THE STOCHASTIC PROPERTIES OF HIGH DAILY MAXIMUM TEMPERATURES

By

DAVID J. KEELLINGS

A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

UNIVERSITY OF FLORIDA

2010
To Cynthia and Jim, my parents, for their love and support
ACKNOWLEDGMENTS

I am very appreciative of Dr. Peter Waylen, Dr. Timothy Fik, and Dr. Mark Brenner as members of my advisory committee and for their academic support in the completion of this research. I am especially grateful to Dr. Peter Waylen for his outstanding mentoring and dedication to the growth of my academic career which has been invaluable throughout. I am also very grateful to Dr. Timothy Fik who has afforded me much advice and encouragement. I am also indebted to the Geography Department for the support of its faculty and staff and to the University of Florida which has supported me financially with an Alumni Fellowship.

I also want to express a special thanks to my very good friends and mentors Dr. Jeanne Fillman-Richards and Dr. Storm Richards who have supported me in a multitude of ways. They have been integral to my success and I will always regard them as family.

Finally, I give my heartfelt thanks to my parents, Cynthia and Jim, for their infinite support and encouragement in the pursuit of my goals throughout my life and I also thank my Aunt Glenys for being there and providing accommodation to a wayward Scottish student.
# TABLE OF CONTENTS

ACKNOWLEDGMENTS .......................................................................................................................... 4

LIST OF TABLES .................................................................................................................................. 7

LIST OF FIGURES .................................................................................................................................. 8

ABSTRACT .......................................................................................................................................... 10

CHAPTER

1 INTRODUCTION .......................................................................................................................... 12

2 THE STOCHASTIC PROPERTIES OF HIGH DAILY MAXIMUM TEMPERATURES ......................................................................................................................................................................................... 14

   Introduction .................................................................................................................................. 14
   Study Locations and Data .............................................................................................................. 15
   Theory and Method ..................................................................................................................... 16
      Annual Event Density ............................................................................................................... 17
      Timing of Events within a Year .................................................................................................. 17
      First and Last Events of a Year ................................................................................................. 18
      Event Magnitude and Duration ............................................................................................... 18
      Critical Threshold ................................................................................................................... 19
      Independence of Events .......................................................................................................... 19
      Extrapolation to Higher Levels ............................................................................................... 20
   Statistical Stationarity and Climate Variability ......................................................................... 20
      Sea Surface Temperature Oscillations .................................................................................... 20
      Land/Water Contrast ............................................................................................................... 22
      Urban Heat Island ................................................................................................................... 22
   Results ....................................................................................................................................... 23
      Event Properties ....................................................................................................................... 23
      Discrete Nature of Temperature Data ..................................................................................... 24
      Extrapolation of Findings to Higher Levels ............................................................................ 25
   Discussion .................................................................................................................................... 25
      Normality of Temperature ......................................................................................................... 26
      Division of the Record ............................................................................................................. 26
      Study Locations and Geographic Variability ......................................................................... 27
   Conclusions ................................................................................................................................ 28

3 CONCLUSIONS .............................................................................................................................. 43

APPENDIX: ALTERNATE LOCATION GRAPHS ........................................................................... 45
<table>
<thead>
<tr>
<th>Table</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>31</td>
</tr>
<tr>
<td>Observed parameters describing the relevant high temperature event characteristics</td>
<td></td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>Study station locations.</td>
<td>31</td>
</tr>
<tr>
<td>2-2</td>
<td>Computed probabilities of historic daily maxima exceeding a critical threshold of 95°F (35°C).</td>
<td>32</td>
</tr>
<tr>
<td>2-3</td>
<td>Relative frequency of historical events compared to a Gaussian distribution</td>
<td>33</td>
</tr>
<tr>
<td>2-4</td>
<td>Historic mean daily maximum temperatures, ± one standard deviation.</td>
<td>34</td>
</tr>
<tr>
<td>2-5</td>
<td>Graphical definition of the stochastic variables (number, timing, magnitude and duration) and independence criteria</td>
<td>35</td>
</tr>
<tr>
<td>2-6</td>
<td>Observed durations of heat wave events, in entire Lake City record, above a 98°F (36.7°C) threshold with four day independence criteria.</td>
<td>35</td>
</tr>
<tr>
<td>2-7</td>
<td>Time series of the annual number of observed heat wave events as defined by a 98°F (36.7°C) threshold and four day independence criteria</td>
<td>36</td>
</tr>
<tr>
<td>2-8</td>
<td>Observed and fitted Poisson distribution of annual numbers of heat wave events in DeFuniak Springs</td>
<td>37</td>
</tr>
<tr>
<td>2-9</td>
<td>Observed POT magnitudes of events in DeFuniak Springs</td>
<td>38</td>
</tr>
<tr>
<td>2-10</td>
<td>Observed durations of events in DeFuniak Springs</td>
<td>39</td>
</tr>
<tr>
<td>2-11</td>
<td>Probabilities of 0, 1, 2, 3, 4 events having occurred in DeFuniak Springs</td>
<td>40</td>
</tr>
<tr>
<td>2-12</td>
<td>Probabilities of first events occurring, in DeFuniak Springs, before any day of the year and last events occurring after any day of the year</td>
<td>40</td>
</tr>
<tr>
<td>2-13</td>
<td>Comparison of observed and fitted event distributions</td>
<td>41</td>
</tr>
<tr>
<td>2-14</td>
<td>Mean daily temperatures and precipitation from the historical record.</td>
<td>42</td>
</tr>
<tr>
<td>A-1</td>
<td>Observed and fitted Poisson distribution of annual numbers of heat wave events in Avon Park</td>
<td>45</td>
</tr>
<tr>
<td>A-2</td>
<td>Observed and fitted Poisson distribution of annual numbers of heat wave events in Fort Myers</td>
<td>46</td>
</tr>
<tr>
<td>A-3</td>
<td>Observed and fitted Poisson distribution of annual numbers of heat wave events in Lake City</td>
<td>47</td>
</tr>
<tr>
<td>A-4</td>
<td>Observed POT magnitudes of events and fitted exponential distribution in Avon Park</td>
<td>48</td>
</tr>
</tbody>
</table>
A-5   Observed POT magnitudes of events and fitted exponential distribution in Fort Myers...............................................................................................................49

A-6   Observed POT magnitudes of events and fitted exponential distribution in Lake City.....................................................................................................................50

A-7   Observed durations of events and fitted exponential distribution in Avon Park.........................................................................................................................51

A-8   Observed durations of events and fitted exponential distribution in Fort Myers.....................................................................................................................52

A-9   Observed durations of events and fitted exponential distribution in Lake City.........................................................................................................................53

A-10  Probabilities of 0, 1, 2, 3, 4 events having occurred, in Avon Park, up to any day during the year. ...............................................................................................54

A-11  Probabilities of 0, 1, 2, 3, 4 events having occurred, in Fort Myers, up to any day during the year. ...............................................................................................54

A-12  Probabilities of 0, 1, 2, 3, 4 events having occurred, in Lake City, up to any day during the year. ...............................................................................................55

A-13  Probabilities of first events occurring, in Avon Park, before any day of the year and last events occurring after any day of the year.................................55

A-14  Probabilities of first events occurring, in Fort Myers, before any day of the year and last events occurring after any day of the year.................................56

A-15  Probabilities of first events occurring, in Lake City, before any day of the year and last events occurring after any day of the year.................................56
The statistical properties of the excursions of maximum daily temperatures above various critical thresholds of interest are analyzed with a view to developing models of heat wave events using more than 100 years of record from meteorological stations in Lake City, DeFuniak Springs, Avon Park, and Fort Myers, Florida. These stochastic variables include; event density (number of such events per unit time), duration, timing, and peak values over the threshold. The theoretical basis for the modeling is found in Crossing Theory, which states that as the threshold of interest becomes particularly large with respect to the mean of a Gaussian process, the number of crossings (up or down) becomes Poisson distributed. The changing seasonal intensity of such events can be incorporated by utilizing a non-homogeneous Poisson model, with time-varying rates. Environmental health studies indicate that both the magnitude and duration of the excursion above the critical threshold are important. As both the number of up-crossings and down-crossings follow a Poisson distribution, it is reasonable to approximate the length of time between the two (the duration of an event) by an exponential, or exponential-like distribution. Similarly, the peak magnitudes of event
over the threshold (POT) represent the extreme tail of the distribution of daily maximum temperatures and might be assumed to follow the same sort of distribution.

The current study only considers a single, arbitrarily defined, critical temperature threshold of 98°F (36.7°C). The threshold that constitutes a medically critical value may well vary spatially, and be dependent upon the ultimate application of the results. It is therefore necessary to be able to extrapolate findings derived at one level of interest to others, particularly in seeking to determine the risks of extremely rare events like those of Chicago (1995), France (2003), London and California (2006) and Melbourne (2009), which had seldom, if ever, been observed in historic series. The methodology has the flexibility to extrapolate to such levels while also having the advantage of being able to be applied to spatially differentiated data to determine risks associated with high temperature events during any time period or at any location of interest.
A scientific consensus now exists with regard to the acceptance of climate change, but there is debate as to its cause and severity (IPCC, 2007). The global medical community has stated that climate change represents the most severe threat to human health across the globe during the 21st century (Costello et al., 2009).

Connections between climate and health are numerous and highly diverse. Many of these climate phenomena have obvious connections to health. They include severe storms, extreme temperatures, drought, and flooding, while some are less obvious and have consequences such as alterations in the ranges of infectious diseases and degradation of air quality. It is anticipated that climate change will cause extreme events to occur with increased frequency and intensity (IPCC, 2007). To better plan for the adverse affects that climate change may have on human health, there is a need for information regarding how the climate will change both quantitatively and geographically and how that change will be connected to health. Specifically, the global health community has outlined the need for accurate modeling with application to adaptable policy and response to health threats, which will most likely have a varied societal context (Costello et al., 2009). The effect that climate change will have on health will most likely vary geographically and as a function of population acclimatization and vulnerability. One such geographically varying impact on human health is the occurrence of high temperature events or heat waves.

High temperatures cause overall death rates to increase, especially when the temperature rises above the local population’s threshold or critical value (Curriero et al., 2002). In response to both the uncertainty of the magnitude of climate change and to
the probable varied impacts that the change may have on humans, this research focuses on the development of flexible models that can quantify the risk of high temperature events and their associated properties. These models can be adapted to incorporate varied critical thresholds and are able to characterize the main stochastic variables that are associated with heat wave events. The stochastic variables investigated include: event density (numbers of such events per unit time), duration, timing, and peak values over the threshold or the magnitude of events. In order to model these variables, this study relies on Crossing Theory. When a physical phenomenon, such as daily maximum temperatures, exhibits a distribution that is approximately Gaussian, many of its properties can be predicted using the simple statistical framework outlined in Crossing Theory (Rice, 1945; Leadbetter et al., 1983; Rodriguez-Iturbe and Bras, 1985). In particular, the theory is applicable to the estimation of physical event properties beyond a given level. Crossing Theory has previously been applied to studies of flood events above critical discharge thresholds, as well as to the analysis of freeze probabilities (below threshold) with regard to agricultural impacts (Waylen, 1988; Waylen and LeBoutillier, 1989; Goto-Maede et al., 2008).

This research applies Crossing Theory to the development of simple stochastic models that quantify the risk of high temperature events above a critical temperature threshold. The theory behind the models is explained and the models are applied to historic maximum daily temperature data spanning the 20th century. The data come from four meteorological stations throughout Florida, chosen to test the applicability of the models across varied geographic locations.
CHAPTER 2
THE STOCHASTIC PROPERTIES OF HIGH DAILY MAXIMUM TEMPERATURES

Introduction

The occurrence of high temperature events, or heat waves, poses a threat to human health, particularly to the more vulnerable segments of the population such as the very young and the elderly. Prior research suggests that extreme high temperatures are linked to increased levels of human morbidity and mortality (Kunst et al. 1993; Hajat et al. 2002) and the Centers for Disease Control and Prevention attributed an average of 688 deaths per year in the United States during 1999-2003 to excessive heat (CDC, 2006). This number is greater than the total attributed to hurricanes, tornadoes, floods, and winter storms combined over the same period. Deaths directly related to heat stress are, however, probably few in comparison to those tied to other medical conditions that are exacerbated by heat. The World Health Organization has identified pre-existing health conditions or co-morbidities, such as diabetes and obesity, respiratory or heart conditions, which result in greater susceptibility to heat wave events (World Health Organization Europe, 1998). Moreover, the currently proposed global warming trend may result in warmer summer temperatures with increased frequencies, durations, and intensities of heat wave events (Gaffen and Ross, 1998; Meehl and Tebaldi, 2004).

Numerous definitions of heat wave events exist in the literature, and the World Meteorological Organization (WMO) has not yet defined the term (World Health Organization Europe, 2009). The National Weather Service characterizes a heat wave as "a period of abnormally and uncomfortably hot and unusually humid weather" with duration of at least two days (National Weather Service, 2009). Typically, if daily high
temperature crosses a medically defined critical threshold for a specified number of days, a heat wave is said to have occurred (Tan et al., 2007). In order to be of epidemiological/medical significance, any statistical approach to the study of heat waves must allow for flexibility in the selection of an appropriate critical temperature and be capable of characterizing the duration of events. Events occurring very early or late within the expected hot season may have greater epidemiological significance and therefore the timing of events is also an important consideration (Sheridan and Kalkstein, 2004).

This study analyzed the statistical properties of the excursions of maximum daily temperatures above various critical thresholds of interest with a view to developing flexible models of heat wave events. These statistical properties or stochastic variables include: event density (numbers of such events per unit time), duration, timing, and peak values over the threshold or the magnitude of events.

**Study Locations and Data**

Four locations were selected for analysis in this study based on the availability of long-term (>100 years) and complete daily temperature records. The locations were also selected to include a broad geographic range throughout Florida (Figure 2-1). DeFuniak Springs is in the northwest, Lake City is in northern central, Avon Park is in southern central, and Fort Myers is in the south. Fort Myers and DeFuniak Springs are both within 30 miles of the coast of the Gulf of Mexico, while Avon Park and Lake City are both more than 60 miles from either the coast of the North Atlantic Ocean or the Gulf of Mexico. The locations also represent settings that have undergone extensive (Fort Myers) or relatively limited (Avon Park, DeFuniak Springs, Lake City) urban growth.
Historic datasets were obtained from the Southeast Region Climate Data Center (SRCDC). The meteorological record for each station includes daily maximum, minimum, and mean temperature from the 1890s to 2008. All datasets were partially incomplete upon acquisition, but all were deemed large enough to allow some years with missing data to be removed prior to the analysis. To reduce data gaps, a critical seasonal period with greater likelihood of high temperatures was identified. This season was defined by fitting a normal distribution to each day’s (1-365) observed data from Lake City and considering only those days returning a probability of 0.10 or greater that the maximum daily temperature would exceed 95°F (35°C) (Figure 2-2). This approach resulted in a critical high temperature band from June 1st through September 6th. Years missing data within this critical band were removed from subsequent analysis at all four locations.

**Theory and Method**

The approach used in this study to model high temperature events is based on Crossing Theory. Crossing Theory allows for the description of the statistical properties of events beyond some high temperature threshold and permits the probabilistic description of the number, timing, magnitude and duration of such events (Rice, 1945; Leadbetter *et al.*, 1983; Rodriguez-Iturbe and Bras, 1985). Similar methodology has been applied to studies of flood events above a critical discharge threshold as well as to the analysis of freeze probabilities (below threshold) with regard to agricultural impacts (Waylen, 1988; Waylen and LeBoutillier, 1989; Goto-Maede *et al.*, 2008).

Crossing Theory states that as a threshold of interest becomes particularly large with respect to the mean of a Gaussian process, the number of crossings (up or down) becomes Poisson distributed. As both the number of up-crossings and down-crossings
follow a Poisson distribution it is reasonable to approximate the length of time between the two (the duration of an event) by an exponential, or exponential-like, distribution. Similarly, the peak magnitudes of event over the threshold (POT) represent the extreme tail of the distribution of daily maximum temperatures and might be assumed to follow the same sort of distribution.

Basing the approach to modeling event properties on Crossing Theory provides this study with a strong theoretical basis while also allowing for the prediction of the statistical properties of events above progressively higher, and seldom encountered, thresholds (Waylen and Woo, 1983; Birikundavyi and Rousselle, 1997).

**Annual Event Density**

The probability mass function of a Poisson distribution is given by:

\[ P(M) = e^{-\lambda} \cdot \frac{\lambda^M}{M!} \]

where \( M \) is the number of crossings or events in a year and \( \lambda \) is a parameter greater than 0. \( \lambda \) is estimated, using the method of moments, as the mean number of events per year:

\[ \lambda = \frac{K}{N} \]

where \( K \) is the total number of events in \( N \) years of historical record.

**Timing of Events within a Year**

The Poisson distribution assumes that events are equally likely within a time period, in this case a year. However, this assumption is unrealistic as heat wave events are strongly seasonal in their nature (Figure 2-2). The Poisson distribution should therefore be modified to include a time-dependent or non-homogeneous function:

\[ P(m(t) = n) = e^{-\lambda(t)} \cdot \lambda(t)^n / n! \]
where \( \lambda(t) \) is the mean number of events expected up to the day of the year, \( t \), and \( n \) is the number of events up to that time in a year. The modeling of distributions of the timings of events can be accomplished through estimation of \( \lambda(t) \) by a Gaussian distribution (Figure 2-3):

\[
\hat{\lambda}(t) = G(t : \mu, \sigma) \cdot \Lambda
\]

where \( G(t : \mu, \sigma) \) is a Gaussian distribution fitted to the timing of events with \( \mu \) being mean date of exceedances and \( \sigma \) their standard deviation.

**First and Last Events of a Year**

The probability distributions of the dates of first, \( F(x \leq t) \), and last, \( L(x \leq t) \), events of the year can be calculated from the time-dependent function shown above as demonstrated by Waylen (1988):

\[
F(x \leq t) = 1 - \exp(-\hat{\lambda}(t))
\]

\[
L(x \leq t) = 1 - \exp(-(\Lambda - \hat{\lambda}(t))
\]

**Event Magnitude and Duration**

As POT events represent the extreme tails of daily maximum temperatures it is appropriate to represent the probability distribution of this event property with an exponential or exponential-like function (Rousselle, 1972; Taesombut and Yevjevich, 1978):

\[
F(x \geq X) = 1 - \exp(-X / \bar{x})
\]

where \( X \) is the POT or magnitude of the event over the threshold and \( \bar{x} \) is the mean POT or magnitude above the threshold.

The duration of events represents the length of time between successive upward crossings of the daily maximum temperature above the threshold and downward
crossings of the daily maximum temperature below the threshold. It is reasonable to assume that the duration of events will follow an exponential distribution (Cramer and Leadbetter, 1967):

\[
F(d \geq D) = 1 - \exp\left(-\frac{D}{\bar{d}}\right)
\]

where \(D\) is the duration of the event and \(\bar{d}\) is the mean duration of all events above the threshold.

**Critical Threshold**

The critical threshold selected for analysis should be sufficiently far above the mean to satisfy the requirements of Crossing Theory, while remaining at such a level as to maximize the number of heat wave events identified within the record. In this study the threshold is set at 98°F (36.7°C), which is at least one standard deviation above the daily mean maximum temperature for any day of the year (Figure 2-4). The choice of this threshold is somewhat arbitrary, other than to satisfy the statistical requirement referred to above, as the threshold which constitutes a threat to human health will vary geographically and will ultimately need to be medically defined.

**Independence of Events**

In the present study, events are considered to be independent when the minimum number of days separating two consecutive events exceeds four days. Events separated by four days or less of sub-critical threshold temperatures are grouped (Figure 2-5). An independence criterion was set in this way to account for the possible epidemiological significance of sub-critical threshold relief days between events. Medical literature confirms this choice because only a weak association between heat-related mortality on any given day and temperatures more than four days
prior has been shown (Curriero et al., 2002). The use of independence criteria creates many longer-duration or compounded events within the series. The majority of the longer-duration events included in the analysis are the result of compounding multiple shorter duration events (Figure 2-6).

**Extrapolation to Higher Levels**

It is possible to extrapolate from the distributions employed in this study to determine the probabilities associated with event parameters above higher truncation levels or critical thresholds. As exponential distributions are "memoryless," any portion of the distribution is itself exponentially distributed and described by the same parameter (Ross, 1976). Therefore, as the critical threshold is raised, the mean parameter remains constant. The expected number of events with a certain magnitude can be approximated using the estimated exponential function of magnitude outlined above. Subsequently, if the exponential distribution is a good representation of the magnitudes of events above a particular critical threshold, and therefore the proportion of events that will survive changes in the critical level, then the number of crossings above any critical threshold can also be estimated. The seasonal characteristic of events (timing within a year, probabilities of first and last events) can be estimated as outlined above, using the estimated number of crossings, in combination with the lower-threshold-generated Gaussian distribution, as its mean and variance remain constant as the truncation level is increased.

**Statistical Stationarity and Climate Variability**

**Sea Surface Temperature Oscillations**

The statistical approach used in this study assumes that the values of the model parameters remain invariable, or stationary, throughout the period of study. However,
variability arising from macro-scale fluctuations in climate operating at low frequencies may partially control event risk. Such low-frequency variability may be associated with sea surface temperature (SST) oscillations. The El Niño-Southern Oscillation (ENSO) and the Atlantic Multi-decadal Oscillation (AMO) appear to have a significant influence on Florida’s climate (Goto-Maede et al., 2008). There is also recent research suggesting that significant Atlantic SST phases exist at the decadal time scale on a global as well as regional scale (Dong and Sutton, 2002; Sutton and Hodson, 2005; Zhang and Delworth, 2005) and that they can be linked to a separate phenomenon known as the North Atlantic Oscillation (NAO) (Wu and Gordon, 2002; Justino and Peltier, 2005).

Research suggests clear links between ENSO phase and winter temperatures and precipitation in Florida (Gershunov and Barnett, 1997), but ENSO phase appears to have little effect on summertime high temperatures and therefore heat wave occurrence. Studies of the impact of the AMO on precipitation over eastern North America abound in the literature (Enfield et al., 2001, Knight et al., 2006, McCabe and Palecki, 2006). They have shown that precipitation is significantly reduced during warm phases of the AMO, but that the effect is variable in both magnitude and spatial extent. The AMO appears to have a significant influence on mean air temperatures in both North America and Western Europe (Kerr, 2000; Sutton and Hodson, 2005; Goto-Maede et al., 2008; Arguez et al., 2009). The high or warm phase (above average) of Atlantic SSTs has been associated with mean temperature anomaly increases of up to 1.5°C (~3°F) in the North Atlantic region with peaks in these anomalies occurring during the summer months of June, July, August, and September.
(Arguez et al., 2009). Enfield calculated an index of the AMO from detrended long run averages of mean SST observations from 1860 to 1994 and identified periods in which the AMO has been in a warm phase or cool phase relative to the mean.

**Land/Water Contrast**

Another major factor in the control and distribution of temperature across Florida is land/water contrasts. Florida is a peninsula with the Atlantic Ocean to the east and the Gulf of Mexico to the west, and land near a large body of water is influenced by the temperature of the water. Water has a high specific heat capacity and allows energy to penetrate to a greater depth than on land. It has the ability to mix both vertically and horizontally as well as a greater capability for evaporative cooling. Therefore, land heats and cools more rapidly than water. In summer months, coastal areas tend to be cooled when air from above the water moves over the land, displacing warmer air and resulting in what is referred to as a sea breeze. Despite Florida’s proximity to large bodies of water, cool sea breezes do not entirely regulate temperatures across the peninsula. However, a temperature gradient does exist as one moves inland. For example, the following are July average temperatures observed at meteorological stations in south Florida: Miami Beach 30.8°C (87.4°F), Miami International Airport (8 miles inland) 31.9°C (89.5°F), Bend-Tamiami Trail (40 miles inland) 33.3°C (92.0°F) (Winsberg & Simmons, 2009).

**Urban Heat Island**

The urban heat island (UHI) phenomenon has also been proposed to operate as a climate control that affects local temperature variation. Florida’s population has grown tremendously over the last several decades and this growth has resulted in urbanization and land cover change. Much of the developed coastal areas of Florida and the central
I-4 corridor have merged together to form what is referred to as a megalopolis of connected urban areas. Urban areas are typically warmer than more open, naturally vegetated areas due to the presence of more energy-absorptive and radiative man-made surfaces. A recent 36-month study of Orlando found that mean daily maximum temperatures of areas in the city center and those on the outskirts could vary by as much as 8°C (14°F) (Yow & Carbone, 2006).

Results

Event Properties

After investigation of likely non-stationarity in the record, as outlined above, the record was considered to be composed of different statistical populations. Empirical evidence suggests that a primary determinant of the climate variability in Florida may arise from fluctuations in the AMO. The annual time series of the number of heat wave events at the four study locations (Figure 2-7) indicates a high degree of inter-annual variability and tendency for a low-frequency clustering of similar total numbers of events with some correspondence to AMO phase as defined by Enfield et al., (2001). Therefore, to accommodate this physically-driven and empirically observed variability, the data were divided by AMO phase for subsequent analysis. Application of the Poisson distribution to the modeling of annual event density is satisfactory (Figure 2-8), as is the application of the exponential distribution to the magnitude and duration of satisfactory events (Figure 2-9; Figure 2-10). Using a one-sample Kolmogorov-Smirnov goodness-of-fit test (Crutcher, 1975), the null hypothesis of no significant difference between observed and predicted frequencies cannot be rejected. The test was carried out at the 0.80 significance level to minimize the risk of type II errors. From these results, it is possible to predict the probabilities of: (1) the annual density of events,
(2) the magnitudes of events above a threshold, and (3) events exceeding a given
duration. Utilization of the non-homogeneous Poisson function allows for prediction of
the probability of observing 0,1,2,3… and up to m events on any given day of the year
(Figure 2-11). The combination of the exponential distribution and the time-dependent
function ($\lambda(t)$) is applied to calculate probabilities of first and last events of the year
(Figure 2-12).

**Discrete Nature of Temperature Data**

It is worth exploring the discrete nature of the temperature data. In reality, temperature is a continuous variable, but the data were rendered discrete (e.g. 98°F, 99°F, 100°F). This may be the result of the use of crude instrumentation or rounding, but the true ranges these discrete temperature values represent cannot be stated with certainty. We could assume, for example, that any temperature greater than 98°F, but less than or equal to 99°F (e.g. 98.01, or 99.00), was recorded as 99°F. If we assume that the group of temperatures within this range (98.01-99.00) is uniformly distributed, we may represent them as being 0.5°F (the mean of the group) above the 98°F threshold. Therefore, the discrete value is shifted to 98.5°F from 98°F to better represent a continuous range of temperature. Such a shift in temperature values would clearly impact parameters in the analysis and the relationship to fitted functions. The observed data and mean, which is used to compute fitted functions, would be shifted 0.5°F lower. However, we may also assume that any temperature greater than 98.5°F, but less than or equal to 99.5°F, was recorded as 99°F and that, if the prior assumptions are correct, the mean is also 99°F and therefore the discrete value is representative of a continuous range. Given the uncertainty as to the nature of the recorded temperature
values, we are therefore unable to relate them to specific real continuous ranges and cannot justify a revaluation of the data away from the discrete record.

Extrapolation of Findings to Higher Levels

To test the ability of the methodology to extrapolate findings from one critical threshold to a higher or seldom encountered threshold, data from 1966-1994 in DeFuniak Springs are used as an example. If the critical threshold is raised to 99°F (37.2°C), we would expect 64.4% (Figure 2-9) of the original 22 events to survive the increase in the threshold. The expected number of events remaining would therefore be 14.17 and the observed number is 11. We would also expect the mean magnitude of events to remain constant at 2.27 as the threshold is increased. The observed mean is 2.55. Raising the critical threshold to 100°F (37.8°C), we would expect 41.5% (9.13 events) of the original 22 events to survive and the observed number is 7, while the mean is 2.43. Pushing the threshold to seldom observed levels (102°F/38.9°C), we would expect only 17.2% (3.78 events) of the original events to remain and 3 are observed while the mean is 2. Expected number of events can then simply be divided by the 21 years of record to yield the mean number of events per year or Λ. The application of a Kolmogorov-Smirnov test confirms that this is a statistically acceptable approach at the 0.80 significance level.

Discussion

The approach to modeling high temperature or heat wave events illustrated in this study is capable of statistically describing the stochastic variables associated with such events and also allows for a flexible definition of the criteria which constitute event occurrence. The probability distributions employed are well known and the methods used have strong theoretical support. Other more complex exponential-like distributions
(generalized Pareto, Gamma) may be used as alternatives to the simple exponential distribution employed in this study. However, such alternatives were investigated and found to add minimal or no improvements to the models so in the interest of parsimony they were not included in this study.

**Normality of Temperature**

The methods employed rely on the reasonable assumption of normality of temperature distribution on any given day. The distribution of the timings of events has also been shown to be statistically similar to that of a normal distribution (Figure 2-3). There are however some notable deviations from normality particularly in the months of June and July (Figure 2-13). A possible explanation for the noted deviation may lie in seasonal climate variability associated with precipitation. Mean daily precipitation from the entire record in Lake City, FL, may have some impact upon the timing of the temperature deviations from simple normality (Figure 2-14). The drier period through the months of April and May and the consequent lack of atmospheric moisture and cloud cover (albedo) may contribute to greater insolation and higher temperatures. Through the month of June and into July, precipitation increases greatly as the wet season begins. Increased precipitation, resulting in greater atmospheric moisture and cloud cover, may lead to decreased insolation and relatively cooler maximum daily temperatures. In this respect, fluctuations in precipitation during these months can be seen to correspond to the deviation of events from the fitted normal distribution.

**Division of the Record**

The data were divided based on phase of the AMO and much of the modeling was conducted using parameters calculated from these sub-samples. This approach allowed for the consideration of the existence of non-stationarity and subsequently
differentiated statistical sub-populations within the historical record. The division of the record in this manner serves two purposes. Firstly, it is necessary due to abundant physical evidence of climate variability which, according to prior research, appears to be at least partially controlled by the phase of the AMO. Graphical results along with the distribution parameters illustrate the periodic variability of the high temperature event properties during alternate phases of the AMO (Table 2-1). The mean parameters of event density, POT, and duration are all generally elevated during the 1926-1965 period which corresponds to the warm phase of the AMO. Although the current study is not focused on the investigation of the relationship between high temperature event parameters and the phase of the AMO, it is interesting that the noted pattern appeared and is in line with previous research into the AMO impact on mean air temperature. Secondly, the division of the record by phase of the AMO is a convenient test of the flexibility of the study method itself. The application of the method to these varied climate periods illustrates the suitability of the method to the analysis of varied climates and as a flexible tool for predicting future high temperature or heat wave event properties under the influence of projected climate change scenarios.

**Study Locations and Geographic Variability**

For this study, geographically distinct locations were selected and analyzed to encompass the variability outlined above. As the goal of this study is to develop flexible models of the stochastic properties associated with high temperature events that can be adapted to any location, it does not focus on relating high temperature events to any particular meteorological, climatological or anthropogenic phenomenon. The main contribution of this work lies in the presentation of a robust statistical methodology that can be applied under varied conditions to render probabilistic estimates of the
stochastic variables associated with high temperature events. Nevertheless, it is worth
discussing the influence of geographic variability on the occurrence of high
temperatures observed at the four study locations around Florida, because the model
parameters reflect a great deal of information about changes in physical environments.
Latitude has less of an effect on high temperature occurrence than one might expect.
For example, Fort Myers has a relatively lower frequency of events and those with a
high POT are rare compared to other locations, despite being the most southerly, and
the most urbanized, of the four. Fort Myers' proximity to the ocean appears to be the
dominant control on the occurrence of high temperatures at this location. The more
northern locations of DeFuniak Springs and Lake City exhibit greater frequencies of
high temperature events, which are typically of higher magnitude and longer duration
(Table 2-1).

Conclusions

Heat wave events are caused by several physical climate processes that interact
to produce dangerous conditions for human health. The interaction of these factors
makes the study of heat waves complex and has led to the use of heat indices. High
temperature however remains the major factor for defining a heat wave event. High
humidity places additional stress on human populations during high temperature events,
but it was not considered in this study as there is a lack of historic humidity data. During
the summer or "hot season," Florida is typically under the influence of prevailing
southerly wind flow. Winds coming from the south over the peninsula carry warm and
typically moist tropical air. Therefore, during the high temperature season in Florida,
there is generally constant high humidity so this factor can be considered a controlled
variable. High temperatures in Florida are influenced by the state's southern location
and proximity to the ocean, but SST oscillations may exert control over much of the variability in high temperatures within the state. The ever-increasing urbanization and associated land cover change throughout Florida have been shown to increase local maximum temperatures (Marshall et al., 2004). Additionally, with climate change scenarios predicting increasing temperatures, the future may bring greater increased heat wave probabilities (Meehl and Tebaldi, 2004). There will be great spatial variability in the response of regional climate to probable climate change scenarios, as suggested by an ensemble of model outputs (Kerr, 2008). The eastern U.S. is not expected to be highly responsive to probable climate change, but southern Florida is a notable exception and is predicted to be relatively responsive to climate change (Kerr, 2008).

The current study sought to develop flexible models that incorporate the stochastic properties associated with the physical phenomenon of high temperature events. The occurrence of such events places stress on the human population and therefore involves potential medical consequences. These events also stress vegetation as well as the often overlooked animal community. The temperature threshold that constitutes a threat to human health will certainly vary spatially and be influenced by physical, social, and even behavioral factors, including the built environment, access to cooling technology, level of acclimatization to heat, and physical activity. These factors are currently the focus of much research in the climate and health community and critical thresholds will ultimately need to be medically defined. The methodology utilized in this study is based on deviation from the mean and although the critical threshold may vary in many respects the statistical relationship
used to model events has the flexibility to extrapolate to differing medically defined levels.

Using Crossing Theory to model event properties provided this study with a strong theoretical basis while also allowing for the prediction of the statistical properties of events above progressively higher, and seldom encountered, thresholds (Waylen & Woo, 1983, Birikundavyi & Rousselle, 1997). The ability to extrapolate findings derived at one level of interest to others is of particular importance when seeking to determine the risks of extremely rare events like those of Chicago (1995), France (2003), London and California (2006) and Melbourne (2009), which had seldom if ever been observed in historic climate data. The methodology has the flexibility to extrapolate to such levels, while also having the advantage of being applicable to spatially differentiated data to determine risks associated with high temperature events during any time period or at any location of interest.
Table 2-1. Observed parameters describing the relevant high temperature event characteristics obtained from the four study locations subdivided by AMO cool/warm phase periods as defined by Enfield et al., (2001).

<table>
<thead>
<tr>
<th>Meteorological Station</th>
<th>Time period</th>
<th>Events/Year</th>
<th>Mean POT</th>
<th>Mean Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avon Park (Cool AMO)</td>
<td>1905-1925</td>
<td>0.11</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Avon Park (Warm AMO)</td>
<td>1926-1965</td>
<td>0.81</td>
<td>2.27</td>
<td>2.50</td>
</tr>
<tr>
<td>Avon Park (Cool AMO)</td>
<td>1966-1994</td>
<td>0.72</td>
<td>1.33</td>
<td>2.50</td>
</tr>
<tr>
<td>DeFuniak Springs</td>
<td>1905-1925</td>
<td>1.57</td>
<td>2.45</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td>1926-1965</td>
<td>2.21</td>
<td>2.58</td>
<td>4.04</td>
</tr>
<tr>
<td></td>
<td>1966-1994</td>
<td>1.05</td>
<td>2.27</td>
<td>3.32</td>
</tr>
<tr>
<td>Fort Myers</td>
<td>1905-1925</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>1926-1965</td>
<td>0.13</td>
<td>2.20</td>
<td>4.00</td>
</tr>
<tr>
<td></td>
<td>1966-1994</td>
<td>0.14</td>
<td>2.00</td>
<td>3.75</td>
</tr>
<tr>
<td>Lake City</td>
<td>1905-1925</td>
<td>1.11</td>
<td>1.95</td>
<td>2.53</td>
</tr>
<tr>
<td></td>
<td>1926-1965</td>
<td>1.37</td>
<td>2.37</td>
<td>3.15</td>
</tr>
<tr>
<td></td>
<td>1966-1994</td>
<td>0.81</td>
<td>2.14</td>
<td>2.19</td>
</tr>
</tbody>
</table>

Figure 2-1. State of Florida showing locations of meteorological stations used in the study.
Figure 2-2. Computed probabilities of historic daily maxima exceeding a critical threshold of 95°F (35°C). Dashed lines represent critical high temperature band defined based on Lake City data.
Figure 2-3. Relative frequency of historical events compared to a Gaussian distribution. Observed and predicted values do not differ at 0.80 significance level. Events are defined as exceeding a 98°F (36.7°C) threshold and events have been grouped if separated by a maximum of four days of sub-critical temperatures.
Figure 2-4. Historic mean daily maximum temperatures, ± one standard deviation.
Figure 2-5. Graphical definition of the stochastic variables (number, timing, magnitude and duration) and independence criteria employed to describe heat waves crossing a prescribed critical threshold.

\[
m(t) = \text{Events up to day } t \\
a = \text{Starting dates of events (day of year)} \\
d = \text{Duration of Events (days)} \\
x = \text{Peak magnitude of event above threshold (°F)}
\]

Figure 2-6. Observed durations of heat wave events in entire Lake City record, above a 98°F (36.7°C) threshold with four-day independence criteria. Events are plotted by date of start. Red points are compounded based on the independence criteria.
Figure 2-7. Time series of the annual number of observed heat wave events as defined by a 98°F (36.7°C) threshold and four day independence criteria. Value of "-1" denotes missing data. Colored arrows represent the phase of the AMO as defined by Enfield et al., (2001).
Figure 2-8. Observed and fitted Poisson distribution of annual numbers of heat wave events, in DeFuniak Springs, above a 98°F (36.7°C) threshold with four day independence criteria. For the corresponding graphs of alternate locations please see Appendix A.
Figure 2-9. Observed POT magnitudes of events, in DeFuniak Springs, above 98°F (36.7°C) threshold with four day independence criteria and fitted exponential distribution. For the corresponding graphs of alternate locations please see Appendix A.
Figure 2-10. Observed durations of events, in DeFuniak Springs, above 98°F (36.7°C) threshold with four day independence criteria and fitted exponential distribution. For the corresponding graphs of alternate locations please see Appendix A.
Figure 2-11. Probabilities of 0, 1, 2, 3, 4 events having occurred, in DeFuniak Springs, up to any day during the year. For the corresponding graphs of alternate locations please see Appendix A.

Figure 2-12. Probabilities of first events occurring, in DeFuniak Springs, before any day of the year and last events occurring after any day of the year. For the corresponding graphs of alternate locations please see Appendix A.
Figure 2-13. Comparison of observed and fitted event distributions. A) Observed cumulative probability of events exceeding 98°F (36.7°C) threshold with four day independence criteria and fitted cumulative normal distribution. B) Deviation of observed event probability from normal distribution.
Figure 2-14. Mean daily temperatures and precipitation from the historical record.
CHAPTER 3
CONCLUSIONS

Simple stochastic models were presented to characterize the major properties associated with high temperature events above a critical threshold. These models were developed using strong theoretical support found in Crossing Theory. Comparison of the models with historic data indicates that they satisfactorily estimate risks of each of the high temperature event properties investigated. The application of these models to varied geographic locations around Florida supports the notion that the models are capable of determining the risks associated with high temperature events through time and across spatially and climatologically distinct locations.

The focus of this research was on modeling high daily maximum temperatures above a critical threshold. Other meteorological variables such as high humidity and poor air quality may increase the stress placed on human populations during high temperature events. Previous research examined the use of heat indices, which attempt to quantify human discomfort (Kalkstein and Valimont, 1986). Public health warning systems or Heat Health Warning Systems (HHWS) have been developed using air mass synoptic classification, e.g., the Philadelphia Hot Weather-Health Watch/Warning System (PWWS) (Sheridan and Kalkstein, 1998). These systems use meteorological forecasts to predict the likelihood of combinations of conditions (air temperature, dew point temperature, cloud cover, sea level pressure, wind speed, and wind direction) that are expected to have adverse impacts on health. It has been found that air masses with particular combinations of these conditions are significantly correlated with increased mortality. Of all the variables investigated, however, maximum temperatures and duration of air mass presence were among the most highly
correlated with increased mortality (Kalkstein et al., 1996). The significance of temperature has also come to light in another study, which found daily average temperature to be a stronger predictor of mortality than dew point (Curriero et al., 2002).

The development of flexible stochastic models in this research is intended as the first step in an on-going study that seeks to establish associations between heat wave event properties and human mortality. These associations can then be combined with heat wave event characteristics derived from future climate change scenarios to give predictions of heat wave events and their associated mortality. The development of an online heat risk mapping tool is envisioned that will combine all three of these elements (statistical theory outlined in this research, mortality associations, climate change scenarios) with web-based programming and Geographical Information Systems. Such a tool would allow epidemiological/medical users to specify their own heat wave criteria and generate risk maps across an area of interest. Through combination with other geographical databases, it may also be possible to include other elements such as demographic, socioeconomic, and lifestyle data with climate and mortality relations to indicate areas that may be at higher risk.

The future development of a heat risk mapping tool will rely heavily on the stochastic models outlined in this research. Unlike the existing HHWS, which are limited to five day forecasts, this modeling provides long term predictive ability that will allow a proactive rather than reactive approach to future policy decisions.
Figure A-1. Observed and fitted Poisson distribution of annual numbers of heat wave events, in Avon Park, above a 98°F (36.7°C) threshold with four day independence criteria.
Figure A-2. Observed and fitted Poisson distribution of annual numbers of heat wave events, in Fort Myers, above a 98°F (36.7°C) threshold with four day independence criteria. Note that during the 1905-1925 (Cool AMO) period there were no observed events above a 98°F (36.7°C) threshold.
Figure A-3. Observed and fitted Poisson distribution of annual numbers of heat wave events, in Lake City, above a 98°F (36.7°C) threshold with four day independence criteria.
Figure A-4. Observed POT magnitudes of events, in Avon Park, above 98°F (36.7°C) threshold with four day independence criteria and fitted exponential distribution.
Figure A-5. Observed POT magnitudes of events, in Fort Myers, above 98°F (36.7°C) threshold with four day independence criteria and fitted exponential distribution. Note that during the 1905-1925 (Cool AMO) period there were no observed events above a 98°F (36.7°C) threshold.
Figure A-6. Observed POT magnitudes of events, in Lake City, above 98°F (36.7°C) threshold with four day independence criteria and fitted exponential distribution.
Figure A-7. Observed durations of events, in Avon Park, above 98°F (36.7°C) threshold with four day independence criteria and fitted exponential distribution.
Figure A-8. Observed durations of events, in Fort Myers, above 98°F (36.7°C) threshold with four day independence criteria and fitted exponential distribution. Note that during the 1905-1925 (Cool AMO) period there were no observed events above a 98°F (36.7°C) threshold.
Figure A-9. Observed durations of events, in Lake City, above 98°F (36.7°C) threshold with four day independence criteria and fitted exponential distribution.
Figure A-10. Probabilities of 0, 1, 2, 3, 4 events having occurred, in Avon Park, up to any day during the year.

Figure A-11. Probabilities of 0, 1, 2, 3, 4 events having occurred, in Fort Myers, up to any day during the year.
Figure A-12. Probabilities of 0, 1, 2, 3, 4 events having occurred, in Lake City, up to any day during the year.

Figure A-13. Probabilities of first events occurring, in Avon Park, before any day of the year and last events occurring after any day of the year.
Figure A-14. Probabilities of first events occurring, in Fort Myers, before any day of the year and last events occurring after any day of the year.

Figure A-15. Probabilities of first events occurring, in Lake City, before any day of the year and last events occurring after any day of the year.
LIST OF REFERENCES


BIOGRAPHICAL SKETCH

David James Keellings was born in 1986 in Glasgow, Scotland. He grew up in the small town of Kirkintilloch and attended primary and secondary school in the adjacent village of Lenzie. In 2001, he moved to Orlando, Florida where he finished his high school education at Trinity Preparatory School of Winter Park. He received a Bachelor of Science degree with Honors in environmental studies from the University of Central Florida in 2007. Throughout this time, he has worked as an environmental consultant on numerous development projects around Central Florida. David hopes to remain in the Geography Department at the University of Florida to pursue a doctorate degree under the advisement of Dr. Peter Waylen.