Applied Geography 46 (2014) 90–97

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

Increased risk of heat waves in Florida: Characterizing changes in bivariate heat wave risk using extreme value analysis

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Keywords:
Heat waves
Bivariate extreme value analysis
Health risk
Florida
Climate change

A B S T R A C T

Maximum and minimum daily temperatures from the second half of the 20th century are examined using a high resolution dataset of 833 grid cells across the state of Florida. A bivariate Extreme Value Analysis Point Process approach is used to model characteristics including the frequency, magnitude, duration, and timing of periods or heat waves during which both daily maximum and minimum temperatures exceed their respective 90th percentile thresholds. Variability in heat wave characteristics is examined across the state to give an indication of those areas where heat waves with certain characteristics may be more likely to occur. Changes in heat wave characteristics through time are examined by halving the temperature record and determining changes to heat wave characteristics between the two periods. This exploration of changes in heat wave risk through time gives a possible suggestion of trends in future heat wave risk. Findings indicate that there is considerable spatial variability in heat wave characteristics although heat waves have become increasingly frequent and intense throughout much of the state.

Introduction

Heat waves are meteorological events that can have pronounced impacts on mortality (CDC, 2006; Comrie, 2007; Ebi, 2008). The occurrence of heat waves and their detrimental health impacts are evident in recent episodes, such as those in 2003 (Europe), 2010 (Russia), and 2012 (U.S.). High temperatures exacerbate pre-existing medical conditions and cause overall death rates to increase, especially when the temperature rises above the local population's threshold or critical value (Comrie, 2007; Ebi, 2008; Hajat, Kovats, Atkinson, & Haines, 2002; Kunst, Looman, & Mackenbach, 1993; World Health Organization Europe, 1998). 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 & Kalkstein, 2004). Health impacts are not only the result of the maximum daily temperatures, but also high minima which prevent night-time relief (Hajat et al, 2006). Heat waves are reportedly occurring more frequently across much of the globe, and under a warming climate they are expected to increase in frequency, intensity, and duration (Coumou & Rahmstorf, 2012; Grumm, 2011; IPCC, 2012; WMO, 2012). Epidemiological studies have found that aged and high density populations are at increased health risk during a heat wave (Vandentorren et al., 2006; Hajat and Kosatsky, 2010).

Florida, the fourth most populous state with a relatively large proportion of its population over the age of 65 (U.S. Census Bureau, 2011) is therefore an important location for the study of heat waves. A study of temperature effects on mortality in cities in the Eastern U.S. found that the rate of increase in heat-related mortality in Miami and Jacksonville was greater than several more northern locations (Curriero et al., 2002). Heat waves can be viewed as extreme meteorological events involving a crossing of a high threshold and can be characterized using extreme value theory. A statistical investigation of these events based in extreme value theory allows for a characterization of their magnitude, frequency, timing, and duration (Coles, 2001; Furrer, Katz, Walter, & Furrer, 2010; Keellings & Waylen 2012; Waylen, Keellings, & Qiu, 2012).

This paper seeks to examine changes in probability or risk of heat wave (combined high maxima and minima) characteristics (magnitude, frequency, timing, and duration) during the second half of the 20th century across Florida. We take an approach based on bivariate extreme value theory in which we examine simultaneous crossings of both high daily maximum and minimum temperatures. This novel approach allows for an exploration of spatial patterns of changes in climatological heat wave risk that moves beyond univariate extremes to provide a more complete characterization of heat waves while also giving an indication of future trends.

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http://dx.doi.org/10.1016/j.apgeog.2013.11.008

Heat wave definition

Heat waves can be defined as a sequence of days/nights with maximum/minimum temperature above a certain high percentile threshold, which have variously been described as being between the 90th and 99th percentiles of the entire daily temperature distribution (Anderson & Bell, 2009; Hajat et al. 2006). In this study, the 90th percentile of the entire distribution of daily maximum and minimum temperature is adopted as a common threshold to identify an extremely hot day. These threshold levels are calculated separately for each grid point from the entire temperature record (1949–2000) at each grid point. However the methods developed are equally suitable for use with other thresholds, defined in either the frequency (percentiles) or magnitude (temperature) domains, for specific applications. Heat waves can also be defined by their duration in terms of how many consecutive days of above threshold temperatures occur (Tan et al., 2007). In this study, a duration criterion of at least 2 days of consecutive above threshold days is set. High maximum daily temperatures may be accompanied by relatively low nightly minimum temperatures that provide relief from daytime heat. The separate occurrence of both extreme high daily maximum temperatures and high daily minimum temperatures, as well as their combination, are examined in order to account for heat waves that allow little such nighttime relief.

Events are considered to be independent if separated by at least four days of below threshold temperatures, otherwise data of consecutive events are grouped. This independence criterion was set to account for the possible epidemiological significance of having fewer than four relief days between events and its choice is confirmed in medical literature by the weak association between heat-related mortality on any given day and temperatures in excess of three days prior (Curriero et al. 2002). The use of an empirical independence criterion is also necessary to satisfy the underlying statistical assumption of independence between events.

Fig. 1 illustrates the heat wave definition used in this study. It shows examples of separate events where above threshold maximum and minimum temperatures are not occurring simultaneously and are therefore not considered to be a heat wave. Two simultaneous crossings of daily maximum and daily minimum thresholds are also shown and represent two separate heat wave events with illustration of maximum exceedances in each margin, duration, events per year, and timing. The second example heat wave event contains one day of below daily maximum and two days of below daily minimum threshold temperatures and thus illustrates the use of four day independence between events which in this case is not exceeded and the series is considered to be one heat wave rather than two heat waves.

Atmospheric moisture has been shown to have an exacerbating effect on mortality, however this variable is collected at far fewer points over space and generally for shorter spans of time than temperatures. For climatological (as opposed to meteorological) purposes, large sample sizes from a long, high resolution historic dataset are favored over the shorter records some of which may contain humidity data. Given Florida's sub-tropical climate, dominantly peninsular characteristics and generally southerly flow during the summer months (Winsberg, 2003), relative humidity tends to be high throughout the season during which heat waves are likely to occur. It can also be argued that by adopting a bivariate heat wave definition, including minimum temperatures, we are indirectly capturing humidity. High nighttime minima are likely accompanied by high humidity that traps heat (outgoing longwave radiation).

Theory and methods

Extreme value analysis using a point process approach is chosen to characterize and model the frequency, timing, magnitude, and duration of heat waves. This approach unifies existing approaches to the modeling of extremes, namely the peak over threshold (POT) and block maxima approaches which have been applied extensively in hydrological and climatological studies of events above high or low thresholds (Rice, 1945; Leadbetter, Lindgren, & Rootzen, 1983; Rodriguez-Iturbe & Bras, 1985; Waylen, 1988; Waylen & LeBoutillier, 1989; Goto-Maeda, Shin, & O'Brien, 2008; Waylen et al. 2012). The point process is formulated in terms of the limiting Generalized Extreme Value (GEV) distribution parameters (μ, σ, ξ) and as a result, extremal properties are characterized by only these three parameters (Coles, 2001). Modeling of the frequency and magnitude of events are effectively combined in a single model instead of being fitted separately as in the POT approach. The approach also optimizes the use of available data, unlike the traditional block (annual) maxima, approach, as all values above the threshold are included resulting in more reliable results.

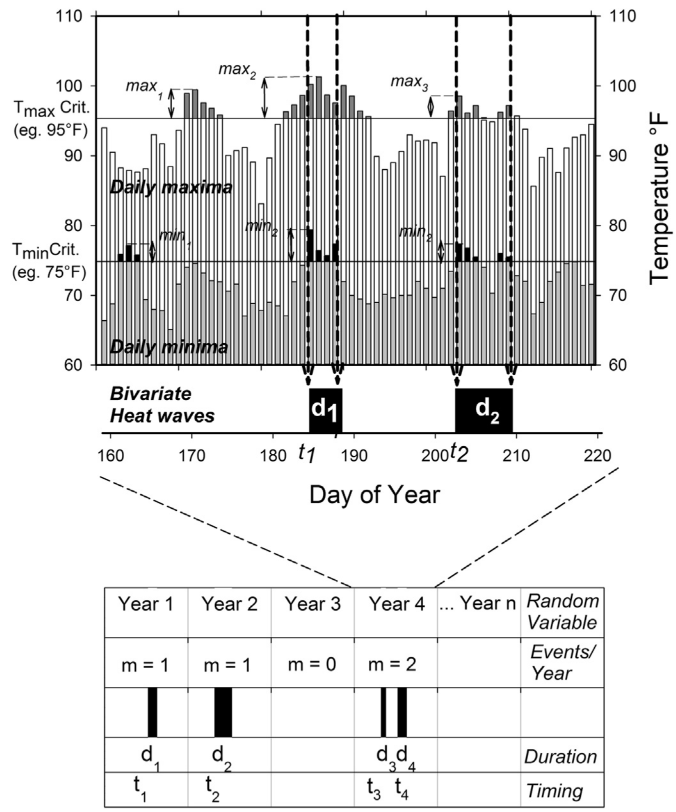

Fig. 1. Illustration of heat wave definition showing example thresholds of maximum and minimum daily temperature as well as heat wave properties of magnitude, frequency, duration, and timing.

If the occurrence of a "heat wave" day is considered as a point in time, then the expected waiting time until the next event is a point process occurring randomly in time, with a variable rate – i.e. a non-homogenous Poisson process with independent occurrence of each point (Coles, 2001). Maximizing the likelihood of this Poisson process leads to estimates of the parameters μ (location or central tendency), σ (scale or variance), ξ (shape or skew) of the limiting GEV distribution of the corresponding block maximum (Coles, 2001). The cumulative distribution function of the GEV is given by:

$$P(x) = \exp\left[-\left\{1+\xi\frac{x-\mu}{\sigma}\right\}^{-1/\xi}\right] \quad (1)$$

Considering N independent events exceeding a threshold u, then $N \sim \text{Poisson}(\Lambda)$, where