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

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

Chapter 1

The Definition of a Heat Wave

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.

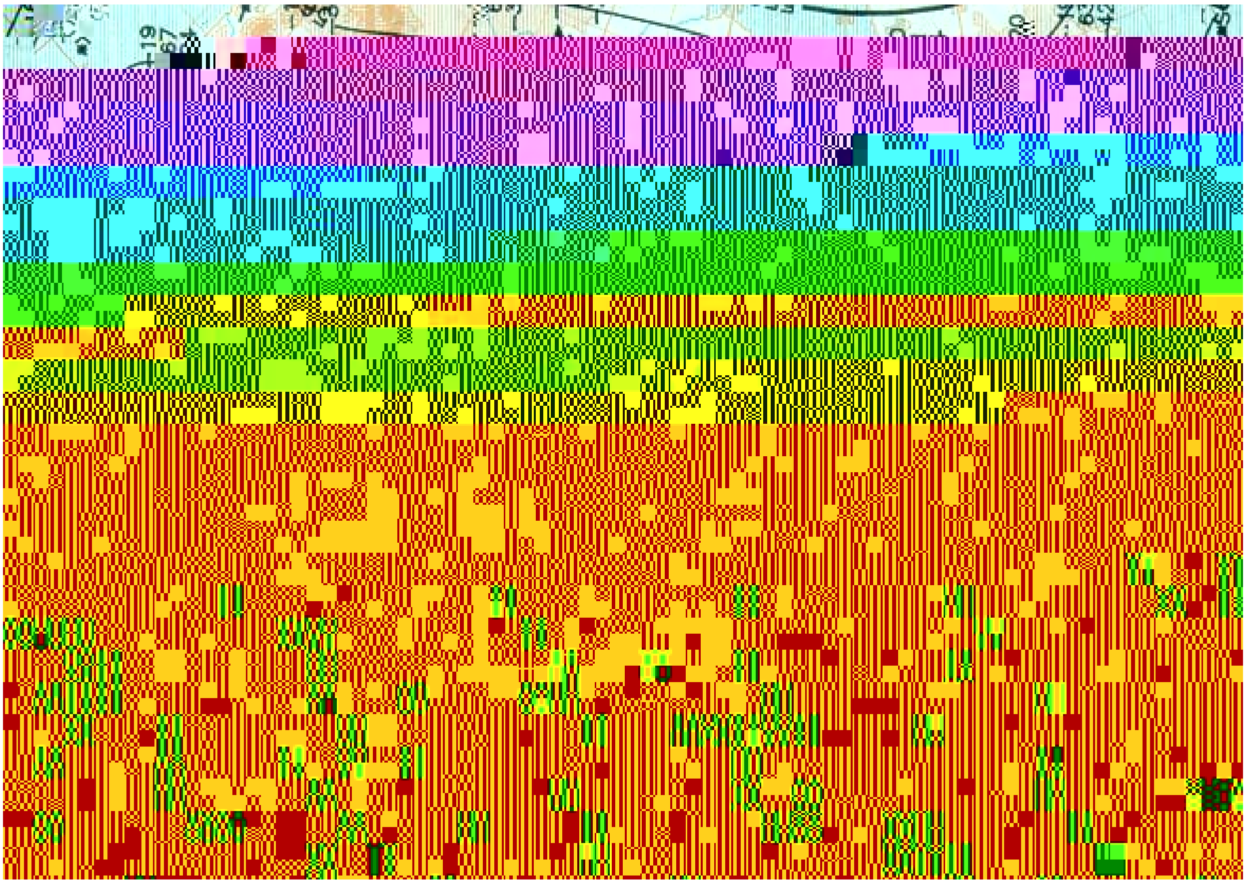


Figure 1.1: 500 mb topography for August 1988 (European Meteorological Bulletin)

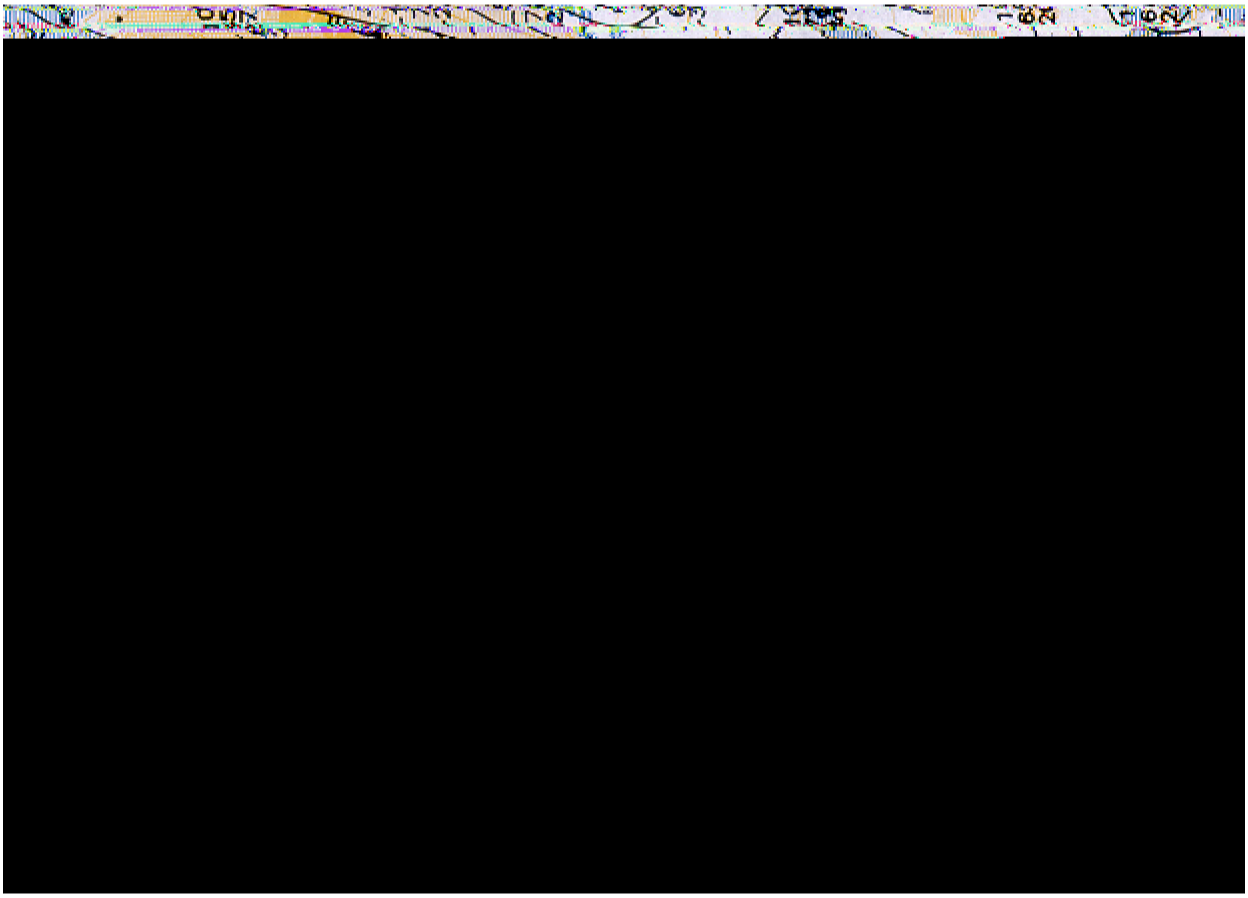
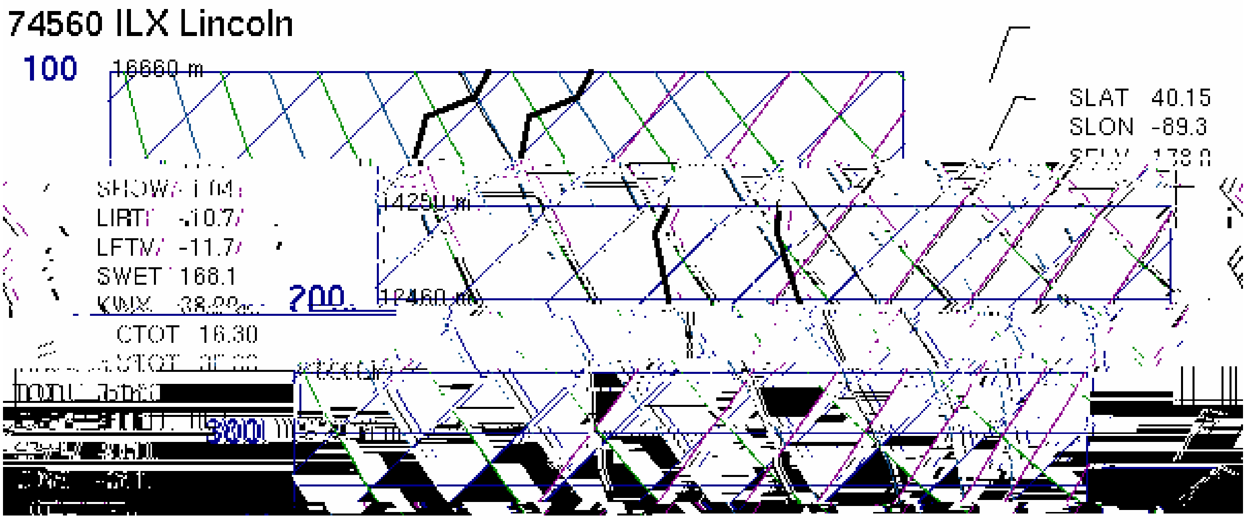


Figure 1.2: 500mb topography over the United States of America for August 1998, (European Meteorological Bulletin)

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.


74560 ILX Lincoln
100
16660 m
SLAT 40.15
SLON -89.3
LIRT -10.7
LFTV -11.7
SWET 168.1
CTOT 16.30
14250 m
200
12460 m
300

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

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.

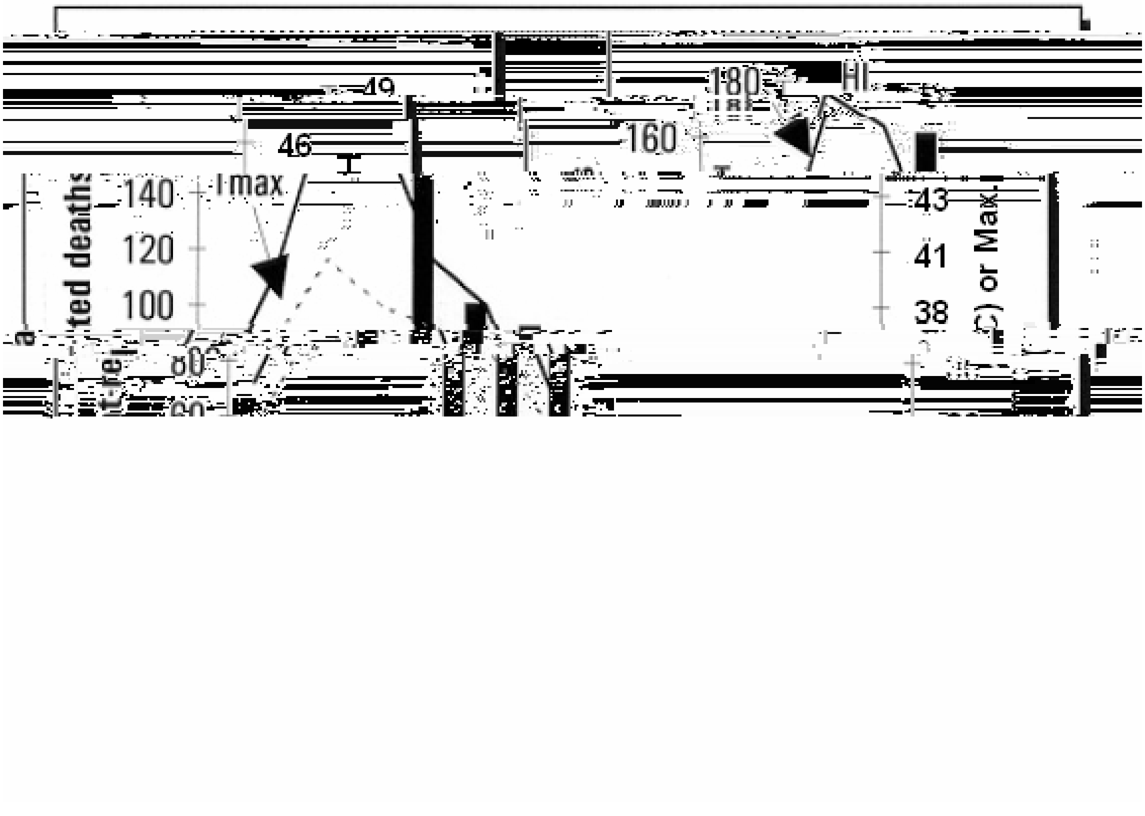


Figure 1.6: Heat –related deaths, Maximum Temperature (T_{max}) and Heat Index (HI), Chicago, July 11-23, 1995. (As reported by theOffice of the Medical Examiner). NOAA, Natural Disaster Survey Report: July 1995 Heat Wave.

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

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

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

(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

HEAT INDEX °C	
	RELA

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 40. this fixe 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 me

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 num

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.

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

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 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 w

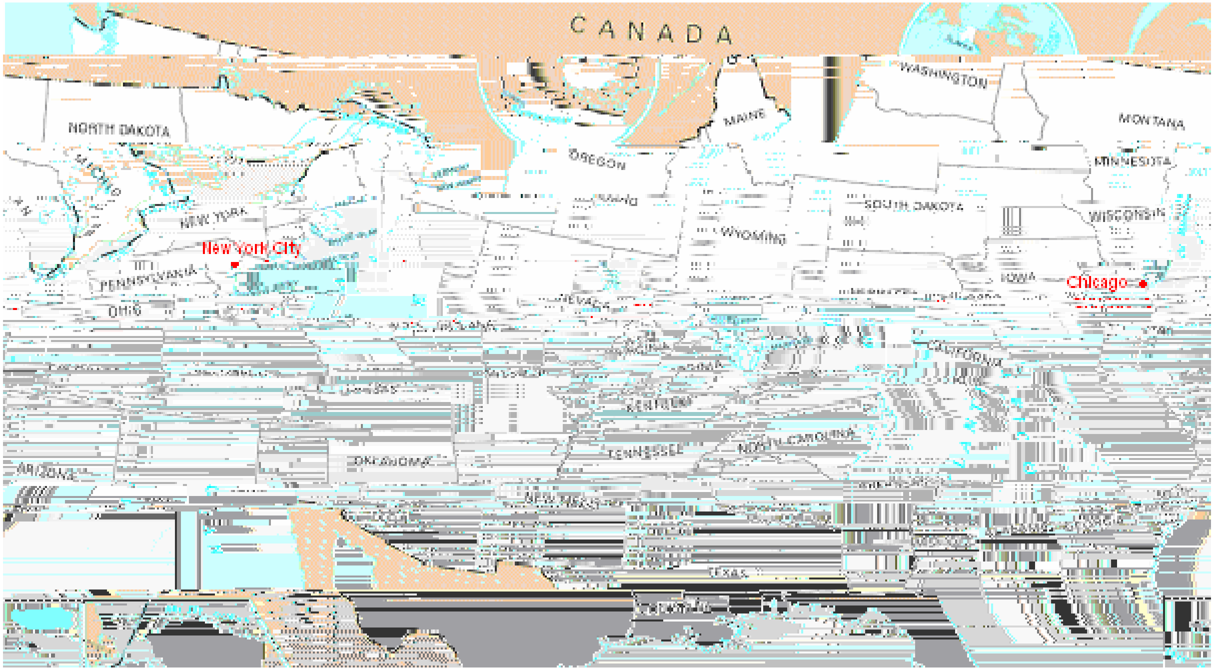


Figure 3.1: The contiguous United States of America, (www.nationalatlas.gov)

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. It

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 em

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

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 ocExtrem

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.

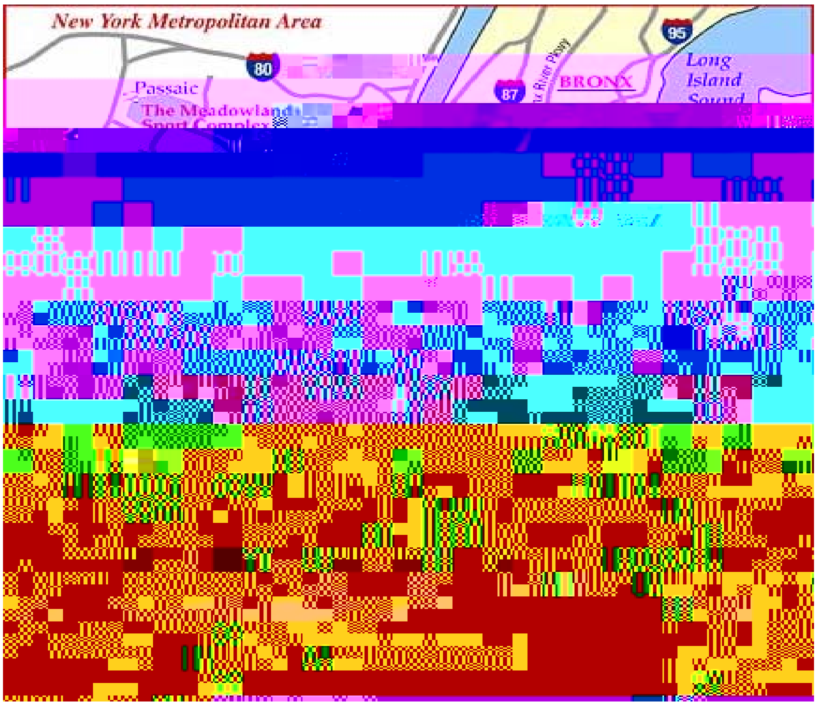


Figure 3.3: New York City, New York detailing the location of the JFK International Airport station (www.aaccessmaps.com)

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

	Max T_{ap} Heat Wave Threshold (°C)		Min T_{ap} Heat Wave Threshold (°C)	
Decade	JJA	MJJAS	JJA	MJJAS
1951-1960	36.9	36.3	25.9	25.4
1961-1970			25.9	25.4
1971-1980	36.9	36.3		

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	-	[redacted]		

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 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)

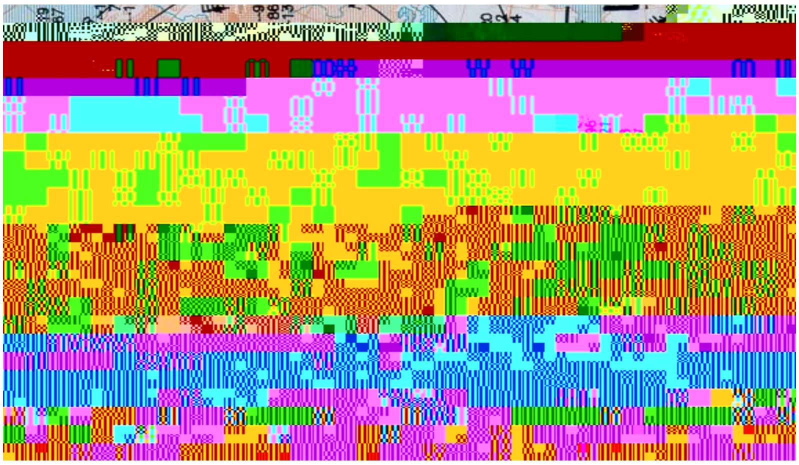


Figure 3.4: 500 mb heights for 11th August 1988 (European Meteorological Bulletin)

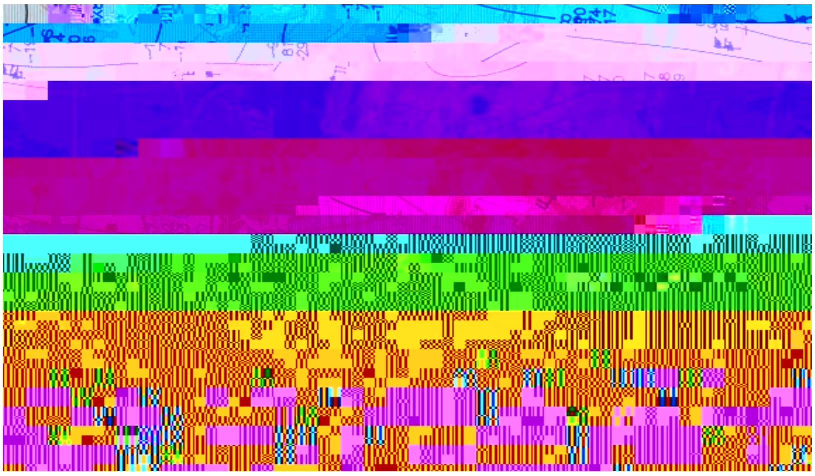


Figure 3.6 500 mb heights for 15th August 1988 (European Meteorological Bulletin)

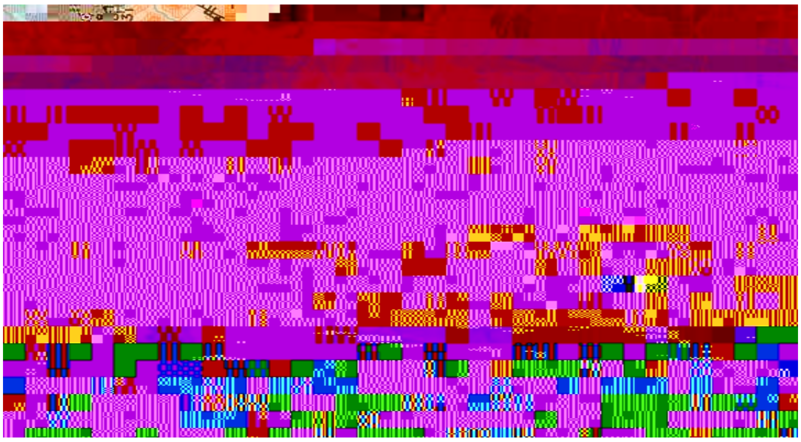


Figure 3.7: 500mb heights for 16th August 1988 (European Meteorological Bulletin)

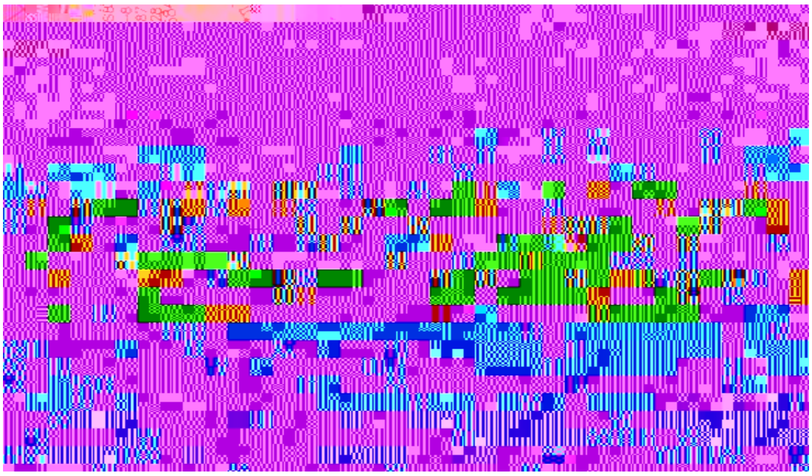


Figure 3.8: 500 mb heights for 17th August 1988 (European Meteorological Bulletin)

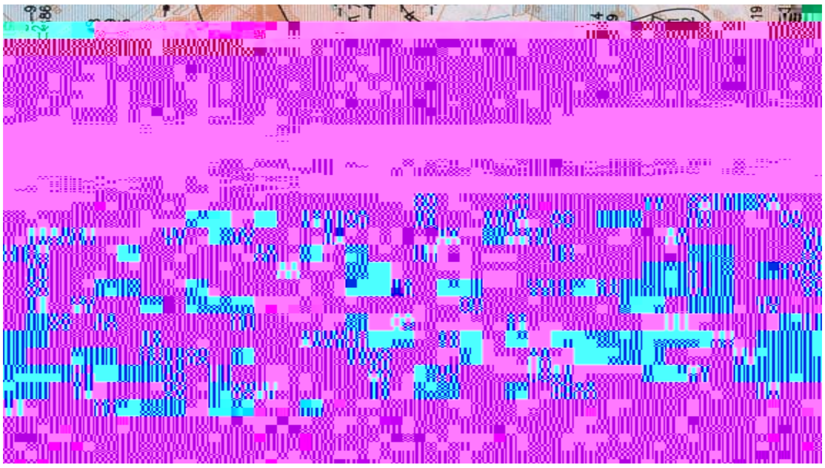


Figure 3.9: 500mb heights for 18th August 1988 (European Meteorological Bulletin)

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.

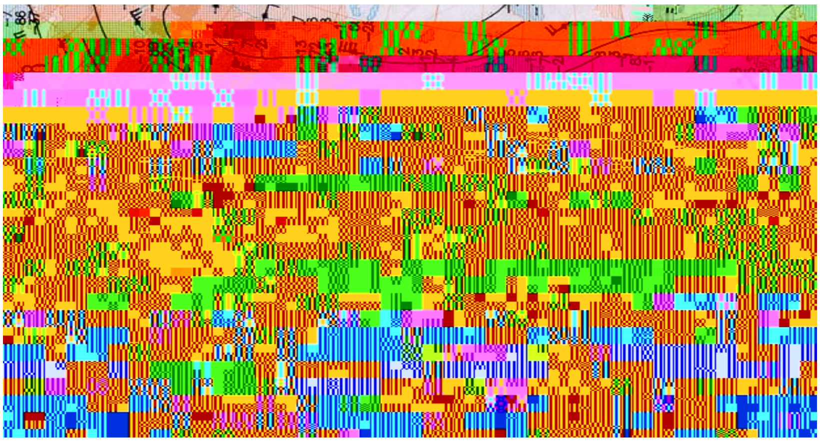
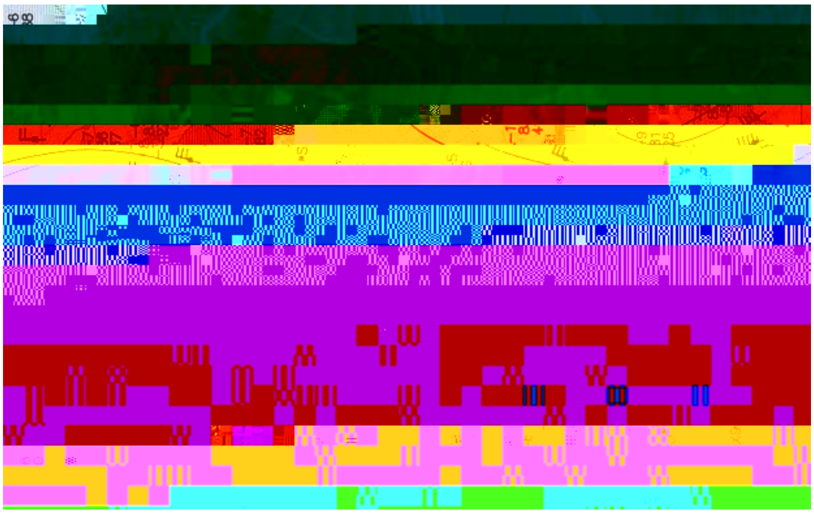


Figure 3.10: 500mb heights for 8th July 1993 (European Meteorological Bulletin)



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

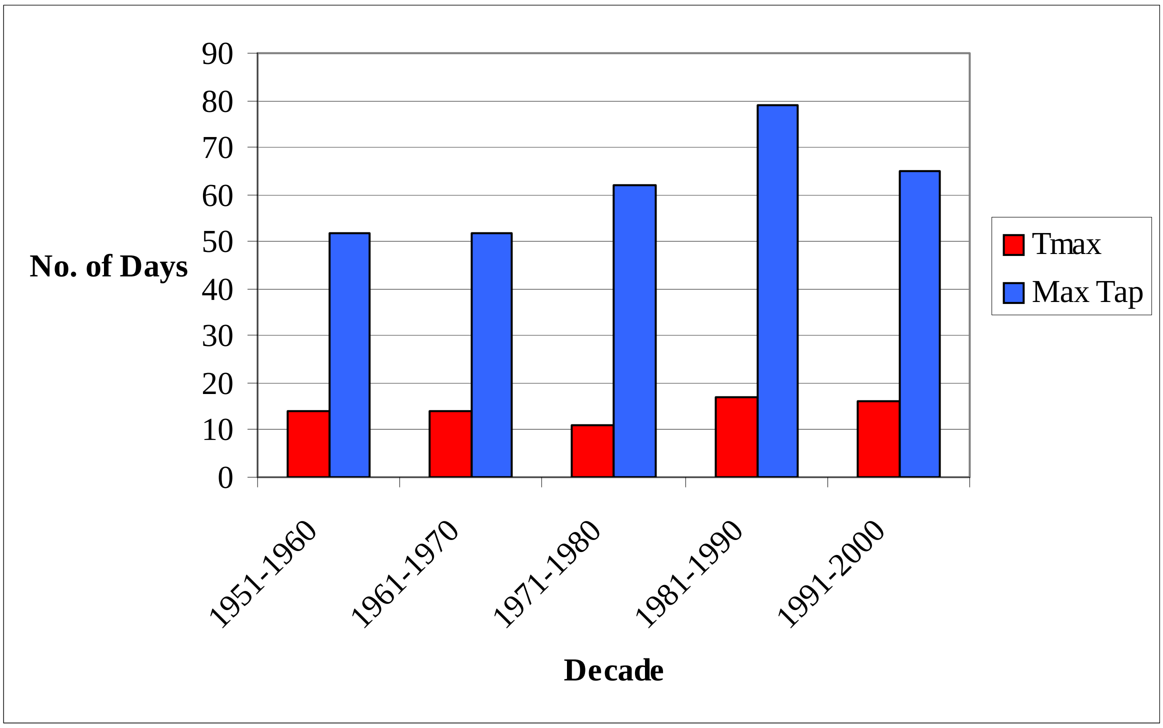


Figure 3.13: The

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 correct. Mupp bility to differentiate between a hot summer

ks (Kunkel et al 1996) have designated

Chicago due to the number of fatali

found here. Whilst daytime tem

temperatures of 31.5°C (3.6°

given thresholds of 41 C as

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 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 dur

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.

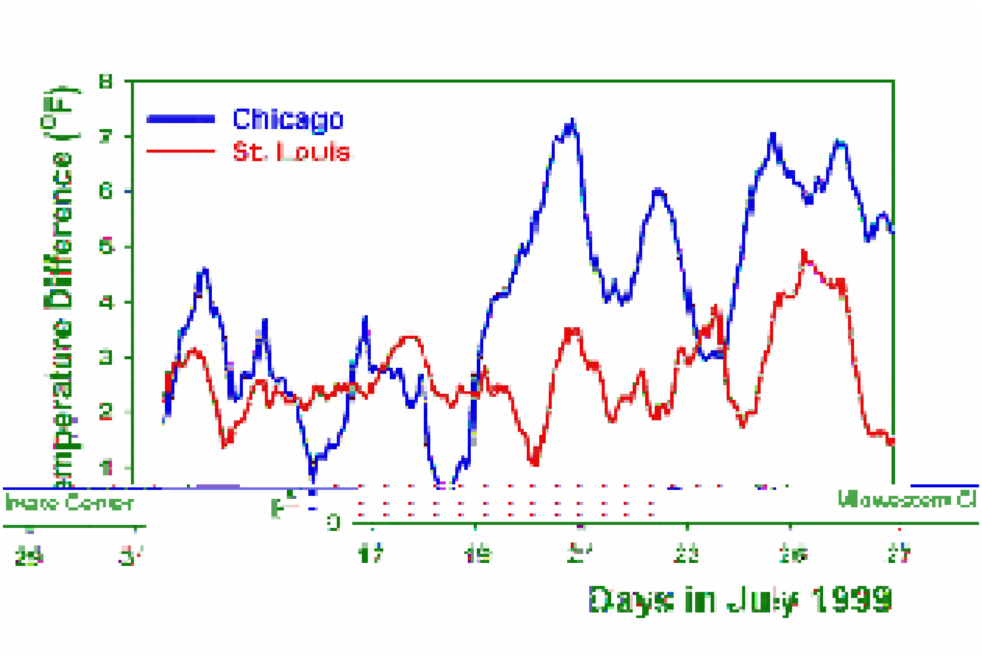


Figure 4.1: Urban-Rural Temperature Comparison 23.9 be p

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 siturab526.uather than jpe7 0.0002 Tc 0 Tw 12 0 0 12 3565ath1pe5 dw882 60ppr667

Conclusions

Throughout this work we have discovered that the impacts of extreme high tem

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

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     *!
!***********************************************************************!
```

READ

```
        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))
```

```
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
```

```
      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.
       2
```

Appendix B

List of Symbols and Acronyms

°C	Degrees Celsius
°F	Degrees Fahrenheit
H_i	Heat index in °C
JJA	Summm

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