Cases of Heavy Precipitation and Flash Floods in the Caribbean during El Niño Winters

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(Manuscript received 25 September 2003, in final form 10 February 2004)

ABSTRACT

The environments associated with three episodes of heavy precipitation and flash floods in the Caribbean are diagnosed. Analysis of the hydrometeorological conditions leading up to flash floods on 3–4 January 1998, 5–6 January 1992, and 4 March 1998 are focused on the synoptic features as well as the surface conditions. Subsequent flood mitigation efforts are briefly discussed.

In the first case, deep convection and heavy precipitation were associated with a surface trough that developed in the wake of a quasi-stationary front. Warm, moist unstable air conveyed by a low-level jet and impinging on steep terrain created a quasi-stationary cloud cluster that produced more than 400 mm of rainfall in 2 days. Upper-level divergence and weak midtropospheric vorticity advection enhanced ascending motion. Antecedent precipitation from the front, the steep terrain, river basin topography, and human encroachment in the flood plain aggravated the flood hazard. The second case had similar conditions, with additional lift induced by an upper-level trough. The third case was weaker than the first two primarily because its low-level airflow was northerly and weaker. In all cases, the orography, the low-level wind velocity, a deep layer of moisture, and potential instability played important roles. These findings agree with other studies of heavy orographic precipitation from convection. Interestingly, these cases of heavy precipitation occurred during what is normally the dry season in the Caribbean. However, during El Niño years, midlatitude systems track well south of their normal tracks. Fronts, prefrontal troughs, and upper-level low pressure systems can then contribute to the development of deep convection and heavy precipitation in the Caribbean.

1. Introduction

One of the greatest problems facing operational forecasters is the prediction of heavy rainfall and flash floods. While great strides have been made in heavy rainfall forecasts in the United States, forecasting in the Tropics presents a greater challenge, especially on islands where rainfall can be intense, localized, and mostly convective. The occurrences of floods and other extreme weather events have devastating effects in the Caribbean islands. Much attention is given to the destruction caused by a major hurricane, but such events are rare for a single country. For more frequent are heavy precipitation and severe weather that cause deaths and serious damage to the economy for which little international assistance is available.

Observational and modeling studies in the United States have identified some common lower- and upper-level patterns associated with catastrophic flooding (Maddox et al. 1979; Maddox and Doswell 1982; Chappell 1986; Doswell et al. 1996; Pontrelli et al. 1999).

Elsewhere, Speer and Geerts (1994) developed a synoptic mesoalpha-scale climatology of flash floods for Sydney, Australia, and Doswell et al. (1998) examined heavy precipitation episodes in the western Mediterranean. Based on those studies, forecasters are advised to examine the amplitude of midtropospheric circulations and the position of low- and upper-level jet axes and jet streaks (Harnack et al. 2001). Often a number of meteorological processes interact on different scales to produce an area of excessive rainfall. Sometimes the timing of the interference between the forcing due to diurnal cycle and synoptic-scale perturbations may be important in determining the rainfall (Segal et al. 2002). Along with the meteorological conditions, the characterization of the space–time variability of rainfall crucial for flooding has been a challenging topic in the hydrologic sciences (Gupta and Waymire 1990).

Steep topography often aids heavy rainfall production through orographic lift or by creating persistent low-level convergence zones that act as a source for new convection (Akeada et al. 1995; Chen and Li 1995; Li et al. 1997; Petersen et al. 1999; Chu and Lin 2000). In general, large amounts of rainfall occur over the first area of high ground encountered with an almost linear increase of rainfall with increasing wind speed (Weston...
and Roy 1994). Studies by Chen and Lin (1996), Kodoma and Barnes (1997), and Chen and Lin (2001) found that the ambient wind direction (below the 3-km height) is a major influence on precipitation formation in Taiwan and Hawaii. Favorable mountain geometry and a confluent low-level flow field also contribute to heavy precipitation (Doswell et al. 1998; Lin et al. 2001). During the Taiwan Area Mesoscale Experiment (TAMEX) in May 1987, it was discovered that a low-level wind maximum on the warm side of a cold front is one of the important synoptic-scale features frequently accompanying heavy rainfall in Taiwan (Chen and Yu 1988). Other studies showed that the terrain and land–sea thermal contrasts in turn affected the low-level wind field near Taiwan (Chen and Hui 1990; Trier et al. 1990). The islands of the Greater Antilles (Cuba, Hispaniola, Jamaica, and Puerto Rico) face similar problems with high terrain.

Forecasters in the Caribbean are handicapped by the lack of a high-resolution observation network and predictive models to provide guidance on small spatial scales and, with the exception of Puerto Rico and Jamaica, modern Doppler radar observations. The inadequacy in flash flood prediction in the Tropics is being addressed in a variety of ways. For example, Carter and Elsner (1997) and Carter et al. (2000) have proposed an alternative for forecasting rainfall in Puerto Rico using statistical methods. Connor and Woodcock (2000) have developed linear regression procedures for 50 potential predictors to stratify precipitation regimes across

**Fig. 1.** Terrain map of Jamaica shaded every 500 m.

**Fig. 2.** Map of the Rio Grande watershed.
the northeast tropical coast in Australia. Their technique uses “synoptically tuned” predictive classification trees and model output statistics from the Australian Regional Model to predict rainfall. Lin et al. (2001) discussed use of a nondimensional moist Froude number to predict the location and propagation of convective systems by combining the wind velocity perpendicular to the mountain, the height of the mountain, and the moist static stability of the inflowing air. Variations in the moist Froude number \( F_m = \left( \frac{U}{N_L h_m} \right) \) have been related to different flow regimes (Chu and Lin 2000). Lin et al. (2001) also introduced a maximum rain-rate index from the product of the low-level wind, mountain slope, and water vapor mixing ratio.

Satellite techniques that combine infrared and microwave sensors to estimate rainfall (e.g., Turk et al. 1998; Jobard and Desbois 1994; Ferraro et al. 1999; Kuligowski 2002) can be used for detection of heavy precipitation in the Tropics. Incorporation of these techniques into the forecasting process requires reliable access to technology for real-time delivery of satellite data, which is not often possible for many countries. Key mesoscale processes that are important in flash floods—for example, convective outflow boundary–sea breeze interactions, cell training, and terrain locking of cells—are difficult to access without information at small scales. Therefore, for much of the Tropics, understanding the synoptic settings under which flash floods occur is the primary means of improving flash flood forecasting. In the absence of comprehensive data and routine observations on the mesoscale, case studies can also be used to increase our understanding of excessive precipitation events.

The primary foci of this study are the hydrometeorological and other environmental conditions associated with a deadly flash flood that occurred in northeastern Jamaica on 3–4 January 1998. The region was inundated by heavy rainfall, flash floods, and mudslides that caused five fatalities and in excess of nine million U.S. dollars in damage to property, agriculture, and infrastructure [Office of Disaster Preparedness and Emergency Management (ODPEM), Jamaica; P. Sanders, ODPEM, 1998, personal communication; H. Thomas, Water Resource Authority of Jamaica, 1998, personal communication]. The most severe impact occurred in Port Antonio, the largest town in northeastern Jamaica and the site of major tourist attractions, where the entire town was inundated. Although forecasters had issued general flood advisories, the scale and timing of the flash flood were unanticipated and not forecasted well. Comparison is made to a less extreme flash flood that occurred in the same region in March 1998 and to another deadly flash flood that occurred on 5–6 January 1992 in Puerto Rico. Interestingly, these extreme precipitation cases occurred during El Niño winters (Northern Hemisphere). El Niño winters are marked by midlatitude cyclone tracks across the southern United States, some of which affect the Caribbean and Central America. The aim is to improve heavy rainfall forecasts by identifying distinguishing features in the environments of heavy precipitation and attendant flash floods in the Caribbean, particularly those in El Niño winters.

Disaster mitigation is constrained by the weakest link in the detection–forecasting–warning–response process. This study focuses on the first three components of the process and reports on efforts being made to improve the fourth. A description of data and analysis methods is presented in section 2. Analyses of synoptic-scale features, satellite observations, radiosonde data, and hydrologic conditions follow in section 3. Comparisons of other flash flood environments are made in section 4, while section 5 is a review of warning and response systems. Finally, a summary discussion is presented in section 6.

### 2. Data and analysis methods

Surface analyses, rawinsonde, and satellite data are used to determine the meteorological environment. The large-scale features were identified from the surface and upper-air analyses. A number of standard thermodynamic parameters and indices were calculated to gauge the convective potential (appendix). Particular attention

![Figure 3. Distribution of rainfall in Portland, 3–4 Jan 1998.](image)
was given to convective available potential energy (CAPE; Moncrieff and Miller 1976), lifted index (Galway 1956) and K index (George 1960), and precipitable water.

Images from the Geostationary Operational Environmental Satellite-8 (GOES-8) were available approximately every 30 min. The National Meteorological Service (NMS) and Water Resource Authority (WRA) of Jamaica provided rain gauge data and basin-scale hydrologic information, respectively. Unfortunately, radar data were unavailable as the aged, conventional radar in operation during 1998 had no archival capability and could not accurately track all thunderstorm cells or storm-total rainfall. In fact, the flash floods of 1998 helped to accelerate the acquisition of a modern Doppler radar by the Jamaican NMS. Estimates of surface rainfall rates during the event were made using the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) measurements (Kummerow et al. 1998) where available. Rainfall data for Puerto Rico were obtained from the National Oceanic and Atmospheric Administration (NOAA). National Centers for Environ-
mental Prediction—National Center for Atmospheric Research (NCEP–NCAR) reanalysis data (Kalnay et al. 1996) were used to generate upper-tropospheric maps and cross sections of specific humidity and vertical motion.

3. Hydrometeorological conditions
   a. Rainfall distribution

   The topography of Jamaica and the prevailing easterly trade winds favor orographic rainfall along the mountainous backbone of the island, particularly along the Blue Mountains (Fig. 1). On 3 and 4 January 1998, the Blue Mountains provided the lifting mechanism for moist onshore flow and the persistence of a precipitating, deep convective cluster over the same area. The result was rainfall of 150–300 mm in the Rio Grande valley (Fig. 2) with a maximum of 425 mm in Port Antonio (Fig. 3). For Port Antonio, this single event total was nearly twice the January normal rainfall. The
Table 2. Thermodynamic indices for Kingston, Jamaica, at 1200 UTC 30 Dec 1997–1 Jan 1998.

<table>
<thead>
<tr>
<th>Date</th>
<th>Precipitable water (mm)</th>
<th>Lifted index</th>
<th>K index</th>
<th>CAPE (J kg⁻¹)</th>
<th>CIN (J kg⁻¹)</th>
<th>LFC (hPa)</th>
<th>LCL (hPa)</th>
</tr>
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<td>30 Dec 1997</td>
<td>48.6</td>
<td>1.03</td>
<td>34.0</td>
<td>474</td>
<td>−21</td>
<td>896.8</td>
<td>949.2</td>
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<tr>
<td>31 Dec 1997</td>
<td>50.0</td>
<td>1.87</td>
<td>31.6</td>
<td>205</td>
<td>0</td>
<td>970.7</td>
<td>971.8</td>
</tr>
<tr>
<td>1 Jan 1998</td>
<td>54.7</td>
<td>−4.84</td>
<td>35.1</td>
<td>1207</td>
<td>−0.03</td>
<td>957.3</td>
<td>972.4</td>
</tr>
<tr>
<td>2 Jan 1998</td>
<td>48.2</td>
<td>−2.93</td>
<td>33.7</td>
<td>570</td>
<td>−40.8</td>
<td>842.8</td>
<td>937.2</td>
</tr>
<tr>
<td>3 Jan 1998</td>
<td>41.2</td>
<td>−0.24</td>
<td>26.5</td>
<td>137</td>
<td>−77.9</td>
<td>656.5</td>
<td>850.6</td>
</tr>
<tr>
<td>4 Jan 1998</td>
<td>49.0</td>
<td>−5.65</td>
<td>37.4</td>
<td>1459</td>
<td>−8.6</td>
<td>913.7</td>
<td>943.3</td>
</tr>
</tbody>
</table>

rainfall totals for the period 1–4 January 1998 (Table 1) was more than 100% of the January normal rainfall (J. Spooner 1998, personal communication) for most of the parish of Portland.

b. Synoptic overview

For several days prior to the flash flood, 30 December 1997 to 1 January 1998, a cold front oscillated across the island and produced periodic heavy rains in and offshore of northern Jamaica. By late evening on 1 January the front dissipated, leaving behind variable cloudiness and weak easterlies. Those conditions remained until 1200 UTC 3 January, when a surface trough formed over the Windward Passage (Fig. 4). The trough persisted, and easterly flow strengthened through 4 January causing dewpoint temperatures to soar above 24°C (Figs. 4c–e).

The Kingston sounding at 1500 UTC 3 January indicated moist midlevel air above drier low-level air.

Fig. 7. East–west cross section, along 17.5°N, of specific humidity (g kg⁻¹; shaded) and vertical velocity (Pa s⁻¹; lines) averaged for (a) 0000 UTC 30 Dec–0000 UTC 31 Dec 1997, (b) 1200 UTC 2 Jan–1200 UTC 3 Jan 1998, (c) 1200–1800 UTC 3 Jan 1998, and (d) 1200–1800 UTC 4 Jan 1998. Thick vertical lines mark Jamaica.
FIG. 8. Enhanced IR satellite images for 3–4 Jan 1998. Enhancement levels are $-33\degree$, $-42\degree$, $-54\degree$, $-64\degree$, and $-80\degree$C, respectively.

(Fig. 5a). In contrast, by 1200 UTC 4 January the environment was very moist from the surface through 650 hPa (Fig. 5b). With little intrusion of dry air into the developing convection, it is likely that precipitation efficiency was higher on 4 January, when approximately 88% of the 2-day total was accumulated. Unlike the previous day, the warm layer from cloud base ($\sim 650$ m) to freezing level ($\sim 4.6$ km) was about 4 km, conditions conducive to rainfall production through warm-rain collision–coalescence. Large contribution by warm-rain processes is characteristic of numerous catastrophic flash flood–producing storms in the United States, including the Big Thompson Canyon, Colorado, storm (Maddox et al. 1978), the Rapid City, South Dakota, storm (Caracena et al. 1979; Maddox et al. 1978), the Rapidan, Virginia, storm (Smith et al. 1996; Pontrelli et al. 1999), and the Fort Collins, Colorado, storm (Petersen et al. 1999).

The development of the surface trough resulted in strong, lower-tropospheric, easterly inflow ($18$ m s$^{-1}$ at 850 hPa, $15$ m s$^{-1}$ at 700 hPa) of marine air impinging on steep topography. In a similar manner to environ-
ments in the TAMEX heavy rainfall episodes (Li et al. 1997), the low-level jet (LLJ), defined as wind speed of at least 12.5 m s$^{-2}$ at 850 hPa and 15 m s$^{-2}$ at 700 hPa, was instrumental in enhancing the orographic precipitation. The heavy rainfall occurred along an axis of maximum equivalent potential temperature ($\theta_e$) at 850 hPa (Fig. 6a), which is not surprising since other studies such as Shi and Scofield (1987) and Juying and Scofield (1989) found that mesoscale convective system (MCS) initiation and propagation is favored along $\theta_e$ ridges. High values of $\theta_e$ indicate significant moisture and potential instability. Advection of air with high equivalent potential temperature by the low-level jet is one of the best indicators of heavy convective rainfall potential (e.g., Chen and Li 1995; Glass et al. 1995; Laing and Fritsch 2000; Li et al. 1997; Petersen et al. 1999). With the apex of the moisture convergence maximum located over eastern Jamaica (Fig. 6c) relatively little lifting is needed to raise boundary layer air to its level of free convection (LFC), which was 913 hPa at 1200 UTC 4 January. Moreover, between 3 and 4 January, the precipitable water increased from 41 to 49 mm and the CAPE increased from 135 to 1458 J Kg$^{-1}$. CAPE in excess of 1000 J Kg$^{-1}$ has been associated with flash floods in the United States, for example, during the Texas Spring Creek flood of 1994 (Smith et al. 2000). The
atmosphere was conditionally unstable throughout the 6-day period, 30 December 1997–4 January 1998 (Table 2); however, the highest values of the $K$ index, lifted index, and CAPE were observed on 4 January, signaling an enhanced potential for heavy rainfall.

At the midlevels of the troposphere, winds are light and variable between a weak low over the western Caribbean and a ridge from the Atlantic subtropical high (Fig. 6c). The trough and vorticity maximum over the western Caribbean is generating positive vorticity advection over Jamaica and the surrounding waters. Vorticity advection by short-wave troughs is associated with heavy precipitation from mesoscale convective systems (Maddox et al. 1979; Doswell et al. 1996; Pontrelli et al. 1999).

In addition to the low-level and midlevel forcing, the environment also exhibited upper-level divergent wind patterns (Fig. 6c). Divergence and diffusience at 200 hPa over Jamaica and regions to the south and east is concomitant with high values of lower tropospheric moisture. East–east cross sections of specific humidity and vertical velocity ($\omega$) between 30 December 1997 and 4 January 1998 (Fig. 7) illustrate the environmental changes throughout the period. The quasi-stationary cold front is marked by opposing circulations, rising motion over and west of Jamaica, and sinking motion to the east (Fig. 7a). A spike in low-level specific humidity, approximately 13 g kg$^{-1}$ at 850 hPa and 10 g kg$^{-1}$ at 750 hPa, was coincident with maximum upward motion. After the front dissipated, mainly sinking motion was occurring over the island, and the maximum in rising motion had shifted higher (Fig. 7b). During that period, the upper atmosphere moistened, but the low-level moisture decreased and became uniformly stratified across the domain. By 3 January, when the surface trough was forming east of the island, an accompanying maximum in upward vertical velocity was observed in the midtroposphere (Fig. 7c). Sinking motion was a maximum over the island, while to the west rising motion was associated with another trough (Fig. 4a) over the western Caribbean. However by the next day, a pronounced region of ascent had developed over the domain with a midtropospheric maximum (~650 hPa) over the island in contrast to the circulation pattern observed with the...
front. A midtropospheric maximum in upward motion is typical of cloud clusters observed off the north coast of Australia, mature cloud clusters observed during the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE; Frank and McBride 1989) and mesoscale convective complex (MCC) environments (Cotton et al. 1989; Laing and Fritsch 2000). A maximum in specific humidity is also evident with the 10 g kg\(^{-1}\) contour reaching as high as 720 hPa. Strong convergent easterly flow ensured a steady supply of moist, unstable air into the region, thereby sustaining deep convection.

The 3–4 January flash floods were characterized by (a) antecedent rainfall saturating the soil, (b) orographic lifting by the Blue Mountains and outflow from thunderstorms on 3 January, (c) an easterly low-level jet advecting high \(\theta_e\) air into the area, (d) moisture convergence through a deep layer in the lower troposphere, (e) upper-level divergence, and (f) high levels of convective instability. These features are common to flash

Fig. 13. Same as Fig. 4 except for Puerto Rico flash flood, 5–6 Jan 1992.
flood-producing environments in other regions and are highly conducive to the development of “training” convection (convective cells forming and moving over the same area) and the development of a quasi-stationary rainfall system (e.g., Chappell 1986; Akeada et al. 1995; Doswell et al. 1996). Ramis et al. (1995) found that synoptic conditions associated with heavy rains in Catalonia included upward quasi-geostrophic forcing, convergence of water vapor at low levels, and convective instability in the lower troposphere.

c. Satellite observations

A broad cold-frontal cloud band stretched in a NE–SW direction across the Greater Antilles from 30 December 1997 to 1 January 1998 (not shown). The clouds associated with the front had retreated to the west Caribbean, with much of Jamaica and the surrounding area to the east becoming clear until 3 January (Fig. 8a). An east–west cloud band to the east of Jamaica at 1415 UTC signaled the strengthening surface trough on 3 January (Fig. 8b). In the absence of radar coverage over the sea, cloud lines in satellite images offer the primary means of tracking surface boundaries and the possible generation of vertical motion. The cloud band grew and advanced westward toward the island, bringing rainfall to parts of eastern Jamaica (Fig. 8c) with most of the deep convection occurring between 1900 and 2300 UTC on 3 January. Over the next several hours most of the convection dissipated (not shown). Between 0900 and 1200 UTC on 4 January, a small cloud cluster formed and became quasi stationary over northeastern Jamaica (Figs. 8c–h). Although extremely small when compared with the broader frontal rainbands, this cloud cluster became “anchored” to the mountains and was able to produce copious amounts of rainfall in a similar manner to the cells that produced the Fort Collins flood (Petersen et al. 1999). Despite the presence of convection over eastern Jamaica and surrounding waters, only a small area close to the steep terrain (greater than 1000 m) attained cloud-top temperatures lower than 209 K (cf. Figs. 1 and 8). A further indication of the intensity of the convection was the expanding cold pool spreading out from the thunderstorm system. The cold pool, marked by arc cloud lines west and north of Jamaica, led first to secondary cell development north of Jamaica between 1600 and 1800 UTC (Figs. 8d, 8e, and 9a–c).

Fig. 14. Analysis of the upper-air synoptic environment at 0000 UTC 6 Jan 1992: geopotential height, temperature, and equivalent potential temperature ($\theta_e$) for (a) 850 hPa; geopotential height, temperature, and relative vorticity for (b) 500 mb; and height, temperature, divergence for (c) 200 hPa. Heights (m) are solid contours; isotherms (°C) are dashed. Shaded areas are $\theta_e$ greater than 338 K in (a), relative vorticity $> 1 \times 10^{-5}$ s$^{-1}$ in (b), and divergence $> 1 \times 10^{-5}$ s$^{-1}$ in (c). The thick arrow in (a) depicts the low-level jet. Points A and B in (a) represent the endpoints of cross sections shown in Fig. 16.

<table>
<thead>
<tr>
<th>Time/date</th>
<th>Precipitable water (mm)</th>
<th>Lifted index</th>
<th>$\kappa$ index</th>
<th>CAPE (J kg$^{-1}$)</th>
<th>CIN (J kg$^{-1}$)</th>
<th>LFC (hPa)</th>
<th>LCL (hPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000 UTC 5 Jan 1992</td>
<td>42.5</td>
<td>-4.2</td>
<td>29.1</td>
<td>1968</td>
<td>-12.5</td>
<td>890.1</td>
<td>930.8</td>
</tr>
<tr>
<td>1200 UTC 5 Jan 1992</td>
<td>52.9</td>
<td>-4.57</td>
<td>38.3</td>
<td>2383</td>
<td>-2.6</td>
<td>918</td>
<td>955</td>
</tr>
<tr>
<td>1200 UTC 6 Jan 1992</td>
<td>42.6</td>
<td>-1.79</td>
<td>34.8</td>
<td>398.3</td>
<td>-159.5</td>
<td>740.8</td>
<td>927.8</td>
</tr>
</tbody>
</table>

Then, as the convection intensified, the outflow boundary spread further and initiated widespread convection over southern Cuba (Figs. 9d–g). Meanwhile, the overshooting top of the thunderstorm cell over northeast Jamaica grew while remaining quasi stationary. High-resolution satellite imagery provided rapid updates on the evolution, and more importantly, the short-term intensification of the thunderstorm systems affecting Jamaica.

Additionally, in the absence of radar observations, satellite techniques for estimating rainfall offer some guidance to forecasters in the Tropics. In this case, the TMI measurements estimated that the cloud cluster was producing surface rain rates in excess of 40 mm h$^{-1}$.

Fig. 15. Enhanced IR images of Puerto Rico flash flood, 5–6 Jan 1992. Enhancement levels are the same as in Fig. 8.
(Fig. 16). In the years since this flash flood, several techniques have combined geostationary infrared with passive microwave measurements from the TMI, Special Sensor Microwave Imager (SSM/I), and/or the Advanced Microwave Sounding Unit (AMSU) for estimating precipitation in the Tropics (Turk et al. 1998; Laing et al. 1999; Xu et al. 1999; Todd et al. 2001; Kuligowski et al. 2003; Nirala and Houser 2003). These techniques remain susceptible to large uncertainties but can be useful in the absence of other precipitation data, especially for organized systems like tropical cyclones.

d. Hydrologic analysis and land use

The timing and size of heavy precipitation are important because they affect the scale of the flooding potential over a stream basin (e.g., local- versus regional-scale basins). The affected area, the Rio Grande watershed (Fig. 2), has a drainage area of 287 km$^2$ consisting of approximately 85% low-permeability basement rocks upstream and 10% white limestone in the lower basin (Douglas 2000). The watershed has a 30-yr mean annual precipitation of 5718 mm, the highest of any catchment area in Jamaica. The area has recorded 19 major floods from 1955 to 1999 with the maximum instantaneous flow, 5585 m$^3$ s$^{-1}$, recorded in January 1993 (Douglas 2000). It should be noted that January 1993 was a weak warm period in the equatorial Pacific during a protracted El Niño from 1991 through 1993 (NOAA–CIRES, Climate Diagnostic Center 2003).

The land-use pattern in the watershed is predominantly agriculture with major crops being banana and coffee. Other land uses include pastureland, forest, small housing settlements, domestic water supply, and sand mining.

As illustrated in Fig. 11, the Rio Grande watershed experienced higher rainfall in the lower third of the basin. The estimated peak flow on the Rio Grande on 4 January was 3.059 m$^3$ s$^{-1}$ (108 cfs), a flow with a return period of approximately 25 yr (H. Thomas, WRA, 1998, personal communication). The rate of return was between 5 and 25 yr for all basins except the Boundary Brook River (western border of Port Antonio), which had a greater than 100-yr flood (Table 3).

In light of the lingering cold front and intermittent precipitation that occurred between 29 December and 2 January, the extremeness of the flooding is also attributed to streams at or above flood stage immediately prior to the heaviest precipitation. Moreover, human-induced factors, such as debris from landslides in deforested areas, building construction in the floodplain, faulty drain construction, and the inadequate carrying capacity of bridges and culverts, were major contributors to the extraordinary flood levels.

4. Comparison with other Caribbean flash floods


Flash flood episodes during the Caribbean cool, dry season are not unprecedented. During 5–6 January 1992, another El Niño winter, heavy rainfall produced flash floods in Puerto Rico and caused 23 deaths and 88 million U.S. dollars in damage (NOAA/NWS 1992). Over the mountainous interior (Fig. 12) and southern portions of the island, rainfall amounts of 200–300 mm, and up to 500 mm at a few stations, were reported. The rainfall was associated with a quasi-stationary front and trough at the surface (Fig. 13) and an upper-level trough (Fig. 14). In a similar manner to the January 1998 flood in Jamaica, the environment over Puerto Rico moistened and became more potentially unstable through 5 January (Table 4). The peak in hourly precipitation rates, more than 100 mm at Rio Guamani in the southeast, occurred between 2300 UTC 5 January and 0000 UTC 6 January (NOAA/NWS 1992). As the front moved eastward and the surface trough began developing, the CAPE increased by 21% and the precipitable water content increased from 42 to 52.9 mm between 0000 and 1200
UTC on 5 January. A flux of high \( \theta_e \), air coupled with warm air advection in the lower troposphere (Fig. 14a) played an instrumental role in the production of heavy rainfall. Development of the surface trough led to south-southeasterly flow toward the Cordillera Central (the mountainous backbone of the island; Fig. 12) and subsequent orographic lift. A weak short wave at 500 hPa generated positive vorticity advection (Fig. 14b). At the upper-tropospheric levels, the trough generated upper-level divergence to the east of the island (Fig. 14c). Satellite images show the cold-frontal passage and development of convection associated with the surface trough (Fig. 15). The period of greatest rainfall coincided with the formation of an apex in the cold cloud over Puerto Rico (Figs. 15e–h). Shi and Scofield (1987) found that an apex in the cold cloud shield signals strong convection and heavy precipitation due to the development and propagation of new cells. Comparisons of east–west cross sections through the domain of both flood environments show some similarities (cf. Figs. 16 and 7). The vertical velocity over Puerto Rico in 1992
Table 5. Thermodynamic indices for Kingston, Jamaica, 1200 UTC 4 Mar 1998.

<table>
<thead>
<tr>
<th>Time/date</th>
<th>Precipitable water (mm)</th>
<th>Lifted index</th>
<th>K index</th>
<th>CAPE (J kg⁻¹)</th>
<th>CIN (J kg⁻¹)</th>
<th>LFC (hPa)</th>
<th>LCL (hPa)</th>
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<td>1200 UTC 4 March 1998</td>
<td>46.23</td>
<td>-1.9</td>
<td>34.0</td>
<td>347.6</td>
<td>-7.04</td>
<td>909.8</td>
<td>939</td>
</tr>
</tbody>
</table>

was less than half of that over Jamaica in 1998; however, the front over Puerto Rico was accompanied by an upper-level trough that provided additional baroclinic forcing. At the same height in the January 1998 case, conditions were stable or neutral. In both cases, an upward shift in the maximum ascent was a signature of longer-lived convection that was associated with the surface troughs.

b. Jamaica, 4 March 1998

On 4 March 1998, heavy rains caused flooding in the parishes of Portland and St. Mary, Jamaica, the same area that had been devastated by the January 1998 floods. Fortunately, there were no fatalities. The rains were associated with an extensive frontal system that stretched southwestward from the Atlantic to Central America to the Pacific (Fig. 17)—well south of normal frontal tracks. Most of the convection and heavy precipitation was associated with the frontal passage, unlike the two deadly floods described earlier. Within the broad band of clouds the coldest cloud tops were over northeastern Jamaica. The Blue Mountains were again instrumental in focusing deep convection over northeastern Jamaica; however, the cloud-top temperatures were warmer than the January case, indicating less vigorous convection (Fig. 18).

Although the lower troposphere was very moist and potentially unstable (Table 5), low-level winds were predominantly northerly and only half as strong as those during the January flood. The airflow–terrain interaction had a less intensifying effect on the convection. Indeed, part of the flooding was attributed to nonhydrometeorological sources like debris that remained from the deadly flash flood that occurred 2 months earlier.

5. Mitigation: Warning, response, and preparedness

a. Detection and warning

The convergence associated with a quasi-stationary front, substantial water vapor, and an upper-level ridge were quickly identified by Jamaican forecasters as a potential flash flood situation. The challenge was to anticipate the magnitude of rainfall and areas at risk. Flash flood watches were posted from 1 to 4 January as the cold front oscillated close to and across the island. The slowly evolving nature of the overall weather pattern may have contributed to a complacent response within the general population. The rainfall was not continuous and did not affect any one area for an extended period. Therefore, the warnings issued by the forecasters began to lose their ability to provoke the public into taking preventative action. The diurnal cycle of the rainfall also hindered communication of warnings. In the January event, some of the flooding occurred during the nighttime when many residents were asleep and thus unable to receive the warnings issued by the broadcast media. Furthermore, without modern radar, rapid intensification and movement of convective cells were difficult to detect. In the same manner that the National Weather Service Weather Surveillance Radar-1988 Doppler (WSR-88D) network has proved successful in decision making for flash flood forecasting (Fread et al. 1995; Baeck and Smith 1998; Vieux and Bedient 1998), the addition of Doppler radar to the Jamaican Meteorological Services has facilitated easier detection of heavy precipitation cells (J. Spooner 2001, personal communication). Implementation of techniques for estimating precipitation accumulations in complex terrain (e.g., Joss and Lee 1995; Lin et al. 2001) may prove to be more valuable.

b. Preparedness

The floods of January 1998 brought several issues to the forefront regarding preparedness and mitigation. On reviewing the event of 4 January, it is noted that people were unprepared for the severity of the event. The previous week had seen rains on and off and the National Meteorological Centre issuing several severe weather alerts and flash flood watches. Doswell et al. (1996)
attributed public apathy to flood warnings to the nature of rainfall. Unlike extraordinary events such as tornadoes and hurricanes, rain is common and, for the majority of episodes, benign. Even if quantitative precipitation forecasts were perfect, the public recognition of a threat is a major obstacle to mitigation. Of the people who heard the warnings of the floods in Puerto Rico, January 1992, about half decided to remain in vulnerable areas (NOAA/NWS 1992).

As a consequence of the January 1998 event, three national agencies, the National Meteorological Service, the Office of Disaster Preparedness and Emergency Management, and the Water Resource Authority spearheaded a Vulnerability Reduction Project for the Rio Grande valley. The project, which was funded by the European Community Humanitarian Office, emphasized landslide loss reduction and environmental rehabilitation. The main components of the 1-yr project that began in February 1999 were

- landslide mapping of the Rio Grande valley and the preparation of hazard maps,
- flood risk assessment,
- development of a flood alert program for the residents (including new river gauges),
- training of the community in preparedness and mitigation, and
- involving the residents in a community mitigation program.

Community response teams utilized their training effectively when heavy rainfall and critical river level rises occurred on 25 October 1999 (Douglas 2000).

6. Summary and concluding remarks

Although these three cases are not adequate for broad generalization, they offer a set of guidelines for forecasters in the Caribbean. The January 1998 flash floods were the result of antecedent rainfall from a strong cold front, a period of intense rainfall associated with 1) a surface trough, 2) an easterly low-level jet in the axis of maximum 850 hPa equivalent potential temperature, 3) a deep layer of moisture in the lower troposphere, 4) a mid-to-upper troposphere trough to the west generating weakly positive vorticity advection, and 5) upper-level divergence. The steep Blue Mountain ridge enhanced and localized convection over northeastern Jamaica. The intensity of the convection was also dependent on the direction and speed of the low-level flow relative to the mountains. The antecedent rainfall, size of the Port Antonio basin, topography of the basin, nighttime occurrence of the peak flows, and land-use practices of the residents (e.g., floodplain encroachment) dramatically exacerbated the flood hazard.

The 1992 Puerto Rico flash flood was associated with a prefrontal surface trough, an upper-tropospheric trough, and an approaching cold front. Potential instability and rising motion were forced by strong lower-tropospheric warm advection and midtropospheric positive vorticity advection. Orographic lifting along the central mountain range enhanced the convection and rainfall rate, causing the maximum accumulations over the interior and southern portions of the island. The March 1998 event in Jamaica was mostly the result of frontal lifting with less convective instability but with a deep layer of moisture to sustain heavy precipitation. Weak low-level flow, although mostly northerly and cooler relative to the January 1998 event, was enhanced by orographic lifting up the Blue Mountains.

In light of the results, several questions arose: In places without Doppler radars (most of the Caribbean and Central America), are satellite precipitation-estimating techniques feasible for operational use? In recent years, data from TRMM, SSM/I, AMSU, and GOES have been used for near-real-time tropical precipitation estimates, particularly for tropical cyclones. Visible satellite images can be useful for detecting mesoscale surface boundaries. Forecaster training in the use of various satellite data is essential. With regard to the hazards of flash floods, what methods of communication will reach the majority of the public in the shortest possible time? What actions are needed to ensure that the public is alerted to the danger of heavy rainfall outside of the normal "wet" season?

Furthermore, it is important to note the climatic element to flood preparedness in the Caribbean since these heavy rainfall events occurred during El Niño winters (NH) when moisture-laden extratropical cyclones track along the southern U.S. border. Strong fronts and prefrontal troughs associated with these cyclones have a significant impact on Caribbean and Central American weather, and forecasters need to be more vigilant during those episodes.

Acknowledgments. Thanks to Mr. Jeffrey Spooner of the National Meteorological Service of Jamaica for local surface observations and rain gauge data. Mr. Herbert Thomas of the Water Resource Authority of Jamaica provided hydrologic and land-use data. Mr. Paul Saunders of the Office of Disaster Preparedness and Emergency Management provided situation reports and information on the mitigation plan.

APPENDIX

Glossary of Thermodynamic Parameters

a. CAPE (J kg⁻¹)

CAPE is the vertically integrated positive buoyancy of an adiabatically rising parcel, an excellent measure of latent instability. Increasing values of CAPE generally lead to progressively more vigorous convection. CAPE depends on the parcel chosen for lifting and on whether the initial lift is mechanically forced or from surface heating. CAPE is represented on a thermody-
namic diagram (skew $T$–log $P$) as the positive area between the moist adiabatic curve and the sounding temperature curve, from the level of free convection to the equilibrium level.

b. Convective inhibition ($J \text{ kg}^{-1}$)

CIN is represented on a thermodynamic diagram (skew $T$) as the negative area between the moist adiabatic curve and the sounding temperature curve below the level of free convection.

c. $K$ index ($^\circ C$)

The $K$ index has been shown to be particularly useful for identifying convective and heavy-rain-producing environments because it accounts for the differences in moisture, not simply temperature. George’s (1960) results indicate that thunderstorm probability ranges from near zero when $K < 20$ to widespread activity when $K > 35$.

$$KI = \frac{(T_{850} - T_{500}) + Td_{500} - Tdd_{500}}{5},$$

where $Td$ = dewpoint temperature, and $Tdd$ = dewpoint depression.

d. Lifted index ($^\circ C$)

$$LI = T_{500} - T_{\text{parcel}},$$

where $T_{500}$ is the temperature in Celsius of the environment at 500 hPa and $T_{\text{parcel}}$ is the 500-hPa temperature in Celsius of a lifted parcel with the average pressure, temperature, and dewpoint of the layer 500 m above the surface.

REFERENCES


