Composite Meteorological Forcing of Puerto Rican Springtime Flood Events

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ABSTRACT

The central Antilles Islands experience short periods of heavy rainfall during the spring season (April and May) when trade winds weaken across the Caribbean Sea. Composite analysis of the top 10 flood events in the period 1979–2005 is carried out to understand the meteorological forcing. Cases are selected when mean rainfall over Puerto Rico exceeds 50 mm day$^{-1}$ and emergency management reports indicate the day is a “declared weather disaster.” In the NCEP–NCAR composite analyses, pulses of moisture shift westward across the tropical Atlantic about 10 days before a flood event. Five days before the composite flood a westerly trough penetrates eastward from the Gulf of Mexico. Northward flow develops over the Caribbean Sea and a southwest-oriented cloud band extends from Colombia toward Puerto Rico. A key feature of the midtropospheric circulation field is the development of anomalous twin rotors east of Florida in the mid- to upper troposphere. The flood events coincide with a change in zonal wind shear from westerly to easterly that is brought about by slow tropical and fast subtropical wave systems.

1. Introduction

The Caribbean Islands extend southeastward in an arc from Cuba to Barbados. The western islands are large with mesoclimates, while the eastern islands are small and barely interrupt the persistent trade wind flow. The precipitation is somewhat bimodal with an initial maximum in spring (May), slightly lower values in midsummer (July), and a second peak in late summer (October) (Giannini et al. 2001; Chen and Taylor 2002). During boreal winter months there is little rainfall across the Antilles Islands as tropical moisture is cut off by persistent trade winds along 15°N and strong subsidence of the northern Hadley cell (Muñoz et al. 2008). The intertropical convergence zone (ITCZ) lies over the Amazon near 10°S from December to February and its outflows usually extend southeastward (Liebmann and Marengo 2001).

Outside of the late summer hurricane season, most Caribbean rainfall involves upper-level troughs that penetrate southeastward from the Gulf of Mexico and draw tropical moisture northward from South America. During boreal spring (April and May) the jet stream may bifurcate, giving rise to high-amplitude, short-wavelength patterns that favor the development of meridional cloud bands (Keyser and Shapiro 1986). Simultaneously, the northern Hadley cell and Caribbean trade winds weaken, and the ITCZ drifts northward toward Venezuela (Amador 1998; Magaña et al. 1999; Amador et al. 2000; Muñoz et al. 2008). There is a greater probability of westerly troughs penetrating into the Caribbean during and immediately after El Niño events (Laing 2004). Rainfall during spring is beneficial for Caribbean-wide crop production as evidenced, from research conducted by the authors, by a positive correlation between time series of year-end yield and collocated March–May rainfall ($r = 0.54$ over 43 yr). However, subtropical troughs may combine with tropical moisture to create floods over the Antilles Islands (Gu and Zhang 2002) that contribute to erosion, landslides, and the loss of infrastructure.

Here, we evaluate the extent to which large-scale meteorological conditions precede and control flood events over Puerto Rico, so that their consequences may be better understood (Doswell et al. 1998; Peterson et al. 2002). Our analysis focuses on composite synoptic weather patterns that are associated with springtime floods in the Caribbean Antilles. Scientific questions that we address include the following:

1) What is the historical context of floods in Puerto Rico?
2) Are the flood-producing troughs of midlatitude or tropical origin?
3) Are slow or fast intraseasonal oscillations implicated in the flood scenario?
4) Are meridional cloud bands extending from South America the main drivers of floods?
5) What forecast potential is possible at lead times from days to weeks?

2. Data and methods

The analysis of Puerto Rico flood events is made using gridded National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data (Kalnay et al. 1996) and daily rainfall time series from January 1979 to December 2005. Here, we isolate events that occur during April and May, when the average rainfall for most stations across the island is \( \sim 130 \text{ mm month}^{-1} \). Cases are defined using data from \( \sim 60 \) quality controlled rain gauge stations over Puerto Rico (cf. Fig. 1a) provided by the State Climate Office. A “flood event” is identified when the average of all stations exceeds \( 50 \text{ mm day}^{-1} \) (\( \sim 2 \text{ in. day}^{-1} \)) and when Federal Emergency Management Agency (FEMA) archives reveal the day to be a “declared weather disaster.” A sample of 10 days that meet these criteria are selected (Table 1). We map the composite mean and anomaly fields before and during flood events over a Caribbean domain using the NCEP–NCAR reanalysis data. To study the vertical structure, composite cross sections of longitude versus height are analyzed across the Caribbean. Variables analyzed include precipitable water, specific humidity, vertical motion, geopotential height, satellite outgoing longwave radiation (OLR), and winds. As the analysis is focused on baroclinic flood events in the satellite era, it is believed that the NCEP–NCAR data will provide an adequate description of the large-scale meteorological forcing (Carter and Elsner 1997). In addition to the composite analysis, we investigate the predictability of flood events by considering climate and weather model data at lead times from days to weeks, and we study three consecutive wet spells in early April 2006 using Hovmöller time–longitude analyses of upper-meridional wind and precipitable water to identify the intraseasonal oscillations present.

3. Results

A statistical analysis of mean daily rainfall averaged over Puerto Rico during the period January 1979–December 2005 reveals that flood events \( >50 \text{ mm} \) are most frequent in May, September, and November (Fig. 1b). Of the 16 days with an island average above 50 mm in April and May, 10 days overlap with FEMA archives as declared flood events. With an area of \( \sim 13,000 \text{ km}^2 \), the volume of water generated exceeds 68,500 m\(^3\). One

Table 1. Top-10 flood cases in April and May from island rainfall time series during 1979–2005. All days are included in the composite analysis.

<table>
<thead>
<tr>
<th>Date</th>
<th>Rainfall (mm day(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 May 1985</td>
<td>88.6</td>
</tr>
<tr>
<td>7 May 2001</td>
<td>88.6</td>
</tr>
<tr>
<td>21 Apr 1983</td>
<td>84.6</td>
</tr>
<tr>
<td>28 May 1980</td>
<td>82.8</td>
</tr>
<tr>
<td>13 May 1986</td>
<td>67.8</td>
</tr>
<tr>
<td>18 Apr 2003</td>
<td>60.7</td>
</tr>
<tr>
<td>14 May 1986</td>
<td>59.9</td>
</tr>
<tr>
<td>24 May 1992</td>
<td>51.6</td>
</tr>
<tr>
<td>17 May 2005</td>
<td>50.3</td>
</tr>
<tr>
<td>19 May 1985</td>
<td>48.5</td>
</tr>
</tbody>
</table>
of the scientific questions is whether meridional flow is a necessary condition for flood events. The scatterplot of low-level meridional wind over Puerto Rico (15°–20°N, 65°–70°W) and daily rainfall for cases >25 mm day\(^{-1}\) (Fig. 1c) reveals a tendency for floods as southerly winds increase to \(\sim 8\) m s\(^{-1}\). This is contributed by a number of factors: 1) localized orographic lifting by east–west-oriented mountains extending to 800 m, 2) the theoretical requirement for vertical motion in horizontal flow experiencing a change of Coriolis force, and 3) positive thermal and moisture advection from lower latitudes. The cross correlation of area-averaged 700–850-hPa wind and island rainfall is 0.16 for a sample length of \(\sim 9000\) days, a statistically significant result given a low autocorrelation. There are also a number of days with low rainfall when southerly winds are strong. Considering daily rainfall since 1948, we find that our 10 flood events rank between the 13th and 57th wettest days out of \(\sim 21\) 000. The top-ranked flood events are occupied by hurricanes in August and September and tropical westerly troughs in October and November. Although the boreal autumn flood events have a similar structure to those during spring, their mean convective available potential energy (CAPE) exceeds 1000 J kg\(^{-1}\) with sea surface temperatures above 28°\(\mathrm{C}\). During the spring floods analyzed here, SST is \(\sim 27°\mathrm{C}\) and mean CAPE is \(\sim 700\) J kg\(^{-1}\), so the dynamical forcing may need to be commensurately stronger.

**a. Composite flood events**

The 10-case composite 850-hPa wind map for the flood day (Fig. 2a) illustrates a southwest–northeast orientation of anomalous flow in response to a subtropical Rossby wave trough. The anomalous wind extends to the northern coast of South America, somewhat like the southerly flow that precedes severe
weather over the central United States (Stensrud 1996; Anderson and Arritt 2001; Kiefer et al. 2006). Low-level wind anomalies exceed 5 m s$^{-1}$, while those above 500 hPa exceed 9 m s$^{-1}$ (not shown). Precipitable water anomalies exceed 6 mm along an identical axis, extending southwest–northeast about $\sim$3000 km from 10° to 40°N (not shown). This feature is quasi-stationary for a few days; thus, rains saturate the land making it more vulnerable to floods. Figure 2b shows the 10-case composite midlevel geopotential height anomaly map for the flood day, emphasizing a low–high anomaly pair northeast of Florida, over the subtropical western Atlantic. The composite low anomaly has a round shape of 3000-km diameter and reaches a minimum of $-80$ m at 35°N, 75°W. It drifts slowly while an anomalous ridge builds to the east, reaching a maximum of $+50$ m at 35°N, 45°W. The low–high anomaly pair create a rotational flow field that helps draw tropical moisture across the Caribbean Antilles Islands, forming a southwest-oriented (hereafter SW) cloud band that is evident in the satellite mean OLR composite for days $-1$ and 0 (Fig. 2c). OLR values are $<210$ W m$^{-2}$ from Colombia to Puerto Rico, stretching $\sim$4000 km in extent from the equator to 40°N. Composite OLR values in the Caribbean along 15°N are higher (220 W m$^{-2}$), which is indicative of remnant subsidence from the northern Hadley cell. The OLR pattern is similar to that for the low-level velocity potential and moisture flux, with alternating divergent–convergent–divergent regions over Central America, the Caribbean, and the central Atlantic, respectively. The wavelength of these anomaly features is 6000 km in the latitude band 10°–25°N. A satellite image for one case (18 April 2003) illustrates the SW cloud band, with an embedded vortex north of Puerto Rico (Fig. 2d).

We track the development of the 10-member composite flood event back in time and find that positive precipitable water anomalies drift westward across the tropical North Atlantic from day $-15$ to $-11$ (Fig. 3a). On day $-10$ there is a jump in the signal, which is possibly related to a pulse of moisture arriving from the tropical North Pacific and Panama. We find the positive precipitable water anomaly drifts north of Colombia on days $-11$ to $-8$ and north of Venezuela on days $-7$ to $-4$, before being picked up by the subtropical trough near Hispaniola.
We similarly track the composite geopotential height anomalies and find that the midlevel trough first emerges from the southern Rocky Mountains 15 days before the composite flood event (Fig. 3b). The trends in the shape and size of the composite anomalies are due to variations in the track and intensity of individual upper lows/troughs as they move toward the Caribbean. The \(-20 \text{ m closed isopleth}\) moves slowly southeastward into the Gulf of Mexico by day \(-10\). After weakening on day \(-7\), the midlevel low intensifies and shifts to Florida by day \(-5\), (e.g., many of the individual low–troughs arrive there). This feature emerges over the Gulf Stream and elongates southward toward the Caribbean Antilles on day \(-2\). Around this subtropical low we find the composite jet stream has split into tropical and polar axes separated by a ridge along 30\(^\circ\)N at 200 hPa (not shown). This is indicative of jet bifurcation and vortex development, which accounts for the slow phase speed of the subtropical westerly trough that contributes to the flood.

Constructing composite mean vertical sections across the Caribbean (15\(^\circ\)-20\(^\circ\)N, 40\(^\circ\)-90\(^\circ\)W) for day 0 (Figs. 4a–c), we observe a moist layer that is 100 hPa (1000 m) deeper in the central Caribbean (65\(^\circ\)-70\(^\circ\)W). The composite meridional wind and vertical motion sections illustrate the Rossby wave train that helps to organize the meridional cloud band (cf. Fig. 2d). We find subsidence and upper northerly winds at 80\(^\circ\) and 45\(^\circ\)W. In between, there is rising motion \(<-0.06 \text{ Pa s}^{-1}\) in the midtroposphere within a southerly wind stream \(>5 \text{ m s}^{-1}\). Although individual cases have slightly different orientations and intensities, they all have a SW cloud band extending from Colombia or Venezuela (not shown). This cloud band draws tropical moisture from both the west (Pacific) and east (Atlantic and Amazon), as evidenced in Fig. 2 and in Fig. 19 of Enfield et al. (2008).

One scientific question concerns the relative influence of slow or fast zonal wave systems in the flood scenario. Zonal wind anomalies are plotted in Fig. 5 over the same east–west slice as in Fig. 4, except to a higher level. Westerly anomalies \(>6 \text{ m s}^{-1}\) dominate the longitudes from 70\(^\circ\) to 80\(^\circ\)W, and progress from the upper to lower troposphere from day \(-2\) to day \(+1\) (Figs. 5a and 5b). Easterly anomalies in the upper troposphere build from \(-2\) to \(-8 \text{ m s}^{-1}\) to the east of 60\(^\circ\)W as the flood unfolds. This pattern of zonal wind shear indicates two potential influences: 1) a subtropical trough–ridge feature has penetrated into the Caribbean and 2) a slow tropical wave has drifted east along the equator. Using band-filtered zonal wind shear data (200–850-hPa \(U\)) over the Caribbean (10\(^\circ\)-15\(^\circ\)N, 60\(^\circ\)-80\(^\circ\)W) averaged for the 10 cases over the period day \(-15\) to day \(+5\), we form a composite time series. The most influential wave bands are 20–60 and 3–12 days, corresponding to the Madden–Julian oscillation (MJO) from the Pacific and either Atlantic moisture pulses or subtropical troughs. The results are presented in Fig. 6a. The MJO band peaks around day \(-12\) and dips to an easterly shear minimum at day \(+2\). Similarly, the high-frequency band peaks around day \(-2\) and dips at day \(+1\). Hence, both bands conspire with low-level westerlies overlaid by easterlies as the composite flood event unfolds (cf. Fig. 5). The shear amplitude oscillates from \(+3\) to \(-3 \text{ m s}^{-1}\); hence, both exert similar levels of influence. It is unclear whether tropical moisture pulses or subtropical troughs induce the fast oscillation, and so this is analyzed for a group of consecutive wet spells in section 3b.
Another scientific question is whether the flood events are predictable. We evaluate the ability of climate and weather models to forecast our small sample of cases in this section. We extract ensemble forecast data from the Climate Forecast System (CFS) of NCEP during each month with an event (7 out of 10 available) and plot the daily rainfall values.

Three of the years (1985, 1986, and 1992) reveal high-amplitude oscillations with peak rainfall; 15 mm day$^{-1}$, compared with observed values that are about 5 times higher. The other half of the cases give no clue that anything more than climatology should be expected (e.g., 2–3 mm day$^{-1}$) and, are, thus inadequate. We extracted operational numerical weather forecasts from the Global Forecast System (GFS) of NCEP for the flood events, and illustrate results for the 18 April 2003 case in Figs. 7a–c. At lead times greater than 4 days the rainfall is light and the trough is too far west. Between 2- and 4-day lead times, the rainfall intensity is adequate (about half of the observed) but the trough is still too far west. Microwave-satellite-estimated rainfall values [Climate Prediction Center (CPC) morphing technique (CMORPH); Joyce et al. (2004)] provide verification fields, and for 18 April 2003 (Fig. 7c) reveal the heaviest rainfall in two zones: over western Puerto Rico and to the north. Within the trough are mesoscale convective systems that drift NE, appearing as strips of high rainfall.

b. Case study of consecutive wet spells

To isolate the interaction of subtropical troughs and tropical moisture pulses, we analyze consecutive wet spells in early April 2006 rather than extreme flood events separated by years. According to the Puerto Rico–averaged time series and its wavelet analysis (Figs. 8a and 8b), the rainfall pulsed three times. The wavelet analysis shows the evolution of spectral energy in different periods, with shading indicating significance at a rhythm of ~8 and ~24 days. During these wet spells, San Juan radiosonde profiles exhibited a moist unstable layer up to 500 hPa and southwesterly winds above 700 hPa, reaching 30 m s$^{-1}$ at 200 hPa (Fig. 8c). Trade winds across the Caribbean were weak, and local CAPE and precipitable water values were ~900 J kg$^{-1}$ and 45 mm, respectively. Quick Scatterometer (QuikSCAT) wind fields for the April 2006 wet spells (not shown) reveal a frontal discontinuity extending 3000 km southwest–northeast across the western Atlantic with northeast winds to the north and southeast winds across the tropics, similar to Fig. 2a. Meteorological fields confirm the frontal feature to be cold-cored with opposing upper-meridional winds of ~10 m s$^{-1}$ on either side, a pattern similar to that found by Anderson and Arritt (1998) and Jorgensen et al. (2003). Subsident northerly flow west of the trough created dry conditions over Florida (cf. OLR >250 W m$^{-2}$ in Fig. 2c).

Streamfunction anomaly maps reveal a cyclone–anticyclone anomaly pair similar to our Fig. 2b. Twin rotors located on either side of a SW cloud band are often associated with flood events (Bennetts and Hoskins 1979; Emanuel 1979, 1983; Xu and Zhou 1982; Miller 1985; Xu 1986). Rapid condensation and high rainfall rates drive a hydrostatic pressure decrease as the column mass is heated, thereby impacting the continuity relationship (Lackmann and Yablonsky 2004). With large values of rising and sinking motion in close proximity affecting a deep layer (Fig. 4c; half wavelength ~2000 km), anomalous zonal overturning provides a feedback to the twin rotors through the vorticity budget (Trenberth 1991) helping to “focus” the SW cloud band.
Convection over Venezuela and narrow outflow extending from Colombia is common in the Caribbean flood scenario (Fig. 2c). What is driving the outflow from South America? A Hovmöller analysis of meridional winds and precipitable water for our consecutive wet spells in 2006 provides some insight. While southerly winds sweep rapidly eastward with successive subtropical Rossby waves, pulses of moisture propagate westward at \( \frac{500 \text{ km day}^{-1}}{2} \) across the tropical Atlantic and northern Amazon (diagonal lines in Figs. 9a and 9b). The interaction of the tropical systems’ transverse circulation and the subtropical perturbation pair occurs within a sheared flow separating two distinct air masses with horizontally extensive boundaries. As the moisture pulse reaches Colombia, it is simultaneously drawn northward by the twin rotors and westerly trough over the western Atlantic. In our 2006 Hovmöller plot, the subtropical Rossby waves are seen to travel \( \frac{1000 \text{ km day}^{-1}}{2} \) through the Caribbean but the tropical moisture pulses move across the tropical Atlantic and northern Amazon at half the speed in the opposite direction. Given the persistent progression of the moisture pulse, an advance warning of Caribbean springtime flood events is possible (cf. Figs. 7a–c).

4. Conclusions

Daily rainfall time series for 60 stations over Puerto Rico were used to analyze spring season flood events during the period 1979–2005. Floods are infrequent events whose study depends on the criteria for inclusion. Here, we selected cases with island rainfall \( \geq 50 \text{ mm day}^{-1} \) occurring during April and May that are “declared weather disasters.” Out of \( \frac{1600 \text{ possible days}}{2} \), we found 10 cases meeting the two criteria, a small sample. Composite maps illustrated the intensity and disposition of the synoptic-scale weather systems. Most flood events can be traced to subtropical westerly waves (Ayala-Carcedo 2002). Spring season floods in Puerto Rico coincide with the development of a low–high pair or twin rotors east of Florida. Davis and Bosart (2004) found that many western Atlantic tropical storms

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Fig. 6. (a) Composite band-filtered Caribbean zonal wind shear (850–200 mb) and observed rainfall for 10-case composite, with 10% error bars indicating variations among the members. (b) CFS ensemble model initialized on the first of each flood month, showing the range of 12-hourly forecasts for the Puerto Rican area (different color for each case, with values \!< 5 \text{ mm day}^{-1} \) omitted) compared with observed rainfall above 25 mm day\(^{-1}\) (dots).

Fig. 7. The (a) 2-day lead precipitation forecasts from the GFS model for 18 Apr 2003, indicating good orientation and intensity. With increasing lead time, the SW cloud band lies too far west. (c) The CMORPH satellite rainfall verification field. Color scale is blue to red: 5–50 mm day\(^{-1}\) interval 5 for model, blue to red: 10–100 interval 10 for satellite.
originate from remnant higher-latitude cold-core upper-level baroclinic disturbances that reach equatorward in the form of long vortex “tails.” In our analysis (Fig. 2a), the frontal band extends ~3000 km from Hispaniola to Bermuda. The deep ascent associated with the upper-level baroclinic disturbance initiates convection over a warm ocean, so the initial cold-core disturbance transitions into a flood-producing system.

Our study found a SW cloud band extending from the vicinity of Bermuda to Colombia. Pulses of moisture
from the tropical Atlantic appear to propagate through the northwestern Amazon basin, then join a narrow outflow of unstable air over the Caribbean Sea. This pattern is a reversal of the low-level jet found over South America (Vera et al. 2006) with many similarities, except that meridional flow does not enter the frontal perturbation directly, but first passes over the Caribbean where it widens to ~500 km. The rhythm of rainfall during spring 2006 reflects the way that moisture pulses energize westerly troughs as they pass through the Caribbean. Our top-10 flood sample does not allow us to distinguish cause and effect, but permit us to point out how the subtropical trough draws in tropical air. The convergence of moisture from the east (Fig. 3a) and zonal shear from the west (Fig. 5a), though ambiguous at 10–15-day lead time, is relatively clear at 3–5-day lead time and may yield forecasting opportunities. Further studies could consider hydrological streamflow data and the impact of changes in land cover over the northwestern Amazon (Martin and Murgida 2004).

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