"Whatever is coming over this country! People struck almost lifeless in the streets, animals falling as though killed by some insidious disease and man and beast in city and country in torture! Anyone who went through Sydney yesterday as a stranger might well exclaim "If this is their sunny New South Wales, Heaven help them!" Who has known business ashore and afloat literally stopped on account of a high temperature rendering men physically unfit for duty! Nor does it appear in the whole of the authenticated weather history of the colony that anything like it has been known. The Association of Old Identities (did such a society exist!) could no doubt tell some interesting facts of the heat of bygone days, when they paddled down about in the Tank Stream and slept under a tree on the slopes of Brickfield Hille battling with the tuneful mosquito"

Sydney Morning Herald, January 14 1896: 5d,e.

Chapter One
INTRODUCTION

Natural hazards are extreme events which exceed normal human expectations of magnitude or frequency, causing significant disruption to human lives and resulting in material damage, injury or loss of life (Heathcote, 1979). They are essentially a human construct created by the interaction of social systems and natural events, and in this context have been described as *negative resources* (Burton *et al.*, 1978). *Figure 1.1* schematically demonstrates this interaction and illustrates the concept that RISK = HAZARD x VULNERABILITY, where *Risk* implies the consequences of the natural hazard, *Hazard* incorporates the natural system and the occurrence of extremes, and *Vulnerability* measures the human component. This figure also emphasises the significance of human perception and adjustment in influencing the impacts of natural hazards.

The impacts of natural hazards and the degree to which human interactions can moderate or exacerbate the scope of these impacts has been increasingly acknowledged. The present decade has been allocated as the International Decade for Natural Disaster Reduction, and as early as 1976, a Symposium on Natural Hazards in Australia recommended increasing our understanding of natural hazard frequency, spatial distribution and impacts (Heathcote, 1979). However, the bulk of natural hazard research in Australia has focused on hazards which incur large financial, as opposed to human, costs.

Heatwaves are probably one of the least studied and most underrated weather hazards in Australia, essentially because they are different to the more widely studied catastrophic hazards, such as earthquakes and cyclones. In comparison to other natural hazards (with the exception of drought) heatwaves tend to be pervasive rather than intensive, with accumulative impacts rather than sudden dramatic shocks, and affect human health rather than generating structural damage (Riebsame, 1985). Because heatwaves are often viewed as a 'passive' hazard they have not been given the same attention by the media or

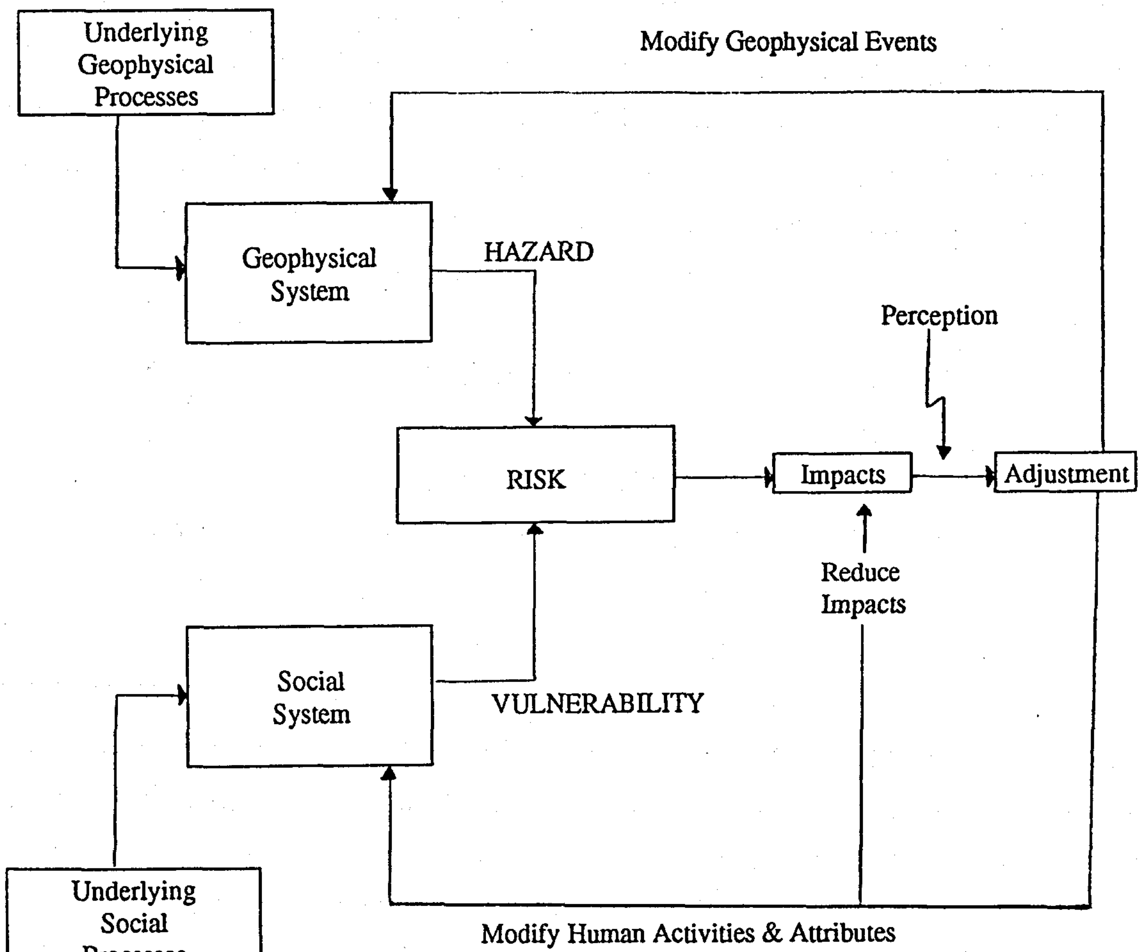

Figure 1.1. An interactive Model Of Natural Hazards (after Riebsame *et.al.*, 1986:1380).

researchers as other hazards, such as floods, cyclones and earthquakes. A 1994 heatwave in Cairns, Australia, in which 5 people died was given no media coverage in Sydney (newspaper or television) (*pers comm.* P. May, Emergency Management Australia, 1994). On a larger scale, the July 1980 American heatwave which caused more than 1,600 deaths was completely overshadowed in terms of media and public interest by the May 1980 eruption of Mount St Helens, in which only 59 people died.

Another deterrent to the recognition of heatwaves as a natural hazard is that they are often (not always) associated with other natural hazards, principally droughts or bushfires. The nature of the inter-relationship between droughts, bushfires and heatwaves is unclear and tends to overwhelm the significance of the heatwave hazard.

1.1 Heatwaves in Australia

While there is little doubt that hazards affected the Aboriginal population, the incidence of hazards and their impacts have been documented with increasing care since European settlement in 1788 (Heathcote, 1979). Sturt referred to excessively hot conditions on many occasions in his diaries (Fitzhenry & Barker, 1994), and references to heatwaves have been recorded in newspapers and other sources. Most extreme heatwaves in Australia have been associated with continentality, inland high pressure systems and offshore lows (Dury, 1972; Bureau of Meteorology, 1991), conditions which in 1939 resulted in Adelaide, Melbourne and Sydney registering their record maximum temperatures (47.8°C, 45.6°C, 45.3°C respectively) on three successive days from 12 through 14 January, 1939. In Sydney, the temperature rose from 31.1°C at 6 am to 40.8°C at 9am and 45.3°C at 2pm, at which point the relative humidity was only 4%. Most of south-east Australia also experienced record temperatures at this time, with the plains of northern New South Wales and the Riverina, and inland stations northwest of Sydney sweltering under temperatures in the mid to high 40s[1], further west, temperatures in Alice Springs reached 45°C[1] on both January 11 and 12 (Dury, 1972).

Excessively long periods of very high temperatures are common in the North West of Australia, where a hundred-day duration of 38°C maximum temperatures is on record for

[1] sea level equivalents. See Dury (1972).

most of this region (Dury, 1972). Daily maxima have exceeded 37.8°C for as many as 160 consecutive days in Marble Bar (Western Australia), and 28 days in Alice Springs (Northern Territory). Perth's record maximum of 44.7°C, which occurred in February 1933, was also associated with extremely high temperatures up to 640km inland. In Brisbane a maximum of 43.3°C was recorded on the 26th January, 1940. Temperatures reached 39.3°C at Hobart on the 7th February 1967 in conjunction with a series of disastrous bushfires.

1.2 Heatwave Impacts in Australia

Available figures suggest that more Australian deaths this century can be attributed to extreme high temperatures than any other weather hazard, however, heatwave-related mortality in Australia has never been assessed in a comprehensive manner. In America where extensive analyses have been undertaken, heatwaves are known to kill more Americans than hurricanes, tornadoes, lightning and floods combined (Posey, 1980). An average of 315 deaths has been estimated to occur per heatwave event throughout the world (Thompson, 1982).

The economic costs of heatwaves can be considerable. The 1980 heatwave in the United States produced an estimated US$15 billion in losses (Riebsame *et al.* 1986). In Australia, the economic implications of heatwaves are unquantified and generally down-played, yet may be quite considerable. A single day of maximum temperature 47°C at Mildura on 3 January 1990 caused $12 million damage to grapevines alone (Commonwealth of Australia, 1992). Stock losses and damage to agriculture and infrastructure are believed to be enormous, although the unexplored relationship between heatwaves and droughts makes delineating between the impacts of these two hazards, when they occur together, often impossible.

1.3 Aims

On available evidence it seems that heatwaves may be a significant natural hazard in Australia. To assess this significance it is important to obtain a real understanding of heatwave consequences, and to achieve this some critical questions need to be answered:

- What is the death toll from heatwaves in Australia and how does this compare to other hazards?

- What are the consequences of heatwaves for lifestyles, human endeavours, lifelines and other material objects?

It is hypothesised that the consequences of heatwaves, particularly mortality, are considerable. Once they are identified and quantified, vulnerable locations, populations, times, industries and activities can be identified by investigating the pattern of impacts, and the way these patterns have changed with time. Understanding the relationship between the hazard and consequence enables them to be reduced. Additionally, long range forecasting of heatwaves is essential to reduce hazard impacts (Riebsame *et al.*, 1986). Another important question to ask is therefore;

- Can the occurrence of extreme heatwaves be predicted?

To approach an holistic appraisal of heatwaves in Australia, an assessment of the ambiguous and unexplored relationship between heatwaves and droughts and bushfires is necessary, and may actually yield results instrumental to minimising consequences.

The next step in most hazards research is a quantification of future risk. Climate and social change in the near future will undoubtedly affect the risk of heatwaves and the pattern of heatwave consequences. Climate change can influence the frequency, distribution and intensity of the heatwave *hazard*, while social changes will affect the *vulnerability* of the population. An understanding of the interaction of these factors is important for quantifying future risk and, in conjunction with the identification of high risk groups and locations, allowing the mitigation of future impacts.

This thesis aims to take the first step towards providing a comprehensive analysis of heatwaves in Australia, in an analysis designed to quantify the place of heatwaves within the ranks of other natural hazards in Australia. Because of the scope of work involved in providing an appraisal of heatwaves in Australia, as outlined above, this is a *preliminary* analysis.

The aims of this research work are as follows:

- To define a heatwave, and to discuss the relevance of this definition.
- To investigate the impacts of heatwaves in Australia on mortality in a manner that will

allow the identification of vulnerable groups, locations and times.

- To investigate the effects of heatwaves on lifelines.
- To explore a plausible hypothesis that heatwaves are correlated with the El Niño-Southern Oscillation (ENSO) phenomena, a correlation which could be useful as a predictive tool.
- To discuss the impact climate and social change will have on future heatwave risk and to review mitigation techniques.

1.4 Thesis Structure

Chapter 2 addresses the problem of heatwave definition, by summarising existing definitions and exploring theoretical considerations involved in defining a heatwave. Three definitions of a heatwave are proposed, and then applied to two study sites, Sydney and Broken Hill. This analysis provides a sense of the frequency and severity of heatwaves in Australia, and an understanding of the difficulties involved in defining a heatwave.

Chapter 3 discusses the effects of heatwaves on mortality and morbidity. A database of heatwave deaths compiled from data from the Australian Bureau of Statistics and *The Sydney Morning Herald* provides a comprehensive analysis of heatwave-associated mortality in Australia, enabling the identification of vulnerable groups, locations and times. The analysis of total death rates and temperature at Sydney and Broken Hill indicates the cost of heatwaves in causing mortality increases, and the relationship between temperature and mortality. The effects of heatwaves on human morbidity will also be reviewed, and a brief analysis of the effect of temperature on crime rates undertaken.

Chapter 4 outlines the effect of heatwaves on lifelines, specifically water supply, electricity supply and transport links, exploring the significance of these findings.

Chapter 5 presents an analysis of the correlation between heatwaves and the El Niño-Southern Oscillation phenomenon, with it's implications for predicting heatwaves.

Chapter 6 looks to the future and the significance of climate and social change on heatwave impacts in Australia, by synthesising earlier conclusions as to vulnerable populations. Mitigation techniques will be reviewed.

Finally, **Chapter 7** presents the conclusions of this preliminary analysis, assesses any inadequacies, and provides suggestions for further work to be undertaken to better understand the total impact of heatwaves on our society.

Chapter Two
DEFINING A HEATWAVE

The term *heatwave* appears to have developed out of the popular vocabulary in the late 1800s (Chang & Wallace (1987:1253). The first media reference to a heatwave in *The Sydney Morning Herald*, was in 1892:

> *"A heatwave is now passing over Victoria. On Monday the heat commenced, the temperature in the shade at Melbourne Observatory being 931/2, and 1461/2 in the sun. Yesterday it was 981/2 in the shade and 1471/2 in the sun, and to-day 94 in the shade and 139 in the sun"*
>
> The Sydney Morning Herald, Friday January 22 1892:5f.

The first heatwave in New South Wales described by *The Sydney Morning Herald* occurred in 1893:

> *"A wave of heat swept over the colony during Sunday and part of yesterday, and the recorded temperatures at many places are said to be higher than ever known. For 48 hours it has blown from the northward down from the tropics across the arid plains of the interior, until the heated air became quite unbearable for white people."*
>
> The Sydney Morning Herald December 12, 1893:5c.

Many of the earlier media references to heatwaves were as *waves of heat* (as the above description), which were *phenomenal* or *severe*. These often *universal* waves *passed* or *swept* across the colony.

2.1 Existing Heatwave Definitions

There is no official Australian definition of a heatwave (*pers. comm.* Ken Batt, Bureau of Meteorolology, 1994). In *The Sydney Morning Herald* 'heatwaves' refer to both the occurrence of unusually high temperatures for a location on any time scale, and to a high temperature event which affects large areas of the continent. The Macquarie Dictionary (1991) defines a heatwave as:-

> *"n. 1. an air mass of high temperature, covering an extended area and moving relatively slowly. 2. a prolonged period of excessively warm weather."*

In 1900, an American, A.T. Burrows defined a *hot wave* as a spell of three or more days on each of which the maximum shade temperature reaches or exceeds 90°F (32.2°C) (Hufchka, 1970). The cutoff point of 32.2°C has since become common to many American studies on heatwaves (see Schuman 1972: Rosenthal & Hammer 1979), although others have chosen different parameters; for example, Marmor (1978) defined a heatwave in New York as a period during which the maximum daily temperature on each of four or more consecutive days exceeded 31.1°C.

In Australia, a 1990 publication by the Bureau of Meteorology discussed "hot spells" as occurrences of more than two consecutive days with temperatures above 30°C, 35°C and 40°C (Bureau of Meteorology, 1990). In 1994, the Adelaide branch of the Bureau of Meteorology specified a selection criteria for "heatwaves" as:

> *"A minimum of five consecutive days at or above 35°C, or three consecutive days over 40°C"* (Bureau of Meteorology, 1994:1).

Similar to Australia, in Greece there is no official meteorological definition of a heatwave, and *"when meteorologists consider problems of excessive heat they do so in terms of a variety of 'Discomfort Indices'"* (Giles & Balafoutis, 1990:505). Metaxos & Kallos (1980, in Giles & Balafoutis, 1990) however defined a heatwave day in Greece with the following criteria:

1) The maximum temperature at the Athens Observatory must be at least 37°C;
2) The average daily temperature must be at least 31°C, at the same station;
3) The maximum temperature at Larissa meteorological station must be at least 38°C on this day.

These two meteorological stations were chosen because they are regarded as representative for the Greek region. In addition, Prezerakos (1989) stated that the term heatwave is used only for summer, while a sudden increase in temperature during any other season of the year is characterised as a 'warm invasion'.

Heatwave definitions are not common in the literature on heatwave consequences. Few studies refer to a specific amount of time, with the length of a heatwave characteristically defined descriptively as a *"short period"* (Mearns *et al.*, 1984) or a *"series of days"* (*pers comm.* E. Linacre 1993), or *"in the order of weeks"* (Chang & Wallace, 1987). As to temperature, in climate change analyses of extreme events, 'hot' summer days are those with temperatures greater than or equal to 35°C (*pers comm.*, K. Hennessey, CSIRO, 1994;

with temperatures greater than or equal to 35°C (*pers comm.*, K. Hennessey, CSIRO, 1994; Mitchell *et al.*, 1994a). In their analysis of excess mortality associated with summer heatwaves in Los Angeles, Oeschli & Buechley (1970) defined a *hot spell* as having a maximum temperature greater than 100°F, and minimum temperature of 80°F. Chang & Wallace (1987) isolated the 25 hottest summer months in a 91 year period for Kansas City, and used these as the baseline for their investigation of the meteorological conditions during heatwaves. Wolfson *et al* (1987) developed a heatwave index which objectively characterised a heatwave pattern at 500mb.

Many definitions referred to in the literature are subject specific, with researchers opting for a custom-made definition for their individual studies. These definitions seek to quantify a heatwave in relation to the object that is being studied, or the purpose of the study, delineating the temperature or conditions under which the object suffers rather than recognising that a heatwave exists and trying to characterise it and it's impacts.

For example, Rosenthal & Hammer (1979:72) stated *"Heatwave is taken here to mean a succession of days with the maximum temperature exceeding a specified critical level. The critical level employed will depend on the susceptibility of the plant or animal under consideration"*. 38°C was delineated as the temperature which when exceeded at the time of head emergence of sorghum, would result in severe damage to the crop, while poultry stocks would suffer death or serious losses at 35°C.

Similarly, Mearns *et al.* (1984) selected a threshold temperature of 35°C in their analysis of extreme events and corn yields in the United States Corn Belt, as this represents the midpoint of the range of high temperatures at which exceedance is commonly reported to be harmful to corn crops during a sensitive phenological period. The likelihood of a run of five consecutive days equalling this temperature was evaluated because five days theoretically covered the silking stage.

Schuman (1982) and Kalkstein & Davis (1989) also applied the concept of threshold temperature to their analyses of weather and mortality (see *Chapter 3*).

2.2 What is a Heatwave?

This bevy of definitions begs the question: *what actually is a heatwave?* In *Figure 2.1*, a model of heatwaves as a natural hazard, based on *Figure 1.1*, illustrates the interaction between *hazard* and *vulnerability* showing how extreme high temperatures and population vulnerability interact to create a heatwave as a natural hazard. The vulnerability of a population is a result of both the social system and the physiological system, which elicits control over physiological responses to extreme high temperatures. The impacts of heatwaves are filtered through public perception and education, and result in adjustments. Physiological adjustments primarily include acclimatisation to high temperatures. Social adjustments involve the implementation of prevention techniques in the modification of hazardous activities and environments, and the development of disaster strategies. These adjustments in turn affect the vulnerability of the population, and therefore the existence of the hazard.

2.3 Theoretical Considerations of a Heatwave Definition

This section aims to illustrate some of the problems involved with defining a heatwave in order to provide a *'chain of thought'* towards a heatwave definition.

According to the framework suggested in *Figure 2.1*, high temperature extremes are a different entity to a heatwave, although they are also implicitly involved in the concept of a heatwave. Quantifying the interaction between *hazard* and *vulnerability* in order to create a heatwave definition is difficult, and many researchers have overcome this problem by referring to heatwaves which were delineated at the time of occurrence. The specific heatwave was defined by those experiencing it, who apart from observing whether specific climatic variables satisfied certain requirements, made a judgement based on their own sense of discomfort.

On an individual scale, the subjective human experience changes depending on a range of variables; place of usual residence, age and health, for example. This very specific human experience relates to a individual *threshold* temperature or discomfort index, representing the point from whence an individual suffers from heat stress. On a larger scale (i.e., group rather than individual), once a threshold level of heat discomforture is reached the population is delineated as experiencing a heatwave. Often this delineation is made

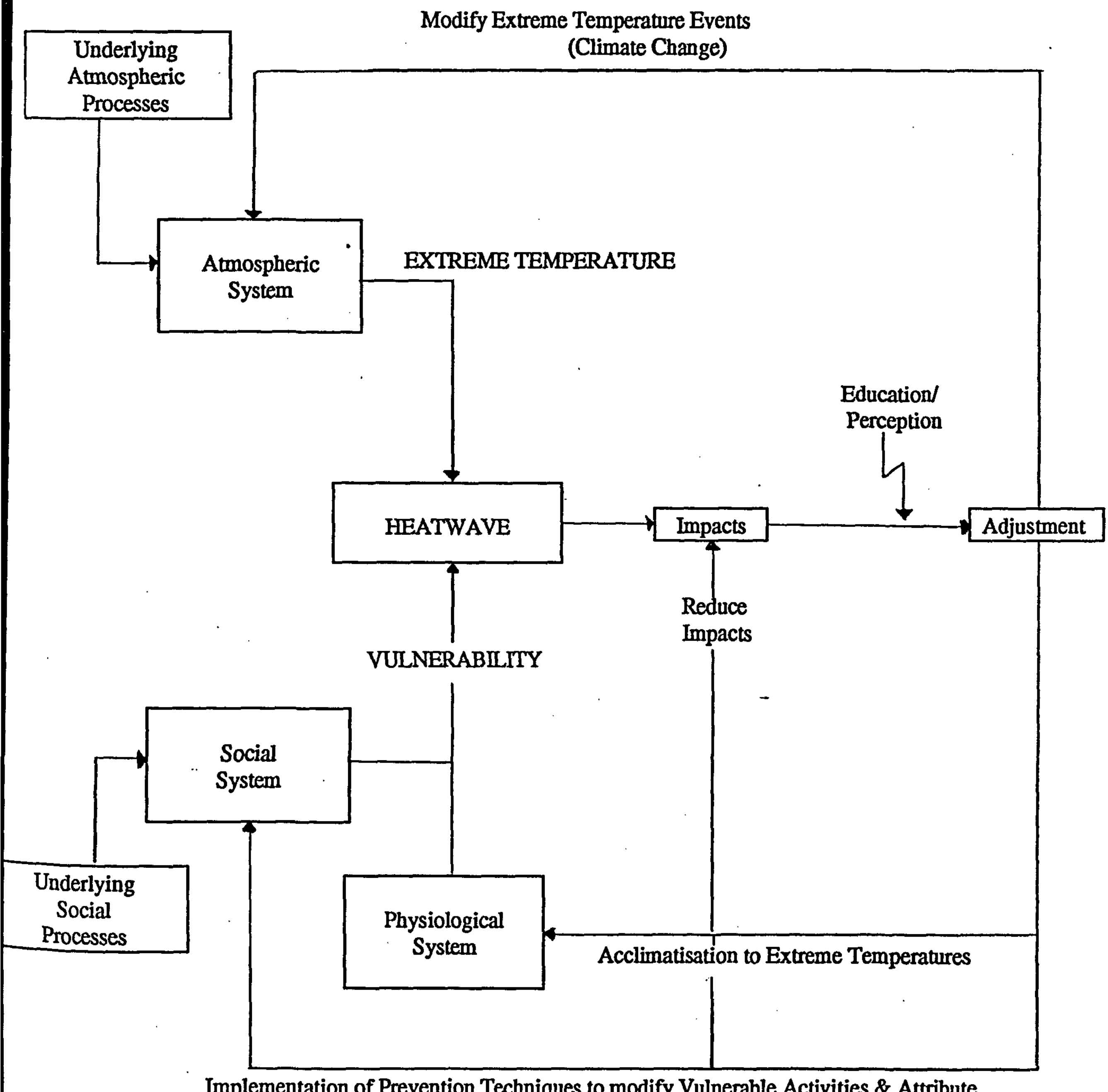

Figure 2.1. An interactive Model of Heatwaves as a Natural Hazards (based on *Figure 1.1*).

official by the media. *'The media'* was the most frequent response of numerous atmospheric scientists as to who defined a heatwave (*pers comm.*, K. Colls; K. Batt; E. Sparke; R. Nurse, 1994).

The problem of a definition is beleaguered by the questions of which variable to use, the length of time involved, and the cutoff point between normal conditions and heatwave? Perceiving the onset and end of a heatwave involves the somewhat artificial delineation of the extreme, and in this manner, heatwaves are similar to droughts (Coughlan *et al.* 1979). A definition of a heatwave requires the designation of the minimum level of a variable, above which technically, a 'heatwave' occurs.

While maximum temperature seems the obvious variable, a heatwave is the result of a potentially complex interplay of variables such as maximum daily and night time temperatures, humidity, wind speed and direction, pollution rates, number of days of high temperature etc. The subjective human experience is often best quantified by 'discomfort' indices relating temperature and humidity (and sometimes wind) to physiological and sensory responses (Giles & Balafoutis, 1990; Lee, 1980). In their analysis of mortality and high temperature, Kalkstein & Davis (1989) found *Cooling Degree Hours*[1] (CDH) to be a more significant measure of heat stress to humans than maximum temperature. In New York, night temperatures were highly significant in affecting mortality increases (Ellis *et al.*, 1975; Bridger & Helfand, 1968).

The delineation of a heatwave event changes with location. A comparison of two significant heatwaves, the Greek heatwave of 1987 and the heatwave in England and Wales in 1976, provides an example. In Greece, temperatures exceeded 38°C for nine successive days in many locations (Giles & Balfoutis, 1990). In Birmingham the heatwave consisted of a run of fifteen days with temperatures over 20°C and a maximum of 25°C (Ellis *et al.*, 1980). Significant numbers of fatalities (see *Chapter 3*) occurred in both these heatwaves, yet they satisfy vastly different temperature definitions.

The logical progression is to a definition based on the climate of a location, thereby effacing the inadequacies of a universal definition. Weather apparently has an affect on

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[1] Cooling Degree Hours (CDH) represents a measure of the day's warmth, accounting for the duration of high temperatures rather than simply the intensity (see Kalkstein & Davis, 1989:49).

human health on the warmest 10 - 20% of days (Kalkstein & Davis, 1989), a delineation which may well describe a suitable heatwave definition based on the temperature pattern for a particular location. However, some climates are riskier than others, with the strongest relationship between mortality and temperature in the United States occurring in regions where hot weather is uncommon (Kalkstein & Davis, 1989). Seasonal acclimatisation adds further complexity to a heatwave definition, in that an individual or population is more susceptible to a heatwave at the beginning of the summer than by the end when the body has adjusted to warmer temperatures. Kalkstein & Davis (1989) found that the timing of a heat event within a summer was often as important as it's severity, in influencing mortality rates.

While heatwaves have historically been defined on subjective experience, the consequence of extreme high temperature events for other creatures and inanimate objects must be acknowledged. For example, a crop could be potentially destroyed following a severe high temperature event at a sensitive time in its growth cycle. Also, the impact of a very hot day on water consumption is unlikely to decrease as the summer continues and, depending on rainfall conditions, may actually increase. These examples indicate a need to define heatwaves in relation to the phenomena/consequences under consideration.

2.4 Defining a Heatwave

On a practical level a heatwave definition requires variables which are reasonably simple and readily available both now and in the past. Especially for retrospective studies, there are limited data available. For example, only morning and afternoon temperatures were available for an investigation of temperatures and death rates within a nursing home in western Sydney (Macpherson *et al.*, 1967).

Because of the complexity involved with the quantification of a heatwave, three definitions proposed by the author are considered. One of these definitions is media based, the other two climatologically derived, in order to compare the appropriateness of the two variable based definitions with the traditional subjective definition.

These three definitions are compared for two study sites to enable analysis of the spatial differences in heatwave incidence. Temporal analysis of the three definitions provides a sense of heatwave incidence and severity. The aim is not to analyse individual heatwaves, but heatwaves in general.

The three definitions are:

Definition 1: Media definition: heatwaves are events defined by the media, where the media is *The Sydney Morning Herald*. References to excessive heat also comprise part of this definition.

Definition 2: A Universal definition: Heatwaves occur when the maximum daily temperature is equal to or exceeds 35°C.

Definition 3: A location-related definition: A heatwave occurs when the maximum daily temperature is equal to or exceeds a temperature which represents the cutoff point of the top 5% of the daily maximum temperature range. This point represents approximately three standard deviations from the mean (95.45%) for a normal distribution.

The length of time will not be specified as part of the definition of a heatwave. The number of days which satisfy the above three definitions, the 'run', will instead be used to describe the duration of a heatwave.

2.5. Methodology

2.5.1 The Study Sites

Two study sites, Sydney and Broken Hill, were chosen to generate a contrast between locations of vastly different climates, within New South Wales. As the major population centre, Sydney was an obvious choice. Broken Hill represents a climatic contrast to Sydney, and in addition, preliminary results for *Chapter 3* suggested it to be significant in terms of human mortality. The location of these two sites are shown in *Figure 2.2*. Broken Hill Meteorology Station is located in Patton Street and the Meteorology station in Sydney is at Observatory Hill.

2.5.2 Data Sources and Methodology

Newspaper accounts of heatwaves were obtained from *The Sydney Morning Herald* (1803-1992). Daily maximum temperatures for Sydney and Broken Hill were acquired from the Bureau of Meteorology National Climate Centre. Data for Sydney extends from 1859 to

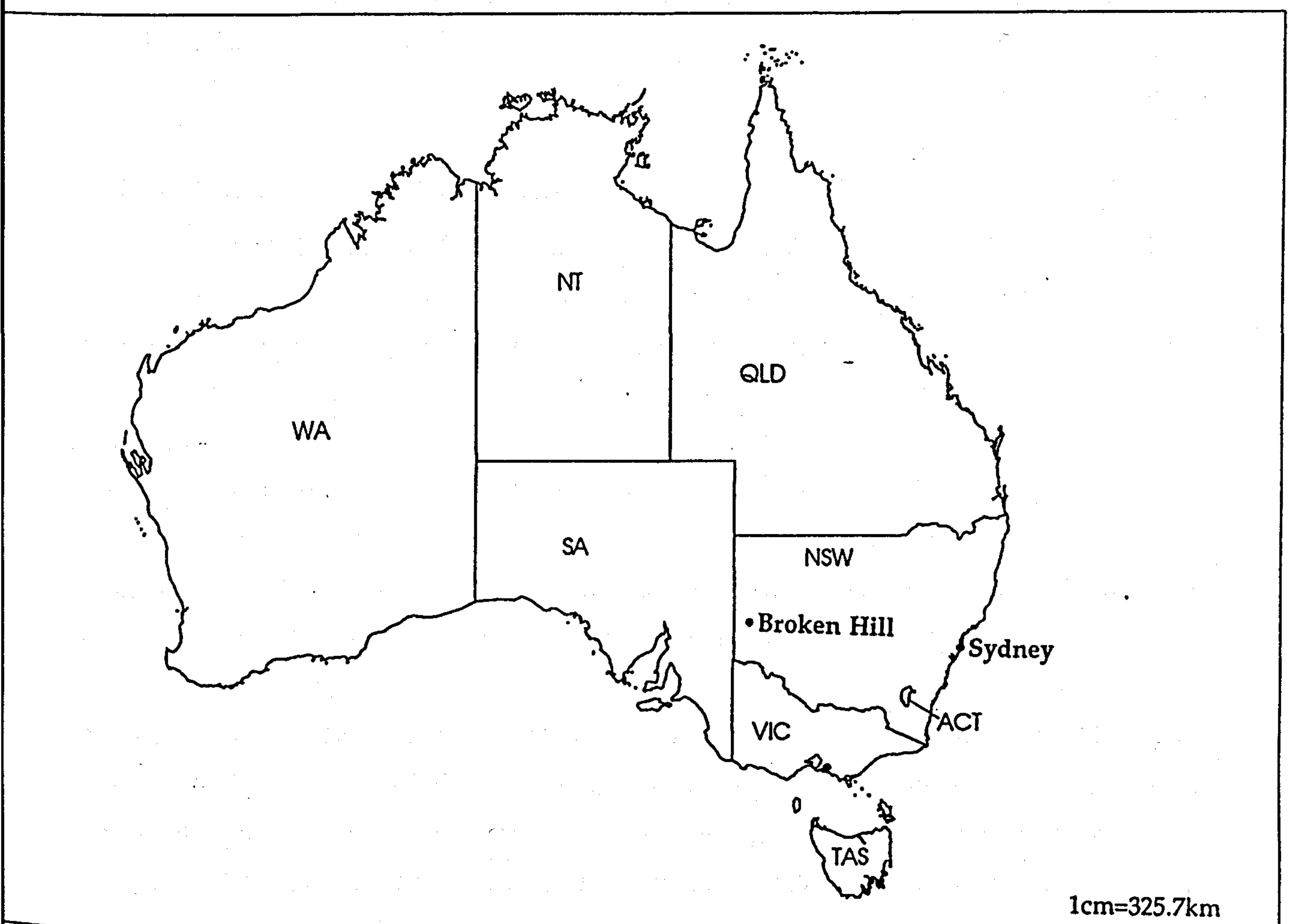

Figure 2.2 Map of Australia showing the location of Sydney and Broken Hill.

1994, while for Broken Hill from 1957 to 1994, with the exception of 1979-85[2].

Newspaper descriptions of heatwaves were formed into a database of heatwave events, describing duration and temperature for Sydney and Broken Hill.

The data were analysed in *Paradox* (a relational database) and *Quattro Pro* (a spreadsheet package), the financial year being used to prevent the artificial division of data into conventional years as opposed to summer periods; i.e., the summer of 1923-24 is referred to as 1924. These years are also referred to as *'summers'*. Days which fit the credentials of the definitions are cited as *'heatwave'* days.

2.6 Results: Heatwave Incidence

The incidence of the three definitions for the two study sites is given in *Table 2.1*, and an inventory of the occurrence of heatwave days, defined by *Definition 2* for Sydney is given in *Appendix 1* to provide a reference for later sections of the thesis.

2.6.1 Sydney

The cutoff point for *Definition 3* for Sydney was 29.3°C.

According to *Definition 1* and *2*, on average three heatwave days occurred each financial year, while according to Definition 3 the average was 18 (see *Table 2.1*).

The distribution of 'heatwave' days for the three definitions by financial year is shown in *Figure 2.3*. The second definition (temperatures equal and above 35°C) was more consistent than *Definition 3* in terms of the frequency of media defined heatwave days (*Definition 1*). However, as illustrated in *Figure 2.3*, years in which numerous heatwave days were reported in *The Sydney Morning Herald* were not always 'hot' years according to the two temperature based definitions (*Definition 2* and *3*). In addition, the relative magnitude of the number of heatwave days occurring according to *Definition 2* and *3* are not always in phase. The greatest number of days with maximum temperature exceeding

[2] The fact that data for Broken Hill is missing for this period was not discovered until after the data was purchased. If this information was made available to the author prior to purchasing, the second study site would have been changed to an alternative location with a complete record.

29.3°C was 34, which occurred in 1990/91. However, only a moderate number of days above 35°C occurred in that summer, and the highest frequency of days exceeding 35°C was 10 in 1896. There were ten years when temperatures did not reach 35°C at all. The minimum number of times that temperatures reached 29.3°C was 6 in 1873.

Table 2.1. Heatwave incidence at Sydney and Broken Hill for the three definitions.
* these results are slightly different to those published recently (June, 1994) by Mitchell (1994a), and discussed in Chapter 6.1. However Mitchell (1994a) only analysed maximum temperatures for summer months.

	No. days	Average No. of days per financial year	Proportion as isolated events
Sydney (1859 to 1994)			
Definition 1: Media Definition :post 1859 :post 1824	 369 375	 2.7 2.2	 60% 60%
Definition 2: Universal Definition (≥35°C)	413	3.03*	86%
Definition 3: Location based Definition (>=29.3°C)	2472	18.2	59%
Broken Hill (1957 to 1994)			
Definition 1: Media Definition :post 1957 :post 1896	 17 355	 0.5 3.62	 35% 37%
Definition 2: Universal Definition (≥35°C)	990	31.87*	18%
Definition 3: Location Based Definition (>=36.9°C)	561	18.06	25%

The average temperature of heatwave days at Sydney reported in *The Sydney Morning Herald* was 35.3°C. Most of these reports compare reasonably well with official temperatures. Only six heatwave days were recorded before 1859 (the year from when

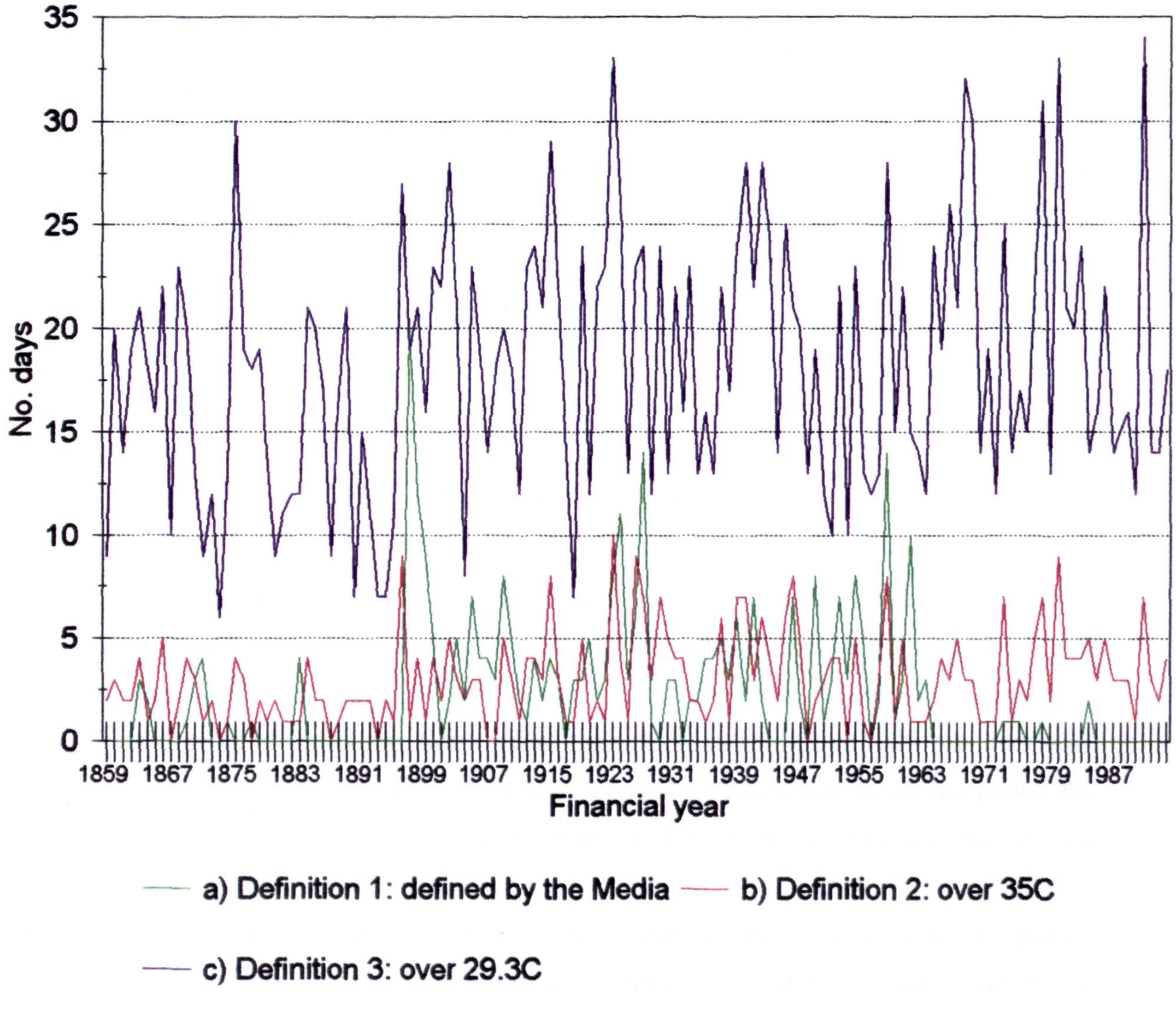

Figure 2.3 Frequency Distribution of Heatwave days at Sydney (1859-1994), according to *Definition 1, Definition 2* & *Definition 3,* by financial year.

official temperature data is available for Sydney).

Over 60% of heatwave days in Sydney, for all definitions, have occurred as isolated incidences, with 86% of all days with temperatures exceeding 35°C occurring alone (see *Table* 2.1). According to this parameter, *Definition 3* is the most consistent with the media defined heatwaves (*Definition 1*), with approximately 60% of days occurring as isolated incidences for both definitions. This contrasts to the correlation exhibited on comparison of frequency alone, as discussed above.

There were 32 occurrences of runs of 2 days reported in *The Sydney Morning Herald* (*Definition 1*) and runs of 3 and 4 days occurred on 5 occasions. Based on *Definition 2*, on only 21 occasions has a run of 2 days with temperatures greater or equal to 35°C occurred. Runs of 3 days and 4 days developed on two instances, in 1936/37, 1993/94 and 1895/96, 1959/60 respectively. Because of the higher frequency of days with temperature equal to or above 29.3°C (*Definition 3*), run length was longer, the maximum being 7 days in 1993/94.

2.6.2 Broken Hill

The cutoff point for *Definition 3* for Broken Hill was 36.9°C.

Because *The Sydney Morning Herald* is Sydney-based the reporting of heatwaves at Broken Hill is irregular, and probably an underestimate of the actual occurrences[3]. Recording of heatwaves was more consistent in the earlier years when the newspaper acted as a chronicler of events, than in the latter years for which temperature data are available. This is demonstrated in *Table 2.1* by the large decrease in heatwave incidence post-1957. Also from *Table* 2.1, the average number of heatwave days at Broken Hill reported by *The Sydney Morning Herald* is markedly low in comparison to the other two definitions, suggesting that this definition does actually underestimate heatwave frequency. Unfortunately, there are no records of heatwave incidence kept at the Broken Hill Library, and perusing Broken Hill papers was beyond the scope of this work.

While the average temperature of 'heatwave' days at Broken Hill recorded in *The Sydney*

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[3] see *Section 3.4.1.i* for a more complete discussion of *The Sydney Morning Herald* as a data source.

Morning Herald was 39.5°C, a figure close to *Definition 3,* there are too many inaccuracies inherent in the data to enable any conclusions regarding the similarity of the two climate-based definitions with *Definition 1.*

On average over 30 days with temperatures above 35°C (*Definition* 2) occur each financial year at Broken Hill (see *Table 2.1*). The frequency of heatwave days according to *Definition 3* is, as would be expected[4], the same as at Sydney for this definition.

The distribution of heatwave days at Broken Hill according to the three definitions is displayed in *Figure* 2.4. A noticeable hot year was in 1990/91 when temperatures exceeded 35°C (*Definition 1*) on 58 occasions and 36.9°C on 45 occasions. At no time, has there been a year when the maximum temperature did not reach 35°C at least once; the minimum number of occurrences being 10 in 1973/74. The number of occurrences of temperatures above 36.9°C ranged from a minimum of 4 in 1973/74 to the maximum of 45 in 1990/91. The relative frequency distribution of these two definitions show a greater degree of consistency than for Sydney.

The maximum temperature exceeded 35°C for 13 days in a row in 1969/70, and for 17 days in 1978/79. The maximum run was 10 days, an event which occurred in 1978/79 and 1987/88.

2.6.3 Run Length and Average Temperature

The average temperature by the length of run for the three definitions for Sydney and Broken Hill are given in *Table 2.2* and *Table 2.3* respectively. At Broken Hill, the maximum temperature averaged 41°C for a period of seventeen consecutive days. In Sydney, the longest sustained period of high temperatures occurred from the 2nd to the 8th of January 1994 when daily maximums averaged 37°C over a seven day period. The lowest temperature described as 'heatwave' at Sydney as reported in *The Sydney Morning Herald* was 22°C, while at Broken Hill it was 31°C. This figure for Sydney is exceptionally low, supporting the suggestions made in *Section 2.3* that heat stress is affected by factors additional to maximum temperature.

[4] since this is a frequency derived definition

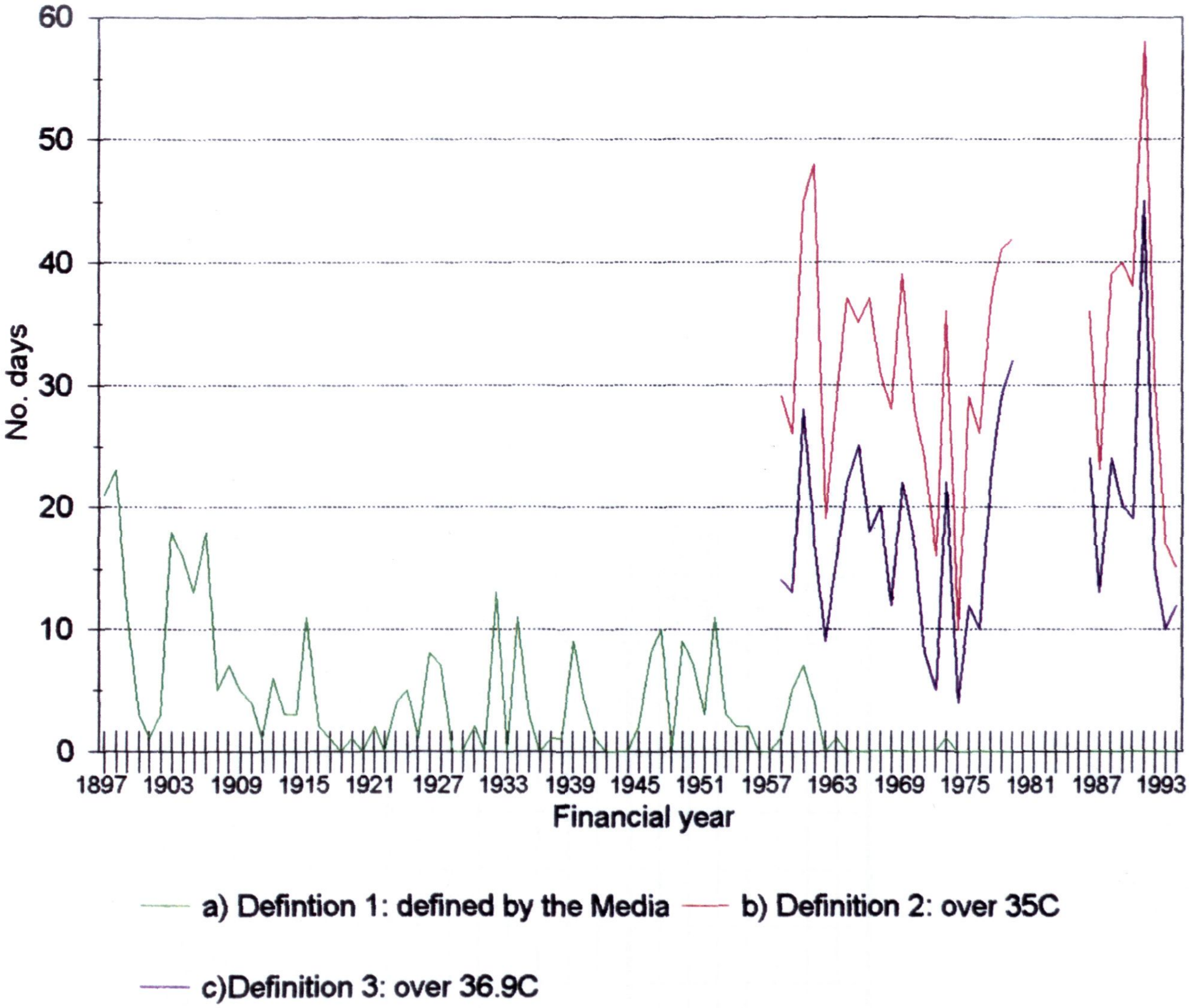

Figure 2.4 Frequency Distribution of Heatwave days at Broken Hill (1957-1994), according to *Definition 1, Definition 2* & *Definition 3,* by financial year.

Table 2.2. **Frequency, and average maximum temperature of runs of various lengths at Sydney according to the three temperature definitions**

Length of run	Temperature (C)																							
	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Definition 1																								
1	2		1		5	2	6	6	6	6	8	6	6	6	6	5	6	2	3	1	2		1	1
2								1	2	2	2	3	2	2	3	1	1	1		2	1			
3					1		1							2	1									
4									1									1		1				
Definition 2																								
1														49	64	59	39	28	21	11	8			1
2														2	6	4	6	3						
3															1	1								
4																	1			1				
5																								
6																								
7																								
Definition 3																								
1								80	126	119	100	82	73	63	46	29	22	12	12	4	2			
2								2	45	44	43	54	45	31	15	9	4	2						
3									6	11	20	12	7	4	7	1	1							
4									1	1	4	4	2											
5										2	1					1								
6										1			1			1								
7																1								

Table 2.3. Frequency, and average maximum temperature of runs of various lengths at Broken Hill according to the three temperature definitions

Length of run	Temperature (C)														
	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Definition 1															
1	1	3	2	3	5	4	5	11	11	8	9	8	6	3	
2								3	6	2	1	2	3	1	2
3					1		1		2		2	1		1	
4					1					1	1			2	
5									1	1		1	1		1
6										2					
7													1		
8									2						
Definition 2															
1					28	24	25	18	6	6		1			
2					6	20	19	12	7	4					
3					3	6	19	13	6	4	2				
4						4	7	5	3	5					
5					1	2	2	7	5			1			
6					1		2	3	2	2	2				
7								1	2						
8							1			1					
9							1	4							
10								1		1					
11							1	1							
13								1							
17											1				
Definition 3															
1							24	28	22	13	5	2			
2							5	18	13	10	1	1			
3							2	9	7	7	5	1			
4							1	6	4	5					
5								3	1	2		3			
6								1		2					
7										1					
8								1	2						
10										1	1				

2.6.4 Monthly Distributions of Heatwave Days

All heatwave days reported in *The Sydney Morning Herald* occurred between the months of October and March (and once in April at Broken Hill), with the highest frequency in January.

Annual distributions of heatwave days are approximately the same for all definitions (October to May/April), with the exception of *Definition 3* at Sydney which has a wider range (August to May). Monthly distributions of heatwave days according to *Definition 2* and 3 are shown in *Figure 2.5,* for the years 1957-1994. Similar to *Definition 1,* the maximum number of heatwave days occur in January at Broken Hill, while in Sydney, January and December are both peak months. Although heatwaves defined by Definition 3 occur on the same frequency at Sydney and Broken Hill, *Figure 2.5* illustrates that these days are spread more throughout the year at Sydney. Also illustrated by *Figure 2.5* is the difference in the number of days with temperatures greater than 35°C between the two sites.

2.6.5 Discussion

A distinct trend in the frequency of 'heatwave' temperatures for Sydney is noticeable in *Figure 2.2.* For the period 1859 to 1894/95, the average number of times that the maximum temperature exceeded 35°C in a summer period was 1.9 days. The maximum number for one summer was 5 in 1865/66. In contrast, the average number of days with temperature above 35°C for the period 1895/96 to 1993/94 was 3.5 days per summer, and the maximum was 10 (in 1923/24). Using a chi squared test, the increase in the number of days above 35°C since 1895/96 is highly significant at less than 0.05%. The distribution of temperatures above 29.3°C since 1894/95 also exhibits this trend (significant at less than 0.05% using a chi squared test). With the exception of one occasion in 1875/76, temperatures above 35°C in the period 1859-1894/95 occurred as single days. All runs of 3 and 4 days duration occurred in the later period from 1895/6 to 1994. For both periods there were five incidences when maximum temperatures did not reach 35°C at all during the entire summer. Considering the time periods involved, since 1895/96 the chance of a year occurring when the maximum temperatures never reaches 35°C has decreased significantly (chi squared test: 10% level). This trend may be the result of various methodological errors; in terms of data recording and the standards applied to earlier

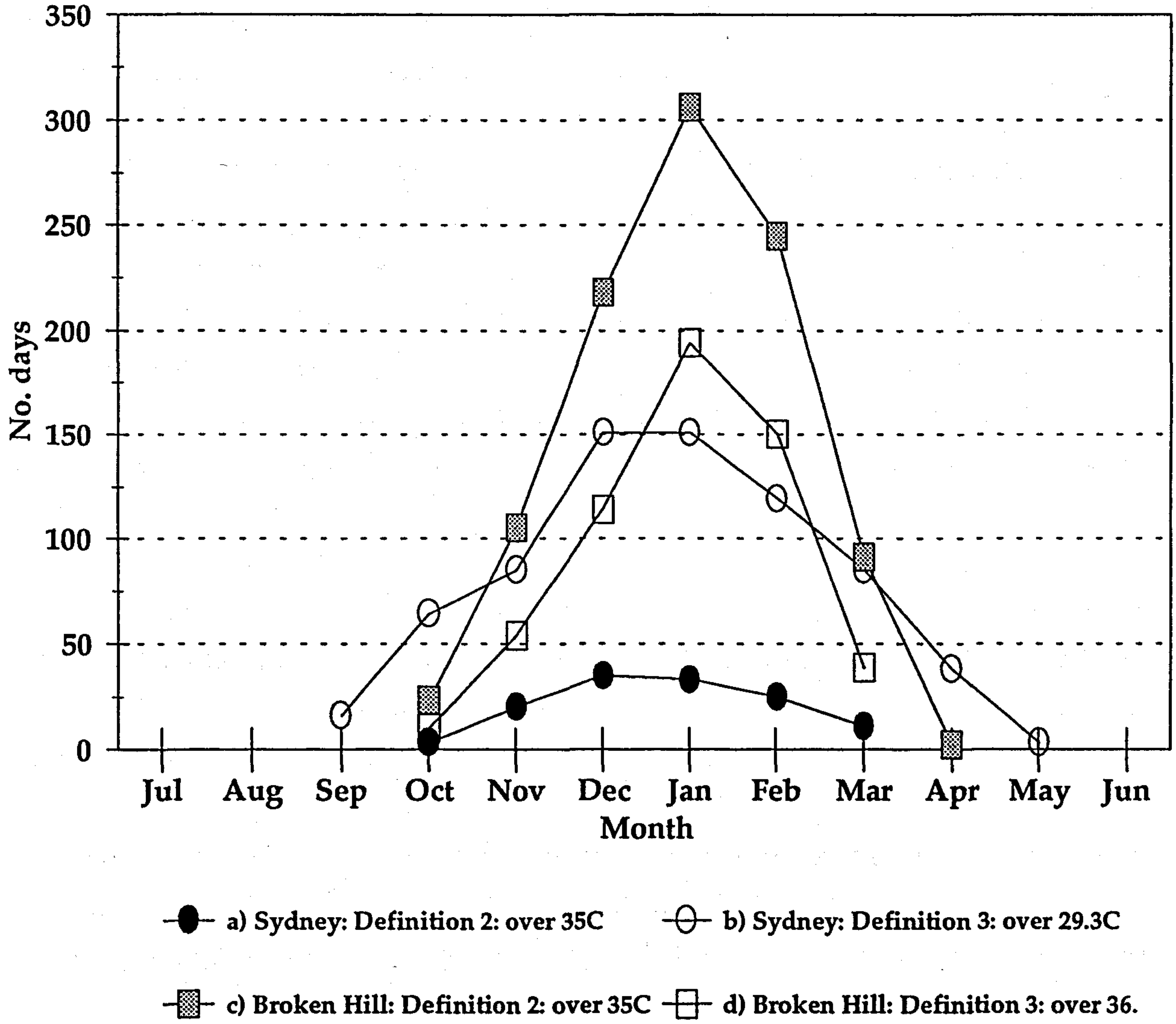

Figure 2.5 Monthly distribution of heatwave days at Sydney and Broken Hill (1957-1994), according to *Definition 2* and *Definition 3.*

temperature measurements; the growth of the urban heat island or other factors. The similar increase in the chance of experiencing a run of more than one 'heatwave' days, may simply follow from the greater frequency of heatwave days. However, it may also signify an increase in the grouping of heatwave days.

The number of 'heatwave' days by financial year in Broken Hill and Sydney since 1957 were correlated to assess whether the annual distribution of 'heatwave' temperatures was similar between the two sites. *Figure 2.6* shows a scatter diagram of these distributions. While there appears as though there is little or no relationship, the correlation coefficient, r, is 0.42, and this is significant at the 2-5% level. It seems that there is a relationship between the number of occurrences of heatwave days by summer at the two sites. This does not necessarily imply that Sydney and Broken Hill experience heatwaves at the same time.

'Heatwave' days at Broken Hill appeared to have a greater tendency towards grouping into runs than in Sydney, with only 18% of days with temperatures above 35°C occurring as isolated incidences, while this was true of 86% of days in Sydney. Since *Definition 2* is delineated by frequency, and the average number of 'heatwave' days per summer is equivalent for the two sites, a similar distribution of run lengths would be expected between the two sites. Still only 25% of days occurred as isolated events at Broken Hill, compared with 59% in Sydney. This suggests that Broken Hill is more prone to the grouping of high temperature days into long periods of heat, probably as a result of the greater annual temperature variability of Broken Hill's climate in comparison to Sydney's (Dury, 1972).

While Broken Hill experiences many more days with temperatures above 35°C than Sydney, there is little difference in the maximum temperatures experienced, as illustrated in the temperature frequency distribution in *Figure 2.7*. Sydney's maximum temperature was 45.3°C on 14/1/1939 and Broken Hill's maximum was 45.9°C in 3/1/1990. The centre of Australia has been described as a heat island, experiencing the highest extremes of temperature most frequently but the magnitude of extreme temperature rises very slowly as recurrence intervals increase (Dury, 1972). In contrast, the temperature difference between low and high recurrence intervals in the coastal areas in the east, south west and west is high (Dury, 1972). High temperature extremes in Sydney are

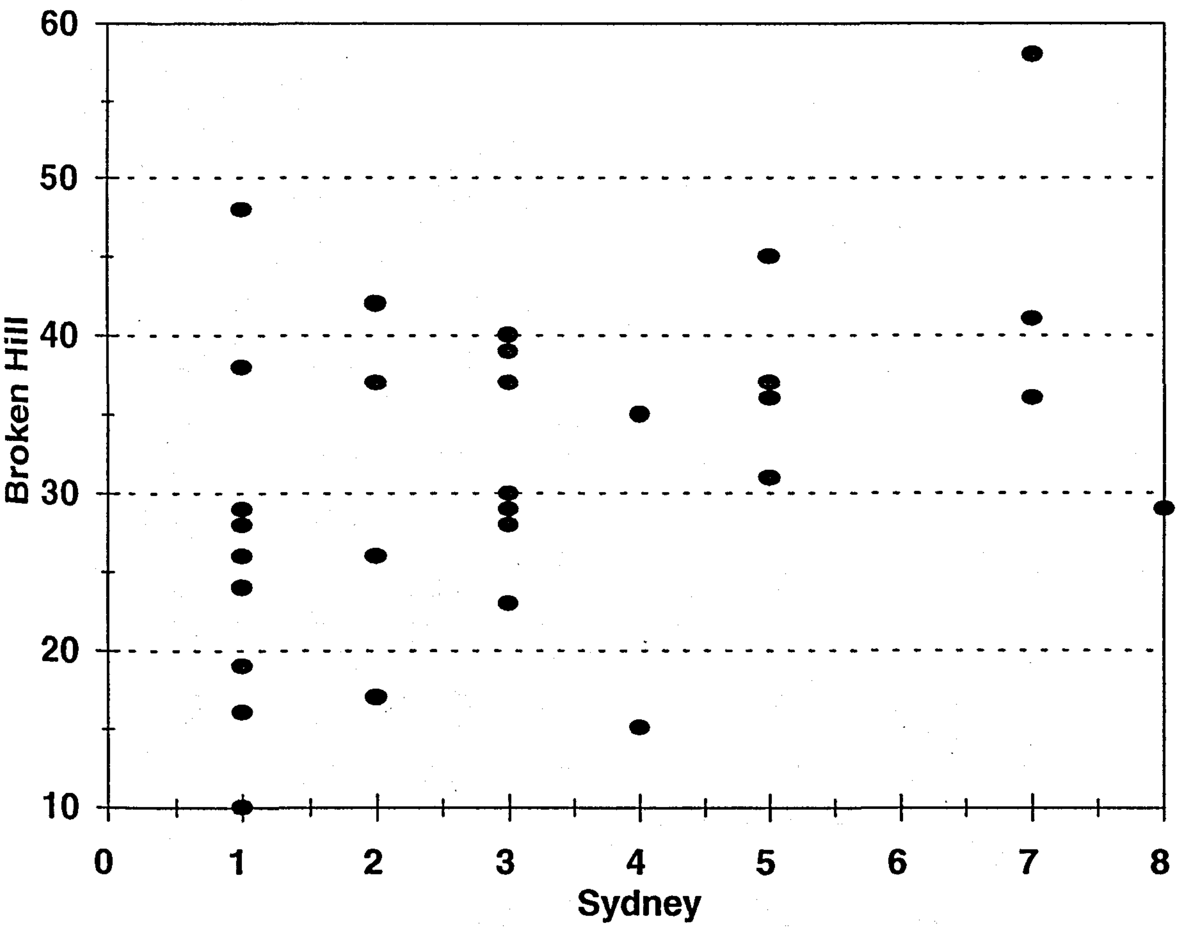

Figure 2.6 Scatter diagram of the frequency of heatwave days (by financial year) at Sydney and Broken Hill, according to *Definition* 2 (temperature above 35°C).

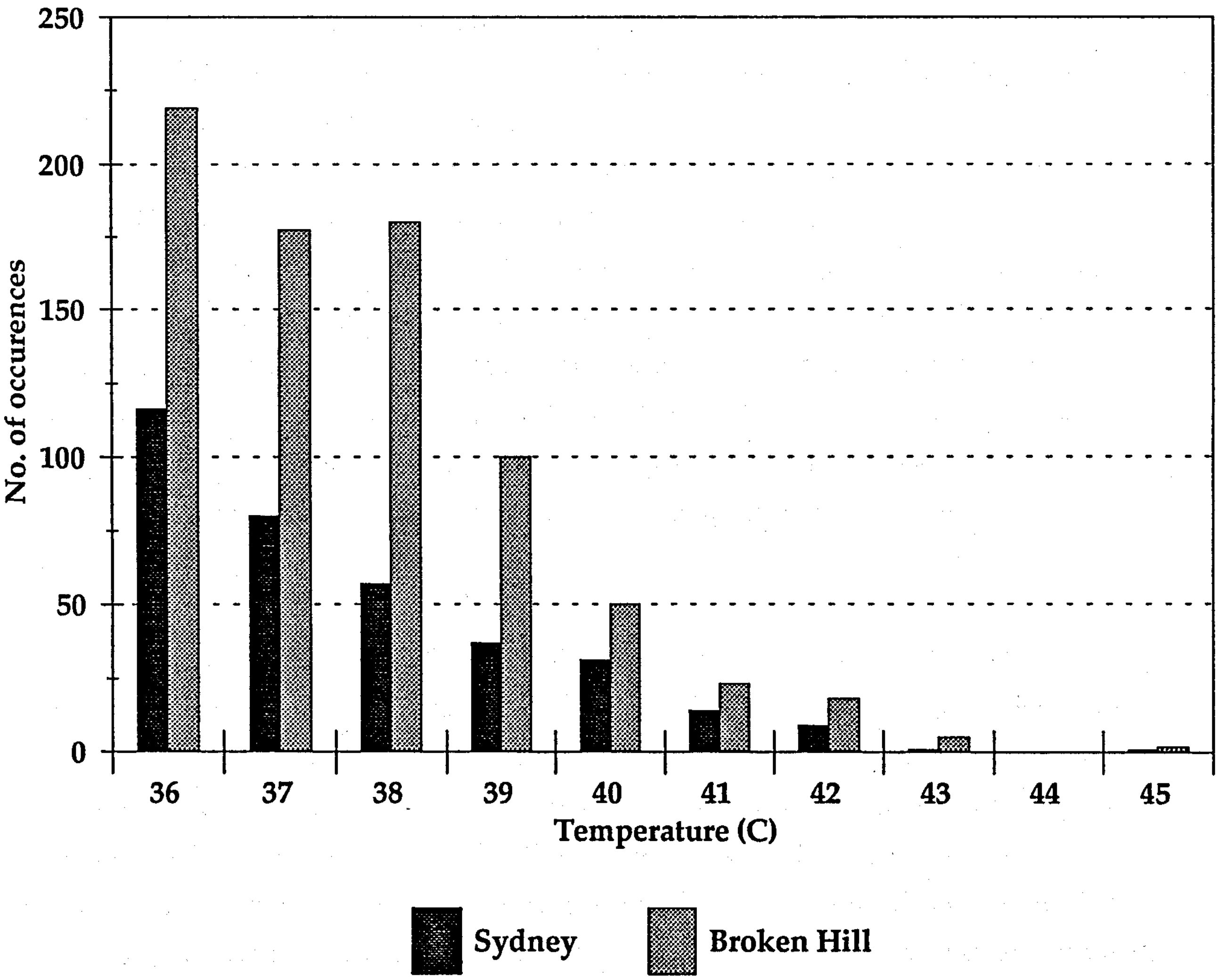

Figure 2.7. Frequency distribution of temperatures above 35°C at Sydney (post 1859) and Broken Hill (post 1957).

associated with the outflow of air from the hot interior, including Broken Hill, to a degree that overcomes maritime cooling influences (Dury, 1972).

2.7 Summary and Conclusions

From these results there are four important points to be made:

• Firstly, in Sydney there appears to have been a change in the frequency of temperatures above 35°C and 29.6°C since 1895/96.

• Secondly, Broken Hill experiences many more days when the maximum is greater or equal to 35°C, and longer runs of 'heatwave' temperatures.

• Thirdly, despite the difference in the frequency distribution of 'heatwave' days, the range of temperatures experienced at the two sites is virtually the same. This means that Sydney experiences unusually high temperatures very rarely, while Broken Hill experiences longer and more frequent periods of high, but not so rare temperatures.

• Fourthly, that high temperatures tend to clump together and aggregate into runs to a greater extent at Broken Hill, despite the same frequency per summer as in Sydney (Definition 3).

This analysis has emphasised the difficulties involved in defining a heatwave. If the definition developed by the Bureau of Meteorology, Adelaide, is applied to Sydney's data, Sydney has not theoretically experienced a heatwave in over a hundred years of records. The comparison of the incidence of heatwaves according to the two climatically-based definitions with those recorded in *The Sydney Morning Herald* has also exemplified that a heatwave is a complex event, resulting from the interaction of numerous factors combining in different ways at different times, and is therefore not easily classified into a simplistic equation.

Heatwaves are very similar to droughts as a natural hazard, for the reasons outlined in *Chapter 1*, and also because of the difficulties which confront a general definition. There is no general definition of drought (McCutchen, 1976), and drought definitions vary from simplistic notions based on rainfall parameters, to more complex definitions involving soil moisture and evaporation variables (Hounam, 1976). Time lengths vary from 48 hours to several months (Hounan, 1976). In addition, because the occurrence of drought becomes evident through it's impacts (McCutchen, 1976), definitions vary according to which impact is of interest. Heathcote (1969) stated that "*a general and useful definition of drought seems to be virtually impossible*". In much the same way, a general heatwave definition may be specious; however, the definitions analysed above appear to give some objectivity to the study of heatwave consequences.