32–46.
13. Loughnan, M.; Tapper, N.; Phan, T.; Lynch, K.; McInnes, J. A Spatial Vulnerability Analysis of Urban Populations during Extreme Heat Events in Australian Capital Cities. Available online: http://www.mappingvulnerabilityindex.com/home/project-overview (accessed on 15 December 2014).
14. McGregor, G.R.; Wolf, T.; Gosling, S.; Pelling, M. Social impacts of heatwave Bristol Science Report—SC20061/SR6; Environment Agency: Bristol, UK, 2007.
15. Defining Heatwaves: Heatwave Defined as A Heat Impact Event Servicing all Community and Business Sectors in Australia. Available online: http://www.cawcr.gov.au/publications/technicalreports/CTR_060.pdf (accessed on 15 December 2014).
16. Langlois, N.; Herbst, J.; Mason, K.; Nairn, J.R.; Byard, R.W. Using the Excess Heat Factor (EHF) to predict the risk of heat related deaths. *J. Forensic Leg. Med.* **2013**, *20*, 408–411.
17. Bureau of Meterology. First heatwave for Adelaide in 2010. Available online: http://www.bom.gov.au/announcements/media_releases/sa/20100115_First_Heatwave_SA_Jan.shtml (accessed on 15 December 2014).
18. Alexander, L. V; Hope, P.; Collins, D.; Trewin, B.; Lynch, A.; Nicholls, N. Trends in Australia’s climate means and extremes: A global context. *Aust. Meteorol. Mag.* **2007**, *56*, 1–18.
19. Stott, P.A.; Stone, D.A.; Allen, M.R. Human contribution to the European heatwave of 2003. *Nature* **2004**, *432*, 610–614.
20. Wilby, R.L. A review of climate change impacts on the built environment. *Built Environ.* **2007**, *33*, 31–45.
21. Hajat, S.; Kovats, R.S.; Lachowycz, K. Heat-related and cold-related deaths in England and Wales: Who is at risk? *Occup. Environ. Med.* **2007**, *64*, 93–100.
22. Arnfield, A.J. Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *Int. J. Climatol.* **2003**, *23*, 1–26.
23. Wong, N.H.; Chen, Y. *Tropical Urban Heat Islands: Climate, Buildings and Greenery*; Taylor & Francis: New York, NY, USA, 2009; p. 259.
24. Georgescu, M.; Morefield, P.E.; Bierwagen, B.G.; Weaver, C.P. Urban adaptation can roll back warming of emerging megapolitan regions. *Proc. Natl. Acad. Sci.* **2014**, *111*, 2909–2914.
25. Keramitsoglou, I.; Kiranoudis, C.; Maiheu, B.; Ridder, K.; Daglis, I.; Manunta, P.; Paganini, M. Heat wave hazard classification and risk assessment using artificial intelligence fuzzy logic. *Environ. Monit. Assess.* **2013**, *185*, 8239–8258.
26. Ruddell, D.M.; Harlan, S.L.; Grossman-Clarke, S.; Byuntajev, A. Risk and exposure to extreme heat in microclimates of Phoenix, AZ. In *Geospatial Techniques in Urban Hazard and Disaster Analysis*; Showalter, P.S., Lu, Y., Eds.; Springer: New York, NY, USA, 2009; pp. 179–202.
27. Priyadarsini, R. Urban Heat Island and its impact on building energy consumption. *Adv. Build. Energy Res.* **2009**, *3*, 261–270.

28. Santamouris, M.; Papanikolaou, N.; Livada, I.; Koronakis, I.; Georgakis, C.; Argiriou, A.; Assimakopoulos, D.N. On the impact of urban climate on the energy consumption of buildings. *Sol. Energy* **2001**, *70*, 201–216.
29. Guan, H.; Soebarto, V.; Bennett, J.; Clay, R.; Andrew, R.; Guo, Y.; Gharib, S.; Bellette, K. Response of office building electricity consumption to urban weather in Adelaide, South Australia. *Urban Clim.* **2014**, *10*, 42–55.
30. Wilhelmi, O.V.; Hayden, M.H. Connecting people and place: A new framework for reducing urban vulnerability to extreme heat. *Environ. Res. Lett*. **2010**, *5*, 1–7.
31. Erell, E.; Pearlmutter, D.; Williamson, T.J. *Urban Microclimate: Designing the Spaces between Buildings*; Earthscan: London, UK, 2011.
32. Characterisation, Interpretation and Implication of the Adelaide Urban Heat Island. Available online: http://hdl.handle.net/2328/26839 (accessed on 13 January 2014).
33. Torok, S.J.; Morris, C.J.G.; Skinner, C.; Plummer, N. Urban heat island features of southeast Australian towns. *Aust. Meteorol. Mag.* **2001**, *50*, 1–13.
34. Adams, M.P.; Smith, P.L. A systematic approach to model the influence of the type and density of vegetation cover on urban heat using remote sensing. *Landsc. Urban Plan.* **2014**, *132*, 47–54.
35. Hartz, D.A.; Golden, J.S.; Sister, C.; Chuang, W.-C.; Brazel, A.J. Climate and heat-related emergencies in Chicago, Illinois (2003–2006). *Int. J. Biometeorol.* **2012**, *56*, 71–83.
36. Zhang, K.; Chen, Y.; Schwartz, J. Rood, R.B.; O'Neill, M.S. Forecast and observed weather data to assess performance of forecast products in identifying heat waves and estimating heat wave effects on mortality. *Environ. Health Perspect.* **2014**, *122*, 912–918.
37. Urban heat islands: hotter cities. American Institute of Biological Sciences: Reston, VA, USA, 2004. Available online: http://www.actionbioscience.org/environment/voogt.html?newwindow=tru (accessed on 17 December 2014).
38. Climate change in Australia-Technical Report-Chapter 6: Application of climate projections in impact and risk assessments. Available online: http://www.climatechangeinaustralia.gov.au/technical_report.php (accessed on 14 January 2015).
39. IPPC. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: New York, NY, USA, 2012; p. 582.
40. Nitschke, M.; Tucker, G.R.; Bi, P. Morbidity and mortality during heatwaves in metropolitan Adelaide. *Med. J. Aust.* **2007**, *187*, 662–665.
41. Nitschke, M.; Hansen, A.; Bi, P.; Pisaniello, D.; Newbury, J.; Kitson, A.; Tucker, G.; Avery, J.; Dal Grande, E. Risk Factors, health effects and behaviour in older people during extreme heat: A survey in South Australia. *Int. J. Environ. Res. Public Health* **2013**, *10*, 6721–6733.
42. Hansen, A.; Bi, P.; Nitschke, M.; Ryan, P.; Pisaniello, D.; Tucker, G., Climate Change and Environmental Health. In *Epidemiology*, Proceedings of the ISEE 22nd Annual Conference, Seoul, Korea, 28 August–1 September 2010; Volume 22, pp. S14–S15.
43. Huang, G.; Zhou, W.; Cadenasso, M.L. Is everyone hot in the city? Spatial pattern of land surface temperatures, land cover and neighborhood socioeconomic characteristics in Baltimore, MD. *J. Environ. Manage.* **2011**, *92*, 1753–1759.

44. Tomlinson, C.J.; Chapman, L.; Thornes, J.E.; Baker, C.J. Including the urban heat island in spatial heat health risk assessment strategies: a case study for Birmingham, UK. *Int. J. Health Geogr.* **2011**, *10*, doi:10.1186/1476-072X-10-42.
45. Chow, W.T.L.; Chuang, W.-C.; Gober, P. Vulnerability to extreme heat in metropolitan Phoenix: Spatial, temporal, and demographic dimensions. *Prof. Geogr.* **2012**, *64*, 286–302.
46. Jenerette, G.D.; Harlan, S.L.; Brazel, A.; Jones, N.; Larsen, L.; Stefanov, W.L. Regional relationships between surface temperature, vegetation, and human settlement in a rapidly urbanizing ecosystem. *Landsc. Ecol.* **2007**, *22*, 353–365.
47. Loughnan, M.; Nicholls, N.; Tapper, N.J. Mapping heat health risks in urban areas. *Int. J. Popul. Res.* 2012, 1–12.
48. Demanuele, C.; Mavrogianni, A.; Davies, M.; Kolokotroni, M.; Rajapaksha, I. Using localised weather files to assess overheating in naturally ventilated offices within London's urban heat island. *Build. Serv. Eng. Res. Technol.* **2011**, *33*, 351–369.
49. Matzarakis, A.; Mayer, H.; Iziomon, M.G. Applications of a universal thermal index: physiological equivalent temperature. *Int. J. Biometeorol.* **1999**, *43*, 76–84.
50. Humphreys, M. Outdoor temperatures and comfort indoors. *Batim. Int. Build. Res. Pract.* **1978**, *6*, 92–105.
51. Brager, G.S.; de Dear, R.J. Thermal adaptation in the built environment: A literature review. *Energy Build.* **1998**, *27*, 83–96.
52. Nikolopoulou, M.; Steemers, K. Thermal comfort and psychological adaptation as a guide for designing urban spaces. *Energy Build.* **2003**, *35*, 95–101.
53. Nikolopoulou, M.; Baker, N.; Steemers, K. Thermal comfort in outdoor urban spaces: Understanding the human parameter. *Sol. Energy* **2001**, *70*, 227–235.
54. Katzschner, L. Open space design strategies based on thermal comfort analysis. *Proc. PLEA.* **2004**, *1*, 47–52.
55. Defining and predicting Excessive Heat events, a National system. Available online: http://www.cawcr.gov.au/events/modelling_workshops/workshop_2009/papers/NAIRN.pdf (accessed on 18 December 2014).
56. Oseland, N.A. Predicted and reported thermal sensation in climate chambers, offices and homes. *Energy Build.* **1995**, *23*, 105–115.
57. American Society for Heating, Refrigerating and Air-conditioning Engineers, Inc. *Standard 55-2010, Thermal Environmental Conditions for Human Occupancy*; American Society for Heating, Refrigerating and Air-conditioning Engineers, Inc.: Atlanta, GA, USA, 2010.
58. Koppe, C.; Kovats, S.; Jendritzky, G.; Menne, B.; Breuer, D.J.; Wetterdienst, D. *Heat Waves: Risks and Responses*; Regional Office for Europe, World Health Organization: Copenhagen, Denmark, 2004.
59. Hoes, P.; Hensen, J.L.M.; Loomans, M.G.L.C.; de Vries, B.; Bourgeois, D. User behavior in whole building simulation. *Energy Build.* **2009**, *41*, 295–302.
60. Oikonomou, E.; Davies, M.; Mavrogianni, A.; Biddulph, P.; Wilkinson, P.; Kolokotroni, M. Modelling the relative importance of the urban heat island and the thermal quality of dwellings for overheating in London. *Build. Environ.* **2012**, *57*, 223–238.

61. Provitolo, D. Resiliencery vulnerability notion—Looking in another direction in order to study risks and disasters. In *Resilience and Urban Risk Management*; Laganier, R., Ed.; CRC Press: Boca Raton, FL, USA, 2012; pp. 1–13.
62. Friend, R.; Moench, M. What is the purpose of urban climate resilience? Implications for addressing poverty and vulnerability. *Urban Clim.* **2013**, *6*, 98–113.
63. Kleerekoper, L.; van Esch, M.; Salcedo, T.B. How to make a city climate-proof, addressing the urban heat island effect. *Resour. Conserv. Recycl.* **2012**, *64*, 30–38.
64. Pullen, S. An analysis of energy consumption in an Adelaide suburb with different retrofitting and redevelopment scenarios. *Urban Policy Res.* **2010**, *28*, 161–180.
65. Responding to the Urban Heat Island: A Review of the Potential of Green Infrastructure; Victorian Centre for Climate change Adaptation Research, 2012. Available online: http://www.vcccar.org.au/sites/default/files/publications/VCCCAR%20Urban%20Heat%20Island%20-WEB.pdf (accessed on 18 December 2013).
66. Palmer, J.; Bennetts, H.; Pullen, S.; Zuo, J.; Ma, T.; Chileshe, N. The effect of dwelling occupants on energy consumption: the case of heat waves in Australia. *Archit. Eng. Des. Manag.* **2013**, *10*, 40–59.
67. Bennetts, H.; Pullen, S.; Zillante, G. Design strategies for houses subject to heatwaves. *Open House Int.* **2012**, *37*, 29–38.
68. Hall, N.; Romanach, L.; Cook, S.; Meikle, S. Increasing energy-saving actions in low income households to achieve sustainability. *Sustainability* **2013**, *5*, 4561–4577.
69. Porritt, S.M.; Cropper, P.C.; Shao, L.; Goodier, C.I. Heat wave adaptations for UK dwellings and development of a retrofit toolkit. *Int. J. Disaster Resil. Built Environ.* **2013**, *4*, 269–286.
70. Greening Australia: The Urban Heat Island Effect and Western Sydney. Available online: http://www.parliament.nsw.gov.au/prod/parlment/committee.nsf/0/403eef7669df9052ca257474001a8b5c/$FILE/08 - Greening Australia.pdf (accessed 16 December 2014).
71. Argueso, D.; Evans, J.P.; Fita, L.; Bormann, K.J. Temperature response to future urbanization and climate change. *Clim. Dyn.* **2013**, *42*, 2183–2199.
72. *Adapting Buildings and Cities for Climate Change (electronic resource): A 21st Century Survival Guide*, 2nd ed.; Crichton, D., Nicol, F., Roaf, S., Eds.; Taylor & Francis Group: Philadelphia, PA, USA, 2009; p. 400.
73. Luers, A.L.; Lobell, D.B.; Sklar, L.S.; Addams, C.L.; Matson, P.A. A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico. *Glob. Environ. Chang.* **2003**, *13*, 255–267.
74. Kovats, R.S.; Hajat, S. Heat stress and public health: A critical review. *Annu. Rev. Public Heal.* **2008**, *29*, 41–55.
75. Pardo, A.; Meneu, V.; Valor, E. Temperature and seasonality influences on Spanish electricity load. *Energy Econ.* **2002**, *24*, 55–70.
76. Santamouris, M. On the energy impact of urban heat island and global warming on buildings. *Energy Build.* **2014**, *82*, 100–113.
77. Santamouris, M.; Kolokotsa, D. On the impact of urban overheating and extreme climatic conditions on housing, energy, comfort and environmental quality of vulnerable population in Europe. *Energy Build.* **2014**, *2014*, doi:10.1016/j.enbuild.2014.08.050.

78. ABS Feature Article-Heating and Cooling. Available online: http://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/1345.4Feature Article1Aug 2009 (accessed on 16 December 2014).
79. A Framework for Adaptation of Australian Households to Heat Waves; 2013. Available online: http://www.nccarf.edu.au/publications/framework-adaptating-australian-households-heat-waves (accessed on 17 December 2014).
80. Adaptive capabilities in the elderly during extreme heat events in South Australia. Available online: http://www.Sahealth.Sa.Gov.Au/Wps/Wcm/Connect/C67cf100436d8e7082a2dfc9302c1003/Adaptive+Capabilities+In+Elderly+People+During+Extreme+Heat+Events+In+SA++Public+Health+Service+-+Scientific+Services+20140328.Pdf?MOD=AJPERES&CACHEID=C67cf100436d8e7082a2dfc9302c1003 (accessed on 17 December 2014).