Flooding threshold rainfall events in Bermuda

Michael C. Johnston[1] , Mark P. Guishard[2], Irene Peñate[3] and Ian D. Currie[3]

[1]Department of Meteorology, University of Reading, Reading, UK
[2]Bermuda Institute of Ocean Sciences, St. George's, Bermuda
[3]Agencia Estatal de Meteorología, Las Palmas de Gran Canaria, Spain
[4] Bermuda Weather Service, CI[2]Aviation Bermuda Ltd., St. David's, Bermuda

*Corresponding author: M. Johnston, (m.c.johnston@pgr.reading.ac.uk)

Abstract

Recent localized flooding events in Bermuda motivate an examination of the daily rainfall record, to determine trends and variability of rainfall accumulations. A conservative catalogue of flood reports is constructed from anecdotal reports of flooding for the last decade. The flood catalogue events are related to daily rainfall amounts to develop a threshold daily rainfall for flood events, determined to be on average 39.3mm of rain. This threshold was used as a basis for examination of the historical record of daily rainfall 1949-2016, in order to assess return frequencies of flood inducing rainfall events. A return period of approximately 2 months for the average daily rainfall amount flood threshold was calculated. A trend in the daily rainfall accumulations indicate an increasing trend in rainfall amounts and counts of days on rain was recorded ('rain days') since 1949.

Introduction

In recent years, the societal profile of flooding events in Bermuda has been increased by the ready availability of photographs and commentary on news websites and social media. These flooding events are highly localized, with primarily what may be deemed 'nuisance impacts'; most widely reported are the instances of disruption to traffic flow, parking and potential vehicle damage. In some cases, the subsequent impacts, such as localized landslides or property flooding (Bell, 2014) may cause disruption, and major infrastructure damage is reported to have resulted from phenomena related to heavy rainfall events (Finighan, 2014). In particular, flooding issues have recently become more topical as businesses and property owners in Pembroke parish look for a means to end the frequent flooding they experience (Johnston-Barnes, 2015). A recent digital elevation model of Bermuda shows that this area is at the bottom of a valley, mostly near sea level (Sutherland et al. 2013).

Case Study – 5 January 2017

A deep long-wave upper level trough over eastern North America moved eastwards on Thursday morning, allowing a cold front to advance towards and across Bermuda (Figure 1a). Deep-layered flow out of the tropics allowed significant moisture transport across Bermuda. The frontal system, supported by upper level dynamics, was able to deploy that moisture in the form of an active band of heavy showers and thunderstorms (Figure 1b) that slowly progressed across the island, with a trailing region of light-moderate rains.

Rain totals for the meteorological day (0600 UTC to 0600 UTC) at the Bermuda Weather Service (BWS) far exceeded several records, with 136mm of rain; 5 January 2017 constituted the 5th wettest day on record in Bermuda (Table 1) . Figure 1c shows that observations around Bermuda indicate a widespread 100-150mm of rain fell with isolated areas experiencing >150mm. This led to widespread flooding of low-lying and poor-drainage areas (Bell, 2017). The 1981-2010 average January rainfall is 138mm (135mm for 1971-2000 climate period).

Events such as this have raised concern from members of the public and decision makers regarding the frequency and intensity of flooding events (Johnston-Barnes, 2015). It is the intent of this study to investigate trends and variability in extreme rainfall events and infer conclusions about the potential for localized flooding.

Historical Rainfall Data

The Bermuda historical record of daily rainfall data examined for the purposes of this study spans 1949-2016 inclusive. It is comprised of meteorological measurements and observations of rainfall accumulations in Bermuda under the purview of the US Naval Air Station (USNAS) January 1949 - May 1995, and BWS, from June 1995 through December 2016. Examination of the heat map in Figure 2a reveals that, in general, rainfall events are highly intermittent and of relatively low intensity, with a maximum daily event of 197 mm recorded at June 1st 1996. 'Rain days' are also defined here as days on which measureable rain occurred in the record. Peñate (2015) concluded that events with the highest rainfall amounts are episodic and tend to occur in the period from June to October. This feature is also noted in the values of the average year, shown in Figure 2b, which suggest the existence of a seasonal pattern of rainfall extremes.

A plot of this time-series of rainfall in Bermuda (Figure 3), we note an upward trend in rainfall accumulations and rain days 1949-2016. The coefficients of determination (r^2) indicate a high degree of variability; this precludes adequate predictability of annual rainfall or numbers of rain days from a linear regression. Given the somewhat stochastic nature of rainfall event occurrence in Bermuda (Peñate, 2015), this is unsurprising.

Increases in rain rates and rain days through the year may be broadly consistent with and expected response to warming of average surface temperatures globally (Berg et al., 2013). Given that Bermuda's rainfall is entirely from a marine source region, it is expected that this be consistent with local observations of upper ocean temperature increases in the last several decades (Bates et al. 2012; Palmer et al., 2007; Trenberth, 2008).

Rainfall and flooding events

Bermuda has no riverine systems, so it is unsurprising that there are no published flood measurements or flood watershed analyses locally. An assessment of localized flash flooding potential requires the use of anecdotal data to develop inferences about the frequency of events. The flooding described in this study excludes seawater inundation and/or tidal influences on local hydrogeology features, and is intended to inform the reader on freshwater flooding events, induced entirely by localized instances of above-average rainfall.

Methods

A catalogue of severe weather reports for the period 2005 to 2015 is created. Reports are sourced from the local news media and BWS monthly and event reports. This timeframe is selected to allow for inclusion of Doppler radar analyses at BWS, (Bermuda's Doppler weather radar was installed in 2005) and frequent online news articles.

The catalogue contains the date, description, and category of each event. For this period of record, most events were of one day's duration. However, in the cases that were more than one day, the first day of the event was recorded. The event categories recorded are Flooding, Hail, Damaging Wind, Tornadoes, and Waterspouts. Flooding reports are subdivided by whether they were due to rainfall, storm surge, unusual tides, or some combination of those. Further, information is included on the geographic location of each reported event, and which sources reported each event.

Daily rainfall data were obtained from three main sources. Official data came from the National Climatic Data Center (NCDC) for the period 1949 to 2016 for the station with the identifier 78016. These data are recorded measurements by USNAS 1949-1995 and subsequently BWS 1995-present. Weather Underground (WU) was the source of additional unofficial reports from personal weather stations for the period 2012 to 2015 to help confirm the nature of heavy rain events in terms of their duration and intensity. Descriptive detail was additionally obtained from the BWS climate pages for the period 2000 to 2015.

Using the severe weather catalogue, a value to define 'heavy' rain events is determined. This value is defined as the mean amount of rain that fell on the meteorological day that coincided with a flood report. This was then used to examine the number of heavy rain events by year, and month. These statistics are then compared to the number of flood reports over the period of record of the severe weather catalogue.

A recurrence interval is then computed using the entire period of record of rainfall data from 1949 to 2015 as follows;

$$RI=(n+1)/m \quad \text{Equation 1}$$

, where *RI* is the recurrence interval, *n* is the number of years in the period of record, and *m* is the number of days with at least each rainfall total. This is used to estimate the recurrence interval of a 'heavy' rain event. The calculated values are fitted to a function with the best r^2 value. This best fit is determined by comparing that of the linear, second and third order polynomial, and natural log fits.

Results

The summary of severe weather reports using this method returned 32 counts of flooding reports exclusively due to heavy rainfall, three counts due to storm surge and rainfall, and two counts due to unusually high tides. The heavy rainfall threshold is found to be 39.3 mm (Figure 4), and the results turned up several areas that flooded on multiple accounts. These areas are mainly low-lying parts of Pembroke parish, including areas within the City of Hamilton.

Figure 5a suggests that there is some relationship between the number of heavy rain days per year and the number of flood reports due to rainfall. However, that relationship is less clear on a monthly comparison (Figure 5b). Further, these figures indicate some inter-annual variability in heavy rain events. Lower counts of both flood reports and heavy rain days are noted for 2009-2011 while the other years have much higher counts (Figure 5a).

The recurrence interval calculations were conducted for the period of record 1949 to 2015. The day with the most precipitation was 1 June 1996 with 197.4 mm (7.77”) of rain. The best fit to the empirical recurrence intervals is a log function,

$$rain=20.61861*\ln(RI)+78.66033 \qquad \text{Equation 2}$$

,where *rain* is the amount of rain that fell in a meteorological day in mm and *RI* is the recurrence interval in years. The recurrence interval for a heavy rain day (at least 39.3 mm) is found to be approximately 0.174 years (2.09 months) using the recurrence interval from observations (eqn. 1), and 0.148 years (1.78 months) using the best fit (the ‘LN’ model, eqn. 2), and This is illustrated in Figure 6.

Conclusions

The estimated threshold for a heavy rain day is suspected to be low-biased. This is because rainfall is distributed unevenly around the island and this study uses only rainfall measured in one location that doesn’t represent the rainfall that causes each flood event. Additionally, the report methods rely largely on news media to determine which flood event is newsworthy and this likely misses some flood events during busy news days. It is also important to remember that improper maintenance of drainage systems could exacerbate flooding issues.

Further, the personal weather station rainfall rates on flood days suggest that many of the flood reports are from short duration high intensity rain events. Using guidelines of the US National Weather Service many of these events would likely be classified as flash floods because of their rapid onset following or during heavy rain and the short duration of the flooding.

Results of this study show that heavy rain days occur more than once every two months. This daily accumulation amount may be interpreted as a contemporary threshold for potential flooding, and utilized for the development of flood guidance in conjunction with forecasts of precipitation.

Figure 7 shows the percentage of daily rain accumulations meeting or exceeding the heavy rain day threshold (39.3mm/day), for successive climatological 30-year periods 1951-1980, through 1986-2015. It is interesting to note that the climatological proportion of rainfall events which can currently produce flooding in Bermuda is not unprecedented, and that perhaps the ability of the modern urban environment to mitigate heavy rainfall events is diminished through recent decades. This may be due to less soil permeability/higher soil moisture content in flood-prone areas, or impedance of drainage in the built environment, exacerbated at low elevations by sea level rise.

One drawback of our methodology is the neglect of the duration of rainfall events. A hydrologic analysis of rain rates at a higher temporal resolution (e.g. mm per hour) would be preferable, however only daily rainfall accumulations are available for the duration of historical record, so a long climatology of rain rates is limited to units of mm per day. Numerical simulation of rainfall mechanisms, coupled with watershed elevation modeling may reveal more detailed flood processes in Bermuda.

Bermuda rainfall occurrence and amounts have limited predictability in space (Penate, 2015), so we cannot hope to predict when floods will occur, but this study provides insight into the conditions in which they may arise. This may in turn provide the backdrop against which a flood forecasting tool may be developed, if accurate predictions of rainfall amounts are available. The relationship between reported flood events in this study and daily rainfall is robust. Flooding induced by non-rainfall causes (e.g. tidal, storm surge) were removed from the catalogue, and there were no instances of flooding detected which were unexplained by an underlying phenomenon.

If the number of annual rain days and annual rainfall accumulations continue their upward trend, Bermuda may expect to incur further challenges, compounded by any reduction in resilience to flooding in the urban environment. It should be noted that non-meteorological influences such as poor drainage or watershed changes will influence the likelihood of flood occurrence.

The methodology presented here shows the utility of using anecdotal evidence for flood-prone locales, such as small islands/non-riverine environments, in the absence of flood depth measurements.

Acknowledgements

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Figure captions

Figure 1: a) BWS synoptic chart for 0600 UTC on 5 January 2017, and b) Local IR satellite imagery, Doppler rainfall and lightning display for the same time. c) Observations around Bermuda indicate a widespread 100-150mm of rain fell with isolated areas seeing >150mm. Reports are sourced from Weather Underground, WeatherLink, and Bermuda Weather Service. Note that shaded areas on this map with fewer reports are less reliable.

Figure 2: Daily rainfall over Bermuda airport for the period 1949-2011 (a), average precipitation for each calendar day (b), and annual average precipitation (c).

Figure 3: a) annual rainfall accumulations and b) rain days as measured by USNAS/BWS, 1949-2016.

Figure 4: Percent of flood reports with less than or equal to the amount of one-day rainfall. Highlighted are the rainfall amounts corresponding to the median, mean, and 2/3 of flood reports. The mean (39.3 mm) is used as the threshold for defining a 'heavy rain day'.

Figure 5: Comparison of Flood Reports by (a) year and (b) month, with 'heavy' rain days by year for the period of record 2005 to 2015.

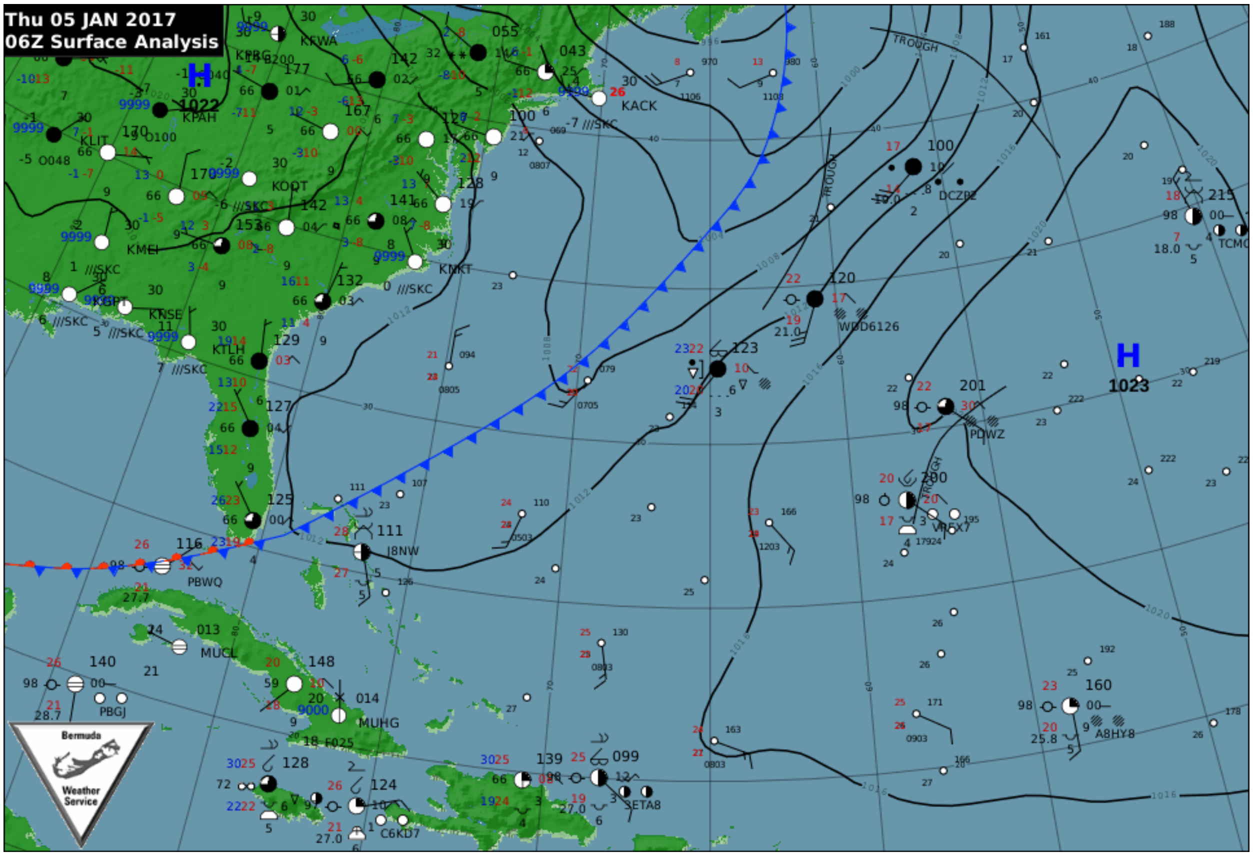
Figure 6 (a): Recurrence intervals observed and modeled using a log fit for data from the Bermuda Weather Service (78016/TXKF) for the period 1949 to 2015. (b) Truncated to the first 50 mm to show the heavy rain recurrence interval. ‘Climate’ refers to return intervals derived from observations in eqn. 1. ‘LN Model’ refers to predictions from eqn. 2.

Figure 7: Proportion of all non-zero daily accumulations which met or exceeded 39.3mm for successive 30-year climatological periods.

Table1: (a) Records broken with the rainfall accumulations of 5 January 2017, with reference to single, meteorological day records for the period 1949-2016 at Bermuda Weather Service. (b) A summary of records for this particular day, month, and the winter season (precipitation records for Bermuda are 1949-2016).

a) Bermuda rainfall accumulation records broken on 5 January 2017	
Type of Record	**Previous Record**
Record Wettest for the date 5 Jan	1.54″ (5 Jan 1994)
Record Wettest Jan Day	3.99″ (11 Jan 1986)
Record Wettest Winter (Dec-Jan-Feb) Day	3.99″ (11 Jan 1986)
b) Summary of Top 5 Bermuda rainfall accumulation records * Hurricane Nicole	(1.) 197.36mm (1 Jun 1996) (2.) 171.96mm (13 Oct 2016)* (3.) 157.73mm (31 Aug 1982) (4.) 140.21mm (14 Jul 1980) ***(5.) 135.64mm (5 Jan 2017)*** (6.) 133.10mm (29 Oct 1967)

Figures

292 
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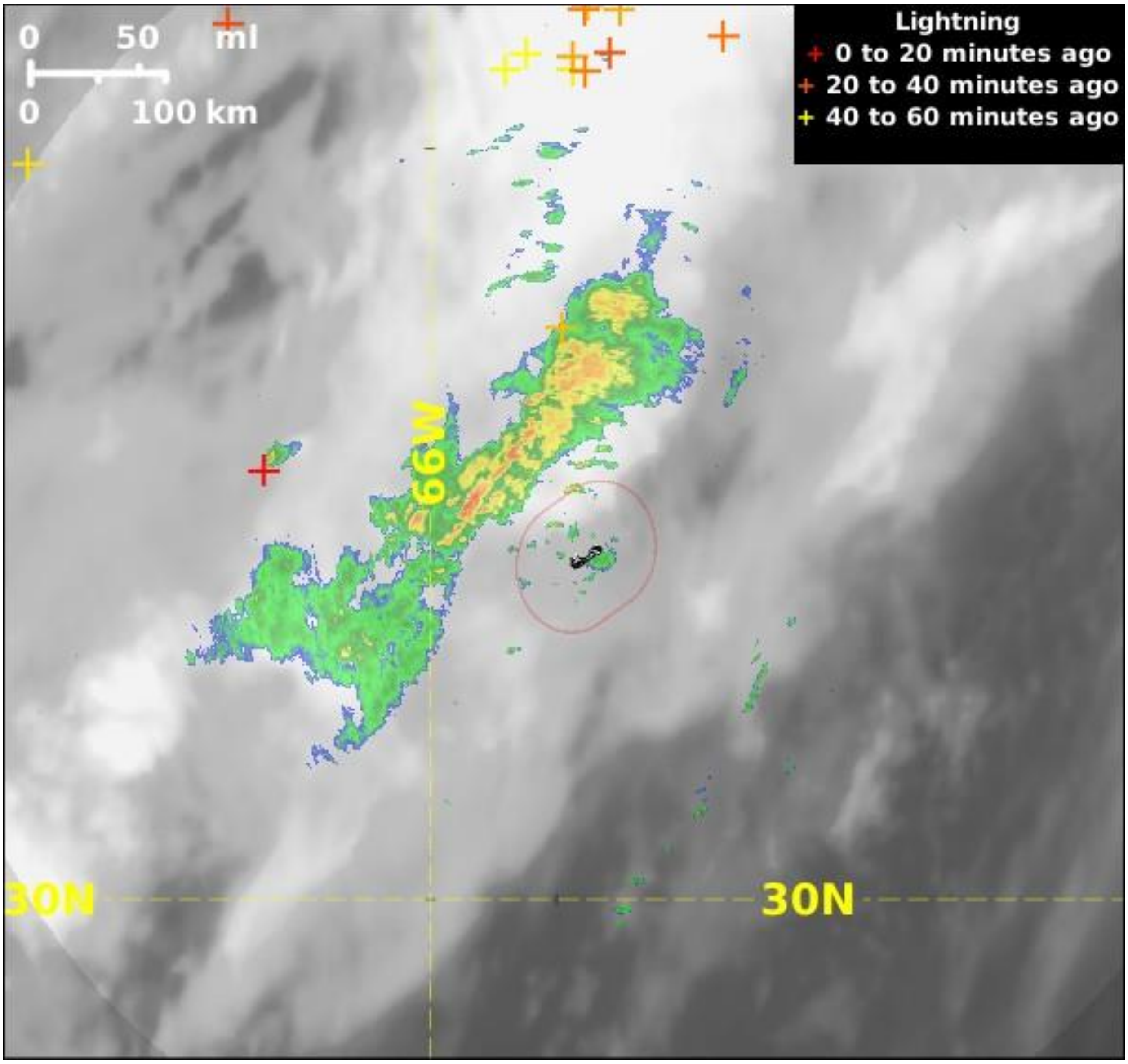
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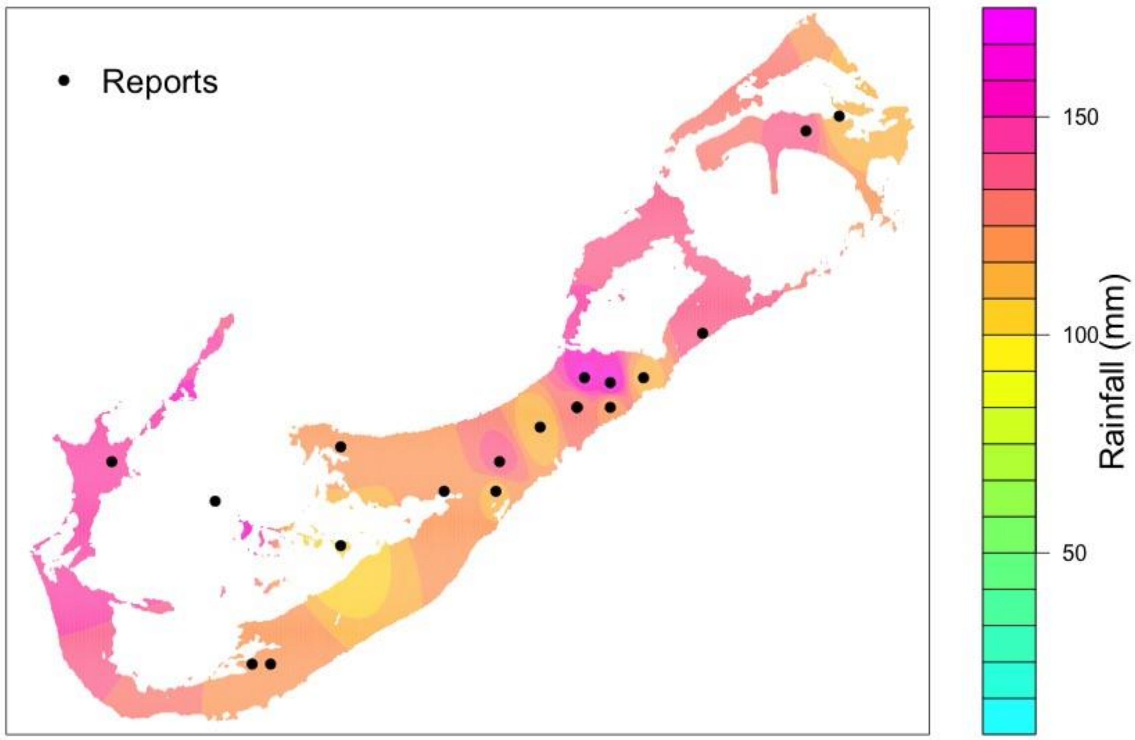

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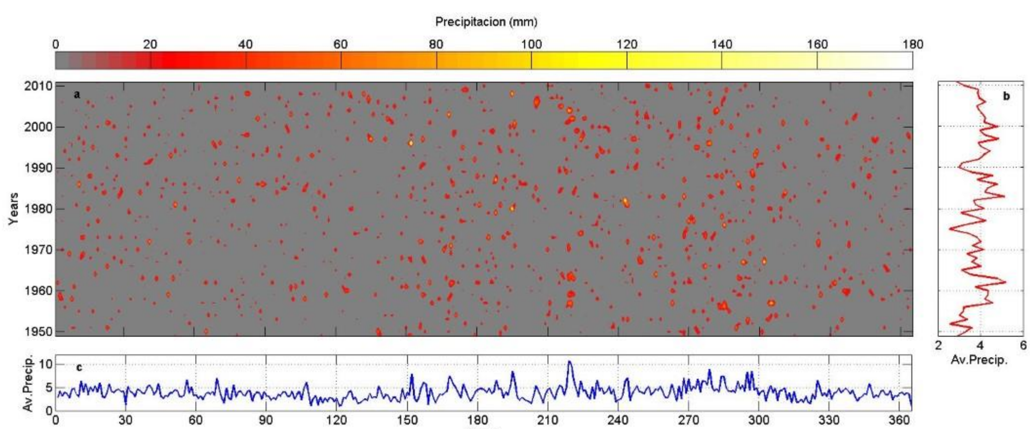

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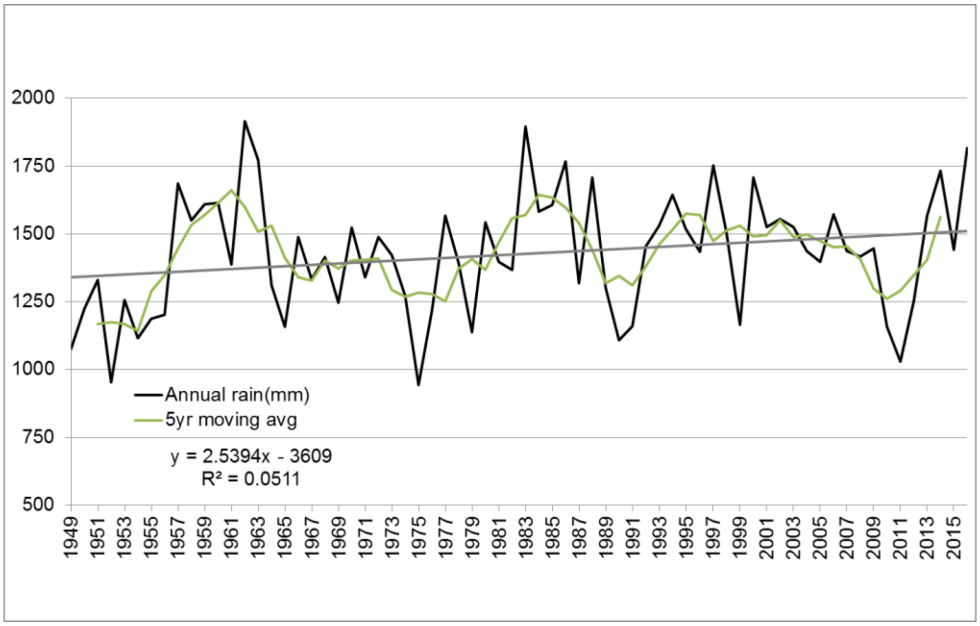

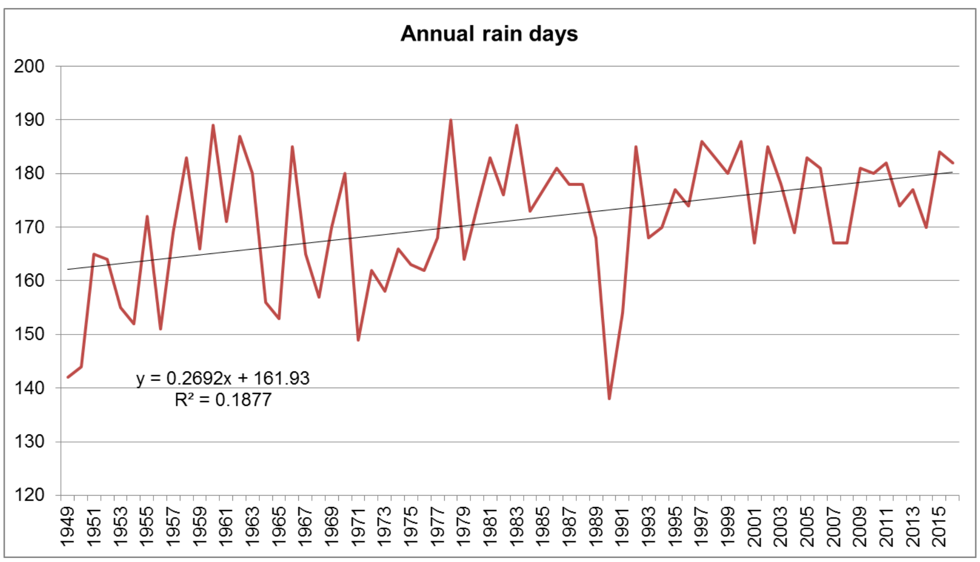

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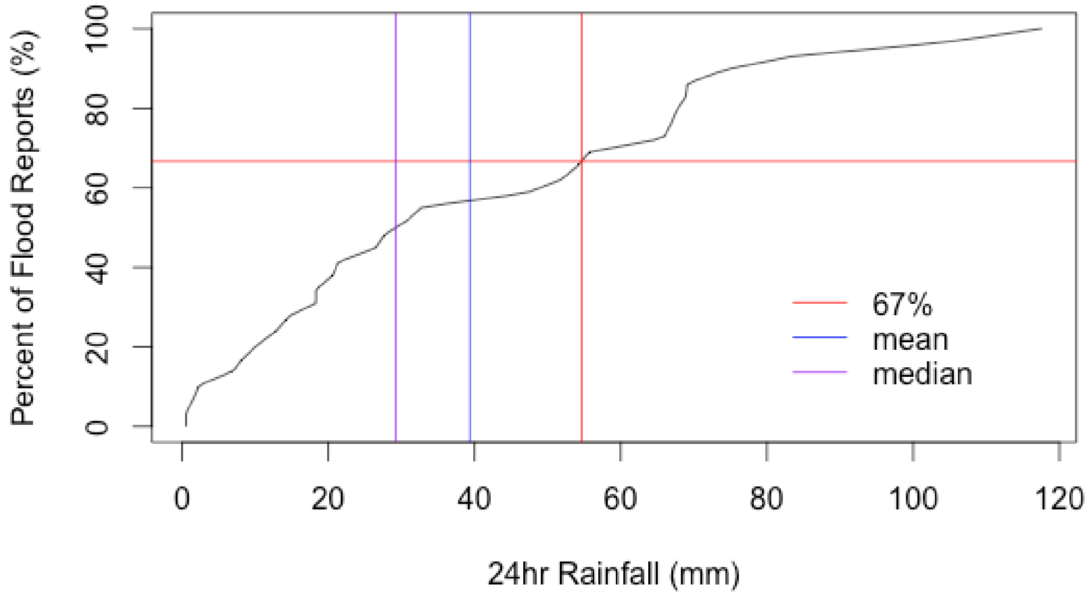

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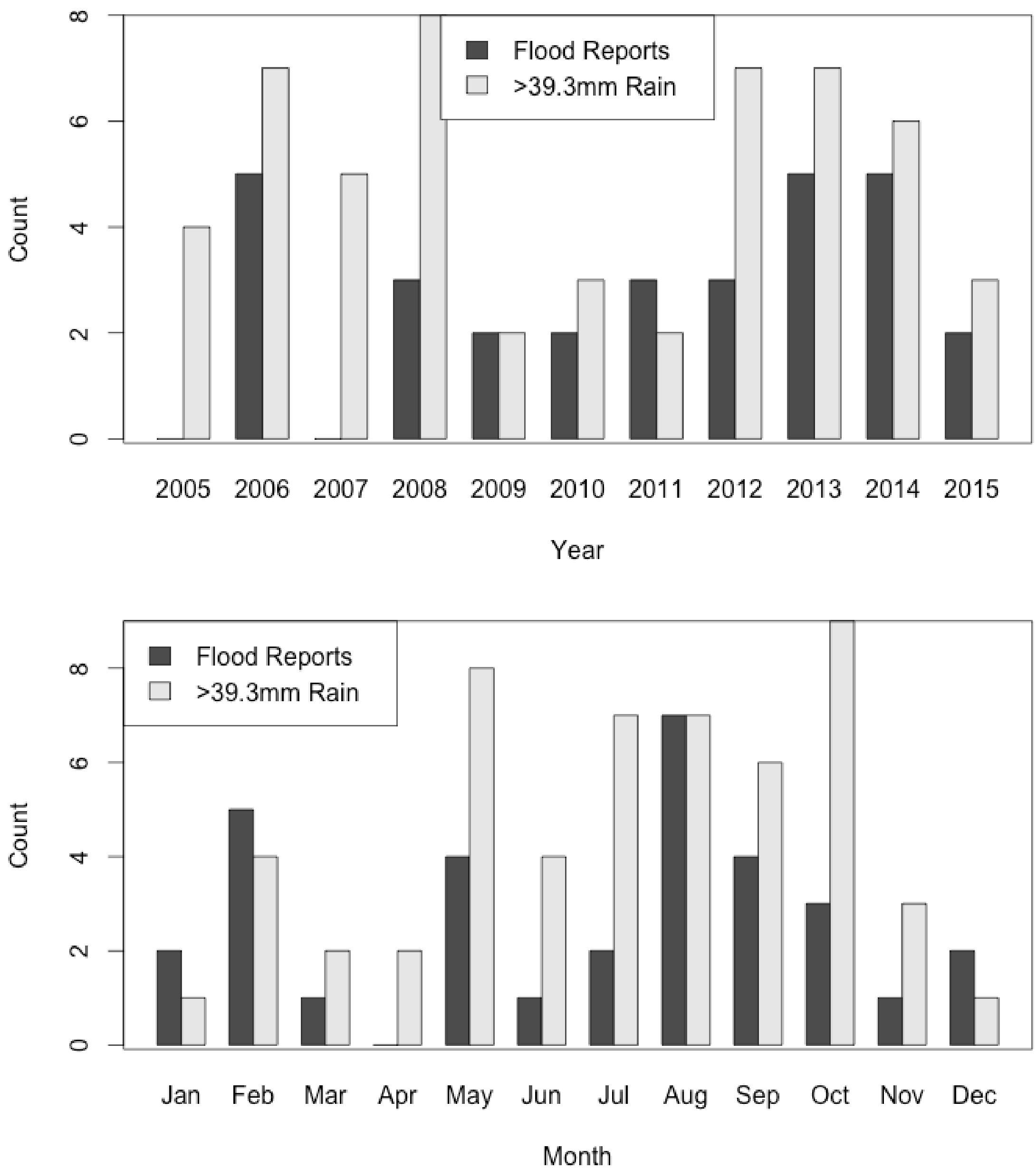

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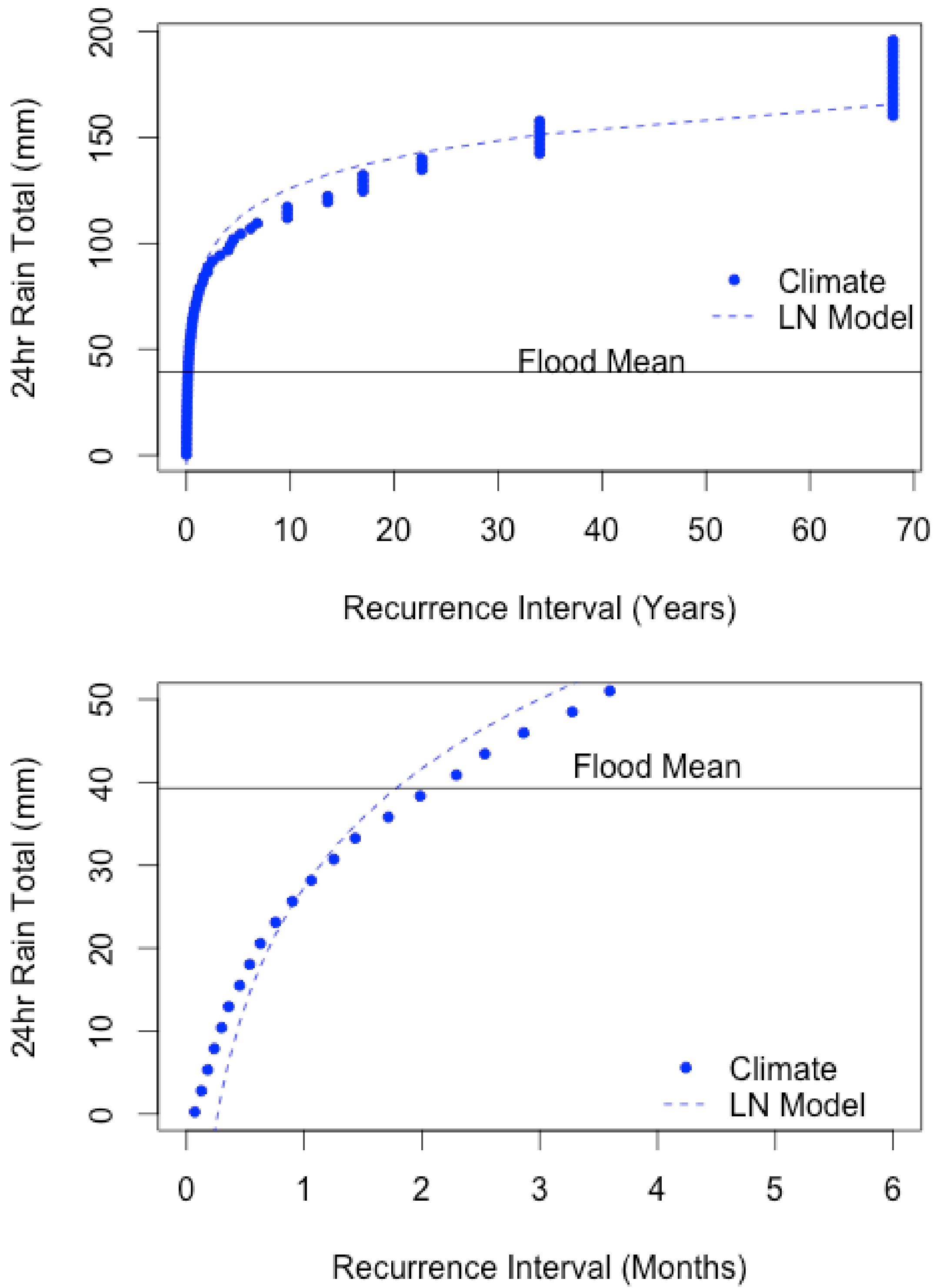

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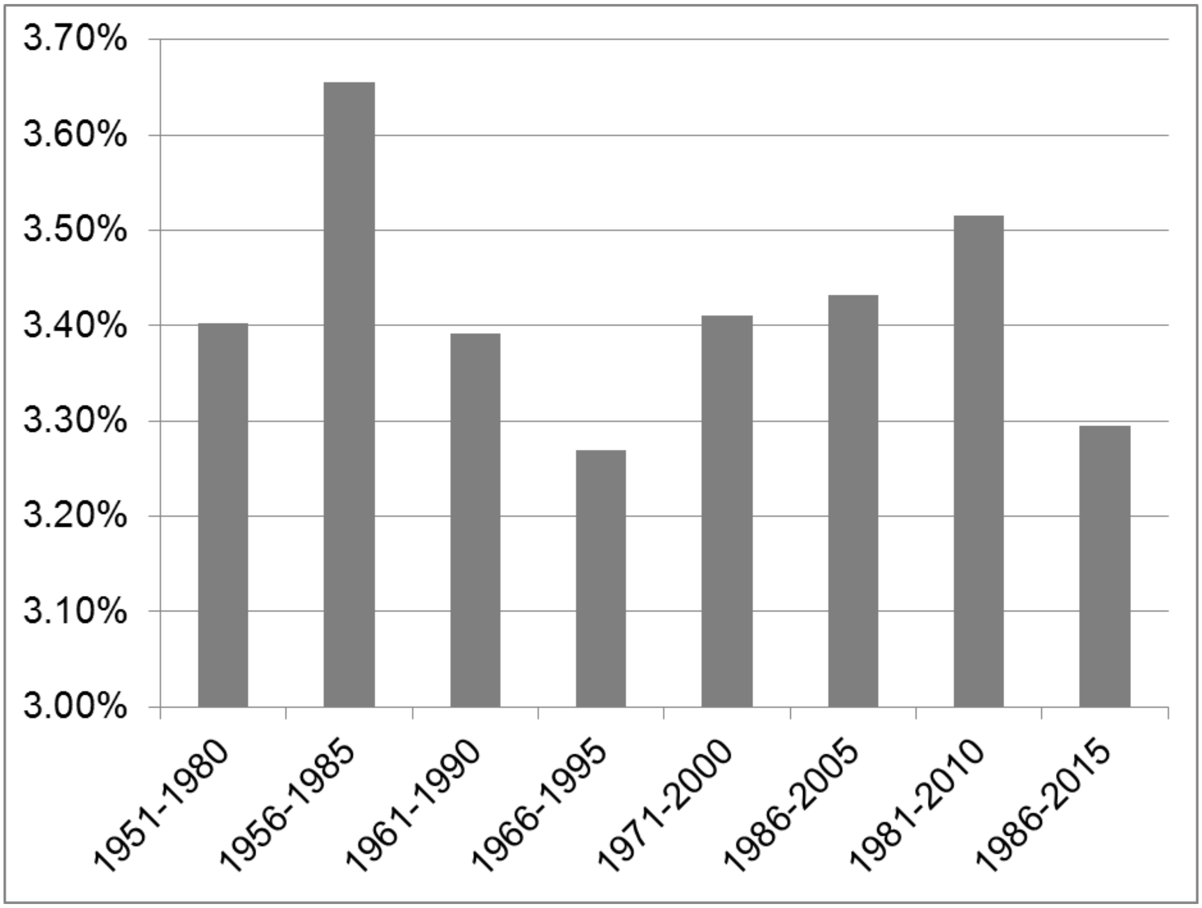

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