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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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CLIMATE-DERIVED WATER BUDGET AND SYNOPTIC-SCALE PRECIPITATION PATTERN ANALYSIS

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ABSTRACT

The Bahamian island of San Salvador is an example of a landscape where detailed climate data can be useful for understanding the hydrological balance of carbonate island landscapes. A Meteorological Observation Network was established to collect weather variables during 2001 resulting in a high-resolution database. Temperature and precipitation records were used to construct a Thornthwaite and Mather water budget, documenting climatic variability of fresh water resources. The synoptic weather patterns responsible for rain events were determined and classified by type.

Results indicate that 1257 mm of precipitation fell during 2001, five events accounted for 38% of the annual total, and at least 446 mm of precipitation was lost from the landscape as runoff. The cumulative potential evaporation value was 1495 mm while cumulative actual evaporation was 741mm. Constant tropical temperatures maintained a steady evaporation rate while input occurred at discrete intervals, limiting water available for aquifer recharge. Stationary fronts were the least frequent weather patterns but produced the most precipitation, whereas meso-gamma scale weather patterns were the most common precipitation producing systems and accounted for the second largest source of precipitation. Tropical disturbances were not a significant source of precipitation for 2001 but cold fronts were predominant during the winter season.

INTRODUCTION

From an annual perspective, San Salvador's landscape experiences a net loss of water, i.e., it has a negative water budget (Davis and Johnson, 1988). Annual precipitation values range from 500-2000 mm/year with an average of 1007 mm, while evaporation averages 1300 mm/year (Shaklee, 1996). Daily temperatures range from 22°C to 28°C, and produce a steady evaporation loss from San Salvador's surface. However, complexity arises in the water budget due to variations in the magnitude and temporal distribution of precipitation events. One method for investigating the interactions between supply and demand is a water budget applicable to the landscape of San Salvador.

A climate-based water budget model such as the one derived by Thornthwaite and Mather (1957) provides a general understanding of water exchange between the atmosphere and a soil column. In this model, precipitation is the source of water to a soil column, which retains water to a specified field capacity. The water retained by the soil is termed storage and is available for diffuse recharge of the aquifer or to supply environmental water demands created by evapotranspiration. When the field capacity is exceeded by input or infiltration limits flux across the landscape surface, extraneous water becomes surplus. Surplus water can be intercepted by epikarst pathways that often bypass vadose zone storage. The result can be aquifer recharge (vadose fast flow / infiltration) or the loss of fresh water by discharge as runoff (Contractor and Jenson, 2000).

Evaporation values for the Thornthwaite and Mather model are determined using average daily temperatures, length of day and a heat index value (Thornthwaite and Mather, 1957). Potential evaporation is calculated as if an infinite water supply were available for removal from an open surface. Actual evaporation values are calculated as the loss of water by the soil column, based on water availability determined by the field capacity to soil capacity ratio.

This study includes an analysis of weather patterns responsible for each precipitation event, linking weather patterns with input characteristics. Yearly precipitation variation will be explained as the result of synoptic scale atmospheric mechanisms. Together these two analyses will integrate precipitation events and fresh water resources so that tools can be developed that more accurately forecast the water input on San Salvador.

PREVIOUS STUDIES

A water budget for San Salvador was evaluated by Foos (1994) using averaged monthly values of precipitation and temperature for 18 years of data collected between 1921 and 1993 (Figure 1). Precipitation amounts were recorded at a government supported meteorological station located at the island airport (ZSA), evaporation amounts were modeled using a mass balance technique (Dingman, 1994), and potential evaporation was calculated using the Thornthwaite method (Thornthwaite, 1948). The monthly resolution provides information regarding seasonal patterns in rainfall, showing large annual variation in precipitation and constant high evaporation rates, which effectively constrain fresh water availability (Foos, 1994).

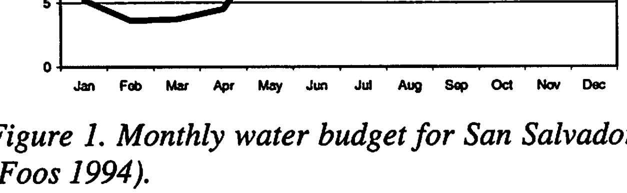

Figure 1. Monthly water budget for San Salvador (Foos 1994).

Recent research has found significant differences within specific weather patterns and rainfall distribution on San Salvador, across a latitudinal transect (Gamble *et al.*, 2002). These patterns, when analyzed by yearly observations, may show how global climatic patterns such as the migration of subtropical high-pressure cells affect precipitation along the Tropic of Cancer. While seasonal patterns are understood, finer scale temporal variability has not been studied, creating a gap in current knowledge about fresh water availability.

The reason for a meager understanding of climate variability is that limited weather information was available for San Salvador. The development of a new database with higher resolution and continuity then previously available provides the ability to quantify fresh water recharge events. In contrast to previous studies, the water budget of San Salvador will be described on a daily time frame resolving contributions from individual synoptic weather patterns.

METHODS

The daily water budget was calculated using an algorithm developed by Willmott (1977) utilizing the methods described by Thornthwaite (1948). This program requires an input file consisting of program instructions, site-specific information, and values for daily average temperature and precipitation. A daily balance method was selected to start January 1, 2001 and continued until December 31, 2001. Site-specific information defines the soil column's field capacity, initial soil moisture attributes, latitude and a calculated heat index. The field capacity was selected to be 100 mm, this value assumes a one-meter thick soil column and a water holding capacity of 0.1, a value between the ranges defined by sand and loam textures (ASCE, 1990). The soil column height is a constant in the calculation requiring a low capacity to be chosen in order to best represent the minimal short-term storage that is present in the landscape. The initial soil moisture was assumed to be 10 mm, because this study was started during a lengthy dry period. The heat index was calculated as 146, using an approach described by Thornthwaite (1948) with monthly temperature values taken from Foos (1994).

Daily values of temperature and precipitation were adopted from the 2001 Weather Summary for San Salvador (Gamble *et al.* 2002).

Daily observations were not recorded for the following dates: 1/1-1/7, 4/18-4/28, 5/20-6/12 and 8/21-9/3. It is suspected that this information was lost because of low battery power after successive days of cloudy sky conditions. In order to reconstruct the precipitation record for these days, the following method was used. First, rain records were collected from two other rain gauges at separate field locations on San Salvador. These records were compared to those of the existing 2001 weather database. Rain events that occurred simultaneously at these locations implied a rain event at the weather station (Gamble *et al.*, 2001). This was used as a proxy for identifying rain events during the missing intervals. The precipitation values for these rain dates was estimated using a linear regression, with the average magnitudes recorded by the two rain gauges as the independent variable and the GRC 2001 database precipitation magnitudes as the dependant variable. This described 60 % of the variance in the observed rain events making it applicable for estimating magnitudes during the "implied" rain days.

Temperature records for dates in the study period not recorded at the GRC were reconstructed using the following technique. Average monthly values were assumed for each day of record without an observation. These monthly values were combined with the observed GRC temperature series and a ten-day moving average was calculated for the combined dataset. The moving average values calculated for missing GRC days were used as the estimated temperature values for the 2001 database. These modifications resulted in a database with precipitation and temperature values either observed or estimated for every day of 2001.

For each precipitation day, the synoptic scale weather pattern was identified using a manual classification technique. First, the dates of precipitation events were identified using the modified 2001 San Salvador weather database. The corresponding NOAA National Center for Environmental Prediction surface weather maps for North America were obtained via the Internet (http://nndc.noaa.gov) and classified according to a modified synoptic climate classification scheme (Gamble and Meentemyer, 1997). Originally developed for use in the southeastern United States, it includes cold fronts (CF), stationary fronts, and synoptic event descriptions. This classification method was modified to include storm classes described as "easterly waves" (EW), "tropical disturbances" (TD) and "meso-gamma scale" (MG). In addition, the modifications included a distinction between Bahamian high influenced stationary fronts (BHSF) and stationary fronts originating from cold fronts out of North America (NASF).

For precipitation event dates where the weather chart was unavailable or the classification could not be completed, a "not applicable" (NA) designation was assigned. In order to maintain consistency throughout the classification, each surface map was subjected to a standardized decision process outlined by Crump (2002). This classification procedure resulted in a listing of precipitation event dates, rainfall magnitude and a synoptic classification of the weather pattern associated with the event.

RESULTS

Output from the water budget algorithm is a data table listing daily values for potential evaporation, actual evaporation, the difference in precipitation and evaporation, and the amount of soil moisture storage, change in storage, soil moisture deficit, and surplus. The results from the water budget are represented herein using three different perspectives.

Figure 3 indicates that daily values for potential evaporation ranges from 1-6 mm/day and actual evaporation ranges from 0-6 mm/day. Potential evaporation occurs uniformly throughout the year with maximums corresponding to higher average daily temperatures. Actual evaporation occurs at a maximum immediately after rain events and decreases with an increase of time between events. The largest daily precipitation record was 150 mm; the five largest precipitation events accounted for 472 mm of the years 1257 mm of rain, greater than 38% of the total yearly amount.

Figure 4 displays the surplus and storage values calculated by the water budget. This graph emphasizes soil column conditions and potential runoff amounts. The soil storage values indicate that uninterrupted drying conditions led to the removal of more than 90% of soil capacity four times during the year. However, the first occurrence may be artificially low because of the initial conditions selected for this analysis. The two in April are grouped together as one period. Therefore, only two periods of dry weather are recognized. These are the two dry seasons for the year, centered on March and June. Seven surplus opportunities were created when precipitation amounts exceeded the ability of the soil column to retain water. The total surplus equals 446 mm, slightly over 35 % of the annual precipitation.

Figure 5 utilizes the same parameters as Figure 3 but the data are represented cumulatively for the year, alluding to the effects of long-term trends and distributions. The only period in which precipitation values exceeded potential evaporation was during May. Total annual precipitation was 1257 mm, the total annual potential evaporation value was 1495 mm, and the annual actual evaporation value was 741 mm.

A histogram illustrates the frequency of each storm type (Figure 6) as well as the total rainfall contribution from each storm type (Figure 7). There were 99 rain days at the GRC during the year 2001, and the most common precipitation-producing pattern was the meso-gamma scale pattern accounting for 35 rain days. The easterly wave pattern produced 22 of the rain days and 16 rain days resulted from cold front patterns.

Figure 7 indicates that the greatest contribution to 2001 precipitation was from both Bahamian high and North American stationary fronts, which contributed more than 500 mm (40%) of the annual precipitation value. The second largest contribution was meso-gamma scale induced precipitation of 246 mm. Tropical disturbances accounted for 8 rain days and contributed less than 8% to the annual total. The monthly distribution of weather patterns for 2001 is displayed in Figure 8. Cold fronts dominate rainfall in the winter months, November through March. During May, all synoptic weather classes were represented. However, in June, a shift occurs from winter classes to summer classes, with the dominant patterns becoming meso-gamma scale and tropical. September through November are the months with the most frequent occurrence of tropical patterns.

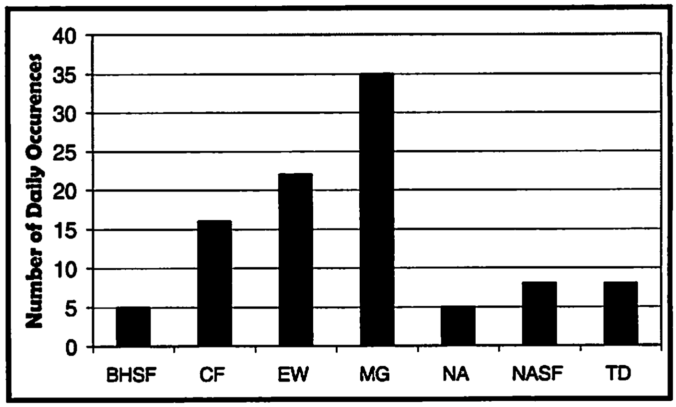

Figure 6. Histogram for each synoptic pattern associated with rain events in 2001.

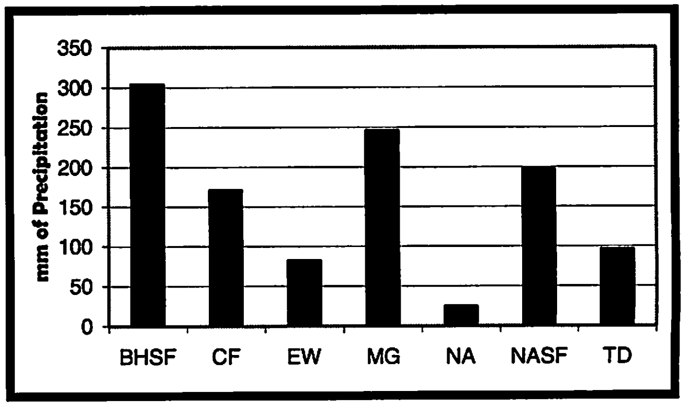

Figure 7. Total amount of precipitation recorded for each weather pattern in 2001.

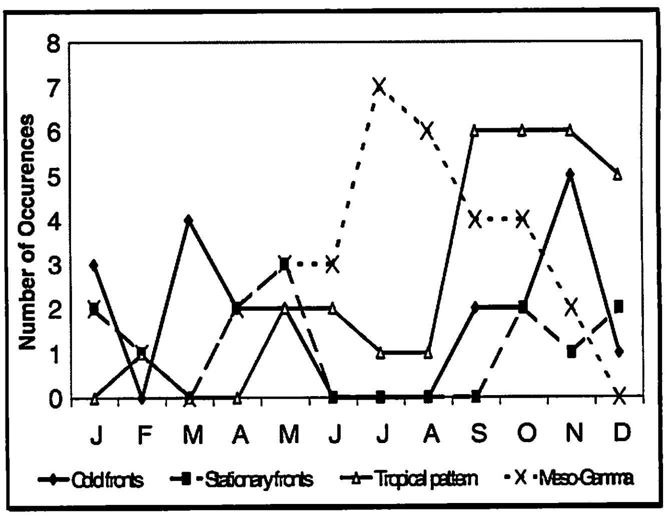

Figure 8. Monthly distribution of weather patterns in 2001. BHSF and NASF are included in stationary fronts, and tropical patterns include EW and TD.

DISCUSSION

The water budget reveals that precipitation is not uniform throughout the year. A few large events account for the majority of the input; whereas smaller events, although more evenly distributed, do not significantly impact the water balance. Constant evaporation losses actively remove water from the landscape causing event-driven periods of water availability followed by a steady decay to dry conditions. Contrary to popular belief that the three-month hurricane season is responsible for the majority of rainfall, the majority of the precipitation for 2001 occurred during the early summer wet season. Large amounts of surplus water during extreme events, suggests that this water is lost by the system and is not available for long-term storage.

The assumptions for soil field capacity may greatly alter the results of a calculated water budget; however, very little information about San Salvadorian soils exists. The value assigned for this study was chosen to represent a minimal storage aspect for the landscape as a uniform surface. These calculations therefore represent an approximation of the water budget across a landscape that stores a very small amount, similar to San Salvador. Ranges of values actually exist and correlate to local soil properties. These soils are not uniform but may be spatially distributed according to landscape morphology. This spatial distribution and field capacity variance may produce significant variation in the local water budget.

The weather patterns responsible for precipitation demonstrate temporal as well as rank relationships throughout the year. Tropical disturbances for the year 2001 contributed rain for only 8 days, or 8 % of the yearly total rainfall. This may be the result of a lack of well-developed hurricanes during the 2001 season; the only one to make contact with the island, Hurricane Michelle, was unusual in that it was characterized by high winds and little rain (Voegeli, 2001, personal communication). As expected, tropical weather patterns were most active from September through December, the traditional hurricane season.

Cold fronts, which move across the Bahamian archipelago from the U.S., are capable of supplying a substantial percentage of yearly rainfall. This supports our expectations that cold fronts dominate precipitation production during the winter from January to April. Meso-gamma scale events are responsible for the largest number of rain days and occur throughout most of the year, creating less than average rainfall amounts per event. Meso-gamma patterns were most active during the summer from July through August, simultaneously with the highest average temperatures and the hottest land surface temperatures. This suggests that the processes resulting in meso-gamma precipitation are seasonal patterns, are active during the summer. Few structured fronts and the presence of widely spaced isobars on the weather maps suggest weak Trade Wind patterns are necessary for this synoptic class to become active. This is indicative of island-controlled weather patterns, where the surface temperatures may drive small-scale convection mechanisms.

Stationary fronts, both North American and Bahamian High, were responsible for the majority of the precipitation during 2001: the two wet seasons of the year were concentrated around their occurrences. Stationary fronts were the most important fresh-water producing weather patterns of 2001 and they were most active after periods of increased cold front activity. This suggests that stationary fronts may be transitional in nature as global weather patterns of the northern hemisphere shift from winter patterns to summer patterns. Temperature and pressure gradients, which power the movement of cold fronts across San Salvador, may lessen during these transitional periods allowing for the evolution of highly productive stationary fronts to be entrenched for lengthy periods of time. As a climatic norm, these conditions may not always exist but they were particularly important for explaining the rainfall total in 2001.

CONCLUSIONS

An analysis at this temporal resolution had not been attempted previously for San Salvador due to the lack of reliable and consistent data. The application of daily data has provided the ability for process linkage between responsible weather patterns and individual precipitation events and amounts.

As predicted by our hypothesis, fresh water availability is described best on daily timescales. Results produced by the water budget indicate that daily surpluses during large rain events are responsible for the existence of fresh water resources. Accordingly, constant evaporation rates lead to seasonal dry periods during months with little rain as seen during the months of April and July. However, contrary to the original hypothesis, tropical disturbances were not responsible for the majority of precipitation for the year. The wet seasons for 2001 were the products of two periods of intense stationary front activity. Another unexpected result of our analysis was the high occurrence frequencies of meso-gamma scale precipitation. These results are important for resource management because they indicate that San Salvador's water budget is event driven as far as supply is concerned. Application of these results would be a strategy that would utilize short-term variability of climate input for resource management. Constant loss from its land surface creates drying conditions that permeate soil storage, effectively limiting aquifer recharge and the island's ability to maintain a supply of fresh water. This would require usage strategies that rely on storage mechanisms such as tanks, reservoirs, or horizontal aquifer recharge techniques. This would allow resource managers to store water during short wet periods for future use during droughts. These results indicate that the early summer wet periods could be used as a time to store water in addition to the traditionally wet hurricane season.

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