Topographic–Thermal Circulations and GPS-Measured Moisture Variability around Mayaguez, Puerto Rico

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ABSTRACT: To investigate topographic–thermal circulations and the associated moisture variability over western Puerto Rico, field data were collected from 15 to 31 March 2011. Surface meteorological instruments and ground-based GPS receivers measured the circulation and precipitable water with high spatial and temporal resolution, and the Weather Research and Forecasting (WRF) Model was used to simulate the mesoscale flow at 1-km resolution. A westerly onshore flow of \( \approx 4 \text{ m s}^{-1} \) over Mayaguez Bay was observed on many days, due to an interaction between thermally driven \( \Delta T \) (10 km) \( \approx 1 \) sea-breeze circulation and an island wake comprised of twin gyres. The thermally driven sea breeze occurred only when easterly synoptic winds favorably oriented the gyres with respect to the coast. Moisture associated with onshore flow was characterized by GPS measured precipitable water (PW). There is diurnal cycling of PW over the west coast during periods of onshore flow. The WRF Model tends to overestimate PW on the west side of the island, suggesting evapotranspiration as a process needing further attention. Fluctuations of PW affect local rainfall in times of convective instability.

KEYWORDS: Subtropics; Coastal flows; Mesoscale processes; Global positioning systems (GPS)

1. Introduction

One of the challenges of short-term (multihour) coastal weather forecasting is factoring in the variable influence of sea-breeze circulations. These often lead to abrupt wind shifts, convergence lines, and thunderstorm downdrafts that impact aviation. Despite extensive research (Atkins and Wakimoto 1997), it is difficult to accurately predict the intensity and position of sea breezes and their interaction with the synoptic flow. The classical definition of sea breeze is a diurnal low-level mesoscale circulation driven by the differential temperatures between adjacent land and sea surfaces. Once initiated in daytime, this circulation causes onshore flow near the surface and return flow aloft. The inland penetration of the sea-breeze front generates convergence with the antecedent flow (Atkins and Wakimoto 1997). The sea breeze usually reaches a peak at the time of maximum solar heating, since it is the land–sea temperature gradient that drives the phenomenon. Past research on sea breezes in eastern Florida found a wind shift, drop in temperature, and increase in dewpoint coinciding with passage (Wakimoto and Atkins 1994). Sea breezes in island environments, however, are complicated by the presence of wind wakes due to flow over the island topography.

The island of Puerto Rico at 18°N latitude has a rectangular shape of 160 km \( \times \) 60 km and a vegetated mountain range of 600–1200-m elevation oriented east–west. The wet season extends from May to November with a progression of easterly waves that bring rainfall of more than 1500 mm yr\(^{-1}\). Puerto Rico is under easterly trade winds more than 80% of the year. A daytime sea-breeze component is often present along the coast of Puerto Rico (Riehl 1947; Carter and Elsner 1996; Jury et al. 2009), enhancing convection over the western interior. The synoptic flow over the island often results in the formation of twin counterrotating gyres on the leeward edges (Jury and Chiao 2013). The downstream mountain wake is wide when the trade winds split around the mountains and narrow when flow goes over the mountains. Boundary layer moisture is also diurnally modulated by evapotranspiration from the dense vegetation (Jury et al. 2009).
The goal of this research is to understand moisture variability in western Puerto Rico contributed by a sea breeze caught between twin gyres. We investigate this through model simulations and field data collection and analysis. The field data were collected as part of an educational research program by 14 undergraduate students from Purdue University and the University of Puerto Rico, Mayaguez.

2. Data and methods

2.1. Observations and processing

Field data collection was from 15 to 31 March 2011 on the west coast of Puerto Rico. The meteorological observations came from permanent stations of the National Oceanic and Atmospheric Administration (NOAA) and temporary Vaisala WXT-520 and Vaisala Mobile Automated Weather Stations (MAWS), along with ground-based global positioning system (GPS) receivers for precipitable water (PW). The five WXT collected temperature, wind speed, wind direction, pressure, relative humidity, and precipitation every 30 s, each coupled to a GPS unit (labeled PSB) with storage and transmission via cellular modem to the Suominet GPS data processing center (Ware et al. 2000). The MAWS collected 10–15-min averages of the same variables, with the addition of solar radiation. Instruments were placed along the coast near Mayaguez (Figure 1 and Table 1) and up to 5 km inland in the Añasco River valley to study the progression of the sea-breeze front. Some instruments were placed inland at varying elevations to investigate the sea-breeze depth. In addition there was PW data from preexisting GPS stations (MAYZ, PRMI, AOPR, and BYSP) and sounding data from the National Weather Service in San Juan (SJU) to quantify the upstream boundary layer. A Scintec-xfas Doppler acoustic sounder was positioned at Mayaguez airport (MAWS1 in Figure 1). It recorded hourly profiles of wind direction, speed, and standard deviation of the

![Figure 1. Topographic map and station locations, including seven temporary stations in the west coast (inset) and four permanent stations across the island. San Juan radiosonde is also shown.](image-url)
vertical motion ($\sigma_w$) at elevations from 40 to 300 m. Technical information on the profiler is found at online (at http://www.scintec.com). These data were analyzed as time–height cross sections for sea-breeze events.

A sea-breeze index (SBI) is calculated from the methods of Frysinger et al. (2003) as $SBI = \frac{U^2}{\alpha h}$, where $U$ is the onshore synoptic wind speed measured at WXT-3 and $\alpha h$ is the sea-to-air temperature gradient consistent with sensible heat flux. The SBI becomes critical when the onshore flow is weak enough that the density gradient within the heated layer of depth $h$ ($=10^2\text{m}$) dominates. The theoretical onshore wind takes a similar form, $dU \approx (\alpha h) (dT/dx) dt$, where $dt$ is the time of diurnal heating and $dT/dx$ is the coast–inland temperature gradient ($\approx 10^{-4}$ K m$^{-1}$). The sea-breeze front will promote uplift (W) according to continuity ($dU/dx = (dW/dz)$, where $dz \approx 10^3\text{m}$ depth of sea breeze and $dx \approx 10^4\text{m}$, based on WRF Model results. From the SJU sounding data and methods of Cao et al. (2007), the Froude number is calculated from $F = \frac{U}{NH}$, where $N^2 = \frac{g(\theta_o)(d\theta/dz)}{\theta}$, $\theta$ is potential temperature, $U$ is the upstream wind, $N$ is the Brunt–Väisälä frequency using SJU radiosonde potential temperature, and $H$ is the mountain height ($\approx 600\text{m}$). For $F < 1$ easterly flow should deflect around the island, for $F > 1$ flow passes over the island, and for $F = 1$ flow generates standing waves. The SBI and Froude number for each day are shown in Table 2.

Ground-based GPS stations have been used to measure moisture in the atmosphere (Rocken et al. 1995; Businger et al. 1996; Haase et al. 2003). GPS signals at 1.2276 and 1.5754 GHz are delayed and refracted due to the atmosphere as they propagate from GPS satellites to surface-based receivers. This refractive delay is a function of pressure, temperature, and water vapor pressure. The component of delay due to the water vapor is nearly proportional to the quantity of water vapor integrated along the signal path (Hogg et al. 1981; Businger et al. 1996). Precipitable water measurements made with GPS have been shown to be comparable to those of radiosondes (Haase et al. 2003); have even been used for their calibration (Wang and Liangying 2008); and, most importantly, yield data at a high temporal resolution.

The method for converting the delay in the GPS signal into PW has been described in Bevis et al. (1994) and Haase et al. (2003) and has been implemented to provide near-real-time estimates for the Suominet GPS data analysis system within the Support/University Corporation for Atmospheric Research (UCAR) Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) program. Typically, PW values are available with less than 1 h latency, meeting the time cycle for operational numerical model assimilation. Here we had five Trimble

### Table 1. Field site locations.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Coordinates (lat, lon)</th>
<th>Elev (m)</th>
<th>Sample rate (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAWS1</td>
<td>18.254°N, 67.148°W</td>
<td>10.41</td>
<td>15</td>
</tr>
<tr>
<td>MAWS2</td>
<td>18.168°N, 67.181°W</td>
<td>1.01</td>
<td>10</td>
</tr>
<tr>
<td>WXT1-PSB1</td>
<td>18.275°N, 67.189°W</td>
<td>2.57</td>
<td>0.5</td>
</tr>
<tr>
<td>WXT2-PSB2</td>
<td>18.270°N, 67.120°W</td>
<td>12.92</td>
<td>0.5</td>
</tr>
<tr>
<td>WXT3-PSB3</td>
<td>18.254°N, 67.148°W</td>
<td>10.41</td>
<td>0.5</td>
</tr>
<tr>
<td>WXT4-PSB4</td>
<td>18.225°N, 67.142°W</td>
<td>76.40</td>
<td>0.5</td>
</tr>
<tr>
<td>WXT5-PSB5</td>
<td>18.194°N, 67.104°W</td>
<td>395.13</td>
<td>0.5</td>
</tr>
</tbody>
</table>
NetR8 GPS units placed at each WXT-PSB station in the Mayaguez area, in addition to those four routinely operated around the island to understand the background PW. GPS observables were sampled at 30 s, with a 10° satellite elevation angle cutoff. Antenna phase-pattern corrections were applied following the International Global Navigation Satellite Systems (GNSS) Service (IGS) recommendations. Both hydrostatic and wet tropospheric delays were mapped into zenith delay using the Niell mapping functions (Niell 2000). The Bernese GPS processing software (Teferle et al. 2007) was used in precise point positioning (PPP) mode to compute daily GPS coordinate solutions and then 30-min GPS zenith total delay estimates were averaged into hourly values. The entire dataset was reprocessed at the end of the campaign to assure consistency, using final IGS orbits and recomputed station positions.

### 2.2. Model setup

The Weather Research and Forecasting (WRF) Model (Skamarock et al. 2008) was used to provide forecast guidance and to study the interaction of thermal sea breeze and topographic gyres. The WRF3.1 meteorological model was implemented with a domain centered over Puerto Rico (17.8°–18.7°N, 67.9°–65.1°W) with 1-km grid spacing and 46 vertical levels. The WRF3.1 Model was initialized each day at 1200 UTC using the 32-km-resolution North American Model (NAM) for the initial and boundary conditions and set to provide hourly forecasts out to 36 h. NAM analyses were obtained from the Environmental Modeling Center of the National Centers for Environmental Prediction (NCEP). The WRF single-moment 6-class scheme (Hong et al. 2004) suitable for high-resolution simulations is used for the cloud microphysics. The Rapid Radiative Transfer Model scheme was selected for longwave radiation (Mlawer et al. 1997), and the Dudhia scheme was selected for shortwave radiation (Dudhia 1989). Surface interactions are characterized in the model using the fifth-generation Pennsylvania State

<table>
<thead>
<tr>
<th>Yearday</th>
<th>Day of month</th>
<th>SBI</th>
<th>SBIcrit</th>
<th>$U^2$</th>
<th>Froude No.</th>
<th>Type of onshore flow</th>
<th>$T_m - T_s$</th>
<th>Synoptic wind direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>76</td>
<td>17 Mar</td>
<td>5.40</td>
<td>1.75</td>
<td>9.19</td>
<td>0.69</td>
<td>Gyre</td>
<td>2.0</td>
<td>75</td>
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<tr>
<td>77</td>
<td>18 Mar</td>
<td>3.46</td>
<td>1.90</td>
<td>13.43</td>
<td>1.22</td>
<td>None</td>
<td>4.2</td>
<td>75</td>
</tr>
<tr>
<td>78</td>
<td>19 Mar</td>
<td>5.44</td>
<td>1.92</td>
<td>20.87</td>
<td>1.12</td>
<td>None</td>
<td>2.2</td>
<td>20</td>
</tr>
<tr>
<td>79</td>
<td>20 Mar</td>
<td>13.28</td>
<td>1.83</td>
<td>19.21</td>
<td>0.98</td>
<td>None</td>
<td>1.7</td>
<td>5</td>
</tr>
<tr>
<td>80</td>
<td>21 Mar</td>
<td>8.48</td>
<td>1.93</td>
<td>28.24</td>
<td>2.49</td>
<td>None</td>
<td>3.3</td>
<td>25</td>
</tr>
<tr>
<td>81</td>
<td>22 Mar</td>
<td>13.10</td>
<td>2.10</td>
<td>23.13</td>
<td>1.46</td>
<td>None</td>
<td>1.8</td>
<td>40</td>
</tr>
<tr>
<td>82</td>
<td>23 Mar</td>
<td>5.52</td>
<td>1.97</td>
<td>21.22</td>
<td>1.39</td>
<td>Late gyre</td>
<td>3.7</td>
<td>40</td>
</tr>
<tr>
<td>83</td>
<td>24 Mar</td>
<td>1.17</td>
<td>1.42</td>
<td>2.50</td>
<td>1.02</td>
<td>Gyre</td>
<td>2.8</td>
<td>80</td>
</tr>
<tr>
<td>84</td>
<td>25 Mar</td>
<td>2.02</td>
<td>1.52</td>
<td>9.45</td>
<td>0.96</td>
<td>Thermo+gyre</td>
<td>3.5</td>
<td>100</td>
</tr>
<tr>
<td>85</td>
<td>26 Mar</td>
<td>1.23</td>
<td>1.60</td>
<td>6.17</td>
<td>0.53</td>
<td>Thermo+gyre</td>
<td>4.3</td>
<td>155</td>
</tr>
<tr>
<td>86</td>
<td>27 Mar</td>
<td>1.64</td>
<td>1.30</td>
<td>1.39</td>
<td>0.8</td>
<td>Gyre</td>
<td>3.7</td>
<td>115</td>
</tr>
<tr>
<td>87</td>
<td>28 Mar</td>
<td>0.01</td>
<td>2.26</td>
<td>0.02</td>
<td>1.02</td>
<td>Thermo+gyre</td>
<td>3.9</td>
<td>115</td>
</tr>
<tr>
<td>88</td>
<td>29 Mar</td>
<td>0</td>
<td>2.30</td>
<td>0.02</td>
<td>0.97</td>
<td>Thermo+gyre</td>
<td>3.6</td>
<td>115</td>
</tr>
<tr>
<td>89</td>
<td>30 Mar</td>
<td>1.62</td>
<td>2.08</td>
<td>0.17</td>
<td>1.06</td>
<td>Thermo+gyre</td>
<td>2.7</td>
<td>150</td>
</tr>
<tr>
<td>90</td>
<td>31 Mar</td>
<td>0</td>
<td>1.82</td>
<td>2.86</td>
<td>1.01</td>
<td>Gyre</td>
<td>3.5</td>
<td>140</td>
</tr>
</tbody>
</table>
University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5) surface layer scheme based on Monin–Obukhov similarity theory. This is coupled with the Noah land surface submodel (Chen et al. 1996). This scheme was used because it takes into account vegetation effects, and predicts soil temperature and moisture for four layers in addition to providing heat and moisture fluxes to the planetary boundary layer. The planetary boundary layer is characterized using the Yonsei University planetary boundary layer/turbulence parameterization (Noh et al. 2003) and determines the depth of the boundary layer from thermal and frictional influences.

3. Results

3.1. Synoptic situation during the study

Over the 17-day field study, the Caribbean Antilles experienced two distinct weather patterns. MAWS1 and MAWS2 (Figure 2) time series indicate relatively higher easterly wind speeds (4–6 m s \(^{-1}\)) from 18 to 23 March (yeardays 77–82) and much lighter speeds (1–2 m s \(^{-1}\)) from 24 to 31 March (yeardays 83–90). In the earlier period there was little variation of wind direction, whereas in the later period diurnal wind shifts were apparent. There was an increase in the amplitude of the diurnal temperature and moisture variables in the later period. These systematic variations are important diagnostic evidence for two different weather regimes and their effects on local weather conditions. The synoptic-scale patterns over the western Atlantic (Figure 3) indicate the marine anticyclone was in a position near Florida with dry northeasterly flow over Puerto Rico in the earlier period. The anticyclone shifted to midocean and thus generated moist easterly flow over Puerto
Rico in the later period. The longer over-island fetch under easterly flow achieves a greater friction and thermal influence. Table 2 indicates days where the return flow is due to a combination of twin gyres and sea-breeze circulation.

3.2. Observations of onshore flow

Our analysis of the surface data showed that the onshore flow sometimes anticipated the peak in diurnal heating by a few hours, possibly in relation to inflow from the dual gyres in the wake of the island. We examine two examples of onshore flow and investigate their signature in the WRF Model.

The onshore flow case that occurred on 26 March (yearday 85) was a thermally driven (Figure 4) sea-breeze onshore flow. It was characterized by an observed
westerly wind shift at all sites near 1530 UTC [1130 local standard time (LST)]. The MAWS2 site near the coast reflected sea-breeze frontal passage in a shift of winds from easterly to westerly accompanied with a temperature decrease and increases in equivalent potential temperature ($\theta_E$), wind speed, and dewpoint temperature (Figure 4). The remaining sites showed similar effects except for reduced changes in moisture with sea-breeze frontal passage. In the case of 29 March (yearday 88), the change in wind direction occurred at 1230 UTC.

Figure 4. MAWS2 meteograms for (a) 26 and (b) 29 Mar 2011. Arrow points to wind shift from east to west. Geostationary Operational Environmental Satellite (GOES) infrared surface temperatures at 1100 LST on (c) 26 and (d) 29 Mar 2011, with clouds masked white.
While at other sites the wind shift was before 1420 UTC (1020 LST), this shift was not accompanied by a jump in moisture or dip in temperature that would be associated with a sea-breeze front.

### 3.3. WRF Model simulations and acoustic sounder data

For the 26 March case, the 10-m streamlines at 1800 UTC reveal the presence of a sea breeze in the island wake (Figure 5). There is a region of divergent streamlines...
over the ocean and convergence over the west coast. The twin gyres are identified by
the bending of streamlines around the northwest and southwest corners of the island.
The sea-breeze circulation lies between the twin gyres. On 26 March, the southern
gyre prevailed and the sea breeze shifted to the north side of Mayaguez Bay.

In contrast, the 29 March onshore flow was supported by symmetrical twin gyres
(Figure 5). The winds wrapped around the island and folded into an onshore flow
centered over Mayaguez Bay. The surface winds along the coast shifted to westerly
quite early. The relationship between the sea breeze and twin gyres is conceived as
a competition between two forcings that drive the onshore flow. The Froude
number, representing the ratio between vertical stability and flow strength (Jury
et al. 2009), predicted that gyres should be present 5 days before yearday 83, but
there was no onshore flow due to the cross-island orientation of the synoptic flow
(cf. Figure 3a). The Froude number predicted that gyres should be present for 8
days after yearday 83. This was indeed the case: onshore winds near Mayaguez
were produced by the gyres and 3°C (10 km)−1 thermal gradient (Figures 4c,d)
under the easterly flow (cf. Figure 3b).

Acoustic sounder time–height cross sections for 26 March 2011 are given in
Figures 6a–c. Weak trade winds prevailed during the night and early morning up
to 0900 LST. Wind directions switched to westerly for 6 h until 1500 LST. The
sea breeze remained steady at 5 m s−1 in the 40–300-m layer through midday. As
trade winds resumed in late afternoon, speeds continued at 4 m s−1. After sunset,
the nocturnal boundary layer was reestablished and winds declined. The σ_w
identifies vertical gusts embedded in the horizontal flow. The gusts were small
(0.2 m s−1) at night but increased rapidly in the 200-m layer through midday as the
sea-breeze front passed (0.7 m s−1). Thermal mixing (0.4 m s−1) continued past
sunset and gradually declined. A feature of the acoustic sounder cross sections is
the variability of directions at the onset of the sea breeze and the sharp resumption
of trade winds after 1500 LST.

3.4. GPS-based PW measurements

The western side of Puerto Rico typically exhibits a precipitation maximum in
the afternoon because of convergence along the sea-breeze front and convection
this reason, it is interesting to quantify the moisture transport associated with sea-
breeze and gyre circulations. Using GPS to measure precipitable water is a unique
way to investigate diurnal variations in moisture because of its high temporal
resolution and insensitivity to cloud water.

Measurements taken with GPS receivers at all of the WXT-PSB measurement
sites (cf. Figure 1) reflected an increasing trend in PW (Figure 7, top). This increase
was associated with the eastward shift of the marine anticyclone, allowing tropical
moisture to spread northward (Figures 3c,d). The synoptic orientation to easterly
flow also yields a longer fetch for daytime moisture uptake from transpiring
vegetation. With the PW time series at BYSP representative of the large-scale
variations, we subtracted it from the PW measured at the western sites, producing a
residual time series (Figure 7, bottom). The western sites then reveal large diurnal
fluctuations up to 3-mm amplitude, especially after 23 March with daytime on-
shore flow. On 26 March (yearday 85), WXT-PSB3 registered the greatest increase
in PW, when thermal forcing and topographic gyres combined to produce a marked sea-breeze frontal passage as described earlier. Even the 395-m elevated station WXT-PSB5 measured large diurnal amplitude, indicating a deep sea breeze. This highlights the influence of onshore flow on the amount of water available for precipitation. Because these conditions also lead to topographic lifting, the probability of precipitation is enhanced.

Only a few studies have been carried out using GPS PW to diagnose the diurnal evolution of the boundary layer moisture (Bastin et al. 2007; Couvreux et al. 2010). The BYSP station shows close agreement to the nearby radiosonde PW, with a
mean difference near zero and an RMS of 0.3 cm (Figure 2). Comparing other GPS sites with the same sounding value gives an idea of the PW variation across the island and an indication of how representative the sounding data are (Table 3). The sites have an RMS difference of around 0.5 cm. This may be partly due to WRF not picking up the full range of variation near the surface, as it also has a large RMS for surface temperature (Table 4). The greater RMS difference of 0.7 for PW at WXT5

Table 3. Mean, standard deviation, and root-mean-square error (RMSE) GPS precipitable water (mm) differences among observations, model values at the site location, and the sounding at SJU.

<table>
<thead>
<tr>
<th>Site</th>
<th>WXT1</th>
<th>WXT2</th>
<th>WXT3</th>
<th>WXT4</th>
<th>WXT5</th>
<th>MAYZ</th>
<th>AOPR</th>
<th>PRMI</th>
<th>BYSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>WRF vs sounding</td>
<td>Mean</td>
<td>−0.06</td>
<td>−0.19</td>
<td>−0.11</td>
<td>−0.13</td>
<td>−0.30</td>
<td>−0.08</td>
<td>−0.38</td>
<td>−0.31</td>
</tr>
<tr>
<td></td>
<td>Std dev</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.51</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>0.50</td>
<td>0.53</td>
<td>0.51</td>
<td>0.51</td>
<td>0.59</td>
<td>0.50</td>
<td>0.62</td>
<td>0.49</td>
</tr>
<tr>
<td>Obs vs sounding</td>
<td>Mean</td>
<td>0.01</td>
<td>−0.17</td>
<td>−0.14</td>
<td>−0.13</td>
<td>−0.51</td>
<td>−0.20</td>
<td>−0.37</td>
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<tr>
<td></td>
<td>Std dev</td>
<td>0.59</td>
<td>0.52</td>
<td>0.46</td>
<td>0.49</td>
<td>0.54</td>
<td>0.46</td>
<td>0.39</td>
<td>0.47</td>
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<tr>
<td></td>
<td>RMSE</td>
<td>0.51</td>
<td>0.54</td>
<td>0.46</td>
<td>0.49</td>
<td>0.73</td>
<td>0.50</td>
<td>0.53</td>
<td>0.46</td>
</tr>
<tr>
<td>WRF vs observed</td>
<td>Mean</td>
<td>−0.10</td>
<td>0.11</td>
<td>0.08</td>
<td>−0.01</td>
<td>0.14</td>
<td>0.23</td>
<td>−0.00</td>
<td>−0.07</td>
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<tr>
<td></td>
<td>Std dev</td>
<td>0.56</td>
<td>0.73</td>
<td>0.77</td>
<td>0.70</td>
<td>0.62</td>
<td>0.68</td>
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<tr>
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<td>RMSE</td>
<td>0.49</td>
<td>0.72</td>
<td>0.76</td>
<td>0.67</td>
<td>0.62</td>
<td>0.68</td>
<td>0.48</td>
<td>0.64</td>
</tr>
</tbody>
</table>
is partly due to its elevation. This comparison shows that the radiosonde is not always representative of PW conditions on the western side of the island. The statistics for the WRF Model comparison with the sounding give consistent values of around 0.5 cm for most sites. The scatterplots (Figure 8) indicate that the WRF Model consistently propagates the information from the sounding throughout the model domain without much variation due to local conditions. The WRF tends to overestimate PW on the western side of the island, suggesting evapotranspiration as the process needing further attention.

### 4. Discussion and conclusions

We have described how the 4 m s\(^{-1}\) onshore flow over Mayaguez Bay is related to a 3°C (10 km\(^{-1}\) thermal gradient and twin gyres derived from trade winds wrapping around the island. Understanding convergence in the island wake is critical for rain forecasts. Our field work investigated conditions in the spring transition season, with little precipitation. This allowed investigation of moisture variability without complications of model cloud physics. High-temporal-resolution GPS PW measurements were useful in describing the diurnally changing mesoscale conditions found in western Puerto Rico.

While a few logistical difficulties were encountered, the cell modems and solar panel powered real-time systems proved to be a feasible way to obtain a focused dataset. The project also served as an educational experience for 14 students involved from Purdue University and the University of Puerto Rico, Mayaguez. The objective of the field work was to study onshore flow in western Puerto Rico and its effects on moisture. The study is unique in its implementation of real-time GPS precipitable water data communication and data processing in a field setting. We incorporated data from a network of temporary and permanent meteorological stations as well as ground-based GPS precipitable water measurements. Surface observations showed different diurnal trends in wind direction and moisture availability depending on the balance between thermally or topographically forced onshore flows, as modulated by synoptic flow angle.

The trade winds often produce twin gyres around the northwest and southwest corners of the island. During our study, sea breezes occurred mainly when the gyres were favorably oriented by a synoptic easterly flow. Onshore flows that break out soon after sunrise could be traced to more topographic forcing. WRF Model simulations were able to show interaction of gyres and sea breezes, which related to Froude number and synoptic flow angle. Diurnal variations of 2–3 cm in PW were

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**Table 4. Mean, standard deviation, and RMSE between surface observations and WRF Model values.**

<table>
<thead>
<tr>
<th>Site</th>
<th>WXT1</th>
<th>WXT2</th>
<th>WXT3</th>
<th>WXT5</th>
<th>MAWS2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp (°C)</td>
<td>0.56</td>
<td>0.73</td>
<td>0.08</td>
<td>0.92</td>
<td>0.47</td>
</tr>
<tr>
<td>Std dev</td>
<td>2.35</td>
<td>2.49</td>
<td>2.46</td>
<td>1.62</td>
<td>2.60</td>
</tr>
<tr>
<td>RMSE</td>
<td>2.40</td>
<td>2.59</td>
<td>2.46</td>
<td>1.87</td>
<td>2.64</td>
</tr>
<tr>
<td>Dewpoint temp (°C)</td>
<td>1.11</td>
<td>-0.03</td>
<td>0.29</td>
<td>0.48</td>
<td>0.52</td>
</tr>
<tr>
<td>Std dev</td>
<td>1.08</td>
<td>1.58</td>
<td>1.33</td>
<td>1.61</td>
<td>1.36</td>
</tr>
<tr>
<td>RMSE</td>
<td>1.55</td>
<td>1.58</td>
<td>1.36</td>
<td>1.68</td>
<td>1.46</td>
</tr>
</tbody>
</table>
Figure 8. Scatterplots of precipitable water comparing (a) GPS at each site location and SJU sounding, (b) WRF and sounding, and (c) WRF and GPS. Ideal linear regression is shown.
noted when gyre formation coincided with peak diurnal heating. The WRF Model did not reproduce the diurnal cycling of PW during periods of return flow, even when run at 1-km resolution. It preserved the moisture characteristics of the original sounding throughout the model domain. So there is potential for improvement of local rainfall forecast models with the assimilation of GPS PW.

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References


