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Substantial Increase in Concurrent Droughts and Heatwaves in the United States

Author
Mazdiyasni, Omid

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Substantial Increase in Concurrent Droughts and Heatwaves in the United States

THESIS

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MASTER OF SCIENCE

in Civil and Environmental Engineering

by

Omid Mazdiyasni

Thesis Committee:
Professor Amir AghaKouchak, Chair
Professor Soroosh Sorooshian
Professor Xiaogang Gao

2015

DEDICATION

To:

My loved ones

“Nearly all men can stand adversity, but if you want to test a man’s character, give him power”
-Abraham Lincoln

If though art drunk with wine, be glad
If seated next to one with the moon’s glow, be glad
Since the world’s work has no hereafter
Think though art not, but since though art, be glad
-Omar Khayyam

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ABSTRACT OF THE THESIS

Substantial Increase in Concurrent Droughts and Heatwaves in the United States

By

Omid Mazdiyasni

Master of Science in Civil and Environmental Engineering

University of California, Irvine, 2015

Professor Amir AghaKouchak, Chair

A combination of climate events (e.g., low precipitation and high temperatures) may cause a significant impact on the ecosystem and society, though individual events involved may not be severe extremes themselves. Analyzing historical changes in concurrent climate extremes is critical to preparing for and mitigating the negative effects of climatic change and variability. This study focuses on the changes in concurrences of heatwaves and droughts from 1960 – 2010. Despite hiatus in rising temperature and no significant trend in drought, we show a substantial increase in concurrent droughts and heatwaves across most parts of the United States, and a statistically significant shift in the distribution of concurrent extremes. While the commonly used trend analysis methods do not show any trend in the data, a unique statistical approach, outlined in this study, exhibits statistically significant change point in the distribution of concurrent droughts and heatwaves.

INTRODUCTION

Heatwaves cause severe damages to society and the environment [6] with impacts on human health, air quality, and vegetation [2][31]. For example, in 2003, European countries faced an unprecedented heatwave, which in turn caused unusually high ozone concentrations [31] and caused severe health problems, especially in France where 15,000 extra deaths occurred during that time [31][25][1]. UNEP considers the European heatwave the world's most costly weather related disaster in 2003; however this was also because the region was in a drought [23]. Heatwaves can result in substantially higher water loss, and lower yields of grains, and other agricultural products [32]. Also, they cause a dramatic increase in energy consumption and can lower the efficiency and curtail the operations of power plants [33]. The duration, size, and intensity of wildfires have also increased due to heatwaves, causing economic losses and catastrophic environmental impacts [33]. Heatwaves have severe direct, indirect, immediate, and delayed impacts on not only human health, but also in air pollution, farming, forestry, glacier melt, energy supply, and technological operations [31][23].

Droughts also have phenomenal impacts on society and the environment such as significant drop in gross primary productivity, leading to shortage in food production and increase in global food prices [2]. The annual economic damage of droughts is estimated to be approximately $7 billion globally [10] with potential impacts on livestock, hydropower production, bioenergy, and energy consumption [33][7][9]. Fuel transport by barge can be affected in rivers if a severe drought brings down water levels [33].

Extreme climatic events can occur simultaneously, causing exaggerated environmental and societal impacts. Environmental hazards often result from a combination of climatic events [24] over a range of spatial and temporal scales [11][17]. A wild fire, for example, may occur on a hot, dry and windy day, although these conditions may not necessarily be extreme by themselves [17]. In the Intergovernmental Panel on Climate Change (IPCC) special report on managing the risks of extreme events and disasters, the combination of multiple climate extreme events is termed a compound event [17][25]. Most analyses of climate and weather extremes typically tend to focus on a single climatic condition; however, this univariate approach may underestimate the effects of concurrent and compound extremes [17].

Heatwaves and droughts have feedback on one another; precipitation deficit can induce hot days even at large spatial scales [20]. Furthermore, heatwaves reduce the total energy transfer to the atmosphere, resulting in a decrease in convective precipitation [32]. This in turn causes a soil-precipitation feedback loop which tends to extend or intensify drought conditions [32]. The interaction between precipitation and temperature has been widely recognized in numerous studies [8]. Heatwaves concurrent on droughts can intensify individual impacts of heatwaves or drought on society, the environment, and the global economy[22]. Studies suggest that changes in the relationship between precipitation and temperature may be more important than the changes in each of the variables individually [17][30].

A heatwave is typically defined as a period of consecutive extremely hot days [21][19], such as 5 consecutive days with temperature above 90th percentile. Here, we use 85th, 90th, and 95th percentiles of the warm season (May – October) temperature as extreme thresholds, and three heatwave durations (3, 5, and 7 days). That is, a 5-day heatwave with 90th percentile threshold is defined as five consecutive days with the maximum temperature exceeding the 90th percentile of the long term climatology for that month. In this study, meteorological droughts are defined as deficit in precipitation relative to the climatology using the Standardized Precipitation Index (SPI) [18]. Throughout this study, a drought is defined as an event that leads to SPI < -0.8

(approximately, 20th percentile precipitation). We use daily temperature and monthly precipitation information to identify historical droughts and heatwaves in the United States (see Data Section).

Chapter 1: Results

Changes in concurrent droughts and heatwaves during 1990-2010 have been evaluated relative to the baseline period 1960-1980. Figure 1 shows percent change in concurrent droughts and heatwaves for different durations (3-, 5-, and 7-day heatwaves) and extreme temperature thresholds (85th, 90th, and 95th percentiles). This figure shows that the concurrence of all combinations of drought and heatwave intensities and durations have increased substantially in the south, southeast and parts of the western United States, and have decreased in parts of the Mid-West and northern United States. Interestingly, the longer and more severe (7-day 95th percentile) drought and heatwave concurrence has increased more than the others (e.g., compare 7-day 95th percentile with the 3-day 85th percentile panels). This indicates that longer heatwaves (i.e., 7-day) have become more frequent in 1990-2010 relative to the baseline compared to the shorter heatwaves (i.e., 3-day).

Investigating the empirical cumulative distribution function (CDF) of the concurrent droughts and heatwaves reveals that a substantial change in extremes in 1990 – 2010 relative to 1960 – 1980 (see Figure 2). The blue line is the CDF for the baseline period and the red line represents the CDF for 1990 – 2010. The CDF is obtained based on data from the continental United States. As shown, for all intensities and durations, in 1990 - 2010 the upper tail of the CDF has shifted to the right compared to the baseline, indicating more extreme events in 1990-2010 relative to the baseline period (compare the red and blue lines in Figure 2). Notice that the shift in the CDFs is far more pronounced in the more extreme 7-day 95th percentile drought and heatwave concurrence as compared to the other combinations. The two-sample Kolmogorov Smirnov test (Methods Section) confirms that the CDFs of the concurrent droughts and heatwaves in the second period are substantially different with those in the baseline period at 0.05 significance level (95% confidence) for all heatwave durations and intensities except for 3-day, 85th percentile heatwaves - see Table S1 in Supplementary Materials.

Several studies have focused on changes in drought trends and conflicting results have been reported [28][5][7][30]. Here, we investigate the percent of the Continental United States in concurrent drought and heatwave for different duration and intensities from 1960 – 2010 (Figure 3). For the 90th percentile threshold, the percent of the country in drought and heatwave can reach up to 3% (7-day heatwave) to 6% (3-day heatwave) – Figure 3. While the CDFs clearly indicate changes in concurrent droughts and heatwaves, the commonly used Mann-Kendal trend test (see Methods Section) does not exhibit a statistically significant trend (95% confidence) in the fraction of the Continental United States under concurrent drought and heatwave (Figure 3). This can be attributed to limitations of statistical trend tests discussed in previous studies or lack of sensitive tools for change detection [3] - see Table S2 in Supplementary Materials.

Here, we explore a novel approach based on the Cramér–von Mises change point detection test statistic (Methods Section) to further investigate changes in concurrent droughts and heatwaves. We argue that this method is more sensitive to potential changes in the time series and offers a unique way to investigate changes in climate time series. This method, primarily used in economics and finance, evaluates different periods of data and determines statistically significant changes throughout the time series. Figure 4 shows the Cramér–von Mises statistics for drought and heatwave concurrences during 1960 –2010. The y-axes indicate a dimensionless measure of divergence between the empirical distributions of data before and after any given year as a continuous function (see Methods Section). For all plots, the maximum divergence occurs between 1998 and 1999, indicating substantial departure of the drought and heatwave CDFs before and after the identified change point. This information cannot be achieved from the commonly used trend analysis method or distribution change evaluation approaches.

Recent reports indicate a hiatus or pause in global warming since the year 1999/2000 [12][26][29]. Several explanations are offered including a long lasting minimum in solar energy output, low stratospheric water vapor, and a more frequent La Niña phase since the major El Niño event of 1997-1998 [12]. However, analyses show that there is no pause in the occurrence of hot extremes over land since 1997 [26]. In fact, there is a positive trend in exceedance of 30 extreme warm days during the hiatus period [26]. The results presented in Figures 2 and 4 indicate a statistically significant change in concurrent drought and heatwave events across many regions (e.g., southwest and western United States) despite the hiatus in rising temperatures. Figure 1 also confirms that the tails of the drought and heatwave concurrences are indicating more extreme events in the latter two decades. This is consistent with the increase in extreme warm days during this period [26]. However, this conclusion cannot be reached using the commonly used statistical trend analysis techniques used in hydrology and climate literature. The methodology outlined in this paper can shed light on changes in statistics of extremes beyond what can be achieved from trend analysis methods.

Chapter 2: Data

The data used for both precipitation and temperature comes from North American Land Data Assimilation System (NLDAS) [16] Variable Infiltration Capacity simulations over the contiguous United States in real-time. These runs support drought monitoring and forecasting systems in the United States. Daily temperature and monthly precipitation data with a spatial resolution of 1/8° are used for detecting droughts and heatwaves.

Chapter 3: Methods

The two-sample Kolmogorov Smirnov (KS) test is used to assess differences between the CDFs of the concurrent drought and heatwave events. KS is a nonparametric test that can be used to evaluate two distribution functions (two-sample) based on the distance between their empirical distribution functions. The null hypothesis of test is that the two distribution functions are drawn from the same distribution at a certain significance level (here, $\alpha = 0.05$). The Mann-Kendall (KL) trend test [14] is used to assess presence of a statistically significant trend in the time series of the fraction of the United States in drought and heatwave. KL test is a nonparametric approach based on the empirical ranks of time series, and has been widely used in hydrology and climatology.

A framework based on the Cramér–von Mises change point detection is used to evaluate temporal changes in the concurrent drought and heatwave events [13][15][4][27]. Let (X_1,Y_1), (X_2,Y_2) , . . . , (X_n,Y_n) be independent random variables with the following distribution functions: $F^{(1)}(x,y)$, $F^{(2)}(x,y)$, . . . , $F^{(n)}(x,y)$. We want to test if the null hypothesis (no change):

$$H_0: F^{(1)}(x,y) = F^{(2)}(x,y) = \cdots = F^{(n)}(x,y)\ for\ all\ (x,y) \in R^2$$

versus the opposite

$$H_A\text{: there is an integer } k*, 1 \le k* < n \text{ such that } F^{(1)}(x,y) = \cdots = F^{(k*)}(x,y), F^{(k*+1)}(x,y) = \cdots = F^{n}(x,y) \text{and } F^{(k*)}(x_0,y_0) \ne F^{(k*+1)}(x_0,y_0) \text{ with some } (x_0,y_0)$$

The Cramér–von Mises approach detects changes in the empirical cumulative distribution functions by comparing two subsamples ($\hat{F}_S(x)$ and $\hat{F}_T(x)$) of the original time series. We divide the subsamples into two parts $\{(X_i,Y_i),1\le i\le k\},\{(X_i,Y_i),k<i\le n\}$ to calculate the corresponding empirical distributions.

$$\hat{F}_S(x) = \frac{1}{k}\sum_{i=1}^{\tau} I(X_i \le x)$$

$$\hat{F}_T(x) = \frac{1}{n-k}\sum_{i=k+1}^{n} I(X_i \le x)$$

where $\hat{F}_S(x)$ and $\hat{F}_T(x)$ are the empirical CDF of the two subsamples, *I* is the indicator function, *n* denotes sample size, and the terms $\frac{1}{k}$ and $\frac{1}{n-k}$ are adjustment factors for the length of each subsample. The test measures the divergence between the empirical distributions as:

$$W_{\tau,n} = \int_{-\infty}^{\infty} \left|\hat{F}_S - \hat{F}_T\right|^2 dF_T(x)$$

$$= \sum_{i=1}^{n} \left|\hat{F}_S(X_i) - \hat{F}_T(X_i)\right|^2$$

Larger divergence values *W*, indicate greater changes in the cumulative distributions. A p-value is computed over the entire time series to indicate whether there has been a significant change. We reject H_0 if

$$\hat{T}_n = \max_{1\le k<n} \frac{k(n-k)}{n^{3/2}} \sup_{x,y} |\hat{F}_k(x,y) - F_k^*(x,y)|$$

is large. Let F signify the common distribution function under H_0. The limit of $\hat{T}_n$ is given by

$$\xi = \sup_{0\le t<1} \sup_{x,y} |\Gamma_F(x,y;t)|,$$

Where $\{\Gamma_F(x,y;t),(x,y)\epsilon R^2, t\ \epsilon\ R\}$ is a Gaussian process with $\mathrm{E}\Gamma_F(x,y;t) = 0\ and$ $\mathrm{E}\Gamma_F(x,y;t)\mathrm{E}\Gamma_F(x',y';t') = \{(t\wedge t' = tt'\}\{F(x\wedge x', y\wedge y') - F(x,y)F(x',y')\}$ where a∧b = min(a,b).

Throughout the study, the 0.05 significance level (95% confidence) is used to assess significance of change. Here, the approximate p-value is computed using a multiplier approach as:

$$\frac{(0.5 + \sum_{i=1}^{N} 1_{\{W_i \geq W\}})}{N+1}$$

where W and W_i are the test statistic and a multiplier replication, respectively.

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Appendix A

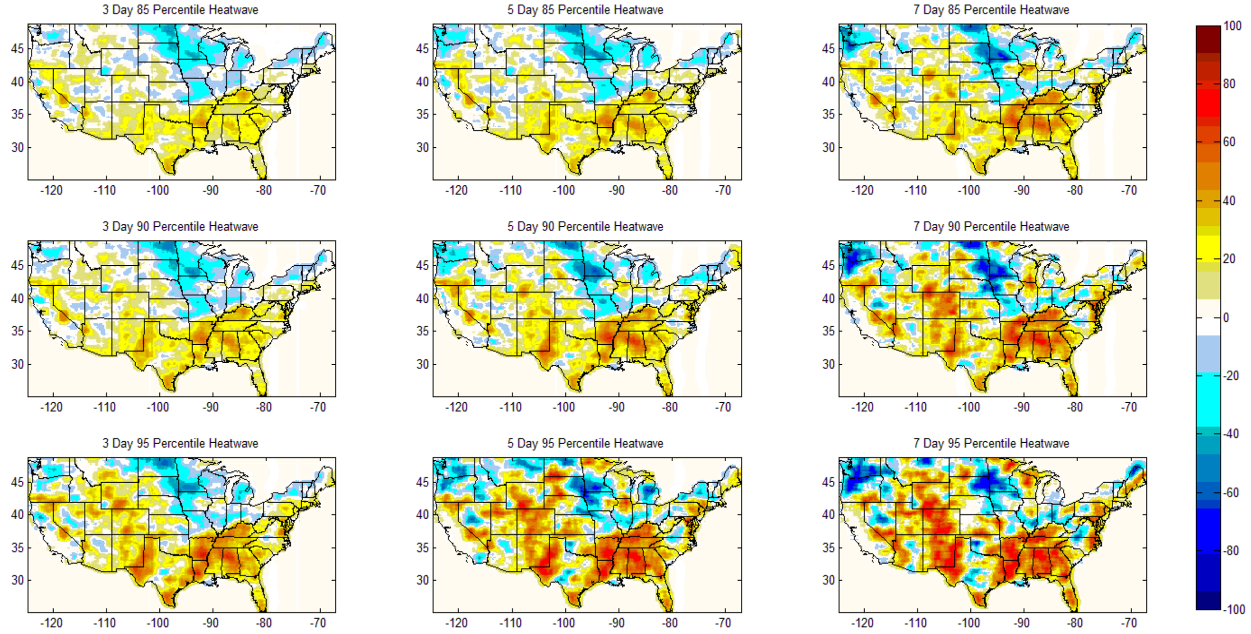

Figure 1: Percent change in concurrent droughts and heatwaves during 1990-2010 relative to 1960-1980. The rows change in heatwave severity (85th percentile, 90th percentile, and 95th percentile) while the columns change in heatwave duration (3-day, 5-day, and 7-day).

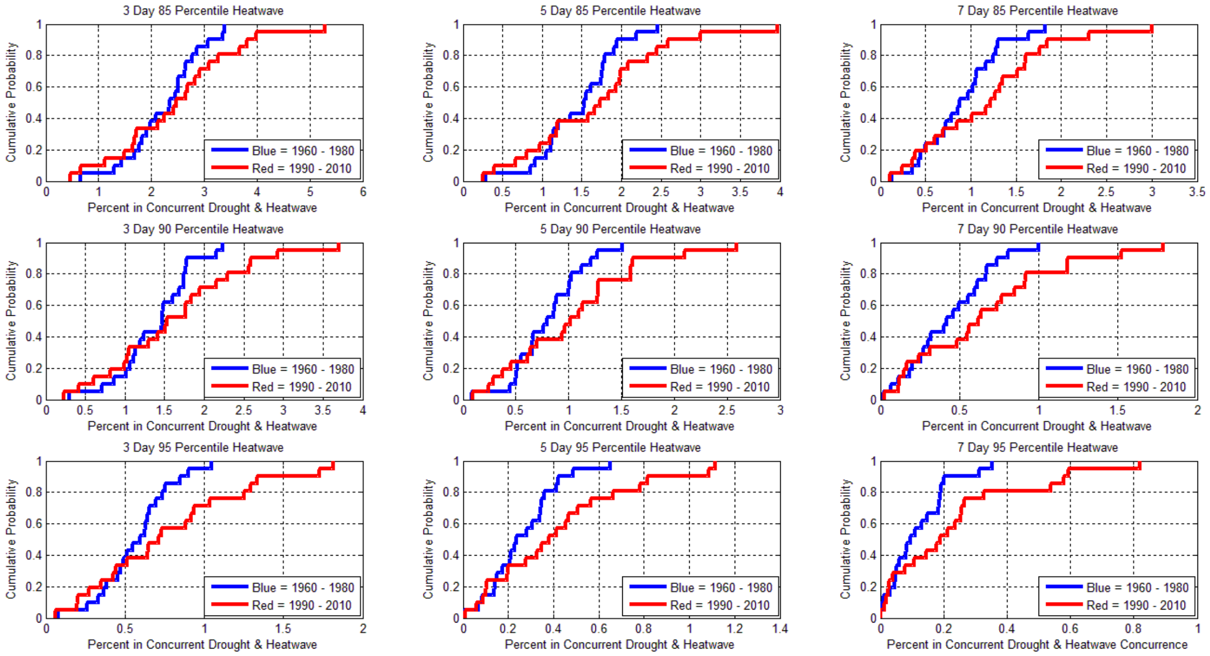

Figure 2: The empirical cumulative distribution functions of drought and heatwave concurrences from 1960-1980 (Blue) and 1990-2010 (Red). The rows change in heatwave severity (85th percentile, 90th percentile, and 95th percentile) while the columns change in heatwave duration (3-day, 5-day, and 7-day).

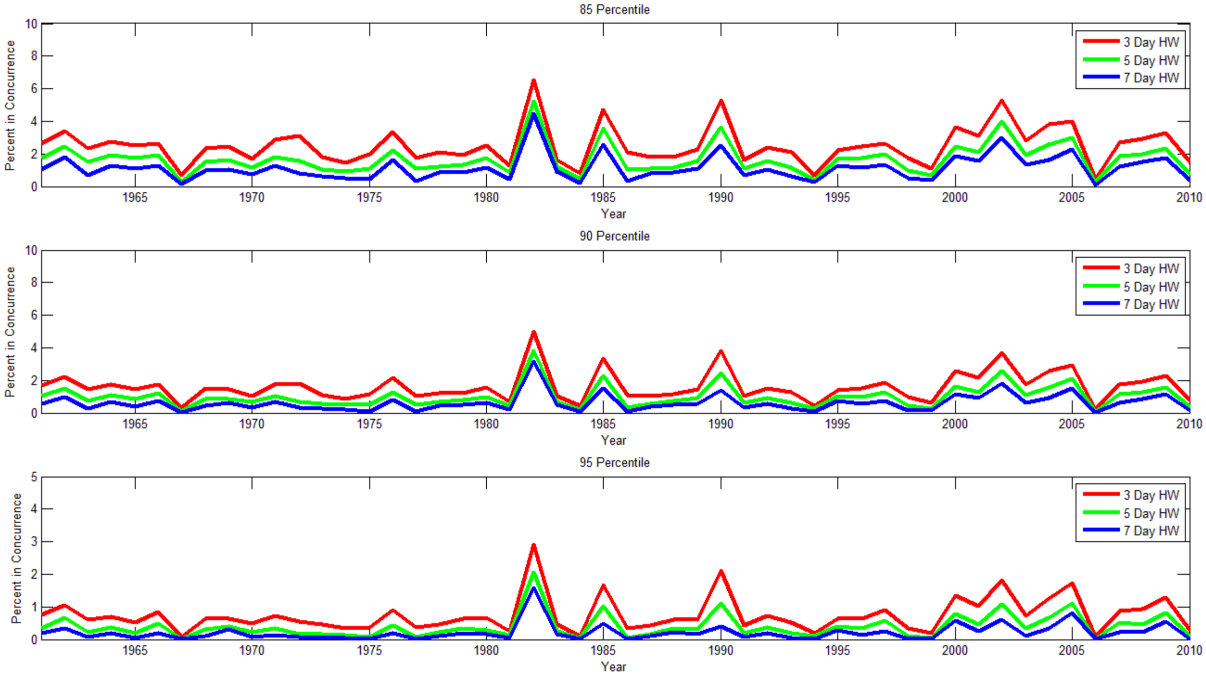

Figure 3: Percent (%) of the contiguous United States in concurrent drought and heatwave from 1960-2010.

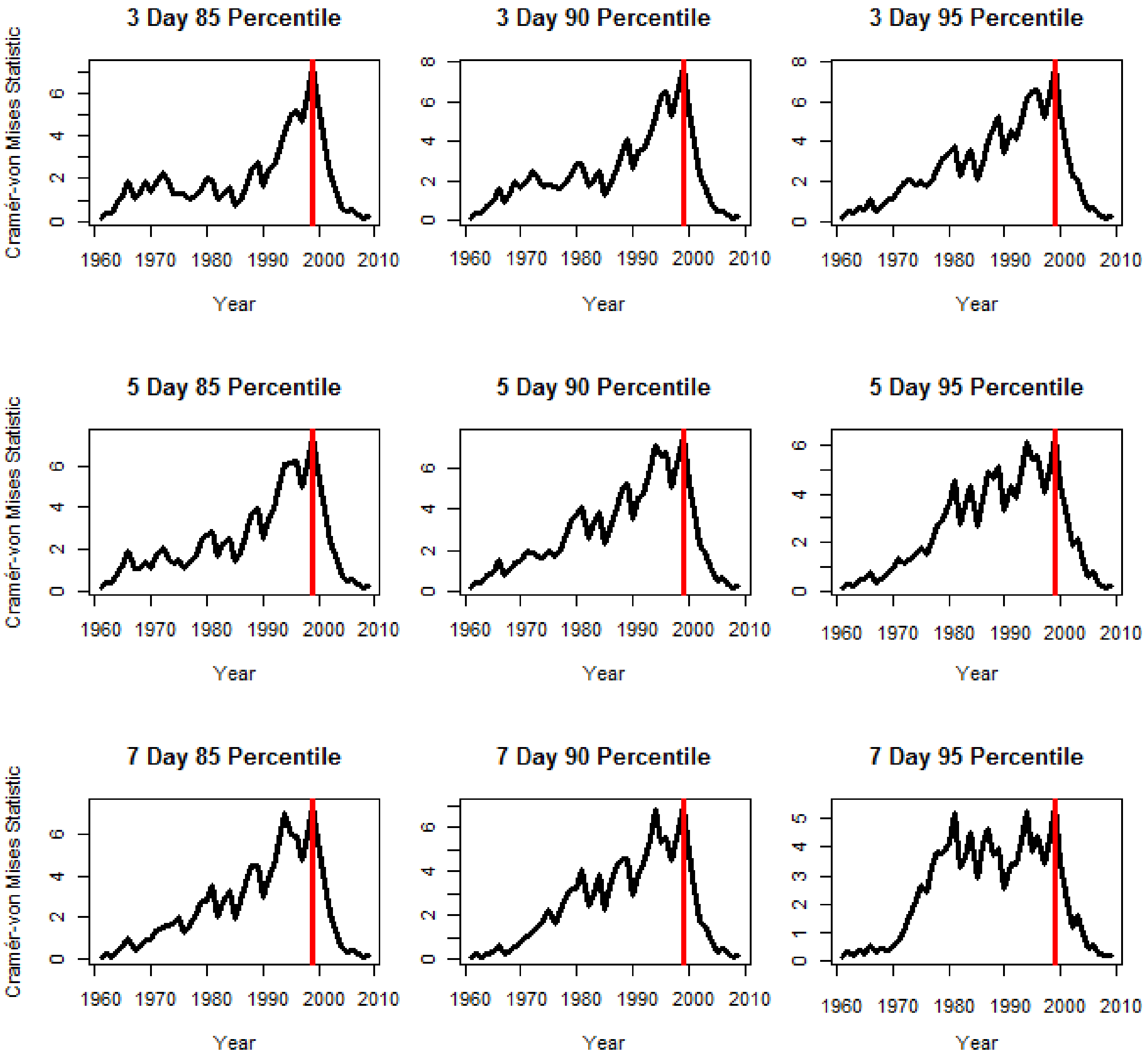

Figure 4: The Cramer von-Mises change point statistic from 1960-2010. The rows change in heatwave severity (85th percentile, 90th percentile, and 95th percentile) while the columns change in heatwave duration (3-day, 5-day, and 7-day). The red lines indicate the point of maximum divergence between the distributions of concurrent drought and heatwave events.

Appendix B

Table S1: Change in distribution functions between 1960-1980 and 1990-2010 based on the Kolmogorov-Smirnov test. Column 2 shows the H values, where 0 indicates the distribution functions are drawn from the same distribution at a significance level of 0.05 (null-hypothesis). The H value of 1 indicates the distribution functions are drawn from different distributions. Column 3 shows the corresponding p-values, where smaller p-values represent higher confidence in rejecting the null hypothesis.

Drought and Heatwave	H	p-value
3-Day, 85 Percentile	0	0.530908
5-day, 85 Percentile	1	0.00108
7-day, 85 Percentile	1	1.57E-05
3-day, 90 Percentile	1	3.10E-06
5-day, 90 Percentile	1	3.10E-06
7-day, 90 Percentile	1	3.10E-06
3-day, 95 Percentile	1	1.68E-09
5-day, 95 Percentile	1	1.68E-09
7-day, 95 Percentile	1	1.68E-09

Table S2: Trends in drought and heatwave concurrence from 1960-2010 based on the Mann-Kendall trend test. Column 2 shows the H values, where 0 indicates no trend with a significance level of 0.05 (p-value > 0.05). The H value of 1 indicates a statistically significant trend with 95% confidence. Column 3 shows the corresponding p-values, where p-values <0.05 represent high confidence in rejecting the null hypothesis of no trend.

Drought and Heatwave	H	p-value
3-Day, 85 Percentile	0	0.9095
5-day, 85 Percentile	0	0.871
7-day, 85 Percentile	0	0.5919
3-day, 90 Percentile	0	0.7576
5-day, 90 Percentile	0	0.6492
7-day, 90 Percentile	0	0.4355
3-day, 95 Percentile	0	0.6728
5-day, 95 Percentile	0	0.4452
7-day, 95 Percentile	0	0.4452