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A macro-scale flood risk model for Jamaica with impact of climate variability

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Abstract Floods account for more than half of the global hydrometeorological risks. Severe floods cause significant economic shocks and loss of lives, particularly for developing countries such as Jamaica. There is need for more information on the present and projected flood risks to justify macro-scale planning for climate change adaptation and facilitate the decision-making processes. In this study, a catalogue of 198 flood events occurring between 1678 and 2010 is compiled for Jamaica and used to examine the climatology, occurrence, trends, causes and duration of the island's severe events. The annual flood risk is estimated to be a loss of life rate of 4 persons and estimated annual damage of USD96.3 million per annum in 2010 values and approximately 0.84 % of GDP per annum. Macro-scale models for flood risks (deaths and damages) are also developed using data from the flood catalogue and maximum precipitation at the town and parish level. The models examine the relationship between flood risks (death and damages) and extreme rainfall depths and intensities. Future climate risks of loss of lives and damages are predicted to increase 11 and 9 %, respectively, to 4.4 persons and USD105.2 million per annum.

Keywords Loss of life · Flood catalogue · Flood risk · Macro-scale · Climate change · Extreme precipitation · Atlantic multi-decadal oscillation

1 Introduction

Globally, severe flood events have accounted for major losses to life and property. It is estimated that floods accounted for USD2.36 trillion or 62 % of the total global damages due to natural hazards between 1980 and 2012 (MunichRe 2013). For the same period, the

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global estimate for the loss of lives due to flood events was 3.34 million from the EM-DAT dataset. Cavallo and Noy (2009) determined that within the Latin American and Caribbean (LAC) region hydrometeorological events accounted for USD31.8 billion or 54 % of the total losses from natural hazards for the period 1970 to 1999, in 1998 dollars. This is in part attributable to the Caribbean's position in the North Atlantic hurricane belt (Rasmussen 2004; Munich Re 2011).

Jamaica has experienced severe hydrometeorological events in the past 100 years (see, for example, Table 1). The Planning Institute of Jamaica [PIOJ] (2002, 2004, 2005a, b, 2007, 2008, 2010, 2012) summarizes that six storm events between 2002 and 2007 resulted in 60 fatalities and damages of approximately JMD70.72 billion (USD1.02 billion). The cumulative losses are equivalent to 8.7 % of the 2007 gross domestic product (GDP) or 1.75 % per annum over the period. The rates of losses for Jamaica per hurricane for the period in GDP reduction are comparable to those for LAC countries (0.83 %) for the period 1950 to 2005 (Strobl 2012) and for Caribbean countries (0.9 %) for the period 1970 to 2006 (Ouattara and Strobl 2013). Additionally, between 2002 and 2007, estimated losses from the EM-DAT database for Jamaica are comparable to those for the 102-year period between 1900 and 2002. This suggests an increasing trend, which deserves to be further investigated given the impact on the economy.

Extreme precipitation is a causative factor in severe flooding for Jamaica (Taylor et al. 2014) along with other factors including location in low-lying vulnerable areas (Mandal and Maharaj 2013) and socio-economic conditions (Ishemo 2009; Toya and Skidmore 2007). Vickers (1966) and WMO (2009) reported that on a global scale Jamaica ranks 4th and 40th, respectively, in its 15 min and 2- to 8-day duration rainfall. Historical and projected trends in extreme precipitation for Jamaica and the Caribbean (Campbell et al. 2011; Stephenson et al. 2014; Peterson et al. 2002) suggest that flood risk may have already been altered and will likely to be further altered under changing climatic conditions (Burgess et al. 2013). A knowledge of past and future flood risk trends which incorporates an understanding of climatic drivers would enhance decision-making in climate resilient infrastructure for island states like Jamaica.

Knowledge of the characteristics of floods in Jamaica in terms of climatology, occurrences, trends, causes and durations is limited. For example, there is no estimate of the

Table 1 Some catastrophic hydrometeorological events that have affected Jamaica since 1933

Year	System	Reported maximum depth of rainfall (mm)	Deaths	Cost (USD million, 2010)
1933	Hurricane	513	70	$22
1940	Cloud bursts	689	125	$13
1951	Hurricane Charlie	432	154	$615
2004	Hurricane Ivan	709	17	$822
2005	Hurricane Wilma	578	1	$169
2007	Hurricane Dean	342	6	$395
2008	Tropical Storm Gustav	491	20	$179
2010	Tropical Depression	400	16	$235
Totals			409	$2450

Sources: Jamaica Weather Reports, ODPEM, MS, WRA and PIOJ/ECLAC

NB: Although Hurricanes Allen and Gilbert resulted in USD219 million and USD2,363 million in damages, respectively, they were not included in the table because they were primarily wind phenomena

present or projected flood risk to inform macroeconomic planning and climate change adaptation, despite precipitation projections and some information on past flood death and damages being available for severe floods since 1678. There are data gaps, however, including the lack of site-specific flood losses and deaths and some loss of rainfall information before 1992 due to a fire at the Meteorological Service of Jamaica. This study attempts to fill some of the gaps in knowledge through (1) a compilation of a catalogue of deaths and damages from various sources of flood data dating back to 1678, (2) the estimation of annualized damage (EAD) and annual loss of life and mortality rate from the database and the comparison to regional and global averages, (3) the association of severe flood hazards with climate and an examination of the impact of climate variability on flood frequencies including the potential connections to two global climatic phenomena—the El Nino–Southern Oscillation (ENSO) and the Atlantic multi-decadal oscillation (AMO), (4) an investigation of the dominant role of hurricanes and the importance of storms of 2 days or longer duration, (5) the construction, calibration and validation of simple macro-scale flood risk models for death and damages that consider spatial extent, precipitation intensity and depth, and (6) the comparisons of the model results to other flood risk models and the projection of flood risk in the future.

The methodology used in compilation of the flood catalogue is similar to that of Barredo (2007) done for Europe and is detailed in Sect. 2 of this paper along with a description of the data sources. Other methodologies of analysis to support the study aims including those for model construction are provided in Sect. 3, while Sects. 4–6 present results. The significance of the results and the implications of the model in the local and regional context are discussed in the final section of this paper.

2 Data

Severe flood events are defined as the wide scale inundation of usually dry land by extreme precipitation events, overflow of rivers or groundwater seepage. To be considered in this study, we propose that the scale of flood affected areas must be several communities (~ 1–10 km^2) and the event must have lasted more than 24 h. Additionally, the event must have been documented by a state agency in Jamaica as having resulted in: (1) at least one death or (2) disruption or damages to infrastructure, agriculture or the housing stock. State agencies from which data were gathered were the Office of Disaster Preparedness and Emergency Management (ODPEM) that has responsibility for disaster management, and the Water Resources Agency (WRA) and the Meteorological Service of Jamaica (MS) record hydrological and meteorological events, respectively. The criteria used are not unlike those used by other regional studies (e.g. Charvériat 2000) but is different from those of EM-DAT (Guha-Sapir et al. 2004). The primary difference in the latter instance is the scale of loss of life. EM-DAT criteria for severe flood events (10 or more persons killed, 100 or more persons affected, declaration of a state of emergency or call for international assistance) are suited for a larger scale than that of the region or Jamaica.

The primary sources of information were the ODPEM catalogue of floods (ODPEM 2000) from 1678 to 1999, the record of Tropical Cyclones affecting Jamaica from 1900 to 2000 and the MS record of significant weather systems affecting Jamaica from 1953 to 2009. These three sources were compiled into a single catalogue and duplicates removed to create a dataset spanning the period 1678 to 1999. The database was further extended to 2010 using detailed information for seven storms from 2002 to 2010 from the Economic

Commission for Latin America and the Caribbean (ECLAC) damage and loss assessment reports done in conjunction with PIOJ (2002, 2004, 2005a, b, 2007, 2008, 2010, 2012). The resulting database covers the period 1678 to 2010 and contains 198 severe flood events. This local flood catalogue has more events than the EM-DAT dataset frequently used for similar studies (e.g. Jonkman 2005; Barredo 2009). For example, EM-DAT records for Jamaica start in 1900 and include 42 events up to the end of 2010, versus 152 from the local catalogue for the same period. Additionally, EM-DAT records 1391 deaths and USD2.815 billion in damages for the period 1900 to 2010. The deaths in the EM-DAT dataset appear to be overstated by 136 % in comparison with the local catalogue with 588 recorded deaths. The source of this variance remains uncertain to us at this time. The damages were, however, comparable being only 16 % lower than the USD3.280 billion from the local catalogue.

Gaps in the rainfall fields of the flood catalogue were filled using information from the MS and Jamaica Weather Reports datasets (Weather Office 1892–1949; West Indies Meteorological Service 1950–1969). Records of losses and damages started in 1896 and were normalized to 2010 values using national sources of inflation information for JMD, USD and GBP currencies. Foreign currencies were converted to JMD using the Bank of Jamaica's exchange rate. The mean exchange rate between USD and JMD in 2010 was USD1 to JMD87.38 (Bank of Jamaica 2013). The approach is consistent with the wealth normalizing techniques of Neumayer and Barthel (2011) except that it was the total GDP and not per capita GDP that was used. Despite the steps taken to normalize the data, it is acknowledged that the reported damages are likely to have several shortcomings common to all global datasets including geographic and accounting biases (Gall et al. 2009). Nonetheless, it represents the best source of information available for Jamaica.

Time series representative of the AMO and ENSO (the N3.4 index) were acquired from the National Oceanic and Atmospheric Administration (NOAA) and the National Center for Atmospheric Research (NCAR), respectively. N3.4 is the anomaly of sea surface temperature over the Pacific Ocean bounded by 120°W–170°W and 5°S–5°N. AMO is the anomaly of sea surface temperature of the North Atlantic. An all-Jamaica rainfall index was also acquired from the Meteorological Service of Jamaica.

3 Methodologies

3.1 Flood hazard and climate connections

The climatology of severe flood events was explored through a distribution analysis of monthly occurrence from 1678 to 2010. Comparisons were made with the rainfall climatology determined by the analysis of MS monthly island-wide rainfall indices. As severe flood events are not stationary, various statistical tests were applied to the flood catalogue on an annual and bi-decadal time scale to detect both trends and sudden changes following the approach outlined by the World Meteorological Organization (WMO) (Kundzewicz and Robson 2000). Tests applied included the Mann–Kendal test, the Pettitt test and standard normal homogeneity test.

Climate connections were initially explored through correlation analysis between decadal occurrences of severe floods and the indices for rainfall, the AMO and N3.4. Annual records of both floods and the latter two climate indices were also subjected to spectral analysis to identify common periodicities.

Causes of severe floods were defined by distribution analysis from the flood catalogue reports. The categories considered were hurricanes, storms, fronts and a classification called "heavy rains". The latter category occurs in the older flood records and likely included distant hurricanes reported on in the Jamaica Weather Reports, which were accompanied by barometric pressure drops. This classification of synoptic climatology approximates those used by Gamble and Meentemeyer (1997). Information on duration of flood events was derived from reports of the time from start to end of the associated rainfall. Continuous rainfall gauge data were not available. The analysis of the durations ranged from 1 to 30 days and was conducted in two batches. That is, firstly, the entire period of 1772 to 2010 was considered; then, secondly two periods were examined—1772 to 1950 and 1950 to 2010, with the latter period coinciding with the last AMO cycle; 1772 is used as the starting year, as this is the first year in which cause of flooding was also reported. The objectives of this analysis were to define the distribution of the severe flood durations and to determine whether there was any change in the distribution of the duration of severe flood events.

Spatial characteristics of flood-prone areas and flood locations from past events in Jamaica were investigated using a geographic information system (GIS) platform. Locations of settlements and communities that had experienced severe flooding were used as a proxy for exposure. Floodplain maps are only available for approximately 10 watersheds across the island. This would not have been adequate to define the spatial extent of the hazard. The flood-prone community database was catalogued using information from ODPEM. Occurrences and proximity of flood-prone locations with elevation, slope and proximity to the river network were also investigated.

3.2 Observed risks

Annualized loss of life and loss of life per flood event were determined for the period of the catalogue. The records were subjected to distribution analysis for the most severe flood events. Mortality was investigated by normalizing the recorded deaths with the estimated population for Jamaica at the time of the reported events. Mortality is defined to be the ratio of the number of fatalities to the total number of persons exposed. Population was used as representative of exposure given the macro-scale approach and the fact that Jamaica is relatively small and most severe storms affect either the entire island or most of it. No distinction is made between mortality from pluvial or fluvial floods as the data do not permit this level of analysis. The records of fatalities also do not distinguish between persons directly impacted by flood waters versus those who died indirectly. Three scenarios were investigated, namely mortality as a function of rainfall depth, intensity and warning time. Duration of the events was used as a proxy for warning time, which is known to be an important factor in fatalities outcome (Reiter 2001).

Damage records were subjected to distribution analysis and estimation of damage per event for the period 1896 to 2010. A windowing average in 20-year increments from 20 to approximately 100 years was used to assess whether there was a trend in the cost per event. EAD was also determined from the data.

Death and damages to total rainfall depth and 24-h intensities were investigated in the data preparation stages. The possibility of a threshold, above which deaths and damages were observed, was also investigated, in order to provide an initiating point for the flood risk model being created. Such a threshold would also have importance for emergency action planning (Golian et al. 2010).

3.3 Macro-scale flood risk model

Macro-scale flood risk models were developed to explain the relationship between extreme precipitation and the risks of loss of life and damages, respectively. Modelling of risk of loss of life and mortality is not a new concept in flood risk assessments (Jonkman 2005, 2007; Jonkman and Vrijling 2008; Johnstone et al. 2005; Aboelata and Bowles 2005; Jonkman 2011; Penning-Rowsell et al. 2005), and several regions have considered or implemented such a model (Meyer and Messner 2005). There are spatial and temporal data limitations that prevented the application of mesoscale or micro-scale risk models [for example, as used in Gaume (2009)], or detailed Source–Pathway–Receptor–Consequence (SPRC) models (Kandilioti and Makropoulos 2012; Gouldby et al. 2006). The use of a macro-scale model in this data scarce region is consistent with the recommendations of Messner (2007) and Li (2012).

The approach of using extreme precipitation (or precipitation intensities) as the source of the hazard at an overall event level does not follow the inundation depth approach of a mesoscale-type model. It is, however, similar to the approach of Czajkowski et al. (2013) who used a flood ratio [flood flow to 10-year return period (RP) flow] to predict flood risk. A threshold was implemented so that predictions from the models were initiated after a total rainfall depth was achieved (see Eq. 1). Data from only nine events from 1942 to 2010 (Table 2) were used in model development. These events had the most detailed records of both fatalities and damages in recent times. We note that events from 2002 were from detailed post-event damage and losses reports from ECLAC that use the Damage Loss and Needs Assessment (DALA) method, described by Jovel and Mudahar (2010). The DALA method is not without its limitations, as Moore and Phillips (2014) point out its tendency to overestimate direct damages and underestimate indirect losses. Records of damages for events before 2002 used a similar framework to DALA but focused on direct damages. It is therefore likely that the damages and losses reported for the earlier events may be less than if they were assessed with the DALA method. However, the information available is the best available information to our knowledge. The events used herein are primarily all-island occurrences, except for the 2002 tropical storm that affected seven of fourteen parishes. A parish scaling factor (PF), defined as the ratio of the number of parishes exposed to the total number of parishes (14), was therefore used. It is acknowledged that the PF does not take into account spatial variations of precipitation extremes, orographic factors or topography. The proposed models have all the essential ingredients of a SPRC model, namely a source of the hazard (rainfall), a pathway (embodied in the use of the threshold), receptor exposure (through the use of the parish scaling factor) and consequence (the prediction or outcome of the model).

In the model development process, both death and damage outliers were identified and removed before calibration. In this regard, the death toll of 154 from Hurricane Charlie (in 1951) and damages from the tropical storms of September and October 2002 was removed after a check was made of their deviation from the expected values relative to the initial linear trend's mean and deviation using both the standard seviation (SD) test and the modified Z test (Seo 2006; Hoaglin et al. 1986). The deaths for Hurricane Allen and damages for the 2002 event were determined to be 2 and 3.3 standard deviations at or above a criteria of 2 adopted herein. Additionally using the more robust Z test, the events had scores of 6.2 and 7.9 and were well above the 3.5 criterion for detection of outliers. It is also acknowledged that stationarity in resilience is inherently assumed, and projections outside of the period used in this study would have to be qualified by this assumption. Validation of the models was done with Hurricane Sandy in 2012 (PIOJ 2012) and a low-

Table 2 List of severe flood events used to develop flood risk model for Jamaica from 1942 to 2010

Year	Total depth of precipitation (mm)	Intensities (mm/day)	Deaths	Damages, JMD (USD) million	Type of system	Impact area
1942	578	83	15	$14,774 ($169)	Not known	All island
1951	432	432	154	$53,760 ($615)	Hurricane Charlie	All island
1977	359	17.1	11	$1424 ($16.3)	Heavy rains for 21 days	All island
2001	380	35	2	$49 ($567.4)	Hurricane Michelle	All island
2002	709	355	17	$71,832 ($822)	Tropical Storm	St. Elizabeth, Hanover, Westmoreland, Clarendon, Kingston, St. Andrew and St. Thomas
2005	590	30	4	$2161 ($24.7)	Hurricane Wilma	All island
2007	342	342	6	$20,997 ($240.3)	Hurricane Dean	All island
2008	491	491	20	$15,609 ($178.6)	Tropical Storm	All island
2010	400	50	16	$20,520 ($234.8)	Tropical Depression	All island

pressure system that affected the island in June 2011. Hurricane Sandy predominantly affected five parishes in the eastern end of the island (St. Mary, Portland, St. Thomas, Kingston and St. Andrew). The low-pressure system of 2011 affected five south-eastern parishes (St. Thomas, St. Andrew, Kingston, St. Catherine and Clarendon).

All-island flood risk (R) models for Jamaica for deaths and damages, where C_i and C_j are calibration coefficients, i is equivalent 24-h rainfall, with parish scaling factor (PF).

$$\text{Flood risk}, R_i = \text{PF} \times \begin{cases} \text{Deaths} = C_{i,\text{death}} \times i + C_{j,\text{deaths}}, & \geq 340 \text{ mm} \quad (1a) \\ \text{Damages} = C_{i,\text{damages}} \times i + C_{j,\text{damages}}, & \geq 340 \text{ mm} \quad (1b) \end{cases}$$

$$(1)$$

3.4 Predictions and projections of loss of life and damages

The flood risk models require an island-wide rainfall maximum for the source of the hazard, similar to the flood catalogue records for rainfall depths. The approach taken was to develop an island-wide pseudo-IDF curve rather than to examine the consequence of a particular station's IDF. However, IDF curves were only available for the 1- to 10-day durations for the two airport stations [the Norman Manley International Airport (NMIA) and the Sangster International Airport (SIA)] (Underground Water Authority 1995; Burgess et al. 2013). Both are coastal stations on the south and north coast, respectively, and orography can be expected to modify the precipitation patterns. Comparisons were made between the flood catalogue rainfall maxima and records from Jamaica Weather Reports

for the period 1895 to 1966 and MS daily precipitation station records for the period 1992 to 2012 in order to ground truth the catalogue entries. Thereafter, the ratio of reported maxima in the catalogue to the reference stations (NMIA and SIA) was assessed using (1) the annual maxima and (2) the event maxima between 2002 and 2007. This period was chosen because of the quality of the damages report and precipitation records. The second method is reported on as it used actual measurements of events and covered a range of durations from 1 to 11 days. In the end, a pseudo island-wide station was derived by a simple averaging of the NMIA and SIA stations and then scaling.

It is possible for flood risks to change with time due to exposure, resilience, land use, etc., but for this study, climate change was the focus. Future development of the models will be done with respect to the other areas, once their usefulness is established. Macro-scale flood risk for both present and future climate was estimated using a probability-based risk model (Eq. 2). Equation 2 estimates the annualized loss of life and damage (Nicolet et al. 2013; Dai et al. 2002; Dierauer 2012; Messner 2007; Merz et al. 2010). Two new variables are proposed, which have not been previously seen in the literature—a climate change factor (CF) (discussed further below) and a probability distribution factor for duration of flood events (p_{duration}). The conceptual framework of risk defined here follows Bayesian logics (Kaplan 1997; Kaplan and Garrick 1981).

Annual flood risk (AFR) applied to loss of life and damages (R), where Δp change in probability from one interval to the next and CF is the climate change factor for durations between 1 and 30 days.

$$\text{Ann. Flood Risk(AFR)} = \int_{p=0}^{p=1} \int_{p=0}^{p=1} R_i \cdot dp \approx \sum_{\text{duration}=1}^{\text{duration}=30} \left[\sum_{p=1/500}^{p=1/5} R_{i.} . \Delta p \right], \quad (2)$$

$$\text{where } R_i = f\left(i_{\text{duration,RP}}, \text{CF}_{\text{RP}}, p_{\text{duration}}\right) = \text{CF}_{\text{RP}} . p_{\text{duration}} \cdot f(i_{\text{ref}})$$

The macro-scale flood risk model was first validated on the present climate's pseudo island-wide IDF based on NMIA and SIA information, for 1- to 30-day durations and return periods (RP) between 5 and 500 years. Duration distributions between 1 and 30 days account for 99 % of all events in the past and 30 days were used as the upper limit of the durations. IDF curves for NMIA and SIA were available for the 1- to 10-day durations and 5- to 100-return period (RP) (Burgess et al. 2013). However, it was desirous to use the 500-year RP as the upper limit of the RP for the probability risk model (Meyer et al. 2009). The lower end of the RP was set at 5 years and corresponded to the start of the IDF curves available. An estimated island-wide IDF curve for the present climate was achieved by utilizing the quantile functions from the existing 5- to 100-year RP IDF curves from Burgess et al. (2013) and extending the quantile predictions to the 200- and 500-year RP for each station. The 1-, 2-, 5- and 10-day IDF curves for NMIA and SIA stations were averaged and scaled by the factor that related NMIA and SIA maxima to the all-island maximum. The duration for the island-wide IDF was then lengthened from 10 to 15 and 30 days by simple curve fitting to the 1- to 10-day duration curves for each RP.

The probability distribution of durations for severe flood events was utilized in the weighting of the modelling of both present climate and future climate. It is acknowledged that the assumption of stationarity in this regard is a shortcoming and that the distribution may change in the future climate (see Sect. 4.1). The estimated present climate loss of life and EAD was derived and compared to the observed risks, similar to Ward et al. (2011).

Future climate loss of life and damages up to 2100 was obtained by applying the $CF_{RP, I=5-500years}$ to the present climate IDF to derive the future IDF curves. CF was determined by the average of the ratio of the future intensities to the present intensities (discussed above) for both the NMIA and SIA stations. Future climate 24-h intensities were derived from the frequency analysis model, with extrapolation of the parameters' temporal trends, to 2100 as discussed in Burgess et al. (2013). In that model, the 2100 values for the frequency distribution model were extended as well from the previous range of 5- to 100-year RP to 500-year RP. It was not possible to determine CF for the 2- to 30-day durations as the future climate intensity predictions were not available. Only the 1-day duration intensities for the 5- to 500-year RP were available, and it is acknowledged that this is a shortcoming at this time. The future climate loss of life and damage was then derived across all probabilities for RP between 5 and 500 years. The difference between the future climate flood risk and present climate risks for death and damages was determined (Hall 2005).

4 Severe flood hazards

4.1 Climatology, trends and climate connections

Flood occurrences in Jamaica have a bi-modal pattern with a minor peak in April–May–June (27 % of occurrences) and maximum in September–October–November (39 %) (Fig. 1a). The bimodality coefficient (BC) test produced a coefficient of 0.61, which is greater than the criterion of 0.555 (Pfister et al. 2013). The mean monthly distribution correlates well (0.89) with the mean rainfall climatology of Jamaica as derived from the MS's island-wide rainfall index (see also Fig. 1a) (Angeles et al. 2010). This suggests that changes in the mean precipitation regime may be accompanied by changes in the frequency of severe floods (Pal et al. 2004; Christensen and Christensen 2003). Decadal events also correlate with N3.4 decadal means (CC = 0.61) and weakly with AMO decadal maxima (CC = 0.20) (see also Fig. 1b, c). The suggestion is that warm phases of N3.4 and AMO correlate with more severe floods and vice versa.

Trend and homogeneity analysis of decadal (Fig. 2a) and annual records (not shown) indicates both an increasing trend and step change. The highest incidence of flooding occurred between 2000 and 2010, when 35 events were recorded (Fig. 2a). The last 20 years, between 1990 and 2010, were 49 % more active (1.55 events with losses per annum) than the last forty years between 1970 and 2010 (0.9 events per annum with reported losses). Figure 2a suggests an increase of 0.6 events per decade ($P < 0.28$ significance), which equates to an increase of 0.375 % per year. This linear increasing trend is less than the estimated global rate of 7.4 % per annum increase determined by Scheuren et al. (2007). Homogeneity analysis revealed a step change in 1890 at $P = 0.035$ significance levels. Pre (post)-1890 mean decadal occurrence was approximately 4 (14) events per decade. The mean of 14 events per decade for the latter period 1890 to 2010 approximates the current maximum of 16. The apparent increase could be due in part to an increase in recording efforts in recent times versus the initial period of the records. There are also other issues that affect historical hydrological records including vagueness, socio-economic conditions and data loss (Yongfei et al. 2013). Breakpoint analysis, however, also revealed an 1894 breakpoint in the AMO time series ($P < 0.145$ significance) (Fig. 2b). The pre-1894 AMO mean was −0.56 versus a post-1894 mean of 0.15. Similar
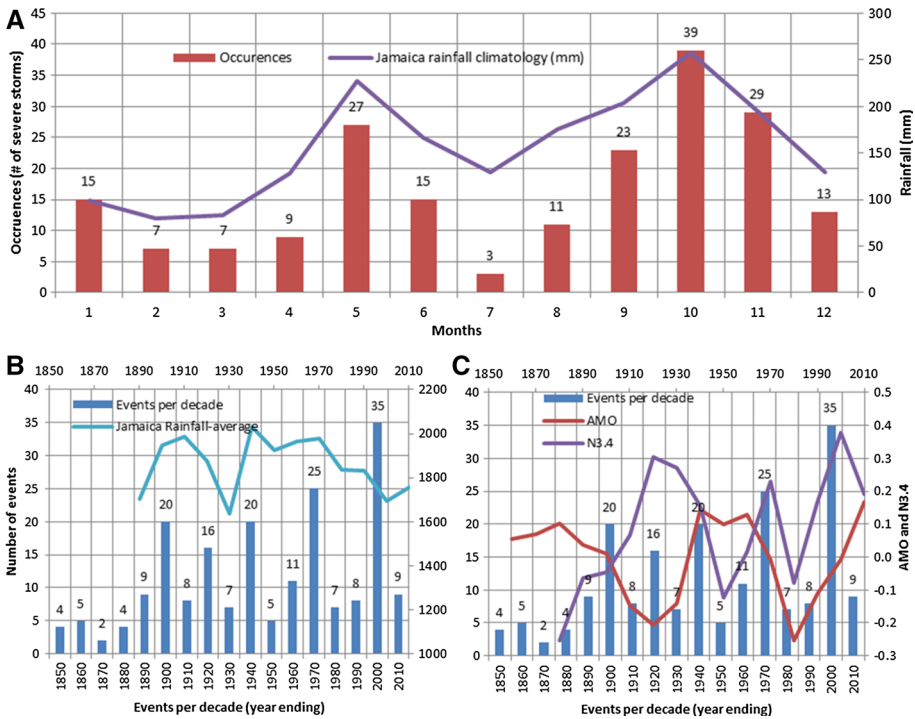
Fig. 1 Severe flood climatology for Jamaica for the period 1850 to 2010 for 198 events (**a**). Occurrences of severe flood events for the period 1850 to 2010 with decadal mean Jamaica rainfall index (mm) (**b**) and Atlantic multi-decadal oscillation (AMO) and N3.4 (**c**). Years correspond with the end of decade year

relationships have been found between large-scale climate circulation and floods in other studies (Drogue et al. 2004; Bardossy and Caspary 1990; Caspary 1995; Pfister et al. 2013; Petrow and Merz 2009).

Visual inspection of Fig. 2a also suggests a 30-year cycle of peaking. Spectral analysis of the annual occurrences of severe floods (Fig. 2b, c) shows a primary harmonic at 30 years. The AMO index has a 27-year peak. A second local maximum exists at a period of 9 years. The 9-year peak is also found in all other climate indices analysed (i.e. AMO, Jamaican rainfall and N3.4). Both the AMO and N3.4 are known modulators of early and late season rainfall (Emanuel 2011; Spence et al. 2004; Stephenson and Taylor 2008; Taylor et al. 2002). Minor 3- and 6-year harmonics correspond with peaks found for N3.4. The N3.4 harmonics are consistent with studies by Bejarano and Jin (2008) and Jin (2010) for ENSO.

4.1.1 Causes and durations

Hurricanes, depressions and tropical waves account for 46 % of all the devastating flood events in Jamaica and are the largest category of responsible meteorological phenomena (Fig. 3a). Storms and troughs account for 21 %. Similar observations were made by Hall (2005). A category termed "heavy rains" occurs in the pre-1900 records and accounts for 21 % of events. As previously noted these were likely to have been passing distant
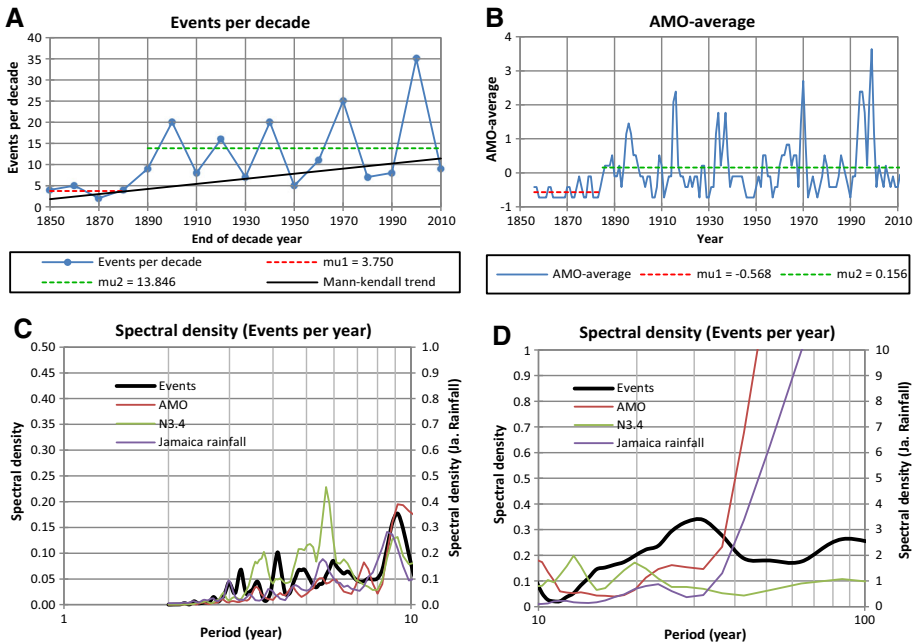
Fig. 2 Homogeneity (Pettitt's) and trend test (Mann–Kendal) of severe flood events per decade (**a**) and AMO (**b**). Note the 1880 flood event breakpoint ($P = 3.5$ % significance using the Pettitt's test), 1884 AMO breakpoint ($P = 1.45$ % significance using the Pettit's test) and increasing trend of 0.6 events per decade at 2.8 % significance using the Mann–Kendal test. Spectral analysis of severe flood events per year with AMO and N3.4 (**c**) and Jamaica rainfall (**d**) for Jamaica for the period 1850 to 2010

hurricanes. It is therefore possible that the aggregated hurricane, depression and wave categories could be as much as 67 %, which is high in comparison with, for example, Texas where hurricanes only account for 10–20 % of the flood flow maxima (Villarini and Smith 2013). A high occurrence of hurricane-related flood events implies that climate modulators of hurricane activity such as AMO and ENSO (Emanuel 2011; Coumou and Rahmstorf 2012) could also affect the occurrence of flooding (Villarini et al. 2014; Czajkowski et al. 2013).

One- and two-day durations of rainfall dominate (67 %) the occurrence of severe events (Fig. 3b). However, there were a number of notable severe events of relatively long durations of between 2 and 30 days in the last 30 years. Examples include the May 1986 rains (6 days), the October and November 1995 rains (30 days) and the June 1977 (21 days). There is an increasing trend in the number of 2- to 5-day duration severe storms. In contrast, there is a decreasing trend in the number of 1-day duration severe storms. Additionally, whereas the longer storms accounted for 26 % of all storms in the 1772–1950 period, they account for 35 % during the period 1951 to 2010. The shorter storms accounted for 57 % of all storms in the 1772 to 1950 period and 26 % during the period 1951 to 2010. Temporal changes in the distribution of storm durations emphasize the need to consider durations greater than the traditional 24-h duration that is often the focus of flood hazard studies (Gül 2013; Borga et al. 2011; Marchi et al. 2010). The increase in longer durations implies that the flood magnitude metric, defined by Kundzewicz et al. (2013), will also increase.
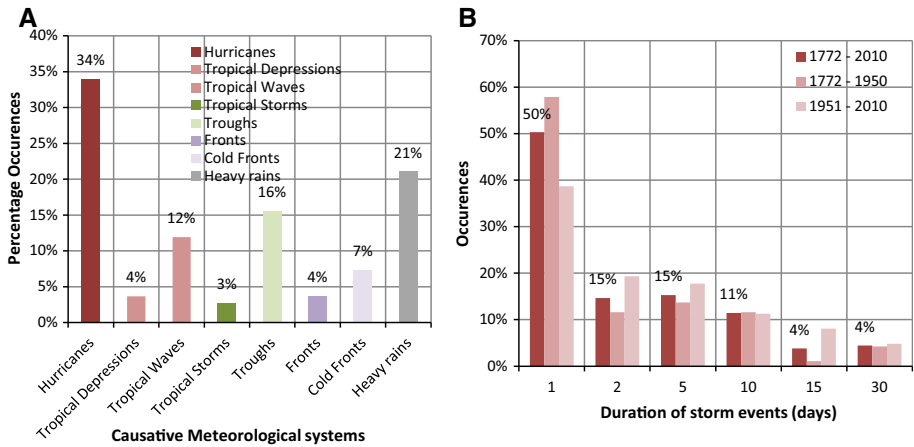
Fig. 3 Frequency distribution of causative meteorological phenomena for flooding (**a**) and durations (**b**) for Jamaica between 1772 and 2010, with two partitions (1772–1950 and 1951–2010)

4.1.2 Spatial aspects

There are 827 communities across Jamaica, ranging from parish capitals to towns and small settlements based upon the PIOJ spatial database. Of these communities, 261 (or approximately 32 %) are categorized by ODPEM as flood prone. Western and central parishes appear to have a higher incidence of flooding, accounting for more than 80 % of the flood-prone communities, while south coast parishes account for 60.1 % (Fig. 4a). This spatial distribution correlates with the areas identified in the regional flood flow analysis of Nkemdirim (1978). These areas have modest to high rates of increases between the mean precipitation and 10-year return period precipitation depths interval, and flooding is believed to be driven by both high topography and modest rainfall depths.

In 90 % of all instances, flooding occurs at elevations lower than 200 m (Fig. 4a) and at an average of 50 m. In general, the flood-prone communities are spatially dispersed across the island, suggesting that, notwithstanding population and investment concentrations, risks are likely to be relatively dispersed as well.

4.2 Observed risks: annual rates, distribution, trends and thresholds

The majority of significant hydrometeorological events (160 of 198) did not result in deaths. For those that did, fatalities were up to 200 persons, such as in Hurricane Charlie (154 persons killed) and the 1940 flood (125 persons killed). Records of death as a result of severe floods started in 1810. Total recorded loss of life since then to 2010 is 802 persons. When deaths do occur, the typical range is 5–25 persons (see Fig. 5a). The annualized deaths caused by flooding are 4 persons. This rate is much less than 119 to 97.6 fatalities per year in the USA for flash flood and river flood (French et al. 1983; Ashley and Ashley 2008). Likewise, the average loss of life for the most severe floods is 21.1 persons per event. This loss of life rate is comparable to that for Europe of 2–35 persons per event for the period 1900 to 1974 (Penning-Rowsell et al. 2005).

An average mortality rate of 0.0021 % per event and maximum of 0.033 % per event were calculated from the flood catalogue. The maximum mortality is related to the October
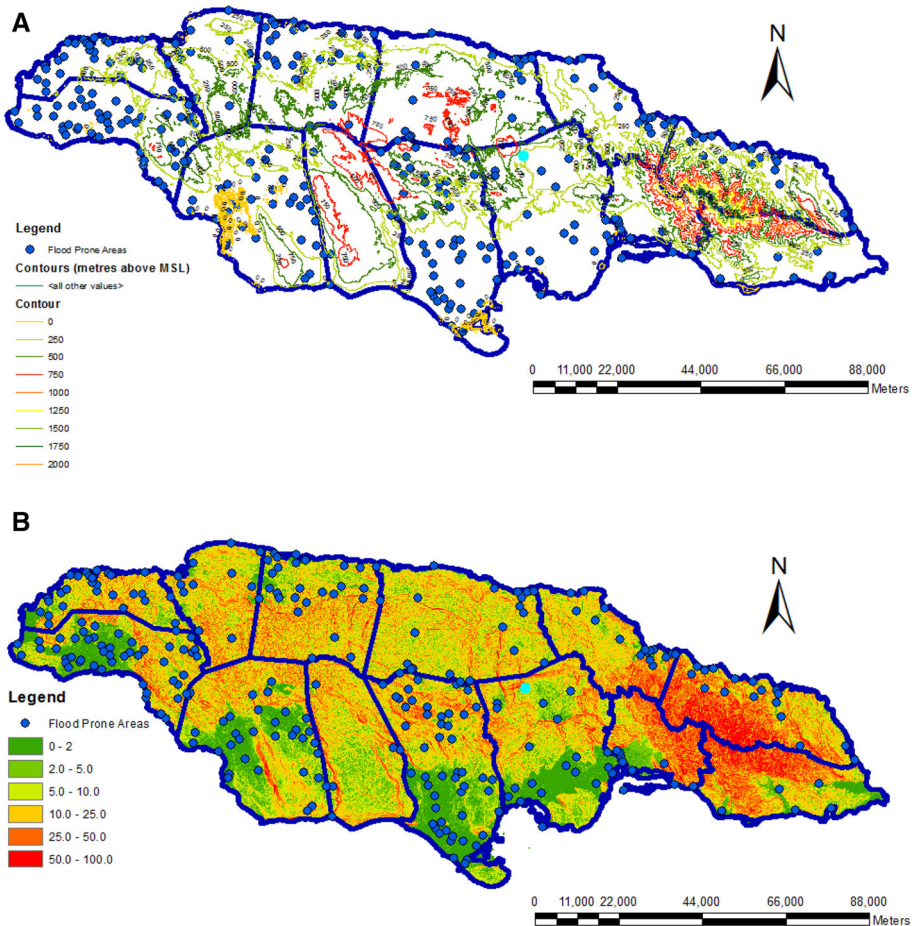
Fig. 4 Flood-prone communities of Jamaica against topographic elevation (**a**) and mean annual rainfall from the period 1992 to 2012 (**b**)

1879 flood that killed 180 persons from a population of 541,000. The maximum mortality for the Jamaican dataset is seemingly much less than other regional averages (e.g. 0.09–1.41 %) across the globe (Jonkman and Vrijling 2008). However, it is to be noted that in Jonkman and Vrijling's analysis, mortality is defined as the ratio of fatalities to affected persons, as opposed to the number of exposed persons, which is used in this study. We use the latter as the number of affected persons (1) is also a function of the intensity and scale of hazard being considered and (2) is often burdensome to define post-event, thereby limiting the applicability of models premised on it in disaster response management.

A trend of increasing mortality with increasing precipitation depth was seen from the analysis of the 35 storms from 1810 to 2010, with low CC of 0.12 for an exponential type function (Fig. 5c). In contrast, there was seemingly decreasing mortality with increasing rainfall intensity (Fig. 5d). Further analysis is needed to see whether the higher intensities have lower depths of precipitation, but this was not pursued given the weak correlation of mortality with precipitation depth. Warning time did not appear to result in reduced
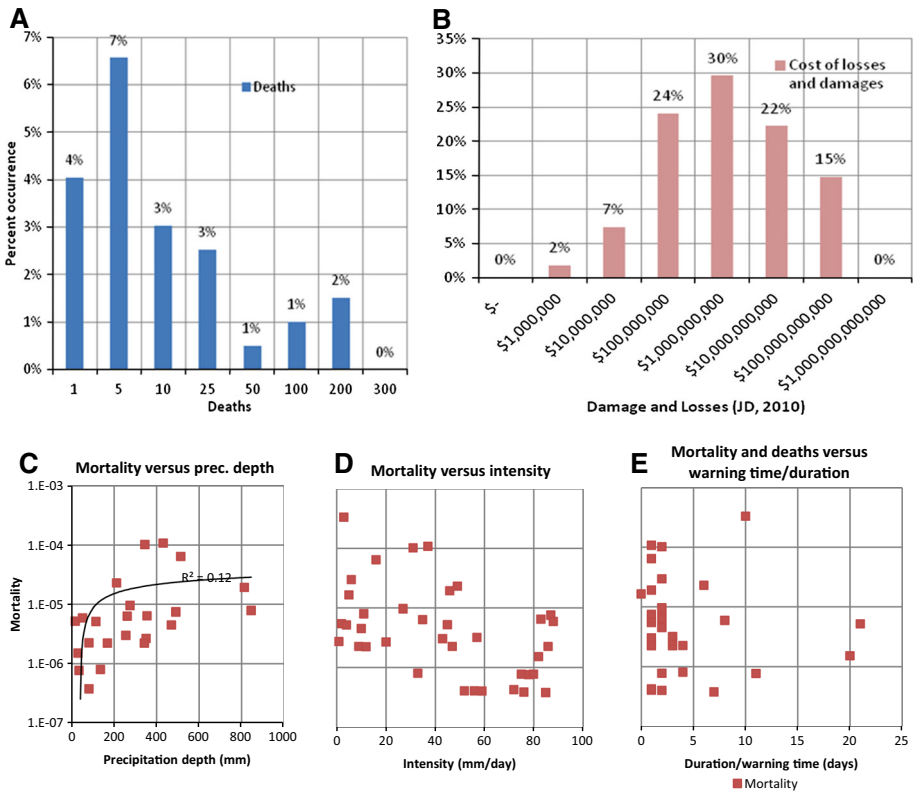
Fig. 5 Occurrences of deaths in floods that have resulted in at least one death (**a**) from 1810 to 2010 and losses and damages (**b**) in JMD2010 prices from 1896 to 2010. Mortality (# of fatalities to # exposed) versus precipitation depth (mm) (**c**), intensity (**d**) and duration (days) (**e**)

mortality (Fig. 5e), unlike in other regions of the globe (Ebi and Schmier 2005). Further analysis of mortality was not pursued given the generally poor results. Rather it was decided to focus on loss of life, especially given the latter's immediate interpretation in disaster risk reduction and following the approach taken by other studies (Zahran et al. 2008; Maaskant et al. 2009).

Of the 114 years of flood records, between 1896 and 2010, 53 events (∼27 %) had reported damages and the total normalized damage was JMD287.0 billion (USD3.28 billion). The average severe flood event costs JMD5.4 billion (USD62.1 million) (see Table 2; Fig. 5b). This is comparably smaller (28 % less) than the average cost for the region (Cavallo and Noy 2009). Cavallo and Noy (2009) determined that the average damage for flood events for the Caribbean region over the period 1970 to 1999 was USD115 million (2010 dollars). A likely reason for the difference could be Jamaica's lower standing on the GDP scale of Latin American and Caribbean countries and the lower economic exposure. Globally, the average cost of a severe flood event is USD134 million, from analysis of 3838 events between 1910 and 2010 in the EM-DAT dataset. This is approximately twice the cost per event for Jamaica, and the same explanation for regional disparity is probably relevant.

The most extreme events with respect to losses include: Hurricane Ivan (2004), with damages of JMD71 billion (USD812 million) or 5.8 % of GDP and Hurricane Charlie

(1951), with JMD53 billion (USD606 million) or 4.4 % of GDP. We note that it was not possible to precisely define flood damage, separate from wind damage in complex hazards due to aggregation in damage catalogue records. The average severe flood event costs about 0.5 % of the GDP (in 2010 value) based upon GDP per annum of JMD1.018 trillion (USD11.65 billion) (PIOJ 2010). Jamaica's losses are comparable to global mean loss of 1.95 % of GDP determined by Hochrainer (2006). The differences are likely because this study used all available events, whereas Hochrainer (2006) used the most severe events.

The estimated annual damage (EAD) of severe floods is JMD8.4 billion (USD96.3 million) or 0.84 % of the GDP per annum (2010 dollars). This places Jamaica in a high vulnerability category similar to Missouri (USD36.3 million adjusted to 2010 values), California (USD65.2 million) and Texas (USD110 million) (Pielke et al. 2002). Strobl (2012) estimated 0.83 % GDP reduction from the average hurricane for LAC countries but noted that the value depended on the timing in the financial year in which GDP is reported and local economic factors. Zapata and Madrigal (2010) estimated 2.08 % GDP reduction for the period 1977 to 2007 for LAC countries. Reductions for other countries in the region are approximately 1 % of GDP, including for Ecuador, Honduras and Nicaragua (Freeman 2000). It is noted that the annualized GDP impact of floods being considered is a combination of the negative short- to long-term post-impact effects and not just the immediate post-impact damages.

Although the frequency of occurrences is increasing, the cost per event has been relatively stable—between JMD4.0 and 5.7 billion (USD46 to 66 million) per event—over the sixty years between 1950 and 2010 (Fig. 6). This is similar to what is reported by Neumayer and Barthel (2011). Analysis of the EM-DAT global dataset shows that damages per event, globally, have only increased from USD127 to 153 million in the last 60 years. A possible explanation for this stationarity in normalized damage per event is increased resilience. This warrants further investigation.

Risks were observed after a threshold of the source of the hazard (i.e. rainfall) had been reached. Records with associated maximum rainfall depths and loss of life and damages in the severe flood catalogue started in 1942. Development of the macro-scale flood risk model (see following section) was therefore limited to the period after 1942. Records of deaths and rainfall totals do, however, start earlier in 1933. A minimum threshold 228 mm was observed below which there were few reported deaths. Where both death and loss records exist concurrently, the observed threshold is 340 mm (see Fig. 7). No correlation was observed between total precipitation depth and death or damages. A better relationship
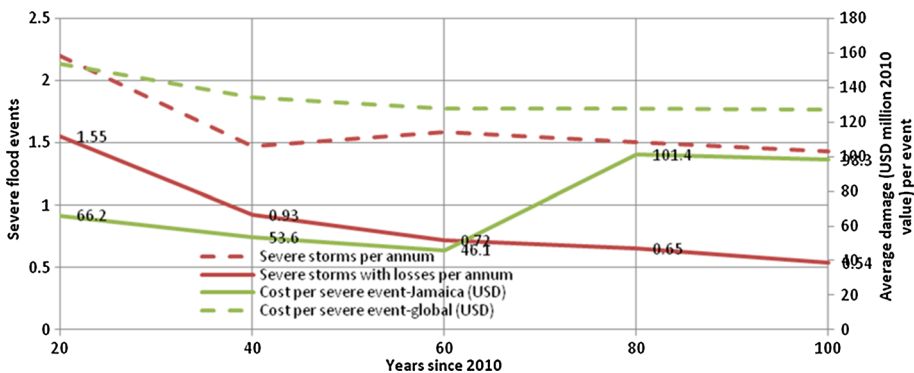

Fig. 6 Annual occurrence of the total number of severe floods, severe floods with reported losses and losses and damages per event from 1910 to 2010 in JMD
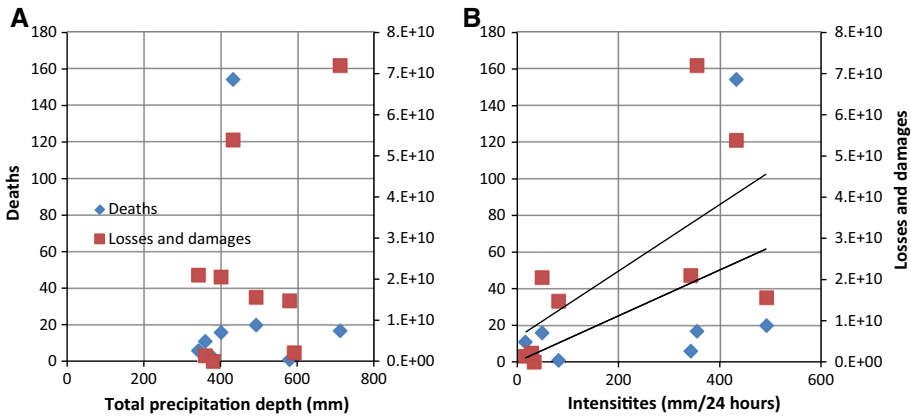
Fig. 7 Scatter plot of deaths versus total precipitation depth (mm) (**a**) and intensities (mm/24 h) (**b**) for severe flood events in Jamaica for the period 1942 to 2010, with approximate linear approximation lines

(CC = 0.4) emerged between damages and rainfall intensities and to lesser extent between deaths and intensities (CC = 0.255). This relationship is logical. As inundation depths increase so too can the expected damageability and associated losses with precipitation intensities based upon hydraulic relationship. There was no threshold observed in the relationships with intensities as both deaths and losses occurred from the minimum (26 mm/day) to the maximum (491 mm/day) intensities. Occurrences of death and damages are therefore seemingly triggered after a threshold and thereafter increase proportionally with intensities. Threshold to deaths relationships have been explored by others (e.g. Czajkowski et al. 2011). Czajkowski et al. (2011) determined a 75-mm threshold above which US land falling hurricanes result in fatalities.

5 Macro-scale flood risk model

5.1 Calibration and validation

The linear regression models developed for flood risk (deaths and damages) based on intensities beyond a threshold are given in Eqs. 3a and 3b and illustrated in Fig. 8a, b. A relatively large confidence interval of 25 % was used to account for some of the uncertainty of the risk model (Merz and Thieken. 2009). The use of thresholds is to prevent over dispersion of the zero damage and fatalities records and is similar to Czajkowski et al. (2011).

An all-island flood risk model for Jamaica for deaths

$$\text{Flood risk}, R_{i=\text{deaths}} = \frac{n_{\text{parishes}}}{14} \times \text{Deaths}$$
$$= \begin{cases} 3.5 \times i/100 + 5.6, \geq 340 \text{ mm}, p_{\text{total}} \geq 340 \text{ mm} \\ \text{Error} = \pm 14.7 \text{ at } 75\,\% \\ 0, p_{\text{total}} < 340 \text{ mm} \end{cases} \tag{3a}$$

An all-island flood risk model for Jamaica for damages (JMD 2010 values). Note JMD:USD = 97.38 in 2010.
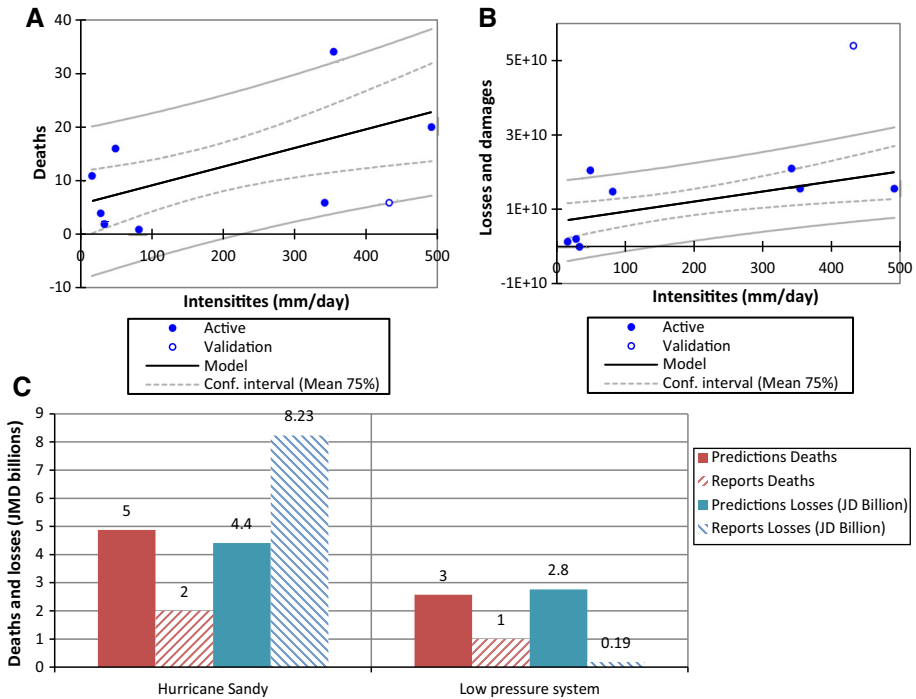
Fig. 8 Linear regression analysis of flood risks for death (**a**) and damages (**b**) versus intensities. Confidence interval of observations (and model) shown in *solid* (*dashed*) lines envelope. Correlation of death and damages with intensities = 0.586 and 0.583, respectively, at $P = 0.129$. Validation results (**c**) of macroscale flood risk model showing observed and predicted risks for Hurricane Sandy and a low-pressure system for Jamaica

$$\text{Flood risk}, R_{i=\text{damages}} = \frac{n_{\text{parishes}}}{14} \times \text{Damages} = \begin{cases} 2.7 \times i/100 + 6.67, p_{\text{total}} \geq 340 \text{ mm} \\ \text{Error} = \pm 11.5 \text{ JMD billion at } 75\% \\ 0, p_{\text{total}} < 340 \text{ mm} \end{cases}$$

$$(3b)$$

In the validation of the model, loss of life was over-predicted by 2.5 persons on average and damages under-predicted by JMD0.6 billion (USD6.9 million) (Table 3). A wider range and number of samples of both observed loss of life and damages values would have been preferable for model validation and calibration. Notwithstanding, the correlations for both death and damages models were relatively high at 0.58 for both risks (at $P < 0.129$). The accuracy of this relatively simple model is comparable with more sophisticated flood risk models used elsewhere (e.g. Winsemius et al. 2013). Winsemius et al. (2013) studied two storms that affected Bangladesh in 1998 and 2004 using land use and population-based flood risk methods. They obtained an estimate of risk that was 50 % less than that observed for both events. Jonkman and Vrijling (2008) achieved a higher correlation of 0.98 with a proposed flood risk model for fatalities, but a larger bias of 11.7 fatalities per event for five events. The model proposed herein possesses some skills in a local context.

Table 3 Validation of flood risk model for deaths and damages (billion JMD 2010 value) for severe floods for Jamaica

System	Precipitation total (mm)	Intensities (mm/day)	Predictions (bias)		Reports	
			Deaths	Damages	Deaths	Damages
Hurricane Sandy	460	230	5 (3)	4.4 (−3.8)	2	8.23
Low-pressure system	365	45.6	3 (2)	2.8 (2.6)	1	0.19
		Average bias	2.5	−0.6		

5.1.1 Present and future climate risks from the models

As previously noted, a determination was made of the accuracy of the reported precipitation depths in the flood catalogue using MS gauge records for six events (Fig. 9a). A correlation coefficient of 0.80 was determined and 0.95, when the 2002 event is considered as an outlier and removed. (In the latter instance, the modified Z test returns a value of 6.9, which is greater than the 3.5 criterion). An average bias of −9 mm was determined when observed station data were compared to reported depths. Flood catalogue records of maximum precipitation depths are therefore taken to be accurate.

Scaled NMIA and SIA station rainfall depths were used as a proxy for maximum island-wide rainfall depths and as input in the macro-scale flood risk model (Fig. 9b). A scaling factor of 3.11 was determined to be necessary to convert the pseudo station (average of NMIA and SIA) precipitation amounts to island-wide station IDF (Fig. 9d). The need for the scaling to explain the differences between NMIA and SIA that are coastal stations and observed island-wide maximum is probably due to orographic factors. It is acknowledged that this is a simplification of complex spatial and temporal precipitation processes (Villarini et al. 2011).

The simulation skill of the annualized flood risk model for death and damage risks was moderate (>50 %). Annualized predicted loss of life was 4.66 versus an observed value of 4 persons, and predicted EAD was JMD4.05 billion versus an observed value of JMD8.4 billion. The biases were 0.66 deaths (+17 %) and −JMD4.35 billion (−USD49.2 million) in damages (−52 %) (Table 4; Fig. 10b). This is a continuation of the trend observed in the calibration and validation exercise where deaths are marginally under-predicted and damages were over-predicted. Biases may have to do with the skill of the model and conceptualization of the extrapolation of the pseudo-IDF curve for NMIA and SIA across the island with the IDF$_{max}$ to IDF$_{NMIA/SIA}$ ratio. It is again acknowledged that this scheme makes assumptions about the temporal and spatial characteristics of the extreme precipitation that should be subjected to further development and research. Another short-coming of the flood risk damage model may be that it over simplifies the effect of the shock of the severe flood events (Safarzyńska et al. 2013). Notwithstanding, the performance of the flood risk model for death was better than the damage model.

Climate change factors of 0.95 to 1.43 were determined for the 5- to 100-year RP, from 2010 to 2100, from Burgess et al. (2013). These change factors were extrapolated to the 500-year return period (see Fig. 9 bottom right panel) and applied to the future climate macro-scale flood risk model to estimate the impacts of climate change up to 2100 (discussed previously in the method).

Risks of deaths and damages to 2100 were projected to increase relative to the present climate predictions by 11 and 9 %, respectively. The projected future climate flood risks in
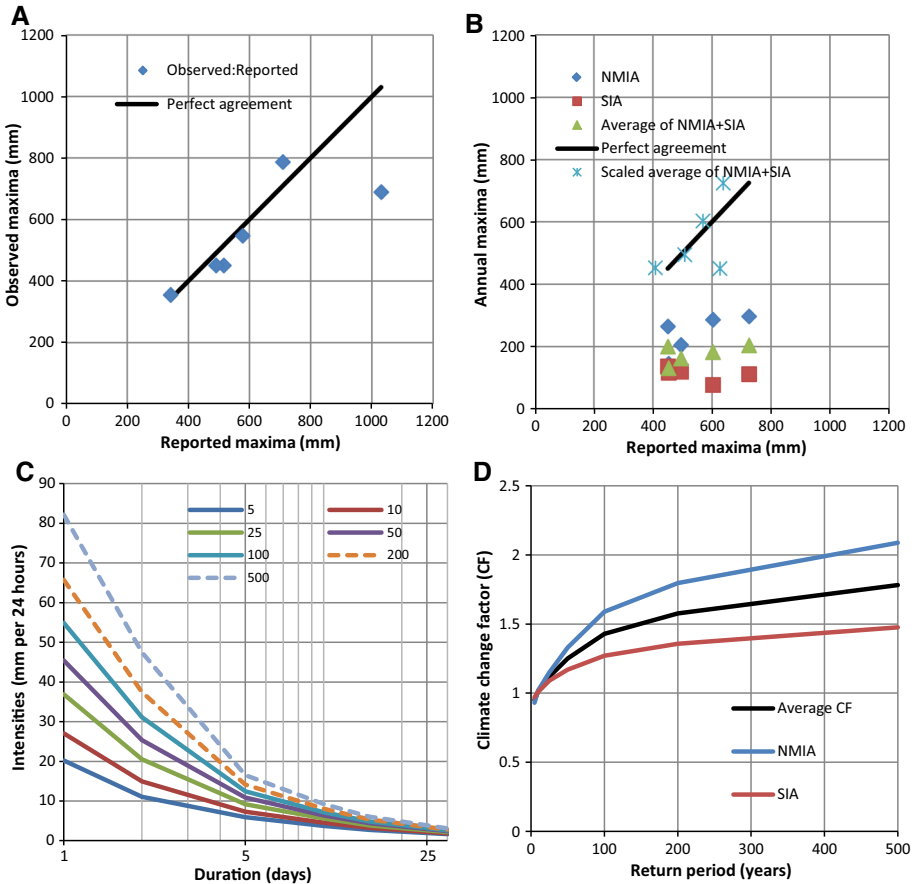
Fig. 9 Island-wide observed versus reported precipitation maxima (**a**), NMIA and SIA, NMIA + SIA pseudo-maxima amounts (**b**) versus observed island-wide precipitation maxima. All-island pseudo-IDF *curve* for 1- to 30-day duration and 5- to 500-year RP, based on NMIA and SIA IDF from Burgess et al. (Burgess et al. 2013) (**c**) and climate change factors applied to future climate risk model for 5- to 500-year RP, from NMIA and SIA 24-h projections (**d**)

2100 are 4.4 deaths per annum and JMD9.2 billion (USD105.2 million). The implications relative to GDP are that in the future climate the 9 % increase will result in an estimated annual damage of ~0.9 % of GDP up from 0.8 % currently. This increase in both deaths and damages with increase in intensities is logical given the likely increase in inundation depths of floods.

6 Summary and conclusions

A severe flood event catalogue of 198 events from 1678 to 2010 was compiled from four independent sources. It is the first time that such an extensive catalogue of events has been collated and analysed for Jamaica.

Data from the catalogue suggest that there is an increasing trend in the occurrence of severe floods with damages. The last 20 years have been more active in terms of severe

Table 4 Observed, present climate predicted and future projected annual flood risks of deaths and damages, JMD billions (USD million) 2010 dollars

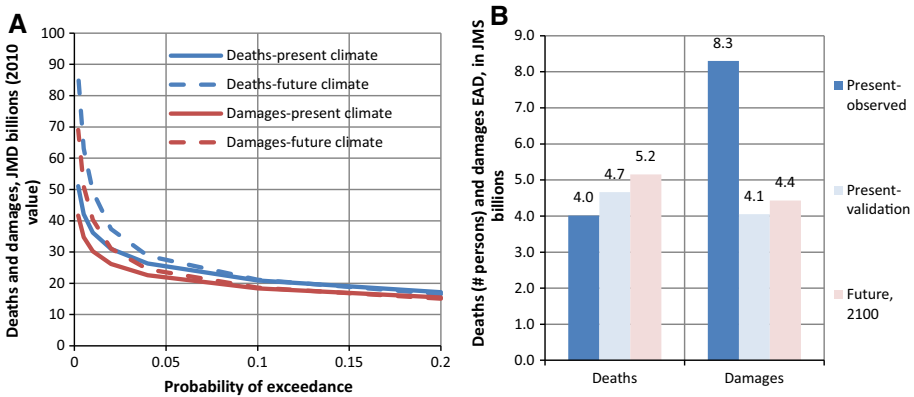| Flood risks	Deaths (# of persons)	Damages in JMD billions (USD million), 2010 dollars
Present-observed	4.0	$8.4 (96.3)
Present-model validation	4.66 (+17 % bias)	$4.06 (46.4) (−52 % bias)
Future (2100) model prediction	5.16	$4.4 (50.3)
Increase, % future to present	11 %	9 %
Future, 2100 (extrapolation of observed with % change)	4.4	$9.2 (105.2)

Fig. 10 Present predicted and future projected death and damage to probability curves for 5- to 500-year RP (**a**) and observed flood risk and flood risk model predictions and projections for deaths and damages in JMD billions 2010 dollars (**b**)

flood events, than the previous sixty years. Similar increasing trends occur elsewhere, for example, in Europe (Tsakiris et al. 2009). The analysis suggested that a current rate is 1.55 events per annum, which is comparably higher ($\sim$300 %) than a long-term 100-year average of 0.52 events per annum. Severe flood events on average resulted in 4 deaths. These results are not comparable to the analysis using the EM-DAT data by Kahn (2005) for the period 1980 to 2002. That is, Kahn derived for Jamaica, 0.6 events per annum (versus 1.1 events per annum from our analysis for the same period) and 12.8 deaths per event (versus 0.33 per event from the local catalogue). These differences may highlight the limitation of using the global datasets in decision-making and the need to produce and examine detailed local datasets.

The increases seen in flood events seem to be beyond natural variability as a result of the climate connections, but it is acknowledged that further work needs to be done to be conclusive about this. Breakpoint and spectral analysis do provide plausible evidence of a climate connection between severe flood events and climate events including ENSO and the AMO. The period of assessment covers at least one AMO cycle and ten N3.4 cycles (using a 6-year period harmonic), suggesting that variability is well accounted for. A plausible explanation for the increased flood occurrence could be climate change due to forced radiation (Milly et al. 2002). However, there may be other factors such as increased

exposure to flood hazards (Barthel and Neumayer 2012), and thus, the matter is deserving of further investigation.

Flood risks were derived from the records of 56 storms. The EAD was determined to be JMD8.4 billion (USD96.3 million) and represents 0.84 % of GDP per annum. This estimate is comparably less than other regional estimates (Strobl 2012; Mirza 2003; Freeman 2000). Interestingly, the cost per event is relatively stable at JMD4.0 and 5.7 billion (USD46 to 66 million), which might imply increasing resilience. It is likely that investments in urban drainage over the last 20 years would have a significant effect in increasing resilience. Barredo (2009) also determined stationarity in the damages for Europe for the period 1970 to 2006. Damages per event for Jamaica are, however, about 28 % less than other regional estimates, but the cumulative effect on GDP of 0.84 % per event is about the same. The annualized loss of life rate is 4 persons per annum.

Macro-scale flood risk models were developed, and moderate correlations were achieved between observed and predicted risks of deaths and damages. Both precipitation threshold and intensities were used as predictors. A 340-mm threshold for the initiation of death and damages was determined below which there were few reported losses or deaths. This threshold is comparably larger than the 75 mm observed by Czajkowski et al. (2011). This may be a measure of Jamaica's resilience and is likely to change in the future as drainage and flood control infrastructure is improved. This warrants further investigation. Deaths were over-predicted and damages were under-predicted. Damages are difficult to model, and the skill of the model proposed herein is similar to that elsewhere.

Predictions of present climate risk using the combined IDF curves for NMIA and SIA had mixed results with fairly accurate death predictions (23 % bias) but damages that were underestimated (−50 %). This trend was also seen in the model validation process. The use of island-wide maximum precipitation depth and intensity represents a generalization of phenomena that have both spatial and temporal variations. This too deserves further research. Notwithstanding, it was estimated that the effects of such biases of the conceptual framework would be consistent and would not preclude determining the change for the future climate.

Climate change factors were applied to the present climate IDF to derive the future climate IDF curves. Flood risks of deaths and damages are expected to increase 11 and 9 %, respectively, to ∼4.4 persons per annum and JMD9.2 billion (USD105.2) in 2010 dollars. Damages in 2100 will account for approximately 0.9 % of 2010 GDP. This is the first time that annual risks have been derived for present climate and estimated for future climate at a macro-scale model for Jamaica. The projected increases determined herein are consistent with global estimates (Coumou and Rahmstorf 2012; Pall et al. 2011). Whilst the driving climate change variables will change at a different rate in the future spatially, the results are of the same order of magnitude. Pall et al. (2011) determined 20 % increase for the period 1900 to 2000 for England and Wales, whereas 14 % was determined in this study for the period 2010 to 2100.

Future work on the flood risk model could involve its implementation in a GIS (Jiang et al. 2009) and replacing the parish factor with vulnerability factors based upon population and assets (road, housing stock and other critical infrastructure). Damage models appear to face the greatest challenge. Economists argue that damage models have been highly aggregated and that they should consider in greater detail the impacts to technology and consumer behaviour after the events (Steenge and Bočkarjova 2007). This aspect deserves further attention. The greatest issue that faces this type of study is the range of definitions and criteria for severe floods and risk. Direct comparison amongst studies is therefore

difficult. There is merit in varying definitions to suit the local context, and this approach should be considered in future studies of developing countries.

Overall, it is felt that the risk models developed should prove useful for planning and development of national Disaster Risk Management (DRM) strategies in Jamaica. The Caribbean islands, in spite of apparent increasing trends in flooding and associated damages, lack such models. This study therefore represents an advancement in that area and a template for doing similar analysis region wide. As more data become available, similar models can be created for other countries of the Caribbean.

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