JP1.7 **ON THE VALIDATION OF THE SIMULATION OF EARLY SEASON PRECIPITATION IN THE ISLAND OF PUERTO RICO USING A MESOSCALE ATMOSPHERIC MODEL**

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1. INTRODUCTION

The weather patterns over the tropical islands of the Caribbean are mostly associated with global scale oscillations, synoptic-scale easterly trade winds, orographic effects, ocean-induced circulations, and convective-scale instabilities related to intense surface heating (Malmgren et al., 1998; Taylor et al., 2002). There is a need to improve our understanding of local and synoptic scales contributions on precipitation for practical or scientific purposes. A better understanding and improved prediction capability of the daily and monthly variability of precipitation may also help to assess possible impacts of global climate changes in this region. Recent research has revealed that global climate changes due to increases in greenhouse gases and local land use may be influencing the Caribbean climate (e.g. Velázquez-Lozada et al., 2006).

Recent efforts have been made to understand the regional climate change over the Caribbean region and its two-way coupling to the global climate (Enfield and Alfaro 1999; Gianinni et al., 2000; Taylor et al., 2002). Most of the reported studies relied upon coarse-resolution data sets and general circulation models (GCMs) of the atmosphere and, in some cases, of the oceans (Polcher and Laval 1994; Blake et al., 1998; Chen and Taylor 2002). A first step towards the goal of understanding regional climate change over the Caribbean is to investigate the ability of a mesoscale atmospheric model to reproduce the spatial and temporal pattern of different atmospheric variables in the region of interest. The work presented in this paper focuses on the goal of predicting monthly precipitation patterns of the Caribbean island of Puerto Rico during the month of April which is located in the Caribbean Early Rainfall Season.

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Because of its coarse resolution, GCM outputs and standard archived global observational atmospheric and ocean data needs to be downscaled to the desired finer horizontal resolution using semi-empirical (Kidson and Thompson 1998) or numerical approaches which use mesoscale atmospheric models (e.g. Kao and Bossert 1992; Pielke et al., 1999). A method that blends downscaled GCM output and/or large-scale observed data with surface and upper-air data has been developed into mesoscale atmospheric models (Walko et al., 1995). In the present work, the ability of a mesoscale atmospheric model to predict precipitation events in the tropical islands of the Caribbean induced by both local convective and synoptic scales forcing is tested. The model uses coarse resolution archived atmospheric and ocean data as input.

An analysis of the climatology of Puerto Rico indicates that two distinct seasons characterize the yearly precipitation pattern in the island, the early and late rainfall seasons, ERS and LRS respectively (Malgren and Winter 1999; Daly et al., 2003), separated by what is referred to as the 'mid-summer drought'. The rest of the Caribbean also follows this bimodal trend (Chen and Taylor 2002). Figure 1 shows the bimodal nature of the Puerto Rico rainfall by presenting the 30-year precipitation climatology and the 1993 and 1998 monthly precipitation totals recorded by the 15 cooperative stations selected for this study. The ERS covers the first 6 months of the year (from January through June), with its precipitation peak in May. The LRS begins after the summer months and peaks in October. Included in the LRS is the hurricane season, occurring between June and November. The precipitation maximum in October occurs mostly due to enhanced low-level convergence to the east of the Lesser Antilles islands, low vertical wind shear, high sea surface temperatures, and greater amounts of deep layer moisture across the tropical North Atlantic, which is advected to the Caribbean area by the easterly trade winds (Taylor et al., 2002).

Malmgren and Winter (1999) identified climate zones in Puerto Rico using a principal component analysis and an artificial neural network. These authors analyzed climate data, seasonal averages of precipitation, and maximum, mean, and minimum temperatures for the period 1960-90, using data from 18 stations located over the island to determine the existence of climate zones in Puerto Rico. The 18 stations selected for the study presented in Malmgren and Winter (1999) are part of a network of 78 cooperative stations located through the island. Daly et al., (2003) mapped the mean 1963-95 precipitation in April for Puerto Rico using cooperative station data, there the authors found a strong correlation between the climatologic Puerto Rico precipitation with the island's topography. The 15 stations used in the study presented in this paper were selected from the same network (please refer to Table 1 for information on the stations). As will be explain later in the paper, the stations were selected on the basis of containing consistent information for the period of interest and of representing the different climatic zones suggested for Puerto Rico (Malmgren and Winter 1999).

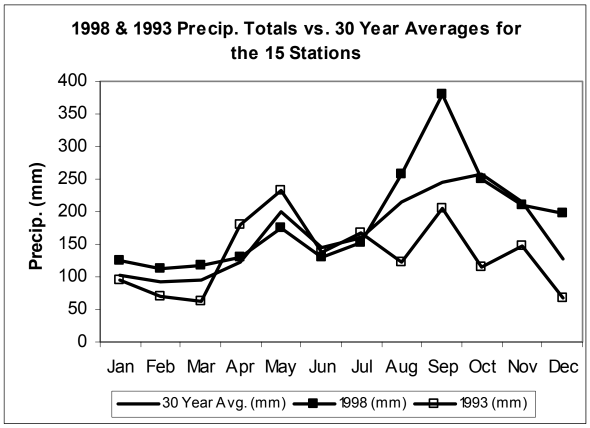

Figure 1 1993 and 1998 monthly precipitation totals and 30-year precipitation averages for the 15 cooperative stations distributed through out Puerto Rico

The results presented here were obtained by carrying out month-long simulations for the month of April with the purpose of analyzing the regional model performance on the prediction of precipitation events over Puerto Rico during the Caribbean early rainfall season. April 1998 was selected as the basic case to test the regional model precipitation prediction because it was the year when record high temperatures were recorded in the island, and it was an El Niño+1 year. Analysis of the Caribbean early rainfall season data reveals a teleconnection accounting for almost half of the season's precipitation variability, resulting in a wetter period one to two seasons after the Equatorial Pacific anomalies referred to as El Niño, which are strongly linked to positive spring North Tropical Atlantic sea surface temperature anomalies (Chen and Taylor, 2002). Because the April 1998 precipitation total was close to the climatological value, additional simulations were performed for the month of April 1993, which recorded higher precipitation totals during the ERS.

2. MODEL DESCRIPTION AND CONFIGURATION

The Regional Atmospheric Modeling System (RAMS) is a highly versatile numerical code developed for simulating and forecasting meteorological phenomena, RAMS v4.3 was used in this research (Pielke et al., 1992; Cotton et al., 2003). The research was conducted with two grids. Grid 1 covers the Caribbean basin (~83-59 W and 25-12 N) at a horizontal resolution of 20km (not shown). Grid 2, which is nested within Grid 1, covers the island of Puerto Rico at 5km horizontal resolution (see Figure 2). For the vertical coordinate, both grids have the same specification. A grid spacing of 100m was used near the surface, stretched at a constant ratio of 1.1 until ΔZ reached 1000m. The model depth is 22.83 km with 40 vertical layers. Initial and time-dependant lateral boundary conditions were given by the NCEP reanalysis fields (Kalnay et al., 1996).

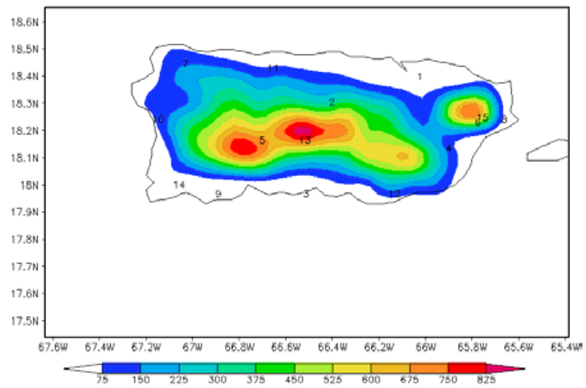

Figure 2 Model topography for Grid 2 (contour inc. 75m). The stations selected for this study are presented at their locations and identified by the number assigned by the authors (see Table 1)

Table 1: Station identification and location

#	ID	Lat	Lon	Elev (m)
1	San Juan	18 25	66 00	2.74
2	Morovis	18 19	66 24	182.92
3	Ponce	18 01	66 31	21.34
4	San Lorenzo	18 08	65 58	140.24
5	Adjuntas	18 10	66 43	557.92
6	Pico del Este	18 16	65 45	1051.21
7	Isabela Substation	18 28	67 04	128.04
8	Roosevelt Roads	18 15	65 37	11.29
9	Ensenada	17 58	66 55	3.04
10	Mayagüez	18 15	67 09	18.29
11	Arecibo	18 27	66 40	3.04
12	Guayama	17 58	66 07	41.76
13	Toro Negro Forest	18 10	66 30	868.29
14	Lajas Substation	18 02	67 03	27.43
15	Paraiso	18 16	65 43	10.97

3. OBSERVATIONS

The two main observational resources used for this study consist of a Cooperative station network and the environmental setting of the two largest precipitation events, identified by the station data, as depicted by synoptic scale fields derived from NCEP data.

3.1 *Cooperative Station Data*

The daily and monthly precipitation totals from a network of stations located throughout Puerto Rico were obtained from the Southeast Regional Climate Center and the Puerto Rico and U. S. Virgin Islands Climate Office. From the network of over 60 stations that collected data for 1998, 15 stations were selected for the analysis on the basis of the completeness of the data recorded for April 1998 and station location. These 15 stations are located along the coastline and in the interior of the island and represent all the climatic zones suggested by Malmgren and Winter (1999), see Figure 2 and Table 1.

Figure 3 shows the daily precipitation totals for April 1998 and 1993 of the 15 COOP stations. From this figure, several important precipitation events could be identified during the month of April 1998 based on the daily precipitation total. The two main precipitation events, however, occurred during the 2nd (167.56 mm) and between the 16th (278.38 mm) and 17th (183.38 mm) of the month. The later one is considered as the most dominant event. Stations numbers 1, 7, 8 and 11, located along the north coast, and stations 6 and 15, located on El Yunque, showed significant precipitation for 16 April 1998. The westernmost stations recorded an average of 30 mm for that day, while the east coast and central mountain stations had an average of 48 mm, showing that the event was island-wide. The second dominant event occurred earlier in the month and at fewer stations. Seven stations showed precipitation for 2 April 1998. Stations 3, 5 and 13 (central-south) showed an average of 28 mm and station 6 (El Yunque vicinity) received 17 mm of rain.

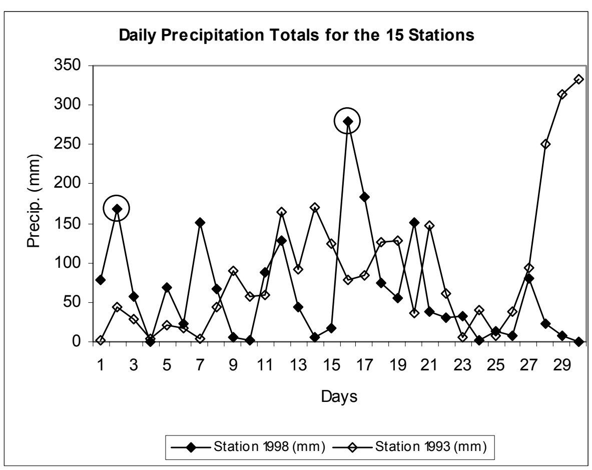

Figure 3 Daily precipitation totals recorded by the 15 stations selected for the study for April 1998 and April 1993

On an individual station basis the highest recorded accumulated precipitation for April 1998 was at Toro Negro Forest in the Central Mountains (station 13) which recorded 319.79 mm of rain. Other prominent observations were at station 5 in Adjuntas (195.58 mm), station 6 in Pico del Este (260.35 mm), and station 15 in Paraiso (El Yunque, 180.85 mm). The lowest accumulated precipitation was recorded at station 9 (45.47 mm), the next driest being station 12 (47.24 mm), located in the southern locations of Ensenada and Guayama, respectively. The highest variability during the month occurred at stations 4, 6, and 15, which are located in the El Yunque area.

3.2 *Synoptic Setting of Main Precipitation Events for April 1998*

It is necessary to analyze the synoptic events that contributed to the rainfall events of the test cases considered. The 12 UTC 2 April 1998 synoptic pattern shows a surface low east of the Caribbean islands, with a weak temperature gradient prevailing over the region at this level (Figure 6, top-left). The 850mb map (Figure 6, mid-left) shows a cyclonic vortex to the northeast of Puerto Rico, with cold air advection approaching the island of Puerto Rico from the north combined with a southerly warm and moist air flow coming from the southern region of the Caribbean. A very strong 300mb low pressure sits to the northeast of the Caribbean, almost in the same position as the low level vortices, with a well-defined trough (Figure 6, bottom-left). This indicated the likely presence of a weak surface cold front over, or slightly south of, Puerto Rico, which enhanced convergence at the low levels, and further enhanced by the large-scale negatively tilted trough to the northeast of the Caribbean. The 16 April 1998 situation is quite different. Sea-level pressure plots at 06, 12, and 18 UTC (Figure 7) show a weak tropical wave passing right over the island of Puerto Rico, moving slightly northward. This setting is also present as an undulation of the 1540m contour line at the 850mb level (not shown). The tropical wave was interacting with an upper level trough, enhancing air parcel instability over the area. This is the day of the month when the most precipitation was observed over the island of Puerto Rico (~278mm of rain, see Figure 3).

4. Model Results

4.1 *April 1998*

The model was initialized on 27 March 00UTC and integrated for 35 days until 01 May 00UTC. The spatial distribution of the accumulated total precipitation for April 1998 is shown in Figure 4, which shows the topographic influence on the precipitation pattern. The model was able to capture the general regional character of the precipitation identified by the 15 stations. The general pattern is for higher precipitation over the Central Mountains and El Yunque, followed by the northern and western coastlines, and finally the south, which is the driest part of the island climatologically. This pattern is in agreement with the precipitation mapping performed by Daly et al., (2003) where the rate of increase of precipitation with elevation was reported, approximately 140% of the average rainfall per kilometer of elevation.

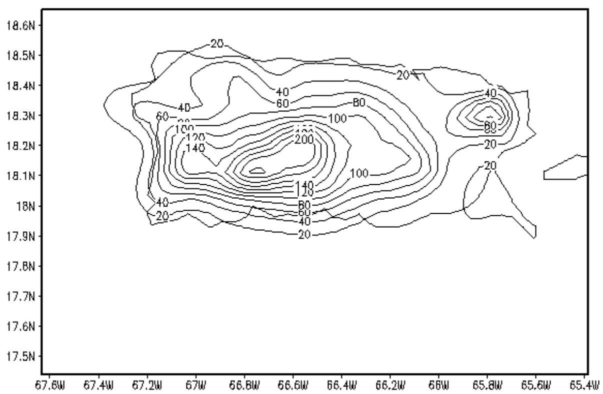

Figure 4 Model accumulated total precipitation (mm) for April 1998 (contour inc. 20 mm)

Table 2 shows a comparison between the monthly-accumulated precipitation observed by the 15 stations selected for the study and the model results for the grid cell closest to each station. It can be seen that the model predictions were more accurate over the Central Mountains and El Yunque vicinity. The highest simulated precipitation total was at station 6, near Pico del Este, with 266 mm of rainfall. It was also the most accurate, departing from the station by 2.1%. The second most accurate point was located near the San Lorenzo station (number 4) with an absolute error of 7.3% and 108 mm of simulated rainfall. The model was able to perform satisfactorily in general in the four climate zones existing within the domain as identified by Malmgren and Winter (1999).

The point near the San Juan station, located in the northeast coast, was the least accurate (under predicting by 82%). The reasons that may have contributed to this under prediction are that at the current configuration and horizontal resolution, the model might not be capturing the complexity of the San Juan Metropolitan Area, the largest urban center of the island and one that generates a strong Urban Heat Island with its subsequent mesoscale and local circulations (González et al., 2005; Velazquez-Lozada et al., 2006). However, a closer look at the difference between the COOP stations and the simulation results (Figure 5), shows that most of the error for the majority of the stations across the island occurs as the result of an under prediction of the 16 April 1998 rain event, the strongest of the month. We assume that a better replication of the large-scale fields across the Caribbean area during that day should have yielded better overall monthly results.

The model was able to replicate the first major precipitation event as it reproduced the same synoptic features seen in the observations (Figure 6). For the case of 16 April 1998, the model did not reproduce the situation described in section 3.2. The tropical wave crossing over Puerto Rico is not seen in the model results for the same time periods (Figure 7), although the upper air pattern (i.e. the 300mb trough) is shown clearly by the model. This is likely the reason for the under prediction of the modeled precipitation when compared with the amount recorded by the COOP stations for that particular day.

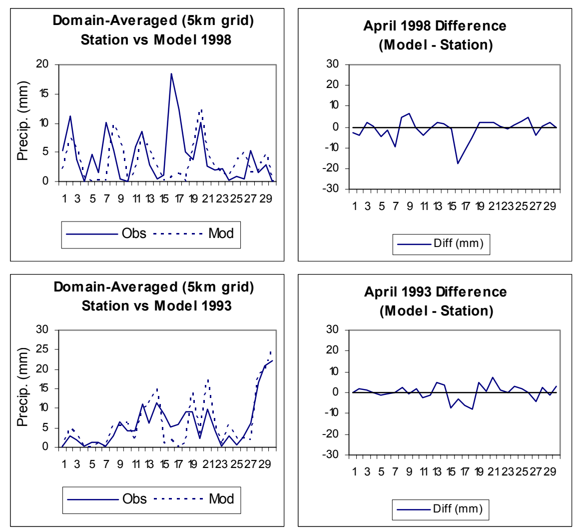

Figure 5 Station and model daily precipitation, averaged over the 15 locations shown in Figure 2. Also presented is the difference between the model and the stations. Top two panels present the information for April 1998, bottom panels for April 1993

4.2 *April 1993*

To investigate the ability of the mesoscale model to predict precipitation in Puerto Rico during the Caribbean early rainfall season, one additional simulation was conducted for the month of April 1993. A comparison of the results for April 1993 and its corresponding stations values is presented in Table 2 and Figure 5.

Here it is clearly seen that for April 1993 the model produced the same spatial pattern of high precipitation totals in areas of elevated terrain, and relatively low precipitation in the southern coastal plain. These results agree with the observed accumulated totals recorded by the station network. The error pattern, although, was strikingly similar in its spatial distribution with the errors calculated for the April 1998 case. It can be noticed that the 1993 case did not present a major precipitation event as the 1998 case, and that the daily pattern was more stable for April 1993 than for April 1998. This resulted in more accurate daily precipitation predictions for 1993, which reinforces the hypothesis of the mesoscale model performing better for locally produced precipitation, induced primordially by orographic lifting and differential heating, than for large-scale synoptic induced precipitation events.

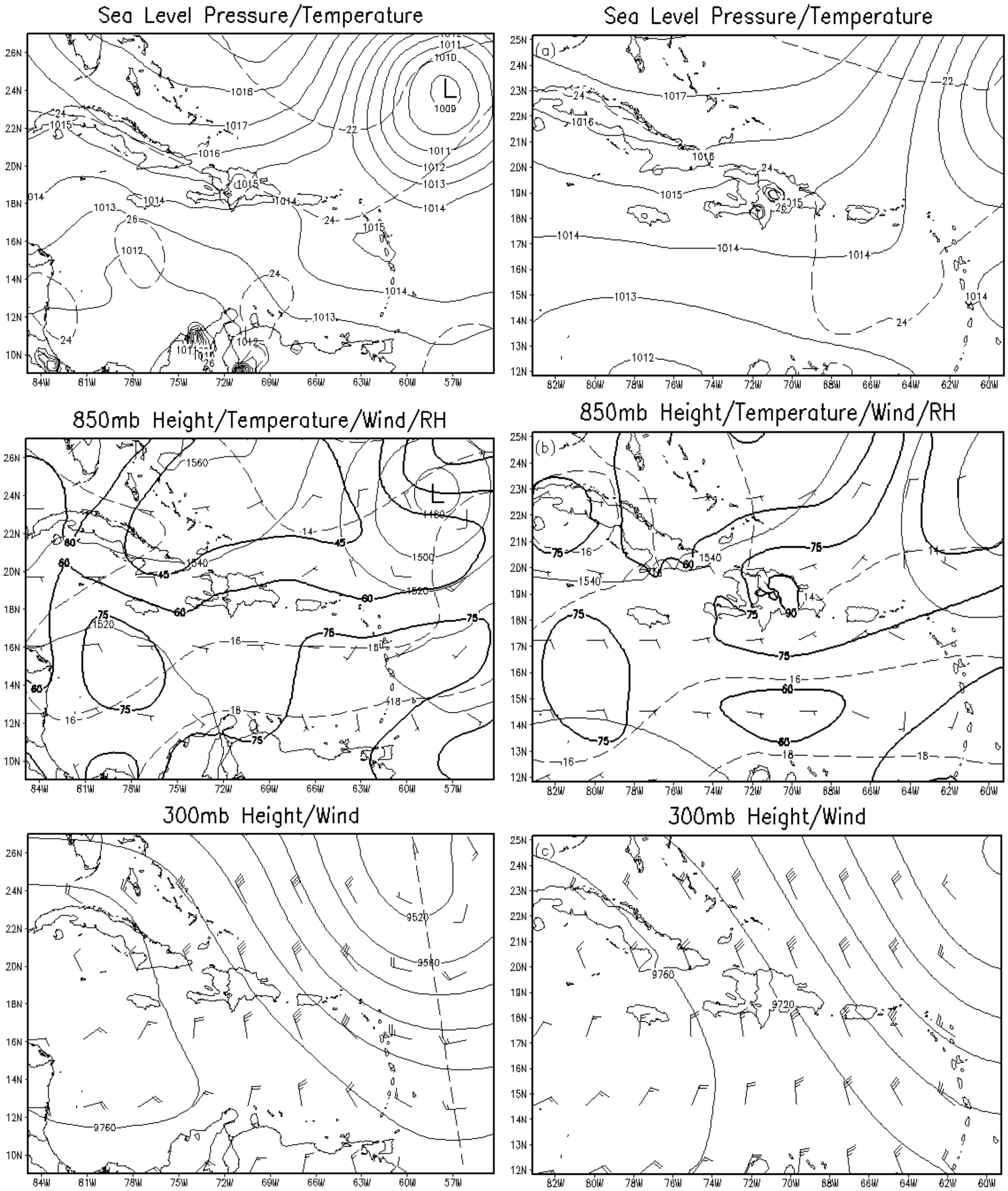

Figure 6 Comparison of synoptic (left panels) and model simulated (right panels) surface and upper-air analyses for 1200 UTC 02 April 1998. (Top row) Sea-level pressure (solid lines) and temperature (dashed lines), contoured every 1mb and 2ºC respectively. (Mid row) 850mb analysis of geopotential height (solid) contoured every 20 m, temperature (dashed) every 2 ºC, and relative humidity (solid-thick) in 15% intervals. (Bottom row) 300mb analysis with geopotential height contoured every 40 m; the dashed line indicates the high-level trough axis

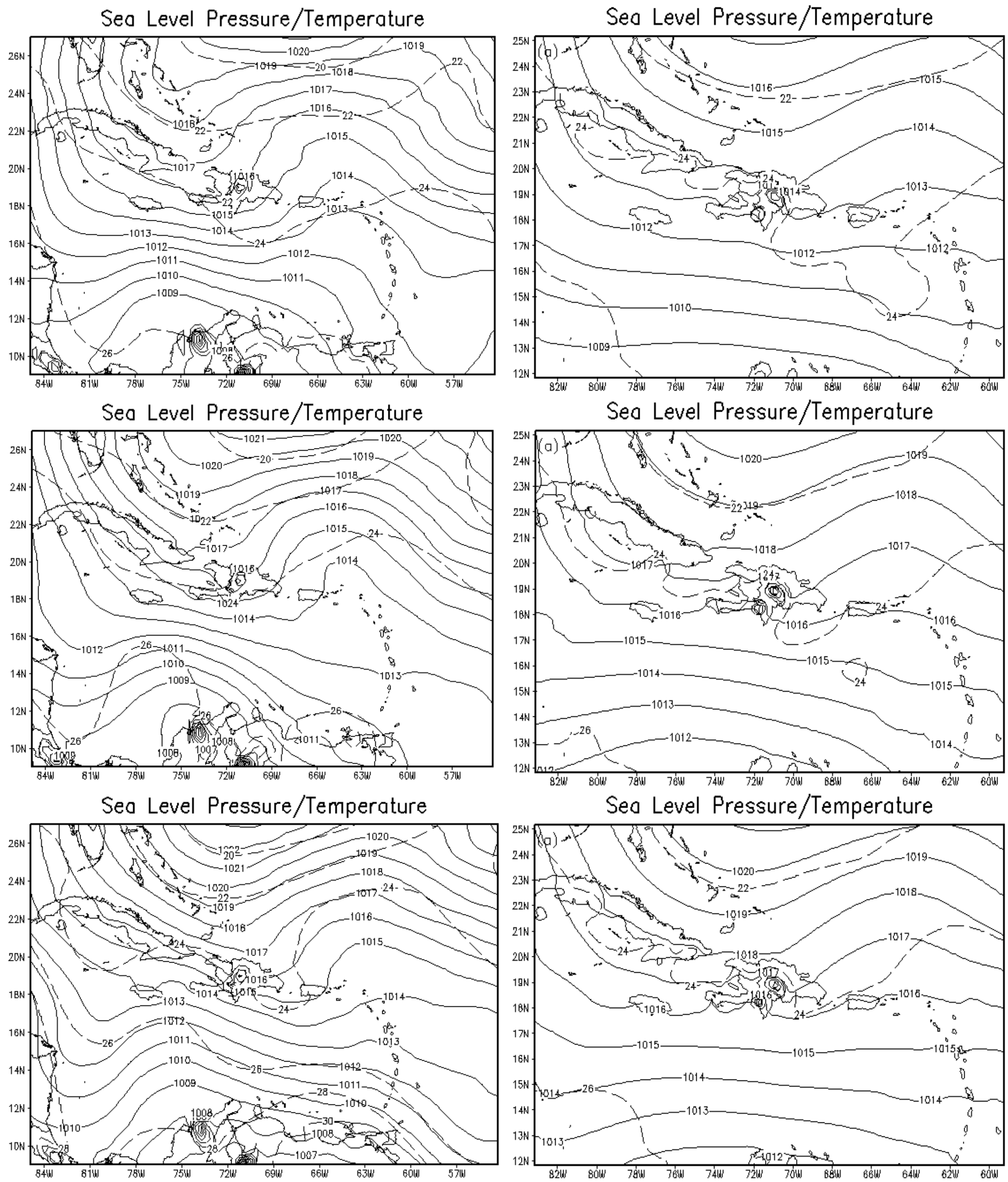

Figure 7 Comparison of synoptic (left panels) and model simulated (right panels) of surface analyses for 16 April 1998 at (top row) 06 UTC, (mid row) 12 UTC, and (bottom row) 18 UTC. Sea-level pressure (solid lines) and temperature (dashed lines) are contoured every 1mb and 2ºC respectively

Table 2: Comparison of station data vs. model results for April 1998 and April 1993

#	Location	April 1998			April 1993		
		Station (mm)	Model (mm)	Error %	Station (mm)	Model (mm)	Error %
1	San Juan	105.16	19	-81.9	166.37	12.49	-92.4
2	Morovis	92.46	113	+22.2	406.14	249.83	-38.4
3	Ponce	74.17	55	-25.8	58.67	58.83	+0.2
4	San Lorenzo	116.59	108	-7.3	146.55	123.42	-15.7
5	Adjuntas	195.58	80	-59.0	234.95	146.66	-37.5
6	Pico del Este	260.35	266	+2.1	277.11	288.19	4.0
7	Isabela Substation	54.36	40	-26.4	227.58	111.95	-50.8
8	Roosevelt Roads	132.08	107	-18.9	86.86	65.14	-25.0
9	Ensenada	45.47	33	-27.4	16.25	13.88	-14.6
10	Mayagüez	88.9	28	-68.5	153.16	67.55	-55.8
11	Arecibo	134.41	76	-44.6	269.49	124.48	-53.8
12	Guayama	47.24	30	-36.4	23.87	26.47	10.8
13	Toro Negro Forest	319.79	246	-23.0	441.70	372.99	-15.5
14	Lajas Substation	99.06	55	-44.4	76.2	36.86	-51.6
15	Paraiso	180.85	142	-21.4	244.85	220.66	-9.8

5. SUMMARY AND CONCLUSIONS

A regional atmospheric model was used as the main research tool to simulate the monthly precipitation pattern of the island of Puerto Rico during the Caribbean early rainfall season. Results from the RAMS model were validated with the recorded precipitation values from a network of cooperative stations located throughout the island. The station data identified two dominant precipitation events during April 1998, namely on 2 and 16 April 1998. The same stations were used to collect the precipitation information for April 1993. The stations also show that the local topography has a strong influence in the observed monthly precipitation pattern across the island. The regional atmospheric model reproduced, to varying degrees of success, the total amounts of rainfall observed for most of the COOP stations for April 1998 and April 1993. The precipitation for the San Juan Metropolitan Area was heavily under predicted, maybe due in part to the lack of ability of the model to capture the complex urban landscape and coastal moisture effects, a phenomena that is currently being investigated by this research group. The model also showed satisfactory results in capturing the precipitation event that occurred on 2 April 1998. However, it could not replicate the second and strongest event in the same month (16 April 1998). This likely caused the majority of simulated precipitation errors during the month for some stations.

The model-resolved precipitation pattern over Puerto Rico appears to be influenced by the island topography and presence of urban areas. This tendency is due primarily to orographic lifting of the easterly flow. As the topography becomes steeper, the updrafts become stronger and help induce a strong convection. The end result is more rainfall occurrence, as in the case over the Central Mountains and El Yunque. In the case of the urban areas, the model may be under predicting enhance convection due to increase in sensible heating in these areas. This work offered a look at the difficulties of predicting precipitation, particularly over a tropical island with complex terrain and varying land cover/land use.

6. ACKNOWLEDGEMENTS

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