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Back Cover: Dr. H. Leonard Vacher, University of South Florida, Keynote Speaker for the 12^{th} Symposium and author of "Keynote Address – Plato, Archimedes, Ghyben Herzberg, and Mylroie", this volume , p. ix. Photograph by Don Seale.

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SPATIAL VARIABILITY OF PRECIPITATION ON SAN SALVADOR, BAHAMAS 2001-2003

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ABSTRACT

The purpose of this project was to assess the spatial variability of rainfall on San Salvador, Bahamas. Accordingly, a small network of meteorological instruments was established in 2001 with rain gauges located at the Gerace Research Center, Grotto Beach, Hog Cay, Ocean House, Six Pack Pond, and Storr's Lake. Analysis of the rain days indicates that, in general, the spatial extent of rain events on the island is split evenly between complete coverage, partial coverage, and rain at a single location. Specifically, between 2001 and 2002, all available rain gauges received rainfall on 114 days, more than one gauge, but not all available rain gauges, experienced rain on 130 days, and only one of the available rain gages experienced rain on 126 days. Statistical hypothesis testing indicated that the differences in mean rain day magnitude by location are not significantly different at the 95% level of confidence. However, if the level of confidence is dropped to 90%, a statistically significant different in mean rain day magnitude does exist for one sample. In this sample, the northern portion of the island received more rainfall than the central and southern portions of the island. A less rigorous direct ranked comparison of mean rain day magnitudes also suggests that the northern portion of the island may have received more precipitation than the central and southern portions of the island during the study period. Given the short period of record used in this analysis, the naturally high climatic variability on San Salvador, and the weak positive results of this study, it is difficult to determine a physical mechanism that can be linked to spatial variation in precipitation on San Salvador. However, it does appear that a series of high magnitude events over a portion of the island is required to create a statistically significant difference in precipitation between locations.

INTRODUCTION

Traditionally, rainfall on San Salvador Island has been recorded at a single station, the Cockburn Town Airport. Accordingly, researchers have had no choice but to assume that rainfall characteristics observed at the Airport are applicable to the entire island. Such an assumption may be problematic given the documented cases of spatial variation in rainfall on other small Caribbean islands (Granger, 1985; McGregor and Niewolt, 1998). However, in almost all of these cases, the spatial variability in rainfall is created by orographic uplift over a mountainous barrier perpendicular to predominant airflow. Thus, it may be inappropriate to assume that small, flat islands, such as San Salvador and the rest of the Bahamas, experience similar spatial variation in rainfall. Further, it has been hypothesized that due to the short residence time of unstable air and the absence of significant orographic barriers, island-scale atmospheric circulation patterns that cause spatial variability in precipitation do not exist on the small, flat islands of the Bahamas (Granger 1985; Carbone et al., 2000; Crook, 2001; Sealey, 1994; Shaklee, 1996). Despite such hypotheses, many individuals, including the authors, have observed rain occurring at one end of San Salvador while the other end experiences no rainfall (Gamble et al., 2004). Accordingly, the purpose of this study was to assess spatial patterns in rainfall on San Salvador in order to determine the validity of the assumption that precipitation is spatially invariant across the island.

DATA AND METHODS

In January 2001, the authors established a meteorological observation network (MON) on San Salvador with the specific objective of assessing spatial variability in precipitation. The hub of this observation system was a Campbell Scientific Metdata 1 weather station (Seahawk 1) located on the campus of the Gerace Research Center. This station records atmospheric pressure, air temperature, dew point, wind speed and direction, and rainfall at 15-minute and hourly intervals. In addition to this hub, up to five 'satellite' Davis tipping bucket rain gauges were deployed to record rainfall at different locations (Grotto Beach, Hog Cay, Ocean House, Six Pack Pond, and Storr's Lake; Figure 1). The establishment of the MON itself was a learning process in which the authors, through a process of trial and error, discovered the most reliable equipment for precipitation observation. The corrosive, isolated environment of San Salvador provided challenges in terms of battery life, consistent power supply, damage from extreme winds and rain, and growth of salt crystals on instruments. Initially, the authors attempted to deploy three small Rainwise WS-2000 weather stations in addition to the Metdata 1. Consistent power supply to data loggers soon became problematic and observations were not being logged by the Rainwise weather stations. The Metdata 1 weather station performed satisfactorily except for damage to communication interfaces from lightening strikes. Overall, the Davis tipping bucket rain gauges with an Onset event logger performed most reliably. The end result of the instrumentation trial and error process was a period of record with intervals of no recorded data at one or more locations across the island (Table 1). Such a 'patchwork' of data available during the study period diminished the capacity for statistical analysis but spatial variability in rainfall could still be assessed to a limited degree.

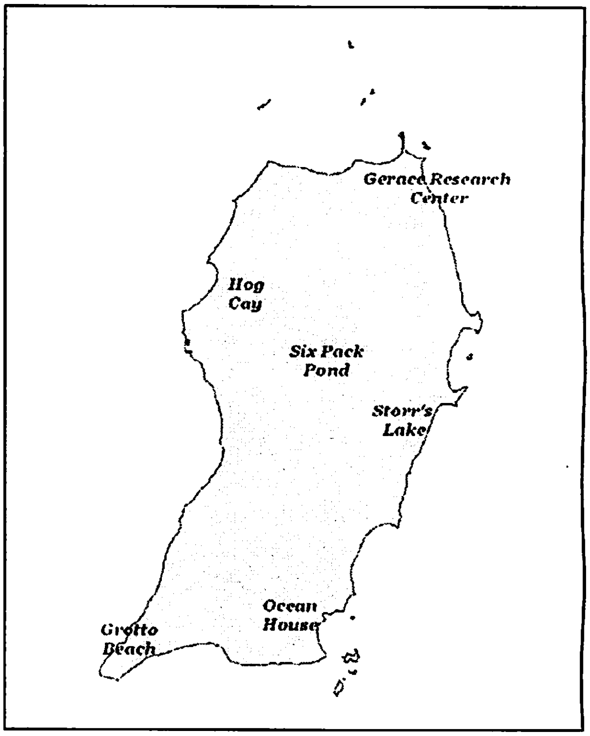

Figure 1. Location of weather station and rain gauges in the San Salvador MON. Map produced with data from San Salvador GIS Data base (Robinson and Davis, 1999).

Due to the discontinuous nature of the data, different aggregation techniques were used to create data sets suitable for statistical analysis. First, a continuous aspatial data set was constructed for the entire period of study, 2001-2003. This data set allowed for a general description of rainfall on the island for the entire period of record. Hog Cay and Storr's Lake data were combined for the continuous record (Hog Cay 2001-2002, Storr's Lake 2003). A t-test of simultaneous observations indicated no significant difference (95% confidence) in the amount of rainfall recorded at these two locations. The second aggregation method was used to facilitate the assessment of spatial variability in rainfall across the island. In this method, periods of simultaneous rain gauge observations at multiple locations were grouped into seven samples for statistical tests (Table 2). The number of stations included in each of the seven samples ranged from five (Sample 2: Gerace Research Center,

Month	GRC	HC	GB	OH	SP	SL
1/2001	√	√	√	000	000	000
2/2001	√	√	√	000	000	000
3/2001	√	√	√	000	000	000
4/2001	√	√	√	000	000	000
5/2001	√	√	√	√	√	000
6/2001	√	√	√	√	√	000
7/2001	√	√	√	√	√	000
8/2001	√	√	√	√	√	000
9/2001	√	√	√	√	√	000
10/2001	√	√	√	√	000	000
11/2001	√	√	√	√	000	000
12/2001	√	√	√	√	000	000
1/2002	√	√	000	√	√	√
2/2002	√	√	000	000	000	√
3/2002	√	√	000	000	000	√
4/2002	√	√	000	000	000	√
5/2002	√	√	000	000	000	√
6/2002	√	√	000	√	000	√
7/2002	000	√	000	√	000	√
8/2002	√	√	000	√	000	√
9/2002	√	√	000	√	000	000
10/2002	√	√	000	√	000	000
11/2002	000	√	000	√	000	000
12/2002	000	√	000	√	000	000
1/2003	000	000	000	000	000	√
2/2003	√	000	000	000	000	√
3/2003	√	000	000	000	000	√
4/2003	√	000	000	000	000	√
5/2003	√	000	000	000	000	√
6/2003	√	000	000	000	000	√
7/2003	√	000	000	000	000	√
8/2003	√	000	000	000	000	√
9/2003	√	000	000	000	000	√
10/2003	000	000	000	000	000	√
11/2003	√	000	000	000	000	√
12/2003	√	000	000	000	000	√

GRC = Gerace Research Center, HC = Hog Cay, GB = Grotto Beach, OH = Ocean house, SP = Six Pack Pond, SL = Storr's Lake, √ = rainfall data recorded during month, 000 = no rainfall data recorded during month.

Table 1. Monthly rainfall observations recorded 2001-2003 by the San Salvador Meteorological Observation Network (MON).

Hog Cay, Grotto Beach, Ocean House, Six Pack Pond, May – September 2001) to two (Sample 6 & 7: Gerace Research Center, Storr's Lake, February-September, November-December 2003). The number of locations with recorded rainfall data in each sample determined the specific statistical test that was used to assess spatial variability in rainfall. For samples with three or more locations, a one-way analysis of variance (ANOVA) was used to determine if a statistically significant difference existed in rainfall between the locations. For samples with only two locations, a t-test was used to determine if a statistical significant difference in rainfall existed between the locations. In both types of statistical tests, the null hypothesis was that there was no significant difference in mean daily rainfall by location and each test was performed at the 95% confidence interval.

Sample	Dates of Observations	Locations
1	May-December 2001	Gerace Research Center, Hog Cay, Grotto Beach, Ocean House (4)
2	May- September 2001	Gerace Research Center, Hog Cay, Grotto Beach, Ocean House, Six Pack Pond (5)
3	June-May 2002	Gerace Research Center, Hog Cay, Storr's Lake (3)
4	August 2002	Gerace Research Center, Hog Cay, Ocean House, Storr's Lake (4)
5	August-October 2002	Gerace Research Center, Hog Cay, Ocean House (3)
6	February-April 2003	Gerace Research Center, Storr's Lake (2)
7	January-September 2002	Gerace Research Center, Storr's Lake (2)

Table 2. A description of the seven samples used in statistical tests with date of record and gauge locations included.

RESULTS AND DISCUSSION

Summary statistics of rainfall data in the 2001-2003 continuous aspatial record displays San Salvador's high inter-annual variability discussed in previous research (Table 3) (Shaklee, 1996). The number of rain days ranged from 107 to 166 and the total annual rainfall ranged from 902 mm to 1210 mm. Such variability represents a difference of two months worth of rain days

	2001	2002	2003	Mean
Rain Days	107	166	151	141
Total Rain (mm)	902	1048	1210	1053
Mean Storm Duration (hours)	2.1	2.0	1.9	2.0
Maximum Daily Rainfall (mm)	98 (May 3)	114 (June 1)	100 (October 6)	

Table 3. Summary statistics of continuous aspatial rainfall data set for San Salvador 2001-2003

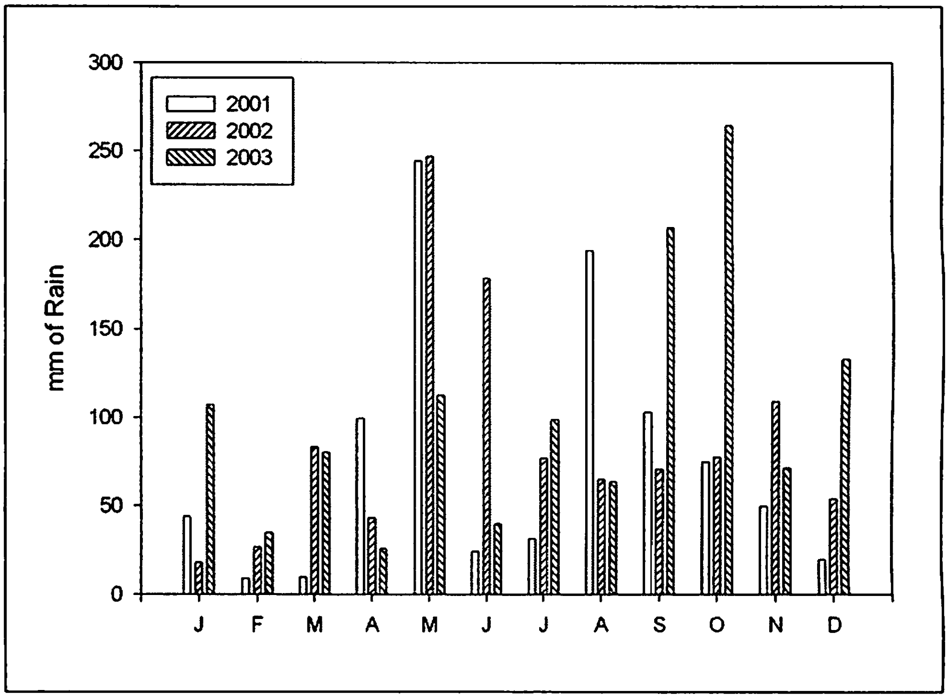

Figure 2. Total monthly aspatial rainfall for San Salvador, 2001-2003.

between 2001 and 2002 and 100-200 mm variability around San Salvador's reported mean annual rainfall (1007 mm) (Shaklee, 1996). Such variability is also evident in monthly totals of rainfall (Figure 2). All months display a range of magnitudes at least 220% of the minimum value for the three year period and a maximum magnitude of 848% of the minimum value. It should also be noted that the time of year of the maximum daily rainfall also varied. For 2001 and 2002 the greatest daily rainfall occurred in May and June, while in 2003 the greatest occurred in October. A review of NOAA Daily Weather Maps indicated that the May 2001 storm was caused by a stationary front that approached San Salvador from the northwest, the June 2002 storm was caused by low pressure that approached from the.west-northwest, and the October 2003 storm was caused by atmospheric mechanisms not evident on a synoptic scale weather map. Thus,

Storm Type	Frequency (Days)	Total Rain (mm)	Average Rain (mm)	Start Time Mode	Average Duration (hr)	Maximum Rain (mm)
Cold Front	44	289	6.6	6	1.7	54.2
Low	2	118	59.0	4	4.0	114.2
Non-synoptic	222	1117	5.0	7	1.75	90.4
Stationary Front	27	542	20.1	12	3	98.0
Trough	30	321	10.7	5	2	97
Tropical System	13	82	6.31	2	2.4	47.4
Tropical Wave	23	86	3.8	2	2.2	14.2

Table 4. Aspatial rainfall storm types for San Salvador 2001-2003.

tropical cyclones alone are not responsible for all intense rainfall events on San Salvador. In fact, as Figure 2 indicates, the hurricane season (June-October) can be fairly dry (2001-2002) in any given year on San Salvador.

A manual synoptic climate classification, as described in Gamble and Meentemeyer (1998), was completed for the 2001-2003 rain days using NOAA Daily Weather Maps. This classification indicates that a wide variety of tropical and non-tropical atmospheric circulations were associated with rain days in 2001-2003 (Table 4). Of particular interests is that more rain days were associated with non-tropical systems (103 rain days) as compared to tropical systems (36 rain days). In addition, the majority of the rain days (222) occurred on days without clearly distinguishable synoptic scale features (e.g. front, trough, pressure cell, tropical wave, or tropical depression/storm/hurricane). Such a high occurrence of non-synoptic rain days leads the authors to believe that some type of regional or meso-scale atmospheric circulation near or on San Salvador, such as warm sea surface temperatures or moisture convergence created by local circulation patterns frequently creates rain. However, it should be noted that even though the total rain caused by the non-synoptic storms is the greatest of all storm types, the amount produced during each non-synoptic storm/rain day was relatively low. Consequently, identifying the atmospheric conditions associated with such small rain events can be very difficult given that only subtle atmospheric perturbations are required to produce rain.

Analysis of rain occurrence at multiple locations across the island indicated that, in general, the spatial extent of rain is split evenly between complete coverage, partial coverage, and single location coverage. Specifically, between 2001 and 2002, when at least three rain gauges were available for observation, rain occurred at all available rain gauges on 114 days, at more than one gauge but not all available rain gauges on 130 days, and at only one of the available rain gauges on 126 days. In 2003, only two rain gauges were available for the collection of rain data and during this period rain occurred at both gauges on 64 days and at only one on 59 days. Thus, it is common for one portion of the island to receive rainfall on a given day while the rest of the island does not. In fact, these data suggest that it is rarer for the entire island to be covered by a rain event than only a portion of it.

Sample	Dates of Observations	Locations	Type of Test	*F* or *t* value	Probability
1	May-December 2001	Gerace Research Center, Hog Cay, Grotto Beach, Ocean House (4)	ANOVA	0.98	0.40
2	May-September 2001	Gerace Research Center, Hog Cay, Grotto Beach, Ocean House, Six Pack Pond (5)	ANOVA	0.29	0.88
3	June-May 2002	Gerace Research Center, Hog Cay, Storr's Lake (3)	ANOVA	0.67	0.51
4	August 2002	Gerace Research Center, Hog Cay, Ocean House, Storr's Lake (4)	ANOVA	0.31	0.82
5	August-October 2002	Gerace Research Center, Hog Cay, Ocean House (3)	ANOVA	2.38	0.09
6	February-April 2003	Gerace Research Center, Storr's Lake (2)	Student's t	0.70	0.24
7	January-September 2002	Gerace Research Center, Storr's Lake (2)	Student's t	0.70	0.25

Table 5. Statistical test results for aggregated rain day samples from San Salvador 2001-2003.

	Gerace Research Center	**Hog Cay**	**Ocean House**
Mean Rain (mm)	6.7	3.8	3.7
Variance	76.7	19.6	18.2
Total Rain Days	25	36	32

Table 6. Summary statistics for three locations contained in Sample 5.

Statistical analysis of the aggregated samples resulted in failure to reject the null hypothesis for all seven of the samples (Table 5). However, if the level of confidence is lowered to 90%, the null hypothesis is rejected for Sample 5, indicating that there was a significant difference in mean rain day magnitude between the Gerace Research Center, Hog Cay, and Ocean House (the north, center, and south portions of the island) from August to October 2003. Comparison of the summary statistics for the three locations indicates that the northern portion of the island, or the Gerace Research Center, received close to twice as much mean daily rainfall as the central and southern portions of the island (Table 6). Examination of daily rain fall data indicates that three rain days caused the significant difference between the locations in Sample 5. On August 14, 2002 a tropical wave passed near the island causing 12.2 mm of rainfall at the Gerace Research Center, 5.8 mm at Hog Cay, and 6 mm at Ocean House. On August 31, 2002 a trough passed close to the island causing 18.3 mm of rainfall at the Gerace Research Center, 1.4 mm at Hog Cay, and 8 mm at Ocean House. On September 17, 2002, another tropical wave approached San Salvador causing 34.0 mm rainfall at the Gerace Research Center, 0 mm at Hog Cay, and 0.6 mm at Ocean House. On each of these days, the northern portion of the island clearly received twice as much rain as the central and southern portions. The ANOVA results indicate the importance of such series of events in creating spatial variability of rain on San Salvador. Without repeated heavy rain over one specific location, it appears that rainfall magnitude is similar across the island.

Since the high variance of the seven samples used requires a large, repeated difference in mean rain-day magnitudes to create a statistically significant difference in rainfall at the various locations and the period of record for the samples was very short, the authors decided to use another, less conservative method of analysis to assess the spatial variability of rainfall on the island. The method used was a direct ranked comparison of the seven sample means for each location. Table 7 provides the mean rain-day magnitude for each location included in the seven samples. The Gerace Research Station ranks as the highest mean rain day magnitude for 4 of the 7 samples and was the lowest mean rain day magnitude once. All other locations have a mixture of the highest and lowest rain-day magnitudes and Grotto Beach never ranked as the highest or lowest rain day magnitude. Such an assessment is not particularly rigorous but hints that the northern portion of the island, or the Gerace Research Center, may have received a higher amount of precipitation during the study period.

CONCLUSIONS

A meteorological observation network was established on San Salvador in 2001 to assess the spatial variability in precipitation across the island. An aspatial data analysis of data recorded from 2001 through 2003 indicates that rain occurred on 38% of the days in the period of record with with an average rain-day magnitude of 7.5mm and storm duration of 2 hours. The months of May were extremely wet during this

Sample	Gerace Research Center	Hog Cay	Grotto Beach	Ocean House	Six Pack Pond	Storr's Lake
1	8.8 mm	5.2 mm**	8.4 mm	9.0 mm*		
2	6.9 mm*	5.8 mm	5.3 mm	6.2 mm	4.5 mm**	
3	12.7 mm*	8.2 mm**				8.6 mm
4	3.4 mm	4.3 mm*		2.8 mm**		3.4 mm
5	6.7 mm*	3.8 mm		3.7 mm**		
6	7.9 mm*					5.8 mm**
7	6.7 mm**					8.6 mm*

Table 7. Direct ranked comparison of seven sample means by location for San Salvador 2001-2003. The greatest mean values in each sample are denoted with one asterisk and the lowest mean value in each sample are denoted with two asterisks.

period and October was extremely dry. Non-tropical storms, particularly stationary fronts, contributed significantly to annual rain totals. A spatial analysis of the data indicates that from 2001 through 2003, the entire island of San Salvador was completely covered by rainfall on 30-50% of the observed rain days. Further, statistical hypothesis testing indicates that the differences in mean rain-day magnitude by location are not significantly different at the 95% confidence level. However, if the statistical tests are performed at the 90% confidence interval, a statistically significant difference in mean rain day magnitude does exist for one sample. In this sample, the northern portion of the island received more rainfall than the central and southern portions of the island. A less rigorous direct ranked comparison of mean rain day magnitudes also suggests that the northern portion of the island, as represented by the Gerace Research Station, may have received more precipitation than the central and southern portions of the island during the study period.

Given the short period of record used in this analysis, the naturally high climatic variability on San Salvador, and the weak positive results of this study, it is difficult to determine a physical mechanism that may be linked to causing spatial variation in precipitation on San Salvador. However, it does appear that a series of events is required to create a statistically significant difference in precipitation between locations. For this study period, a series of tropical waves caused the significant difference and therefore perhaps during an active tropical season, rainfall magnitude may not be equal across the island.

Future analysis of this data set and data currently being collected will include the comparison of different storm characteristics (type, duration, time of initiation) by location and a refinement of the storm classification methodology in order to better understand physical processes associated with non-synoptic precipitation, tropical wave, and trough storm events. Through such analysis a better understanding of potential spatial variation in precipitation on San Salvador can be achieved

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