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Front Cover: Close-up view of a patch-reef coral head in Grahams Harbor, north of Dump Reef. As shown here, Caribbean shallow-water reefs have declined since the mid-1980s and are now largely overgrown by fleshy green macroalgae and a variety of encrusting organisms. See Curran et al., "Shallow-water reefs in transition," this volume, p. 13. Photograph by Ron Lewis.

Back Cover: Dr. A. Conrad Neumann, University of North Carolina, Chapel Hill, NC, Keynote Speaker for the 11th Symposium and author of "Cement loading: A carbonate retrospective," this volume, p. xii. Photograph by Mark Boardman.

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A 2001 WEATHER SUMMARY FOR SAN SALVADOR, BAHAMAS: IMPLICATIONS AND APPLICATIONS FOR THE GEOSCIENCES

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ABSTRACT

The purpose of this research was to establish a meteorological observation network that can provide climatic data for geosciences research on San Salvador. Meteorological observations collected on San Salvador in 2001 indicated that the mean annual temperature was warmer than normal. Further analysis indicated that the warmer-than-normal temperatures were a result of high monthly minimum temperatures. In regard to precipitation, 2001 was an exceptionally wet year due to a series of frontal storms in April and May. Monthly atmospheric pressure statistics follow the seasonal temperature cycle, with high pressure in winter and low pressure in summer. Analysis of individual extreme events for 2001 indicate that frontal storms caused the greatest daily rainfalls, low-level warm advection created by southerly winds created the highest daily maximum temperatures, and Hurricane Michelle produced the lowest minimum daily atmospheric pressure.

The two greatest implications of the 2001 weather summary for geoscientists are the seasonal and spatial variability on San Salvador Geoscientists should not assume that an extreme hydrologic event is created by a hurricane or tropical system. In regard to spatial variability, it is improper to assume spatial homogeneity in rainfall coverage on San Salvador.

INTRODUCTION

The interaction between climate and geological processes has been well documented in the geosciences. Many geologic processes, particularly those near the surface, are related to the cycling of water between the atmosphere and the Earth's surface. As geologists and geomorphologists research earth surface processes, they usually rely upon other researchers for climatic data. On small, isolated islands, this reliance upon other sources for climatic data becomes problematic. Many small islands do not have the resources to support a stable, accurate meteorological observation network (MON). In addition, when climatic observations are recorded, they are only recorded at one location on the island, creating little knowledge of spatial variation in precipitation across the landscape.

The purpose of this research was to establish a MON that can provide climatic data to be used for geosciences research on San Salvador. The project will represent the first MON on San Salvador with previous measurements of precipitation only reported for a single location, the Cockburn Town Airport. In particular, the San Salvador MON was designed to assess spatial variation in precipitation processes and island hydrology and assist in assessment of surface geologic processes across the island. seasonal and spatial variability on San Salvador.

METHODOLOGY

The San Salvador MON was established in January 2001. The hub of the MON is a Campbell Scientific Metdata 1 weather station located on the campus of the GRC. The Metdata 1 has instruments that measure atmospheric pressure, air temperature, dew point, rainfall, and wind speed/direction. The observations are stored on a data logger within the station housing every fifteen minutes, hour, and twenty-four hours. In addition, the times of the daily maximum and minimum of each of these variables are recorded on the data logger. The data logger is connected by a wire to a computer in the office of Mr. Vince Voegli, Executive Director, GRC, where data is downloaded monthly. Beyond the Metdata 1 weather station, up to four Davis tipping-bucket rain gages were placed at various locations around the island during 2001. These rain gages were located at Hog Cay, Grotto Beach, Ocean House, and Six Pack Pond (Figure 1). An event logger attached to the Davis tipping- bucket rain gages recorded the time at which 0.2 mm of rain fell into the gage, causing a small bucket to tip and send an electronic signal to the logger. Data was downloaded via a laptop computer from the event loggers every six months.

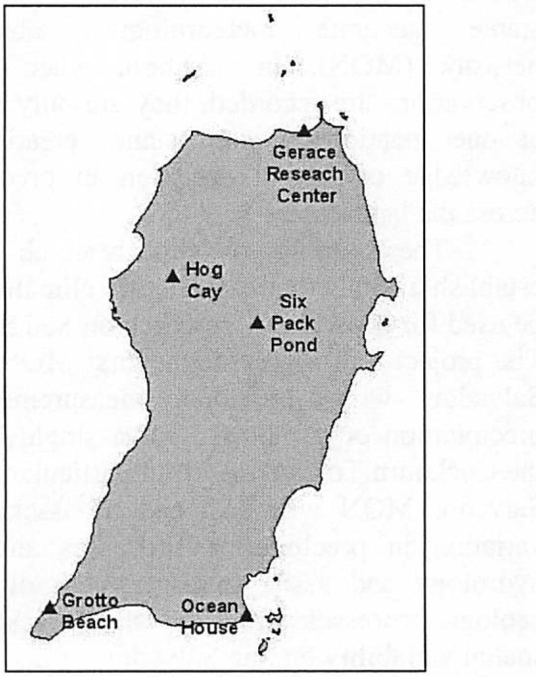

Figure 1. Location of weather station and rain gages on San Salvador, Bahamas.

In order to create a 2001 climatic summary for San Salvador, the meteorological observations collected by the Metdata 1 station at the GRC were aggregated into average, maximum, and minimum values for each month. The 2001 monthly values were then represented as bar graphs and compared to the climatic normals reported by Shaklee (1996). This comparison allows for the determination of 2001 as a 'normal' or 'anomalous' climatic year on San Salvador.

Beyond monthly averages, meteorological observations were ranked to determine significant events. The significant events represent the five highest or lowest daily values for rainfall, maximum and minimum temperature, maximum wind speed, and maximum and minimum atmospheric pressure in 2001. Daily synoptic weather charts for North America were then examined to determine the weather system that created the significant event, providing some insight into the climatology of extreme events on San Salvador.

RESULTS AND DISCUSSION

Monthly Climatology

Temperature

Comparison of the 2001 monthly average, maximum, and minimum temperature values to the climate normals indicates a year slightly warmer than usual (Figure 2). Average values for February, March, June, September, October, and December were warmer than Shaklee's (1996) reported climatic normals. The only month that was lower than the climatic normal was May. However, it should be noted that observations were not recorded for 11 days in May due to instrument malfunction. The missing days may be the reason for the lower than average temperatures.

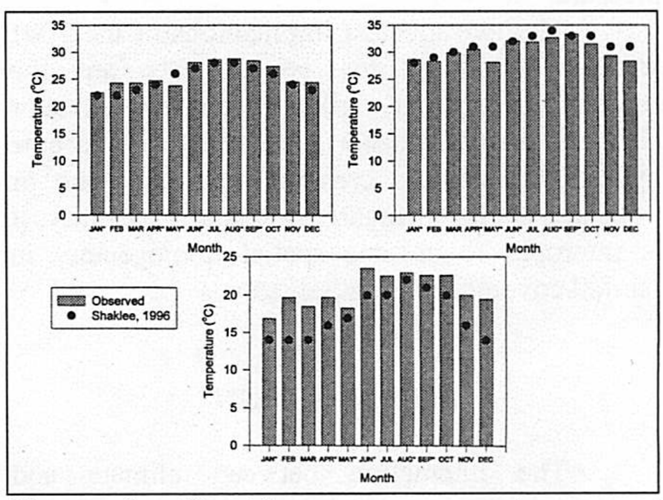

Figure 2. Monthly average, maximum and minimum temperatures for 2001 (bars) and climatic normals (circles) for San Salvador. Asterisks indicate months with missing data.

Some days were also missing from other months: January (7 days), April (10 days), June (12 days), August (10 days), and September (3 days). However, it appears that these missing values did not have a significant effect upon the monthly average temperatures since they were similar to the reported normal values.

The higher than normal monthly average temperature values appear to be a result of warmer than normal minimum temperatures. Every month of 2001 had monthly minimum temperatures warmer than the climatic minimum temperatures. In some cases, the 2001 monthly minimum temperatures were 3 to 5° C warmer than the climatic normal. All 2001 monthly maximum temperatures, except for two, were lower than the climate normal. However, it is unlikely that these low maximum temperatures had a large impact on the monthly temperatures based on relatively small differences from the normals.

Two factors may be attributed to creating the high monthly minimum and average temperatures. The first is nightly cloud cover. 2001 was an exceptionally wet year, with much frontal activity causing cloud cover and rain in spring and winter. Such cloud cover can act as a thermal blanket, holding long-wave radiation close to the Earth's surface and increasing nightly low temperatures. Secondly, an instrumental bias may have caused the high monthly minimum temperature. The instruments used for this study may have been located over a different land surface or closer to the coast as compared to the instruments used by the Bahamian Meteorology Department (BMD) and summarized by Shaklee (1996). In particular, the GRC weather station was located on a grass surface while the BMD's observation site was most likely on concrete at the airport. Due to the thermal properties of concrete as compared to grass, a concrete surface will lose heat faster at night and result in a lower nightly minimum temperature.

In addition, the position of the GRC weather station is much closer to the coast as compared to the airport. Since water acts as a heat sink during the night, there is a greater probability of warm air advection from the coast to the GRC as compared to the airport, which would elevate nightly minimum temperatures. The combination of the cloud cover, land surface type and proximity to the coast can all combine to cause the warm monthly minimum temperatures. Long term monitoring of monthly minimum temperatures at the GRC will allow for a determination if the GRC weather station can be directly compared to BMD records or whether correction factors need to be applied.

Rainfall

San Salvador had a relatively wet year in 2001: 1124 mm as compared to the climate normal of 1007 mm. This above-normal annual total was created by very high rainfall totals in April, May (despite missing daily observations) and in November. April experienced 175.5 mm of rain, 398% of normal, May had 251.4 mm, 273% of normal, and November had 200.4 mm, 182% of normal (Figure 3). The months of June, August and September were below normal, but were missing daily rainfall data. Analysis of the other four rain gages across the island indicate that, if daily rainfall totals at the GRC were similar to these four gages, the three months with missing data would have been greater than average.

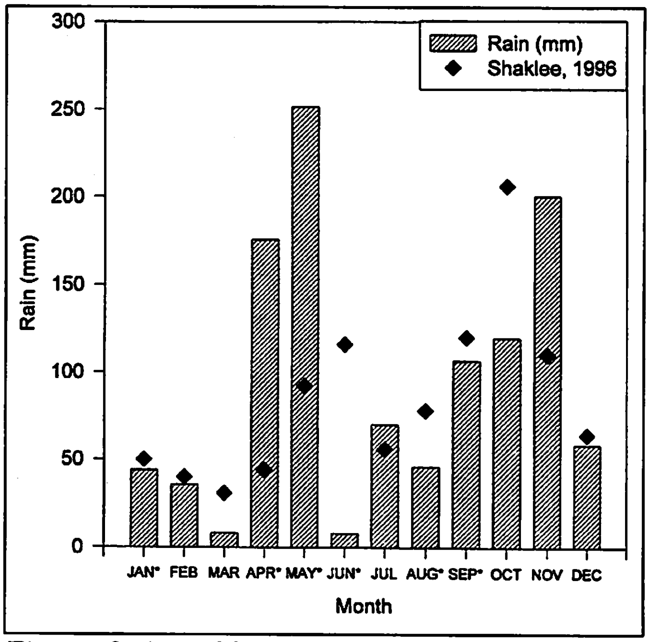

Figure 3. Monthly total rainfall (bar) for 2001 and climatic normal monthly total rainfall (diamond) on San Salvador. Asterisks indicate months with missing data.

Despite the very high rain values for April, May, and November, the months of March and October were well below normal in 2001.

The large amounts of rainfall in April, May, and June were created by a high frequency of fronts traveling from North America across the Straits of Florida towards San Salvador. By the time these fronts had reached San Salvador, the North American air mass had been modified enough by the warm, shallow waters of the Straits and the Bahamas Bank to become stationary. This modification of the air mass caused the associated front to increase its residence time over San Salvador and increased the total amount of rain that fell over the island. The above normal rainfall in November was in part created by a late hurricane, Michelle, which dropped 123 mm of rain on San Salvador November 1-5.

Wind Speed and Direction

The recorded monthly average wind speeds were below normal for all of 2001 (Figure 4). The only months for which the monthly average speeds were close to normal were May and November. In both of these months, extreme wind events existed (fronts in May and a hurricane in November) that increased the overall average monthly wind speed.

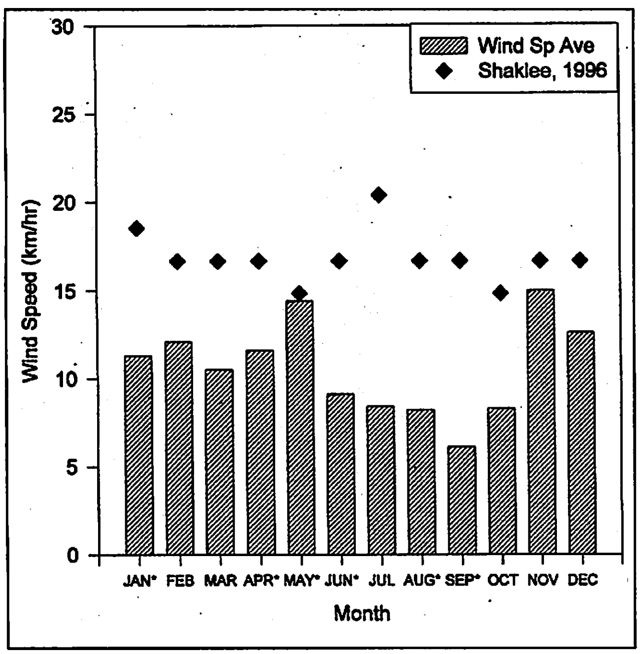

Figure 4. Monthly average wind speed for 2001 and climatic normal monthly wind speed on San Salvador. Asterisks indicate months with missing data

The low confidence in the accuracy of 2001 wind observations at the GRC suggests that this data should not be used in the analysis. The authors intend to correct the inaccuracies of current instrument configuration by raising the anemometer to a higher elevation at the GRC, perhaps to 10 m above the ground. The authors believe the below-average wind speeds for the entire year can be attributed to instrumentation error, rather than to a meteorological process. Specifically, the height of the anemometer was not sufficient to avoid wind interference from buildings on the GRC campus. Monthly mean wind direction values also support this hypothesis. In general, monthly mean wind vectors included a greater frequency of southeasterly winds as compared to the climatic normals (Table 1). Observations by a student indicated that the wind vane on the Metdata 1 station did not accurately correspond to west, northwesterly winds.

Month	2001 Mean Direction	Climatology Direction
J	SSE	NNE
F	ESE	NNE
M	SSW	SSE
A	ESE	NNE
M	ENE	SSE
J	ESE	SSE
J	SSE	SSE
A	ESE	SSE
S	SSE	E
O	ESE	NNE
N	ESE	NNE
D	ESE	NNE

Table 1. Monthly wind direction frequency for 2001 and climatic normal wind direction frequency on San Salvador.

Atmospheric Pressure

The authors could not find published climatic normals for atmospheric pressure on San Salvador. However, a discussion of broad seasonal patterns in observed atmospheric pressure for 2002 can still be provided. As expected by the seasonal temperature regime (cool fall and winter followed by warm spring and summer) of San Salvador, atmospheric pressure reaches it highest monthly average value in January and decreases through August (Figure 5). As temperature begins to decrease in September, the atmospheric pressure begins to rise from September through December. The only

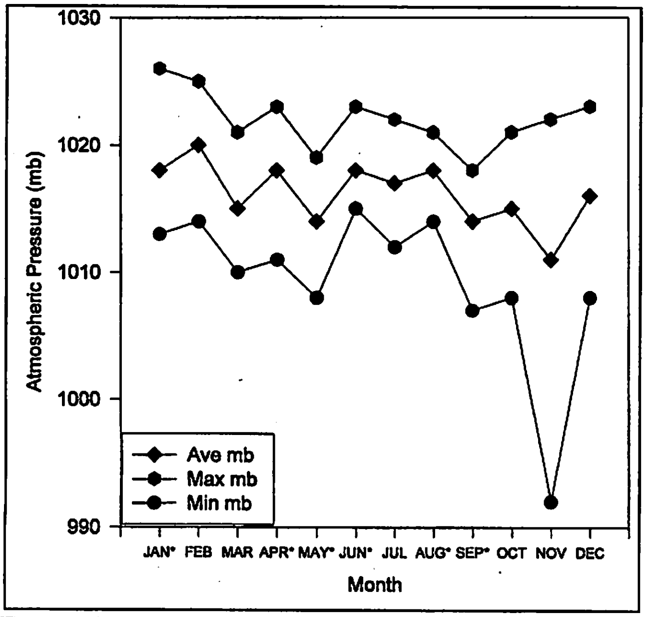

Figure 5. Monthly average, maximum, and minimum atmospheric pressure for San Salvador 2001. Asterisks indicate months with missing data.

significant deviation from this broad seasonal pattern is the influence of individual tropical systems. During 2001, Hurricane Michelle passed by San Salvador November 1-5. The result was a very low minimum atmospheric pressure for the month, and a lowering of the monthly average value. Despite this impact upon the minimum and average monthly values, the maximum atmospheric pressure value continued the fall trend of rising. This demonstrated that Hurricane Michelle only impacted the beginning of November, while the remainder of the month returned to typical fall/winter conditions.

Significant Events

Four of the five greatest daily total rainfalls were associated with frontal systems (Table 2). This dominance of frontal systems was a surprise given the fact that tropical systems are generally accepted as the major rain producers in the Bahamas and Caribbean (Granger, 1985; Sealey, 1992; Shaklee, 1996). The five greatest daily maximum temperatures occurred in late summer when high solar angles created very warm-island and sea-surface temperatures (Trewartha, 1981). In addition, low-level warm air advection created by southerly flow existed on these hot days, and the greatest maximum temperature was aided by strong southerly flow around Tropical Storm Gabrielle. The minimum daily temperatures predominately occurred, as expected, in the month of January as continental polar air in the form of a cold front, or high-pressure cell, traveled towards San Salvador from the North American continent. The greatest maximum daily wind speeds were created by Hurricane Michelle, a tropical wave, a cold front, and an unexplained meso-gamma scale storm event (most likely a strong thunderstorm). The atmospheric pressure extremes were either created by Hurricane Michelle (lowest) or by high-pressure cells associated with North American continental polar air masses (greatest).

Implications and Applications

The most significant implication for the geosciences from 2001 weather observations is the variability of rainfall on San Salvador. Shaklee (1996) has already pointed out the year-to-year variability in precipitation on San Salvador. Annual totals can vary greatly across a spectrum of severe drought to extreme water surplus. The observations collected in 2001 indicate that this year-to-year variability is more complex. Not only do annual totals vary, but distribution within a year can also vary. It is incorrect to assume that the wet season on San Salvador always corresponds with the hurricane season. Rainfall total for April and May far exceeded totals for August through November in 2001. Also, preliminary observations for 2002 indicates that the spring received a greater amount of rainfall as compared to the following fall.

Table 2. Extreme Meteorological Events for 2001 on San Salvador.

Five Greatest Daily Total Rainfalls

Daily Total Rainfall	Date		Weather System
150.4 mm	4/30/01		Stationary Front
79.5 mm	10/1/01		Stationary Front
75.7 mm	5/13/01		Easterly Wave
75.4 mm	5/3/01		Stationary Front
65.8 mm	9/30/01		Cold Front

Five Greatest Daily Maximum Temperatures

Temperature	Date	Time	Weather System
33.4°C	9/16/01	1418	S Flow Gabrielle
33.1°C	7/10/01	1151	S Flow BH
33.1°C	7/21/01	1333	S Flow Trough
33.0°C	7/9/01	1415	S Flow BH
32.9°C	7/14/01	1146	S Flow BH

Five Lowest Daily Minimum Temperatures

Temperature	Date	Time	Weather System
16.9°C	1/25/01	357	cP -- Cold Front
17.5°C	1/12/01	501	High
17.9°C	1/23/01	1810	cP -- Cold Front
18.1°C	1/12/01	2139	High
18.2°C	1/24/01	6	cP-- Cold Front
18.3°C	5/17/01	424	Passive Cold Front

Five Greatest Maximum Daily Wind Speeds

Wind Speed	Date	Time	Weather System
75.2 kph	11/5/01	2309	Michelle
57.4 kph	11/6/01	840	Michelle
55.4 kph	3/5/01	1944	Cold Front
50.2 kph	5/19/01	1226	Meso Gamma
49.6 kph	8/13/01	1232	Topical Wave/Trough

Five Highest Maximum Daily Atmospheric Pressures

Atmospheric Pressure	Date	Time	Weather System
1026 mb	1/28/01	1000	High
1025 mb	2/12/01	2300	High
1025 mb	2/13/01	1900	High
1024mb	6 days		

Five Lowest Minimum Daily Atmospheric Pressures

Atmospheric Pressure	Date	Time	Weather System
992 mb	11/5/01	1600	Michelle
1002 mb	11/6/01	0	Michelle
1006 mb	11/4/01	0	Michelle
1007 mb	9/30/01	500	Extratropical Low
1007 mb	5/11/01	1500	Trough

Such variation can have a profound effect upon the interpretation of geologic formations in the Northern Caribbean. It has been the authors' experience that the majority of extreme hydrologic events in the Caribbean are assumed to be hurricane related. Thus, for example a sedimentologist may interpret a bed in a core as having been created by surface runoff during a hurricane. Observations for 2001 and 2002 suggest that such an assumption may not be appropriate: frontal activity in spring can also create extreme hydrologic events with high surface runoff and resulting geologic features.

Considering this second mode of precipitation variability, the question arises, "How often does more rain fall in the spring as compared to hurricane season?" A review of monthly precipitation records for San Salvador 1921-1985 indicate that 46 years have complete records and can be used for a comparison of spring non-tropical rainfall (March, April, May, June) to fall tropical storm/hurricane rainfall (August, July, October, November). Out of these 46 years, 10 years had more rainfall in spring as compared to fall. Assuming that such seasonal rainfall totals approximate frontal rainfall versus hurricane rainfall, extreme hydrologic events on San Salvador have a 22% probability of being related to frontal storms. True, the comparison is coarse, as it does not contain information regarding individual storms, but it does indicate that geoscientists should approach with caution the assumption that extreme hydrologic events on the San Salvador are created by hurricanes. This discussion can be widened from San Salvador to the northern Caribbean because recently completed research by the lead author indicates that North American continental air masses and frontal storms may impact the region as far south as Puerto Rico (Parnell, 2002).

The second significant implication of meteorological observations on San Salvador in 2001 involves the secondary observation sites in the MON. Information presented as the 2001 weather summary was collected at the GRC with the Metdata 1, the only instrument capable of collecting a variety of meteorological variables. In addition to the Metdata 1, up to four other rain gages recorded precipitation observation throughout 2001. These five rain gages allowed for a spatial analysis of rainfall across San Salvador.

The spatial analysis indicates that the percent of days in 2001 that recorded rain varied across the island, ranging from 32-42% (Figure 6). However, comparison is difficult between locations because the period of observation for the year was not identical at each of the rain gages. The GRC, Hog Cay, and Grotto Beach rain stations all have at least a 310-day period of record for 2001 allowing for a partial comparison. Grotto Beach had the highest frequency of rain as compared to the other two stations, but only 6% higher than the other two stations. Given the potential for sea spray to create false rain events at the Grotto Beach location, the authors do not believe the difference between Grotto Beach and other stations is significant. Thus it appears that the frequency of rain days is fairly consistent across San Salvador.

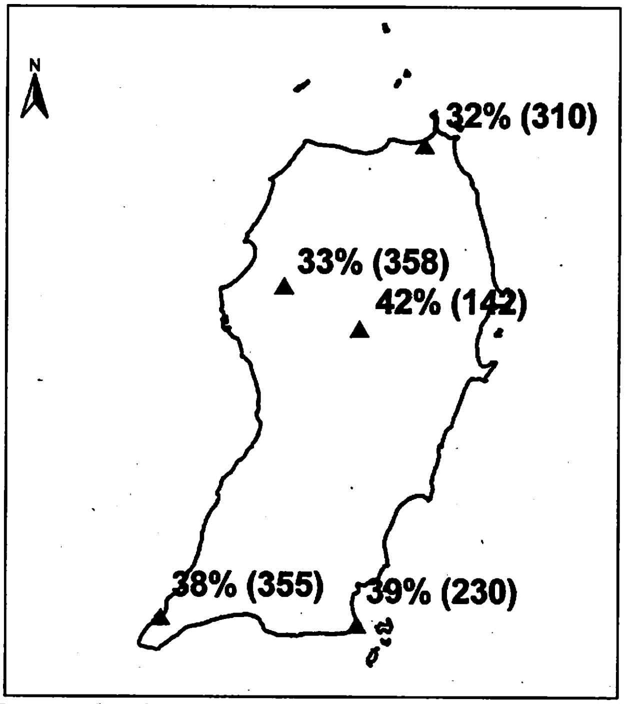

Figure 6. The percentage of days receiving rain during period of record on San Salvador 2001. Number in parentheses indicates total number of days in observation period. The black triangles represent the location of rain gages in the meteorological observation network.

In regard to the spatial coverage generated by rain events, storm events from 2001 could be classified as either complete island coverage (all 5 stations), partial island coverage (2-4 stations), or local coverage (1 rain gage). Only one third (32%) of the rain events in 2001 completely covered the entire island, 37% of the rain events covered the island partially, and 32% of the rain events covered only one rain gage. The results are interesting in light of literature indicating that many of the Bahamian islands are too small to generate their own rainfall. The existence of two thirds of the rain events at partial and local coverages suggests that such an assumption may not be entirely accurate. Small spatial coverage of rainfall is associated with small convective thunderstorms (Orlanski, 1975; Hirschboeck, 1988). Surface heating and free convection on small scales in agricultural regions and large island environments commonly create such storms (Brown and Arnold, 1998; Beringer et al., 2001). Thus, further investigation is required to determine if the interaction between atmospheric circulation and land surface on San Salvador can create such small storms. If such storms do exist, geoscientists must not assume spatial homogeneity in climatic inputs to the island.

CONCLUSIONS

Meteorological observations on San Salvador in 2001 indicate that the mean annual temperature was warmer than normal. Further examination indicates that the warmer- than-normal temperatures were a result of high monthly minimum temperatures. These high minimum temperatures could be created by a combination of cloud cover, weather station location with respect to water bodies, and land-surface thermal properties. In regard to precipitation, 2001 was an exceptionally wet year due to a series of frontal storms in April and May. Wind observations collected by the San Salvador MON appear to be problematic and should not be used in analysis. A repositioning of the MON anemometer should correct such data problems in the future. Monthly atmospheric pressure statistics follow the seasonal temperature cycle with high pressure in winter and low pressure in summer. Analysis of individual extreme events for 2001 indicate that frontal storms caused the greatest daily rainfalls, low-level warm advection created by southerly winds created the highest daily maximum temperatures, and Hurricane Michelle produced the lowest minimum daily atmospheric pressure.

The most important results of this weather summary for geoscientists are the seasonal and spatial variability in precipitation on San Salvador. Geoscientists should not assume that an extreme hydrologic event is created by a hurricane or tropical system. Analysis indicates that for the northern Caribbean (north and west of Puerto Rico) frontal storms can create extreme rainfalls, which are greater than the totals for the following hurricane season. For San Salvador there is a 22% probability that spring (frontal) rains will be greater than fall (hurricane) rains in a given year. In regard to spatial variability, it is improper to assume spatial homogeneity in rainfall coverage on San Salvador, and possibly other small islands in the Caribbean. For 2001, only one third of the rain events covered the island completely. The remaining two-thirds of the storms covered between 1 and 4 rain gages on the island. Such storms may be small, isolated thunderstorms created by the interaction of prevailing winds and the heated island surface. Future research is needed to determine the specific cause of these small storms.

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