The University of Reading
School of Mathematics, Meteorology & Physics

HEAT WAVES: THEIR CLIMATIC AND BIOMETEROLOGICAL NATURE IN TWO NORTH AMERICAN REGIONS

by

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Abstract

Heat waves are a major summer killer in the United States with approximately 237 people dying every year. Whilst in the past people have failed to recognize the dangers of heat, the impacts of heat on human health are becoming an issue of increased significance, especially because of predictions for warmer weather over the next century.

This lack of appreciation of the effects of a heat wave have in many ways stemmed from the absence of a rigid definition and scientifically calculated temperature thresholds above which to warn the public. With the role of humidity in calculating how hot it actually “feels” becoming increasingly understood, the use of Steadman’s apparent temperature in defining these thresholds has become paramount and will be continued throughout this study.

Two of the cities most susceptible to heat waves in the United States, Chicago, Illinois, and New York City, New York have been examined in detail. Here the National Weather Service thresholds for heat emergencies, daytime high of greater than or equal to 40.6°C and night time low of greater than or equal to 26.7°C, are too high and hence ineffectual at preventing loss of life. Therefore, new heat wave criteria have been calculated by obtaining the most appropriate percentile level of the normally distributed apparent temperature over the extended warm period (May, June, July, August, September) of 1901 to 1990 for Chicago and 1951 to 2000 for New York. These new thresholds are able to capture all of the significant heat waves over the period in question whilst being stringent enough to discount hot summers.

Furthermore, trends in humidity were examined and dew point temperature was seen to increase relative to the mean over the latter part of the century. Although no conclusive evidence was found to suggest a trend, frequency and duration of heat waves have also been analysed along with the potential effects of climate change.

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I confirm that that this dissertation is all my own work and any materials used from other sources have been duly acknowledged.

Contents

Introduction

Heat waves are considered to be a major cause of weather related death in the United States second only to extreme cold. An average of 237 people die every year from heat related illnesses which when compared to the 129 fatalities each year from events such as hurricanes, tornadoes and lightning illustrates how crucial it is to accurately predict the onset of a heat wave. In fact, the United States National Weather Service (NWS) states that over the period from 1936 to 1975 almost 20,000 people died in the United States from the effects of heat**.** However these are what can be classed as direct casualties, in reality no–one can know how many deaths are associated with extreme hot weather.

The objectives of this study are to examine the various influences on and effects of a heat wave, to ascertain methods of identifying them and how best to forewarn the public in order to reduce the varied impacts that such extreme high temperature events induce.

In order to accurately identify a heat wave the initial task is to obtain a meaningful definition. The American Meteorological Society defines a heat wave as ‘A period of abnormally and uncomfortably hot and usually humid weather. To be a heat wave such a period should last at least one day, but conventionally it lasts for several days to several weeks’. In 1900 A.T. Burrows more rigidly defined a *hot wave* as a period of three or more days on each of which the maximum shade temperature reaches or exceeds 32.2°C (American Meteorological Society, 2000). The first definition provides no help in ascertaining the levels at which heat becomes dangerous and is far too vague to be of any practical use, whilst the second would lead to Phoenix, Arizona spending most of the year within a *hot wave*. More realistically, the comfort criteria for any one region are dependent upon the normal conditions of that region and hence more specific definitions are desirable.

The domains in which extreme high temperature events affect human society are wide ranging and include among others, agriculture, water supply, industry and of course mortality. The extent to which these impacts occur will be investigated in order to appreciate the necessity for improved heat warning systems.

Ironically the cities most vulnerable to heat waves are the ones that do not experience them very often. This is because where sporadic hot weather is less common, it is much more taxing on the population than where prolonged heat and humidity is typical. Chicago, Illinois and New York City, New York are two such cities. Their climates have a wide range of variability and hence during times of extreme heat, impacts are severe. It is desirable therefore that accurate heat warning thresholds are calculated which specifically pertain to the local climates of each region. Relationships between the various elements of a heat wave are analysed in order improve the prediction process. Furthermore, with the potential for an increasingly warm climate it is important to assess if climate change throughout the last century is reflected in changing heat wave incidence in order to predict possible future change in the frequency of heat waves

All these enhancements in our knowledge of heat waves can only aid in the process of forecasting future events. Forecasting plays an important role in alerting the public to the dangers of extreme heat and we must therefore examine the various value added aspects of a forecast in order to minimise loss of life.

Chapter 1

The Definition of a Heat Wave

According to international literature there is no strict definition for the term ‘heat wave’. It is, in fact, possible that the term has arisen more from common usage than from being a definable phenomenon. However, in an attempt to save lives there have been many efforts to define such extreme heat events so as to accurately warn the public of their onset. For example, the Weather Channel uses the following criteria in order to specify a heat wave for the United States:

a) A minimum of 10 states with maximum temperature greater than 32°C

b) Temperatures must be at least 5°C above the normal in parts of that area for at least two days or more.

This would appear to be an adequate definition; however it lacks any specific detail and can only be applied nationally, providing no assistance for such things as a statewide heat wave.

An alternative definition (Robinson, 2001) states that a heat wave ‘is an extended period of unusually high atmosphere-related heat stress, which causes temporary modifications in lifestyle and which may have adverse health consequences for the affected population.' This definition indicates that although a heat wave is a meteorological event it cannot be truly understood without considering the human impacts. It also indicates that providing a forecast solely of the dry bulb temperature may not be the most accurate method of understanding how hot it will feel to the general public. We will take a closer look at how best to quantify a heat wave in section 1.3.

1.1 Meteorological Conditions

When considering the important meteorological aspects of a heat wave it is necessary to investigate the origins of the air masses involved. Essentially, the air masses would be expected to flow from much lower latitudes bringing the warm air northwards. This would create constant warm advection, boosted (ideally) by a suppression of both clouds and precipitation. However, in some instances, scattered cloud will be observed due to the instability of the boundary layer; the intense heating of the ground causing parcels of air with substantial water vapour content to be released from the ground and, due to the cooler environment, the parcel of air rises and cools until it reaches such a point that it becomes saturated and clouds form. In addition to this, such extreme high temperature events are sustained as wind speeds tend not to exceed approximately 2-3ms^{-1}, anything stronger and the warm air masses would be moved away from the region in question. Throughout a heat wave we would also witness increased insolation and strong subsidence.

The pattern of 500mb heights in Figures 1.1 and 1.2 indicate the difference between a summer with an intense heat wave (Figure 1.1) and one whose temperatures were near average (Figure 1.2). The intense heat wave displays a pronounced ridge over the central United States with marked troughs over the two oceans. A region of high pressure is observed over the centre of the country with anticyclonic conditions reaching down to the surface. For the summer exhibiting near normal temperatures in Figure 1.2 however, a weak ridge occurs over the western United States. Heat waves over the region are thus possibly a consequence of downstream development i.e. a smaller ridge gaining amplitude in time and space, which leads to the type of feature illustrated in Figure 1.1.

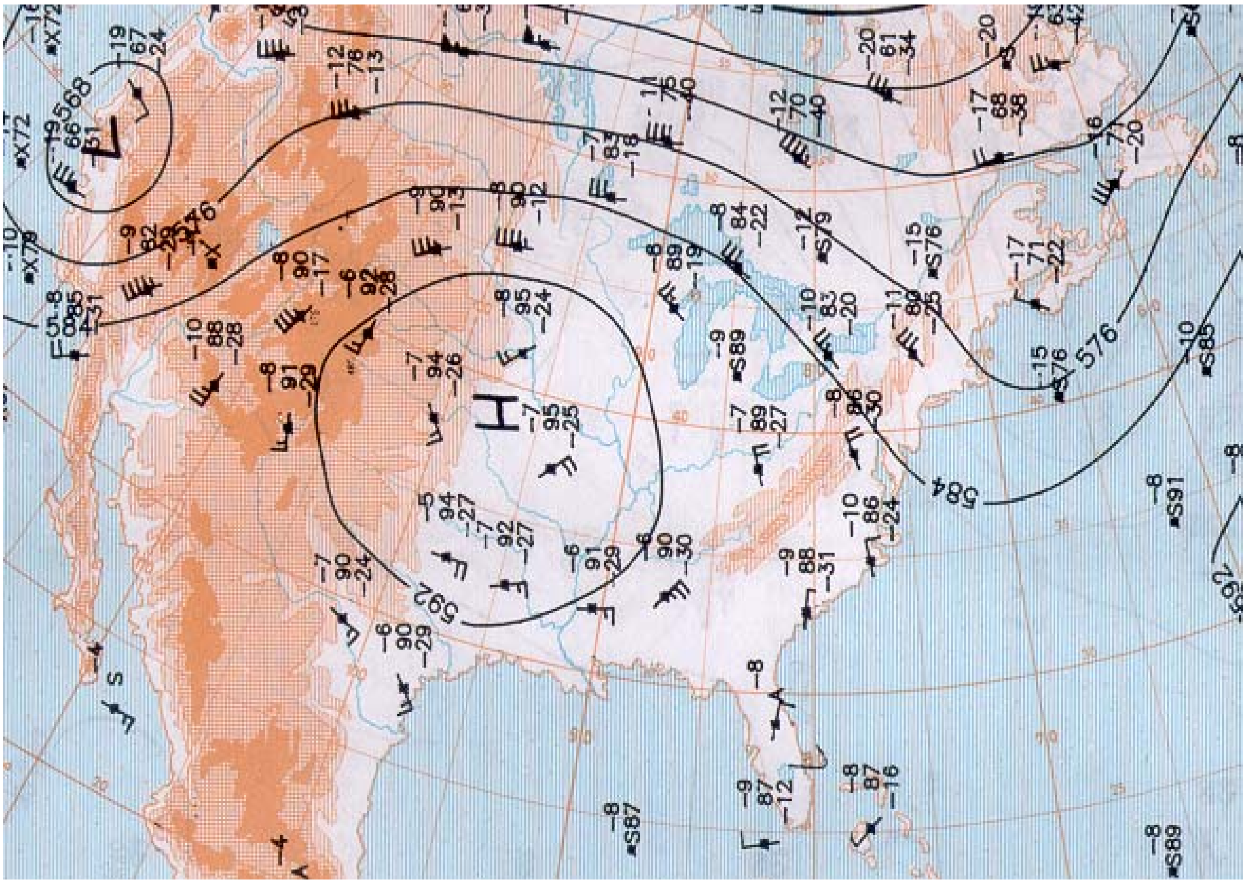

Figure 1.1: 500 mb topography for August 1988 (European Meteorological Bulletin)

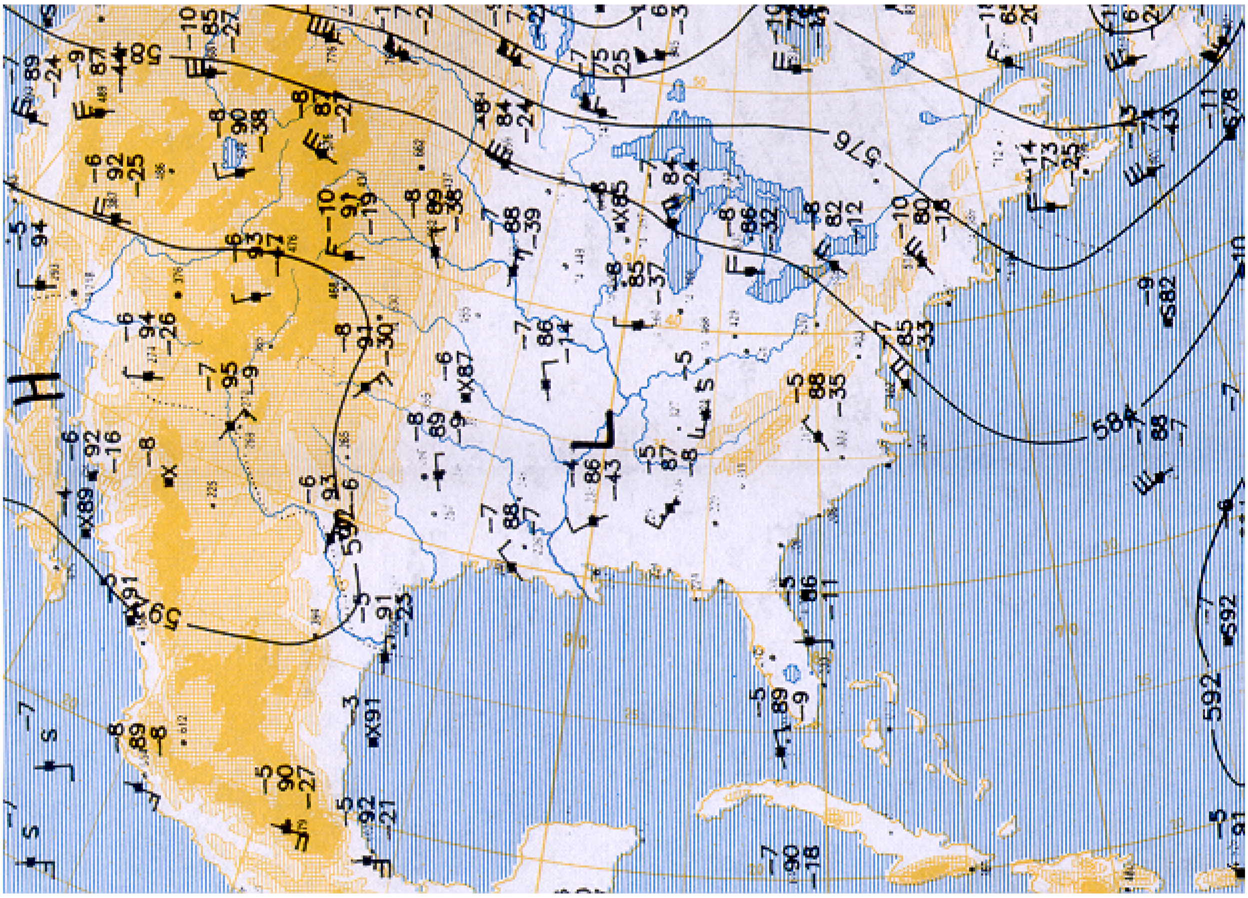

Figure 1.2: 500mb topography over the United States of America for August 1998, (European Meteorological Bulletin)

Additionally humidity plays a critical role in a heat wave. High humidity is linked to the origin and track of the air mass. Considering the central states for example, a southwesterly air stream would travel over the very arid areas of Arizona and hence by the time it reaches the centre of the country is unlikely to be carrying much moisture. However, a southerly flow from the Gulf of Mexico or a southeasterly one from the Atlantic would transport a much greater quantity of water vapour. The dew point temperature, the temperature at which a parcel of air becomes saturated by cooling at constant pressure, is an indication of the number of grammes of water vapour in one kilogramme of air. Along with the water vapour evaporated from the sea, there are a number of other factors influencing this dew point temperature. These include the meteorological potential for evaporation, soil moisture availability, and also the depth of boundary layer vertical mixing.

Potential evapotranspiration (PET) is a measure of the ability of the atmosphere to remove water from the surface through the processes of evaporation and transpiration. As the temperature increases, PET values increase. Couple this with a high level of soil moisture availability related to high levels of precipitation in the preceding weeks, then the dew point temperature will increase due to increased evaporation. Finally we must also consider the vertical mixing depth of the atmosphere. If this is reduced then the moisture in the air will be confined to a much shallower layer and hence increase dew point temperature.

Figures 1.3 and 1.4 detail the vertical profile of the atmosphere at Lincoln, Illinois for a 24-hour period during the heat wave of July 1995. Figure 1.3 demonstrates the early morning (6am Central Daylight Time) profile for July 13. The elevated dry bulb and dew point temperatures indicate that even overnight temperatures are very warm and humidity is high. As suggested earlier, winds are light at 5 knots and are transporting the warm air from the south. The surface inversion stretches up to approximately 960 mb, a night time phenomenon which is characteristic of heat waves in the United States. This is important to note when discussing heat waves within major cities as it brings with it the potential to trap pollutants near the surface.

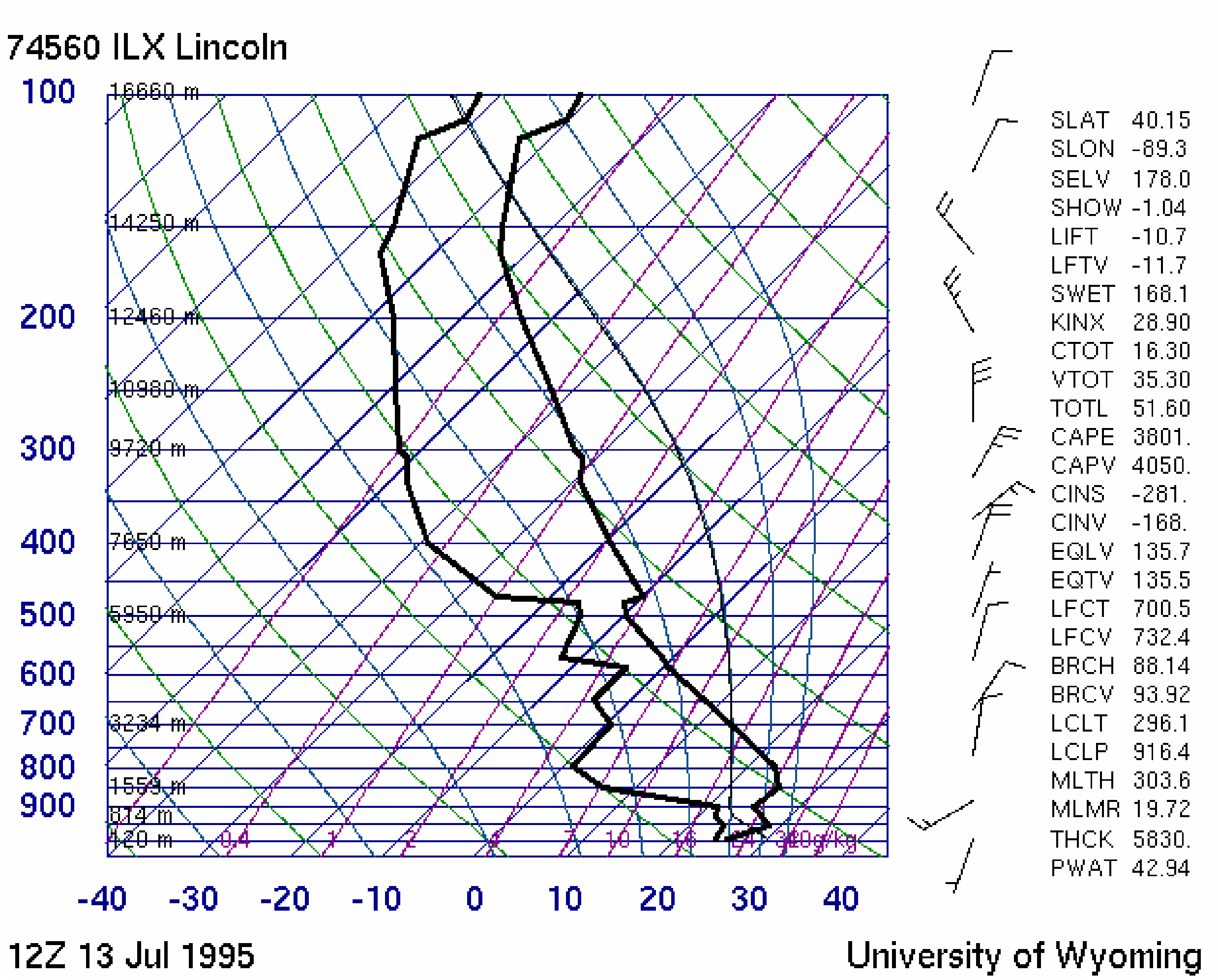

Figure 1.3: Log p skew T vertical profile of the atmosphere at Lincoln Illinois, 12z 13 July 1995.

Figure 1.4 shows the vertical profile at 6pm CDT on July 13. An extremely high surface dry bulb temperature of 36°C with a dew point temperature of 25°C created by surface heating throughout the day has led to an unstable boundary layer capped by a dry inversion with a base at approximately 880mb. Again wind speeds are low at between 5 and 10 knots and there is likely to be strong sunshine throughout the day.

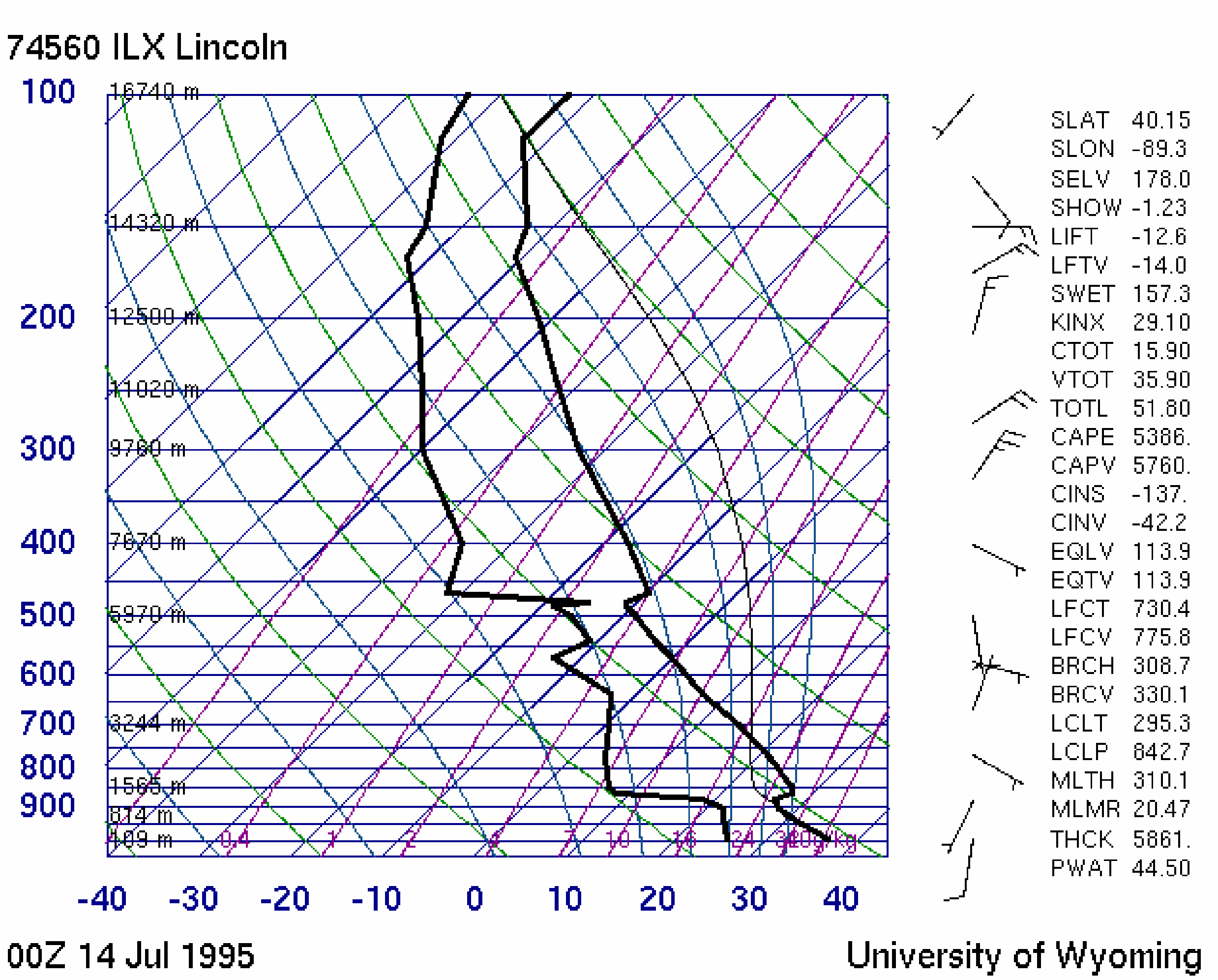

Figure 1.4: Log p skew T vertical profile of the atmosphere at Lincoln Illinois, 00z 14 July 1995.

1.2 Geography and Topography

Geography plays an important role in temperature forecasting. Figure 1.5 shows that certain areas of the United States are more prone to heat waves than others. For example, states such as Washington and Oregon experience very few heat waves due in part to the fact that, as air flows over land it obtains sensible heat from the ground, however, air travelling towards these particular regions would predominately come from the Pacific Ocean which is a cool course in the summer season. Add to this the fact that mean temperatures in these regions are generally lower due to the oceanic influence then it can be inferred that should such places experience heat waves, temperatures would not be as high and hence the event would be much less stressful to the body.

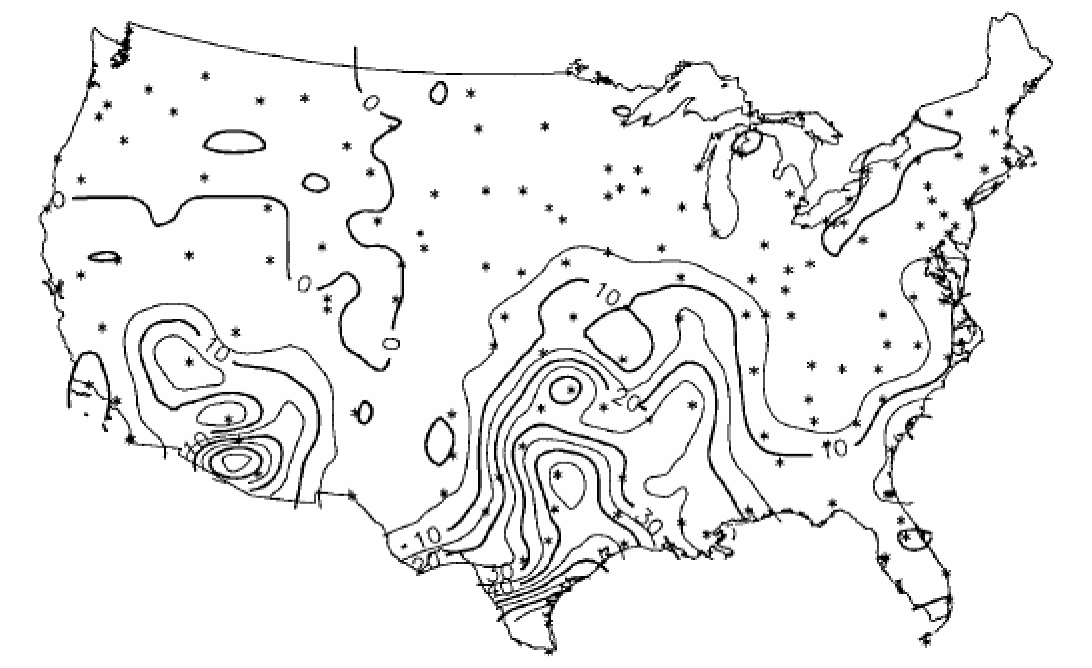

Figure 1.5: The Number of extreme high temperature events per decade when a heat wave is defined as a minimum of 48 hours with minimum heat index exceeding 27°C and maximum heat index exceeding 40°C. The contour interval is 5 events/decade (Robinson, 2001)

In addition to the geographical location the topography of the surrounding area can help to explain why heat waves occur. For example, should a mass of air flow over a mountainous region then as it flows down a slope, it compresses as its altitude decreases and atmospheric pressure increases. This compression increases the temperature of a parcel of air adiabatically as the average speed of the air molecules increases. An example of this phenomenon is the Chinook Wind that flows down the eastern side of the Rocky Mountains. Forecasters in the United States call it "downsloping," and heat waves are occasionally known to accompany a flow of wind that descends from higher elevation.

1.3 Duration

There has been much discussion as to how long an extreme high temperature event should last before it can be classed as a heat wave. The American Meteorological Society's Glossary of Meteorology states that a heat wave need only last one day, but in reality this could be simplifying the event somewhat. There is evidence that mortality is more likely during or after the second hot night when the interior of an unairconditioned building is likely to reflect the outdoor apparent temperature (Kalkstein and Smoyer, 1993; Robinson, 2001). This is demonstrated in Figure 1.6 where, for the 1995 Chicago heat wave that began on 12th July, the coroner reported the majority of deaths from the 14th July onwards.

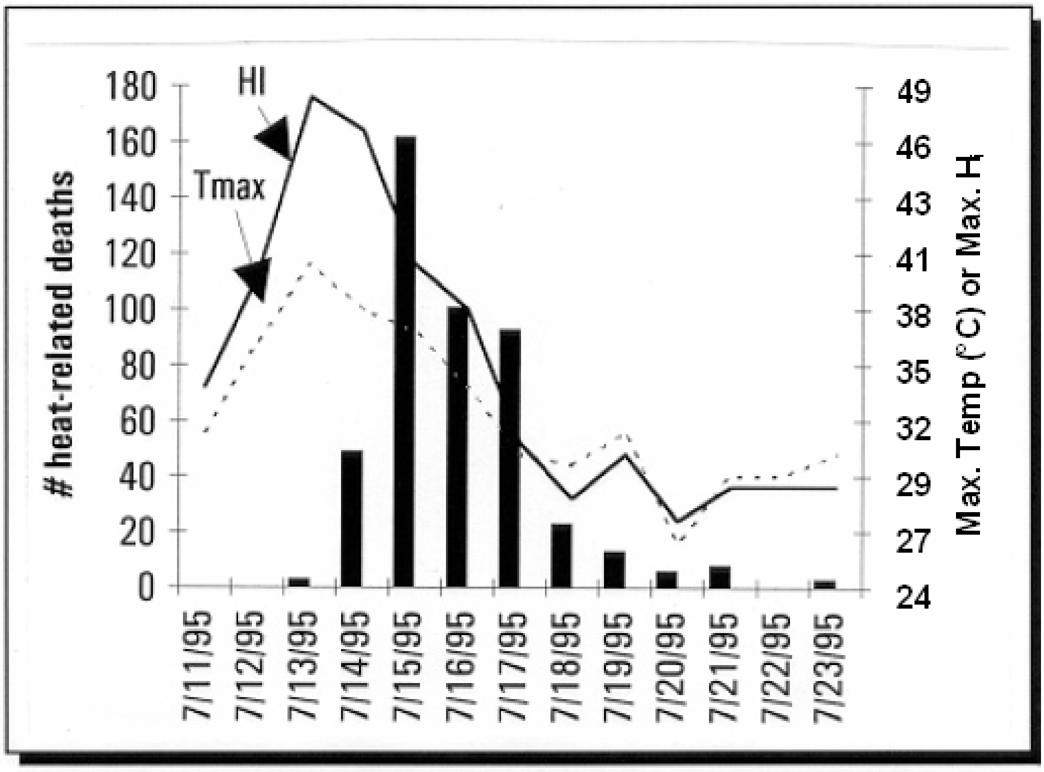

Figure 1.6: Heat –related deaths, Maximum Temperature (T_{max}) and Heat Index (HI), Chicago, July 11-23, 1995. (As reported by theOffice of the Medical Examiner). NOAA, Natural Disaster Survey Report: July 1995 Heat Wave.

The National Weather Service therefore states that for a heat wave to be established there should be four consecutive observations exceeding given thresholds: two minima exceeding the night time low threshold and two maxima exceeding the daytime high threshold. Moreover, this implies the importance of analysing the night time low temperature which, if still elevated, does not permit significant overnight cooling and hence provides little relief from the heat stresses of the day.

1.4 Apparent Temperature

Throughout the years a number of differing heat stress indices have been proposed which relate atmospheric conditions to the heat sensations we feel. However, the one matter upon which they all agree is the importance of considering the whole heat balance of the human body. Therefore, it is not only necessary to calculate such things as temperature, wind speed, humidity and solar radiation but we must also consider non-meteorological components such as amount and type of clothing, fitness level and physiological adaptation to a particular environment. The distinction therefore between dry bulb temperature and how hot it actually 'feels' is critical when analyzing the requirement for heat watch warnings. Steadman (1979a,b,1984) investigated these effects and devised an apparent temperature T_{ap} or heat index H_i, the name for the National Weather Service modified operational version, which can more accurately represent how hot a person is feeling. His equation includes approximately 20 different variables ranging from vapour pressure and effective wind speed to the dimensions of a human and clothing resistance to heat transfer. Many of these variables have had to be parameterized, for example Steadman takes the effective wind speed to be 5 knots and average height of a person to be 5'7". Therefore, whilst apparent temperature can be used as a more accurate representation of how hot a person feels it cannot be used to indicate the onset of any particular heat induced illness.

In practice, in order to replicate Steadman's table of apparent temperature the NWS uses a model comprising a collection of equations, which in turn represent the numerous variables.

A simplified version of the overall equation, as shown, can be obtained by performing a multiple regression analysis on this model.

$$H_i = ((16.923 + 0.185212T + 5.37941R - 0.100254TR + 9.4169x10^{-3}T^2 + 7.28898x10^{-3}R^2 + 3.45372x10^{-4}T^2R - 8.14971x10^{-4}TR^2 + 1.02102x10^{-5}T^22R^2 -3.8646x10^{-5}T^3+2.91583x10^{-5}T^3+1.42721x10^{-6}T^3R+1.97483x10^{-7}TR^3 -2.18429x10^{-8}T^3R^2 + 8.43296x10^{-10}T^2R^3 - 4.81975x10^{-11}T^3R^3 + 0.5) - 32)*5/9$$

(Robinson, 2001)

where H_i = heat index (°C)

T = ambient dry bulb temperature (°F)

R = relative humidity (integer percentage)

Even though temperature and relative humidity are the only two variables in the equation, all other 18 variables are implied and due to the multiple regression analysis there is a ±0.7°C error. A final point to note when considering these calculations is that they are performed to represent temperatures in the shade and hence full sunlight could add up to 8°C to values shown in Table 1. For consistency, throughout this study, T_{ap} will be used.

HEAT INDEX °C													
	RELATIVE HUMIDITY (%)												
Temp.	40	45	50	55	60	65	70	75	80	85	90	95	100
43	58												
42	54	58											
41	51	54	58										
40	48	51	55	58									
39	46	48	51	54	58								
38	43	46	48	51	54	58							
37	41	43	45	47	51	53	57						
36	38	40	42	44	47	49	52	56					
34	36	38	39	41	43	46	48	51	54	57			
33	34	36	37	38	41	42	44	47	49	52	55		
32	33	34	35	36	38	39	41	43	45	47	50	53	56
31	31	32	33	34	35	37	38	39	41	43	45	47	49
30	29	31	31	32	33	34	35	36	38	39	41	42	44
29	28	29	29	30	31	32	32	33	34	36	37	38	39
28	27	28	28	29	29	29	30	31	32	32	33	34	35
27	27	27	27	27	28	28	28	29	29	29	30	30	31

Table 1.1 The relationship between relative humidity and dew point temperature when calculating the Heat Index. National Weather Service Forecast Office, Birmingham, Alabama

1.5 Thresholds

Once we have established an accurate representation of how hot it feels, the next step is to ascertain appropriate threshold criteria above which heat warnings can be issued. The National Weather Service has created two methods for the establishment of heat wave thresholds.

The first option is for a temperature exceeding a fixed absolute value. The NWS states that it is possible to define an absolute value, which approximately represents the lower limit for a heat wave. They state that “conditions above this value would affect most of the population and require some form of modification of activities in order to prevent discomfort or health problems” (Robinson, 2001). In areas where they have adopted the fixed value approach the NWS have stated that their criterion for a heat watch warning requires a daytime T_{ap} greater than or equal to 40.6 °C with nighttime lows greater than or equal to 26.7 °C for 2 consecutive days. However, there are shortcomings to this definition. If such a fixed threshold is adopted it effectively prohibits the use of the term ‘heat wave’ defined on any other basis. For example events with temperatures falling below this absolute value would be ignored, however extreme they may be in the particular local climate. Furthermore, for the majority of the United States, it also limits the event to summer, however stressful an event during any other season may be. For example, a continually elevated temperature in winter could result in the extensive melting of snow in the northern reaches of the United States and potentially lead to flooding. Although perhaps an extreme example this demonstrates the inflexibility of the definition.

However, for stations in particularly warm areas, such as the South Western part of the country, they discovered that this fixed absolute value was exceeded on an unrealistically high proportion of days and hence the NWS, in recognizing the geographically variable nature of heat waves, has considered a threshold dependent upon deviation from normal. This allows a heat wave to be quantified by some measure of departure from the mean conditions. As temperature is normally distributed there are three possible approaches to take when considering deviation from the normal: exceedence of a fixed percentile of all observed values, exceedence of the daily mean value by a fixed standard deviation, or the exceedence of the daily mean by a fixed absolute value. The first option has proved to be the most successful as it is analogous to the method for the fixed absolute value and only requires the calculation of a single value for the whole station record, whereas the others require separate thresholds to be calculated for each day. This alternate threshold criterion allows for some areas of the country to experience T_{ap} values of up to 43.3°C before heat warnings are issued. In Section 3 we will discuss the approaches adopted by the NWS with reference to Chicago and New York.

Another way to quantify a heat wave, (Kysely, 2002) suggests that we calculate mean daily maximum air temperature over the period of the weather event and, should it exceed certain values, then it can be designated a heat wave. A further method, (Karl and Knight, 1996) was to again look at the weather event as a whole and work out the probability of the return period. Both these methods are only useful when studying a heat wave in retrospect and are unhelpful when discussing the issuance of heat watch warnings and hence the saving of lives

An approach, however, which could be extremely useful in determining appropriate thresholds is to investigate what percentage increase in temperature would be necessary in order to induce heat related illness and other associated impacts. This information could prove useful when trying to delineate a heat wave in seasons other than summer and also could account for the ability of the human body to acclimatise during the summer period. For example, it is possible that a temperature of 32°C has more of an effect in May than in August due to the fact that the body has become used to the cooler temperatures of winter and spring whereas towards the end of the summer period a certain amount of acclimatisation has taken place. This definition however, would take into account only the human elements of a heat wave ignoring other impacts such as those discussed in Chapter 2 but would be a useful start in achieving more meaningful thresholds.

In summary, therefore, the threshold values throughout the United States are very much dependent upon location and hence climatic norms and lead us to appreciate the over simplification of the Weather Channel definition discussed earlier.

Chapter 2

Impacts

2.1 Impacts on health and mortality

Recent heat waves have revealed that the majority of American people do not comprehend the relative danger of heat in comparison to other extreme weather events. For example, they are awed by the threat of tornadoes and prepare accordingly but fail to realise that heat is in fact a much greater threat. A potential reason for this is that statistics for heat related deaths are often unreliable and generally underestimate actual numbers. As heat waves are multi-day events it becomes more difficult to attribute any loss of life to temperature extremes as the affected individuals also frequently suffer from other health problems. In fact, the U.S. Senate Special Committee on Ageing estimated that more than 15,000 people died during the summer heat wave of 1980 pointing explicitly to the dangers involved in such extreme high temperature events. Table 1.2 shows the average number of fatalities per weather event per annum based on a 10-year period. It also details the maximum number of deaths recorded in any one event.

Weather Event	10-year average[1]	Maximum in one event[2]
Tornadoes	58	739
Heavy rain/floods	84	2200
Hurricanes	18	6000
Lightning	53	Unknown
Winter storms and cold	71	500
Heat waves	237	>10,000[3]

Table 2.1: Number of deaths attributed to weather in the United States.

[1] As provided by the National Weather Service

[2] As provided by Munich Reinsurance (1993) except where noted (Changnon et al, 1996)

[3] US Senate Special Committee on Aging 1983 (Changnon et al, 1996)

One issue is that there is no federal definition of a ‘heat death’ and hence medical examiners have varying ways of defining one. All medical examiners record heat stroke as a cause of death; however, differences occur when people die from illness such as heart attacks and strokes during a heat wave. In these scenarios heat is sometimes only listed as a contributing factor and not the primary cause of death. To address this problem it may be more desirable to compare the number of deaths during a heat wave to those during the same period in years with near average temperatures. Ellis’s studies in 1972 discovered that actual heat related deaths can be up to ten times greater than those recorded. For example, in August 1988 the Chicago Medical Examiner acknowledged 55 heat related deaths but the number of deaths recorded above the average was 232 (Whitman, 1995).

2.1.1 How Heat Affects the Body

Human bodies dissipate heat by varying the rate and depth of blood circulation, by losing water through the skin and sweat glands. Sweating, by itself, does nothing to cool the body, unless the water is removed by evaporation, and high relative humidity retards evaporation. The evaporation process works by extracting the heat energy required to evaporate the sweat from the body, thereby cooling it. Under conditions of high temperature (above 32°C) and high relative humidity, the body needs to work extremely hard to maintain an internal temperature of 37°C.

Heat disorders generally involve a reduction or collapse of the body's ability to shed heat by circulatory changes and sweating, or a chemical (salt) imbalance caused by too much sweating. When heat gain exceeds the amount the body can remove, or when the body is unable to compensate for fluids and salt lost through perspiration, the body's internal temperature begins to rise and heat-related illness may develop. Studies indicate that, other things being equal, the severity of heat disorders tends to increase with age - heat cramps in a 17-year-old may be heat exhaustion in someone who is 40, and heat stroke in a person over 60. Acclimatization requires, among other things, the adjustment of sweat-salt concentrations, the idea being to lose enough water to regulate body temperature with the least possible chemical disturbance.

2.1.2 Increased Mortality

Although there were perhaps more intense heat waves in the earlier part of the 20th century, fewer deaths were experienced than in the heat waves of today. In fact, Kalkstein (1995) estimated that a 21% reduction in the number of heat related deaths has occurred due to the increased use of air conditioning. So what factors have led to the increase in heat related mortality that has been observed over recent years?

Firstly, changes in social conditions have meant that in many cases the elderly are now more afraid of crime than their counterparts in the early 20th century and hence do not want to leave doors and windows open during the night, or even, as they did during the heat waves of the 1930s, sleep outside. Furthermore, during the 1930s more of the elderly population lived with family who could care for them should they become ill, however during the intense heat waves of the 1990s there was a large population of elderly people living alone. In fact, both the elderly population and the population as a whole have increased over the 20th century again pointing to reasons why fatalities may have increased. The two main factions of the population affected by heat related mortality are the poor and the elderly. Avery (1985) suggested that more than 70% of heat related deaths occur in people aged 65 and over. While air-conditioning may be a luxury in normal times, it can save lives during heat wave conditions and as the heat wave progresses the cost of cool air moves steadily higher, adding an economic slant to heat wave fatalities. Indications from the 1980 Texas heat wave suggest that some elderly people on fixed incomes, many of them in buildings that could not be ventilated without air conditioning, found the cost too high, turned off their units, and ultimately succumbed to the stresses of heat (Changnon et al 1996).

Throughout extreme heat, cities can create particular hazards. A map of heat-related deaths in St. Louis during 1966, for example, shows a heavier concentration in the crowded alleys and buildings of the inner city, where air quality would be poor. The stagnant atmospheric conditions of a heat wave can trap pollutants in urban areas and can lead to increased air quality problems that affect health, particularly as ozone concentrations increase. However, Kalkstein (1995) has shown that the effect of this air pollution is a much less significant factor than that of the heat itself.

In times of emergency, deaths such as these can be heightened even more due to the insufficient number of ambulances and as hospitals become increasingly overloaded.

2.2 Agriculture

Wheat, rice, maize, potato and soybean crop yields can all be significantly reduced by extreme high temperatures at key development stages. For example, there can be an adverse effect on corn yields should a heat wave occur during its 2-4 week period of pollination and cranberry yields can be drastically reduced when maximum temperatures exceed a relatively moderate threshold of 29°C.

2.3 Industry and Transport

Throughout heat waves energy use vastly increases due to the extensive requirement for air conditioners and fans. This puts a massive strain on the power industry and has led to large-scale power failures during times of peak stress. Adding to the already stretched power supply there is the problem of superheated elevated power lines which can stretch and sag, potentially touching trees or buildings and shorting to the ground. Furthermore, underground transmission lines can overheat and short out. Hence whilst power companies can expect huge increases in revenue during heat waves they can often face liability for power failures. For example, in 1995 a group of businessmen and women in Chicago filed a suit against the local power company stating that a prolonged power outage had damaged their businesses. It was during this intense heat wave that 40,000 people were left without power (Champaign-Urbana News-Gazette, 16th July 1995).

Transport can also be affected, highways and railroads can be damaged due to heat induced buckling and heaving of both roadway and rail joints. Asphalt roads can soften whilst concrete roads have been known to virtually explode under extreme high temperatures. Furthermore, airports have found it necessary to close as it was deemed unsafe for aircraft to take off as they experienced substantially reduced lift due to the high temperatures. In addition to this, reports from companies indicate that work efficiency is greatly reduced as people tire under the stresses of extreme heat and although difficult to quantify this can lead to a reduction in revenues.

2.4 Water resources

Along with the fact that there is obviously very little precipitation during times of extreme high temperatures, water is often used to cool bridges and other metal structures susceptible to heat failure. This causes a reduced water supply which can significantly contribute to fire suppression problems for both urban and rural fire departments. Furthermore, an increase in water temperature can contribute to a degradation of water quality and negatively impacts fish populations. It can also lead to the death of many other organisms in the water ecosystem and is linked to rampant algae growth, causing fish to be killed in rivers and lakes (Adams, 2004).

As with most things however, there are winners and losers. The manufacture and sale of air conditioners vastly increases, as does the attendance at public swimming pools leading to increased revenue for both types of organisation. The larger air conditioned malls report increased sales figures as people go there to escape the heat and tourism soars as people travel into the hot regions to enjoy the summer sun that is inherent with a heat wave.

Chapter 3

Case Studies

This section will discuss heat waves with particular reference to Chicago and New York City. Chicago and New York City are located at similar latitudes but different longitudes (Figure 3.1). The construction of appropriate thresholds will be analysed as will the frequency of heat waves in both areas along with their main characteristics, discussing any differences or similarities. The future is discussed regarding the effect that climate change may have on heat waves.

Figure 3.1: The contiguous United States of America, (www.nationalatlas.gov)

3.1 Chicago

3.1.1. Local Climate

Chicago is located along the southwest shore of Lake Michigan at approximately 200m above sea level within a region of frequently changeable weather. The climate ranges from relatively warm in summer to relatively cold in winter and as such is predominantly continental. However, this continentality is somewhat reduced by Lake Michigan and to a lesser extent by the other Great Lakes. In summer the higher temperatures are produced by south or southwesterly flow and are therefore not generally affected by the lakes with the pronounced urban heat island often adding to these high temperatures. The only moderating influence is the local lake breeze; however, strong south or southwesterly flow may overcome this breeze and cause high temperatures to extend over the entire city.

During the warm season, when the lake is cold in relation to the land, the lake breeze is seen to reduce daytime temperature near the shore, often by more than 6°C below those observed farther inland (NCDC, 2004). When the breeze off the lake is light, this effect usually only reaches up to a mile or two inland. However with stronger on-shore winds the whole city can be cooled. In contrast to this, the lake has little effect at night (Changnon et al, 1996) leading to warmer temperatures in this area. Therefore, on the whole, 24-hour averages are only slightly different in various parts of the city and suburbs. At O'Hare International Airport temperatures of 36°C or higher are observed in approximately 50% of summers (National Climatic Data Centre, 2004).

Summer thunderstorms are often locally heavy and variable so parts of the city may receive substantial rainfall whilst other parts see none. Longer periods of continuous precipitation are mostly observed during autumn, winter, and spring from larger scale systems.

The main topographical effect on air flow is that of the reduced frictional drag over Lake Michigan. This frequently leads to stronger winds along the lakeshore and often results in northerly air masses reaching shore areas up to an hour before arriving at western parts of the city (National Climatic Data Centre, 2004). Chicago has attained the nickname "The Windy City", from the strong gusts that result from the winds being channelled between its many tall buildings. In fact the average wind speed is no greater in Chicago than in many other parts of the United States (National Climatic Data Centre, 2004).

3.1.2 Data

In order to accurately analyse trends in heat waves, a long-term serially complete set of data is required. A high quality data set of daily maximum and minimum dry bulb temperature, (T_{max} , $T_{min,}$) and dew point temperature ($T_{d,}$) for 1960 to 1990 were obtained from the U.S. National Climatic Data Center (NCDC). For the periods 01/01/65 to 31/08/65, 01/04/66 to 31/10/67 and 01/07/69 to 31/12/72 hourly data was unavailable and hence three-hourly data were utilised. Data, were incomplete for years preceding 1960 so for this period the values were obtained from Professor Kenneth Kunkel (The University of Illinois) who interpolated the available NCDC observations to make a complete hourly data set. Once the data was collated T_{ap} was calculated using Steadman's table via a FORTRAN program based around that used by Kunkel to interpolate the 1901 to 1960 data (Appendix A).

Figure 3.2 Chicago, Illinois (maps.mapnetwork.com)

The observations used were taken at Chicago O'Hare International Airport (42°00'N / 87°56'W) (Figure 3.2) in the north western suburbs of the City. Its inland location means that the effect of the lake breeze is reduced in comparison to downtown Chicago which lies much closer to the lakeside. During the period of interest both the location and elevation of the site have remained constant. However there have been a number of instrument changes that may have detracted from the homogeneity of the data. This could be investigated further with the benefit of more time.

3.1.3. Thresholds for Chicago

The NWS currently has three heat wave thresholds in place for Chicago. The predicted T_{ap} must be greater than or equal to 32.2°C for a heat *watch* to be issued, greater than or equal to 32.2°C for at least 3 days for a heat *warning* to be issued and greater than or equal to 40.6°C for two days in order for the city to declare a heat emergency.

If we analyse the occurrence of heat waves based on the NWS criterion of a daytime T_{ap} greater than or equal to 40.6 °C and night time low greater than or equal to 26.7 °C for 2 consecutive days leads to only 1 heat wave for the period 1961 to 1990. This indicates that the thresholds are too high as there have been a number of extreme high temperature events that have caused severe impacts during this period. The 32.2°C level utilised for heat watches and warnings in Chicago indicate the existence of a heat wave almost every year. From this we can construe that neither values are particularly appropriate and must seek to adopt an alternative definition.

We therefore return to the NWS's second threshold option discussed in Section 1, which is the exceedence of a fixed percentile of all observed values. Once this percentile is established we will then be able to apply it to all 30-year periods through the period of interest in order to obtain more appropriate thresholds.

In order to discuss these thresholds and put them into context for previous years and their varying climate, we must first consider the time period over which mean temperatures are calculated. Whilst the majority of heat waves occur in July and August, there is evidence of heat waves in June and also, to a lesser extent, in May and September. Therefore in order to accurately analyse trends in such extreme temperature events we should consider thresholds based on mean maximum and minimum T_{ap} for both the summer period (June, July August) and the extended warm period (May, June, July, August, September). The means used throughout this analysis were calculated by using the standard arithmetic mean of maximum and minimum T_{ap} throughout the various periods in question.

A maximum T_{ap} of 40.6°C represents the 99th percentile for the extended warm period of 1961- 1990 and the 98.5th percentile of the summer period. A minimum T_{ap} of 26.7°C represents the 99.4th percentile for the extended warm period and the 99th percentile for the summer period. The first step in the analysis was to examine whether it was simply the nighttime low that was too high as its percentile was higher than that of the daytime high. Upon reducing both night time percentiles to the equivalent daytime high levels of 99 and 98.5 respectively there was no significant increase in the number of heat waves. However, upon reducing all thresholds to the 98th percentile a significant rise in the number of heat waves was observed. When deciding whether or not the 98th percentile is appropriate it is important to recall that heat waves are rare events. Further reduction to the 97th percentile leads to heat waves occurring almost every year so that the 98th percentile is the most suitable choice, see Table 3.1 for actual thresholds.

	Max T_{ap} Heat Wave Threshold (°C)		**Min T_{ap} Heat Wave Threshold (°C)**	
Decade	JJA	MJJAS	JJA	MJJAS
1901-1910	42.3	41	25.3	24.9
1911-1920	42.3	41	25.3	24.9
1921-1930	42.3	41	25.3	24.9
1931-1940	42.7	41.1	26	25.2
1941-1950	42.8	41.1	25.4	24.9
1951-1960	42.5	41.2	25.7	24.9
1961-1970	41.6	40	25.4	24.6
1971-1980	39.7	38.4	25.4	24.7
1981-1990	39.7	38.4	25.4	24.6

Table 3.1: Heat wave thresholds for 1901 to 1990.

Each decade's thresholds are based on percentiles of observations for that decade plus the two prior decades. The exception to this is the period 1901-1920 whose thresholds are based on observations from the period 1901-1930 due to lack of data from the 20th century.

Heat waves were noted in September, although not in May, indicating that the extended warm period thresholds were the most appropriate and hence will be used throughout our study.

Whilst mean max T_{ap} has increased by 1.2°C over the period of interest the corresponding thresholds are seen to reduce by 2.6°C. This is due to a decrease in variability from the mean. Conversely, mean min T_{ap} were seen to decrease by 1.5°C and thresholds decrease by 0.5°C thus indicating an increase in variability of night time low temperatures.

3.4 New York

3.2.1 Local Climate

Approximately 780 miles (1,155Km) east of Chicago, New York City is located on the Atlantic coastal plain at the mouth of the Hudson River. The region has many waterways with all but one of the five city boroughs being situated on an island. Elevations range from less than 15 metres over most of Manhattan, Brooklyn, and Queens to almost 100 metres in northern Manhattan and the Bronx, and over 140 metres in Staten Island.

New York City is situated close to the path of frontal systems that track along the U.S. eastern seaboard. Consequently, weather systems affecting the city most often approach from a westerly or south-westerly direction (NCDC, 2004). New York City therefore experiences higher temperatures in summer and lower ones in winter than would otherwise be expected in such a coastal region. However, this frequent passage of weather systems can often help to reduce the length of both warm and cold spells, and is also an important factor in reducing periods of prolonged air stagnation.

Extreme high temperatures can occur as a result of a number of factors. Prevailing winds from the south and southwest transport warm, humid air from the Gulf of Mexico and adjacent subtropical waters and hence heat waves are often accompanied by relatively high near surface atmospheric water vapour content. Another important effect on air flow is that of the Appalachians. With a westerly flow of air, heat waves can often occur as a result of the extra heat gained when air descends the eastern slopes. Furthermore, as the United States' largest city, New York has a pronounced urban heat island.

During the summer, local sea breezes, blowing onshore from the cooler water and penetrating the entire city, often moderate the afternoon heat and lead to the city not experiencing the same extreme high temperatures that are more common in Chicago where the lake breeze is much weaker.

3.2.2 Data

The T_{max}, T_{min}, T_d and wind speed information required for this study was again obtained from the NCDC in the form of hourly data. Although the availability of serially complete data for New York City was reduced compared to Chicago, five complete decades data were obtained (1950-2000), giving sufficient information for trend analysis. For the full period, daily T_{max} and T_{min} were noted with the corresponding T_d and wind speed. T_{ap} was once again calculated using Steadman's table via the FORTRAN program used earlier.

Figure 3.3: New York City, New York detailing the location of the JFK International Airport station (www.aaccessmaps.com)

The observations used were taken from New York's John F Kennedy International Airport which is located at 40°38'N / 73°46'W (Figure3.3). Lying on the coast of the Atlantic Ocean, the station is highly susceptible to sea breezes. While any changes in location of the site are negligible, the elevation, which is currently 3.4m above sea level, has changed by 6.5m over the period of interest, causing negligible inhomogeneity in the data.

3.2.3 Thresholds for New York

In New York there are no local definitions for heat wave thresholds so the NWS values as used initially. As with Chicago, the application of these thresholds produced only one heat wave over the whole 50-year period, indicating that the NWS absolute value thresholds are too high and that another approach is required. The concepts discussed in section 3.1 and thresholds based on the 98th percentile of observations lead to the values in Table 3.2

Decade	Max T_{ap} Heat Wave Threshold (°C) JJA	MJJAS	Min T_{ap} Heat Wave Threshold (°C) JJA	MJJAS
1951-1960	36.9	36.3	25.9	25.4
1961-1970	36.9	36.3	25.9	25.4
1971-1980	36.9	36.3	25.9	25.4
1981-1990	37.2	36.6	25.9	25.9
1991-2000	37.5	36.7	26.5	25.9

Table3.2: Daytime high and nighttime low heat wave thresholds per decade

Each decade's thresholds are based on percentiles of observations for that decade plus the two decades prior. With the exception of 1951-1970 whose thresholds are based on observations from the period 1951 to 1980 due to lack of data from the earlier half of the century. Once more, heat waves were noted in September and hence the extended warm period thresholds will be utilised.

Thresholds increase for mean max T_{ap} by 0.4°C and by 0.5°C for mean min T_{ap}. Mean max/min T_{ap} are 0.2°C and 0.4°C respectively indicating a small increase in variability of summer temperatures.

3.5 Results

Using the thresholds established in Section 3.4, the number of heat waves observed for Chicago and New York City were as detailed in Table 3.3.

	No. of heat waves observed (Chicago)		No. of heat waves observed (New York City)	
Decade	JJA	MJJAS	JJA	MJJAS
1901-1910	0	0	-	-
1911-1920	3	4	-	-
1921-1930	0	1	-	-
1931-1940	1	2	-	-
1941-1950	2	4	-	-
1951-1960	0	1	1	1
1961-1970	0	2	1	3
1971-1980	1	5	3	5
1981-1990	2	5	2	4
1991-2000	-	-	2	3

Table 3.3: The no. of heat waves in Chicago and New York City based on the thresholds detailed in tables 3.1 and 3.2.

Although there is no long term trend in the number of heat waves per decade to suggest any similarities between the heat waves experienced in Chicago and New York, the frequency of heat waves did increase in both cities during the period 1971 to 1990. No heat waves were noted that occur at approximately the same time in both cities: the closest heat waves temporally, occurred one month apart in 1968. This suggests that Chicago and New York are not affected by the same weather systems. For example, when warm tropical air masses (leading to anomalous warmth) are transported towards Chicago via a pronounced ridge, the distance between the two cities usually means that New York City will be under the influence of polar air masses and anomalously cool weather.

There is also a marked difference in the duration of heat waves in both cities. The maximum duration for New York City was three days, supporting the assertion of the frequent passage of weather systems across the area. In contrast, heat waves in Chicago were often observed to last up to four days indicating more stagnant weather systems and little influence from the lake.

In order to ascertain whether heat waves are predominantly due simply to an increase in dry bulb temperature or whether increased humidity is an important factor. It is necessary to make a comparison between the humidity levels during the heat wave and those of a normal summer. Mean dew point temperatures were taken for the 30-year periods in Section 3.1 and compared to the T_d values during each high temperature event. For Chicago, although mean T_d did not increase, there is a stark contrast in the humidity levels between the early and later parts of the century. For the period 1961 to 1990, T_d exceeded the mean by an average of 28%, equivalent to 15°C, during the day and 35%, also equivalent to 15°C, at night. For the heat waves experienced in New York City, again there was no mean increase in humidity, however observed T_d exceeded the mean by an average of 22% (13°C) during the day and 27% (15°C) at night.

For both cities therefore, there is conclusive evidence that a heat wave is not only an increase in dry bulb temperature but also an increase in humidity.

3.3.1 Large Scale Circulations

Figures 3.4, 3.5, 3.6, 3.7, 3.8 and 3.9 demonstrate the pattern of 500mb heights for the Chicago heat wave of August 1988. Figure 3.4 shows an area of high pressure developing over the western United States. The air mass reaches Chicago three days later (Figure 3.5) demonstrating its slow moving nature however by day three of the heat wave the ridge has begun to weaken (Figure 3.6 and 3.7). Although this heat wave was reasonably widespread across the U.S. its affects on the north-eastern region of the country were minimal as the ridge had virtually disappeared by the time the area of high pressure reached the northeast (Figure 3.8) and was replaced by westerly flow bringing with it a reduction in temperatures. Four days after it began the heat wave was over and the Midwest was experiencing westerly flow and more normal summer temperatures (Figure 3.9)

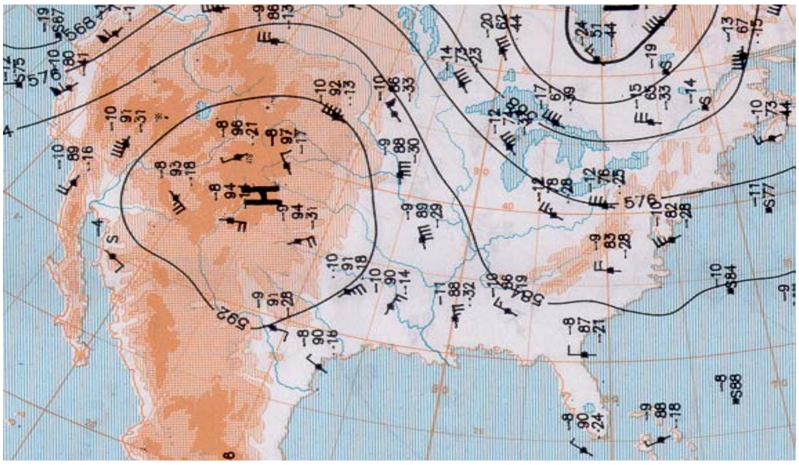

Figure 3.4: 500 mb heights for 11th August 1988 (European Meteorological Bulletin)

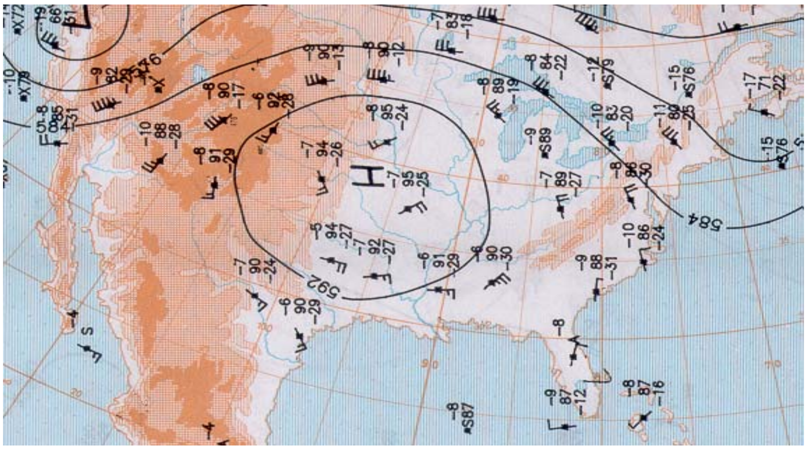

Figure 3.5: 500 mb heights for 14th August 1988 (European Meteorological Bulletin)

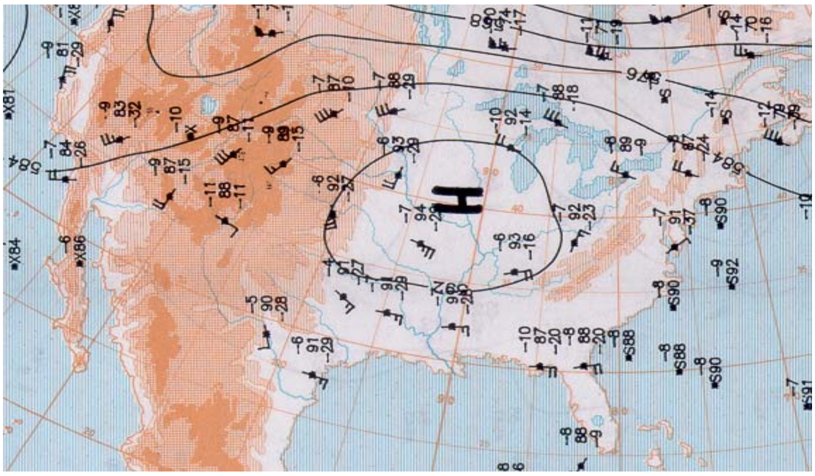

Figure 3.6 500 mb heights for 15th August 1988 (European Meteorological Bulletin)

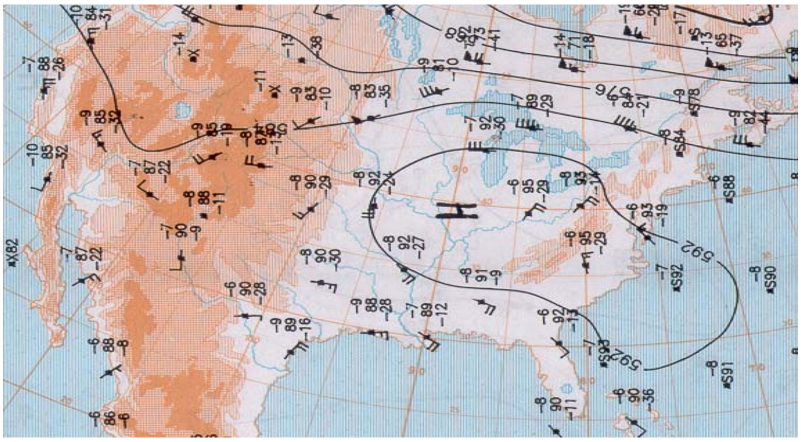

Figure 3.7: 500mb heights for 16th August 1988 (European Meteorological Bulletin)

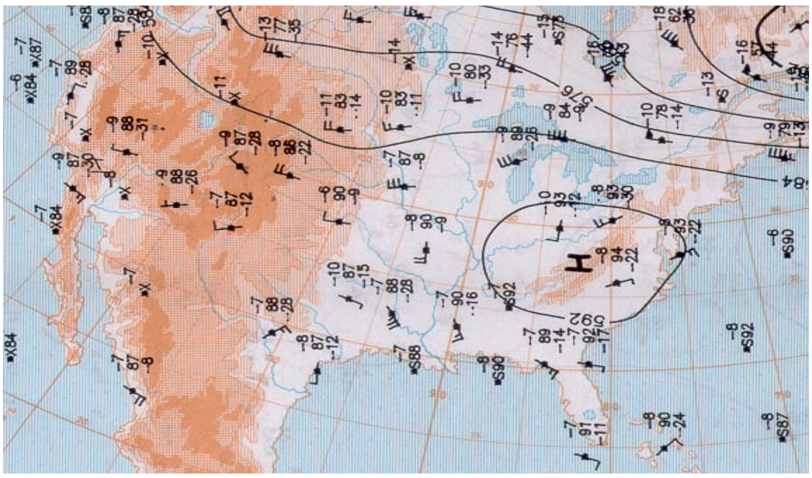

Figure 3.8: 500 mb heights for 17th August 1988 (European Meteorological Bulletin)

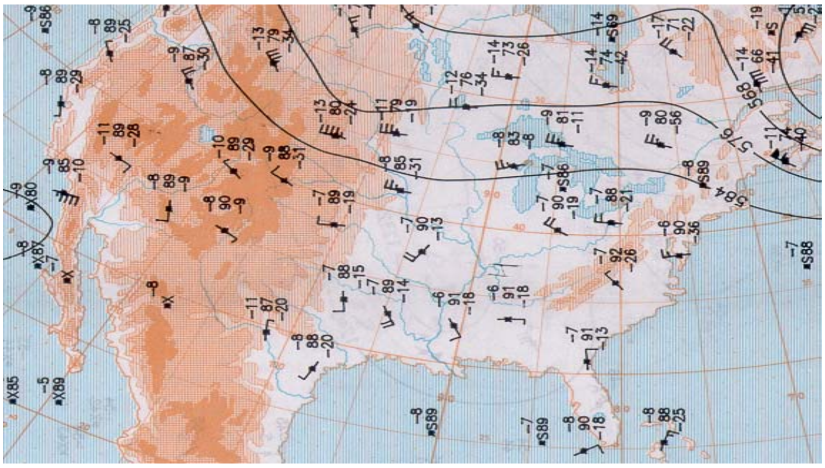

Figure 3.9: 500mb heights for 18th August 1988 (European Meteorological Bulletin)

Figures 3.10, 3.11 and 3.12 illustrate the 500mb heights for the lifespan of the July 1993 heat wave over New York. Again they demonstrate a reasonably stagnant area of high pressure above the region, which has possibly been enhanced by air masses flowing down the leeward side of the Appalachians. Air flow is south-westerly as the heat wave commences bringing the warm tropical air into the region, however as the heat wave progresses air begins to flow from the west bringing with it temperatures more expected for the time of year.

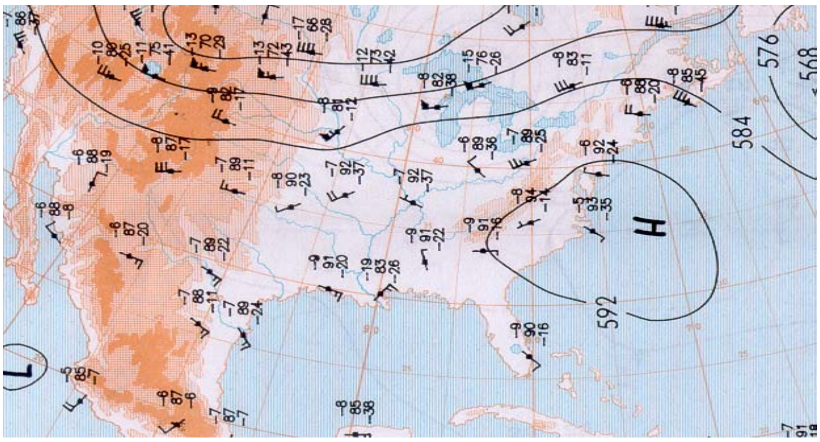

Figure 3.10: 500mb heights for 8th July 1993 (European Meteorological Bulletin)

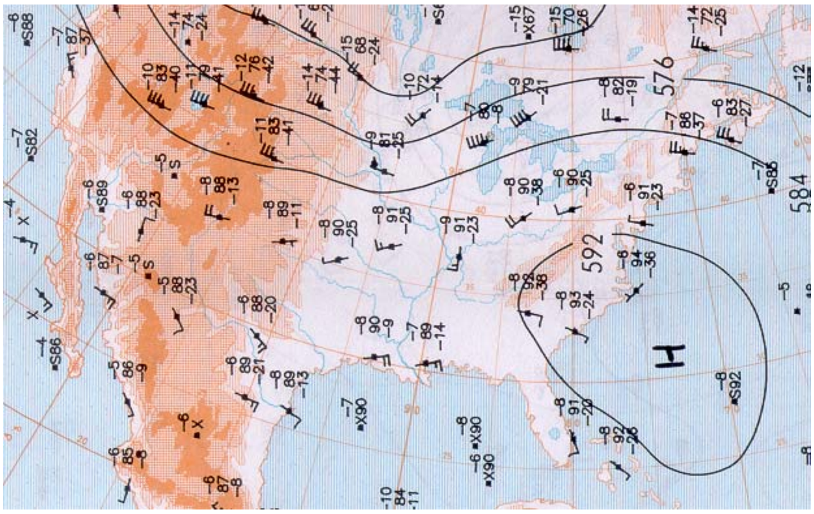

Figure 3.11: 500mb heights for 9th July 1993 (European Meteorological Bulletin)

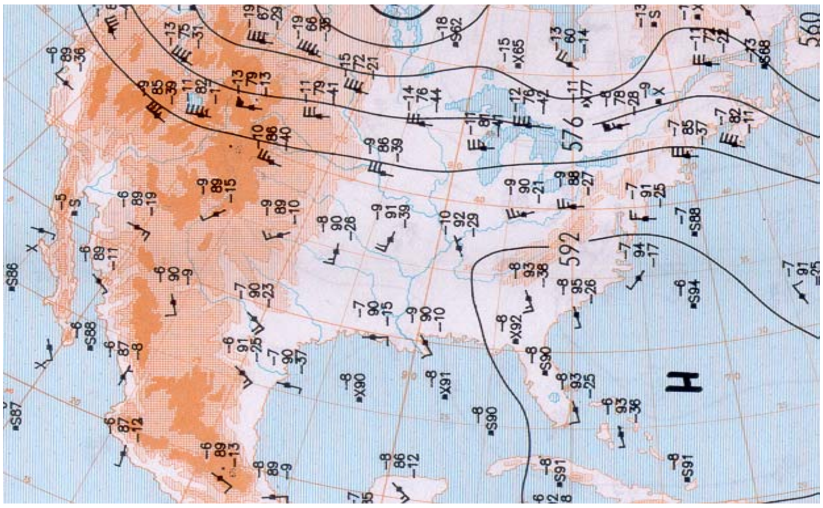

Figure 3.12: 500mb heights for 10th July 1993 (European Meteorological Bulletin)

3.3.2 Impacts of Climate Change

With the growing concerns over possible climate change, it is important to analyse any potential changes in characteristics of heat waves. With a potential increase of 3ºC in global mean temperature by the end of the next century, (IPCC, 2001) we might expect both the frequency and intensity of heat waves to increase. Karl and Knight (1996), performed analysis on various climate models, to indicate that a 3ºC rise in global mean temperature would lead to an increase in return period of a 1-day T_{ap} of 47.8ºC in Chicago from 1 in 23 to

1 in 6 years. Other important factors are the change in interannual and intramonthly variability.

The observed increase in mean summer maximum apparent temperatures of 1.3ºC in Chicago and 0.2ºC in New York City in this study, have not been associated with increases in the frequency of heat waves. Degaetano (1996) states that for the period 1951 to 1990 the frequency of the number of days with temperatures greater than 35ºC in the Northeastern United States decreased, but Balling and Idso (1990) found the opposite for the period 1948-1987. The number of days with dry bulb and apparent temperature above 35ºC, for New York City, (Northeastern United States), and Chicago from my data set are summarized in Figures 3.13 and 3.14. Note the huge difference between the maximum dry bulb temperature and the maximum apparent temperature criteria. This demonstrates that just the dry bulb temperature is inadequate index of summer heat.

Figure 3.13 demonstrates support for Balling and Idso's study. However the 1991-2000 data appears to contradict their theory with a decrease in the number of occurrences. Figure 3.14 for Chicago, demonstrates that there is no evidence to support an increase in the frequency of days with temperatures above 35ºC

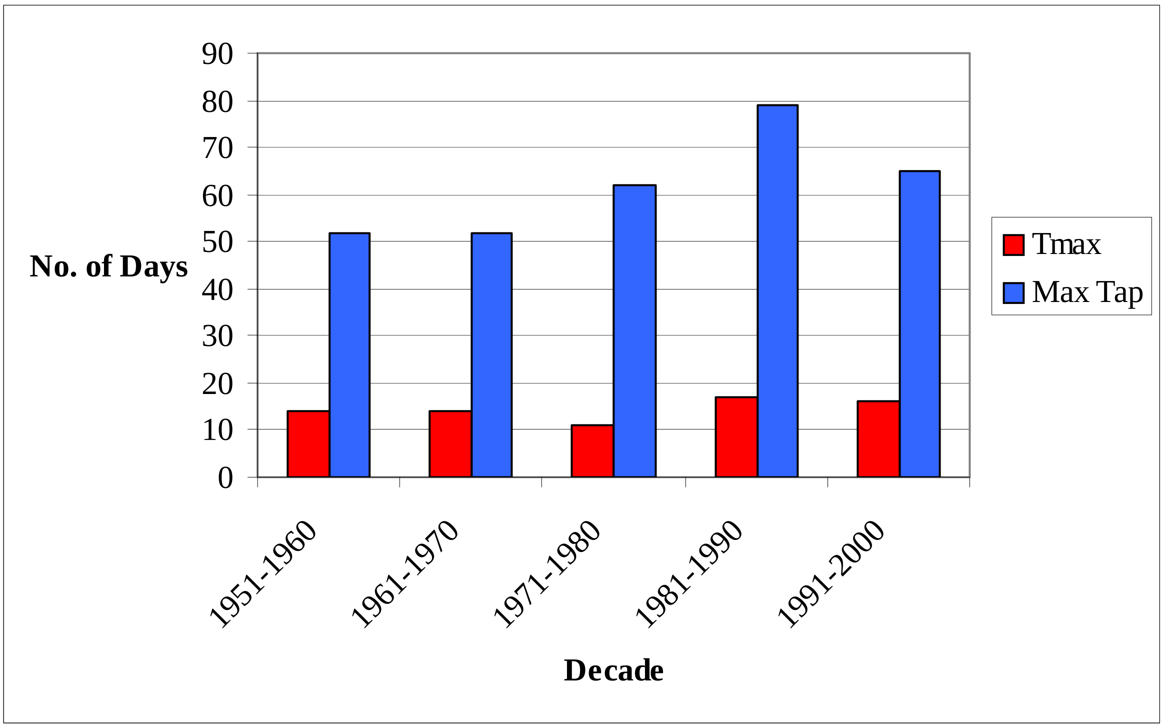

Figure 3.13: The no. of days per decade in New York City with T_{max} or max T_{ap} of greater than 35ºC

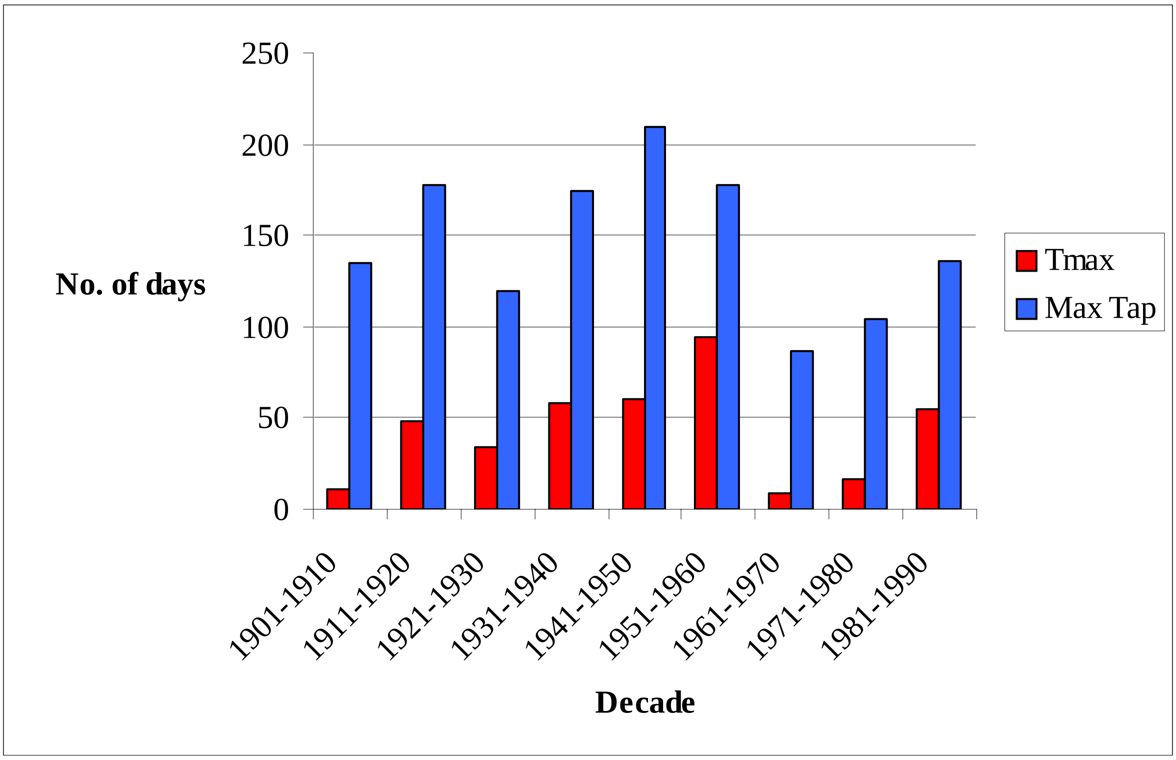

Figure 3.14: The no. of days per decade in Chicago with T_{max} or max T_{ap} of greater than 35ºC

Kunkel et al (1996) in fact supported this theory for the whole of the United States saying that there is no evidence of changes in the frequency of intense heat waves since 1930 throughout the United States of America. .

Another hypothesis (Kalkstein and Davis, 1989) suggests that an increase in mean temperature will not simply lead to an increase in heat wave thresholds. Previous studies (Robinson 2001) have indicated that in warmer climates human reactions to hot weather simply occur at a higher temperature than in cooler climates, i.e. when the temperature reaches 40ºC in Phoenix residents will react in a similar manner to the residents of Chicago when local temperatures exceed 34ºC. Kalkstein, however, states that there is evidence to suggest that this is not entirely correct. Mortality figures indicate that, upon the exceedence of heat wave thresholds, far fewer deaths occur in Phoenix than in the cooler climate of say New York City. This could potentially be due to a level of physiological acclimatisation and an increased understanding of how to adapt a lifestyle to accommodate a hotter environment. It is feasible therefore, that, contrary to popular opinion, in the event of a rise in mean temperatures, acclimatisation would occur and possibly lead to a decrease in the impacts of heat waves in the cities most severely affected.

In contrast to this however, it is possible that the impact of climate change would result rather from changes in variability and extreme event occurrence than from an increase in mean temperature (Parmesan et al 2000). This is due to the fact that even relatively minor changes in means and variations of climate variables can induce considerable changes in the severity of extreme events (Katz & Brown, 1992).

3.3.4 Hot Summers Versus Heat Waves

An important factor throughout this study is the ability to differentiate between a hot summer and a heat wave. A number of previous works (Kunkel et al 1996) have designated July/August 1936 as a heat wave of note in Chicago due to the number of fatalities occurring; however this is contrary to the results found here. Whilst daytime temperatures reached a high of 46.7°C with mean July daytime temperatures of 31.5°C (3.6°C higher than the norm), no two consecutive days exceeded the given thresholds of 41.1°C and 25.2°C as demonstrated in Figure 3.15.

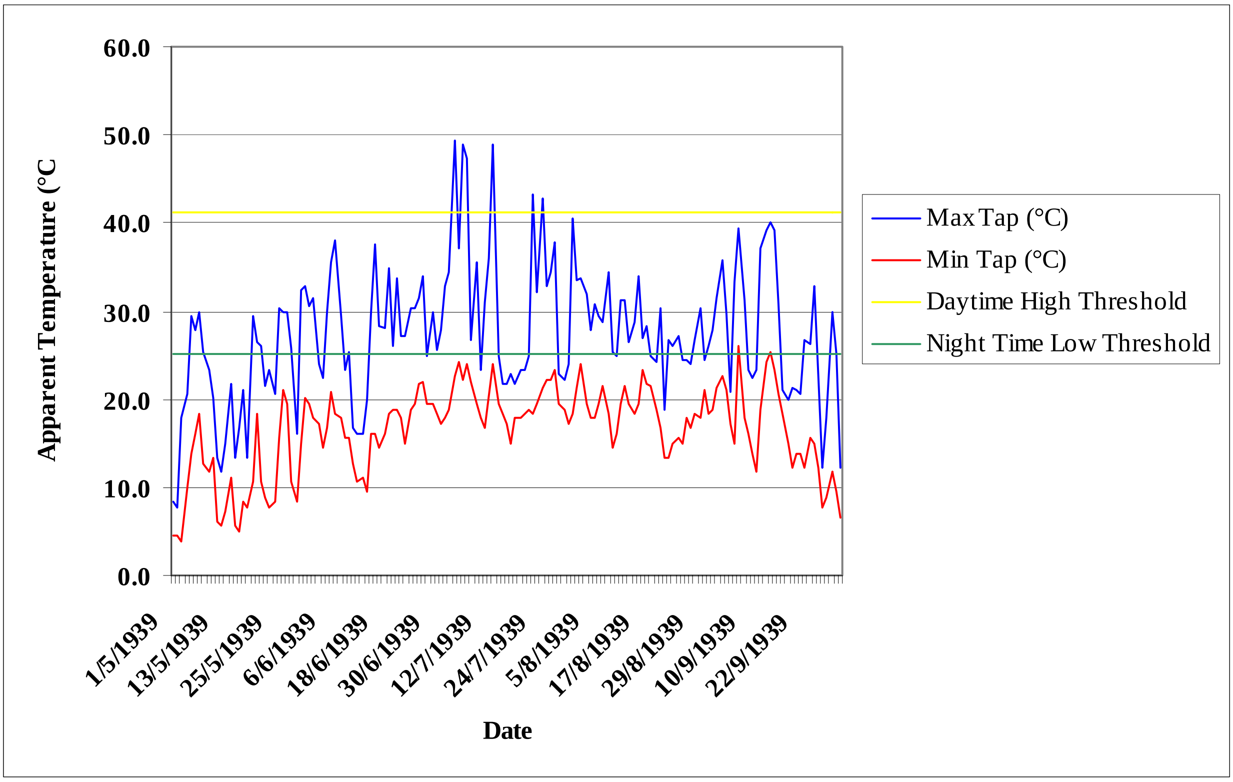

Figure3.15: Apparent temperature throughout the summer of 1936 in comparison to heat wave thresholds.

This returns us to the point raised earlier that perhaps statistical methods are not the most appropriate when considering the establishment of heat wave thresholds. Perhaps more suitable definitions could be realised following further work into the impacts of extreme heat and the temperature at which these impacts commence. Unfortunately until these studies are performed statistical methods are our best solution.

Chapter 4

Forecasting a Heat Wave

4.1 The Important Aspects of a Heat Wave Forecast

We have seen throughout our discussions that it is crucial to be able to accurately predict the onset of a heat wave in order to prevent the array of impacts that such an event creates. By utilising the measure of apparent temperature or heat index as a more accurate representation of how hot it "feels", we have identified the importance of accurately forecasting not only the dry bulb temperature but also the dew point temperature. Local governments require a number of days notice in order to ready their emergency services for such an event so it is essential that the NWS is able to predict both dry bulb and dew point temperature with a substantial lead time. Multiple day heat events are associated with slowly overturning large-scale atmospheric circulation features (as discussed in section 3.3.1). These are well predicted a few days ahead of their arrival and the public alerted to the impending warm weather. However, the models currently in place are only able to predict accurate temperatures a day or two ahead of their onset therefore official advisories or warnings are delayed until this time so that more accurate information can be disseminated. This can often lead to a state of unreadiness for the emergency services and hence improved lead time, as with any forecast, is desirable.

Another key element to a forecast is the ability to predict the night time low accurately. As was shown earlier the impacts of a heat wave are more severe if the nighttime low remains elevated so that no overnight relief is gained. During the Midwest heat wave of July 1995, daytime temperatures were forecast to an accuracy of 1.5°C, however, it was the night time temperatures, underestimated by 3.5°C, that took the region by surprise and contributed to the large number of fatalities observed.

An experienced meteorologist who can accurately translate the physical characteristics of the event to local governments and the emergency services is another important constituent of a heat wave forecast. As many people do not fully understand the implications of intense heat it may not be adequate to simply provide temperature forecasts, the meteorologist should be able to relate the potential impacts of the heat in order to help decision makers in their duties. In fact, a real problem that has been faced during some of the more recent heat waves in Chicago is that the events are so widely spread in time that two consecutive heat waves rarely have the same decision makers and meteorologists involved. Defined heat wave procedures are therefore necessary in order to minimise the effects of this lack of experience. Furthermore, it is crucial that information as to the severity of the situation along with methods by which to stay cool is disseminated via the media in a quick and effective fashion.

4.2 Urban Heat Island

In order to prepare warnings for future heat conditions in urban areas it is important to delineate the magnitude and dimensions of the urban heat island. Although the urban heat island is insignificant during the day it exhibits much less nocturnal cooling than occurs in rural areas (Changnon et al, 1996). Furthermore, due to varying local climate and other effects urban heat islands are likely to vary from city to city (Kalkstein and Davis, 1989).

Summer time forecasts should therefore be provided based on temperature observations in urban not rural areas. Figure 4.l demonstrates the difference in temperatures observed in St Louis, a less urban area, and downtown Chicago during the heat wave of 1999. It illustrates that Chicago experienced temperatures of up to 4°F higher than those of St. Louis. In fact, Labas (personal communication, 2004) of NOAA, he noted that since the high level of fatalities in the urban core of Chicago during the heat wave of 1995, heat waves for the inner city have been defined very differently than for the rest of Illinois due to the large heat island effect.

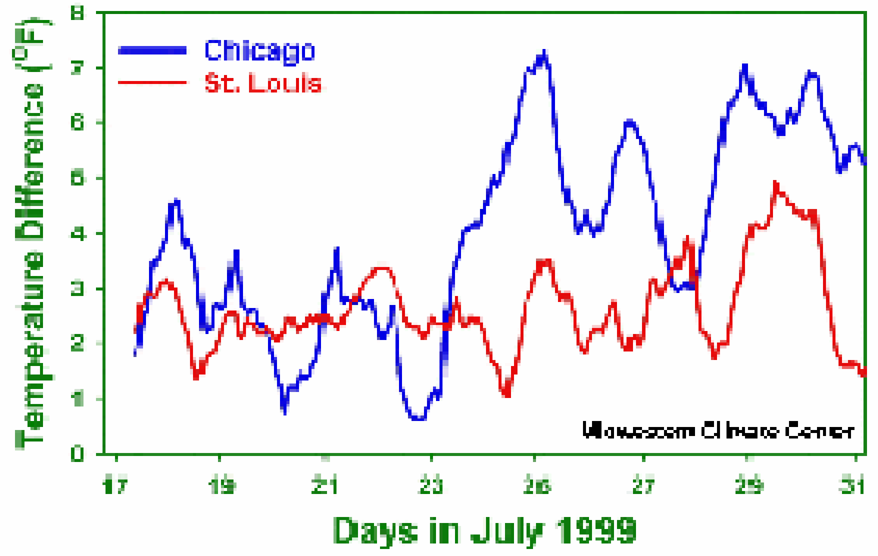

Figure 4.1: Urban-Rural Temperature Comparison 24-hr Running Mean Difference July 17-31, 1999. (Palecki & Changnon, 1999)

It is clear therefore, that this study could be extended by investigating the impact of the urban heat island as observations for both cities were taken in suburban areas. However, available climatological data for many cities throughout the U.S. are not adequate to define the heat island on a 24-hour basis.

4.3 Heat-Health Warning Systems

Dr Laurence Kalkstein of the University of Delaware, in collaboration with such bodies as the World Meteorological Organisation, the World Health Organisation, The United Nations Environment Programme and the United States Environmental Protection Agency has developed a heat-health watch/warning system which is to be deployed in vulnerable cities across the world. The system, currently operational in, amongst other cities, Philadelphia, Pennsylvania, is specially adapted to the individual climate, social structure and urban landscape of each city. In doing this, it is set up to appreciate that the reaction of residents to extreme weather events varies from one city to the next. It is one of the first systems based on actual weather and its human-health relationships, and is based around identifying stressful weather situations rather than just meteorological variables such as temperature, humidity etc.

In Philadelphia between the dates of July 12 and August 16, 1995, the Kalkstein model was able to accurately predict 45% of days where heat related deaths occurred. While not a high percentage this remains 21% higher than the level of accuracy achieved by the NWS systems (NOAA, Disaster Survey Report July 1995), and highlights the requirements for the inclusion in forecasting models of non-meteorological variables such as the manner in which people react to the different weather systems.

Of course, whatever system is in place to forecast heat waves, one final crucial element is that its accuracy levels are high enough to instil within it the faith of the public. The main aim should always be to reduce the number of false forecasts so that when a heat wave is predicted, the public understand the dangers and act accordingly.

Conclusions

Throughout this work we have discovered that the impacts of extreme high temperature are both severe and widespread. With the threat of climate change the need to understand heat waves, their origins and their effects becomes all the more relevant.

After studying the differing measurements of dry bulb temperature and apparent temperature it is clear that the effects of humidity must be considered when evaluating a heat wave. High levels of humidity can add up to 22°C to the recorded dry bulb temperature hence dry bulb temperature alone is an inappropriate indication of the severity of a heat wave. Furthermore, as humidity levels increase during times of extreme high temperature, the need to factor them into our calculations becomes even more critical.

Having found in apparent temperature a more suitable means of measuring heat waves it is necessary to establish meaningful heat wave thresholds above which modifications in lifestyle would be necessary in order to prevent health problems. It is clear from this study that the NWS heat wave thresholds cannot be applied without careful consideration and in many cases alterations will be necessary to suit local climatic regimes. In fact, when considering Chicago and New York the 40.6°C suggested by the NWS should be lowered to

38.4°C and 36.7°C respectively. These thresholds are able to capture all significant heat waves during the period of interest without incorporating such things as summers with generally elevated temperatures. More work needs to be performed in relation to Kalkstein's model which does not base the heat wave thresholds purely on a statistical analysis of meteorological variables moreover it recognizes the need to analyse the impacts effected by the varying weather systems.

Duration of heat waves was shown to be dependent on location, and coastal areas such as New York will experience shorter lived events than regions of a more continental location such as Chicago.

Although no upward trend in frequency was observed over the last century, in the event of future climate change we need to consider whether things such as the heat wave thresholds need to be modified to take into account increased mean temperatures. In addition, further studies are required into the effects of increased variability and the potential for acclimatisation.

Two crucial elements to forecasting heat waves within cities were found to be night time low temperature and the urban heat island. Relief from heat is often gained overnight when temperatures cool. Therefore accurate predictions of the level to which night time temperatures will remain elevated is essential when quantifying the expected impacts of a heat waves and preparing accordingly. The urban heat island was found to have a distinct effect within cities leading to an increase in temperature of up to 4°C above those in more rural areas.

Following recent extreme heat waves in the United States, measures are now being to taken to ensure a reduction in fatalities, cooling centres have been established in certain cities which provide air-conditioned places and facilities where people can relax and recover from the stresses of the outside heat. However, it is crucial that these centres are advertised appropriately so that the poor and elderly can make as much use of them as possible.

Furthermore, the facility to register vulnerable people, living alone, with the local government has been established so that home visits can be arranged during times of extreme heat. Combine this with the ever-improving understanding of heat waves and how to predict them, then it is to be hoped that in the heat waves to come the United States will be better prepared and a reduction in fatalities will be visible.

Appendix A

```
!*******************************************************************!
!* Program to calculate apparent temperature interpolation  from dry-bulb/ dewpoint    *!
!*  temperature (Table 2) after  Steadman, R. G. (1979), JAM, 18, 874-885              *!
!*  tmpd (dbt) = dry bulb temperature (F)                                               *!
!*  dptp (dpt) = dew point temperature (F)                                              *!
!*  wspd (wsk) = wind speed (knots)                                                     *!
!*  apt = apparent temperature (F)                                                      *!
!*  tmpdp = NWS version from above (in F)                                               *!
!*                                        Kenneth Kunkel & Sarah Grintzevitch           *!
!*******************************************************************!
 PROGRAM apparenttemp
  IMPLICIT NONE

   DOUBLE PRECISION::tmpdp(16,16),dbindx(16),dpindx(16)
   INTEGER::tmpd,dptp,wspd,i,ios
   DOUBLE PRECISION::ap

   OPEN (UNIT=13,FILE="resultsny_min.dat",IOSTAT=ios)  !Open output data file
   IF (ios /=0) THEN
     PRINT*,'Problems opening output file, closing program'; STOP
   ENDIF

   CALL apread(tmpdp, dbindx, dpindx)

   !* pass tmpd - dry bulb temp
   !* pass dptp - dewpoint temp
   !* pass wspd - wind speed
   !* retrieve ap - apparent temp
   OPEN(UNIT=10,FILE="mintempny.prn")

   DO i=1,19902
```

```
      READ(10,*) tmpd, dptp, wspd
      CALL aptemp(tmpd,dptp,wspd,ap,tmpdp,dbindx,dpindx)
      WRITE(13,*) ap
    END DO

    CLOSE (13)
    CLOSE (10)

   END PROGRAM apparenttemp
!*********************************************************************
  SUBROUTINE aptemp(tmpd,dptp,wspd,ap,tmpdp,dbindx,dpindx)
   IMPLICIT NONE

     INTEGER::tmpd,dptp,wspd
     DOUBLE PRECISION::tmpdp(16,16),dbindx(16),dpindx(16)
     DOUBLE PRECISION::apt, ap
     DOUBLE PRECISION::ws, tc, rat, rad, ratio, mxapt, t1, t2
     INTEGER::i, j, ii, jj
     INTEGER::yr,mn,dy

     mxapt = -100.0
!* If any input is missing, set app temp = missing, and go to end (counter)
!* Input values are interpolated, so this should never happen
    IF (dptp.eq.999 .or. tmpd.eq.999 .or. wspd.eq.999)THEN
        WRITE(*,*) 'HEY!  Input to app temp = 999'
        WRITE(*,3) dptp,tmpd,wspd,i*100,yr,mn,dy
        STOP
3    FORMAT('dptp (',i3.3,'), tmpd (',i3.3,'), wspd (',i3.3,') at ',  &
    &  i4.4,' on ',3(i2.2))
    END IF
!* If Dew point > Air temp, set app temp = missing, and go to end (counter)
!* This will already be taken care of when the data come in
       IF (dptp .gt. tmpd) THEN
        WRITE(*,*) 'HEY!  dptp > tmpd'
```

```
          WRITE(*,4) dptp,tmpd,i*100,yr,mn,dy
          STOP
        END IF
4    FORMAT('dptp (',i3.3,') > tmpd (',i3.3,') at ',i4.4,     &
     &       ' on ',3(i2.2))
!*  Check that temp and dew point are inside table domain,
!*  if not, set app temp = air temp and go to end
!*  Print out values if tmpd>110 or dptp>84
        IF (tmpd .lt. 68 .or. tmpd .gt. 122 .or.     &
             & dptp .lt.  0 .or. dptp .gt.  86) THEN
              apt = float(tmpd)
           IF (tmpd .gt. 122 .or. dptp .gt.  86)    &
               & WRITE(*,5) dptp,tmpd,i*100,yr,mn,dy
              GO TO 18
         END IF
5    FORMAT('OFF CHART -- dewpoint (',i3,'), temp (',i3,') hr ',&
     &       i4.4,' on ',3(i2.2),' (apt=tmpd)')

!*  Convert wind speed from knots to m/sec
         ws = wspd / 1.94

!*  Find row and column of table according to temp/dewtemp input.
!*  If > value of last column, set = value at last column (this won't
!*  happen though, since off chart was examined just above)
         DO jj = 1, 16
           IF (float(tmpd) .gt. dbindx(jj)) GO TO 11
         END DO
         jj = 16
11       CONTINUE
         DO ii = 1, 16
           IF (float(dptp) .lt. dpindx(ii)) GO TO 12
         END DO
         ii = 16
12       CONTINUE
```

```
!*  Determine table position, then go to take wind speed into account
      IF (float(tmpd) .eq. dbindx(jj-1) .and.&
        &float(dptp) .eq. dpindx(ii-1)) THEN
        ii = ii-1
        jj = jj-1
        apt = tmpdp(ii,jj)
        GO TO 50
      END IF

      IF (float(tmpd) .eq. dbindx(jj-1) .and.&
        &float(dptp) .ne. dpindx(ii-1)) THEN
        jj=jj-1
        rad=(float(dptp)-dpindx(ii-1))/(dpindx(ii)-dpindx(ii-1))
        apt = rad*(tmpdp(ii,jj)-tmpdp(ii-1,jj))+tmpdp(ii-1,jj)
        GO TO 50
      END IF

      IF (float(tmpd) .ne. dbindx(jj-1) .and.&
        &float(dptp) .eq. dpindx(ii-1)) THEN
        ii=ii-1
        rat=(float(tmpd)-dbindx(jj-1))/&
           &(dbindx(jj)-dbindx(jj-1))
        apt = rat*(tmpdp(ii,jj)-tmpdp(ii,jj-1))+tmpdp(ii,jj-1)
        GO TO 50
      END IF

      rad=(float(dptp)-dpindx(ii-1))/(dpindx(ii)-dpindx(ii-1))
      rat=(float(tmpd)-dbindx(jj-1))/(dbindx(jj)-dbindx(jj-1))
      t1=tmpdp(ii-1,jj-1)+rat*(tmpdp(ii-1,jj)-tmpdp(ii-1,jj-1))
      t2=tmpdp(ii,jj-1)+rat*(tmpdp(ii,jj)-tmpdp(ii,jj-1))
      apt=t1+rad*(t2-t1)
!*  Account for wind speed effects
!*  Wind has a cooling effect at temps <  93 degF and
!*                 a warming effect at temps >= 93 degF
```

```
50      CONTINUE
        tc = (float(tmpd)-32.0)/9.0*5.0
        IF (tc .lt. 28.5 .and. ws .ge. 3.5 .and. ws .lt. 6.0)&
     &      apt = apt-1.*1.8
        IF (tc .lt. 21.5 .and. ws .ge. 5.0 .and. ws .lt. 7.0)&
     &      apt=apt-1.*1.8
        IF (tc .lt. 21.5 .and. ws .ge. 6.0 .and. ws .lt. 10.0)&
     &      apt=apt-3.*1.8
        IF (tc .ge. 21.5 .and. tc .lt. 28.5 .and.&
     &      ws .ge.  6.0 .and. ws .lt. 10.0)    &
     &      apt=apt-2.*1.8
        IF (tc .ge. 28.5 .and. tc .lt. 32.5 .and.&
     &      ws .ge.  6.0 .and. ws .lt. 10.0)    &
     &      apt=apt-1.*1.8
        IF (tc .ge. 38.5 .and. tc .lt. 48.5 .and.&
     &      ws .ge.  6.0 .and. ws .lt. 10.0)    &
     &      apt=apt+1.*1.8
        IF (tc .lt. 21.5 .and. ws .ge. 10. .and. ws .lt. 14.)&
     &      apt=apt-4.*1.8
        IF (tc .ge. 21.5 .and. tc .lt. 28.5 .and.&
     &      ws .ge. 10.0 .and. ws .lt. 14.0)    &
     &      apt=apt-3.*1.8
        IF (tc .ge. 28.5 .and. tc .lt. 31.5 .and.&
     &      ws .ge. 10.0 .and. ws .lt. 14.0)    &
     &      apt=apt-2.*1.8
        IF (tc .ge. 31.5 .and. tc .lt. 33.5 .and.&
     &      ws .ge. 10.0 .and. ws .lt. 14.0)    &
     &      apt=apt-1.*1.8
        IF (tc .ge. 35.5 .and. tc .lt. 38.5 .and.&
     &      ws .ge. 10.0 .and. ws .lt. 14.0)    &
     &      apt=apt+1.*1.8
        IF (tc .ge. 38.5 .and. tc .lt. 49.5 .and.&
     &      ws .ge. 10.0 .and. ws .lt. 14.0)    &
     &      apt=apt+2.*1.8
```

```
      IF (tc .ge. 49.5 .and. ws .ge. 6.0 .and. ws .lt. 10.0)&
    &      apt=apt+1.*1.8
      IF (tc .lt. 25.5 .and. ws .ge. 14.0) &
    &      apt=apt-4.*1.8
      IF (tc .ge. 25.5 .and. tc .lt. 29.5 .and. ws .ge. 14.0) &
    &      apt=apt-3.*1.8
      IF (tc .ge. 29.5 .and. tc .lt. 31.5 .and. ws .ge. 14.0) &
    &      apt=apt-2.*1.8
      IF (tc .ge. 31.5 .and. tc .lt. 33.5 .and. ws .ge. 14.0) &
    &      apt=apt-1.*1.8
      IF (tc .ge. 34.5 .and. tc .lt. 36.5 .and. ws .ge. 14.0) &
    &      apt=apt+1.*1.8
      IF (tc .ge. 36.5 .and. tc .lt. 39.5 .and. ws .ge. 14.0) &
    &      apt=apt+2.*1.8
      IF (tc .ge. 39.5 .and. tc .lt. 49.5 .and. ws .ge. 14.0) &
    &      apt=apt+3.*1.8
      IF (tc .ge. 49.5 .and. ws .ge. 6.0 .and. ws .lt. 10.0)  &
    &      apt=apt+2.*1.8

18     CONTINUE
      mxapt = max(mxapt,apt)
      ap = apt
     RETURN
     END
!*************************************************************
   SUBROUTINE apread(tmpdp, dbindx, dpindx)
    IMPLICIT NONE

     DOUBLE PRECISION::tmpdp(16,16),dbindx(16),dpindx(16)
     INTEGER::itp(16),ita(16),iap(16,16)
     INTEGER:: i,j,jj,k,l

     OPEN(unit=21,file='aptable.dat')
     READ(21,100)(itp(jj),jj=1,16)
```

```
      DO 200 k=1,16
      l=17-k
      READ(21,300)ita(l),(iap(jj,l),jj=1,16)
200   CONTINUE
100   FORMAT(4x,16i3)
300   FORMAT(i2,2x,16i3)

      DO 400 i=1,16
      dbindx(i)=1.8*ita(i)+32.
      dpindx(i)=1.8*itp(i)+32.

      DO 500 j=1,16
      tmpdp(i,j)=1.8*iap(i,j)+32.
500   CONTINUE
400   CONTINUE
      RETURN
1000  STOP
      END
```

Appendix B

List of Symbols and Acronyms

°C	Degrees Celsius
°F	Degrees Fahrenheit
H_i	Heat index in °C
JJA	Summer period - June, July, August
mb	Millibars
MJJAS	Extended warm period – May, June, July, August and September
NCDC	National Climatic Data Center
NWS	National Weather Service
PET	Potential evapotranspiration
RH	Relative humidity
SLP	Sea level pressure
T_{ap}	Apparent temperature in °C
T_d	Dewpoint temperature in °C
T_{max}	Maximum daily dry bulb temperature in °C
T_{min}	Minimum daily dry bulb temperature in °C
U.S.	United States

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