CLASSIFYING HEAT WAVES IN THE UNITED STATES

by

ERIK HENRY BOWLES

B.S., Kansas State University, 2002
M.A., Kansas State University, 2004

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Geography
College of Arts and Sciences

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Abstract

Extreme heat is a hazard that is capable of causing economic problems and potentially high mortality rates across several regions simultaneously. This dissertation was designed to provide a better understanding of how often and where heat waves occur within the United States. The research design assessed all places equally in order to evaluate geographic variations in the character of heat waves. In order to simplify the variety of extreme heat events that occur, this research developed two classifications; one for accumulated daily heat stress and a second for extended periods of extreme conditions (heat waves). Both new classification systems were designed to objectively categorize individual events using a scale from 1 (minor) to 5 (extreme). The heat wave classification system was applied to 70 locations for years 1980-2001 to determine the frequency, magnitude, and duration of daily heat stress events and heat waves. Hourly temperature and humidity data were used to determine heat index values, which were accumulated to provide the daily heat intensity measurement. Major findings from this research include: how heat stress distribution is influenced by topographical relief variations as well as latitude; daily heat stress classifications during an event were typically not in an intensify-then-weaken progression; Category 1 heat waves were the most frequent overall followed by Category 2 and Category 3 heat waves, however Category 5 events outnumbered Category 4 events over the temporal period of this study; and heat stress days/heat waves occurred most frequently in the Southeast, with the fewest occurring in the Northwest. The classification was also used to illustrate the extent and magnitude of the 1995 heat wave that caused high human mortality in the Midwest. Results from this research are presented in maps and tables to provide a detailed insight on the characteristics of heat stress throughout the United States as a function of the exposure component of hazard vulnerability.

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Dedication

For my mom and dad

CHAPTER 1 - Introduction

Addressing the Heat Wave Problem

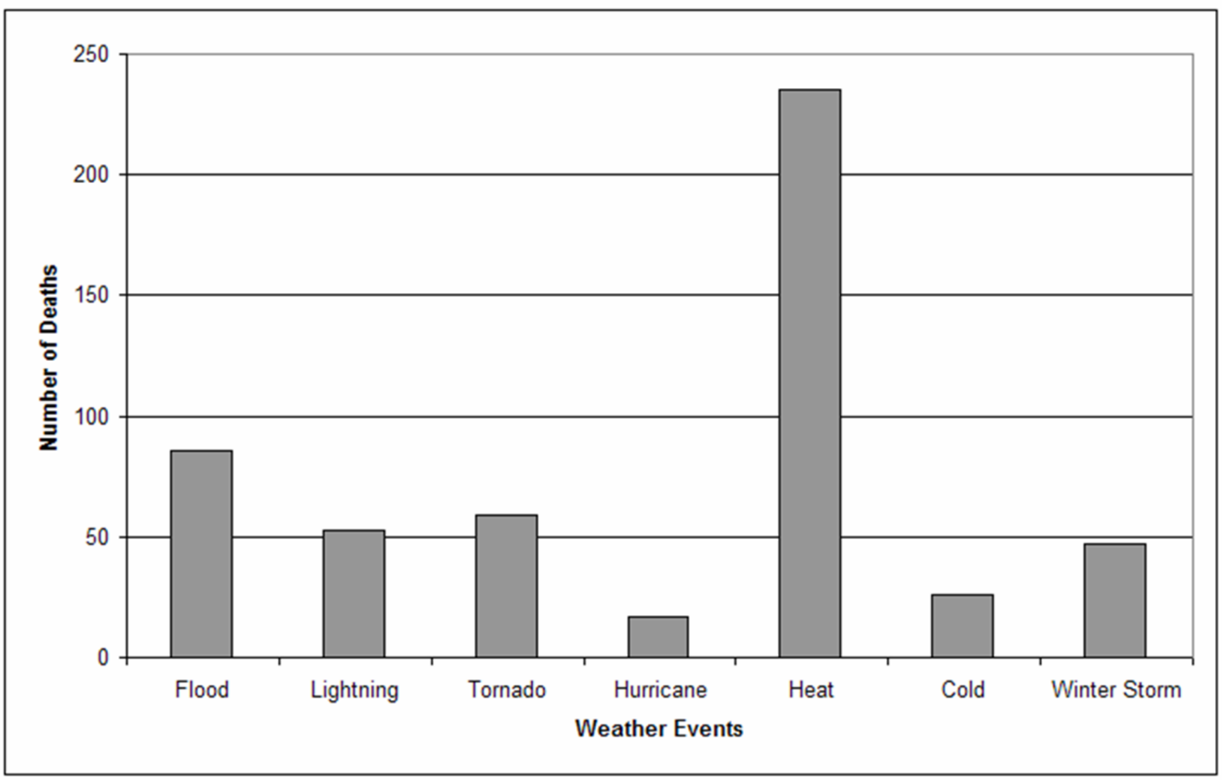
The United States experiences a wide variation of climate from year to year, which has a significant influence on the livelihood of living organisms (Rosenberg *et al*. 1993). Viewing the 'environment as hazard' is a topic on which geographers focus their research, including heat stress or bioclimatological health effects (White 1974, Burton *et al.* 1978, Mitchell 1989, Kalkstein 1991, and Cutter 2001). Heat stress events produce the potential for harm and, as they investigate these events, researchers are examining phases of the oldest of the traditions within geography, the manner in which humans interact with their environment (Mitchell 1989). A major subset of human-environment interaction research deals with climatic hazards such as thunderstorms, floods, droughts, blizzards, and heat waves, and the biological impacts of these hazards (Bryant 1991). There is a practical aspiration to inform decision makers and the public about the specific environmental conditions that have harmful effects on humans, animals, and other natural resources (Harrington and Bowles 2002). As a result, the sharing of new ideas between bioclimatologists and hazard researchers has been considerable.

Applied climatology covers a vast number of topics, one of which is identifying weather hazards with respect to the vulnerability to a particular population. Spreading awareness of the impacts of high heat has been slow; although publications since at least 1900 have noted that the duration of high temperatures are the most destructive weather hazard to humans and agriculture (Burrows 1900). Climatologists, whom are most interested in the biological response and the resilience of living things when faced with stressors from the environment, are working in bioclimatology (Kalkstein 1991). Bioclimatology is defined as "The branch of climatology that deals with the relations of climate and life, especially… on the health and activity of human beings and on animals and plants" (AMS 2000, p. 86). There are numerous studies in this field ranging from extensive flooding and human mortality (Gruntfest *et al*. 2000 and Smith *et al.* 2001), geographical distributions of plant species due to precipitation amounts (Dirmeyer 1994 and Zeng *et al*. 2002), to finding what specific climatic changes induce mass bird migrations (Hockey 2000).

Vulnerability to hazards is viewed as a composition of exposure, in which the conditions that are considered hazardous are identified, sensitivity, and adaptive capacity (Cutter *et al*. 2003). Kalkstein (1991) points out that there has been a major movement of bioclimatologists toward studying the effects of extreme events, primarily in the direction of impacts that humans and animals have from hazards as a form of sensitivity to them. The manner in which people respond to change in their environment including the responses to the change, resiliency capabilities, and mitigation for future hazards are considered parts of adaptive capacity (Smit, *et al*. 1999). The focus of this research is based on the exposure component of vulnerability by identifying the frequency of extreme heat days and events to determine how often or regularly heat waves impact different areas of the United States.

The work proposed in this project aims to gain knowledge of an underrepresented climatic hazard. Annual human mortality differences among other weather hazards indicate that extreme heat causes more deaths than most other weather events combined (Changnon *et al*.

Figure 1.1: A sixteen-year comparison of mortality in the U.S. among the seven most fatal weather events (from NOAA 2007)



1996, Robinson 2001, and NOAA 2007) (Figure 1.1). Heat-related mortality was not available from the National Oceanographic and Atmospheric Administration (NOAA) until 1986, therefore comparisons among heat and the other six weather events are from 1986 to 2001. Human fatalities from heat outnumber all six other top weather-related mortality events during this sixteen-year period. Heat events in 1995 totaled 1,021 fatalities in the U.S., which was the highest one-year weather-related cause of death on record. If the anomalous 1995 record of 1,021 was subtracted from the total number of heat deaths in Figure 1.1, fatalities from heat would still outnumber all six other weather types during this time period. However, heat waves have proven to be difficult events for which to mitigate and manage primarily because they have not been universally or rigorously defined. The American Meteorological Society (AMS) simply defines a heat wave as "a period of abnormally and uncomfortably hot and usually humid weather" (AMS 2000).

There are several other attempts at adding detail to this definition, which has unfortunately made the problem more complex by not having a collective set of parameters (Ward 1925, Kalkstein *et* al. 1996, Robinson 2001, Choi and Meentemeyer 2002, and Burroughs 2003). The definition by Burrows a century prior defined a heat wave as three or more consecutive days where the maximum shade temperature reached or exceeded 90° F (32.2 °C) (Burrows 1900). Robinson (2001) identifies how vague the explanation of a heat wave still is, and attempted to illustrate percentile variations across the United States. Lack of a rigorous definition of a heat wave is not from the lack of effort, but because of the inconsistent distribution of what is considered 'hazardous' geographically and temporally. Robinson (2001) used the same data that were used for this study to find a decadal event distribution across the U.S. that was based on heat index (HI) measurements.

Heat waves like the ones in Chicago in 1995 and Paris in 2003 have proven that heat stress affects tens of thousands of people at a time, even in developed economic locations (Kalkstein 1995 and Vandentorren *et al.* 2004). The 1995 Chicago event is known to have killed over 500 people, and some numbers for Western Europe from 2003 have surpassed 20,000 deaths. Smoyer *et al*. (2000) provide information that, not only are cycles of hot conditions to continue, but also to increase in intensity into the future. This prediction is supported by the assessment of the Intergovernmental Panel on Climate Change (IPCC) Working Group I noting that increases in heat waves on a continental and regional scale have increased in recent decades with the trend expected to continue well into the future (IPCC 2007). With these indications becoming more and more evident, it is imperative to push forward in our understanding of heat event phenomena to prevent more tragedies like the two modern events listed above.

Objectives

The primary objectives of this research are to generate a climatology of daily heat stress and a record of heat waves at individual weather station locations that are applicable to the United States. Robinson (2001) states that one of the three major factors limiting an appropriate description of heat waves as a meteorological hazard is the lack of an adequate climatological record of weather variables over a homogenous temporal period. The research presented herein focused on the exposure to extreme heat and humidity during a 22-year period as an indication of typical heat stress characteristics for varying areas. Hourly temperature and humidity data was obtained for 70 locations across the United States, and then were converted into hourly HI values. The manner in which sultry conditions are described to the general public in the United States by the NWS is done by temperatures in degrees Fahrenheit, relative humidity as a percent, and the combination of the two as a HI value in degrees Fahrenheit. Data was obtained in English units and the classification methods in this study were designed based on these units. However, although this research is intended as a basis for providing heat stress information to people in the United States, English units are reported throughout the document parenthetically with the International System of Units in degrees Celsius.

The new heat stress and heat wave classifications were developed and employed to classify heat stress days and heat wave events by including the magnitude of accumulated daily heat stress for all locations. The number of, and magnitude of, heat waves an area experienced were documented and set up for easy comparisons to other regions of the country. This permits better understanding of what a heat wave category would mean uniquely to different areas over different climatic regions. Perhaps a Category 3 heat wave does not bring much of an alarm to people in Birmingham, Alabama, but would a Category 3 heat wave be a concern to people in Denver, Colorado, or in Minneapolis, Minnesota? Have Denver or Minneapolis experienced a Category 3 since 1980? This applied climatology aims to provide answers to the spatial vulnerability question for heat waves with a focus on the level of event exposure.

Tables and maps were developed using the summary statistics derived from the application of the heat wave classification system. Tables will indicate locations of highest (or lowest) frequency, and maps will display dispersion of heat stress across the country. These maps will document the accumulated daily sum of annual hours of magnitude for both HI categories of > 32.2° C (> 90° F) and > 40.6° C (> 105° F). Areas that do not normally experience elevated heat stress levels, but are known to have experienced heat stress events in the past are areas of concern. One example of such an occurrence was the Midwest heat wave of 1995, which is used as a case study in this research to illustrate the daily fluctuations of heat stress magnitudes over space during a major event. A daily map analysis was made to illustrate how the heat wave classification system can display extent and magnitude of heat stress for a heat wave throughout its duration. Recognizing the geographic patterns of how heat stress exposure levels vary from one area to another would aid social scientists considerably as they address sensitivity and adaptive capacity aspects of these hazards.

Broad differences in heat stress distribution were expected across the country because of varying air stream/air mass types and topography across the country. However, there are expectations for which to base the results that were obtained with this research:

1. Temperature decreases with elevation, and days classified with the heat wave classification in this study were expected to be rare at elevations above 1,220 m (4,000 ft)
2. Latitude plays a role in the amount of solar energy a location receives as well as the duration of the warm season, making northern locations cooler than southern locations on an annual basis
3. Areas along the west coast were not expected to exhibit much of a heat stress hazard because of the primary Westerlies moving onshore after being cooled and regulated by the Pacific Ocean
4. Relative humidity would be generally highest for stations around the Gulf of Mexico because of the prominent warm, moist air masses that frequently exist in the area

Because of continental air masses and presence of several large mountain ranges, most stations in the western half of the United States were generally expected to measure low atmospheric moisture levels, and therefore lower heat stress levels

Purpose

Effects of climate change are expected to be noticed worldwide, and trends in increasing temperature are raising awareness of the need to understand the characteristics of extreme heat events (Meehl *et al*. 2000, Houghton *et al*. 2001, O'Niell *et al*. 2003, and IPCC 2007). Trends are showing fewer frost days and higher minimum temperatures into the 21st century (Easterling *et al*. 2000). Since nearly 400 people die annually from extreme heat conditions in the United States at present, it is a responsibility of the scientific community to be able to develop a reasonable way to reduce this number as temperatures are slated to increase in coming years (Bernard and McGeehin 2004). Cutter *et al*. (2003) produced a vulnerability model that illustrates the interactive nature of social systems, biophysical vulnerability, and hazard potential as a function of place vulnerability. Results from this study are expected to illustrate that geographic location coupled with their dynamic weather systems are necessary for understanding the characteristics of extreme heat exposure across the U.S. The classification scheme is designed to focus on accumulated heat stress on a daily basis from hourly data. Daily classifications are ultimately used as a building block for identifying and classifying individual heat waves. Therefore, when daily accumulation of heat is mentioned, this study is referring to heat stress, which is why the classification is termed as a heat stress classification. Heat waves are referred to by this study as individual events made up of accumulated heat stress days. It is hoped that results from this research will, in part, help to identify how heat stress is such a dominant weather hazard to human mortality, and to potentially become a solution for reducing losses from extreme heat events.

The NWS division of NOAA provides a mission statement with the subtitle "Working Together to Save Lives" and asserts that its purpose is to provide forecasts and warnings of impending hazardous conditions "for the protection of life and property and the enhancement of the national economy" (available at http://www.weather.gov/mission.shtml). As extreme heat events continue to cause preventable human mortality, it is hoped that the classification proposed in this study will be adopted as a foundation to understanding heat stress spatially for the purposes of saving lives and reducing economic losses. This research would be considered successful if it proved reliably and consistently capable of identifying increasing magnitudes of daily heat stress coupled with the ability to recognize and classify periods of heat stress days as heat waves. The new classification in this study was designed to be applied to all weather station data identically for the purpose of discriminating heat stress differences over space. It is not the intent of this research to provide descriptions on mortality, social responses, or mitigation techniques for extreme heat hazards. However, the results and conclusions herein could be applied to heat wave hazard discussions in the future.

CHAPTER 2 – Literature Review

Warm Season Air Streams in the United States

Influences on climate for the contiguous United States range from the global circulation processes of the pressure gradient force and Coriolis effect to local geographic factors such as adjacency to large water bodies or other topographical features. In the northern hemisphere, airflow is directed from the thicker vertical profile of the equatorial atmosphere to the thinner layer over the North Pole, however, large-scale influences on airflow are interrupted by friction from the earth's rotation from west to east (Hare 1960). The meridional thermal gradient that is formed from about 30° northward becomes a driving force for a circumpolar airflow spanning the mid-latitudes termed the westerlies (Harman 1991). This redirected flow coupled with the Hadley Cell, a vertical rotating belt of air over the tropics, produces centers of high pressure that typically range from 30° to 35° N latitude (Latif and Barnett 1994 and Davis *et al*. 1997). Semi-permanent eddies of high pressure exist within this range over the northern Pacific and Atlantic oceans, and air from these centers of clockwise (anti-cyclonic) rotation sinks to the surface, which adiabatically warms and dries the parcel properties. Most summertime atmospheric characteristics of the contiguous United States rely on the positions of semi-permanent high pressure centers in the North Atlantic and North Pacific (Latif and Barnett 1994).

Temperature and moisture properties of westerly flow from the Pacific Ocean onto the American West Coast become regulated by the conditions of the underlying water. The sub-tropical high over the North Pacific thus provides air that is temperate and able to evaporate moisture from the sea surface. These air properties are maintained onto the land mass of the western U.S. providing a coastal environment that is seldom prone to sustained periods of high heat stress. Warm periods can occur on the lee side of the coastal mountain chains aided by both the dry adiabatic processes and the Southwestern monsoon (Carleton 1987). Because of the surface variability of the cordillera in the American West, it is difficult to provide general descriptions of regional warm air streams in the mountains. However, the mid-summer pressure gradient that develops is capable of sending moisture from the Gulf of California to Arizona, California, and areas of southern Nevada (Anderson *et al*. 2000). Only on rare occasions does the energy and moisture combine to hazardous levels north of southern Nevada and Utah.

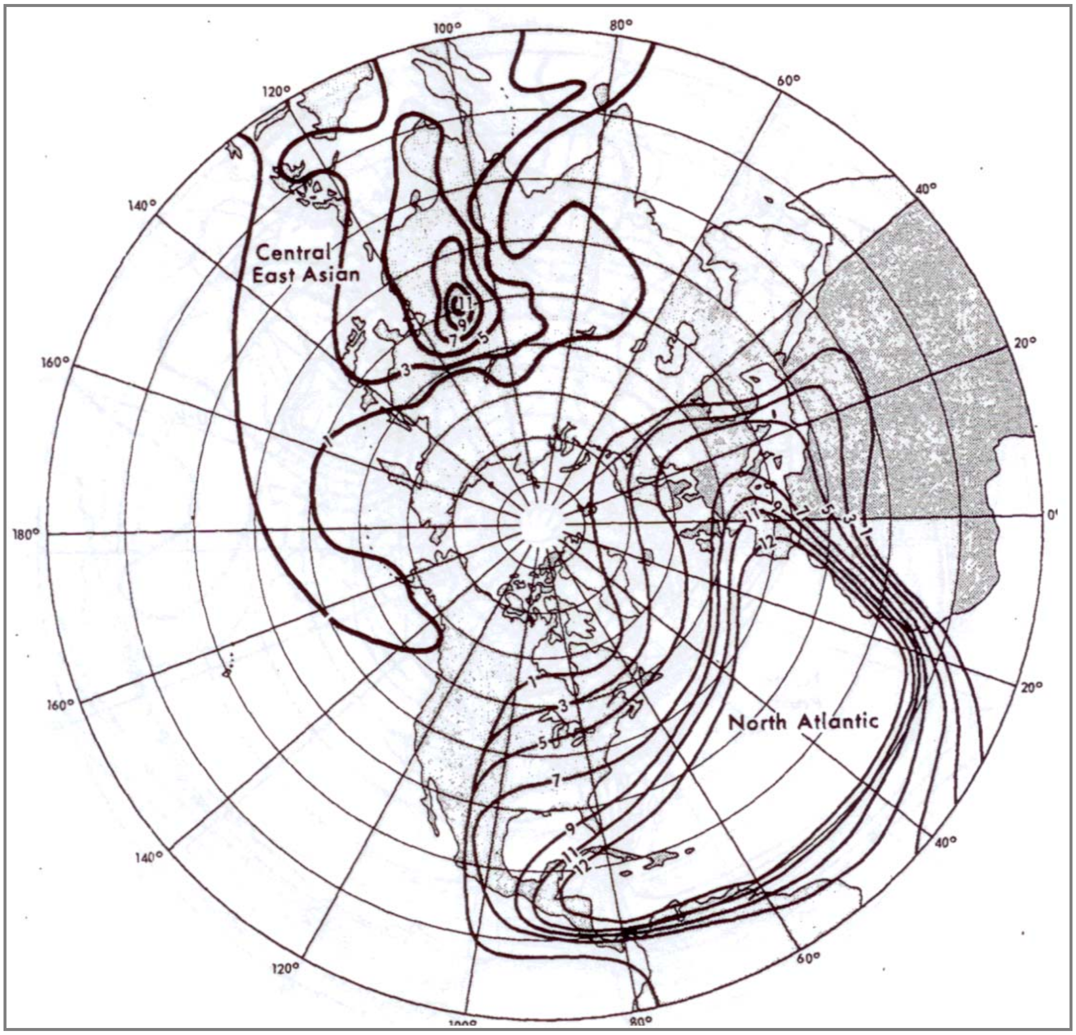
A near surface air stream known as the low-level jet (LLJ) is responsible for a majority of southerly summer warm/moist air advection from the Gulf of Mexico (Higgins *et al*. 1997). Effects from this air stream are observed through the central Plains and across the American Southeast (Bonner 1968). Development of the surface winds that transport warm, moist air northward across the central and southern U.S. often correlates with cyclogenesis over the Rocky Mountains (Djuric and Ladwig 1983). Lowering air pressure propagates a counterclockwise rotation which directs air from the warm Gulf of Mexico over the Plains states until its southerly advection encounters the drier Primary Westerlies. Influences from the LLJ are most common throughout the Plains states below 1km in elevation from Texas through North Dakota (maxima over Oklahoma and Kansas), with trends decreasing eastward (Bonner 1968). East of the Appalachian Mountains, warm southerly flow in the summer is more directly attributed to the outflow of air from the Bermuda High over the North Atlantic Ocean (Figure 2.1) combined with the warm Gulf Stream ocean current (Wendland and Bryson 1981).

Humidity and Heat Stress

Human health is complicated by heat stress simply by forcing the body to continue functioning as it tries to maintain core temperatures (Souch and Grimmond 2004). The human body's natural reaction to warm temperatures is perspiration, a process where the moisture from within the body is expelled through sweat glands (by mostly water content) to the outer surface of the skin. Ideally, the water will evaporate and cool the outer surface of the skin, thus removing all or some of the excess heat load from the body. However, in periods of elevated humidity in the atmosphere, the air is not as apt to accept the moisture from the skin's surface. If evaporation of perspiration does not occur, the energy is not removed and this inhibits the body's ability to maintain a safe temperature (Steadman 1984).

It has long been known that the stress caused by heat is compounded by the amount of moisture in the air (Lally and Watson 1960). Alvin Burrows published one of the first, if not the first, overall definitions of a 'hot' wave in 1900 as a period of three or more consecutive days, during which the maximum temperature reaches or passes 90° F (32.2° C) (Burrows 1900).

Figure 2.1: Northern Hemisphere map that illustrates the annual extent of climatic influence by the Bermuda High over the North Atlantic Ocean; lines are labeled with the number of months that the circulation is responsible for the air streams in that area annually (from Wendland and Bryson 1981)



Burrows went on to describe the high atmospheric moisture levels that contribute to the uncomfortable nature of heat waves.

Karl and Quayle (1981) looked at the 1980 United States heat wave that occurred within a regional drought. The extreme nature of the 1980 anomaly was well-presented, noting the persistent high pressure dominating the southern U.S. for over four months. However, since the event was studied as a function within the drought, temperatures were observed with precipitation values, not atmospheric humidity. This method of omitting humidity levels does not represent the severity of the heat stress conditions during that period. Water, itself, is a natural energy storage substance, especially with respect to heat. So, as air temperature rises, the potential vapor content rises, meaning even more latent heat energy can be stored in the air. The effect that humidity has on warm temperatures is similar to how cold temperatures are affected by wind to produce ‘windchill’ (Steadman 1979a). As heat and humidity continue to rise, humans and animals become more uncomfortable, and the sultry surroundings can become hazardous to an organism’s health to the point of causing death (Thom 1959, Steadman 1984, and Kalkstein and Valimont 1986). A 35-year study by Gaffen and Ross (1999) identifies a consistent rise in average humidity levels in all regions of the country, which have been noticed in increasing apparent temperatures as well. Their findings coincide with the claims by Wilhelmi *et al*. (2004) that the risk of more intense heat waves is increasing. Several indices have been suggested to characterize how the environmental synergism of the air actually feels to an organism combining temperature and humidity levels.

Development of methods to establish a measurement that explains the sultriness of the air have been ongoing for decades, even though people have observed more discomfort on days of high humidity for centuries (Lally and Watson 1960). Several mathematical models combining air temperature with moisture now exist: Effective Temperature (Houghton and Yaglou 1923) which was found to be unreliable if winds diminished (Court 1974); Humiture was developed in 1937 (Hevener 1959), the Temperature-Humidity Index (Thom 1959) which is still in large use for agricultural systems; the Humidex was developed in 1965 (Quayle and Doehring 1981) which is more prominent in Canada, and was used in the Sheridan and Kalkstein (2004) study; and the heat index (HI) (Steadman 1984), initially called apparent temperature, which has been in wide use as a measurement for discomfort in the U.S. by the NWS and media outlets. Persistent Positive Temperature Anomalies were identified in 2002 (Choi and Meentemeyer 2002), but proved to be inconsistent for relating to hazardous events. When attempting to raise awareness of heat stress and intensity for people in the U.S., use of the HI is most accepted and understood.

Components of Vulnerability

Natural hazards are defined as interactions of people with nature influenced by the ability of the people to adjust to a situation caused by an extreme event (White 1974). An extreme event, then, is a natural occurrence that surpasses normal conditions to the point of causing a negative impact. Natural hazard studies incorporate numerous aspects which include: the possibility of harm to come from the event of an environmental phenomenon, the knowledge of these events and their impacts, risk assessments, mitigation action in case of an event, the utility of education, and warning systems (Burton *et al.* 1978). When a hazard occurs and affects people, the event now becomes a 'natural' disaster, noting the need to identify differences in the terminology of extreme events. Three primary factors regarding vulnerability are differentiated by Cutter (2001), *risk* is recognizing the possibility of some dangerous event, a *hazard* is planned and prepared for, and a *disaster* is reacted to. The number of people impacted and the amount of money associated with a disaster is commonly used as a measure of event severity.

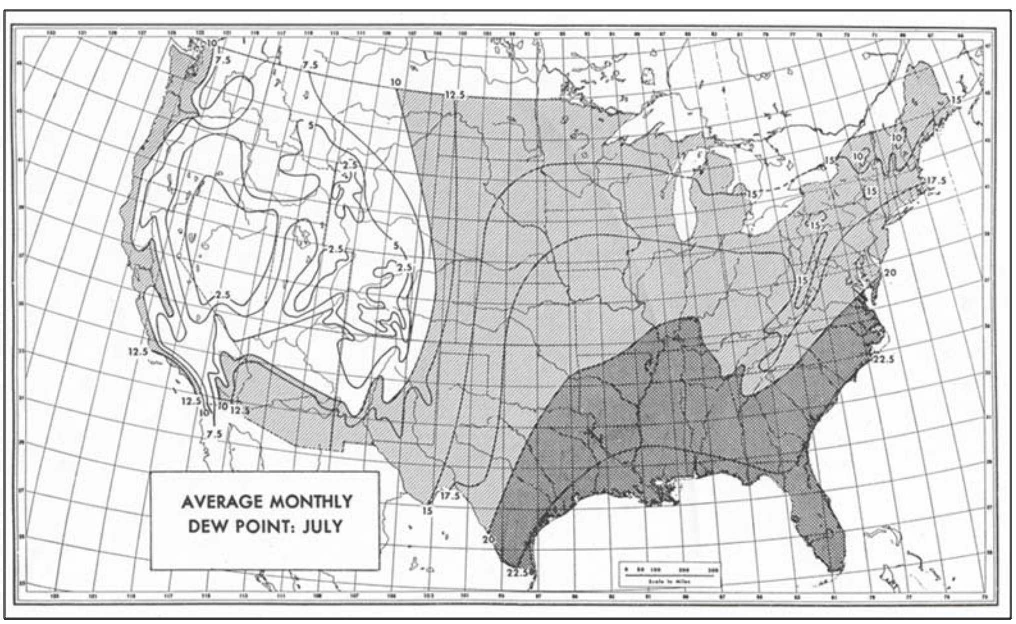
Vulnerability to a natural hazard can be seen as a function of exposure, sensitivity, and adaptive capacity, where exposure is the frequency of an event sensitivity involves the magnitude of an event in relation to human response, and adaptive capacity refers to the ability that people have to adjust in the past, and for the future, to minimize damages from particular hazards. In the case of heat waves, with the number of factors that can dictate their severity, new datasets and analyses are currently needed to develop an improved geography of the vulnerability in the hope that we can mitigate the effects of heat stress events.

Identifying the exposure levels of extreme heat events is different than an assessment that might be used for other hazards. Spatial variations of climate that determine which temperatures are considered extreme from one place to another makes the understanding of heat waves complex. When assessing the effects of heat stress extremes, several aspects need to be examined, such as: what the typical moisture levels are for a particular region, the temperature range, how temperature and humidity combine for harsh conditions (heat indices) indicating how the conditions feel, the recurrence interval of local extremes, and the seasonal timing of sultry conditions.

The difference in frequency, duration, and severity of excessive heat stress creates a problem with the explanation of the heat wave hazards (Robinson 2001). The cultural and economic status of the people that experience a major disaster are also a factor (Bryant 1991), with a lower perception of risk in urban areas than rural areas (Burton *et al*. 1978). However, these factors alone do not define the extent of the problems that hinder the definition of and classification of heat waves. The thresholds of humans to differing heat conditions are not the same over space or time (Souch and Grimmond 2004), nor are the scales of the heat waves themselves, which can cover a large and varying sized area during a single event. People living in the Southeastern United States regularly experience warm seasons with higher temperatures and atmospheric moisture content than the north-central states, like the Dakotas. Moreover, if an intense heat event occurs early in the season, the lack of an acclimatization period magnifies the stress level for the event (Kalkstein *et al*. 2008). Elevated heat stress conditions vary annually and seasonally across the country making it difficult to compare the sensitivity and adaptive capacity components of vulnerability (Cutter 2001).

Recent work done by the author has found how moisture levels work as a driver for making weather conditions worse. Instances exist when temperatures in western Kansas can exceed those in the eastern portions of the state, but higher moisture levels in eastern Kansas result in much more intense heat events. Dodd (1965) presented a monthly climatology of where the moisture gradients exist for the United States using dew point averages (Figure 2.2). There is a clear southeast-to- northwest decrease of atmospheric moisture content from the Gulf States

Figure 2.2: Average atmospheric moisture content for the United States with a gradient decreasing from the southeast to the northwest (from Dodd 1965)



to the northern Rockies, suggesting that typical heat stress magnitudes should follow the same pattern. Given that people acclimatize to their regional climate norms this would imply that similar heat events would affect people more severely in areas where the heat stress events occur with less frequency. Examining daily heat stress indices for the different climate regions in the U.S. will aid in identifying how exposure levels and frequencies vary over space.

Measuring Heat Stress

The Heat Index

There is a continuing need to describe how conditions feel for humans during periods of excess heat, humidity, and solar radiation. Dr. Steadman at Texas Tech University provided an index, apparent temperature, in the late 1970s (Steadman 1979a and Steadman 1979b). Apparent temperature, now more commonly known as heat index, depicts the combined effect of temperature and humidity on the skin of humans (Steadman 1979a and Dixon 1997).
The NWS has used HI in their effort to convey hazardous heat stress levels to the general public. Explanation of HI is relatively simple for the public to understand in that an actual air temperature is provided, and then the apparent temperature, or how the conditions feel, is given as a temperature as well. For instance, an air temperature of 33.3° C (92° F) could be reported followed by a HI report of 36.7° C (98° F), indicating how the relative humidity has altered the perception of how conditions feel (Table 2.1).

Table 2.1: Temperatures and effects related to HI from the National Weather Service

Category	Heat Index/ Apparent Temperature	General Effect of Heat Index on People in High Risk Groups
I	54° C (130° F) or higher	Heat/sunstroke highly likely with continued exposure
II	41° C - 54° C (105° F - 130° F)	Sunstroke, heat cramps, or heat exhaustion likely and heatstroke possible with prolonged exposure and/or physical activity
III	32° C - 41° C (90° F - 105° F)	Sunstroke, heat cramps, and heat exhaustion possible with prolonged exposure and/or physical activity
IV	27° C - 32° C (80° C - 90° F)	Fatigue possible with prolonged exposure and/or physical activity

The information in Table 2.1 provides an attempt at categorizing the effects of high instantaneous HI temperatures and their corresponding impacts on people. Unfortunately, the category numerals increase as the conditions decrease. One would believe that if conditions have reached a 'Category IV,' the situation would have become worse, as is the case with other natural hazards. The accumulative effects from the thermal extremes indicate that there are problems associated with prolonged exposure, but there is no parameter denoting what is 'prolonged.' However, Table 2.1 provides heat stress categorical thresholds that have been established and are used by the National Weather Service in warning citizens about heat stress exposure.

Previous Heat Stress Measurement Techniques

The author's recent work employed the Temperature-Humidity Index (THI) from Thom (1956) to characterize heat stress in the central United States for feedlot cattle. THI is a derived value obtained using equation [1], which combines corresponding temperature and humidity values, much like HI. The method is not nearly as complex as obtaining HI values, and reported levels of THI have shown to be comparable to HI levels (Table 2.2).

$$THI = T_f - (0.55 - (0.55 * (H / 100))) * (T_f - 58) \qquad [1]$$

T_f = Temperature °F

H = % Humidity

Table 2.2: Comparison between the Temperature-Humidity Index and HI

HI (F)	HI (C)	THI
130	54.4	90
115	46.1	87
105	40.6	84
90	32.2	79
80	26.7	73
77	25.0	70

THI values are unitless and are used to rank levels of heat stress intensity. By determining general responses from either people (Thom 1959) or feedlot cattle (Hahn *et al*. 1999) categorical ranges were developed to signify an observed heat load magnitude on the body. If THI values were 74 or below, there was no heat hazard for that time period. In working with cattle, THI values of 75-78 were 'alert' levels, 79-83 THI were 'danger' levels, and THI greater than 84 were considered 'emergency' levels (Hahn *et al*. 1999). Reviewing Table 2.2 reveals that these levels correspond to HI categories in Table 2.1. A heat wave classification for feedlot cattle in the central U.S. using accumulated daily THI values was proposed by Hahn *et al*. (1999). By identifying the accumulated amount of 'danger' level THI per day, the amount of 'emergency' level THI per day, the amount of recovery THI (< 70) per night, and the number of days these levels persisted, one of six categories could be subjectively assigned as shown in Table 2.3. Subjective analysis was needed because the boundaries between categories were not precisely defined.

Table 2.3: The Hahn *et al*. (1999) heat wave classification model using THI

Category	Duration	THI hrs > 79	THI hrs > 84	Nighttime Recovery (hrs < 70 THI)
1. Slight	Limited (3-4 days)	10-25/day	none	good: 5-10 hr/night
2. Mild	Limited (3-4 days)	18-40/day	< 5/day	some: 3-8 hr/night
3. Moderate	More persistent (4-6 days usual)	25-50/day	< 6/day	reduced: 1-6 hr/night
4. Strong	Increased persistence (5-7 days)	33-65/day	< 6/day	limited: 0-4 hr/night
5. Severe	Very persistent (usually 6-8 days)	40-80/day	3-15/day for 3 days in a row	very limited: 0-2 hr/night
6. Extreme	Very persistent (usually 6-10 days)	50-100/day	15-30/day for 3 days in a row	none: < 1 for 3 or more days in a row

Bowles (2004) applied the feedlot cattle heat wave classification to data from stations in Missouri, Iowa, Nebraska, and Kansas. Results that were obtained with the THI modeling proved that two components of heat stress, temperature and humidity, could be used to identify the magnitude of specific events with respect to feedlot cattle.

Values for both indices, THI for livestock and HI for humans, illustrate that their categories correspond very well with each other (Table 2.2). Moreover, there are descriptions of physiologic impacts on humans for HI thresholds; all implying that using a procedure similar to the one with the THI classification is possible.

Defining Heat Waves

There is no universal definition of a heat wave (Robinson 2001). Normal ranges of spatial and temporal factors that combine to cause conditions that are hazardous to people are commonly restricted by geographic location. Anomalous levels of heat and humidity in most locations can lead to human mortality, but a single description that includes all areas is yet unavailable. Attempts have been made since the end of the 19th century including Burrows' (1900) publication stating that a heat wave as a period when 32.2° C (90° F) is surpassed for three or more consecutive days, also noting that elevated atmospheric moisture levels contribute to unhealthy conditions. Robinson's (2001) definition a century later acknowledges atmospheric moisture by incorporating the heat index and determining that lows are above 26.7° C (80° F) and highs surpass the 1 percentile range for an area for more than two days. If the heat index surpasses the 1 percentile temperature by more than 5.6° C (10° F) and the low is above the 26.7° C (80° F) threshold for longer than 36 hours the event is termed an intense heat wave.

Less quantitative definitions have also been made in the last hundred years including Ward's (1925) of a period of uncomfortably hot weather during the warm season lasting more than a day, which worsens as it prolongs. Choi and Meentemeyer (2002) defined a 'heatwave' on the basis of daily deviations from daily temperature norms which could include non-hazardous conditions in cooler months. Karl and Quayle (1981) studied the considerably hot summer of 1980 that struck the eastern U.S. and identified the severity that the conditions had economically, however their working heat wave definition was based on temperature and lack of precipitation instead of the moisture present in the air. These definitions are all correct on the way that heat affects people, however, they either imply availability and access to local climatological records, or an indirect and vague description that some southern U.S. locations would not contend was a heat wave hazard. What a heat wave is depends on local norms and the statistical deviation from those norms, such as rare percentiles or standard deviational analyses. Heat waves are also a major source of human and economic losses with human mortality, livestock mortality, structural damages including buckled roadways and railways, and also disruptions of public works such as water main bursts or shorts in the electrical grid (Burrows 1900, Ruffner and Bair 1984, and Hahn *et al*. 1999).

A Working Case Study

A successful case study testing a heat watch/warning system as a method to warn people of harmful heat levels was done for the city of Philadelphia, PA (Ebi *et al*. 2004). In this study, the National Weather Service announced advisories of oppressive heat conditions based solely on HI. Since HI relies on just two weather factors, it was felt that too many factors of weather were being neglected, primarily the duration of events. Therefore, when the presence of an oppressive air mass was identified and expected to impact the Philadelphia area for a prolonged period of time, a heat watch/warning was issued on local airwaves. The study estimated that the system saved 117 lives in three years.

Results found from the study by Ebi *et al*. (2004) illustrate that impending danger from excessive heat can be predicted, can be categorized, and warnings can be given on a local level to which people responded. The conditions that were identified were specifically for the greater

Philadelphia area and addressed a level of oppressiveness that was statistically determined for that region. Therefore, there is a reinforcement to further identify climatological occurrences in more areas across the country. Analysis of past events for other cities would allow for explicit knowledge of what level of events typically occur and what conditions the people in different areas have adapted to locally.

Heat Wave Trends

Aside from noticeably lower near-surface mean annual global temperatures that coincide with major volcanic eruptions, anthropogenic and natural forcings combined throughout the 20th Century and into the 21st Century to aid in the persistent increase of global temperatures (IPCC 2007). Emissions of gasses known to exacerbate warming scenarios, most notably carbon dioxide, have been documented to be continuously rising for decades into levels that have never before been recorded (Perrings 2003 and Zeng *et al*. 2005). A 50-year dataset from the Mauna Loa Observatory in Hawaii has produced a graph (called the Keeling Curve) that represents the carbon dioxide concentrations (ppm) in the atmosphere as they oscillate annually and rise over time and is continuously updated by NOAA (Figure 2.3) (Keeling 1960 and (NOAA 2009). Graphical evidence from ice core records obtained at Vostok, Antarctica from the past 350,000 years indicates that global temperatures changes closely correlate with variations in carbon dioxide concentrations (Figure 2.4) (Stoudt *et al*. 2008).

This global concentration of carbon dioxide has now surpassed 388 ppm according to the NOAA Earth System Research Laboratory and has surpassed the natural range that is capable of being absorbed by the world’s oceans and terrestrial plant life (IPCC 2007). Data presented in the previous two graphs provides a foundation for the argument that temperatures are expected to rise globally going in to the next few decades. From these analyses, it is inferred that higher annual temperatures (which allow for greater levels of humidity) should affect areas worldwide, prolonging hot conditions in typically warm regions and occurring more frequently in areas that do not normally get affected by hazardous heat stress conditions.

Figure 2.3: Keeling curve illustrating carbon dioxide concentrations in the atmosphere from 1958 to 2009, peaks are Northern Hemisphere winters, troughs are summers (adopted from NOAA 2009)

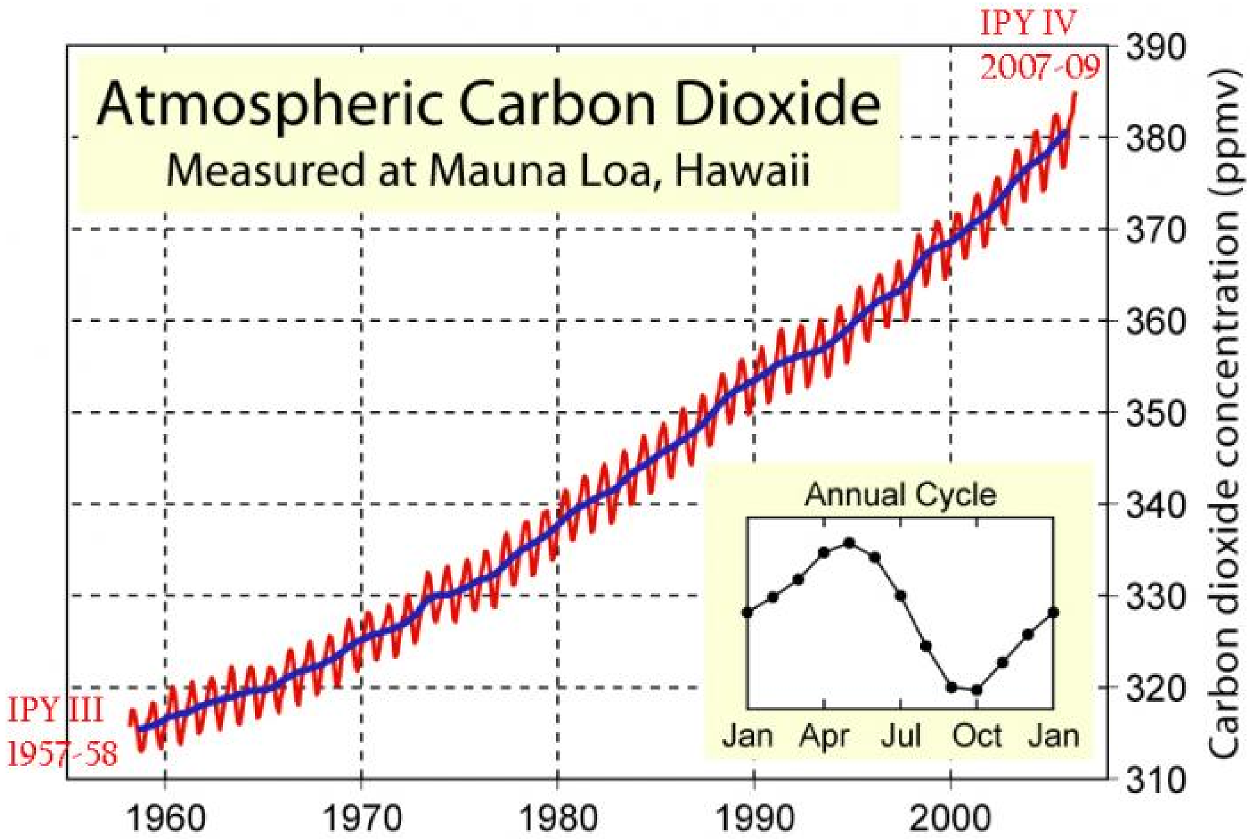


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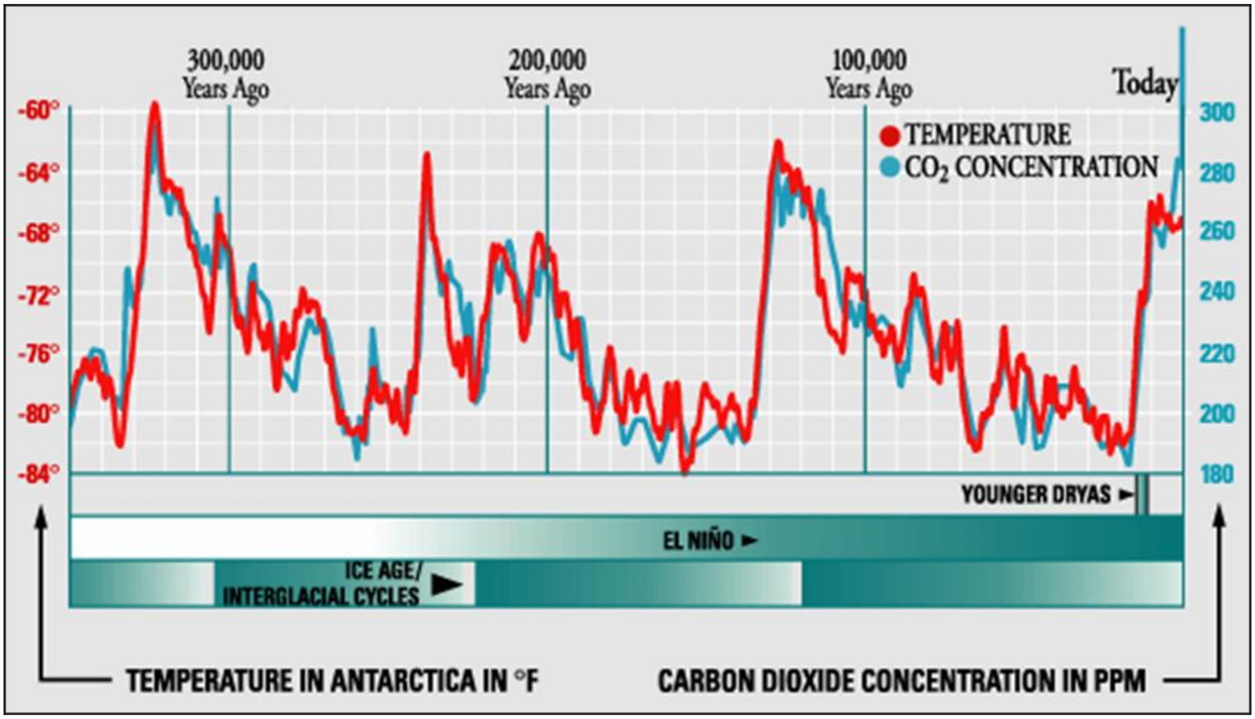
Figure 2.4: Historical correlations between global temperatures and carbon dioxide concentrations in the atmosphere (from Stoudt *et al*. 2008)



Classifying Weather Events

Organizational and synthesis analyses provide a basis for determining comparative associations among phenomena and processes in scientific disciplines. Hence, classifications are developed in fields like climatology and other sciences to reduce the amount of perceived uniqueness that is observed in nature (Oliver 1991). The functional climatic classification provides an interpretation of a complex system that is structured and simplified with a cognitive segregation of continuous temporal data into discernible components using appropriate parameters. The resulting logic is a system that is designed to inform people how impacts can be affected by differential magnitudes from forces such as weather.

The classification of climate types has been, and will be, an important tool in understanding the natural environment (Oliver 1991). Consequently, the classification of climatic extremes would also be a useful tool to assist in building on knowledge based on of how the natural environment affects people and their property. Research is continuing to illustrate the deadly impacts heat has on humans. Chestnut *et al*. (1998) provided mortality rates for 44 U.S. urban areas using the largest U.S. metro areas that were studied by Kalkstein and Greene (1997).

This assessment had an eastern bias; nevertheless, it was found that areas, like the American Southeast, that experience long periods of sultry conditions do not necessarily have the highest mortality rates (a sign of acclimatization) (Chestnut *et al*. 1998). A better spatial coverage of U.S. climate types, such as the north-central states, with a large, continental climatic regime, need to be observed as well.

Extreme hazards involving weather events affect all people in some way, and can also be associated with causing impacts on large populations at a time. Predictions of exact tornado strike locations are still not available, but knowledge of atmospheric conditions favorable for tornado formation has increased greatly over time. Dr. Fujita attempted to provide a method for studying tornadoes, which are elusive and dangerous funnels that can last from seconds to hours, by analyzing the amount of damage that was caused. In this manner, he used ranges of estimated windspeeds in relation to their known damage capabilities and arranged them into categories that increase in magnitude from F0 to F5 (windspeeds above the F5 top range of 142 m s^{-1} are not expected to be reached naturally) (Fujita 1981). Therefore, tornadic activity could be studied and sorted into a classification system based on level of damage even if the storm had not been witnessed. Descriptions of the events were simplified, and changes in tornado intensity could be documented along their tracks.

In 1969, Herbert Saffir and Dr. Bob Simpson developed the scale that classifies the magnitude of hurricanes based on sustained windspeeds. Categories of windspeed ranges were set into five classifications of increasing magnitude (from Category 1 to Category 5) to denote the escalation of potential damage from a hurricane (Elsner and Kara 1999). Forecasts for hurricanes are made days in advance which provide not only the expected storm track, but also the expected category upon landfall. Specialists at NOAA have been communicating the destructive characteristics of hurricanes by stressing to the public the expected category at landfall as a vehicle to describe magnitude of an impending storm.

A form of regional classification was developed by Kocin and Uccellini (2004) to categorize massive snow storms in the northeastern United States. This index was designed to account for the population of affected areas as well as projected snow fall rates (in inches) to provide societal and economic impact assessments. When spatial aspects of the storm are calculated into a GIS, the snowfall and population information are combined to calculate a NESIS score (Northeast Snowstorm Impact Scale). The calculated score correlates to one of five

NESIS categories of increasing magnitude: Notable, Significant, Major, Crippling, and Extreme. A regional classification such as this one was necessary because of the uniquely powerful snow storms in the American Northeast mixed with the high population density for the region. Heat waves are regionally unique because of local acclimatization to climatic norms, and can also be devastating to society and the economy. The three aforementioned weather events were considered devastating enough to have been assigned a classification system, which, based on the information in Figure 1.1, suggests that there is merit to classifying the magnitude of heat waves.

Recent events have fueled an increasing need for better understanding of heat waves. The event that has been dubbed the Chicago heat wave of 1995 showed us that rare conditions can, and will, recur (Kunkel *et al*. 1996). The hottest 4 events that were comparable in Chicago's history were all between 1900 and 1937, almost 60-years removed from the event in 1995. Although the duration of the1995 event was considerably shorter than other events, the rapid increase in heat stress intensity that was experienced was unusual, leading to the deaths of over 700 people regionally, and with over 500 in Chicago alone (Changnon *et al*. 1996). The 1995 event was abnormally intense and spatially widespread exhibiting an unknown level of intensity in rural areas. A similar week to ten-day time-span was observed in the 2003 event in Western Europe that killed thousands of people in France alone (Vandentorren *et al*. 2004). The anomalous nature of these events was more severe than almost anyone there had ever witnessed, and therefore they were not prepared for such conditions. Analyzing the heat wave on a daily basis can reveal how fast people responded to the conditions, and that identifying the magnitude of an event by daily intensity would be necessary.

The events that occurred at these two locations and the associated human cost should be a clear reason to study the nature of heat stress exposure more closely. Because as Wilhelmi *et al*. (2004) state, the highest heat measurements are within urban areas, urban areas are expanding, and the intensity and frequency of heat waves are projected to increase into the future. Therefore, the need to determine daily heat stress intensity is increasing, and new areas will be experiencing conditions to which they had not adapted.

Classifying Heat Stress for Humans

When attempting to assess something like the magnitude of heat stress, one cannot just report that a threshold was met; rather one should report the amount by which conditions surpassed that threshold (Hubbard *et al*. 1999). Hourly THI values could reach over 90 (unitless value) indicating very hot and sultry conditions. If a value, for example at 3:00 pm, was 90 THI, that single hourly recording is a value of 11 THI higher than the ‘danger’ threshold of 79 THI, and 6 THI higher than the ‘emergency’ threshold of 84 THI. The description, then, would be that at 3:00 pm, there were 11 THI hours above the danger threshold, and 6 hours above the emergency threshold. If values were high like this example for several hours in a day, then it is clear how an accumulation of hours above specific thresholds could accumulate to reach hazardous levels.

Categories used by the National Weather Service could be applied in the same manner. Hourly HI temperatures will be derived, and then each now can be analyzed to determine a magnitude above the thresholds of 32.2° C (90° F) and 40.6° C (105° F). For instance, if a 3:00 pm HI temperature were 41.9° C (107.5° F), one would know that such a value had surpassed both thresholds of 32.2° C (90° F) and 40.6° C (105° F). To calculate the magnitude of heat stress for that hour, one would state that there were 9.7 hours above the 32.2° C (17.5 above 90° F) threshold, and 1.3 hours above the 40.6° C (2.5 above 105° F) threshold. Hourly sums above each threshold for each day would reveal the diurnal accumulated magnitude of heat stress, and these are the daily values that would be evaluated to identify a string of days denoting a heat wave. Therefore, a qualitative daily value can be assigned from numeric analyses and then grouped into recognizable events.

A New Heat Stress Classification

Simple 5 or 6 integer category classifications exist for a number of hazards. These classifications have helped the general public understand the magnitude of the event that has occurred, is occurring, or will occur. Therefore, when designing a classification for heat waves, it was believed relevant to follow a similar methodology. Heat waves are hazards that can be based on human impact; therefore, classification of events could be based upon the physiologic stress loads produced by the weather conditions themselves. Therefore, the model has been developed to classify daily heat stress as a category from 1-5.

In classifying extended periods of daily heat stress exposure, a heat wave, the proposed research will examine a string of consecutive days (at least 2) with at least a category of 1. A summary category for a heat wave will be based on the highest classified day(s) for the whole event. An example could be that if a six-day event had daily categories of 1-2-4-3-3-2, the heat wave would be a Category 4 event. This rationale follows closely with how tornadoes and hurricanes are referenced (Fujita 1981 and Elsner and Kara 1999) as well as northeastern U.S. snowstorms (Kocin and Uccellini 2004). A Category 4 hurricane or an EF-4 tornado does not hold that category for the duration of the event, but is forever remembered for reaching that status. Heat waves can be further analyzed to determine how many days each daily category (or stage) occurred, if there is a trend for stress levels (or stages) to increase during the event, and other climatic methods used to analyze runs. If losses were to occur on day four of the above hypothetical heat wave, they would have occurred on a stage 3 following a stage 4 of a Category 4 heat wave. This exposure-based classification can also be used in local sensitivity assessments.

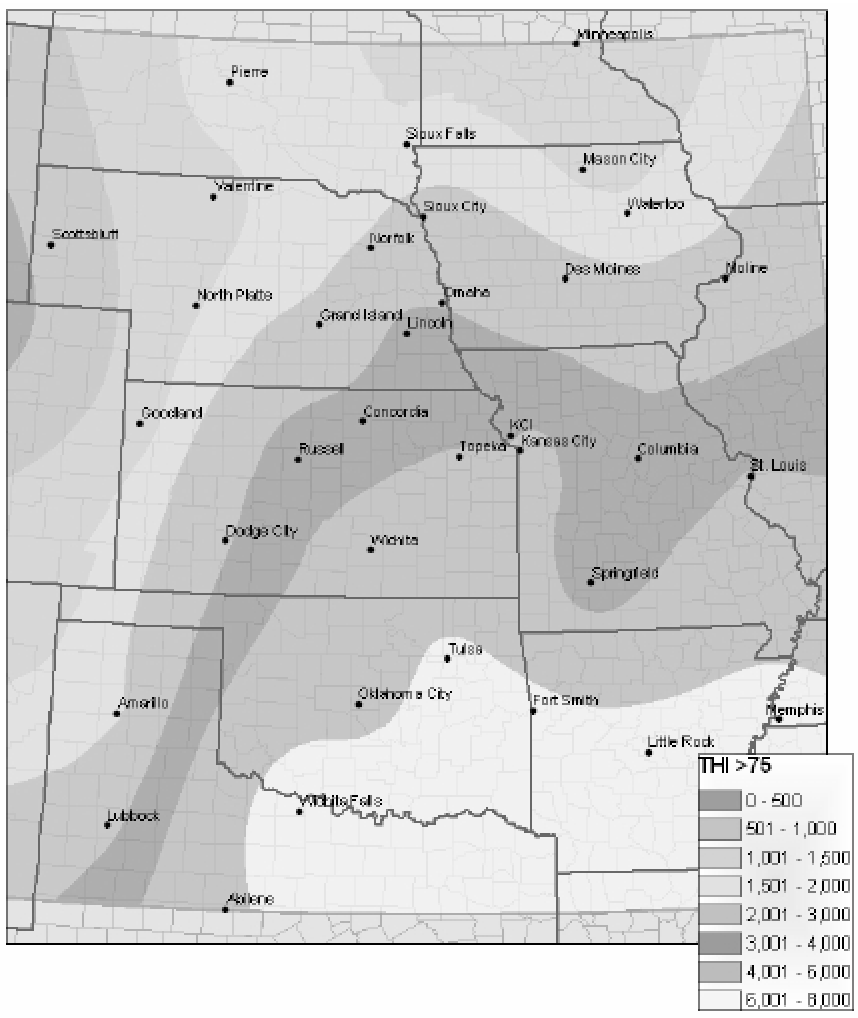
Mapping Heat Stress in the United States

Previous work by the author has effectively mapped the pattern and distribution of heat stress for the central United States using the Temperature-Humidity Index (THI). There are two categorical thresholds of increasing magnitude that are of concern, 32.2° C (90° F) and 40.6° C (105° F), and interpolating the average annual hours of accumulated HI above each threshold will illustrate why some areas would be more affected by high heat stress conditions than others. The map in Figure 2.5 is an example of how danger-level THI (much the same as a HI of 32.2° C [90° F]) is distributed in the central U.S. Figure 2.5 presents a pattern with a gradient that decreases from the southeast to the northwest, and this pattern is similar to warm season atmospheric moisture content (Figure 2.2). These results suggest a strong relationship between the amount of moisture available and the climatology of heat stress.

Since HI thresholds are similar to the THI thresholds (Table 2.3), this map should provide a good idea of what to expect for the central U.S. when climatic analysis of HI is performed on a national scale. The central U.S. is a major transition zone with respect to weather. Cooler drier air advection from the north, warm dry air moves in from the southwest, and warm moist air streams in from the Gulf of Mexico (Bryson and Hare 1974).

Expansion of the study area will allow for heat stress analysis in many other areas like the Desert Southwest, West Coast, Interior Mountain and Interior Northwest, Great Lakes, New England, the East Coast, and the Southeast. Inclusion of these areas will further clarify the geography of heat stress for the United States; however, high mountainous areas in the Rockies will be avoided because data are generally not available.

Figure 2.5. Distribution of alert-level THI heat stress in the central U.S., levels increase southeastward (map made by the author)



A focused study on the intensity and spatial distribution of the 1995 event will be conducted for the Midwestern United States. Works done by Kunkel *et al*. (1996), Livezey *et al*. (1996), and Palecki *et al*. (2001) illustrate that the spatial coverage of extreme heat conditions were in the eastern half of the country, providing a basis for a focused study within the affected region. Since the extremes of the event occurred in mid July 1995, the data extracted for the additional stations will be confined to the days within that month. Results will illustrate that further analyses could also be compared between the heat wave classification proposed by this study and researched events that occurred prior to 1980. Such events could include Chicago 1955, Los Angeles 1955, St. Louis 1966, New York 1972, and other noted events for which data are available (Henschel *et al*. 1969 and Whitman *et al*. 1997). Work can also identify details of day-to-day change in heat stress to determine how the event escalated to levels that caused notable deaths of local citizens.

Moving Forward from Existing Literature

Continuing reports of human mortality because of the effects brought on by extreme heat events worldwide supports the necessity for the research proposed in this study. Vulnerability to the heat and humidity conditions that can lead to harmful stress levels for people includes the understanding of exposure, or the nature of the events themselves. Variability of heat stress climatology can be vast during a single season for one location. Daily magnitudes, event durations, day-to-day magnitude variability, overall frequency of events, seasonal timing of events, and other factors all combine to increase the difficulty of characterizing heat stress and heat waves. Work is ongoing to determine how people are affected by extreme heat events as well as their adaptation to mitigate for the possibility of a similar event occurring in the future. However, defining a heat wave as a hazard is not universal over space because of the differences in climate norms. People acclimatize to the typical weather conditions of their location, which perpetuates impacts on mortality when normal highs, and especially previous extremes, are exceeded for even just two or three days. Identifying what the extremes are for many locations is necessary to appropriately understand the nature of heat waves as a hazard for which to prepare.

This dissertation introduces a new classification method that dissects a heat wave event into daily magnitudes of heat stress. The model proposed here quantitatively and objectively classifies heat waves as strings of consecutive days of heat stress that can be clustered into individual events. Daily magnitude variation and overall duration can vary greatly during an event just as an EF-5 tornado is not an EF-5 during the entire duration of the event, nor does a category 5 hurricane maintain that intensity from the beginning to the end. However, like these two events, the categorization of an individual day within a heat wave can be determined for days when mortality noticeably increases, as well as the conditions prior to that day that may have contributed to the escalated stress levels during the natural disaster.

Normalizing the classification model for all locations is a manageable solution to the problem surrounding the issue of regional differences in climate norms. Although it may be improbable for an area like Denver, CO or Billings, MT to experience a Category 5 heat wave using the parameters of this model, their local extremes can be identified and used as a basis for determining the extremes that the people in such areas experience. If conditions in any area reach hazardous levels, especially levels that occur with a very low frequency, more accurate communication can be provided to people by indicating the rarity and severity of the event.

Previous work by the author (Bowles 2004) indicates that this classification method is plausible, and preliminary classification results support the concept that this system is working. Several accumulated daily heat stress values have been devised to assist the effort to better understand the heat conditions that lead to mortality impacts. Classification schemes have proven useful for generalizing the effects of many weather hazards, however one has not yet be developed to help simplify and compare the effects of the hazard that is responsible for the most deaths worldwide, heat waves.

CHAPTER 3 – Data, Methods, and Study Area

Data

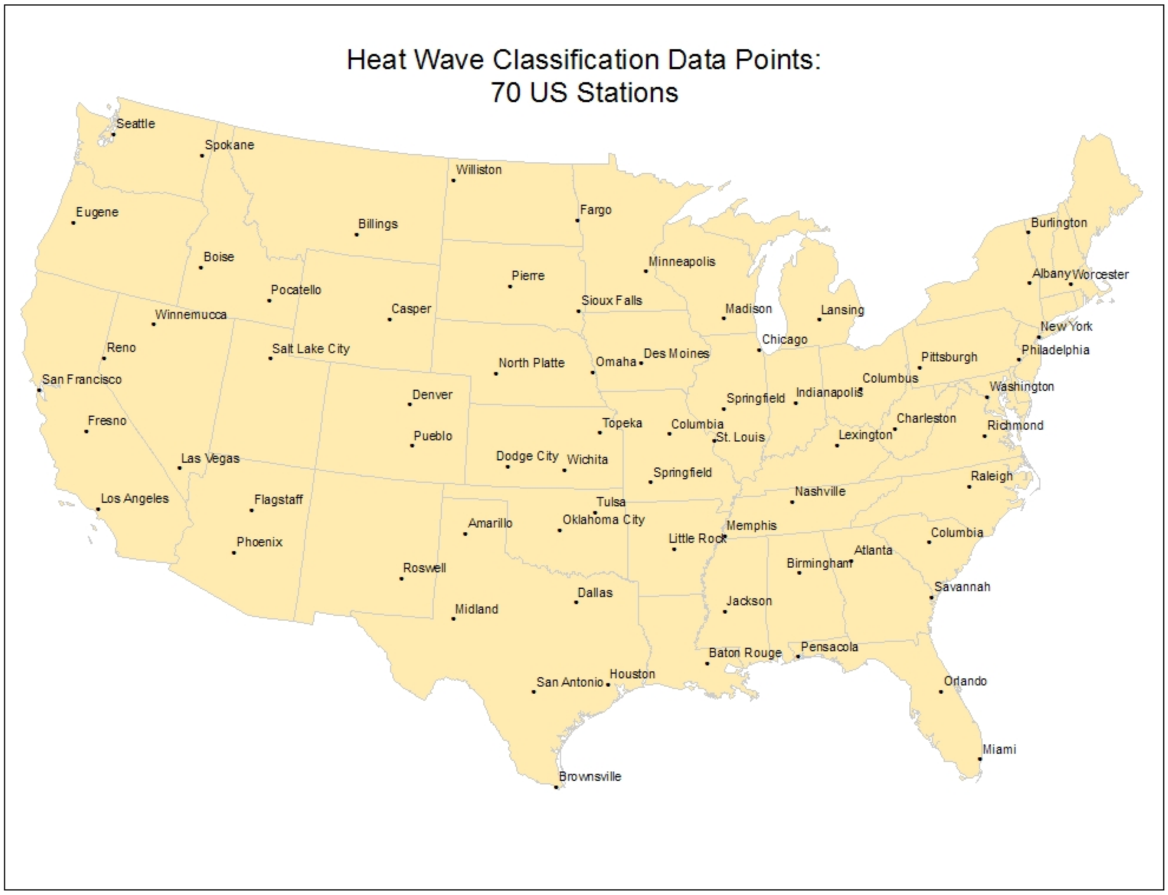
When it is necessary to obtain long-term weather data for multiple stations across the United States, the National Climatic Data Center (NCDC) has proven to be a reliable source. Previous work with these data has provided assurance that the information needed is available for the temporal period of 1980-2001. First-order/airport weather stations were used in this study that provided hourly data from the Surface Airways data set. Stations were selected first based upon their strategic location, however if the data record was not complete, the nearest station in the area with adequate weather recordings was used. There are numerous observations available at each location such as wind speed/direction, air pressure, solar radiation, temperature, humidity, and others, on an hourly basis. Only temperature and humidity were extracted for this research and combined to find hourly heat index (HI) values.

In some instances, stations with shorter, semi-complete records were retained to improve spatial coverage, but no stations with less than ten years of usable data was included in the analysis. Seventy stations were selected for analysis from across the contiguous United States (Figure 3.1). Hourly temperature and humidity values were obtained during each day on record for 22 years starting in 1980.

After the hourly temperature and humidity data were collected in English units from the Surface Airways data set, hourly values of HI were determined using equation [2] from Dixon (1997) with T = hourly temperature (°F) value and H = hourly humidity (%) value:

$$\begin{aligned} HI = {} & 16.923 + 0.185212 * T + 5.37941 * H - 0.100254 * T * H + (.0941695 * 10^{-2}) * T^2 + \\ & (0.728898 * 10^{-2}) * (H^2) + (0.345372 * 10^{-3}) * T^2 * H - (0.814971 * 10^{-3}) * T * H^2 + \\ & (0.102102 * 10^{-4}) * T^2 * H^2 - (0.38648 * 10^{-4}) * T^3 + (0.291583 * 10^{-4}) * H^3 + \\ & (0.142721 * 10^{-5}) * T^3 * H + (0.197483 * 10^{-6}) * T * T^3 - (0.218429 * 10^{-7}) * T^3 * H^2 + \\ & (0.843296 * 10^{-9}) * T^2 * H^3 - (0.481976 * 10^{-10}) * T^3 * H^3 + 0.5 \end{aligned} \qquad [2]$$

Figure 3.1: Map of 70 data point locations across the U.S. for this heat stress research



This equation is available in FORTRAN from NCDC and is considered a computational advantage; however it may produce values that are unnecessarily precise (Robinson 2001). In a technical attachment for the National Weather Service by Rothfusz (1990) (SR 90-23), another Heat Index calculation was provided and is shown in equation [3]:

$$HI = -42.379 + 2.04901523 * T + 10.14333127 * RH - 0.22475541 * T * RH - .00683783 * T * T - 0.05481717 * RH * RH + 0.00122874 * T * T * RH + 0.00085282 * T * RH * RH - 0.00000199 * T * T * RH * RH \quad [3]$$

where T is temperature in °F and RH is the relative humidity (%). This equation is complicated by two adjustments if climate parameters fall within specific ranges. If the humidity is less than 13% with an air temperature between 26.7° and 44.4° C (80° - 112° F), then the adjustment in equation [4] must be subtracted from the HI value:

$$ADJ = [(13 - RH) / 4] * SQRT \{[17 - ABS (T - 95)] / 17\} \quad [4]$$

where T is temperature in °F and RH is the relative humidity (%) and SQRT and ABS are functions of the square root and absolute value respectively. However, if relative humidity surpasses 85% and air temperature is between 26.7° and 30.6° C (80° - 87° F), then the adjustment in equation [5] must be added to HI:

$$ADJ = [(RH - 85) / 10] * [(87 - T) /5] \quad [5]$$

This equation by the National Weather Service assumes a 1.3° C (2.3° F) error which is accounted for in the work by Steadman (1984) calculating the original term for heat index as apparent temperature in equation [6]:

$$AT = -1.3 + 0.92 * T + 2.2 * e \quad [6]$$

where T is the temperature in °C and e is the vapor pressure in kPa. This equation is simple, but does not account for the detailed variables that are in the two HI equations above. The data used for this research was provided by the NCDC, which does endorse a HI equation. The definition in equation [2] was therefore chosen for this study because of its connection with the NCDC, computational accuracy, lack of complexity, and its use and availability of the relative humidity variable rather than vapor pressure.

The National Weather Service heat stress management categories for HI began at 26.7° C (80° F), however it was decided that all values greater than 21.1° C (70° F) would be kept in the analysis spreadsheets and all lower HI values were changed to zero. Maintaining the hourly HI values between 21.1° C (70° F) and 26.7° C (80° F) allows analysis of conditions prior to or just after a heat stress event and analysis of the degree of nighttime relief provided during the early morning hours. Any day that did not have at least one hour of HI greater than 21.1° C (70° F) was eliminated from the data set. This procedure left out the usually cold periods of winter, early spring, and late fall.

Methods

Data Conversion

Each 24-hour period was listed sequentially as a row of data, which for most stations were initially 8,036 rows of HI values. Any HI value that was recorded below 21.1° C (70° F) was converted to a value of zero noting an hourly recording not high enough to be used for heat analysis. Assigning the zero values provided the method necessary to reduce the number of days in the data set, so if a day did not register at least one hour of HI > 23.9° C (> 75° F) (daily sum = 0), that day was eliminated from the data set. The benefit from this step is higher for some stations (Madison, WI reduced from 8,036 days to 3,349 days) than for others (Miami, FL reduced from 8,036 days to 7,936 days), but did provide early observations on the differences of annual heating geographically.

After the station's data set was reduced, the next step was to identify how many hours in each day met the thresholds of 32.2° C (90° F) and 40.6 ° C (105° F) set by the National Weather Service, as well as the number of hours that met the cooling criteria below 23.9° C (75° F). These values were found by employing 3 columns to the right of the 24-hourly HI values with function statements in a spreadsheet (Appendix A.1). Outcomes of these functions are a sum of the hours of each day that meet the criteria set by the statement. The next step uses these values to acquire daily accumulated heat stress amounts.

Since the assessment of heat stress is done more accurately by identifying how much the above thresholds were surpassed, each day now had to be assigned accumulated heat values above 32.2° C (90° F) and 40.6° C (105° F) (The rest of this manuscript will refer to these HI thresholds as HI 90 and HI 105 respectively). The value for nighttime cooling remained the same, as a daily sum, because it is only necessary for conditions to reach this threshold to be effective as a deterrent to daily heat stress. Accumulated values were derived by the functions provided in Appendix A.2, and are statements that now sum only the daily HI values that are at least 32.2° C (90° F) or 40.6° C (105° F). Since the purpose for this function is to identify how much the daily heat stress surpassed the thresholds, the last part of the statement took the summed value from the previous step and subtracted the number of hours that recorded 32.2° C (90° F) or 40.6° C (105° F). An example of hourly heat index values is provided below from July 17, 1980 in Atlanta, GA between just the hours of 10:00 AM and 5:00 PM in Table 3.1:

Table 3.1: Atlanta, GA example from July 17, 1980 between the hours of 10:00 am-5:00 pm

	10:00	11:00	12:00	1:00	2:00	3:00	4:00	5:00
7/17/1980	93.02	96.44	103.12	108.68	113.49	114.00	110.00	109.98

Each of the 8 hours recorded a HI value > 90° F (>32.2° C), so all 8 are summed to a total of 848.73 in F (329.3 in C). To find out how much these values surpassed the threshold, 90 (32.2) must be subtracted from each value. This is the summed value provided in the cell AB2 from the previous step. In this case, 90 * 8 = 720 (32.2 * 8 = 257.6), therefore 720 (257.6) is subtracted from 848.73 (329.3) leaving an accumulated HI 90 heat stress value from these 8 hours as 128.73 (71.7). The same process is done for the 105° F (40.6° C) threshold. Five of the 8 values are greater than 105 (40.6), so only those values are summed to a value of 556.14 in F (220.1 in C).

The number in cell AC2 is then subtracted which is 525 from multiplying 105 by 5 (203 from multiplying 40.6 by 5) to obtain an accumulated heat stress value from these 8 hours as 31.14 in F (17.1 in C). This example is one third of a hot day in Atlanta that ended up registering a Category 3 heat stress classification, and exemplifies how heat stress values can accrue to high values during hot and sultry conditions. However, if there were no HI values for the day that reached these thresholds, the functions resulted in a zero. The two accumulated values and the summed nighttime cooling value were the numbers used to classify each day with the heat wave classification proposed in this study.

The Daily Heat Stress Classification System

The heat stress classification system introduced here was designed to be applied to every day of the year that registered at least on hour of HI > 23.9° C (> 75° F). These days were the lowest unit of analysis and, like most days, would be assigned a heat stress classification of zero, as there were no hours above 32.2° C (90° F) or 40.6° C (105° F). But for days that did accumulate suitable HI values, each day was compared to the 13 criteria of the heat stress classification (Table 3.2).

The daily heat stress classification system categorizes every day with a value from 0 – 5, where 0 means that the day did not reach high enough or persistent enough HI conditions to warrant being classified as a heat stress hazard. Categories between 1 and 5 assigned to a day measures its level of heat stress intensity for that 24-hour period from minor to extreme. If the accumulated HI 90 is a value of 22.2 (40) or higher, then that day has met the minimum requirements necessary to be classified as a heat hazard. If the accumulated HI 90 is less than 44.4 (80) with no HI 105 and abundant nighttime recovery hours, then the classification for that day is a Category 1, or Minor. If there are accumulated HI 90 of at least 44.4 (80) with HI 105 accumulation of at least 0.5 (1) and 10 or fewer recovery hours, then the day's heat stress classification is graduated to a Category 2, or Moderate. In order for the day to be classified as a Category 2, all three criteria must be met; otherwise the classification remains a Category 1. This method is the same for Categories 3, 4, and 5 as well. For instance, if a day has accumulated HI 90 of 116.7 in C (210 in F), accumulated HI 105 of 18.9 in C (34 in F), with no recovery hours, that day is still a Category 4, not a Category 5. Although it appears close, the thresholds are observed directly and the day is not graduated to the higher classification.

Table 3.2: The daily heat stress classification system in °F (left) and °C (right)

Category	HI - 90°	HI - 105°	Recovery
1 Minor	≥ 40	-	-
2 Moderate	≥ 80	≥ 1	≤ 10
3 Strong	≥ 120	≥ 10	≤ 6
4 Severe	≥ 160	≥ 20	≤ 2
5 Extreme	≥ 200	≥ 35	0

Category	HI 32.2°	HI 40.6°	Recovery
1. Minor	≥ 22.2	-	-
2. Moderate	≥ 44.4	≥ 0.5	≤ 10
3. Strong	≥ 66.6	≥ 5.5	≤ 6
4. Severe	≥ 88.8	≥ 11.1	≤ 2
5. Extreme	≥ 111.1	≥ 19.4	0

Application of the heat stress classification to each day was also done in the spreadsheet with the previous functions. There were 13 columns with statements used to identify if the day's HI values met the criteria of the classification system. The statements refer to cell columns AF, where the daily accumulated HI 90 is located, AG, where the daily accumulated HI 105 is located, and AH, where the summed nighttime cooling value is located. The statements are if-then functions, so if the value in the referenced cell meets the criteria in the function, the cell is assigned the appropriate value. If the criterion is not met, the cell is assigned a zero. There is one statement for a Category 1, since there is only one threshold that needs to be met, however the other 4 classifications require 3 statements each. The function for meeting a Categories 1 through 5 are provided in Appendix A.3

These functions are provided in 13 sequential columns (AJ to AV) and applied to every day remaining for the station. When the functions are applied, many days, especially in the winter and early and late portions of the warm season, are represented by 13 zeros, indicating that there was no heat hazard for that day. A result of a 1 in the first column followed by 12 zeros indicates that conditions had reached the minimum requirements to be classified as a Category 1 for that day. A day that is classified as a Category 2 must have the '1' value and all three '2' values, and so on for categories 3, 4 and 5.

In order for a heat wave to be identified, consecutive days must be classified as a Category 1 or higher. If two consecutive days are classified, and one or both of those days reach a Category 2 or higher, then it is considered a two-day heat wave. When three or more consecutive days are classified as a Category 1 or higher, each individual group of days is considered a single heat wave. The first day of an event is the first that is classified as a Category 1 or higher, and the event has ended when the next unclassified day (Category 0) is recorded. Duration of any event is noted by the number of consecutive classified days, and the final tally provides the number of heat waves that occur in any given year, the duration of each event, and the categorical magnitude of each day within the events.

To classify each heat wave as individual hazards, the logical solution was to follow the same procedure as classifying hurricanes. Hurricanes vary in intensity across a 5-category scale throughout their durations; however they are ultimately identified as the highest category they achieved. Similarly, heat waves are assigned a value from the heat wave classification based on the day within the event that recorded the highest value. An event with daily categories listed as 1-2-2-3-2-2, for example, would be a 6-day event registering as a Category 3 heat wave. If one were to examine the event specifically, the heat stress magnitude can be determined for any day, as well as the progression of the event throughout its duration.

Mapping Heat Stress and Heat Waves

Summary statistics were obtained upon the application of the heat stress classification system to all 70 stations. The number of days occurring during heat waves that were classified from 1-5 were recorded, as well as the number of days that were Category 1s that were not part of heat waves. The total number of classified days for each station's temporal record was also obtained, as well as the average number of Category 1 – Category 5 days that occurred each year. Other statistics obtained were: total number of heat waves for Category 1 – Category 5 at each station, average annual occurrence of each level of event, average duration of events, and the number events that occur per year at each station. The summary tables of the 22-year record for all 70 stations are provided in Appendix B.

Values logged in these tables provide the data needed to map heat stress results across the United States. ArcGIS 9.2 developed by the Environmental Systems Research Institute (ESRI) was the program used to map results from the heat stress classification. Each data point from Figure 3.1 has results in the same format as found Appendix B. Therefore, all points would, for example, have a value for the number of days that were classified as a Category 1 during a heat wave. Those values are only provided at the point shown on the map, and the ArcGIS program runs an interpolation process to estimate the number of days at between-point locations, in this case by running a spline interpolation.

Of the three available interpolation methods in ArcGIS, the spline function worked the best when representing climatic changes over space in the Unite States. Inverse Distance

Weighted (IDW) is a very common method; however, the data point density in this study is not high enough to employ the IDW. When the program was run, inland hot areas such as Tulsa and Memphis were depicted as disconnected islands of heat stress rather than part of the air stream that flows northward from the Gulf of Mexico. The Krige method was capable of illustrating the flow of the phenomena over the surface better than the IDW, but consistently displayed jagged, unnatural errors in the smoothness of the contours. The spline interpolation method displayed the surface smoothly, represented the data points correctly, and produced a pattern of the dispersal of heat stress phenomena that was expected based on the known climatology and topography of the United States.

Prediction maps were developed in the Spatial Analyst tool to access use of the interpolation program. The spline type was set to 'regularized' with a weight of 0.1 and the number of points that influenced estimation values was usually set with the default at 12. However, some maps that were designed with values of less frequent nature, such as the frequency of Category 4 or 5 heat waves, required the influential point value to be reduced to 4. This was because when a station in the Great Lakes area would display an anomalous value compared to surrounding points, the interpolation would place too much weight on the value and misrepresent increasing contours northward. A combination of fewer interpolation points with fewer contour classifications produced an estimation layer that was appropriate for mapping the data. All contour maps were made with the same process for any of the heat stress variables in the tables in Appendix B and Appendix C.

Correcting Synoptic Data

Temperature and humidity data was recorded synoptically for 26 stations in the study area for this research (Table 3.3) for either one year or one year and seven months. Recordings were obtained once every three hours instead of every hour for 1980 at all 26 stations, and through July 31, 1981 at 17 of them. On January 1, 1980 (bolded in table), or July 31, 1981 the weather recordings resumed an hourly schedule. Such recording methods greatly underestimate the amount of accumulated heat stress calculations than if data was obtained hourly. A pressing issue is that for the time period 1980-2001 in the United States, 1980 had one of the most actively intense heat wave seasons for most of the central and eastern portions of the country.

In June of 1980, a surface high pressure system developed over the southern U.S., and maintained its general position over the Southeast through September. Heat conditions combined with a severe drought to sustain heat conditions in the upper 5-10 percentile, especially for the month of July (Karl and Quayle 1981). The persistence of extreme conditions in this year warranted an adjustment to attempt to estimate heat wave conditions from the data available.

Table 3.3: Stations with synoptic recordings starting on January 1, 1981: bolded through Dec 31, 1980; non-bolded through July 31, 1981

Albany, NY	Flagstaff, AZ	Roswell, NM
Amarillo, TX	Lansing, MI	Sioux Falls, SD
Billings, MT	**Little Rock, AR**	**Spokane, WA**
Birmingham, AL	Oklahoma City, OK	Springfield, IL
Casper, WY	**Pensacola, FL**	Tulsa, OK
Charleston, WV	Pierre, SD	Williston, ND
Columbus, OH	**Pocatello, ID**	**Winnemucca, NV**
Dallas, TX	Pueblo, CO	Worcester, MA
Eugene, OR	**Reno, NV**	

Figure 3.2 illustrates the HI recording differences on the same date between the 1980 synoptic year and 2000, a year of hourly recordings. There are yellow and orange lines provided to identify the thresholds of HI 90 and HI 105 respectively. Graphically, one can identify the 24-hour similarities between the two dates from 12:00 am to 11:00 pm. Because of the missing information in 1980, the category assigned to July 12, 1980 was a Category 1. However, the same date in 2000 exhibited a very similar progression of HI values throughout the day and was assigned a Category 4, a significantly higher level of magnitude. The other stations in the eastern U.S. with synoptic readings for 1980 were examined as well and identified as also having been under-classified for this time period.

An attempt to address the under-representation issue for 1980 was made using estimations for the remaining 16 hours without recordings on July 12 in Dallas with the curve from the existing data. Now the accumulated heat stress for July 12, 1980 was 195 hours HI 90 and 26 hours HI 105, making the day a category 4 like the similar day in 2000 (these days had 0 recovery hours). Having obtained graphically-derived values of HI to use as a base, a new attempt was made to reduce the time needed to get them. This new attempt follows the assumption that during a hot and humid day, adjacent hourly HI values will not be significantly different (i.e. > 5.6° C [> 10° F] HI apart, see Figure 3.3). Since there are 8 existing values recorded at regular intervals throughout the day, the accumulated HI values used in the heat

Figure 3.2: Synoptic conditions in Dallas on July 12, 1980 compared to the same day in 2000. Actual HI recordings are listed for 1980 illustrated with blue dots. Estimated values are shown as red dots

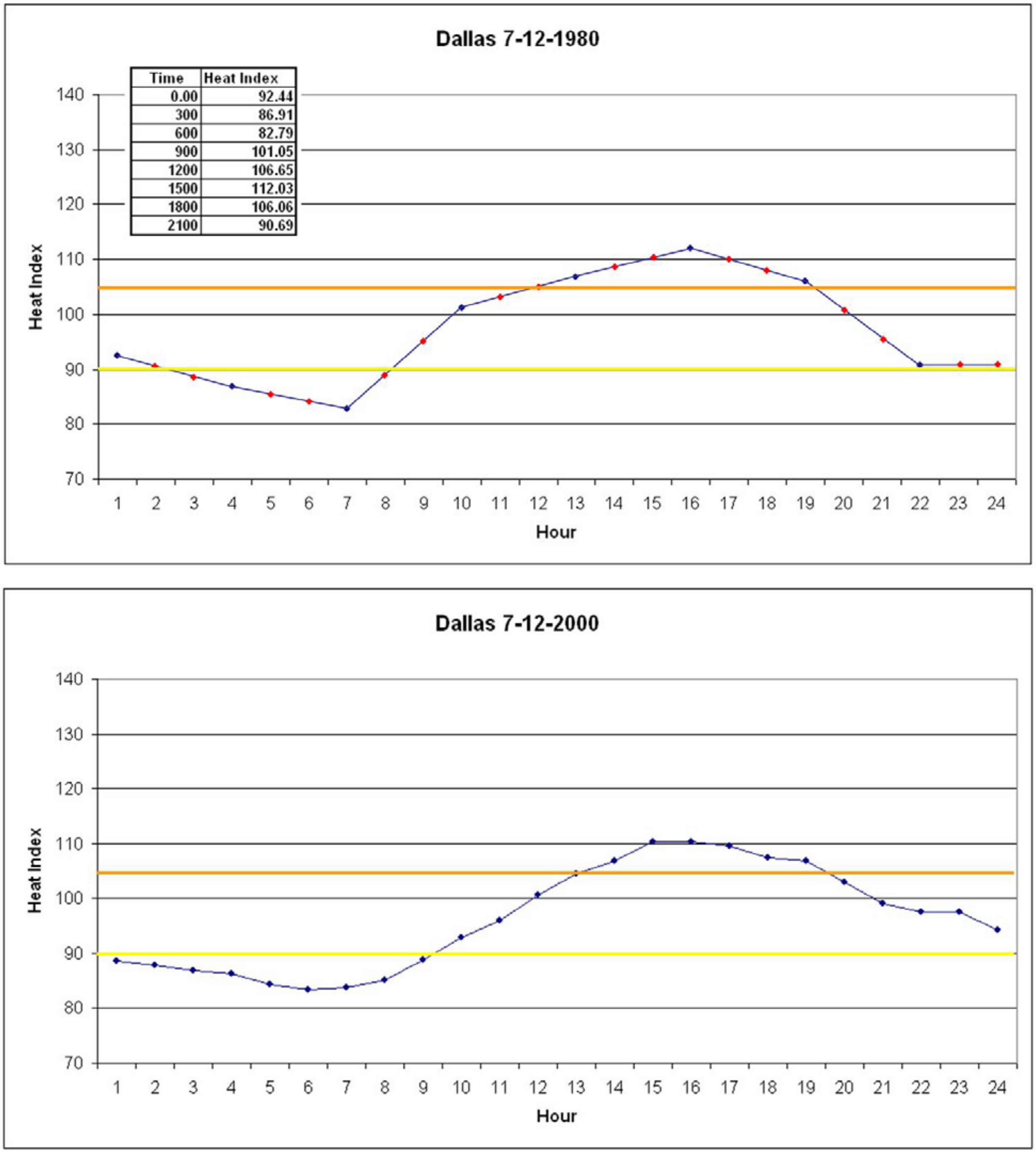
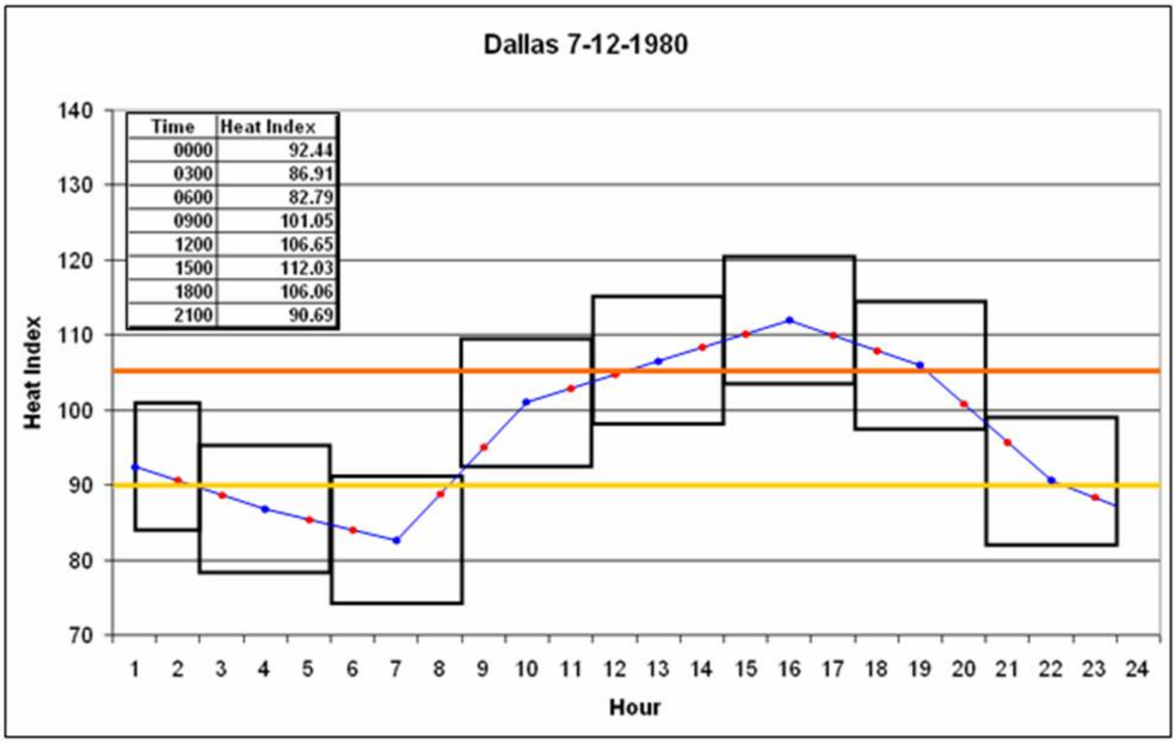


Figure 3.3: Similarity of adjacent values during a hot day in Dallas

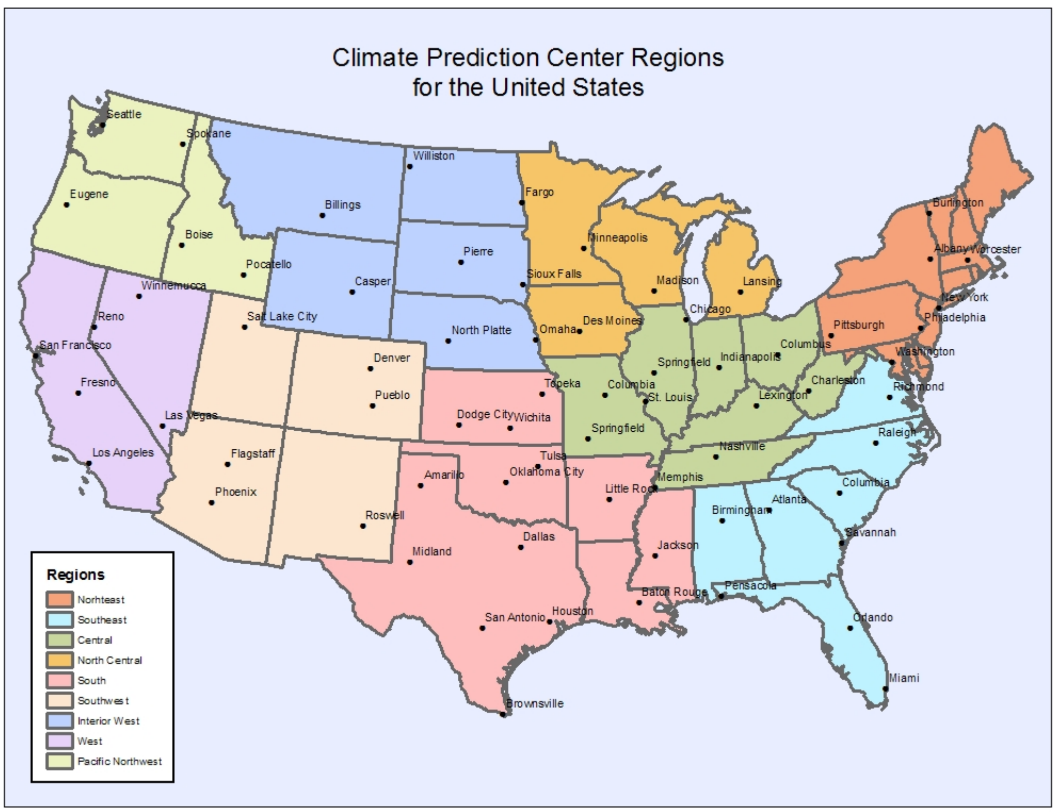


stress classification were derived with the 8 existing values then multiplied by 3. With this method, the accumulation values for July 12, 1980 in Dallas were 115 (207) hours HI 90, and 16.1 (29) hours HI 105. Not only are these numbers close to (although higher than) the values from the above method, they also still place the classification for the day at a Category 4. Random July dates were chosen at other eastern U.S stations and ran through the same comparison as the date above at Dallas with comparable results. For instance, July 9, 1980 in Little Rock originally was classified as a Category 1. New values were obtained with the longer graphical method, and the shorter 'multiply-by-3' method as done for Dallas. The graphically derived accumulated values for this date in Little Rock were 139.4 (251) hours HI 90 and 27.8 (50) hours HI 105, and the multiplication method attained accumulated values of 143.3 (258) hours HI 90 and 31.3 (56) hours HI 105. The multiplication method is still a little higher, but results are still close enough to consider usable for the realm of this study. In this case, a previously classified Category 1 day is now more adequately classified as a Category 5. Even with the possibility of slightly inflated values, these multiplied values are considerably more representative of the conditions for that year. Thus, the multiply-by-3 method was employed for all synoptically recorded days.

Study Area

Heat wave analyses for this research have been limited to the coterminous United States. Climate types in this region are not bound by political boundaries. However, the National Weather Service Climate Prediction Center uses the U.S. climate regions from Easterling (2002) that delineate 9 areas separated along selected state boundaries shown in Figure 3.4. It is not to be assumed that climate patterns are uniform throughout each region, for instance, the West region includes the states of California and Nevada. California alone has several factors affecting its climate variability based on its west coast location, latitudinal orientation (covering 9.5° north to south), and tall mountain ranges just to name a few. The regions do allow climate descriptions to be more representative to locations that are relatively close together, rather than including locations with different climatic norms and source regions.

Figure 3.4: Climate regions of the United States (from Easterling 2002)



Weather patterns that become climate records are not available for the continuous landscape of the United States. Researchers are dependent on the weather recordings from point locations decided upon by the National Weather Service, where in situ data is gathered over time. The recordings from each weather station are used as a representation for its surrounding area. Some stations are closer together than others, and some areas have a steeper gradient of climate variability than others, so recordings are provided at a point and are interpolated by the amount of variation that exists among surrounding stations to estimate conditions continuously across the landscape.

CHAPTER 4 – Results and Discussion

Daily Heat Stress Classification Results

A two-step process was developed to determine if individual days were hot and humid enough to accumulate heat stress exposure above selected threshold levels and then strings of days that were stressful were grouped into heat waves and classified in one of five possible categories. This chapter presents the results for both steps in the process, beginning with a summary of the frequency and magnitude of daily accumulated heat stress at the 70 stations used in this analysis. Categories used in the classifications of heat stress and heat waves are the same for all stations facilitating comparison among stations and the mapping of related patterns. Since the classification system used within this research is new, the value of the classification can be judged in part by the reasonableness of the results of applying the system. In a sense, it is hoped that the results presented herein answer the question: are these findings what might be expected?

Classifying heat stress and heat waves for this study was done by transferring the selected classification logic from Table 3.2 in the Data and Methods chapter into basic spreadsheet functions and then analyzing 22 years of data for 70 stations. Although the discomfort from sultry conditions caused by the fundamental combination of high temperatures and humidity is well understood, understanding heat wave occurrence and frequency over space and time is not, however a few exceptions such as Robinson (2001) do exist. Following the analysis and classification, maps have been developed in support of this research to provide graphic evidence of heat wave frequency and magnitude differences from one location to another across the United States. Because of the large amount of data used in this research, summary tables for each of the 70 stations are provided in Appendix B.

Daily Results: Total Days

Determination of the total number of heat stress days of any category for the length of the study period provides an ordinal comparison of actual accumulated heat stress among all stations across the country. Initial hypotheses regarding United States climatology are drawn from well-known climate patterns, primarily that higher heat values accumulate in the southern areas, and lower values exist in the northern reaches of the country. Reduced heat stress was also expected in drier areas, in areas of higher elevation (for this study, 1,220 m [4,000 ft] and up) and along the West Coast. Highland regions are less likely to experience the climatic variables necessary to cause a heat wave with low air moisture content and decreasing temperatures with increasing elevations. Mountainous areas such as the Cascades, Sierra Nevadas, Rockies, and Appalachians, were not heavily represented for this research. Elevation examples can also be lower-relief areas such as Casper, WY and Pueblo, CO, which are still over 1,220 m (4,000 feet) above sea level.

Eleven of the 70 stations had zero days of accumulated heat stress exposure, all of which are from near the eastern edge of the Rocky Mountains westward (Table 4.1). Of these stations, Denver and Flagstaff never recorded a single day that accumulated heat and humidity to the point of being considered a heat stress day. Denver and Flagstaff are also the two highest elevation stations in this study, both above 1,675 m (5,500 ft). The other nine stations had one day or more that was a Category 1, but there were no instances when those heat stress days occurred consecutively for three days; therefore these locations did not have a heat wave hazard. Pueblo, for example, recorded 40 individual days that were classified as heat stress Category 1 from 1980-2001; however they were typically 2-3 seemingly randomly separated hot days in the month of July.

Table 4.1: Stations that recorded zero days during a heat wave throughout the period of study

	Station		Station
1	Billings MT	**6**	Pocatello, ID
2	Casper, WY	**7**	Pueblo, CO
3	Denver, CO	**8**	Reno, NV
4	Flagstaff, AZ	**9**	San Francisco, CA
5	Los Angeles, CA	**10**	Seattle, WA
		11	Spokane, WA

At the opposite end of the spectrum, Brownsville and Phoenix each recorded over 2,000 heat stress days (total summed of all categories) during the study period (Table 4.2). There were 8,036 days from 1980-2001, so more than 25% of the days at these two locations were classified as heat stress days. There is a climate factor at these stations, however, that is notably different. Brownsville has a mean relative humidity of 77%, with Phoenix averaging just 35%. One similar statistic is in average annual temperature where Brownsville has a mean temperature of 23.3° C

(74° F), and Phoenix averages about 23.3° C (75° F). Phoenix reaches higher temperatures that persist considerably longer than in Brownsville, but Phoenix can have longer periods of lower temperatures in the winter months.

Table 4.2: Stations with the highest total number of heat stress days from 1980 – 2001

	Station	Days		Station	Days
1	Brownsville, TX	2456	**6**	Dallas, TX	1477
2	Phoenix, AZ	2131	**7**	Baton Rouge, LA	1243
3	Houston, TX	1783	**8**	Orlando, FL	1179
4	Miami, FL	1524	**9**	Jackson, MS	1153
5	San Antonio, TX	1504	**10**	Pensacola, FL	1141

The primary difference climatically between southern Arizona and south Texas is the availability of moisture. It is in the humidity statistic that one can better understand the difference in how heat stress would affect people in the western half of the U.S. versus the eastern half. Of the 19 westernmost stations, only 4 had notable quantities of heat stress days: Fresno, Las Vegas, Phoenix, and Roswell. The lowest ranking of these four stations is Roswell by a large margin with 116 total classified days, substantially lower than the 626 days at third-highest Fresno. Roswell is at an elevation of 1,118 m (3,669 ft), which is above 915 m (3,000 ft) where marked signs of decreasing heat stress begin to appear. (Elevations from 915 m [3,000 ft] to 1,220 m [4,000 ft] were observed as the range where heat stress declined most significantly, see Figure 4.1.) The 116 classified days is 70 days higher than the next highest sum for any station above 915 m (3,000 ft) (Amarillo), and no other station above 915 m (3,000 ft) recorded more than 15 total heat stress days. Fresno had a mean relative humidity of 60%, whereas mean relative humidity levels for Phoenix and Las Vegas were 35% and 32% respectively. Incidentally, Las Vegas and Phoenix both recorded more than 1,000 total classified days each. These results suggest that the levels of heat stress at two hottest western stations are based primarily on warm, dry continental air from Mexico and persistent solar radiation, not as much on humidity.

Humidity becomes much more of a factor determining heat stress in the eastern half of the country, eight of the ten stations in Table 4.2 are in eastern half. Other than Phoenix, San Antonio just west of the 98th meridian, is shown as having the fifth highest occurrence of heat stress days throughout the study. However, since it is located just west of the primary W-E moisture gradient, nearly all of its 1,442 classified days are classified as a Category 1, as seen in the next section.

Figure 4.1: Scatterplot of station elevation with corresponding total heat wave day frequency

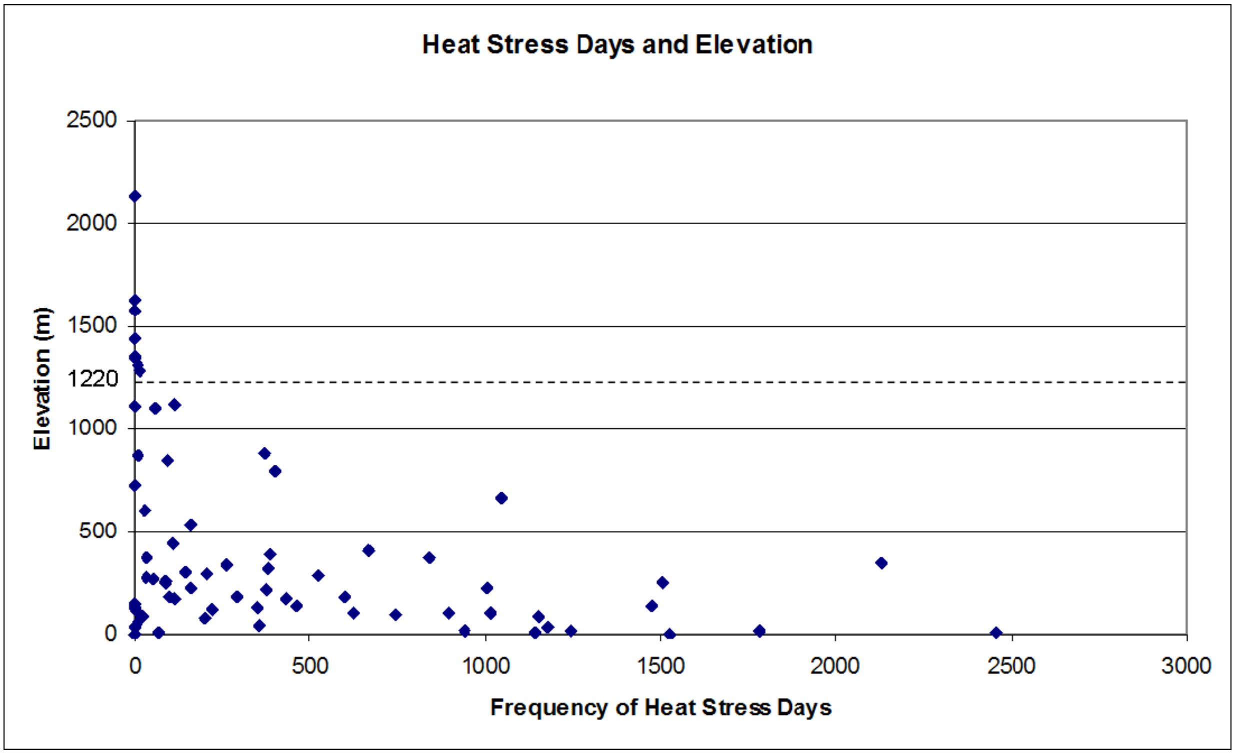
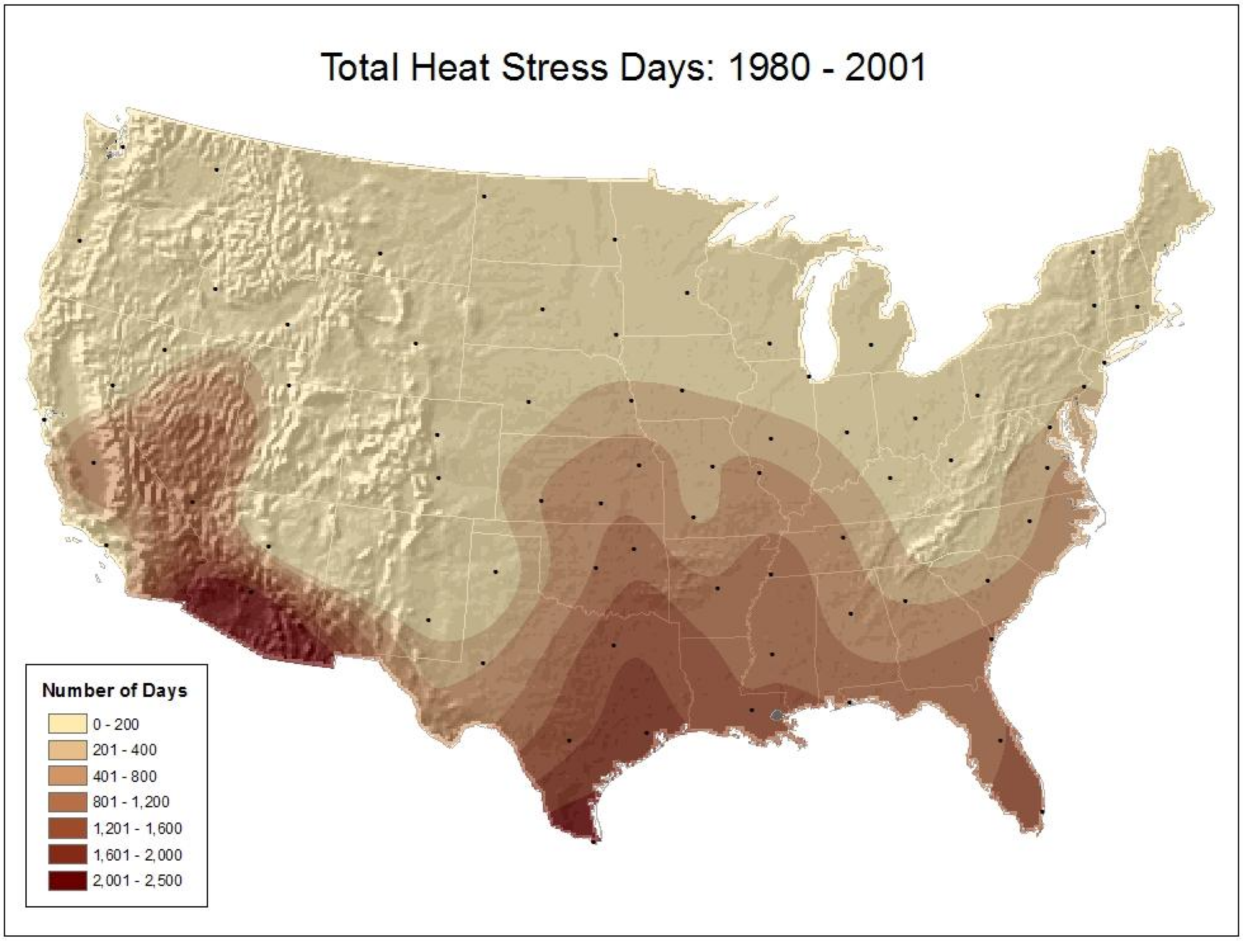


Figure 2.2 (Dodd 1965) illustrates the average air moisture content in the U.S. and aids in understanding the results in Table 4.2, as well as results for other classes of heat stress and heat waves categories. Nearly all of the locations that will be listed as the top recipients of heat stress days will be found in the darkest (southern) two contour fills in Figure 2.2. Similar results are found in the distribution of heat stress days for each station in the study determined by temperature and moisture content (Figure 4.2). The contours in Figure 4.2, measured in heat stress days, form a tight gradient in the lower Sonoran Desert. Notable heat stress levels are also occurring in Nevada and parts of southern California. This potion of the western U.S. is consistently the only area exhibiting notable heat stress of any category.

Moisture advection northward from the Gulf of Mexico into the warm southeastern states is characterized well by the contours in Figure 4.2. The highest values are found in the southern tip of Texas, around Brownsville, and regularly decrease northward to central Iowa. A north-south axis is evident from Houston through northeast Kansas with an evident disruption in the number of heat stress days over northern Arkansas and southern Missouri. The contours then turn southward through Kentucky and Tennessee, then are redirected northward along the Atlantic coastal plain.

Figure 4.2: The total number of heat stress days occurring during a heat wave as defined for this study



Stations in the lowest contour category recorded from 0-200 days classified as a heat stress hazard. The western-most 19 stations that fall within this contour interval recorded no more than 15 total heat stress days (Salt Lake City), suggesting that if an additional contour were added at the lower end of the data range, it would highlight these western locations. Proximity to the coastline along the Pacific Ocean has the effect of limiting heat stress days; the opposite occurs for locations near to the warm waters of the Gulf of Mexico or the Atlantic Ocean.

In addition to elevation and coastal properties, these heat stress day frequency results reflect properties of known prominent air streams patterns across the country, correlating positively with known climatic distributions. Patterns observed in Figure 4.2 will not deviate greatly when one analyzes the other maps throughout this chapter. However, the magnitude that the contours represent will change as different heat stress levels are presented for analysis. These maps provide a visual comparison of heat exposure over space, and the following sections provide analyses for the results of individual daily categories from 1-5.

Daily Results: Category 1

The class with the highest frequency of occurrence is 'Minor' or Category 1 of daily heat stress accumulation. There were no stations in this study where Category 1 heat stress days were outnumbered by another category. This lowest heat stress category was identified as a day when the average heat index (HI) value was in the low 30s C (upper 80s F) with notable warming in the afternoon. As mentioned, in the Methods chapter, the classification strategy followed the model developed by Hahn *et al.* (1999). Overnight recovery periods are common during a Category 1 day, however daily HI maximums can reach into the high 30s C (low 100s F). Minimum heat stress levels required to achieve Class 1 is a daily accumulation of 22.2 C (40 F) excess hours of HI 90 with zero hours of HI 105 hours for the day. The upper threshold of accumulated HI 90 hours that occurs during a Category 1 day is technically limited; however, that day would have to record a HI of 40° C (104° F) for all 24 hours. One example of a higher-end Category 1 day was July 8, 1991 in Orlando. This day reached a total accumulated heat stress of 68.3 C (123 F) hours of HI 90 with 6 hours of the day surpassing a HI of 37.8 (100° F), but it was Category 1 because there were no recorded hours surpassing the HI 105 threshold. All daily heat stress categories above 1 require at least one hour recording an HI above the HI 105 threshold.

Stations experiencing the highest frequency of Category 1 days (Table 4.3) are in the south and especially the southeast, where the warm season is long. There are nearly seven stations that recorded 1,000 or more Category 1 heat stress days (Baton Rouge had 997), four had over 1,100 days, and Brownsville had over 1,900 Category 1 days, averaging 87 per year. Known hot spots in the Southwest, Phoenix (4^{th}) and Las Vegas (10^{th}), are also in the top 10. South Texas experiences the most Category 1 days with Brownsville recording over 400 more days than the second-highest location, Miami. Annual averages at these top ten stations range between 38 and 67 Category 1 days per year up to Miami, and then the 87 per year at Brownsville.

Distinctions can now be made between the stations that have high frequency of heat stress days with either a low or high level of heat stress magnitude. If one were to examine the top five stations in Table 4.3 compared to their overall totals in Table 4.2, a deduction can identify between truly hot locations and persistently warm locations. For example, Phoenix and Brownsville recorded the most classified days overall, with Category 1 days making up 56% of the total at Phoenix, and 78% at Brownsville. Although the 78% at Brownsville appears to be high, there are still nearly 500 days left to be classified into higher heat stress categories. Three stations tend to experience less overall heat intensity even though they have some of the highest frequency values in both tables. Of the total recorded heat stress days, the frequency of Category 1 days at Miami (97%), San Antonio (93%), and Orlando (92%) is clearly dominant.

Table 4.3: Stations with the most days classified as a Category 1 during a heat wave: 1980 – 2001

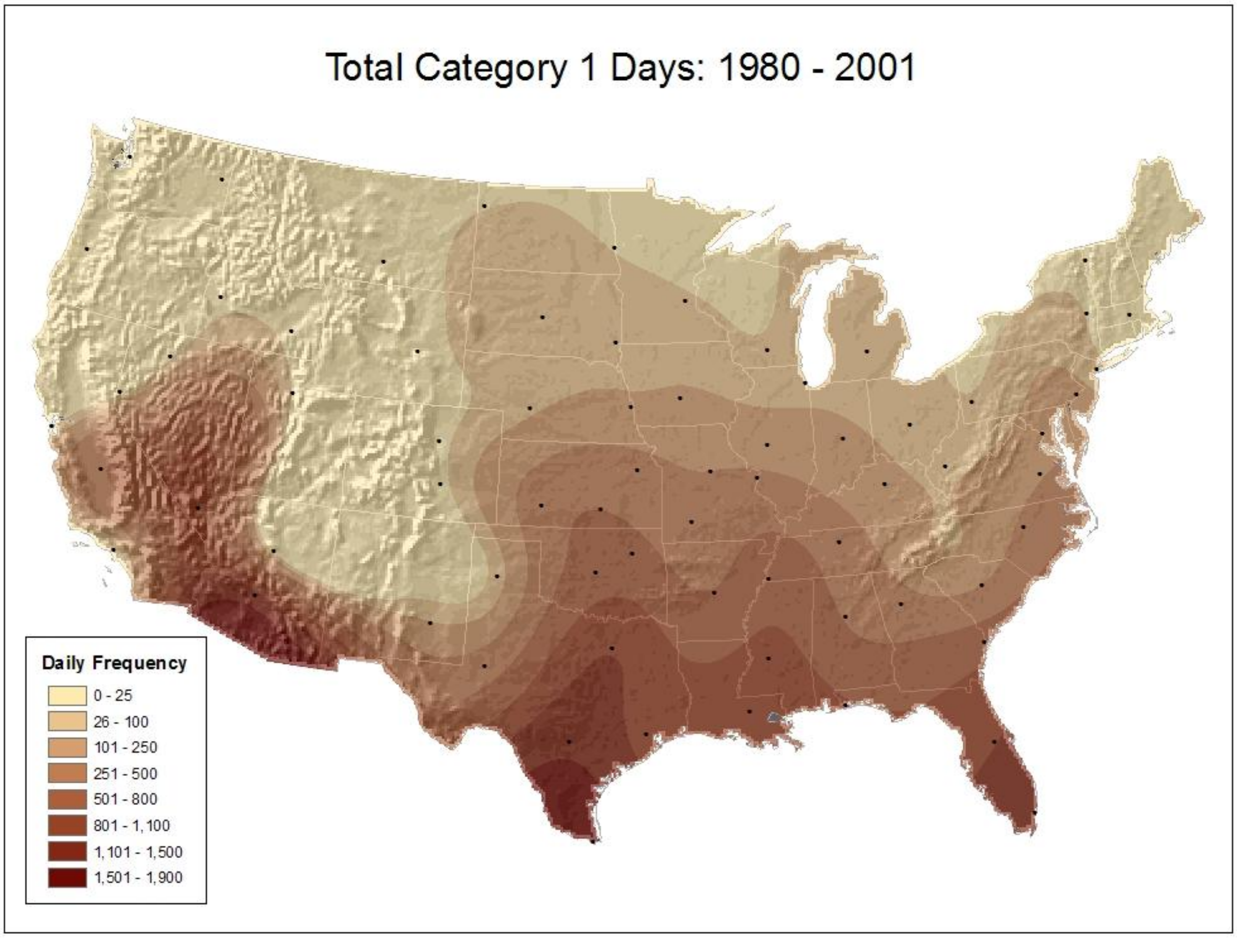
	Station	Days		Station	Days
1	Brownsville, TX	1909	6	Dallas, TX	1073
2	Miami, FL	1473	7	Baton Rouge, LA	997
3	San Antonio, TX	1392	8	Houston, TX	989
4	Phoenix, AZ	1188	9	Jackson, MS	883
5	Orlando, FL	1083	10	Las Vegas, NV	854

The spatial distribution of Category 1 days (Figure 4.3) suggests low frequencies in the mountainous and coastal West, as well as the Northeast. The southwestern lobe of higher Category 1 day observations includes the stations of Las Vegas, and Phoenix, but this lobe is likely limited to a specific geographical zone related to lower elevation desert locations. The 145 miles between Flagstaff and Phoenix presents the steepest heat stress gradient among the stations used in this research, and the gradient is likely even steeper with most of the change probably occurring with transit up onto the Mogollon Rim. Phoenix is routinely one of the hottest locations in the country during the summer months, and Flagstaff did not record heat stress days.

Occurrences of Category 1 days fill the central U.S. nearly to the Canadian border, with frequency increasing southward. The fifth highest category (251-500 days) in Figure 4.3, stretching from Midland to Richmond, indicates areas that experience between 10 and 20 days of Category 1 heat stress (during a heat wave event) per year on average. Areas north of this contour typically have less than 10 Category 1 heat stress days per year. Contour lines in the central U.S. indicate the effects of slightly higher elevations and lower heat stress frequencies in the Ozark Plateau. The effect of elevation is also evident as contours cross the Appalachian

Mountains; so it is again apparent in the East that elevation changes in the landscape impacts local heat stress levels.

Figure 4.3: Distribution of Category 1 heat stress days in the U.S.



Daily Results: Category 2

An important factor that separates a 'Minor' Category 1 day from a 'Moderate' or Category 2 day is the occurrence of at least one heat stress hour that surpass HI 105. There now must be an accumulation of at least 44.4 C (80 F) excess hours of HI 90, at least 0.5 C (1 F) excess hour of HI 105, and no more than 10 total hours during the 24 hour period of recovery (HI 75). The NWS states that as apparent temperatures surpass 40.6° C (105° F), effects on humans from the hot conditions become more likely. This heat stress classification category is designed to document hot days that may have an impact on human performance in outdoor activities.

The most Category 2 days occurred in South Texas at Brownsville, with 455 days in the study period, or 20.7 annually (Table 4.4). This value is added to the 1,909 Category 1 days with 2,364 of the total 2,456 classified heat stress days in Brownsville. Savannah, roughly 5 miles inland from the Atlantic Ocean, is the tenth-highest on the list having a total of 168 Category 2 days, 7.6 per year. There are five stations that are not in Table 4.4 that were in Table 4.3: Jackson, Las Vegas, Miami, Orlando, and San Antonio. A review of the summary tables (Appendix B) for these stations reveals that the number of Category 1 days that occurred at these locations made up the majority of the total number of classified days. Jackson recorded only 270 more classified heat stress days after the 883 recorded Category 1 days, and the 159 Category 2 days it registered narrowly missed the list in Table 4.4. The other 4 locations each had fewer than 200 total classified days left after the Category 1 days were selected, suggesting that they are warm locations that infrequently experience really sultry days. Baton Rouge did make both the lists in Tables 4.3 and 4.4, however, with a total sum of 1,243 heat stress days, there are just 70 classified days left in higher categories. The results for these six locations demonstrate that accruing a high amount of heat stress days quantitatively does not automatically suggest that they are areas of highest heat magnitude.

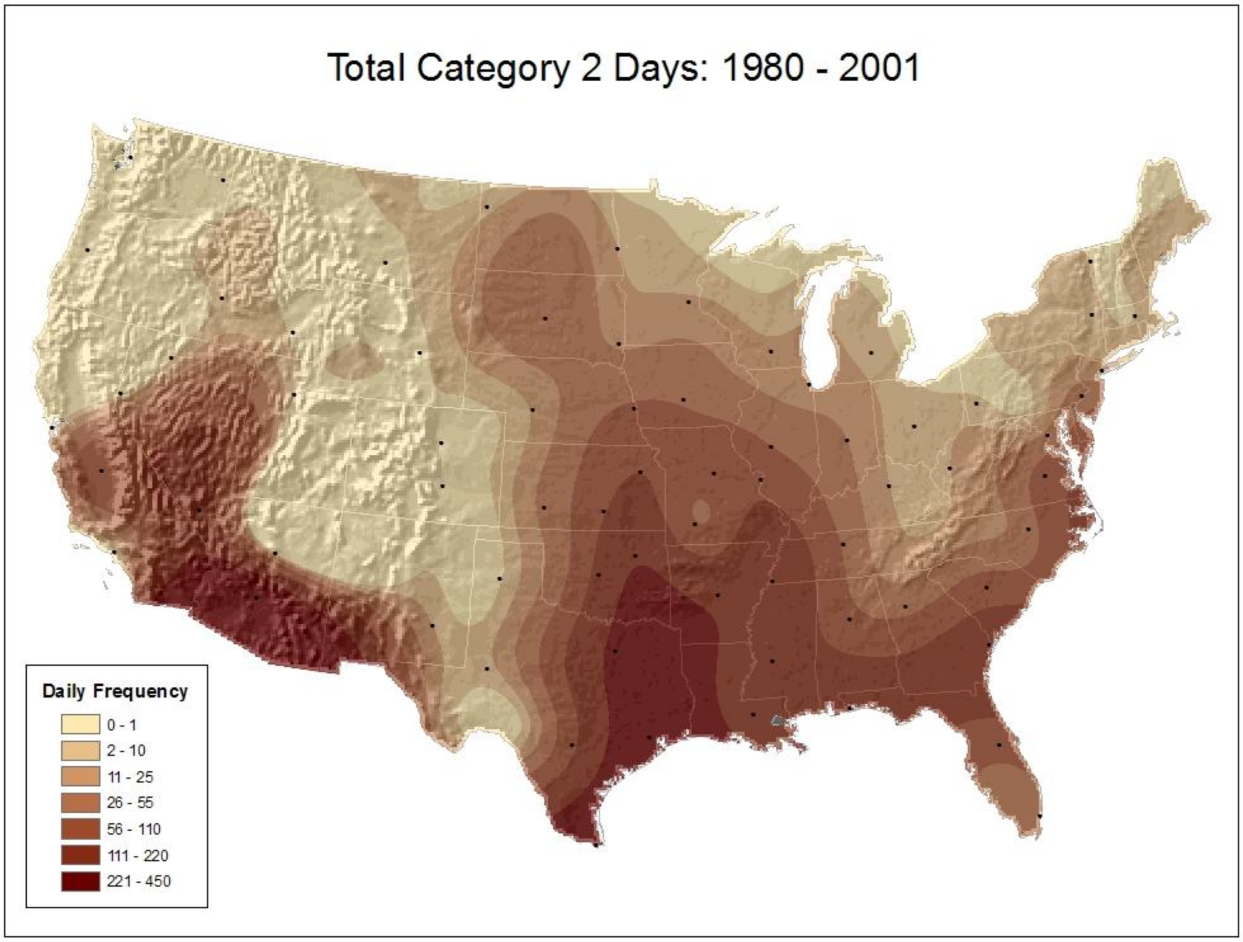
Table 4.4: Stations with the most days classified as a Category 2 during a heat wave: 1980 – 2001

	Station	Days		Station	Days
1	Brownsville, TX	455	6	Pensacola, FL	201
2	Phoenix, AZ	405	7	Little Rock, AR	188
3	Houston, TX	356	8	Memphis, TN	186
4	Dallas, TX	252	9	Baton Rouge, LA	174
5	Tulsa, OK	205	10	Savannah, GA	168

Conversely, the three remaining stations that are in both Tables 4.3 and 4.4, Dallas, Houston, and Phoenix, are in the two hottest regions of the U.S. These three locations not only exhibit some of the highest amounts of Category 1 and Category 2 days, they are among the locations with high heat stress areas in all 5 categories. In contrast to San Antonio and Miami, which have a large amount of classified days, that are mostly Category 1s, Dallas, Houston, and Phoenix have a large amount of classified days in all categories, and average between 11 and 18 Category 2 days per year.

As daily accumulations of heat stress increases, the contours in the maps appear more meridional. Although the contour patterns in Figure 4.4 appear similar to those of Figure 4.3, the frequency of occurrence is markedly lower for the Category 2 days. The two lightest contour intervals in Figure 4.4 indicate that 10 or fewer Category 2 days occurred during the entire 22-year study. Yet the low daily frequency of excessive heat stress does not mean a reduction in potential hazard. High heat stress events that occur sparingly in some areas might indicate those locations where the level of acclimatization is not sufficient for when sultry conditions spike, especially if hot and humid days occur consecutively. Pierre and Indianapolis are areas that do not experience days reaching Category 2 status often, but as the climatology indicates, they do occur. It is imperative to identify the rarity of each level of heat stress so the possible consequences can be lessened when conditions arise that people have not adapted to or experienced.

Figure 4.4: Distribution of Category 2 heat stress days in the U.S.



Moderate heat stress days are notable in the Great Basin and the extreme Southwest (Figure 4.4) and a pronounced lobe of high frequency extends northward from the Texas Gulf Coast. The difference in local heat stress accumulation levels is now more evident between Houston and San Antonio with a rapidly decreasing gradient westward, a possible indicator of the effects from the abrupt rise of the Edwards Plateau leading into the Texas Hill Country or perhaps indicating the influence of more cT air streams as one progresses westward across Texas. This westward-decreasing gradient is prevalent up through the central Plains as elevations rise continuously from east to west and are found farther away from the moist air from the Gulf of Mexico. One location of note is Amarillo in the Texas Panhandle. Amarillo is a station that is above 915 m (3,000 ft) in elevation (1,100 m or 3,607 ft), and the frequency of heat stress days are affected in that the 46 heat stress accumulation days there are all in the Minor category. These results are represented well by the maps in Figures 4.3 and 4.4. By contrast, Midland, 240 miles south of Amarillo and 223 m (730 ft) lower in elevation, recorded 345 total heat stress days with seven Category 2 days (three Category 3 days and two days in Category 4). Although summer temperatures above 37.8° C (100° F) are common, the lack of humid air in High Plains locations around Roswell, Midland, and Amarillo means that these areas are excluded from daily heat stress accumulation classes above Category 1.

The lower-HI anomaly in southwestern Missouri is becoming more evident as the daily heat stress accumulation categories increase in magnitude. An area of lower values is centered near Springfield (MO), which is located on the northern face of the Ozark Plateau facing away from the moist warm air streaming northward from the western Gulf of Mexico. This elevated area appears to act as a barrier to the streamlined northward flow, so the low level jet is more pronounced west of the Ozarks (Walters *et al*. 2008). The impact of elevation on excessive heat days is again noticeable in the east as the contours bend around the southern end of the Appalachian Mountain range.

Daily Results: Category 3

For a day to be classified as a 'Strong' or Category 3 heat stress day, a minimum of 66.6 C (120 F) accumulated hours of HI 90 must occur with at least 5.5 C (10 F) accumulated hours of HI 105 and less than 6 hourly observations during the night when the HI < 75. While a 'Moderate' or Category 2 designation indicates that heat indices of 40.6° C (105° F) are being exceeded, Category 3 days suggest conditions that are becoming even more hazardous. Longer periods of the day are sustaining indices above 32.2° C (90° F), and the hottest portions of the afternoon are maintaining dangerous levels with respect to prolonged exposure.

Brownsville, which has dominated the daily frequency of Category 1 and Category 2 heat stress days, is still one of the top locations of Category 3 days with 51, but has now dropped to the 10th highest position (Table 4.5). The number of events has decreased markedly again, with a total of 204 Category 3 days in Phoenix, or slightly fewer than ten per year.

Table 4.5: Stations with the most days classified as a Category 3 during a heat wave: 1980 – 2001

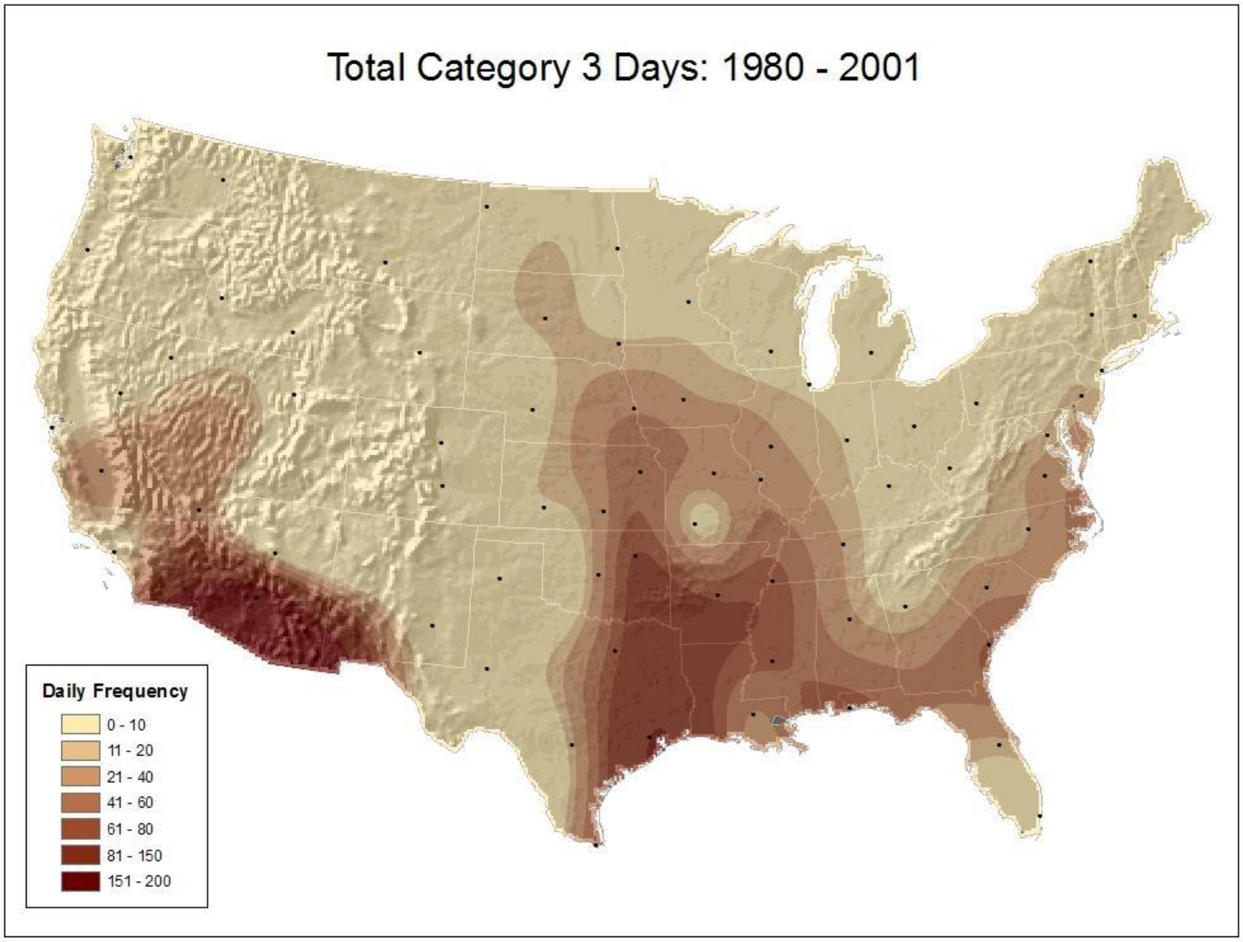
	Station	Days		Station	Days
1	Phoenix, AZ	204	6	Memphis, TN	69
2	Houston, TX	149	7	Pensacola, FL	67
3	Tulsa, OK	81	8	Jackson, MS	64
4	Little Rock, AR	74	9	Brownsville, TX	63
5	Dallas, TX	73	10	Savannah	62

Although a notably hot location like Brownsville is dropping in rank as the categorical magnitudes become higher, there are other locations that become recognized for their higher frequency of hot days. Phoenix and Houston occupy the top two spots, which is where they will remain for the frequency of Category 4 and Category 5 days as well. Five stations that were recognized as areas of high frequency heat stress days were excluded from the table just by increasing from a Category 1 to a Category 2 threshold. Now as the daily accumulated heat stress magnitudes are reaching higher levels of severity, locations that experience high heat stress magnitudes are becoming clearer. Moving beyond Phoenix and Houston, one finds that high levels of Category 3 daily accumulated heat stress occurs in locations such as Tulsa, Little Rock, Dallas, Memphis, and Jackson.

The steep gradient that decreases rapidly westward from Houston is present through Kansas to the north (Figure 4.5). An examination of 6 stations illustrates the steepness of this gradient. Frequency of Category 3 heat stress days along the trajectory of mT air moving north from the western Gulf of Mexico through Dallas (73 days), Tulsa (81 days), and Topeka (58 days) contrasts markedly with San Antonio (16 days), Oklahoma City (30 days), and Wichita (34 days) just about 70 miles to the west, where the frequency of cT air masses is higher. These north-south transects are nearly parallel, but differ considerably over a relatively small amount of space. When compared to the location of the moisture gradient from the Gulf of Mexico, the

Category 3 heat stress map matches up well. This observation suggests the influence of moisture availability has on heat stress severity, even over a relatively flat landscape. Further assessment of the Category 2 map (Figure 4.4) with the Category 3 map (Figure 4.5) indicates that the areal extent of Category 3 days has reduced significantly along with the rate of occurrence.

Figure 4.5: Distribution of Category 3 heat stress days in the U.S.



Finally, the impact of the Ozark Plateau is now very clear. Extreme heat and humidity conditions that make up a Category 3 day follow an air stream northward from the western Gulf, and appear to be forced around the low mountains rather than over them. The results indicate that excessive heat effects are reduced in southwestern Missouri compared to surrounding areas, and the air stream trajectory also produces a 'downwind' effect of lowered heat stress northward through the state. Hot conditions can occur in central Missouri, Columbia (MO) had 32 Category 3 days, but the results suggest that daily accumulated heat stress frequency levels are lower than locations at similar latitudes to both the west and east. The effects that the Appalachians have on reducing daily accumulated heat stress are clearly evident, as well (Figure 4.5).

Daily Results: Category 4

Category 4 accumulated heat stress days are considered 'Severe' and are established if a day has at least 88.8 C (160 F) accumulated hours of HI 90, and 11.1 C (20 F) accumulated hours of HI 105, with no more than two hours below 23.9° C (75° F). To exemplify the prolonged conditions that lead to a Category 4 designation, July 16, 1988 at Little Rock had 15 consecutive hours with heat indices surpassing HI 90, and 7 consecutive hours with heat indices surpassing HI 105 (HI high of 43.7° C or 110.64° F).

Identifying the locations of the most instances of each category is imperative to the understanding the nature of the different levels of daily accumulation of excessive heat. Perennially hot locations like Phoenix and Houston experience an annual average of 9.36 and 5.27 Category 4 heat stress days respectively (Table 4.6). A comparison between Tables 4.5 and 4.6 reveals that Phoenix recorded 2 more Category 4 days than Category 3 days, which is likely due to the hot ambient summer air temperatures occurring without the thermal inertia of water.

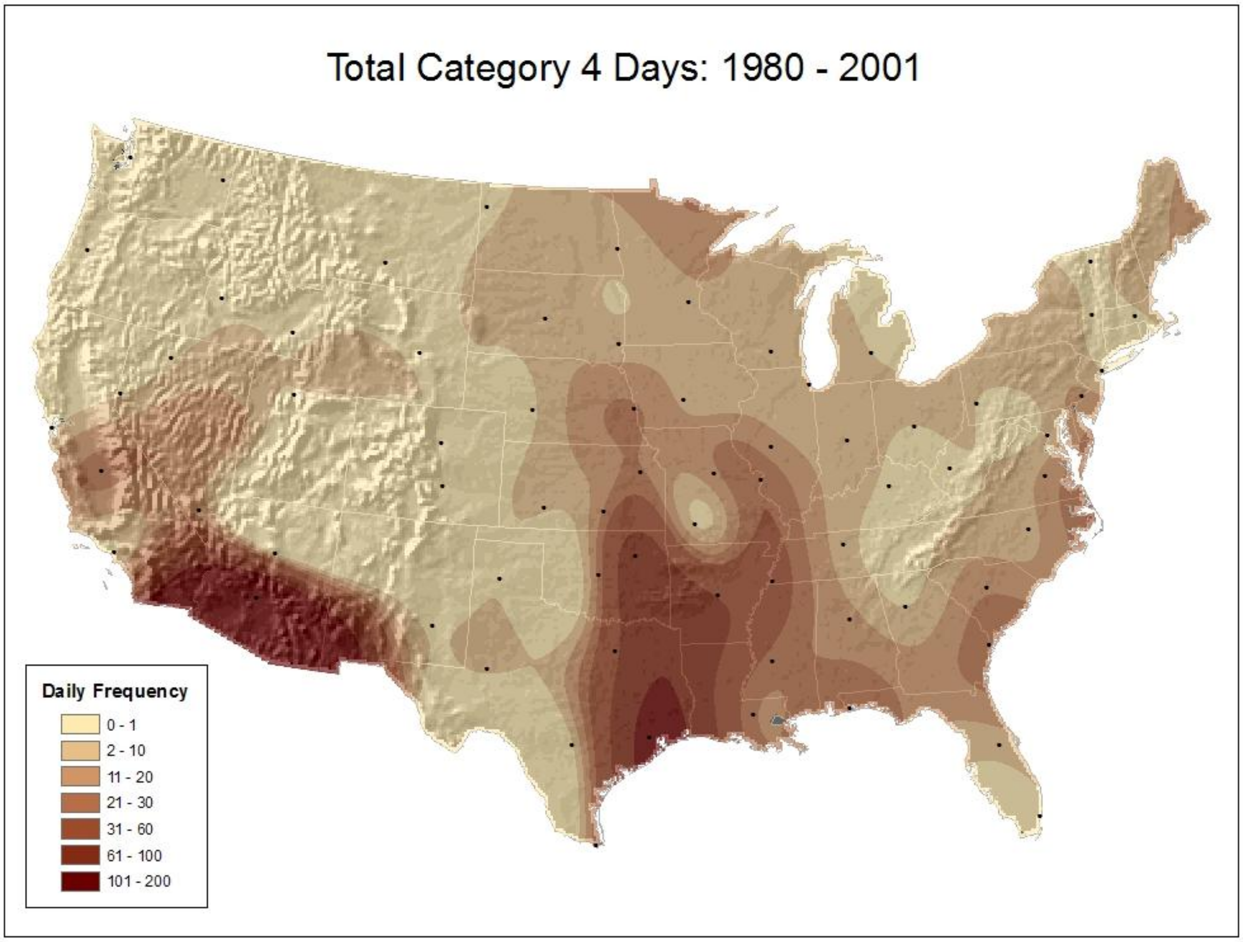
Table 4.6: Stations with the most days classified as a Category 4 during a heat wave: 1980 – 2001

	Station	Days		Station	Days
1	Phoenix, AZ	206	**6**	Memphis, TN	40
2	Houston, TX	116	**7**	Pensacola, FL	29
3	Tulsa, OK	78	**8**	St. Louis, MO	28
4	Little Rock, AR	57	**9**	Savannah, GA	28
5	Dallas, TX	55	**10**	Jackson, MS	26

Occurrences of Category 4 heat stress days are likely an annual event for Tulsa, Little Rock, Dallas, and Memphis, with these stations averaging between 2 and 3 per year (Table 4.6). The rest of the list in Table 4.6 consists of two coastal locations (Pensacola-Gulf and Savannah-Atlantic), two eastern inland locations (Jackson and St. Louis), and another western station (Fresno). The frequency of Category 4 days has declined from Category 3 day frequencies, which was expected, however the spatial distribution is similar between the two.

Concern for the increasing magnitudes, duration, and spatial extent of hot weather is best illustrated by the second lowest contour interval in Figure 4.6 (2-10 days). The area within this interval have documented Category 4 days, from one day overall to one day every couple of years. However, it is suspected that with global climate change these areas may begin to experience these excessive heat days more often, and that the areal extent of Severe daily accumulated heat stress will expand, perhaps into eastern locations of the High Plains and southern Florida. Finally, the gradient between Houston and San Antonio has steepened because San Antonio did not register any days as a Category 4. Conversely, Springfield (MO) did have one Category 4 day, which suggests that some vulnerability to heat stress in southern Missouri.

Figure 4.6: Distribution of Category 4 heat stress days in the U.S.



Daily Results: Category 5

Reaching the ‘Extreme’ category in daily heat stress requires at least 111.1 C (200 F) accumulated hours of HI 90 and at least 19.4 C (35 F) accumulated hours of HI 105 in one day. Recovery hours can not occur during the 24-hr period, and days of this magnitude of excessive heat generally do not approach the HI < 23.9° C (< 75° F) threshold. An example of how a day can reach Category 5 status is from July 25, 1999 in Little Rock where 18 hours were above HI 90, with 12 consecutive hours above HI 105, and a HI maximum of 50° C (122° F). For Little Rock on this day, the accumulated HI 90 was 154.4 C (278 F), and the accumulated HI 105 was 39.4 C (71 F) for the day.

The extreme nature of a Category 5 heat stress day is demonstrated by its rarity. Houston recorded the most Category 5 days on a rate of nine per year over 22 years (Table 4.7), and the extended periods of extremely sultry weather in Houston occurs when the air temperatures are mostly between 32.2° and 37.2° C (90° – 99° F), and relative humidity levels are averaging 75% or higher. These findings suggest that HI is necessary to assess excessive heat stress levels in humid areas such as Houston. However, the 128 Category 5 days registered in the Phoenix area tend to occur when the air temperatures surpass 40.6° C (105° F) on their own, because the summertime relative humidity percentages average in the teens.

Table 4.7: Stations with the most days classified as a Category 5 during a heat wave: 1980 – 2001

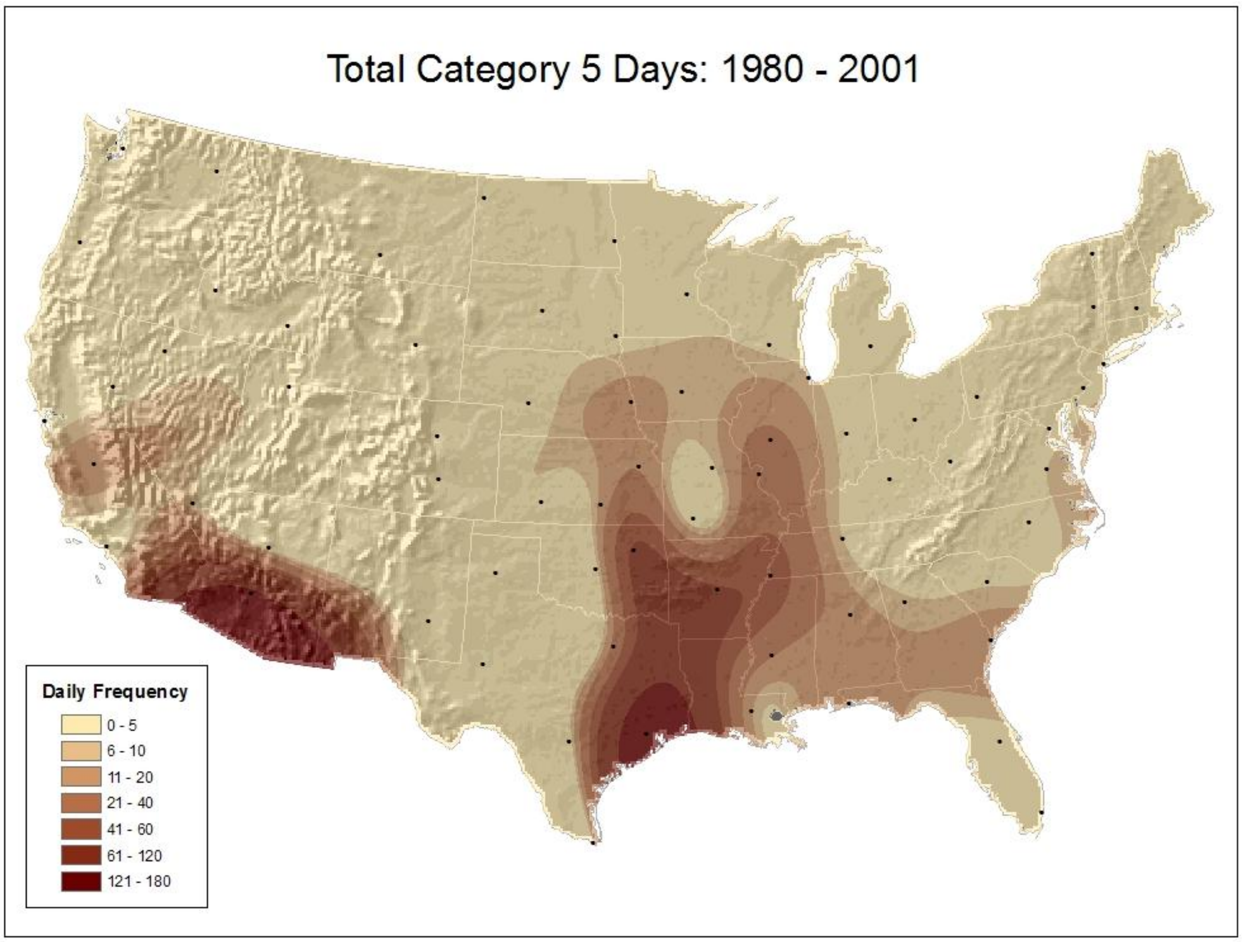
	Station	Days		Station	Days
1	Houston, TX	172	6	St. Louis, MO	28
2	Phoenix, AZ	128	7	Dallas, TX	24
3	Little Rock, AR	62	8	Springfield, IL	23
4	Tulsa, OK	62	9	Jackson, MS	21
5	Memphis, TN	51	10	Topeka, KS	19

Three areas north of Houston are the next highest in Extreme heat stress day frequency. Little Rock and Tulsa recorded 62 days and Memphis recording about 50 days each, or about 2-3 days per year. These three locations are north of the Gulf Coast Region, but also immediately border the southern boundaries of the Ozark Plateau where moist surface air streams from the Gulf are topographically redirected (Figure 4.7). This redirection is clearly evident as the spatial distribution forks around the Springfield (MO) station, yet still decreases northward through southeastern Nebraska and central Illinois.

Stations that are listed in Table 4.7 indicate that the majority of Category 5 days occur in a flat land corridor from Houston northward, and Phoenix is the only location that is not located in this region. Much of the Gulf Coast and Atlantic Coastal Plain area experiences an Extreme day at least every year or two, except for locations like Atlanta, Columbia (SC), Orlando, and, unexpectedly, Baton Rouge.

As previously stated in Chapter 2, Projections for 21st Century climate change suggest that excessive heat conditions are expected to increase and expand, which raises concerns for the locations that are not on the list in Table 4.7. Results provided in Davis *et al.* (2003) detail that although the southern areas receive the some of the highest and most persistent heat stress levels, mortality is considerably lower than in Midwestern cities. Stations that lie outside the 11-20 day contour interval are likely to face extreme heat events that are climatologically rare for their locations. Places of concern are represented by the data from Pierre, Sioux Falls, Minneapolis, Madison, Chicago, Lansing, Indianapolis, Columbus, and Pittsburgh. There were 31 stations that did not register a Category 5 day in the study period, 15 stations had between one and five days of Extreme heat stress days, and seven stations had between five and 10 days of Category 5 daily accumulated heat stress. Therefore, only 17 stations in this study recorded 10 or more Extreme days throughout the 22-year study. This climatology illustrates that there are some areas that are more adapted to extreme heat conditions, but there are large portions of the country that are not accustomed to Category 4 – or Category 5 – level heat.

Figure 4.7: Distribution of Category 5 heat stress days in the U.S.



Heat Wave Classification Results

Total Heat Waves

A daily heat stress classification value from 1-5 assigned to three or more consecutive days (on seldom occurrences 2 days) signifies that a heat wave event had occurred. A sum of total classified days during heat waves for the study period represents the amount of a heat stress hazard each location experiences as a comparison foundation. Brownsville, located 12 miles inland from the Gulf Coast town of Port Isabel at the southern tip of Texas recorded the most categorized days that occurred during a heat wave with 2,456 (Table 4.2). Four of the top six stations in Table 4.2 are in Texas, which correlates with the most frequent location of the warm southerly low-level jet in the summer months (Walters *et al*. 2008). Table 4.8 lists the areas that experienced the greatest number of heat waves in the 22-year study period and locations at or near the Gulf Coast and southern Atlantic Coast have the highest event frequency, most with more than 150 events.

Houston, with the third highest total of accumulated heat stress days, is the area with the most heat waves. Miami, Orlando, Brownsville, Baton Rouge, and Pensacola line the Gulf Region with Jackson, San Antonio, and Dallas also showing the effect of the southerly flow from the Gulf.

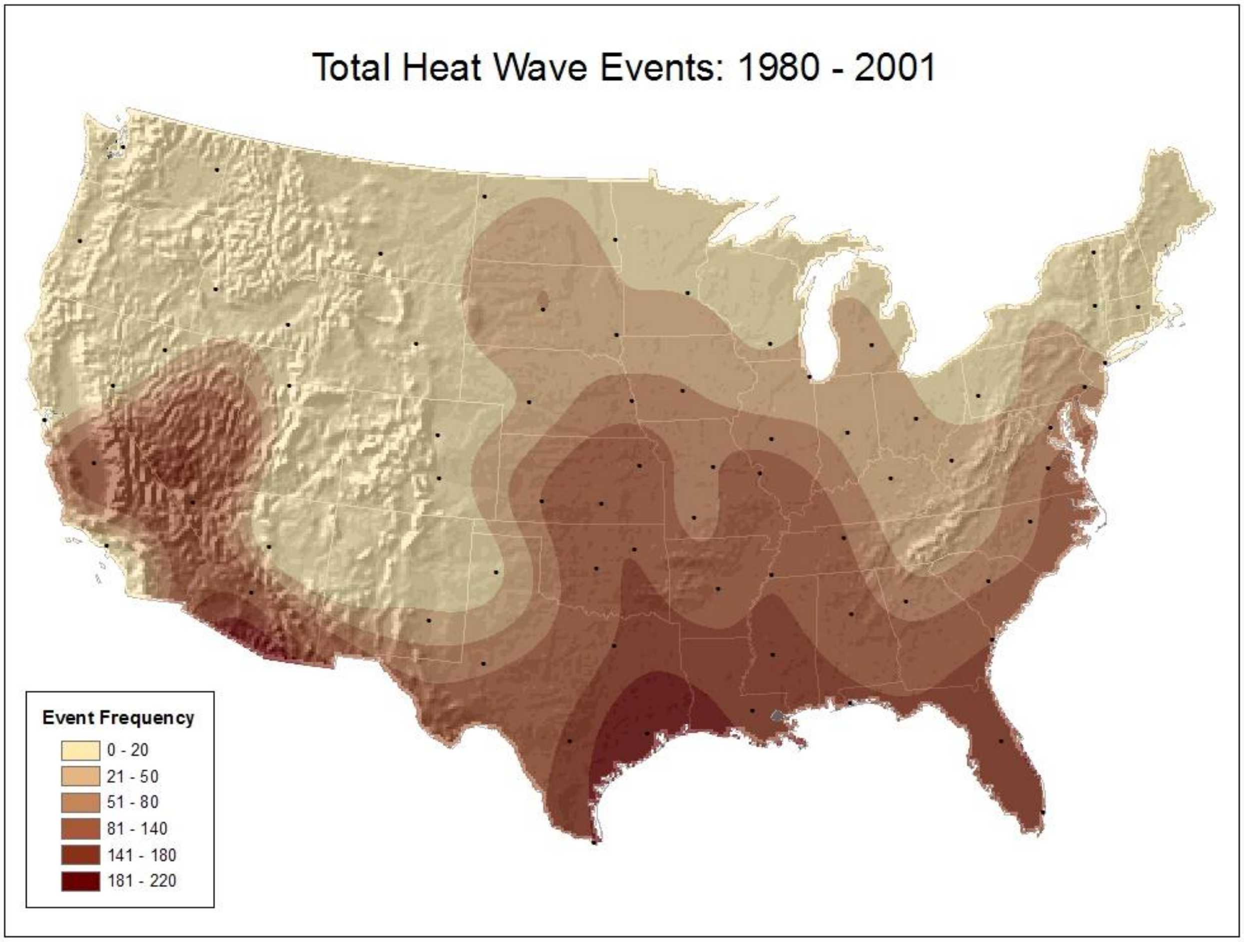
Table 4.8: Locations with the highest number of total heat waves

	Station	Events		Station	Events
1	Houston, TX	227	**6**	Pensacola, FL	156
2	Brownsville, TX	181	**7**	Jackson, MS	153
3	Miami, FL	179	**8**	San Antonio, TX	150
4	Orlando, FL	177	**9**	Dallas, TX	142
5	Baton Rouge, LA	166	**10**	Savannah, GA	137
			10	Tulsa, OK	137

Areas well into the northern plains are prone to an average of one or two heat waves per year (Figure 4.8), as well as much of the Midwest. Patterns in the total events map are similar to others in this study where the higher values are along the southern coasts decreasing northward and avoiding areas of higher elevation, while including the low elevation and non-coastal areas in the southwest (Phoenix, Las Vegas, and Fresno).

Evaluation of each heat wave was performed with the same classification logic independent of the time of year or location. Just as a hurricane is known for highest Saffir-Simpson category it reaches along its storm track (as well as an assigned name), a heat wave is

Figure 4.8: Distribution of heat waves in the U.S.



classified by the highest daily value attained with the daily heat stress classification system. For instance, a 5-day event at St. Louis in 1986 started on July 24, and received the daily classifications of 2-4-1-1-2. The highest daily classification was a Category 4 on July 25, the second day of the event; therefore the July 24, 1986 heat wave at St. Louis was a Category 4 or Severe heat wave. These classifications are to be observed as occurring only near the local St. Louis area. By contrast, the same time period at Columbia (MO), 120 miles west of St. Louis, recorded different heat wave activity. A three day event started on July 23, 1986, then a four day event started on July 27, 1986, making the eight days starting from July 23 classified as 1-1-1-0-1-3-1-3. These are therefore two events classified as a Category 1 and a Category 3. The zero is an unclassified day separating the events, which occurred during the middle of the event in nearby St. Louis at the same time. Results such as these suggest the necessity to understand heat waves on a more local scale, which can be done with the individual station data from this study.

Heat Wave Durations

A notable exemption from Table 4.8 is Phoenix. Phoenix is in a hot desert environment where moisture plays little role in the heat of the summer. However, summers in Phoenix are persistently hot with a single event of 82 consecutively classified days starting June 16 of 1981. This heat wave had ten Category 5 days occurring periodically throughout the event, with four of them consecutively near the end. In every year of this study, Phoenix had at least one heat wave event of 25 consecutive days or longer and averaged 97 days per year as being classified as occurring during a heat wave. With an average duration of over 18 days per event, there are just 5.32 events per year (117 total). Eastern locations in this analysis, primarily near moisture source, experience varying weather scenarios throughout the warm season, which provide a day or two of relief from oppressive conditions and allows for a higher frequency of heat waves. Houston contrasts with Phoenix in that the sultrier conditions are broken up into many more events. For example, in 1995 Houston had 93 classified heat stress days, but those days were lumped into 14 separate events. The average duration of events in Houston was 7.54 days with nearly 11 events annually and a mean of 82 days per year that were classified.

Duration of a heat wave is likely correlated with the local variability of weather conditions and perhaps a change in air mass types. These variations can be seen in the map in Figure 4.9 where heat waves generally last longer in San Antonio and Dallas than in Houston where there are more rain events. Other variations occur between Tulsa and Oklahoma City, Orlando and Miami, as well as Las Vegas and Fresno.

There were 13 weather stations where the average length of any given heat wave lasted longer than one week (Table 4.9). Identifying the mean length of heat waves is another factor to consider when assessing this climatological hazard and how oppressive weather conditions are present in the recent climatological record.

The Heat Wave Season

It is common in climatology to analyze the warm season, providing data on when it starts, how long it lasts, when it ends, and how those data differ from one location to another. However, the warm season is typically measured at a location by the number of days between the last and first frost-free days, or by the growing season for plants. Results in this study provide an alternative measure of the warm season using the dates when heat waves occur, which include

Figure 4.9: Mean heat wave lengths across the U.S.

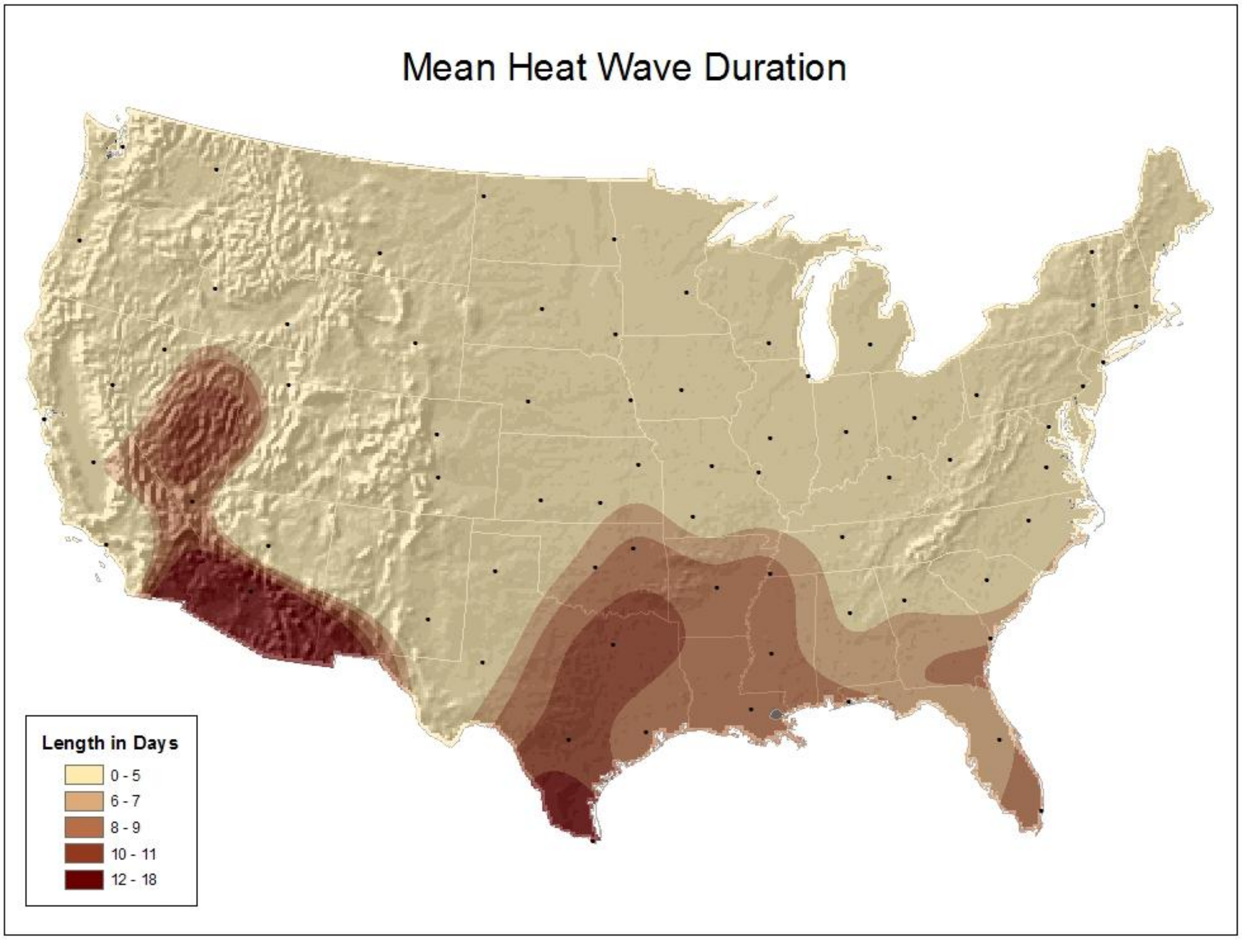


Table 4.9: Locations where the average heat wave length was longer than 7 days

Station	Days	Station	Days	Station	Days
1 Phoenix, AZ	18.21	**6** Las Vegas, NV	8.24	**11** Tulsa, OK	7.38
2 Brownsville, TX	13.57	**7** Baton Rouge, LA	7.95	**12** Memphis, TN	7.36
3 Dallas, TX	10.40	**8** Little Rock, AR	7.71	**13** Pensacola, FL	7.24
4 San Antonio, TX	10.00	**9** Houston, TX	7.64		
5 Miami, FL	8.45	**10** Jackson, MS	7.52		

the first and last day of heat waves each year at a location. An average starting and ending date was acquired for all locations, unless a location did not record a heat wave, illustrated in Figures 4.10 and 4.11. The western stations were left out of this analysis because eleven locations recorded zero heat wave dates, and four additional locations recorded less than five. This lack of data over a large area restricted the development of representative contour estimations.

Contours in Figures 4.10 and 4.11 present expected trends where heat waves begin earlier in the year in the south, and start later in the year gradually northward. Anomalies exist in the

Midwest from Lexington to Madison and in the Dakotas where the average date of the first annual heat wave occurs later that surrounding locations. Ultimate heat wave dates also occur later in the year in the south, which correlates with the migration of direct sunlight from the equator to the Tropic of Cancer and back, providing more energy to southern locations for longer periods of the year. Lengths of heat wave seasons were expected to be shorter in the north, although it is apparent that mountainous regions in Arkansas/Missouri and the Appalachians still play a role on the availability of heat stress factors. Comparisons of central and eastern U.S. heat wave seasons are provided in Figure 4.12. Most of the eastern U.S. experiences a heat wave season of less than two months, with the areas from Wichita, Little Rock, Nashville, and Columbia (SC) southward having heat wave seasons potentially reaching 4-5 months in length annually.

Figure 4.10: Central and eastern U.S. stations are shown with contours designating the average annual first date of a heat wave

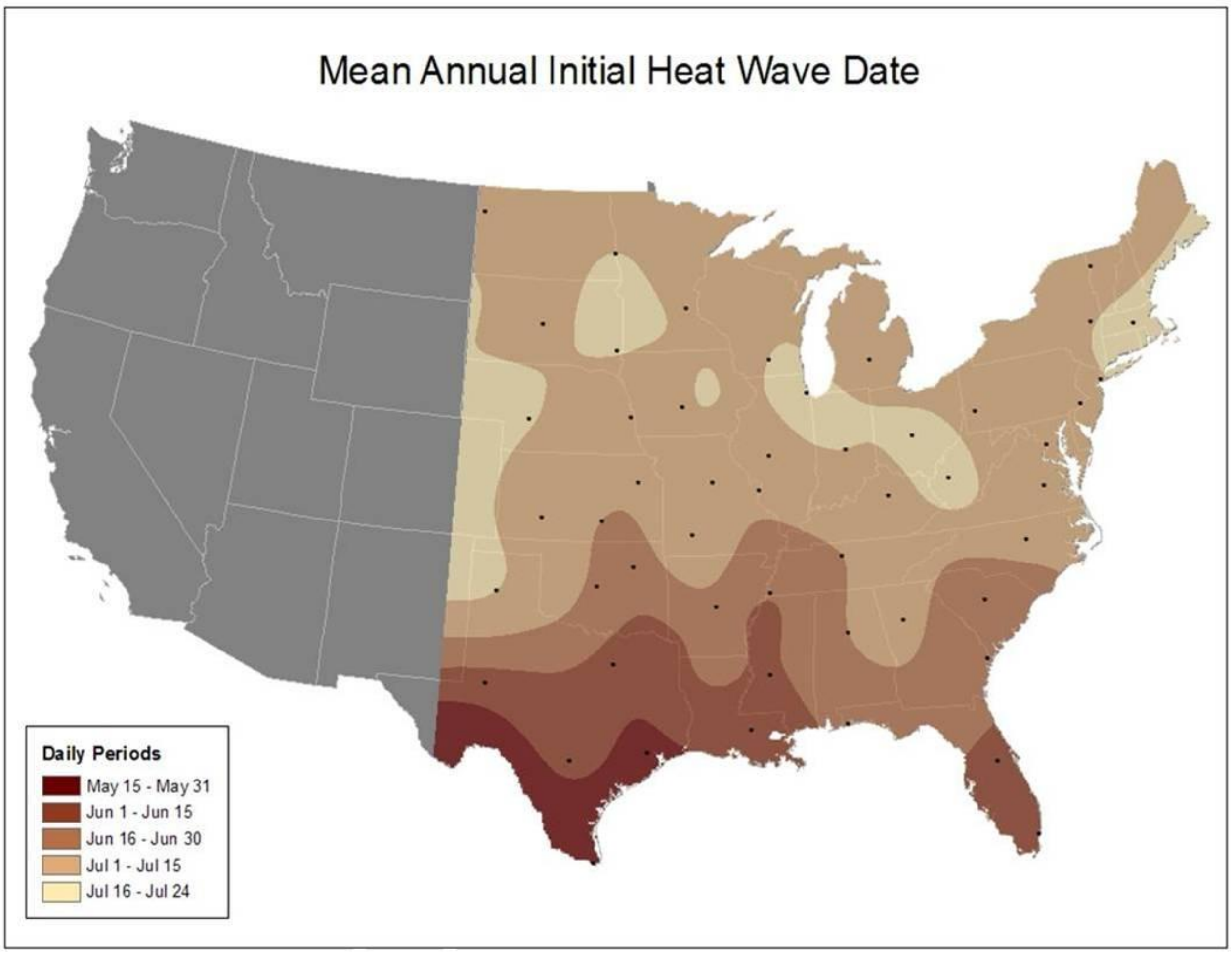
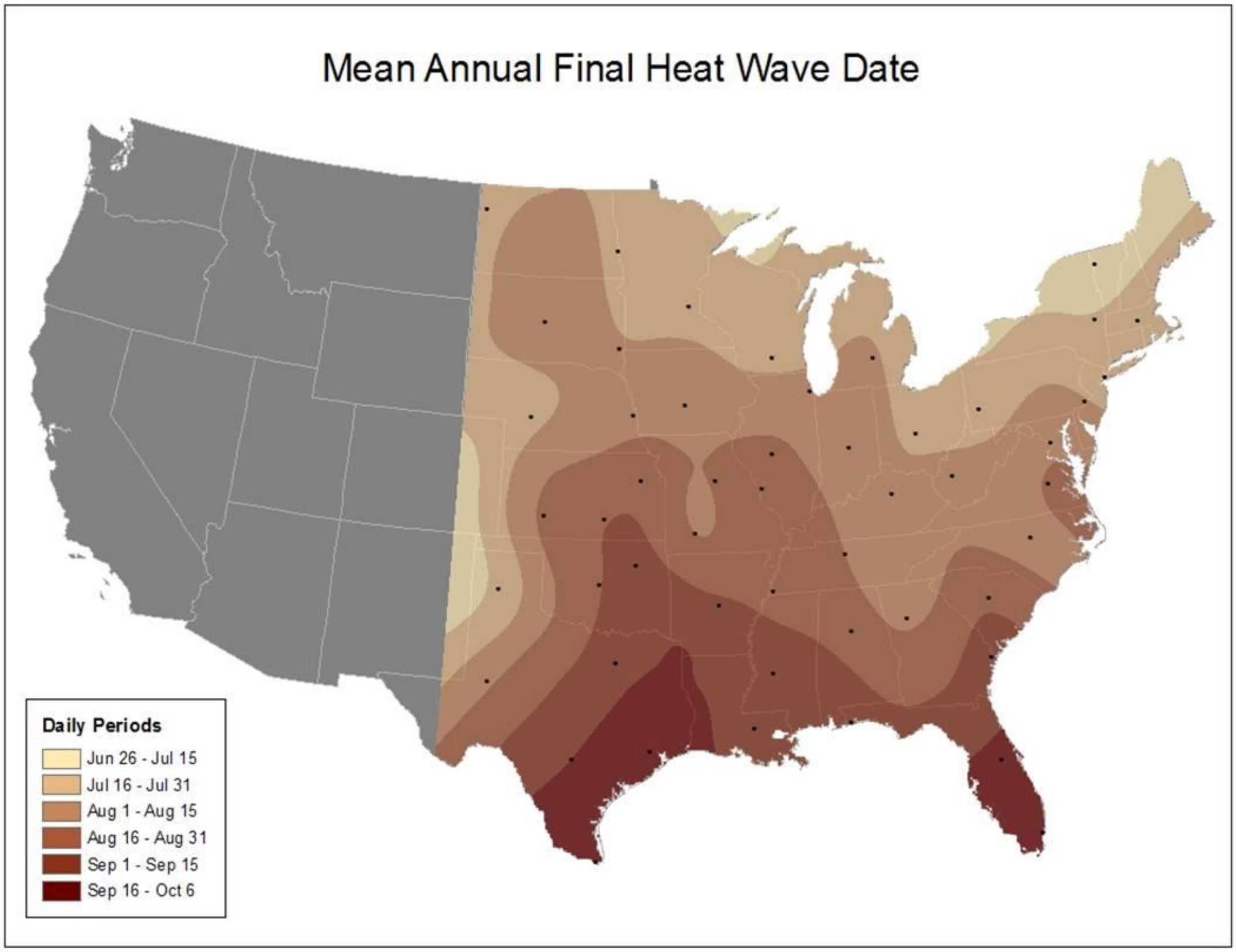
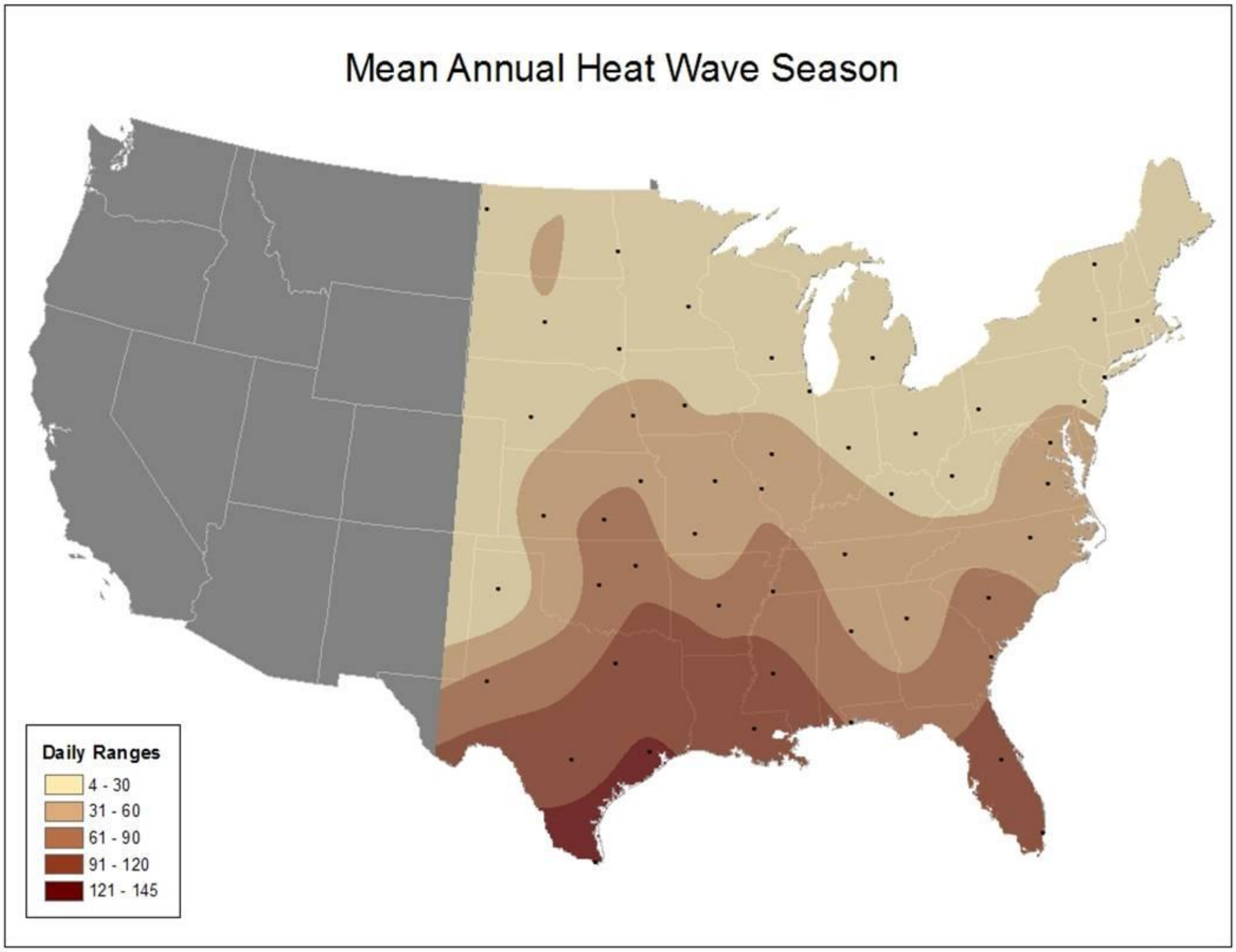


Figure 4.11: Central and eastern U.S. stations are shown with contours designating the average annual final date of a heat wave



Heat wave length decreases northward in non-mountain areas, which is indicative of the Spring-to-Fall progression of direct sunlight towards the Tropic of Cancer then back equatorward. The northern half of the country experiences adequate day lengths for heat stress later in the year and for a shorter period of time. An example comparison from the map in Figure 4.12 is that Dallas has a heat wave season of over three months, whereas Madison's heat wave season in southern Wisconsin lasts two weeks (Appendix C). The results in Figure 4.12 illustrate how exposure changes over space and how the exposure component of heat wave vulnerability increases with the amount of time a location is prone to periods of excessive heat. Acceptance is growing, however, that the length of the heat wave season will increase with 21st Century climate change (IPCC AR4).

Figure 4.12: Length of the typical heat wave season in the central and eastern U.S.



The next sections of this chapter will document the number of heat waves that occurred during the study period for each classification level. It would be beneficial to refer to the previous maps displaying the total number of events (Figure 4.8) and the normal duration of events (Figure 4.9) when assessing the frequency of an event of a specific magnitude for individual location assessments.

Category 1 Heat Waves

Category 1 heat wave events are most often the event with the highest frequency at a location. A Minor heat wave event consists of a string of consecutive days classified as Minor (Category 1) in the daily heat stress classification system. There is a need for a minimum of three consecutive days classified as Category 1 for the event to be classified as a Minor heat wave. However, there is no upper limit to the number of consecutive days classified as a Category 1 to continue that level of event. A 3-day Category 1 event is most common in 2 scenarios: locations with lower heat wave activity or at the beginning and/or end of a location's heat wave season when the climate is shifting to or from warmer weather.

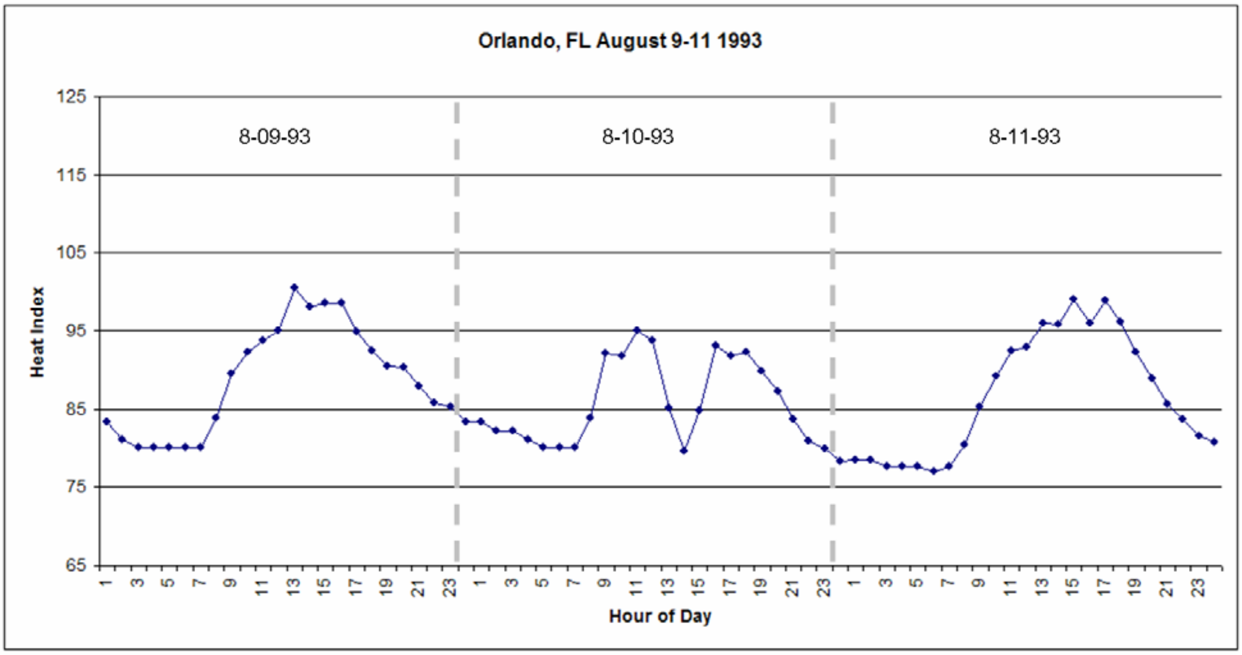
Miami and Orlando, in the Florida peninsula, both recorded well over 100 Category 1 events each from 1980-2001 (Table 4.10). Category 1 heat stress days make up 67% of the classified days at Miami, and 85% of the heat waves are Category 1s. Events in Miami are predominantly Category 1s, such as in 1996 when there were 7 events that would have all been Category 1s if day 5 in the third event that year was not classed as a Category 2 (therefore that event was a Category 2). This phenomenon is because the incoming solar energy is going into latent heat of evaporation from the abundant moisture nearby, so there is not much change in sensible heat. The first event was in late May and was 3 days long, the longest event was in July and was 20 days long, and the last event was in mid-September and was 3 days long. Miami averages over 8 events per year, and usually only one of which is not a Category 1. Orlando experienced almost the same number of total events as Miami, but there are more events in higher categories at the station located more inland.

Table 4.10: Stations with the highest frequency of Category 1 heat waves

	Station	Events		Station	Events
1	Miami, FL	153	6	Brownsville, TX	88
2	Orlando, FL	140	7	Las Vegas, NV	78
3	San Antonio, TX	97	8	Pensacola, FL	76
4	Baton Rouge, LA	91	9	Columbia, SC	71
5	Jackson, MS	89	10	Oklahoma City, OK	66

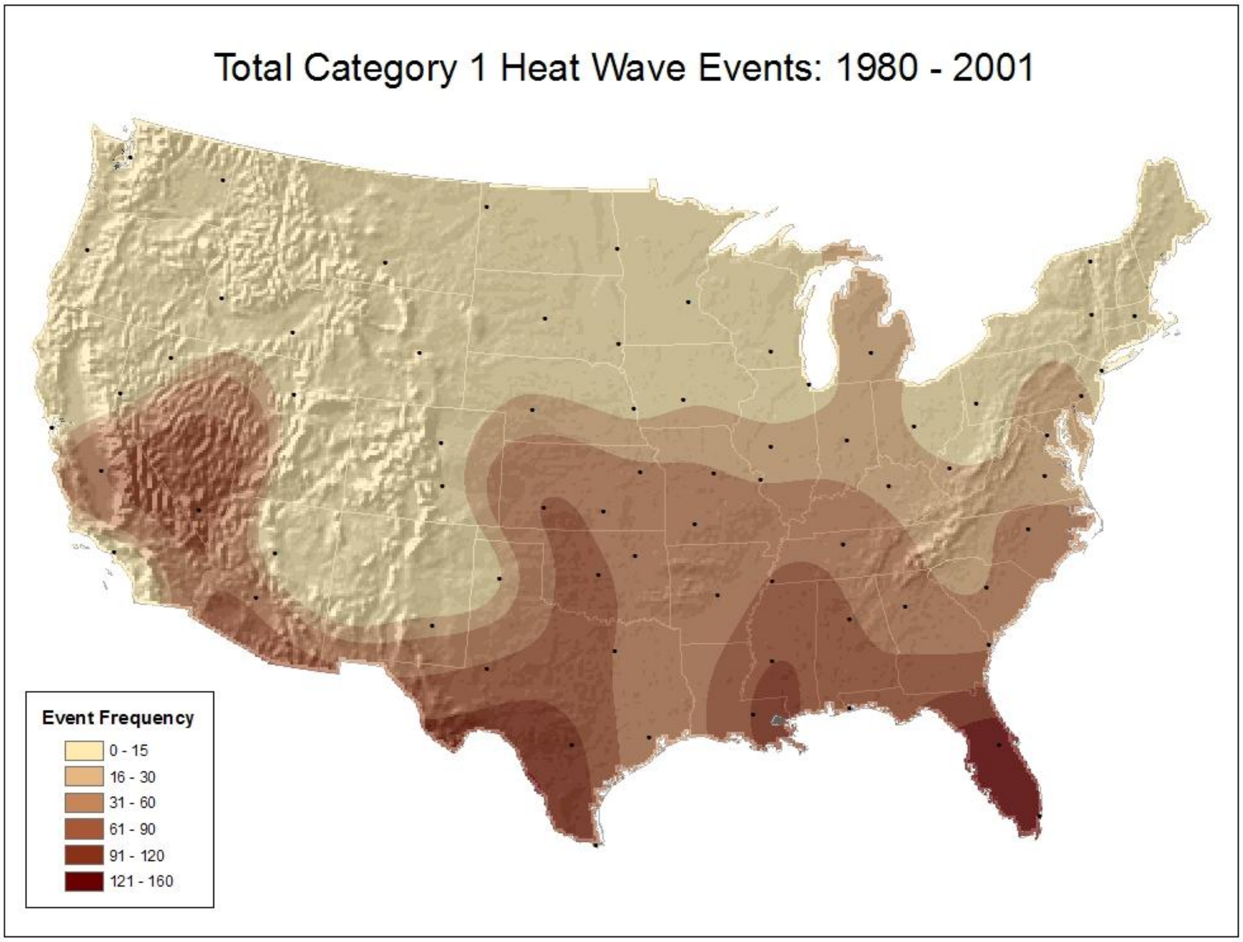
An example at Orlando in August of 1993 provides insight into why there may be such a high number of events at some southern locations. A 17-day event began on July 24, followed by a 3-day Category 1 event that began on the 11th of August. The results suggest that this may have been a 21-day event that was separated into 2 events because August 10th was not classified as a heat hazard day. The 24-hour HI values were graphed for August 9th (the last day of the earlier event), August 10th (the non-classified day), and August 11th (the first day of the subsequent event) (Figure 4.13). On August 10th, the graph is appearing similar to the graphs for the 9th and 11th. However, there is a significant mid-afternoon drop in heat indices when they should have been nearing their daily maximum. Further examination into the weather data for the day of August 10th revealed that hourly changes affected the daily heat magnitude: a) 6:00-10:00 am – heat stress levels begin to elevate, b) 10:00 am – cloud cover increases, c) 11:00 am – light rain falling, d) 12:00-1:00 pm – heavy thunderstorm occurring, e) 2:00 pm – cloud cover decreases, f) 3:00 pm – clear and warm conditions resume. Short midday rain events like this one are common throughout Florida, and the five hours cooled by this storm disallowed the day to be classified as a heat stress day, and shortened what would have been a longer event.

Figure 4.13: Rain events such as this one on August 10 at Orlando can provide recovery during prolonged heat waves, and break single heat periods into several heat wave events



If one were to compare Table 4.8 with Table 4.10, it is clear that the majority of heat waves for Miami, Orlando, and San Antonio were Category 1s, and that Houston with the highest number of overall events is not on the list for locations with a high frequency of Minor heat waves. Since many stations (e.g., Houston, Little Rock, Tulsa, and Dallas) are not listed as any of the high frequency Category 1 heat wave locations; it was suspected that the contour patterns of Category 1 event frequency would differ from common pattern from the previous maps, especially in the south central Plains. The map in Figure 4.14 confirms that there is a gap of Category 1 event frequency in what might be considered the sultriest portions of the country. The majorities of heat waves in this hot and humid region is of higher categories, and are occurring while the surrounding areas are having significant but less oppressive conditions. Las Vegas recorded a high frequency of Minor heat waves, but Phoenix did not, because of the differences in heat wave duration. Southwest Texas, Southern Mississippi, and the tip of Louisiana are the other primary locations of Category 1 heat wave frequency.

Figure 4.14: Distribution of Category 1 heat waves in the U.S.



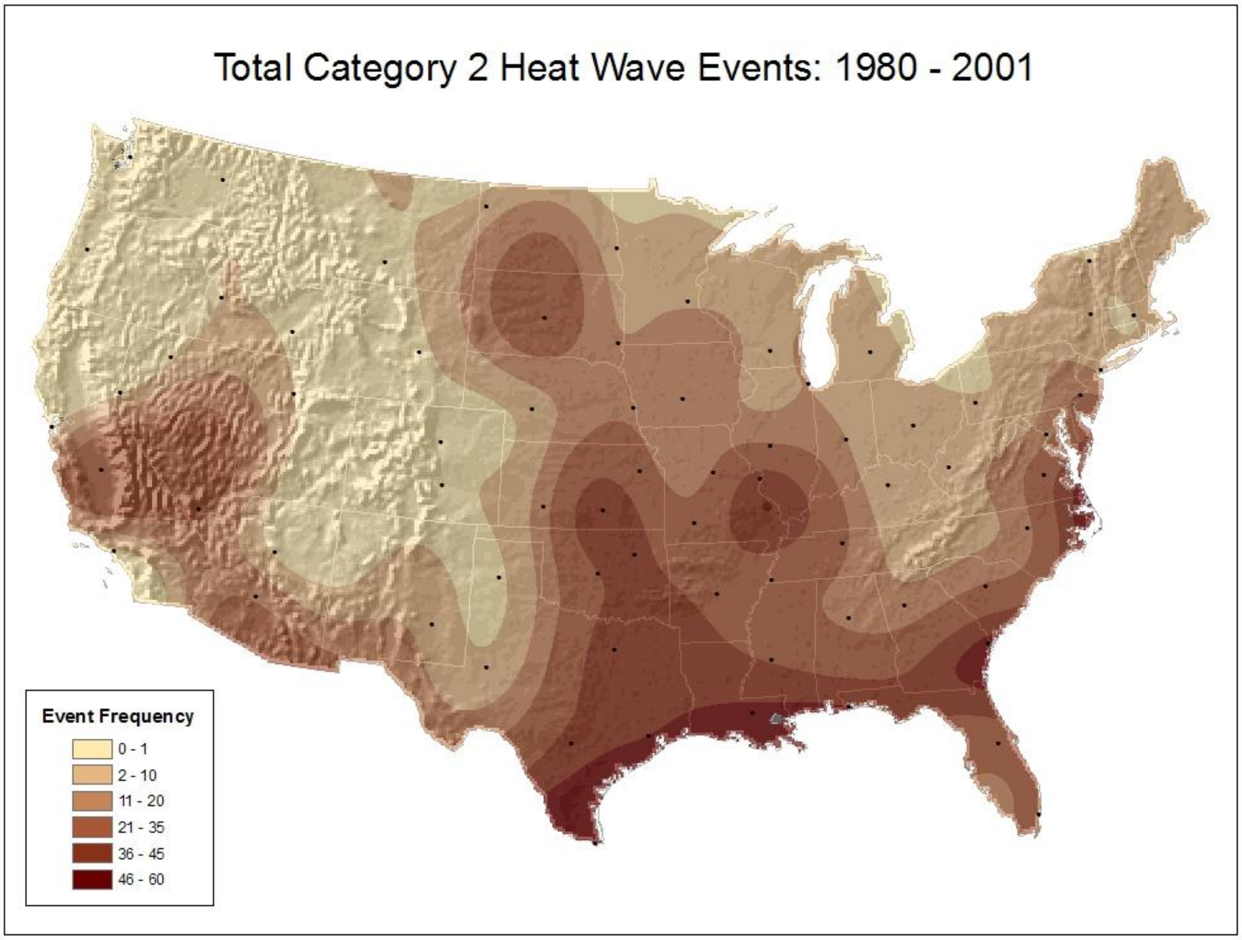
Category 2 Heat Waves

Category 2 heat waves occur when a consecutive string of two or more days occur with at least one day classified as a Moderate heat stress day and with no heat stress days in a higher class. Category 2 heat wave frequency drops considerably when compared to that of Category 1 events (Table 4.11). Brownsville had the most Category 2 heat waves with 60, no other station recorded more than 48. Since the higher magnitude events occur less frequently, separate areas exhibiting the same number of events becomes a higher probability, such as Baton Rouge and Savannah with 48 Category 2 heat waves. All the stations in Table 4.11 average about 1 or 2 Category 2 heat waves annually. Areas in the Great Plains and the Gulf Coastal Plains experience the highest frequency of Category 2 heat waves (Figure 4.15). The corridor from Houston northward is now exhibiting signs of increasing event frequency compared to the map in Figure 4.14; Category 2 or Moderate heat waves 'hot spots' occur in association with weather stations in southern Nevada, central South Dakota, and southeastern Missouri.

Table 4.11: Stations with the highest frequency of Category 2 heat waves

	Station	Events		Station	Events
1	Brownsville, TX	60	6	Wichita, KS	43
2	Baton Rouge, LA	48	7	Dallas, TX	42
3	Savannah, GA	48	8	San Antonio, TX	39
4	Houston, TX	45	9	St. Louis, MO	39
5	Pensacola, FL	45	10	Tulsa, OK	38

Figure 4.15: Distribution of Category 2 heat waves in the U.S.



Typically, natural hazards occur less frequently as the event magnitude increases. This situation is not always true in the occurrence of heat waves. Most stations in the study exhibit the normal progression with Category 1 events occurring most often, with fewer occurrences for each higher category. Thirteen stations, however, registered more Category 2 events than Category 1 events. Two stations in the east, Philadelphia and Richmond, recorded Category 2 events as the highest frequency, and Houston's second most frequent class was Category 2 with, surprisingly, Category 5 events being the most frequent. This Category 2 phenomenon was mostly concentrated amongst ten stations in the north central U.S. (Figure 4.16). An anomaly in the northern Great Plains is Pierre where eight Category 1 events were exceeded by 30 Category 2 events out of 50 events total (Appendix B). Category 2 heat waves made up 60% of the total number of events at Pierre, and Categories 3-5 made up another 25%, meaning that Category 1 heat waves occurred just 15% of the time.

Figure 4.16: Stations where the frequency of Category 2 events outnumbered Category 1 events are shown with the larger dots

Category 3 Heat Waves

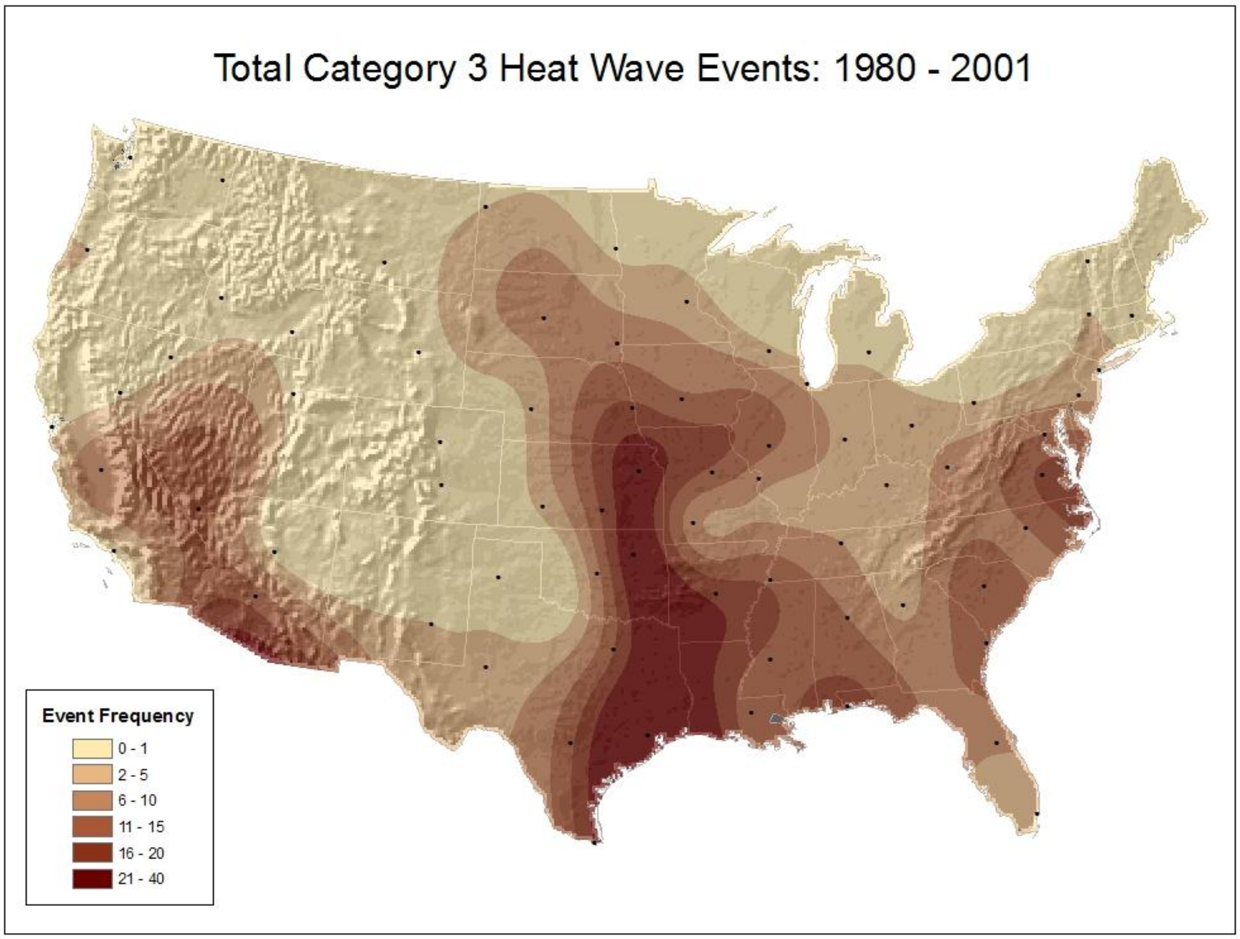
When the highest daily heat stress accumulation class during an event is categorized as a 3, the heat wave is considered Strong. The heat levels that are needed to obtain a Category 3 status for a day are becoming oppressive enough that the NWS recommends that concern should be given to those unable to spend some time of the day in shelter. A Category 3 event indicates that the Strong levels of heat and humidity are being exacerbated by preceding or subsequent days that are considered hazardous at equal or lower levels. For example, Lexington was on the southern fringe of the severe heat wave that struck the Midwest in July of 1995 (which is discussed later in this chapter). Lexington recorded a total of three Category 3 days and three separate Category 3 events during the month, which means that none of the Category 3 days occurred during the same event. Since only one day was recorded higher during the study period (Category 5 in 1999), it is reasonable to assume that the local sensitivity/acclimatization to Category 3 exposure levels for the Lexington area is of some concern. Although not reaching the levels of heat stress that stations to the north did during the 1995 heat wave, a four-day heat wave, with individual days classified as 1-1-3-2 has two Minor days, followed by a Strong heat stress day, followed by a Moderate heat stress day. People who live in locations like Memphis, which regularly experience these heat stress levels, may not view this particular event as a concern. However, exposure to an event of this magnitude at a location like Lexington, where 90% of the heat stress days are Category 1s and Category 2 and 3 days occur in sequence, could be cause for alarm locally.

Most of the Category 3 heat waves in the U.S. occur in the corridor from Houston northward. Houston had the most Category 3 events with 36 (Table 4.12), which is just 16% of that area's heat wave total. Overall, event frequency is reduced significantly again as the event magnitude has increased; and several locations now have similar frequencies of Strong heat waves. Due to the lowered frequency of events as magnitude increases, an increasing number of locations will exhibit similar results of classified events. One may expect locations with the same results to be near each other, however, some of the stations that recorded the same number of Category 3 events are near each other regionally, and some are not. Dallas and Richmond both had 15 Category 3 events in this study; however this similarity more of a coincidence than Tulsa and Topeka both having 23 events along the same northward air stream from the Gulf (Figure 4.17). Five locations recorded 14 Category 3 events during the study period: Columbia (MO), Jackson, Memphis, San Antonio, and Savannah, which were focused upon two distinct regions. Four of the stations are on the fringes of the heat stress corridor from Houston northward, however, Columbia (MO), Memphis, and Jackson are separated from San Antonio by areas of more frequent heat wave activity. Savannah is the fifth station with 14 events and is near the Atlantic coast, well east of the central locations. Even though Miami was higher in both total heat stress days and total heat waves, Savannah is the Atlantic Coast hot spot since it recorded 32 heat waves as a category 3 or higher, and Miami had no higher than one Category 3 event.

Table 4.12: Stations with the highest frequency of Category 3 heat waves

	Station	Events		Station	Events
1	Houston, TX	36	6	Pensacola, FL	17
2	Tulsa, OK	23	7	Omaha, NE	16
3	Topeka, KS	23	8	Wichita, KS	16
4	Brownsville, TX	19	9	Richmond, VA	15
5	Little Rock, AR	18	10	Dallas, TX	15

Figure 4.17: Distribution of Category 3 heat waves in the U.S.



The gap in high values across eastern Texas along the state borders towards Topeka from the Category 1 event map in Figure 4.14 is now more understandable when combined with the information discernable on the map of Strong heat wave frequency (Figure 4.17). The dark areas in the Category 3 map attain heat wave classifications of higher magnitude more often than the surrounding areas, which is in contrast with Minor event distribution. There are a comparatively high number of Category 1 days at the stations from the Texas Gulf Coast up through Oklahoma and western Tennessee, but there is more of a chance for a day during a heat wave to reach higher categories in the corridor north of Houston. Stations that are outside of the corridor that recorded a high number of heat stress days do not have the moisture levels to attain higher heat wave categories as often. Furthermore, heat waves at locations like Houston, Tulsa, and Little Rock can be made up of many Category 1 days, but it is more likely to have one or more days per event that are above a Category 1, elevating the event classification. This remains the case as the next two heat wave levels are analyzed. This effect occurs as maritime tropical air is advected northward from the Gulf of Mexico and perpetuated at times by low-level jet maxima.

Category 4 Heat Waves

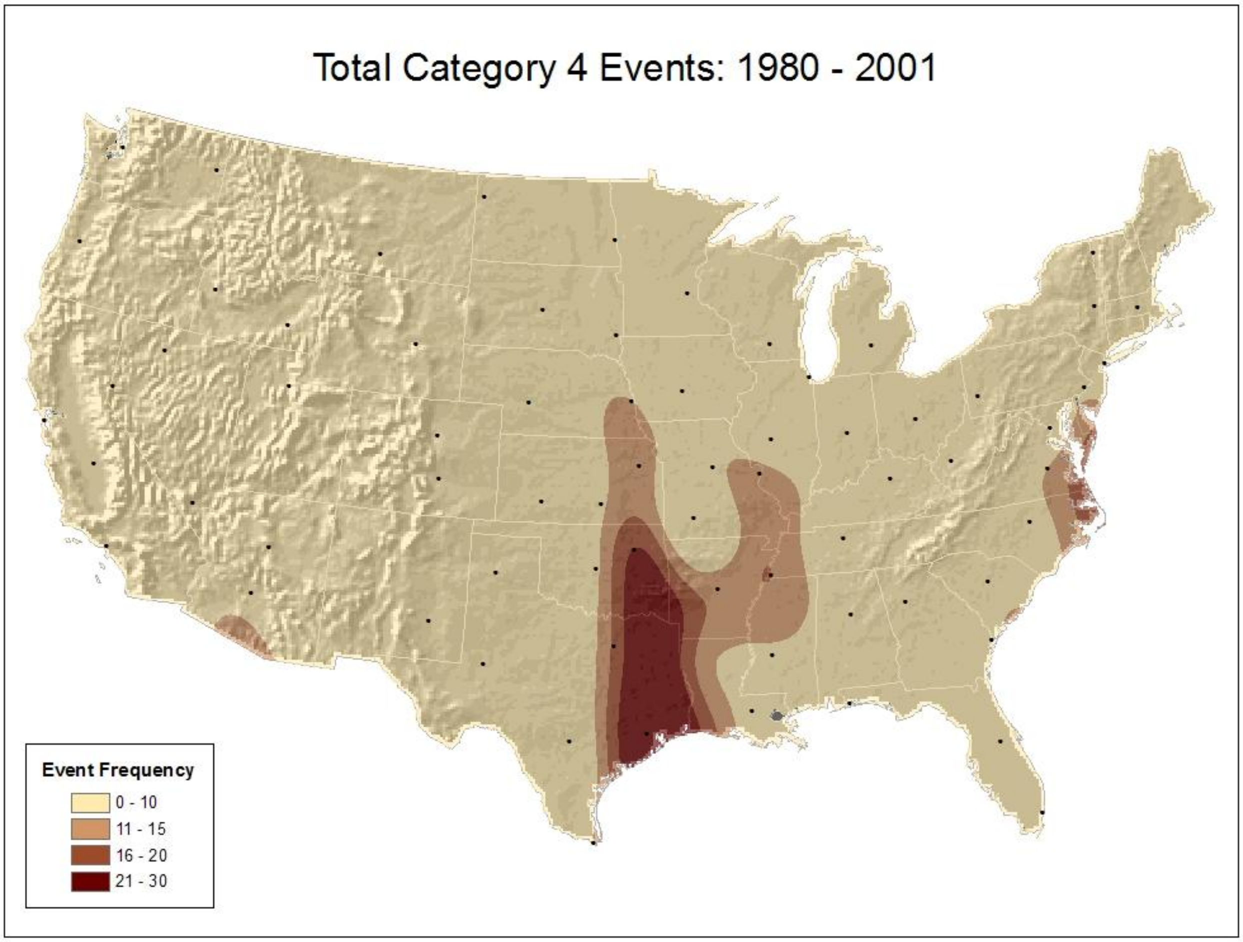
Houston was again the primary hot spot where 28 Severe events occurred during the study period (Table 4.13). Stations that recorded the most Category 4 events (12-28) were all in the heat stress corridor from Houston northward reaching Topeka and St. Louis. Spatial patterns of Category 4 or Severe heat wave frequency identify two primary regions (Figure 4.18), in the Southwest and in the heat stress corridor from Houston northward.

Table 4.13: Stations with the highest frequency of Category 4 heat waves

	Station	Events		Station	Events
1	Houston, TX	28	**6**	St. Louis, MO	12
2	Tulsa, OK	20	**7**	Topeka, KS	12
3	Dallas, TX	16	**8**	Brownsville, TX	10
4	Memphis, TN	15	**9**	Omaha, NE	10
5	Little Rock, AR	13	**10**	Richmond, VA	10

Exposure to a Category 4 or Severe heat wave is difficult to comprehend without the direct experience of an event. As is the case with all heat waves, Category 4 event durations can range over a wide number of days. Therefore, in this study, one measure of severity of an event can be determined by the local rarity of Category 4 events/days combined with the daily progression of heat stress accumulation during the event. Heat wave progression is determined not just by the duration, but also by the sequence of heat stress days of different magnitudes. For instance, is it a five-day heat wave with one Category 4 heat stress day, or is it a five-day heat wave with three consecutive Category 4 heat stress days? Both of these examples would have the same heat wave classification (i.e., Severe), but the two examples are considerably different in accumulated stress levels over the course of the five-day event. Furthermore, comparisons among Severe heat waves in most cases should be primarily focused on the location of which they occur. How often does this level of heat exposure occur at Dallas or Little Rock versus Madison and Minneapolis? Why do similar heat waves meteorologically cause different effects over space?

Figure 4.18: Distribution of Category 4 heat waves in the U.S.



There was one Category 4 heat wave in Springfield (MO) corresponding with the only Category 4 heat stress day at that station occurring in June of 1981. This was just a 2-day event (1-4) that was immediately followed by 28 days that were not classified as a heat stress hazard. June 9, 1981 was the hottest day in this time series for the Ozark region, and its isolated occurrence was a considerable anomaly. This occurrence is proof, however, that these severe heat levels do occur in areas where they are normally not expected. The average heat wave season in Springfield (MO) starts on July 8 (Appendix C), indicating that the most stressful day in 1981 occurred a month early and prior to local acclimatization to the normal warm season heat stress hazard. Questions must be raised including asking what could happen if an event of this magnitude, occurring so early in the year at a location that almost never experiences such excessive heat, lasted closer to the average heat wave event duration of 5.5 days? Research on heat stress exposure at the station-level is needed to improve our ability to mitigate the multiple components of vulnerability to hazards, including sensitivity and adaptability.

Another example can be illustrated by comparing Tulsa and Indianapolis. In August of 1983, Tulsa had a 23-day Category 4 event in which six of the days were in the Severe daily accumulated heat stress class. A corresponding event occurred at Indianapolis that was 4 days long with the daily progression 2-4-3-2. Tulsa had 20 Category 4 heat waves that ranged from 3 to 23 days in length. By contrast, Indianapolis had just four Severe heat waves, ranging from 3 to 6 days. One might conclude that the event in Tulsa was greater in heat stress magnitude; however, the ratio of severity to frequency for these corresponding events suggests that the amount of exposure vulnerability could be a concern for either location.

Category 5 Heat Waves

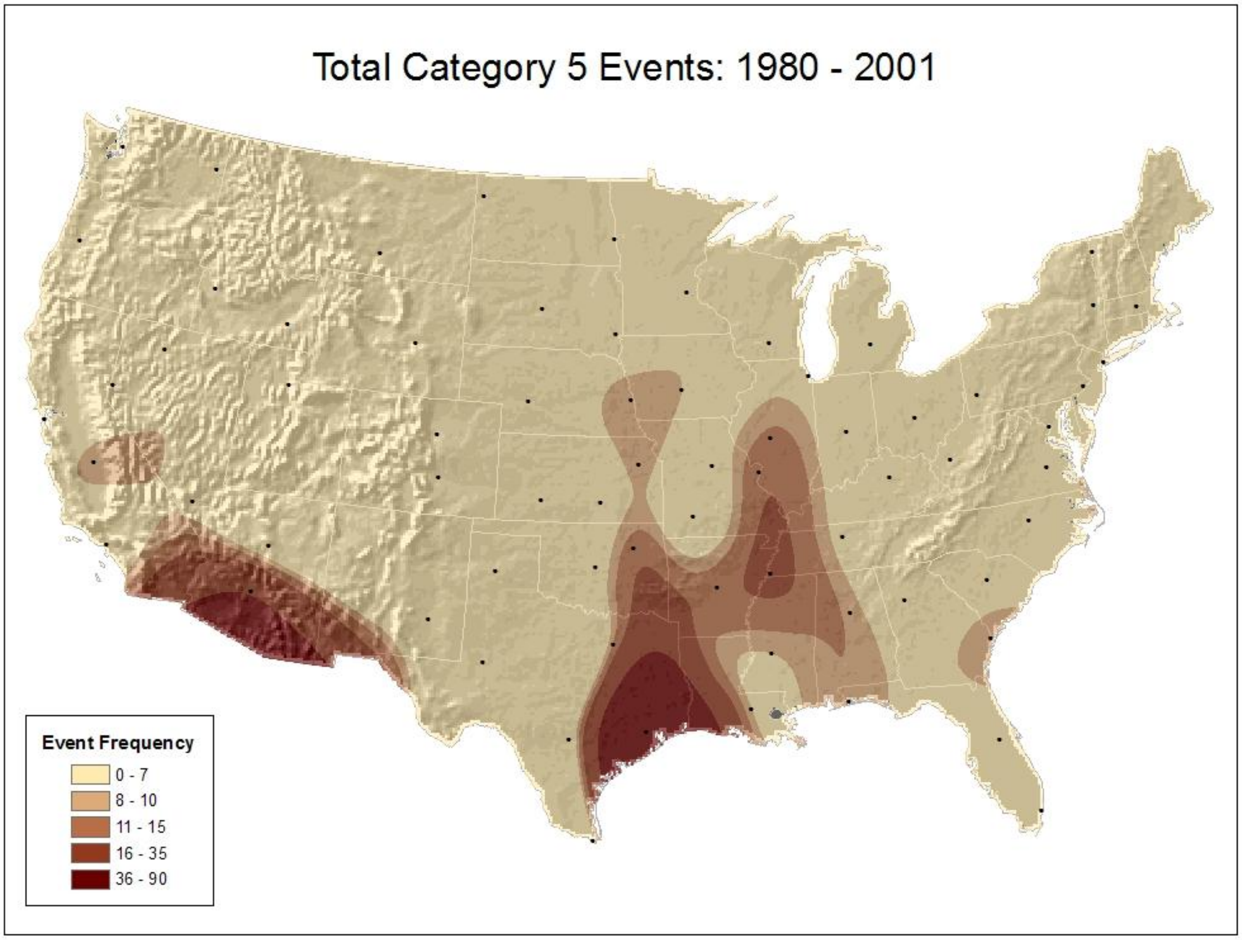
There were 39 (of the 70) stations that recorded a Category 5 heat wave from 1980 – 2001, 10 of which are listed in Table 4.14. Houston's outlier-like value of 86 Category 5 heat waves is attributable to two factors: the heat and humidity is typically available throughout the 122-day heat wave season and the variable weather patterns, such as convective thunderstorm development, that break otherwise long continuous periods of excessive heat into several shorter events. In the summer of 1995, 7 of the 9 Category 5 events at Houston were only separated by 1-3 non-classified days. Although the heat wave season at the second-highest station, Phoenix (115 days), is similar to that of Houston, it contrasts with Houston because the periods that are

Table 4.14: Stations with the highest frequency of Category 5 heat waves

	Station	Events		Station	Events
1	Houston, TX	86	**6**	Tulsa, OK	12
2	Phoenix, AZ	32	**7**	Springfield, IL	11
3	Memphis, TN	17	**8**	Dallas, TX	10
4	Little Rock, AR	13	**9**	Pensacola, FL	10
5	St. Louis, MO	13	**10**	Savannah, GA	9

classified as Category 5s are typically much longer and routinely last over a month. Heat waves of an Extreme magnitude, outside of the above two locations, are infrequent.

Figure 4.19: Distribution of Category 5 heat waves in the U.S.



Category 5 heat wave distribution in the U.S. (Figure 4.19) highlights areas from east Texas across Louisiana and up the Mississippi River valley toward the confluence with the Ohio River. Station locations in the river floodplain may have higher humidity and heat stress levels compared with nearby locations outside the floodplain. The gradient representing the decrease in Category 5 frequency from Houston toward San Antonio has now become the steepest transition on the map as San Antonio did not record a single Category 4 or a Category 5 event, and Houston recorded the highest of both.

Finally, comparison of the maps for Category 4 heat wave frequency (Figure 4.18) and Category 5 event frequency (Figure 4.19) indicates that there is a difference in the longitude where the northward penetration of a higher frequency of events occurs. Higher values for the

Category 4 events tended towards the western side of the Ozarks in Oklahoma and Kansas whereas the higher values for the Category 5 events penetrated northward up the Mississippi River valley.

Heat Stress Days Not Occurring During a Heat Wave

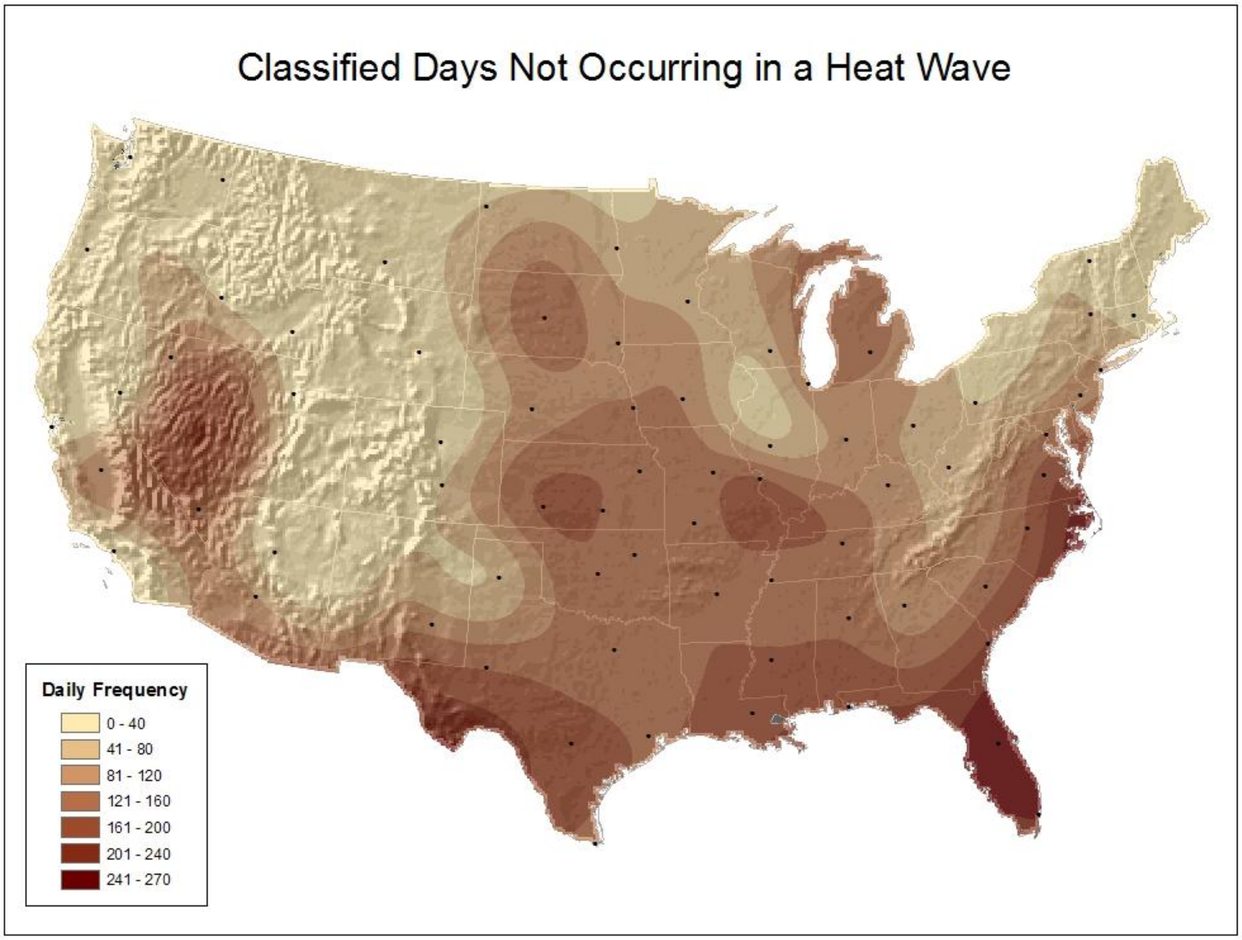
Solitary days that are hot and/or humid enough to be given a daily accumulated heat stress classification do not always occur consecutively. These isolated days are not considered as part of heat waves, but they do provide insight into how the nature of hot conditions occurs at a location. For instance, results from Phoenix (Appendix B) show that 2,131 classified days occurred during heat waves, and there were 80 additional classified days that did not occur during a heat wave for the 22-year period. The large number of categorized days that fall within a heat wave with such a small 'Unclassed 1s' value suggests once a day reaches enough accumulated heat stress to be categorized as a heat stress day, it is very likely going to be sustained as a heat wave. The opposite scenario exists at Columbus (Appendix B) where the total number of heat stress days was 91, with another 75 isolated but classified days that did not occur within a heat wave. These results suggest a lower likelihood of a classed heat stress day extending into an oppressive heat wave.

A list of locations with the highest number of unclassified 1s throughout the 22-year study period is provided in Table 4.15. All of these stations are located in the American Southeast local factors may play a role in the higher number of classified days that do not materialize into a heat wave. A possible explanation is that frequent convective cloud development, especially from daytime heating combined with moisture-laden air, can prevent what would have been a sultry day from reaching a high enough daily heat stress accumulation. Rapid afternoon cloud development and cooling rains can provide a period of recovery that keeps an individual day to an accumulation level just below the classification threshold. The geography of days that meet the heat stress classification criteria (Figure 4.20), but are not in heat waves, highlights areas in the Desert Southwest, south Texas, and the Gulf/Atlantic coasts. Other areas include locations in the Great Plains and southern Mississippi Valley which have over 120 non-heat wave days during the study period that registered a classification value. These days were generally occurred during the beginning and end of the warm season transitioning with a cooler season.

Table 4.15: Areas with the most heat stress days not classified into a heat wave from 1980-2001

Station	Days	Station	Days
1 Orlando, FL	267	6 Baton Rouge, LA	185
2 Miami, FL	245	7 Columbia, SC	180
3 Savannah, GA	203	8 Richmond, VA	176
4 Pensacola, FL	201	9 Dodge City, KS	173
5 San Antonio, TX	189	10 Jackson, MS	167

Figure 4.20: Frequency distribution of days that were categorized but not classified into a heat wave



Classifying the Midwest Heat Wave of 1995

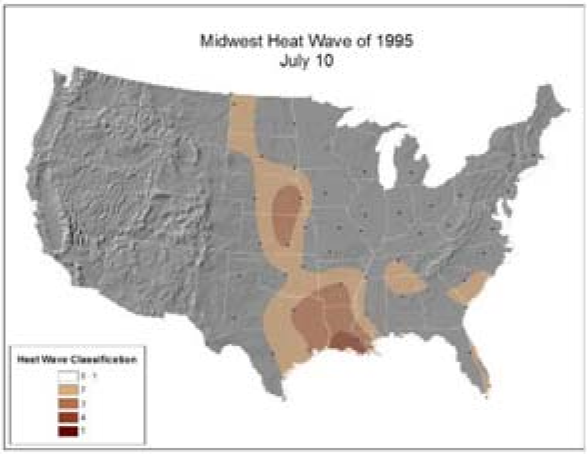
Design of the heat stress classification system was focused around the ability to describe an individual event in detail, such as analysis of hourly HI progression during a given day or the changing intensity of heat stress during the days of a lengthy event. In addition, assignment of an individual daily heat stress accumulation category for each day at each weather station across the country provides spatial data that can be used to illustrate the geography of the daily heat stress exposure hazard. Mapping several days in succession provides an indication of the changing geography of an excessive heat event throughout its duration. This procedure provides a new way to visualize well-known heat waves like the one that occurred in the Midwest in July 1995.

In mid-July of 1995, a heat wave occurred in the Midwest that is widely known for the casualties in the city of Chicago and Cook County, IL. Details on this heat wave have been documented in several studies related to the event and its consequences (Karl and Knight 1997, Whitman *et al*. 1997, Klinenberg 1999, and Palecki *et al*. 2001). This event was not exclusive to Chicago (e.g., Weisscoph 2002), and results from this analysis can be used to illustrate how the event progressed across the region over the course of 6 days (Figure 4.21 a-f).

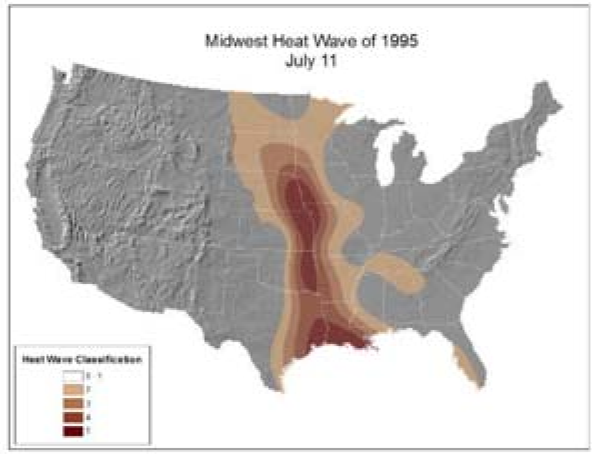
The maps in Figure 4.21 indicate the varying locations of daily heat stress classes in the eastern U.S. during six days during July, 1995. Assessment of the difference among the maps allows one to document the event's origin, its daily expanse, and its migration eastward. On July 10 (Figure 4.21 a), the central Plains recorded Category 1 (Topeka) and Category 2 (Omaha) accumulated heat stress days, with none of the Midwestern stations experiencing heat stress conditions. The next day (Figure 4.21 b) shows that areas of hazardous conditions had shifted eastward over the Missouri River Valley and had already intensified to Category 5 or Extreme status at Topeka and Omaha. The next day, July 12 (Figure 4.21 c) illustrates a potential Gulf of Mexico connection to the intensification and persistence of this event as hazard levels in eastern Kansas and Nebraska remained Extreme, but the Category 4 and 5 daily accumulated heat stress had spread eastward into Illinois and as far north as Minneapolis. It was on July 12th that the event was first recognized in Chicago with a Category 1 heat stress day.

On July 13, 1995 (Figure 4.21 d) the HI at the Chicago O'Hare station was only below 32.2° C (90° F) for the three hours just before sun rise (all three were 31.1° C or 88° F). Twenty-one hours were above the HI 90 threshold, with 12 consecutive hours above the HI 105 threshold, and a HI high of 48.3° C (119° F) for two hours. These were the two highest HI

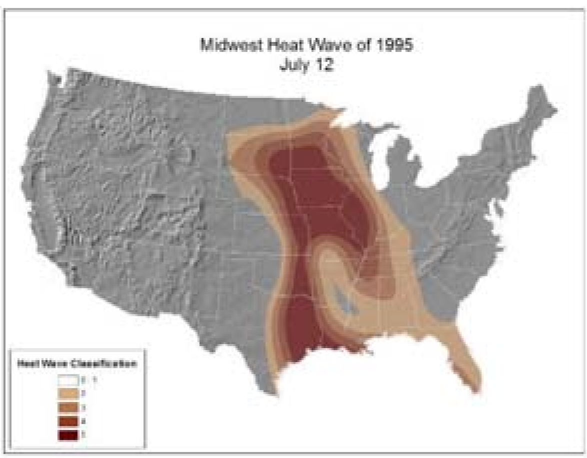
Figure 4.21 [a-f]: The Midwest Heat Wave of July 1995. Only U.S. stations east of the Continental Divide were used and map patterns represent daily heat stress classes



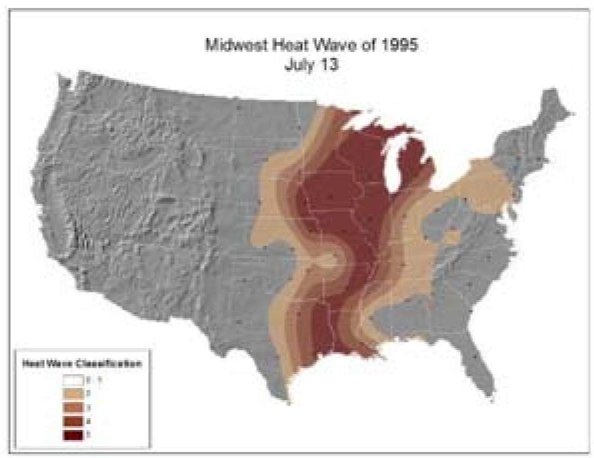
a.



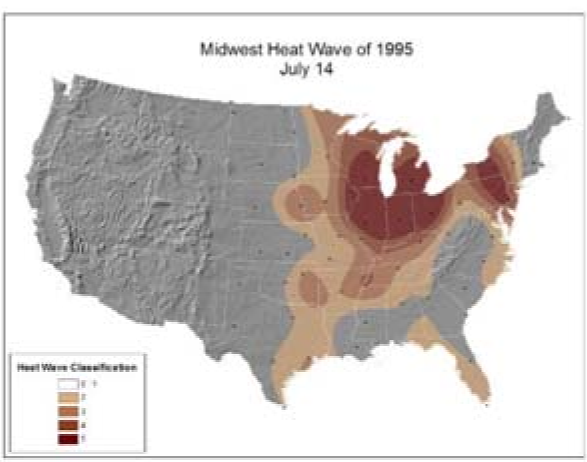
b.



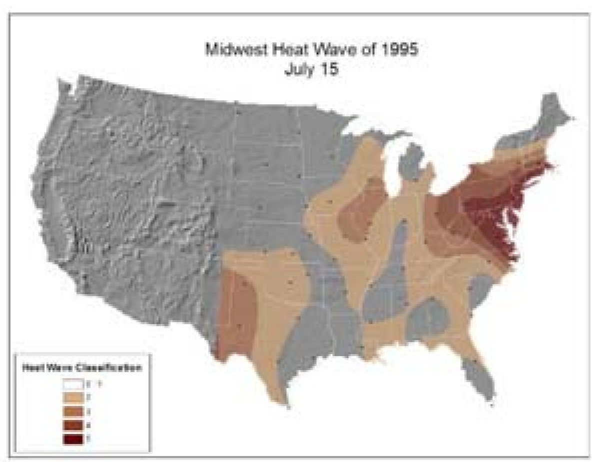
c.



d.



e.



f.

recordings at Chicago during the time period analyzed for this study. The accumulated heat stress surpassing HI 90 for that day was 195 (351) HI 90 hours, and the accumulated heat stress surpassing HI 105 was 59.4 (107) HI 105 hours, making this date one of the most stressful on record for the Chicago area. On July 13th, Category 5 heat stress was also observed at Madison and across Lake Michigan in Lansing.

July 14 (Figure 4.21 e) illustrates how the Category 5 heat stress extent of the heat wave had shifted eastward to the Great Lakes and Mid-Atlantic States, with Philadelphia also registering a Category 5 day. To the west, Topeka and Omaha had daily heat stress levels back down Minor or Moderate. Eastward, heat stress at Indianapolis and Columbus has reached Extreme levels, and Chicago is near the center of the area of Extreme daily heat stress for the event with its second consecutive Category 5 day. The highest category contours were cut off from the Gulf on the 14th, which had been evident in maps b-d.

On the final day of notable excessive heat stress during this event, July 15 (Figure 4.21 f), the Extreme class has shifted eastward to be over locations such as Washington (DC), Philadelphia, Pittsburgh, and New York City. On this day, which was classified as Moderate or Class 2, Chicago recorded the greatest level of daily human mortality during the event. In this case, the rarity and magnitude of the heat stress levels on the previous days had taken their toll on human sensitivity. The fourth day of the event provides an example of how vulnerability from exposure needs a more localized examination with respect to excessive heat stress. For Chicago, this heat wave was only 5 days in duration (July 16 was a Category 1 day). However, with two Extreme days in succession, excessive heat stress mortality occurred and did not return to normal for almost a week (Whitman 1997).

This chapter began with the suggestion that the value of the classification can be judged in part by the reasonableness of the results of applying the system. Correlations between the findings from this study with the research previously completed on the July 1995 heat wave were strong, suggesting that the methods presented in this research provide a capability of mapping regional heat waves on a daily basis. Daily categorization of accumulated heat stress exposure coupled with local measures of loss (such as human mortality or economic costs) might provide a multivariate assessment of local vulnerability to the heat stress hazard.

Heat Wave Nature and Predictability

Detailed analysis of individual events suggests that a heat wave as a single event does not generally follow what might be thought of as a natural progression of increasing daily heat stress magnitude from one day to the next, followed by decreases in magnitude as the event ends. If an event had a heat stress classification progression of 1-2-3-2-1 for a 5-day event, it would be a rare exception to what is more commonly an erratic day-to-day progression of daily heat stress classes during a heat wave. A four-day event has the possibility of occurring in 625 different combinations of the daily heat stress classification system. The most common 4-day event was a Category 1, which implies that all 4 days were a Minor (1-1-1-1). A Category 2 event lasting 4 days has 15 possible outcomes of occurrence since a Category 2 day must be assigned to at least one of the days, and no higher than a Category 2 can be assigned (1-2-1-1, 1-2-1-2, 2-2-1-2, etc.).

Instead of just being statistical possibilities, the 625 possible 4-day combinations are all feasibly realistic in the natural system. A Category 3 heat wave at Houston (beginning on July 25, 1991) had the progression of 3-1-1-2 daily heat stress classes whereas a Category 5 heat wave (beginning on Aug 15, 1988) was 1-5-5-1. However, a 4-day occurrence of 5-5-5-5 would be of extreme rarity, and was not recorded at any station during the time period for this study. Moreover, locations that can have more than 4 consecutive days of Category 5 heat stress, such as Houston, Little Rock, Memphis, and Tulsa, also have weather variability that can break up long and extremely sultry heat waves could potentially produce such an event. This observation is contingent on the climatology of the area. Increasing distance to the north and west from the Houston area reduces the likelihood of extreme 4-day combinations from occurring, because the frequency of severely hot and humid days occurring consecutively decreases.

For each daily addition in heat wave duration, the possibility of classification combinations increase by a factor of 5, for instance a 5-day heat wave has 3,215 possible outcomes (although, as more days are considered, probability of the most extreme scenarios would realistically diminish). Therefore, each day added to the duration adds another level of irregularity to an event. Two events in Dallas can be used as an example:

July 12, 1988 – 2-2-1-1-2-3-4-1 (Category 4)

July 15, 1989 – 1-4-2-2 (Category 4)

Both heat waves have been assigned the same event classification, although the 1988 heat wave was twice as long; in the 1989 heat wave the highest daily class occurred near the beginning of the event whereas in 1988 the highest class occurred near the end of the heat wave.

The irregular patterns from day to day throughout an event can be caused by a large number of factors or combinations of factors like air mass changes, convective storms, cloud cover, and changes in humidity. Daily classifications on heat stress levels reveal the erratic nature of heat waves, and also provide a detailed account of individual events. Using the methods presented in this study, local casualty rates or measures of economic loss can be matched with day-to-day heat stress levels to understand how people, their crops, or their livestock will respond to events. Future use of these methods can examine the sensitivity aspect of vulnerability based on exposure measures such as: overall category of the event, daily progression of categorical assignments, local frequency of these heat stress levels, the date an event began, heat wave duration, procession (1^{st} heat wave of year, 2^{nd} heat wave of year, etc.), and succession (heat waves that occur with less than a week of recovery from a prior heat wave).

Prediction is another factor in our ability to understand heat waves. Observation of regional and global weather patterns by local broadcast meteorologists has been providing an increasingly more detailed synopsis of approaching weather systems. Predicted hourly values of heat and humidity for upcoming days could yield a forecasted daily accumulated heat stress category over the course of a few days to forecast upcoming heat stress, compare the forecast event to previous occurrences at that location, and provide local emergency managers with better information regarding the need to prepare for upcoming conditions.

United States Climate Regions and Heat Waves

There were 30,822 heat stress days among all 70 stations from 1980 – 2001 that occurred during 4,431 total heat waves accounted for at all stations. Distribution of heat waves among the five categories generally occurs as one would expect for climatic events, decreasing in frequency with increasing magnitude (Figure 4.22). The variation from expectation is observed by the frequency of Category 5 events outnumbering Category 4 events by 1%. Nonetheless, Category 4 and 5 events accounted for less than 15% of total heat waves nationwide. The dispersion of heat waves in the United States is not uniform, as shown in the maps above, which can be attributed to dominant weather patterns and associated air streams in different regions of the

United States. Heat wave regions of the United States become apparent, which were statistically corroborated by quartile and K-Means cluster analyses.

Figure 4.22: Percentage of heat waves in the United States by category from 1980 – 2001

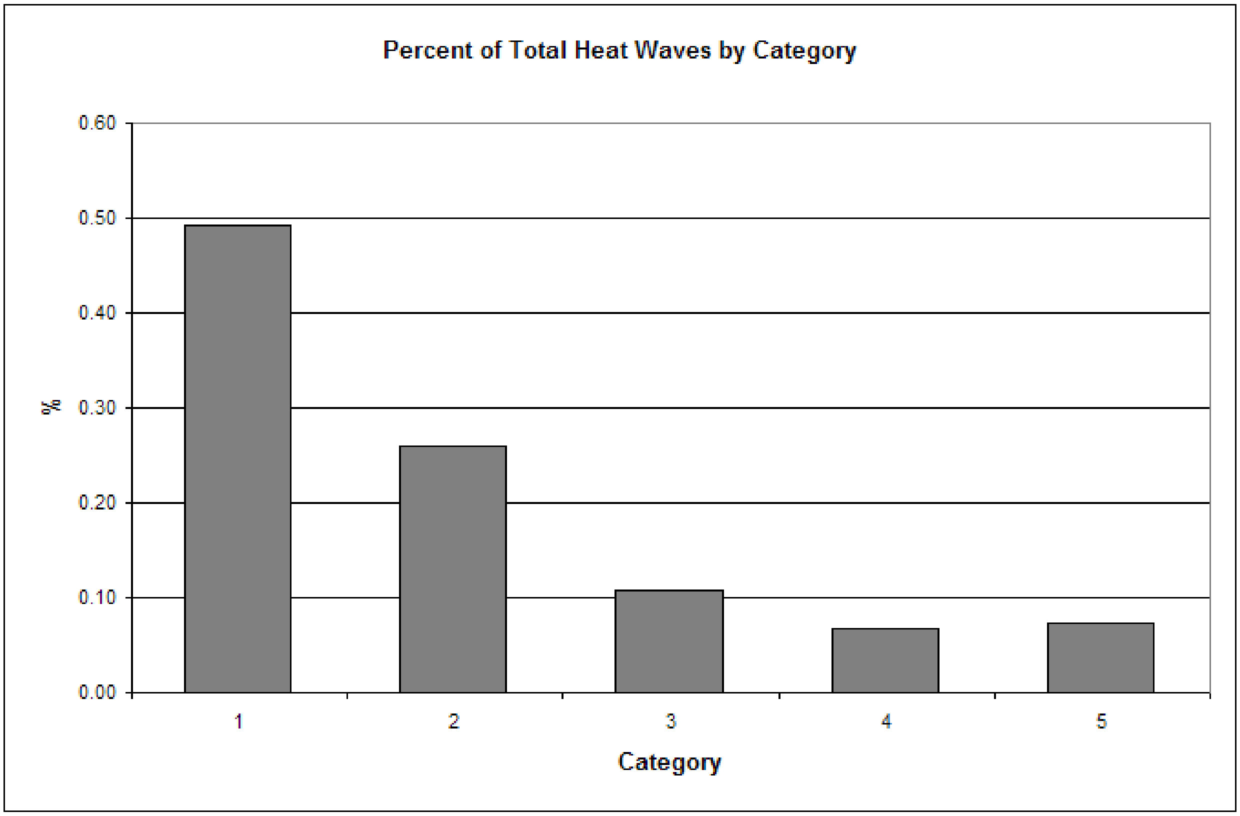
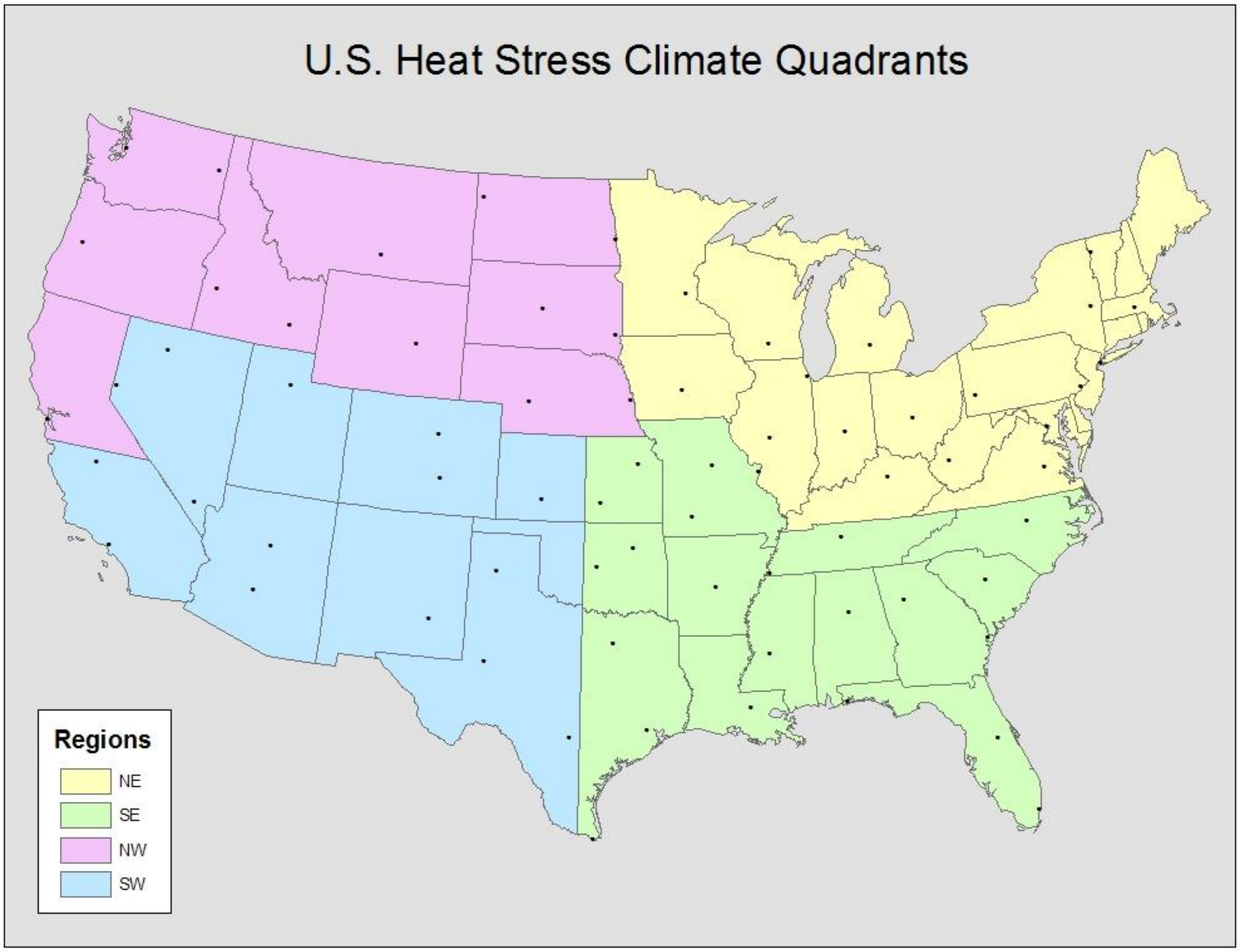


Figure 4.23 illustrates a simplification of Easterling's (2002) climate regions from Figure 3.4 based on heat stress climatology. A generalized heat stress climatology for these four regions is based on typical temperature and humidity levels, and is listed as either warm or cool and moist or dry. Data in this study provide the number of heat waves recorded at each station. The number of heat waves per station in the Northwest quadrant ranges from zero to 61, with an average of just 13 heat waves per station for the region. Temperatures at some locations in this quadrant can get well above 32.2 (90° F), but the warm season is considerably shorter than southern locations, and the specific humidity values are usually low. Therefore, the NW quadrant is labeled as cool/dry.

The Northeast quadrant stations experience a similar length of warm season, especially in the northern locations, but have higher humidity levels than locations in the Northwest. Heat wave frequency for the stations in the Northeast ranges from 1 to 80, with an average of 30 events. A higher atmospheric moisture content makes a difference for this quadrant and the NE is

Figure 4.23: Heat stress climatology in the U.S. can be simplified four quadrants



labeled cool/moist. Results from the study by Davis *et al*. (2003) indicate that the highest levels of heat-related mortality from 1980-1998 were at the locations in this quadrant, suggesting that populations in these areas are susceptible to unusual periods of excessive heat stress.

The southern stations are naturally warmer overall than those in the north, however, those at or near the coastlines or at higher elevations are an exception for the Southwestern quadrant. These exceptions include Denver, Flagstaff, Los Angeles, Pueblo, and Reno. Otherwise, temperatures in this quadrant reach the highest in the country in southeastern California, southern Nevada, and across southern Arizona. Desert landscapes of the Southwest are indicative of the lack of moisture in these areas. Stations in the Southwest quadrant of the U.S. have a range from zero to 196 heat waves with an average of 47. Phoenix is a notable location where a single heat wave event can last for months. The generalized heat wave climatology characterization for the SW quadrant is labeled as warm/dry.

The Southeastern quadrant has a long warm season and is also a direct recipient of the moisture advection from the Gulf of Mexico and tropical Atlantic. Of the 23 stations in this quadrant, the lowest number of heat waves was 66 (Atlanta), and the highest was 227 (Houston). This quadrant has the highest number of heat waves recorded in this research. The average number of heat waves in the Southeast was 131. The generalized heat wave climatology for the SE is therefore labeled as warm/moist.

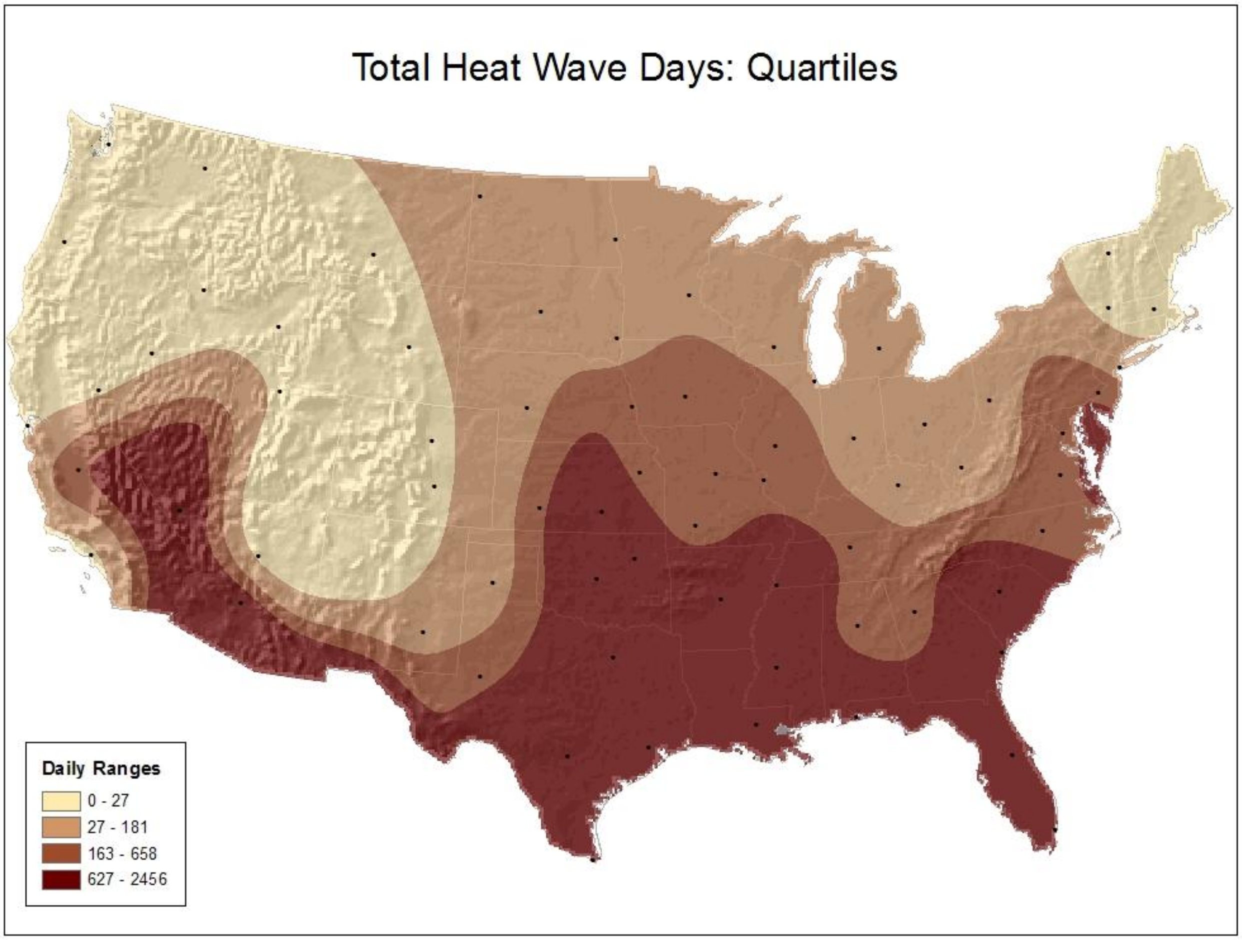
Contrasting the heat and humidity differences among the four quadrants is further simplified in Table 4.16. These representations aid in the general understanding of heat stress characteristics as they exist in the four main heat stress climatology regions in the U.S. A quartile statistical analysis was done using the 'Total Days' values from all 70 stations resulting in class breaks at 27, 181, and 658. The pattern in Figure 4.24 further illustrates the simplified heat stress designations provided in Table 4.16 with the Northwest having data mostly in the first or second quartiles, and the Southeast has locations with data predominantly from the fourth quartile. The Southwest and Northeast demonstrate a mix of locations with data in multiple classes because of wide variations of temperature and humidity across the regions.

Table 4.16: Heat stress characteristics for the four quadrants are simplified symbolically. Climate controls are listed in order of temperature and available moisture as + (yes) or – (no). The average number of recorded heat waves for all stations in each quadrant is also given

	13 HWs	30 HWs	
NW	–, –	–, +	NE
SW	+, –	+, +	SE
	47 HWs	131 HWs	

Evidence of these generalized weather and air mass factors is reflected by the sum of events per region (Figure 4.25). The four heat stress regions can be compared by raw heat wave sums amongst the five categories. The Northwest region, characterized by Table 4.16 as [**–, –**], averaged just 13 heat waves for the 14 stations compared to the Southeast region, characterized by [+**,** +], which averaged 131 heat waves per station among 23 locations. Although there is clearly more station data in the Southeast than the Northwest in this study, it should be noted that 112 of the 201 (56%) total heat waves in the Northwest are from Fargo, Sioux Falls, and Omaha, which are on the easternmost border of the region. Of the remaining 89 recorded heat waves, 50

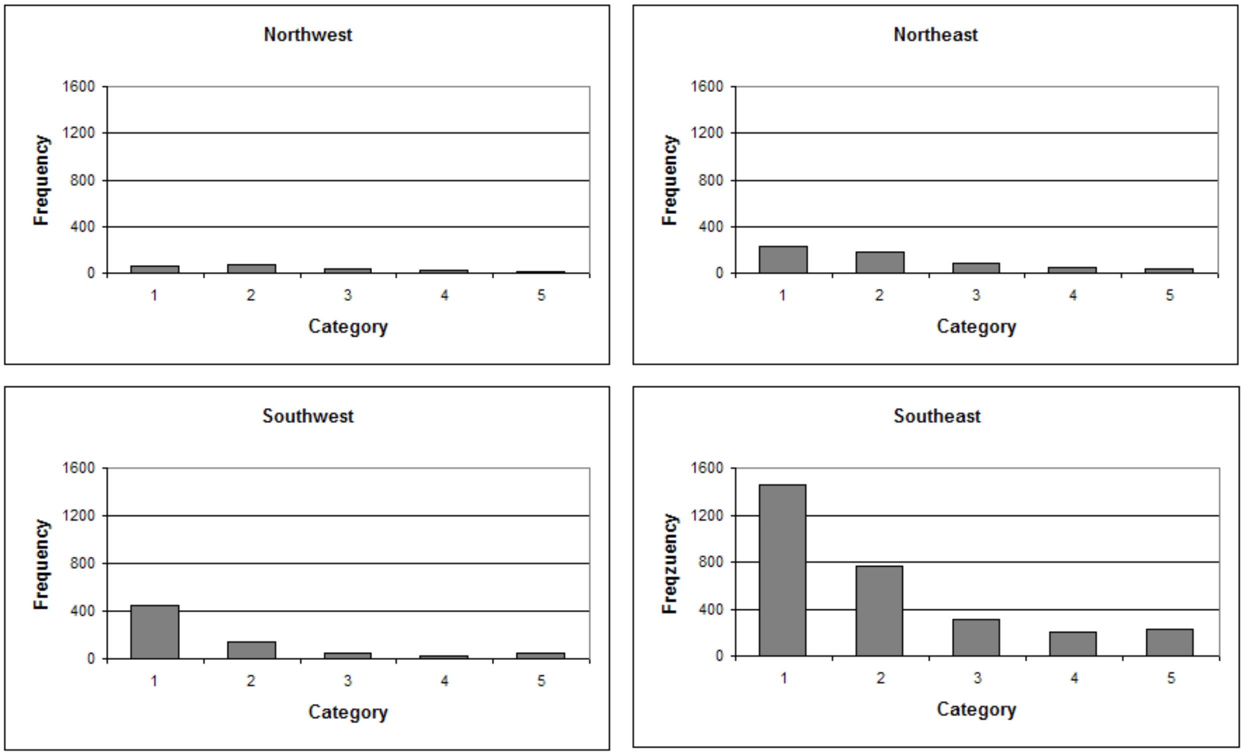
Figure 4.24: Heat stress distribution in the U.S. based on a quartile analysis of total days classified as a heat stress day from 1980-2001



(56%) were in Pierre, also in the eastern portion of the NW region. It is believed that the addition of more representative stations would not have significantly changed the results for the Northwest region as a whole. Therefore, the comparisons in Figure 4.25 are considered appropriate despite the differences in the number of stations per region.

The other two opposing regions, the Southwest and the Northeast, are quite similar in raw heat wave frequency by category. It is assumed that the higher humidity values that are present in the Northeast region [–, +] is well matched by the long periods of high temperatures in the Desert Southwest [+, –], although the states of Colorado, New Mexico, and Utah are not real contributors to the heat stress of the Southwest region. A final observation of the graphs finds that both the Southwest and Southeast recorded a higher frequency of Category 5 heat waves than Category 4. The high number of Category 5 events in Phoenix in the Southwest and Houston in the Southeast are what account for higher Category 5 frequency.

Figure 4.25: Categorical frequency distribution of heat waves by heat stress region



A k-means cluster analysis was conducted to statistically confirm that heat stress levels in the United States could be separated by four regions. The analysis placed the 70 stations into one of four clusters based on their sum total of all heat waves. These statistical clusters were generated, in part, to determine the validity of the regions delineated in Figure 4.23. Houston's high heat wave total was such that it was a station placed in its own cluster as an outlier, therefore five clusters were chosen with Houston being combined with the fourth (or highest) cluster. Results from the cluster analysis are provided in Appendix D.

Results from the statistical clustering suggest that the 70 stations can be grouped into spatially coherent regions, but these regions do not match perfectly with the regions identified in Figure 4.23. Clusters 1 and 4 were grouped together (see the data in Appendix D) to form the highest cluster, and the stations in this cluster occur across the southern U.S., especially near the Gulf Coast. Cluster 2 grouped the stations with the next highest frequency of heat waves, which are primarily located in the Southeast latitudinally north of the Gulf Coast, as well as the three warmest stations in the Southwest. Cluster 3 grouped the stations with the second lowest frequency of heat waves outlining the stations in Cluster 2 to the north and west. Cluster 5 was grouped as the lowest mean center which was prevalent among stations in the mountain and coastal areas of the western U.S. regions where zero heat waves were typically recorded, as well as most of the Northeast where heat waves are comparatively rare.

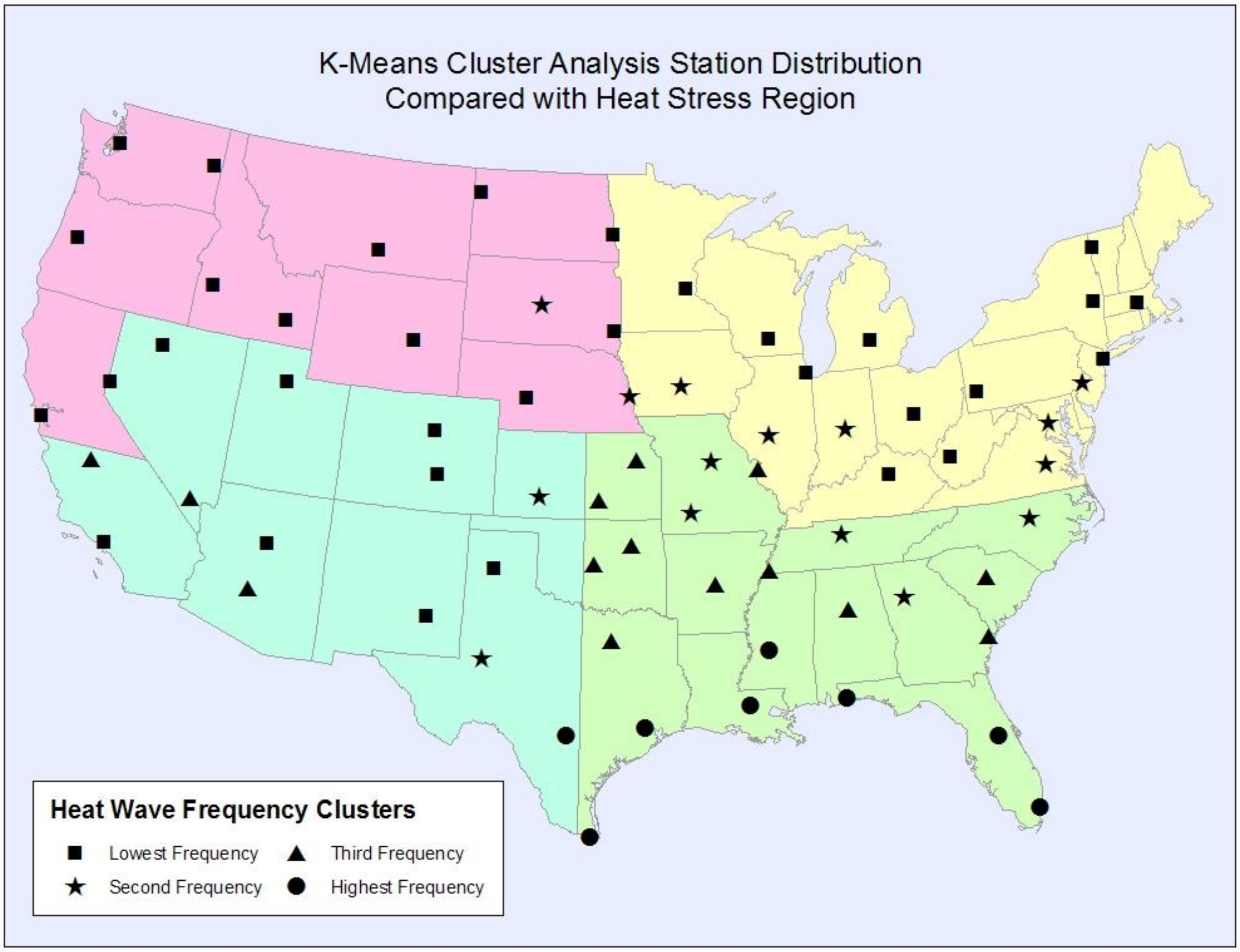
Analysis of the k-means results using the geographic areas identified for Figure 4.23 indicates that the spatially defined regions have some validity. For the Northwest region, all but two of the fourteen stations were grouped in the lowest cluster, and the two remaining stations fell into the second cluster. Twelve of eighteen stations in the Northeast were grouped in the lowest cluster, and six of the remaining stations were in the second cluster. All four clusters were represented in the Southwest region with one station, Phoenix, in the highest cluster, three stations in the third cluster, two stations in the second cluster, and the remaining nine were grouped in the lowest cluster. For the Southeast, zero of the 23 stations were in the lowest cluster, seven stations were grouped in the highest cluster, eleven were in the third cluster, and the remaining five in the second cluster.

These statistical results correlated well with the spatial observations made above. Areas in the Northwest region comparatively had the lowest susceptibility to heat waves, and the Southeast region had the highest frequency. The Southwest was also represented well by this analysis with stations clustering high and low, with respect to heat waves, which was also evident in the quartile map (Figure 4.24). However, results for the Northeast resembled the Northwest with most of the stations falling in the lowest cluster rather than being grouped in the second cluster as expected. Overall the raw data suggests that the stations in the Northeast experience heat waves more frequently than those of the Northwest, and the spatial distribution of stations by cluster values is supportive of regional distinctions being observed in the United States because of their similarities in heat wave frequency (Figure 4.26).

Review of Results

Results from this research, which produced both a system to classify daily heat stress and a technique to categorize heat waves, provides data on an underrepresented climatic hazard that can be compared across space and through time. As the sultriness of heat and humidity progresses hourly to reach hazardous levels, the methods presented in this research provide a way to integrate those hourly observations into a daily heat stress measure which is classified from 1-5 depending on the magnitude of the accumulated stress. Daily heat stress classes at individual weather stations then provide an ability to identify and categorize strings of

Figure 4.26: K-means statistical results in geographic space



consecutive heat stress days that make up a heat wave. These heat waves were then categorized into one of five classes based on the highest daily heat stress class during the event.

Analysis of 22 years of data provided results on the frequency and magnitude of heat stress for all 70 stations. Spatial and temporal differences among the stations provide insight into climatology of the heat stress hazard across the U.S. Results from previous research were used as the basis for setting expectations for the results in this study. Analysis of individual heat wave events indicates that events do not typically exhibit an increasing-decreasing pattern of daily stress levels. Duration of events were not related to heat stress magnitude or heat wave classification level, and the heat waves consisting of days with varying classification level rarely exhibited a predictable pattern. Category 1 heat waves could be 3 days long or several weeks long this characteristic was also true for heat waves in Categories 2-5.

Short-term weather forecasts could be made using the daily accumulated heat stress and heat stress classification system to warn citizens regarding an upcoming hazardous event.

Knowledge of the results from this climatology could be used to place the forecast event into a historical context to help communicate the hazard and perhaps assist in mitigating vulnerability. Location plays a major role in the amount of heat stress that is considered excessive locally. Elevation above sea level, distance from moisture sources, and dominant air streams dictate the temperature and humidity levels that determine the frequency and rarity of excessive heat stress.

CHAPTER 5 – Summary and Conclusions

Summary

Applied climatological research on human vulnerability to weather hazards has been studied for well over a century. Better understanding of the impacts of extreme weather events, such as hurricanes, tornadoes, heavy snow, flash flooding, and nor'easters, has been made available to the general public in the hope of limiting loss of life and property. Climatic generalization of the complexity associated with atmospheric hazards was made possible, in part, by simplifying the variable nature of atmospheric anomalies using classification schemes, which have classes that increase in value with event magnitude and rarity. Impending hazardous events can be assigned a potential class value and then watch/warning systems can report when the event might occur, who might be affected by it, and potential damages. Use of classification systems allows hazardous events to be compared with the historical record to identify a context of similar event magnitude, frequency of occurrence, or to help document a possible trend in changing event severity that parallels ongoing global climate change.

This research used the heat index to examine daily levels of accumulated hot and humid conditions by adding hourly values of HI that exceeded specific thresholds, such as HI = 90 and HI = 105. When accumulated hourly values of HI 90, HI 105, and HI <75 were analyzed, the 22 years of data were used to identify days that accumulated enough heat stress to be classified from 1-5. Once the daily heat stress classification was established, consecutively classified days were located and classed into heat waves. Using this method of assessing accumulated stress for each day and then grouping together strings of stressful days allows one to find exact dates of heat stress, the location of events, the seasonality of events, heat wave lengths, the progression of daily heat stress values during a heat wave, and overall event magnitudes. In addition, the criterion for identifying a heat stress event are the same for all weather stations, but the methods established herein allow comparison of a location's exposure to heat stress events across time and space.

Heat waves are an atmospheric hazard with less visible impacts than blizzards, hurricanes and other severe storms, but studies have documented that the highest frequency of human mortality is from periods of excessive heat. Objectives for this study were to develop a climatology of heat stress at multiple locations across the U.S. and map the varying levels of exposure at multiple time scales. Individual station temperature and humidity records were used to derive hourly heat index (HI) values over the course of 22 years. Accumulating hourly HI values over a 24-hour period provided a local daily heat stress measure, and a collective assessment was used to identify general heat stress distributions in the United States. A formal heat wave definition was developed for use in this study by combining logic from three primary sources: 1. HI thresholds were selected regarding human biophysical response to excessive heat and humidity based on the NWS heat watch/warning criteria, 2. the concept of daily heat stress accumulation (Hubbard *et al*. 1999), and 3. the possibility of using multiple measures of heat stress magnitude and overnight recovery in a heat wave classification (Hahn *et al*. 1999). For this research, a heat wave was recognized when three consecutive days met the minimum parameter in the heat wave classification system, meaning each day accumulated at least 40 accumulated hours surpassing HI > 90 in Fahrenheit (22.2 accumulated hours surpassing HI > 32.2 Celsius). A less common heat wave was also recognized over two consecutive days if at least one of the two classified days met or exceeded the Moderate parameters in the heat wave classification. This exception occurs when 80 accumulated hours surpassed HI > 90 with 1 hour surpassing HI > 105 in Fahrenheit (44.4 accumulated hours surpassing HI > 32.2 with 0.5 accumulated hours surpassing HI > 40.6 in Celsius) and 10 or fewer hours of recovery (≤ 75° F or 23.9° C) occur.

The major findings from this research include:

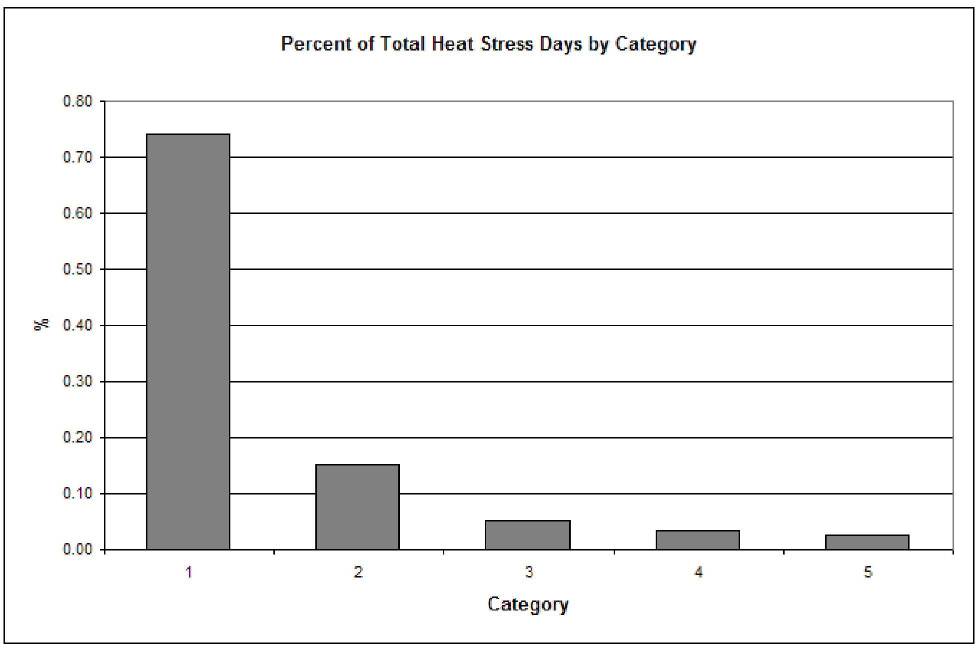
1. accumulated daily heat stress, based on the HI, can be used to characterize temporal and spatial variations in exposure to the climatic hazard of extreme heat and humidity
2. once days have been categorized based on daily accumulated heat stress, it is possible to use that information to identify consecutively classified days, and then characterize and categorize heat waves
3. when a heat wave is identified, it can then be analyzed to determine severity of the daily class values and duration of the hazard at individual weather stations

4. regions of heat wave similarity was identified in four primary quadrants of the United States with the Southeast registering 67% of all heat waves in this study and the Northwest experiencing very limited heat wave activity at 5%
5. the highest heat wave frequency in the Southeast identified by this study does not correspond with the region of highest human mortality in a study by Davis *et al*. (2003), which illustrated that the highest mortality from heat stress was in the Northeast quadrant
6. heat waves varied over space ranging from zero events (at 11 locations studied) to 10.6 events per year (Houston), and with events lasting up to 98 days (Brownsville) in duration with a 5.5 average daily duration nationwide
7. Category 1 heat waves were the most common in the United States from 1980 – 2000, followed by Category 2 and Category 3, however Category 5 heat waves outnumbered Category 4 events; based on the current parameters of the classification system
8. the day-to-day progression of heat stress classes during a heat wave were generally erratic if the event was not a Category 1, demonstrating no evidence of a regular day-to-day magnitude pattern during heat waves
9. heat wave activity was shown to be heavily influenced by topographical variations and decreased markedly as elevation increased, mountainous areas also acted as an obstruction to higher HI values along prominent humid air stream trajectories
10. the heat stress classification system can be used to analyze the magnitude and spatial extent of individual heat waves (such as mid-July 1995) through an assessment of day-by-day heat stress values as well as changes in geographic extent of heat stress as the system migrates over time

The heat stress and heat wave classification systems developed in this research built on the methods of previous weather hazard classification by using graduated categories of magnitude ranging from 1-5. Heat wave magnitudes were based on the accumulated heat stress per day surpassing thresholds of HI 90, HI 105 and the number of hours of recovery below HI 75. The daily accumulated heat stress classes were aggregated for all 70 stations and Figure 5.1 provides an indication of percentage distribution by heat stress category. Category 1 days occurred 74% of the time, with Category 2 days occurring just 15% of the time. Category 3, 4, and 5 days decreased respectively and were all well below a 10% occurrence rate.

Next, the heat wave events and categorical frequencies were analyzed to determine heat stress distributions across the United States. Heat waves classified in this research were based solely on daily heat and humidity accumulation regardless of location. This technique provides a heat stress climatology based on an exposure measure of vulnerability and provides a basis for comparison among different areas. Quantitative assessments that are location specific are available and those studies provide insight into how acclimatization to a longer heat wave season with frequent heat wave activity may mean less sensitivity or more resiliency to heat stress exposure as compared with those locations that experience a major heat wave on an infrequent basis.

Figure 5.1: Distribution of heat stress days by class in the United States from 1980 – 2001



Classifying heat waves in this study was closely aligned with the classification of hurricanes. Hurricane classification is contingent upon the meteorological factors that make up the storm, particularly wind speed. This Saffir-Simpson classification is assigned regardless of its landfall location, if it makes landfall at all, and estimates potential damage based on wind speed. A category 5 hurricane is still a category 5 hurricane if the eye makes landfall on a sparsely inhabited coastline or at a major metropolitan area. Since the primary impacts from excessive heat are based on an ultimate loss like human mortality, it was believed that a Category 5 heat wave should likewise be the same anywhere regardless of the local population density. Robinson (2001) states that "…although a heat wave is a meteorological event, it cannot be assessed without reference to human impacts." (p. 763). The author agrees that including the human element in the description of a heat wave is necessary when setting the parameters of event magnitude and determining event impacts, but does not intend on the use of human factors to determine the occurrence and extent of a heat wave. Additionally, while HI is based on the response of humans, the thresholds established for heat stress exposure categories are likely to be valuable in studying other organisms. A potential need to include concepts such as human impact and mitigation is a likely one reason why heat waves still do not have a universal definition.

An example of how the two classification schema developed for this dissertation can work together is provided in Table 5.1. This table has daily results for Topeka and Chicago for the notable heat wave in July 1995. The first task was to identify a string of days when discomfort surpassed the daily minimum threshold of HI 90 for > 40 hours. The dates and results provided in Table 5.1 are similar, with the classified heat stress days shaded in gray. With just this information, one can begin to hypothesize a migration of stressful conditions across the central U.S. from Topeka toward Chicago. At these two stations, the heat wave was first observed at Topeka on July 10. Heat stress conditions were not recorded until July 12 at Chicago, two days later. The duration of the heat wave at the two locations can be identified as having lasted for 6 days in Topeka, and just 5 in Chicago; however, the event ended a day earlier in Topeka. These observations provide insight into the synoptic progression of heat stress conditions as they migrated to the east during this time period.

Table 5.1: Accumulated daily HI values in July of 1995 for Topeka and Chicago indicating timing, duration, and magnitude of the event

Topeka	HI 90	HI 105	HI<75	Category
7/9/1995	0	0	23	0
7/10/1995	58	0	1	1
7/11/1995	234	53	0	5
7/12/1995	212	42	0	5
7/13/1995	202	23	0	4
7/14/1995	127	0	0	1
7/15/1995	86	0	0	1
7/16/1995	21	0	0	0

Chicago	HI 90	HI 105	HI<75	Category
7/9/1995	0	0	1	0
7/10/1995	0	0	7	0
7/11/1995	17	0	0	0
7/12/1995	154	0	0	1
7/13/1995	351	107	0	5
7/14/1995	351	86	0	5
7/15/1995	141	3	0	2
7/16/1995	50	0	0	1

Using the results provided in Table 5.1, it might be concluded based on the higher values for HI 90 and HI 105 on July 13 and 14 that the Chicago heat wave was more intense than the Topeka heat wave. Chicago's daily magnitudes of HI above 32.2° C (90° F) and 40.6° C (105° F) are clearly higher than those at Topeka, with neither experiencing notable hours of recovery during the event. (The one-hour of recovery during the event at Topeka was in the early morning of the first day.)

Since both of these locations recorded a Category 5 day during the event, the heat wave for both is considered a Category 5. However, comparisons of the hottest days between the two locations indicate that although the highest classification category was achieved, accumulated daily heat stress in Chicago became significantly greater, although the event was longer in Topeka. July 11th and 12th for Topeka both reached overnight recovery levels below 26.6° C (80° F) for at least one hour, although no hours were below HI 23.9° C (75° F). Indices surpassing 40.6° C (105° F) occurred after noon and lasted through 7 pm. In contrast to Topeka, July 13th and 14th in Chicago recorded just three total hours below HI of 32.2° C (90° F). These data indicate that hazardous HI levels were maintained throughout the overnight hours, and for 45 consecutive hours into the morning of the 15th. The lack of recovery was coupled with a steep increase of HI in both mornings when indices surpassed 40.6° C (105° F) by 9:00 am, and sustained these indices (up to 48.3° C [119° F]) through 7 pm. The significance of event intensity and very rapid onset of intense conditions in Chicago has been linked to the sensitivity component of hazard vulnerability; 735 deaths in the Chicago area were attributed to the July 1995 heat wave (Karl and Knight 1997).

Comparisons between Topeka and Chicago during this event not only indicate how a system that produces a heat wave can migrate over time with varying magnitude at different locations, they also may illustrate the importance of identifying the rapidity that indices reach 40.6° C (105° F) during the day. Indices that surpass dangerous levels by mid morning produce conditions that are hazardous for extended periods through the day, which is more apt to increase human mortality. Future studies may decide that events, like the one impacting Chicago in July 1995, are so important that an additional classification category is needed to highlight these very extreme events.

Some economic data variations could provide signals that the population is reacting or has reacted to a period of increased heat, especially over prolonged periods. Consumptive spikes in utilities usage such as electricity or water are likely to correlate with the human reaction to heat wave exposure. Differences in use that are significantly above average could also be an indicator of a population response that is distinctively local. The classification system proposed in this research is normalized for all locations with a focus on the frequency that certain levels of

HI occurred per station. Observation of public work usages would address sensitivity and adaptive capacity and indicate a strong correlation between HI and local impacts.

Maps and tables presented in this research were made from the statistics extracted from the summary tables in Appendices B and C. They illustrate the spatial distribution of general heat stress patterns across the United States. Contours were used to show the totals for the number of days classified per category and number of events per category. Results document little or no heat wave activity in areas of high elevation or in northern portions of the country. High heat wave frequency patterns indicate that the highest values centered on two locations, the Desert Southwest and the lowlands extending from the western Gulf Coast northward to the west of the Ozark Plateau. Maps were also used to present the heat wave season at all locations nationwide and a sequence of maps was used to illustrate the daily magnitude, extent, and migration of a single heat wave over the temporal period of its occurrence.

Examination of a particular case study regionally and temporally, the July 1995 event, was accomplished with the heat stress classification system. When a heat wave is the cause of excess mortality in an area, corresponding heat stress data can be collected for all surrounding areas and then analyzed. Exact hourly progression of HI levels during the day can be evaluated. On a day-by-day basis, the heat stress classification per location can be examined/compared, with the consecutive classification assignments denoting the temporal development of the heat wave. GIS can be used to map areas experiencing a heat wave at or above a certain category, say 3 or greater, and determine the spatial extent of strong to extreme heat wave conditions. Use of additional data sets, such as population, would permit identification of the population at risk from these extreme conditions. Identifying the duration, magnitude, geographic extent and migration of a heat wave provides insight into the heat wave itself, which would be associated with the impacts on local areas throughout the event.

Results from this study illustrate that the magnitude of heat stress can vary markedly over short distances. It is extremely rare for stations near each other to exhibit the same day-to-day progression of daily heat stress categories. A heat wave does not end when one weather station ceases to record a heat stress category, just like Hurricane Katrina was not over after it passed the southern tip of Florida in August of 2005. The 1995 heat wave that caused high mortality rates in the Midwest was an event that lasted about one week and migrated eastward, however the duration at Chicago was just 5 days.

In contrast, the Central Plains and American Southeast experienced a heat wave that correlated with a severe drought in the summer of 1980 (Karl and Quayle 1981 and Namias 1982). Areas around Little Rock, Nashville, St. Louis, and Wichita experienced Category 5 heat waves lasting 3-4 weeks, and Atlanta recorded all six of its Category 5 days during one heat wave (five of the category 5 days were consecutive and all six were within 8 days). Development of an objective method to compare heat waves of different durations and amounts of daily magnitude in greater detail is part of the future research that can stem from this study.

Improvements and Future Research

Daily heat stress categories were designed to separate increasing magnitudes of excessive heat based on systematic breaks in the amount of HI accumulation. Assignment of a Category 1 began with 40 excess hours of HI 90, with each successive category adding 40 more excess hours (Table 3.2), and the thresholds of HI 105 accumulation increased with successive categories as well. These thresholds were inspired by the work by Hahn *et al*. (1999) who established fuzzy boundaries based on his experience with the THI and losses in cattle feedlots.

Upon completing the analysis for this project, it was believed that the parameters for reaching a Category 5 heat stress day may have been set too low. With 14 of the 45 stations (31%) that had days recorded in the top two categories equal or more Category 5 heat stress days than Category 4 heat stress days, one could argue to adjust the Category 5 threshold upward. This research project was a first run with the new classification, and used thresholds based on a quick assessment of a few selected Midwestern locations. Possible adjustment of the class breaks might be expected following a more complete understanding based on completion of this entire study and/or analysis of additional places or years.

Determination of the actual differences among heat waves of the same category is still a concern as these hazards have considerable internal variation. Identification of the effects of a 6-day heat wave versus a 16- or 41-day event could be done in any of a number of ways: by comparing average daily heat stress levels to those of events in the past per location, by comparing cumulative daily heat stress over the period of the heat wave, by looking to see if there are day-to-day changes in heat stress that ‘shock’ the local system (as happened in Chicago in 1995), or by looking at the total economic loss during the event if one is interested in other aspects of vulnerability beyond the exposure component.

Questions that have risen from analysis of these results include: How should one differentiate heat waves of different durations and levels of daily magnitude? How should the amount of change in heat magnitude from one day to the next be interpreted? What combinations of heat stress days are needed to cause heat-related mortality at a specific location? What effect does the climatology of heat wave exposure duration have on the vulnerability measures of sensitivity and/or adaptive capacity? Do people acclimatize to events that persist for weeks or months so that economic impacts become minimized over time? To obtain answers to these questions, results from this research addressing the exposure component of vulnerability need to be combined with local sensitivity and adaptive capacity, which would require records of local impacts on humans from data characterizing work reductions during period of heat stress or past medical records correlating health issues with a known event. Since adaptive capacity depends in part on access to resources, measures that identify knowledge or financial resources would be important in studies that advance this area of scholarship.

Development of local heat stress modeling would also be beneficial to better understand the effects that vegetation type and land management has on heat stress. The foundation for these analyses are based on the Bowen Ratio, which indicates that energy can be computed as sensible heat in proportion to the latent heat of evaporation($\beta = H / LE$). Latent heat is the amount of energy needed to change the state of a substance (in this case water) from a liquid to a vapor. In areas with a higher density of vegetation biomass, more solar radiation is used for plant respiration rather than heating surface temperatures and the overriding air. The city of Atlanta is surrounded by the dense forests of northern Georgia, which could in part explain the heat stress values in that area being lower than expected.

Knowledge that dense settlement patterns produce a phenomena known as the urban heat island effect has lead urban planners to consider developing green zones and green roofs. Since the presence of man-made objects like buildings and roads are constructed by substances like concrete, asphalt, and metal, which have high thermal conductivity, there are higher temperatures in urban areas than surrounding rural land (especially at night). Development of zones of vegetation in an urban area would make the horizontal temperature profile less homogenous. Green roofs are now being more adopted by cities in the U.S. with locations like Chicago and Atlanta planting vegetation on the roofs of buildings (Worden *et al* 2004). Not only would the solar absorption and transpiration rates aid in reducing temperatures caused by urban heat island effect, but also a 45° C (81° F) reduction in surface temperatures was found in a study by Liu and Baskaran (2003) markedly reducing the energy usage of a building. Understanding the impacts of these urban thermal modifications would require more localized modeling that incorporates smaller-scale temperature variations. Such modeling would demonstrate the geography of heat stress within urban areas as compared to surrounding areas and provide a better local understanding of why relatively nearby areas exhibit widely different heat stress characteristics.

Heat wave durations in some areas may warrant more attention. Individual analyses may need to be conducted for locations where heat wave duration is routinely long. It is difficult to compare the 67-day Category 5 event in Phoenix (that began on June 29, 1996) to considerably shorter events in the Middle West; a heat wave at Phoenix tends to have certain periods that are more extreme while base summer temperatures in the area sustain Category 1 daily heat stress levels. There were seven periods during this 1996 event when daily categories increased to categories between 2 and 5, and then decreased back to a Category 1. One modification of the current classification might be to slightly increase the threshold for what is a Category 1 heat stress day. Developing a heat stress based heat wave climatology solely for Phoenix would be highly likely to transform this 67-day event into several individual events when heat and humidity levels increased above the local base line. This scenario begs the question: Are the current Category 1 heat stress days considered as a recovery, or non-hazard, in the Phoenix area? Because of the ‘dry heat’ characteristic of the southwestern deserts, just reaching air temperatures surpassing 32.2° C (90° F) throughout a day in mid-summer may not be considered hazardous to an acclimated local population.

Continuing clarification may still be needed for defining the character of heat waves. This work focused on the 48 contiguous United States, and employed the HI which uses the same two weather components of temperature and humidity for all locations. Results illustrate that conditions which produce periods of excessive heat stress in the eastern half of the country (Texas to North Dakota eastward) were not the same as the locations in western states. The only weather station in the West that registered heat events that was related to relatively high humidity was Fresno in the San Joaquin Valley of central California, which is an area of intensive agriculture and irrigation. When periods of excessive heat occur without the influence of moist air, those periods of heat stress perhaps should be distinguished from the sultry conditions that characterize the southeastern United States.

This research posits that the definition of a heat wave may be hindered by the apparent need to assume these two types of events are difficult to separate. Based on how organisms respond differently to dry heat as compared to sultry conditions, further work defining heat waves might address moist versus dry heat waves and the intersection between these two different forms of climatic stress in places such as the eastern edge of the High Plains, where both types can occur at the same geographic location. Heat stress exposure and heat waves, as examined in this research, may be a significant component of a larger social/intellectual construct, the hot weather hazard. The hot weather hazard represents an idea that couples natural and human systems and as such combines exposure with local sensitivity and adaptive capacity. To separate different types of exposure, perhaps heat waves should be characterized by locally and regionally oppressive heat stress exposure conditions that are perpetuated by the combination of high temperatures and abundant moisture. Situations, such as those in Phoenix and Las Vegas, when excessive heat events occur based almost entirely on elevated air temperatures alone should be defined separately, perhaps as a hot spell.

Conclusion

The records of daily heat stress analyzed in this research are intended to serve as a basis for understanding heat stress variations across the 48 contiguous states of the United States. A goal was to provide a way to compare the record that occurs on a local scale with regional patterns so that heat waves could then be better understood in time and space. This study was successful in its intent on classifying heat stress magnitude on a daily basis, and accomplished the identification of heat waves by magnitude by using daily heat stress accumulations as a foundation. The application of the new heat wave classification to numerous locations in the United States documented that the characteristics of heat stress vary considerably over short distances.

The persisting difficulty that exists in objectively defining a heat wave is because of the inherent variability in several related factors: daily weather variability, local climatic norms, resistance/adaptation to extreme heat by local crop types and confined livestock, and the innumerable factors regarding vulnerability among humans. There are also social issues that are linked to heat waves, such as ideas of environmental injustice, an apathy towards those in need during times of this climatic hazard, and the potential for elevated rates of crimes against other people either through anger or desperation (Hipp *et al*. 2004). Developing a better grasp on the differences in how heat stress exposure is experienced at the local scale is necessary for building a more robust set of varying definitions that can characterize the heat wave hazard.

However, although heat stress levels and organism response can vary considerably over time and space, attempting to assign locally specific heat wave definitions for all places would not be practical for those involved in working to mitigate this hazard. This study suggests that the use of a simple classification system, which is normalized for any location based solely on the daily accumulation of heat stress, can produce meaningful results. Response to a forecast for a specific category of heat wave lasting for a specified length of time should be founded on the local knowledge of past climate variations and local sensitivity.

One intent for this research was to provide an available climatological record of heat stress levels and heat wave activity to assist hazard warning services in the United States. It is hoped that the results have been presented in a way that can be quickly understood by the general public. For example, if local broadcast meteorologists in Indianapolis predict that heat and humidity levels are going to reach a Category 4 in the coming days, they can say that this forecast suggests that severe heat stress levels predicted during the upcoming period have only been experienced 4 times in the past 22 years. Local vulnerability concerns can then be expressed as an immediate hazard to all local inhabitants, not just the sick or infirm (those typically most at risk), because of the low frequency of such an excessive heat hazard. With global climate change, extreme heat waves have already begun to exert impacts on human mortality in unsuspecting areas that are considered developed technologically and economically (Klinenberg 1999 and Vandentorren *et al*. 2004). Future climate scenarios suggest that extreme heat stress events will be more likely in areas where air conditioning may not be as available as other places because, climatologically, it not generally necessary. More progress is needed to adequately communicate the level of danger that exists during periods of elevated heat stress. It is hoped that results from this research will promote actions that will produce lowered impacts from heat stress events and heat waves because the information is succinct enough for public reaction.

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APPENDIX A – Spreadsheet Functions Used to Obtain Daily Heat Stress Values

A.1: Functions determining how many hourly thresholds were met per day. The values in these examples are in row 2 between the 24 columns of C and Z.

=COUNTIF(C2:Z2,“>=90”)
=COUNTIF(C2:Z2,“>=105”)
=COUNTIF(C2:Z2,“<75”)

A.2: Functions that determine the amount of accumulated daily heat stress above the thresholds of HI 90 and HI 105. The values in these examples are in row 2 between the 24 columns of C and Z. Columns AB and AC are the values obtained for ‘90’ and ‘105’ in the A.1 functions above.

=SUMIF(C2:Z2,“>=90”,C2:Z2)-(AB2*90)
=SUMIF(C2:Z2,“>=105”,C2:Z2)-(AC2*105)

A.3: Functions used to determine if a daily accumulated heat stress magnitude met specific criteria in the heat stress classification. All of these examples are shown for row 2, which is the first available day for all stations.

Category 1: =IF(AF2>=40,1,0) – If criteria meets 40, value is a 1; if not value is a 0

Category 2: =IF(AF2>=80,2,0) – If criteria met, value is a 2; if not value is a 0
=IF(AG2>=1,2,0) “
=IF(AH2<=10,2,0) “

Category 3: =IF(AF2>=120, 3, 0) – If criteria met, value is a 3; if not value is a 0
=IF(AG2>=10, 3, 0) “
=IF(AH2<=6, 3, 0) “

Category 4: =IF(AF2>=160, 4, 0) – If criteria met, value is a 4; if not value is a 0
=IF(AG2>=20, 4, 0) “
=IF(AH2<=2, 4, 0) “

Category 5: =IF(AF2>=200, 5, 0) – If criteria met, value is a 5; if not value is a 0
=IF(AG2>=35, 5, 0) “
=IF(AH2=0, 5, 0)

APPENDIX B – Weather Station Summary Tables

Albany, NY	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	23	2	1	0	0	26
Avg Days	1.05	0.09	0.05	0.00	0.00	
Events	5	2	1	0	0	8
Events/year	0.63	0.25	0.13	0.00	0.00	
Avg Events	0.23	0.09	0.05	0.00	0.00	
Avg Duration	3.25 Days					
Events/yr	0.36					
Unclassed 1s	45					

Amarillo, TX	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	61	0	0	0	0	61
Avg Days	2.90	0.00	0.00	0.00	0.00	
Events	14	0	0	0	0	14
Events/year	1.17	0.00	0.00	0.00	0.00	
Avg Events	0.67	0.00	0.00	0.00	0.00	
Avg Duration	4.21 Days					
Events/yr	0.64					
Unclassed 1s	64					

Atlanta, GA	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	323	44	8	1	6	382
Avg Days	14.68	2.00	0.36	0.05	0.27	
Events	47	14	4	0	1	66
Events/year	0.71	0.21	0.06	0.00	0.02	
Avg Events	2.14	0.64	0.18	0.00	0.05	
Avg Duration	5.76 Days					
Events/yr	3.00					
Unclassed 1s	98					

Baton Rouge, LA	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	997	174	39	22	11	1243
Avg Days	45.32	7.91	1.77	1.00	0.50	
Events	91	48	13	7	7	166
Events/year	0.55	0.29	0.08	0.04	0.04	
Avg Events	4.14	2.18	0.59	0.32	0.32	
Avg Duration	7.49 Days					
Events/yr	7.55					
Unclassed 1s	185					

Billings, MT	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	0	0	0	0	0	0
Avg Days	0.00	0.00	0.00	0.00	0.00	
Events	0	0	0	0	0	0
Events/year	0.00	0.00	0.00	0.00	0.00	
Avg Events	0.00	0.00	0.00	0.00	0.00	

Avg Duration	0.00 Days
Events/yr	0.00
Unclassed 1s	11

Birmingham, AL	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	479	70	24	13	14	600
Avg Days	21.77	3.18	1.09	0.59	0.64	
Events	62	18	10	5	9	104
Events/year	0.60	0.17	0.10	0.05	0.09	
Avg Events	2.82	0.82	0.45	0.23	0.41	

Avg Duration	5.81 Days
Events/yr	4.72
Unclassed 1s	145

Boise, ID	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	8	2	0	0	0	10
Avg Days	0.36	0.09	0.00	0.00	0.00	
Events	2	1	0	0	0	3
Events/year	0.67	0.33	0.00	0.00	0.00	
Avg Events	0.09	0.05	0.00	0.00	0.00	

Avg Duration	3.33 Days
Events/yr	0.14
Unclassed 1s	35

Brownsville, TX	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	1909	455	63	25	4	2456
Avg Days	90.90	21.67	3.00	1.19	0.19	
Events	88	60	20	10	3	181
Events/year	0.51	0.34	0.11	0.06	0.02	
Avg Events	4.19	2.86	0.95	0.48	0.14	

Avg Duration	13.57 Days
Events/yr	8.23
Unclassed 1s	148

Burlington, VT	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	7	1	0	0	0	8
Avg Days	0.32	0.05	0.00	0.00	0.00	
Events	2	1	0	0	0	3
Events/year	0.67	0.33	0.00	0.00	0.00	
Avg Events	0.09	0.05	0.00	0.00	0.00	

Avg Duration	2.67 Days
Events/yr	0.14
Unclassed 1s	26

Casper, WY	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	0	0	0	0	0	0
Avg Days	0.00	0.00	0.00	0.00	0.00	
Events	0	0	0	0	0	0
Events/year	0.00	0.00	0.00	0.00	0.00	
Avg Events	0.00	0.00	0.00	0.00	0.00	

Avg Duration	0.00 Days
Events/yr	0.00
Unclassed 1s	1

Charleston, WV	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	85	10	6	0	0	101
Avg Days	3.86	0.45	0.27	0.00	0.00	
Events	16	6	6	0	0	28
Events/year	0.57	0.21	0.21	0.00	0.00	
Avg Events	0.73	0.27	0.27	0.00	0.00	

Avg Duration	3.61 Days
Events/yr	1.27
Unclassed 1s	64

Chicago, IL	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	78	19	7	5	6	115
Avg Days	3.55	0.86	0.32	0.23	0.27	
Events	11	10	4	4	4	33
Events/year	0.33	0.30	0.12	0.12	0.12	
Avg Events	0.50	0.45	0.18	0.18	0.18	

Avg Duration	3.48 Days
Events/yr	1.50
Unclassed 1s	105

Columbia, MO	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	250	76	32	18	4	380
Avg Days	11.36	3.45	1.45	0.82	0.18	
Events	31	21	14	8	3	77
Events/year	0.40	0.27	0.18	0.10	0.04	
Avg Events	1.41	0.95	0.64	0.36	0.14	

Avg Duration	4.94 Days
Events/yr	3.50
Unclassed 1s	141

Columbia, SC	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	581	121	20	16	6	744
Avg Days	26.41	5.50	0.91	0.73	0.27	
Events	71	32	13	7	3	126
Events/year	0.56	0.25	0.10	0.06	0.02	
Avg Events	3.23	1.45	0.59	0.32	0.14	

Avg Duration	5.90 Days
Events/yr	5.73
Unclassed 1s	180

Columbus, OH	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	78	4	5	1	3	91
Avg Days	3.55	0.18	0.23	0.05	0.14	
Events	14	4	3	0	2	23
Events/year	0.61	0.17	0.13	0.00	0.09	
Avg Events	0.64	0.18	0.14	0.00	0.09	

Avg Duration	4.04 Days
Events/yr	1.05
Unclassed 1s	75

Dallas, TX	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	1073	252	73	55	24	1477
Avg Days	51.10	12.00	3.48	2.62	1.14	
Events	59	42	15	16	10	142
Events/year	0.43	0.30	0.11	0.12	0.07	
Avg Events	2.81	2.00	0.71	0.76	0.48	

Avg Duration	10.40 Days
Events/yr	6.45
Unclassed 1s	150

Denver, CO	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	0	0	0	0	0	0
Avg Days	0.00	0.00	0.00	0.00	0.00	
Events	0	0	0	0	0	0
Events/year	0.00	0.00	0.00	0.00	0.00	
Avg Events	0.00	0.00	0.00	0.00	0.00	

Avg Duration	0.00 Days
Events/yr	0.00
Unclassed 1s	0

Des Moines, IA	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	116	50	24	8	8	206
Avg Days	5.27	2.27	1.09	0.36	0.36	
Events	13	18	11	4	7	53
Events/year	0.25	0.34	0.21	0.08	0.13	
Avg Events	0.59	0.82	0.50	0.18	0.32	

Avg Duration	3.89 Days
Events/yr	2.41
Unclassed 1s	115

Dodge City, KS	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	361	31	8	2	1	403
Avg Days	17.19	1.48	0.38	0.10	0.05	
Events	61	16	2	1	1	77
Events/year	0.79	0.21	0.03	0.01	0.01	
Avg Events	2.90	0.76	0.10	0.05	0.05	

Avg Duration	4.98 days
Events/yr	3.50
Unclassed 1s	173

Eugene, OR	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	3	0	1	0	0	4
Avg Days	0.14	0.00	0.05	0.00	0.00	
Events	0	0	1	0	0	1
Events/year	0.00	0.00	1.00	0.00	0.00	
Avg Events	0.00	0.00	0.05	0.00	0.00	

Avg Duration	4.00 Days
Events/yr	0.05
Unclassed 1s	18

Fargo, ND	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	20	10	1	4	0	35
Avg Days	0.91	0.45	0.05	0.18	0.00	
Events	4	5	0	4	0	13
Events/year	0.31	0.38	0.00	0.31	0.00	
Avg Events	0.18	0.23	0.00	0.18	0.00	

Avg Duration	2.69 Days
Events/yr	0.59
Unclassed 1s	59

Flagstaff, AZ	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	0	0	0	0	0	0
Avg Days	0.00	0.00	0.00	0.00	0.00	
Events	0	0	0	0	0	0
Events/year	0.00	0.00	0.00	0.00	0.00	
Avg Events	0.00	0.00	0.00	0.00	0.00	

Avg Duration	0.00 Days
Events/yr	0.00
Unclassed 1s	0

Fresno, CA	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	472	86	31	23	14	626
Avg Days	21.45	3.91	1.41	1.05	0.64	
Events	57	32	8	7	8	112
Events/year	0.51	0.29	0.07	0.06	0.07	
Avg Events	2.59	1.45	0.36	0.32	0.36	

Avg Duration	5.59 Days
Events/yr	5.09
Unclassed 1s	102

Houston, TX	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	989	356	149	116	172	1783
Avg Days	47.10	16.95	7.10	5.52	8.19	
Events	38	45	36	28	86	233
Events/year	0.17	0.20	0.16	0.12	0.38	
Avg Events	1.81	2.14	1.71	1.33	4.10	

Avg Duration	7.64 Days
Events/yr	10.59
Unclassed 1s	163

Indianapolis, IN	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	118	25	9	4	3	159
Avg Days	5.36	1.14	0.41	0.18	0.14	
Events	20	10	4	4	3	41
Events/year	0.49	0.24	0.10	0.10	0.07	
Avg Events	0.91	0.45	0.18	0.18	0.14	

Avg Duration	3.89 Days
Events/yr	1.86
Unclassed 1s	86

Jackson, MI	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	883	159	64	26	21	1153
Avg Days	40.14	7.23	2.91	1.18	0.95	
Events	89	34	14	9	7	153
Events/year	0.58	0.22	0.09	0.06	0.05	
Avg Events	4.05	1.55	0.64	0.41	0.32	

Avg Duration	7.52 Days
Events/yr	6.95
Unclassed 1s	167

Lansing, MI	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	84	6	0	1	1	92
Avg Days	3.82	0.27	0.00	0.05	0.05	
Events	19	4	0	0	1	24
Events/year	0.79	0.17	0.00	0.00	0.04	
Avg Events	0.86	0.18	0.00	0.00	0.05	

Avg Duration	3.83 Days
Events/yr	1.09
Unclassed 1s	131

Las Vegas, NV	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	854	136	33	16	8	1047
Avg Days	38.82	6.18	1.50	0.73	0.36	
Events	78	23	12	9	5	127
Events/year	0.61	0.18	0.09	0.07	0.04	
Avg Events	3.55	1.05	0.55	0.41	0.23	

Avg Duration	8.24 Days
Events/yr	5.77
Unclassed 1s	145

Lexington, KY	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	130	10	3	0	1	144
Avg Days	5.91	0.45	0.14	0.00	0.05	
Events	24	4	3	0	1	32
Events/year	0.75	0.13	0.09	0.00	0.03	
Avg Events	1.09	0.18	0.14	0.00	0.05	

Avg Duration	4.36 Days
Events/yr	1.45
Unclassed 1s	95

Little Rock, AR	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	514	188	74	57	62	895
Avg Days	23.36	8.55	3.36	2.59	2.82	
Events	41	31	18	13	13	116
Events/year	0.35	0.27	0.16	0.11	0.11	
Avg Events	1.86	1.41	0.82	0.59	0.59	

Avg Duration	7.71 Days
Events/yr	5.05
Unclassed 1s	144

Los Angeles, CA	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	0	0	0	0	0	0
Avg Days	0.00	0.00	0.00	0.00	0.00	
Events	0	0	0	0	0	0
Events/yr	0.00	0.00	0.00	0.00	0.00	
Avg Events	0.00	0.00	0.00	0.00	0.00	

Avg Duration	0.00 Days
Events/yr	0.00
Unclassed 1s	1

Madison, WI	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	36	13	2	2	3	56
Avg Days	1.64	0.59	0.09	0.09	0.14	
Events	4	9	2	1	2	18
Events/year	0.22	0.50	0.11	0.06	0.11	
Avg Events	0.18	0.41	0.09	0.05	0.09	

Avg Duration	4.58 Days
Events/yr	0.82
Unclassed 1s	64

Memphis, TN	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	673	186	69	40	51	1019
Avg Days	30.59	8.45	3.14	1.82	2.32	
Events	62	28	14	15	17	136
Events/year	0.46	0.21	0.10	0.11	0.13	
Avg Events	2.82	1.27	0.64	0.68	0.77	

Avg Duration	7.36 Days
Events/yr	6.18
Unclassed 1s	133

Miami, FL	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	1473	50	1	0	0	1524
Avg Days	66.95	2.27	0.05	0.00	0.00	
Events	153	25	1	0	0	179
Events/year	0.85	0.14	0.01	0.00	0.00	
Avg Events	6.95	1.14	0.05	0.00	0.00	

Avg Duration	8.45 Days
Events/yr	8.14
Unclassed 1s	245

Midland, TX	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	362	7	3	2	0	374
Avg Days	17.24	0.33	0.14	0.10	0.00	
Events	64	3	2	2	0	71
Events/year	0.96	0.04	0.03	0.03	0.00	
Avg Events	3.05	0.14	0.10	0.10	0.00	

Avg Duration	5.24 Days
Events/yr	3.23
Unclassed 1s	164

Minneapolis, MN	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	33	12	4	7	0	56
Avg Days	1.50	0.55	0.18	0.32	0.00	
Events	2	9	3	5	0	19
Events/year	0.11	0.47	0.16	0.26	0.00	
Avg Events	0.09	0.41	0.14	0.23	0.00	

Avg Duration	2.95 Days
Events/yr	0.86
Unclassed 1s	70

Nashville, TN	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	352	51	19	5	5	432
Avg Days	16.00	2.32	0.86	0.23	0.23	
Events	50	22	5	1	5	83
Events/year	0.60	0.27	0.06	0.01	0.06	
Avg Events	2.27	1.00	0.23	0.05	0.23	

Avg Duration	5.20 Days
Events/yr	3.77
Unclassed 1s	150

New York, NY	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	49	17	3	1	2	72
Avg Days	2.23	0.77	0.14	0.05	0.09	
Events	9	9	2	1	2	23
Events/year	0.39	0.39	0.09	0.04	0.09	
Avg Events	0.41	0.41	0.09	0.05	0.09	

Avg Duration	3.17 Days
Events/yr	1.05
Unclassed 1s	95

North Platte, NE	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	85	11	2	0	0	98
Avg Days	4.05	0.52	0.10	0.00	0.00	
Events	19	5	2	0	0	26
Events/year	0.79	0.21	0.08	0.00	0.00	
Avg Events	0.90	0.24	0.10	0.00	0.00	

Avg Duration	3.77 Days
Events/yr	1.18
Unclassed 1s	109

Oklahoma City, OK	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	650	135	30	24	3	842
Avg Days	30.95	6.43	1.43	1.14	0.14	
Events	66	35	9	9	3	122
Events/year	0.56	0.30	0.08	0.08	0.03	
Avg Events	3.14	1.67	0.43	0.43	0.14	

Avg Duration	6.90 Days
Events/yr	5.55
Unclassed 1s	162

Omaha, NE	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	128	60	37	21	14	260
Avg Days	6.10	2.86	1.76	1.00	0.67	
Events	12	18	16	10	9	65
Events/year	0.20	0.30	0.26	0.16	0.15	
Avg Events	0.57	0.86	0.76	0.48	0.43	

Avg Duration	4.00 Days
Events/yr	2.95
Unclassed 1s	131

Orlando, FL	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	1083	74	16	5	1	1179
Avg Days	49.23	3.36	0.73	0.23	0.05	
Events	140	27	6	3	1	177
Events/year	0.79	0.15	0.03	0.02	0.01	
Avg Events	6.36	1.23	0.27	0.14	0.05	

Avg Duration	6.66 Days
Events/yr	8.05
Unclassed 1s	267

Pensacola, FL	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	829	201	67	29	15	1141
Avg Days	37.68	9.14	3.05	1.32	0.68	
Events	76	45	17	8	10	156
Events/year	0.49	0.29	0.11	0.05	0.06	
Avg Events	3.45	2.05	0.77	0.36	0.45	

Avg Duration	7.24 Days
Events/yr	7.09
Unclassed 1s	201

Philadelphia, PA	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	136	36	13	12	3	200
Avg Days	6.18	1.64	0.59	0.55	0.14	
Events	17	20	4	8	3	52
Events/year	0.33	0.38	0.08	0.15	0.06	
Avg Events	0.77	0.91	0.18	0.36	0.14	

Avg Duration	3.85 Days
Events/yr	2.36
Unclassed 1s	104

Phoenix, AZ	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	1188	405	204	206	128	2131
Avg Days	54.00	18.41	9.27	9.36	5.82	
Events	48	18	12	7	32	117
Events/year	0.41	0.15	0.10	0.06	0.27	
Avg Events	2.18	0.82	0.55	0.32	1.45	
Avg Duration	18.21 Days					
Events/yr	5.32					
Unclassed 1s	80					

Pierre, SD	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	99	45	12	5	1	162
Avg Days	4.50	2.05	0.55	0.23	0.05	
Events	8	30	7	4	1	50
Events/year	0.16	0.60	0.14	0.08	0.02	
Avg Events	0.36	1.36	0.32	0.18	0.05	
Avg Duration	3.20 Days					
Events/yr	2.27					
Unclassed 1s	145					

Pittsburgh, PA	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	31	3	1	1	0	36
Avg Days	1.41	0.14	0.05	0.05	0.00	
Events	6	2	1	1	0	10
Events/year	0.60	0.20	0.10	0.10	0.00	
Avg Events	0.27	0.09	0.05	0.05	0.00	
Avg Duration	3.60 Days					
Events/yr	3.60					
Unclassed 1s	39					

Pocatello, ID	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	0	0	0	0	0	0
Avg Days	0.00	0.00	0.00	0.00	0.00	
Events	0	0	0	0	0	0
Events/year	0.00	0.00	0.00	0.00	0.00	
Avg Events	0.00	0.00	0.00	0.00	0.00	
Avg Duration	0.00 Days					
Events/yr	0.00					
Unclassed 1s	5					

Pueblo, CO	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	0	0	0	0	0	0
Avg Days	0.00	0.00	0.00	0.00	0.00	
Events	0	0	0	0	0	0
Events/year	0.00	0.00	0.00	0.00	0.00	
Avg Events	0.00	0.00	0.00	0.00	0.00	
Avg Duration	0.00 Days					
Events/yr	0.00					
Unclassed 1s	40					

Raleigh, NC	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	281	42	20	7	0	350
Avg Days	12.77	1.91	0.91	0.32	0.00	
Events	39	18	10	6	0	73
Events/year	0.53	0.25	0.14	0.08	0.00	
Avg Events	1.77	0.82	0.45	0.27	0.00	

Avg Duration	4.78 Days
Events/yr	3.12
Unclassed 1s	166

Reno, NV	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	0	0	0	0	0	0
Avg Days	0.00	0.00	0.00	0.00	0.00	
Events	0	0	0	0	0	0
Events/year	0.00	0.00	0.00	0.00	0.00	
Avg Events	0.00	0.00	0.00	0.00	0.00	

Avg Duration	0.00 Days
Events/yr	0.00
Unclassed 1s	2

Richmond, VA	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	235	74	28	13	5	355
Avg Days	10.68	3.36	1.27	0.59	0.23	
Events	21	29	16	10	4	80
Events/year	0.26	0.36	0.20	0.13	0.05	
Avg Events	0.95	1.32	0.73	0.45	0.18	

Avg Duration	4.41 Days
Events/yr	3.64
Unclassed 1s	176

Roswell, NM	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	105	10	1	0	0	116
Avg Days	4.77	0.45	0.05	0.00	0.00	
Events	21	6	1	0	0	28
Events/year	0.75	0.21	0.04	0.00	0.00	
Avg Events	0.95	0.27	0.05	0.00	0.00	

Avg Duration	4.14 Days
Events/yr	1.27
Unclassed 1s	102

Salt Lake City, UT	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	14	1	0	0	0	15
Avg Days	0.64	0.05	0.00	0.00	0.00	
Events	3	1	0	0	0	4
Events/year	0.75	0.25	0.00	0.00	0.00	
Avg Events	0.14	0.05	0.00	0.00	0.00	

Avg Duration	3.75 Days
Events/yr	0.18
Unclassed 1s	23

San Antonio, TX	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	1392	96	16	0	0	1504
Avg Days	66.29	4.57	0.76	0.00	0.00	
Events	97	39	14	0	0	150
Events/year	0.67	0.27	0.10	0.00	0.00	
Avg Events	4.62	1.86	0.67	0.00	0.00	

Avg Duration	10.00 Days
Events/yr	6.82
Unclassed 1s	189

San Francisco, CA	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	0	0	0	0	0	0
Avg Days	0.00	0.00	0.00	0.00	0.00	
Events	0	0	0	0	0	0
Events/year	0.00	0.00	0.00	0.00	0.00	
Avg Events	0.00	0.00	0.00	0.00	0.00	

Avg Duration	0.00 Days
Events/yr	0.00
Unclassed 1s	6

Savannah, GA	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	669	168	62	28	16	943
Avg Days	30.41	7.64	2.82	1.27	0.73	
Events	57	48	14	9	9	137
Events/year	0.42	0.35	0.10	0.07	0.07	
Avg Events	2.59	2.18	0.64	0.41	0.41	

Avg Duration	6.88 Days
Events/yr	6.22
Unclassed 1s	203

Seattle, WA	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	0	0	0	0	0	0
Avg Days	0.00	0.00	0.00	0.00	0.00	
Events	0	0	0	0	0	0
Events/year	0.00	0.00	0.00	0.00	0.00	
Avg Events	0.00	0.00	0.00	0.00	0.00	

Avg Duration	0.00 Days
Events/yr	0.00
Unclassed 1s	1

Sioux Falls, SD	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	72	23	11	5	2	113
Avg Days	3.27	1.05	0.50	0.23	0.09	
Events	9	11	8	4	2	34
Events/year	0.26	0.32	0.24	0.12	0.06	
Avg Events	0.41	0.50	0.36	0.18	0.09	

Avg Duration	3.32 Days
Events/yr	1.55
Unclassed 1s	102

Spokane, WA	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	0	0	0	0	0	0
Avg Days	0.00	0.00	0.00	0.00	0.00	
Events	0	0	0	0	0	0
Events/year	0.00	0.00	0.00	0.00	0.00	
Avg Events	0.00	0.00	0.00	0.00	0.00	
Avg Duration	0.00 Days					
Events/yr	0.00					
Unclassed 1s	7					

Springfield, IL	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	173	55	25	15	23	291
Avg Days	7.86	2.50	1.14	0.68	1.05	
Events	20	21	11	4	11	67
Events/year	0.30	0.31	0.16	0.06	0.16	
Avg Events	0.91	0.95	0.50	0.18	0.50	
Avg Duration	4.25 Days					
Events/yr	3.05					
Unclassed 1s	55					

Springfield, MO	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	322	58	7	1	0	388
Avg Days	14.64	2.64	0.32	0.05	0.00	
Events	37	25	7	1	0	70
Events/year	0.53	0.36	0.10	0.01	0.00	
Avg Events	1.68	1.14	0.32	0.05	0.00	
Avg Duration	5.50 Days					
Events/yr	3.18					
Unclassed 1s	126					

St. Louis, MO	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	278	94	36	28	28	464
Avg Days	12.64	4.27	1.64	1.27	1.27	
Events	29	39	7	12	13	100
Events/year	0.29	0.39	0.07	0.12	0.13	
Avg Events	1.32	1.77	0.32	0.55	0.59	
Avg Duration	4.63 Days					
Events/yr	4.55					
Unclassed 1s	163					

Topeka, KS	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	318	109	58	21	19	525
Avg Days	15.14	5.19	2.76	1.00	0.90	
Events	33	25	23	12	8	101
Events/year	0.34	0.26	0.23	0.12	0.08	
Avg Events	1.57	1.19	1.10	0.57	0.38	
Avg Duration	5.19					
Events/yr	4.59					
Unclassed 1s	162					

Tulsa, OK	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	583	205	81	78	62	1009
Avg Days	27.76	9.76	3.86	3.71	2.95	
Events	43	38	24	20	12	137
Events/year	0.33	0.29	0.18	0.15	0.09	
Avg Events	2.05	1.81	1.14	0.95	0.57	

Avg Duration	7.36 Days
Events/yr	6.23
Unclassed 1s	150

Washington, DC	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	169	31	13	4	2	219
Avg Days	7.68	1.41	0.59	0.18	0.09	
Events	22	17	10	4	2	55
Events/year	0.40	0.31	0.18	0.07	0.04	
Avg Events	1.00	0.77	0.45	0.18	0.09	

Avg Duration	3.98 Days
Events/yr	2.50
Unclassed 1s	125

Wichita, KS	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	495	105	34	21	13	668
Avg Days	23.57	5.00	1.62	1.00	0.62	
Events	49	43	16	9	2	119
Events/year	0.43	0.38	0.14	0.08	0.02	
Avg Events	2.33	2.05	0.76	0.43	0.10	

Avg Duration	5.61 days
Events/yr	5.41
Unclassed 1s	162

Williston, ND	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	22	7	1	0	0	30
Avg Days	1.00	0.32	0.05	0.00	0.00	
Events	3	5	1	0	0	9
Events/year	0.33	0.56	0.11	0.00	0.00	
Avg Events	0.14	0.23	0.05	0.00	0.00	

Avg Duration	3.33 Days
Events/yr	0.41
Unclassed 1s	43

Winnemucca, NV	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	8	0	0	0	0	8
Avg Days	0.36	0.00	0.00	0.00	0.00	
Events	2	0	0	0	0	2
Events/year	1.00	0.00	0.00	0.00	0.00	
Avg Events	0.09	0.00	0.00	0.00	0.00	

Avg Duration	4.00 Days
Events/yr	0.09
Unclassed 1s	18

Worcester, MA	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Totals
Sum of Days	1	1	0	0	0	2
Avg Days	0.05	0.05	0.00	0.00	0.00	
Events	0	1	0	0	0	1
Events/year	0.00	1.00	0.00	0.00	0.00	
Avg Events	0.00	0.05	0.00	0.00	0.00	

Avg Duration	2.00 Days
Events/yr	0.09
Unclassed 1s	16

APPENDIX C – Length of the Heat Wave Season per Station

Station	Avg 1st Day	Avg Last Day	Avg Length
Albany	July 12	July 16	5
Amarillo	July 13	July 20	8
Atlanta	June 29	August 13	46
Baton Rouge	June 5	September 11	99
Billings	-	-	-
Birmingham	June 26	August 22	58
Boise	July 23	July 27	5
Brownsville	May 15	October 6	145
Burlington	July 2	July 5	4
Casper	-	-	-
Charleston	July 17	August 4	19
Chicago	July 15	August 4	21
Columbia, MO	July 6	August 16	42
Columbia, SC	June 16	August 28	74
Columbus	July 15	July 29	15
Dallas	June 6	September 10	97
Denver	-	-	-
Des Moines	July 11	August 10	31
Dodge City	July 2	August 18	48
Eugene	August 7	August 11	5
Fargo	July 20	August 4	16
Flagstaff	-	-	-
Fresno	June 20	August 27	69
Houston	May 27	September 26	123
Indianapolis	July 13	August 7	26
Jackson	June 10	September 14	97
Lansing	July 8	August 1	25
Las Vegas	June 15	September 2	80
Lexington	July 8	August 4	28
Little Rock	June 19	September 3	77
Los Angeles	-	-	-
Madison	July 13	July 27	15
Memphis	June 12	August 24	74
Miami	June 9	September 25	109
Midland	June 6	August 12	68

Station	Avg 1st Day	Avg Last Day	Avg Length
Minneapolis	July18	August 2	16
Nashville	June 26	August 15	51
New York	July 12	July 23	12
North Platte	July 14	July 28	15
Oklahoma City	June 23	August 30	69
Omaha	June 30	August 10	42
Orlando	June 9	September 18	102
Pensacola	June 15	September 10	88
Philadelphia	July 6	August 1	27
Phoenix	June 1	September 24	116
Pierre	July 10	August 6	28
Pittsburgh	July 8	July 24	17
Pocatello	-	-	-
Pueblo	-	-	-
Raleigh	June 30	August 11	43
Reno	-	-	-
Richmond	July 1	August 16	47
Roswell	June 27	July 16	20
Salt Lake City	July 19	July 25	7
San Antonio	June 1	September 15	107
San Francisco	-	-	-
Savannah	June 14	September 6	85
Seattle	-	-	-
Sioux Falls	July 14	August 11	19
Spokane	-	-	-
Springfield, IL	July 11	August 15	36
Springfield, MO	July 8	August 18	42
St. Louis	July 1	August 23	54
Topeka	June 30	August 24	56
Tulsa	June 19	September 5	79
Washington	July 5	August 11	38
Wichita	June 26	August 30	66
Williston	July 9	July 26	18
Winnemucca	August 2	August 6	5
Worcester	July 18	July 21	4

APPENDIX D – K-Means Cluster Analysis Results

Station	Cluster	Station	Cluster
Billings	1	Indianapolis	2
Casper	1	Pierre	2
Denver	1	Philadelphia	2
Flagstaff	1	Des Moines	2
Los Angeles	1	Washington	2
Pocatello	1	Omaha	2
Pueblo	1	Atlanta	2
Reno	1	Springfield (IL)	2
San Francisco	1	Springfield	2
Seattle	1	Midland	2
Spokane	1	Raleigh	2
Eugene	1	Columbia	2
Worcester	1	Richmond	2
Winnemucca	1	Dodge City	2
Boise	1	Nashville	2
Burlington	1		
Salt Lake City	1	St. Louis	3
Albany	1	Topeka	3
Williston	1	Birmingham	3
Pittsburgh	1	Fresno	3
Fargo	1	Little Rock	3
Amarillo	1	Phoenix	3
Madison	1	Wichita	3
Minneapolis	1	Oklahoma City	3
Columbus	1	Columbia (SC)	3
New York	1	Las Vegas	3
Lansing	1	Memphis	3
North Platte	1	Savannah	3
Charleston	1	Tulsa	3
Roswell	1	Dallas	3
Lexington	1		
Chicago	1	San Antonio	4
Sioux Falls	1	Jackson	4
		Pensacola	4
		Baton Rouge	4
		Orlando	4
		Miami	4
		Brownsville	4
		Houston*	4

*Houston as an outlier is clustered with the 4s

Initial Cluster Centers

	Cluster				
	1	2	3	4	5
tot_evts	181.00	127.00	65.00	233.00	.00

Iteration History[a]

	Change in Cluster Centers				
Iteration	1	2	3	4	5
1	9.200	2.063	3.176	.000	9.323
2	5.800	3.795	3.776	.000	1.465
3	.000	.000	.000	.000	.000

Final Cluster Centers

	Cluster				
	1	2	3	4	5
tot_evts	166.00	121.14	65.60	233.00	10.79

Number of Cases in each Cluster

Cluster	1	7.000
	2	14.000
	3	15.000
	4	1.000
	5	33.000
Valid		70.000
Missing		.000