International Conference on Hydroinformatics

2014

Investigating The Sources Of Fresh Water Affecting The Hydrological Balance Of Lakes Enriquillo And Azuei (Hispaniola) – Data Analysis

Daniel Comarazamy

Jorge Gonzalez

Fred Moshary

Michael Piasecki

Mahrokh Moknatian

See next page for additional authors

Authors

Daniel Comarazamy, Jorge Gonzalez, Fred Moshary, Michael Piasecki, Mahrokh Moknatian, and John Ibsen

11th International Conference on Hydroinformatics
HIC 2014, New York City, USA

INVESTIGATING THE SOURCES OF FRESH WATER AFFECTING THE HYDROLOGICAL BALANCE OF LAKES ENRIQUILLO AND AZUEI (HISPANIOLA) – DATA ANALYSIS

DANIEL COMARAZAMY, JORGE GONZALEZ, FRED MOSHARY, MICHAEL PIASECKI, MAHROKH MOKNATIAN, JOHN IBSEN (1)
(1): NOAA-CREST, The City College of New York, 140 Convent Ave, New York, NY, USA

Enriquillo and Azuei are saltwater lakes located in a closed water basin in the southwestern region of the island of La Hispaniola, these have been experiencing dramatic changes in total lake-surface area coverage during the period 1980-2012. Determining the causes of lake surface area changes is of extreme importance due to its environmental, social, and economic impacts. The overall goal of this study is to quantify the changing water balance in these lakes and their catchment area using satellite and ground observations and a regional atmospheric-hydrologic modeling approach. Data analyses of environmental variables in the region reflect a hydrological unbalance of the lakes due to changing regional hydro-climatic conditions. Historical data show precipitation, land surface temperature and humidity, and sea surface temperature (SST), increasing over region during the past decades. Salinity levels have also been decreasing by more than 30% from previously reported baseline levels. Here we present a summary of the historical data obtained, new sensors deployed in the surrounding sierras and the lakes, and the integrated modeling exercises. As well as the challenges of gathering, storing, sharing, and analyzing this large volume of data in a remote location from such a diverse number of sources.

INTRODUCTION

Lakes Enriquillo (Dominican Republic) and Azuéi (Haiti) are saltwater lakes located in the Neyba valley, a former marine strait isolated from the Caribbean Sea around 5000-2800 BP by tectonic uplift and river sediments [1]. They are located in southwestern Hispaniola in the border region between Dominican Republic and Haiti. These are the largest lakes in the Caribbean, with Lake Enriquillo also being the lowest point in the region (currently at ~30 mbsl). Lake Azuéi is a slightly smaller and less saline lake located about 50 m above Lake Enriquillo. The lakes are surrounded by two high elevation sierras to the north (Neyba, ~2400 masl) and south (Bahoruco, ~2700 masl), providing a large catchment area while isolating the watershed from the ocean and, along with the mountain shadow effects of the much higher Central Mountains, the approaching northeasterly trade winds. The lakes have been experiencing dramatic changes in total lake-surface area coverage during the period 1982-2013 (Figures 1). The size change of the lakes was determined and analyzed using LANDSAT images and geographic information system (GIS) software.

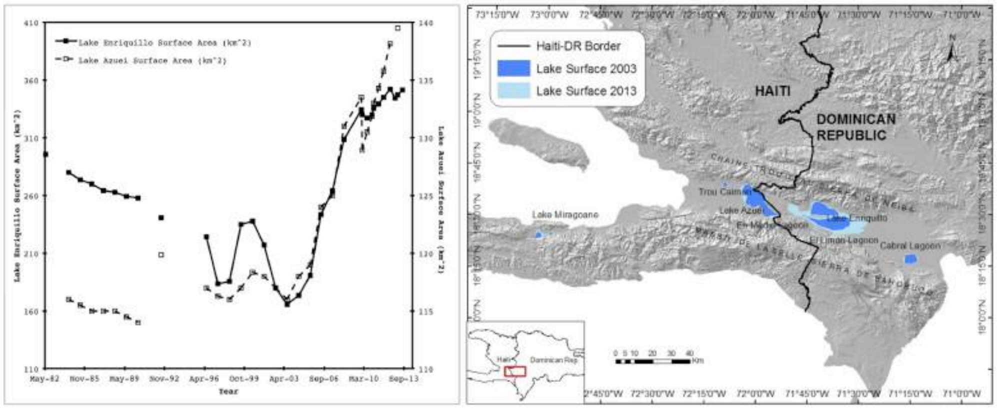

Figure 1. Time series of surface area coverage (km^2) for Lake Enriquillo (solid line-closed squares) and Lake Azuéi (dashed line-open squares) (a). GIS analysis of surface area coverage based on satellite images for 2003 (dark blue) and 2013 (light blue) (b).

The size calculation for Enriquillo shows the lake had an average surface area of approximately 280 km^2 in 1984 that gradually decreased to 183 km^2 in 1997. After a period of fluctuations between 1997 and 2002, lake surface area reached its lowest extent in the remote sensing record in 2003, at 165 km^2. Starting in 2003-04, the lake has experienced constant growth reaching its 1984 size (280 km^2) between 2007-08, and exceeding 350 km^2 in 2013, 30% larger than in 1984 and almost double that in 2003. During the same period, 2003-2013, Lake Azuéi's area increased by 22% (from 114 to 140 km^2). Recent bathymetry measurements, combined with the surface area calculations and a digital elevation model of the area, revealed a 4x volume increase for Lake Enriquillo (from 1.2 to 4.7 km^3) in that period while Azuéi grew by ~1.35x (from 1.7 to 2.3 km^3). The salinity of the lakes also showed dramatic changes. Lake Enriquillo went from a hypersaline lake (102-105 ppt in 2003 [2]) to a brackish one (20-25 ppt in 2013), while Azuéi went from brackish (8-13 ppt [3]) to nearly fresh (~6 ppt in 2013). The differences in absolute volume changes between the lakes are mostly due to differences in the catchment area for each lake, Enriquillo 3000 km^2 and Azuéi 700 km^2.

Determining the causes of lake surface area changes is of extreme importance due to the ecological, social, and economic impacts. In 2009 more than 18,865 hectares of agricultural land around the lake Enriquillo were flooded impacting 16 communities and some 10,000 families, while flooding the highway connecting the two countries at the Malpasse/Jimani border crossing, affecting commercial traffic and associated economic activity [4]. Several hypotheses have been proposed to explain the lakes behavior including; geological movements, tropical storms and hurricanes, hydrological cycle changes that affect the water balance in the basin, changes in land cover for burn wood and agriculture, or a combination of these factors. However, the recent increase in surface area suggests that the changes are mainly due to local impacts of regional climate and hydrological cycle variations and changes.

The hydro-climate change hypothesis postulates that higher regional SSTs increased evaporation from the surrounding ocean, which in turn increases relative humidity, convective and orographic cloud formation, accumulated surface precipitation, while reducing evaporation off the lakes' surfaces due to the air being saturated. This, in combination with possible land cover and land use (LCLU) changes along the sierras north and south of the lakes, would increase surface run-off to the base of the closed basin and to the subterranean aquifers that feed the lakes. Preliminary studies performed analyzing historical data obtained from satellites and surface weather and hydrological stations appear to support the hydro-climate change hypothesis. These climate datasets include sea surface temperatures (SSTs) of waters surrounding the Pedernales peninsula, air temperature, dew point temperature, and precipitation from the cooperative (COOP) station in Barahona as archived by the National Climatic Data Center (NCDC), and several weather stations managed by the authors of this work.

REGIONAL AND LOCAL CLIMATE DATA

Regional Scale Climate Data and Long-Term Climate Change

To assess long-term regional climate change in the Caribbean basin, and how global climate change reflects in the region of interest, atmospheric and oceanic conditions were analyzed. SSTs are derived from two NOAA products: the Extended Reconstructed Sea Surface Temperature version v3b (ERSST) [5] and the Optimum Interpolation 0.25˚ Daily Sea Surface Temperature Analysis (OISST) [6]. Surface weather data was obtained for Barahona from Cooperative (COOP) stations as archived by the National Climatic Data Center.

The ERSST for the open waters surrounding the Pedernales peninsula show that SSTs have increased, on average, 1 ˚C during the past 30 years (Figure 2a, solid black line). The higher resolution OISST product shows a clear SST increase pattern over the region during the same timeframe, with much of the warming occurring over the summer months and widening to intrude into the late stages of the Caribbean early rainfall season and the onset of the late rainfall season (Figure 2c). The COOP station located in Barahona shows an increase in dew point temperature (Fig. 2a, air temperature and dew point temperature, red and blue lines respectively). Figure 4a shows how relative humidity decreased in the early 1980s, a time when the surface area of the lakes was decreasing. It is also seen that from mid-late 1990s to early 2000s, relative humidity increased considerably, periods of transition and growth of lake surface area, unfortunately there are a large number of missing data during this period in the station’s temperature time series. Precipitation, as recorded by the Barahona station (Fig. 2b), has increased since the year 2000, after the period of missing data, in relation to the period 1980-1995. There is also an increase in precipitation events recording 100 mm or more of rain, some of these events are associated with tropical storms and hurricanes and are believed to replenish aquifers that feed the lakes and other bodies of water in the region of interest.

Local Scale Weather and Climate Data

Since the NCDC stations are located outside the Enriquillo basin, and given the relative lack of surface data sources within the basin, a series of weather stations and temperature/relative humidity (T/RH) sensors were deployed along the sierras surrounding the lakes and at lake level between February 2012 and March 2013, referred as CCNY-INTEC network. The CCNY-INTEC network consists primarily of 21 T/RH sensors, six (6) precipitation gauges, and five (5) fog gauges, all deployed across 18 locations in the Neyba Sierra and three locations in the Bahoruco Sierra. Other variables recorded by the CCNY-INTEC network include soil moisture, wind speed, wind direction, and solar radiation. This new network of stations and sensors provide a base line of climate conditions in the area and valuable data for model validation and calibration. This is especially true in the higher locations in the Neyba and Bahoruco sierras, where no data existed due to the remoteness of the area.

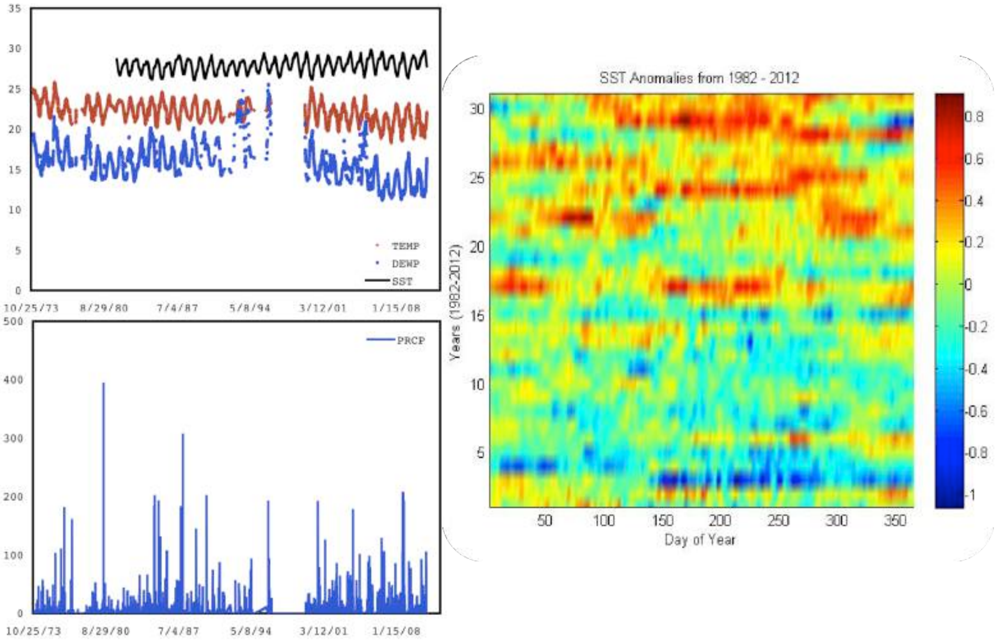

Figure 2. Top panel (a) shows monthly SST, Barahona daily mean air and dew point temperatures (all in ˚C). Bottom panel (b) shows daily-accumulated precipitation at Barahona (mm). Right panel (c) Regional-scale OISST anomalies (˚C) for the period 1982-2012.

Figure 3 shows data from the temperature and relative humidity sensors along the Neyba Sierra, where the first set of deployments occurred, for one 12-month period (July 2012 to June 2013). The vertical profiles shown for temperature and relative humidity against altitude were calculated averaging the data for each location over two different periods of time, to account for relatively dry and wet periods according to precipitation seasons in the island. These periods were specified from July-December 2012 (Summer months and Late Rainfall Season [LRS]) and January-May 2013 (Dry Season and Early Rainfall Season [ERS]). For temperature, values for the LRS are slightly shifted accounting for the temperatures being a few degrees cooler (Fig. 3a). For relative humidity, it is shown that the environment is much drier at lake level and low mountain elevations, whereas starting at about 1325 masl and within the tropical montane cloud forest (TMCF, >1550 masl) humidity values are similar for both seasons (Fig. 3b). This indicates that the TMCF maintains its capacity to produce fresh water and releasing it to the ecosystem. It is hypothesized that this fresh water production mechanism is enhanced by regional climate changes and, along with the observed increased surface accumulated precipitation, is affecting the general water balance of the basin. The importance of the TMCF in producing fresh water is further evidenced by the fact that measurable water from fog gauges installed in both sierras show that fog events are in the same order of magnitude as precipitation events, and that they can occur even when little or no precipitation is recorded (Figure 4). It is worth noting that the fog gauge equipment is a novel design that needs to be further tested in controlled laboratory experiments in order to produce calibration curves and be able to interpret the field measurements appropriately.

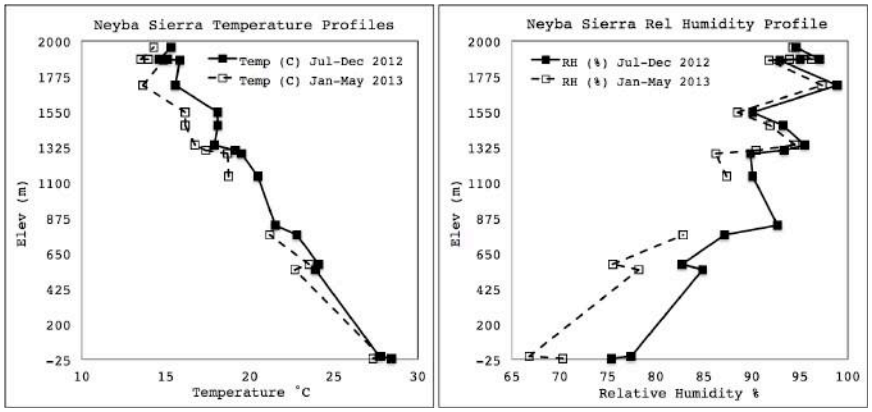

Figure 3. Vertical profiles of averaged temperature (˚C) (a, left) and relative humidity (%) (b, right) for each location between July-December 2012 (Summer and Late Rainfall season, solid line-closed squares) and January-May 2013 (Dry and Early Rainfall seasons, dashed line-open squares).

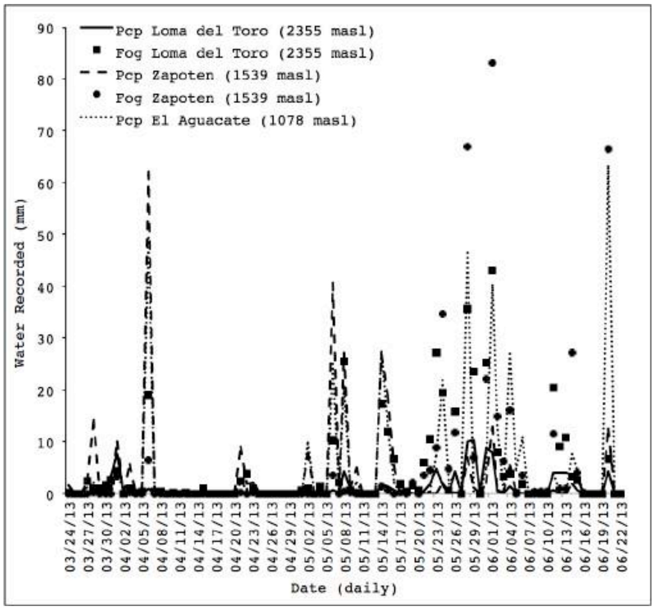

Figure 4. Accumulated precipitation (solid, dashed, and dotted lines) and fog catchment (squares and circles) data from the weather stations in the Bahoruco Sierra (mm).

REGIONAL ATMOSPHERIC MODELING AND SENSITIVITY ANALYSIS

General Descriptions and Experimental Set-up

To complement the observations and to help validate the hydro-climate hypothesis, an integrated atmospheric modeling approach was used. The atmospheric model chosen for the study is the Regional Atmospheric Modeling System (RAMS) [7], which has been used to study different phenomena at various temporal and spatial scales in the Caribbean basin [8, 9]. The simulations are configured to integrate different atmospheric and oceanic conditions in order to study the behavior of important atmospheric and hydrological cycle variables that could be affecting the Enriquillo basin water balance.

The simulations use three nested grids to dynamically downscale the large-scale gridded datasets, with the highest-resolution modeling grid centered on lake Enriquillo and covering Lake Azuéi, the Neyba/Trou d'Eau Sierra, Bahoruco Sierra/Massif de la Selle, Pedernales peninsula, and surrounding ocean. The use of a regional atmospheric model allows the analysis of variables and phenomena for which no observations exist (i.e., atmospheric liquid water content, orographic cloud formation, cloud base height and depth). The atmospheric model simulations during key periods of lake surface area decrease and increase will allow to study the relation between atmospheric variables during such times. Simulations include yearlong runs for April 2003 to March 2004 and for April 2012 to March 2013. The 2012-2013 timeframe was chosen to match the data period generated by the CCNY-INTEC station network to validate model results, and also because 2003-2013 represents the growth period for the lakes in the Enriquillo basin.

After all input information and parameters were incorporated into the atmospheric model and the simulations were performed, the 12-month averaged temperature and relative humidity and individual values of daily minimum and maximum temperatures from the 2012-2013 simulation were validated with corresponding observed values. In general, acknowledging slight tendencies found to under predict minimum temperatures, the model chosen for the study, complemented with digital LCLU maps and driven with reanalysis atmospheric and oceanic conditions, is an adequate tool to study the impacts due to medium-term changes in climate conditions on the hydrological balance of a closed tropical lake basin.

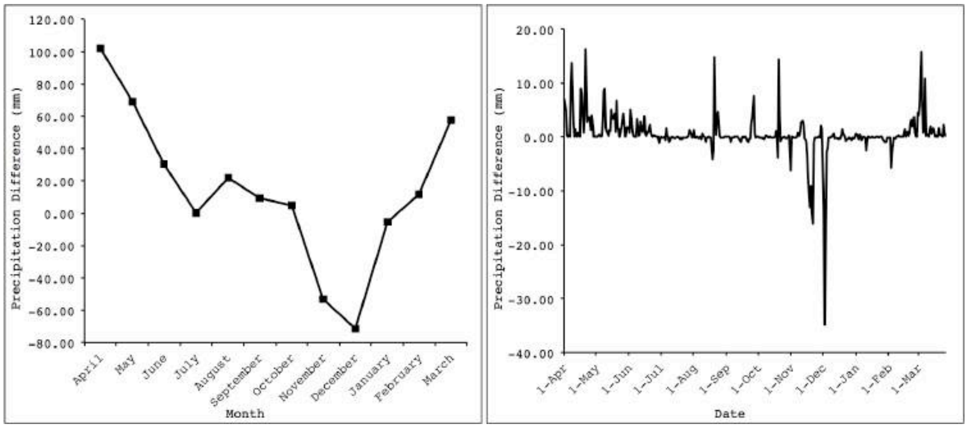

Figure 5. Monthly (a, left) and daily (b, right) accumulated surface precipitation difference (mm) between April 2012-March 2013 and April 2003-March 2004.

Sensitivity to Medium-Term Climate Changes

A key objective of this study is to test the sensitivity of model simulated hydrological variables (i.e., cloud formation, rain development, and surface precipitation), to different input parameters and driving conditions. The yearlong simulations show that differences in monthly-accumulated surface precipitation between the periods 2012-13 and 2003-04, averaged over the grid points closest to the 24 observation sites, are larger at the beginning of the modeling period and remain positive during the Caribbean ERS, diminishing steadily until the summer months (Figure 5a). Monthly precipitation differences then show that more precipitation was produced by the model in the LRS of 2003 than in 2012, before increasing again at the onset of the following ERS. However, when examining the daily precipitation difference we notice a pattern where most of the differences found for the ERS are produced over much of the period spanning April to mid-June, whereas the precipitation differences over the summer and LRS are produced by single events over one or two days at a time for 4-5 extreme events (Figure 5b). During the ERS precipitation in the Caribbean is dominated by local and regional factors, so changes in local and regional climate and environmental conditions are bound to have a direct impact on the hydrological balance of the Enriquillo Basin. An in-depth analysis of results for the month of April, during the ERS, supports the hypothesis that fresh water is being produced as a result of changes in local and regional climate conditions.

Results for April during the years 2003 and 2012 are shown in Figure 6. They represent a growing period with 2003 being the lowest point in the recent record and 2012 showing the lakes in their continued expansion. Monthly accumulated precipitation difference over the Bahoruco mountains (Fig. 6a) shows that April 2012 produced more precipitation over the high elevations than April 2003, ~260-300 mm. The atmospheric column over the high sierras (integrated between 700 and 1500 m in the vertical) shows larger amounts of liquid water content in the growing period (Fig. 6b). These liquid water content differences are not only larger in the Bahoruco Sierra slopes but also span a larger portion of the sierra with no areas showing decreasing values thus generating increased cloud cover over the elevated terrain (Fig. 6d). We also observe from the differences in the wind patterns that wind advection produces a convergence zone along the ridge of both sierras, which is the main mechanism responsible for orographic clouds formation (Fig. 6c). This wind pattern supports a positive feedback mechanism that transports heat and moisture up the slopes of the surrounding sierras and maintains high humidity and liquid condensate levels in the TMCFs, which in turn produce fresh water via total precipitation (horizontal, vertical, and potential), that feeds into the system closing the loop.

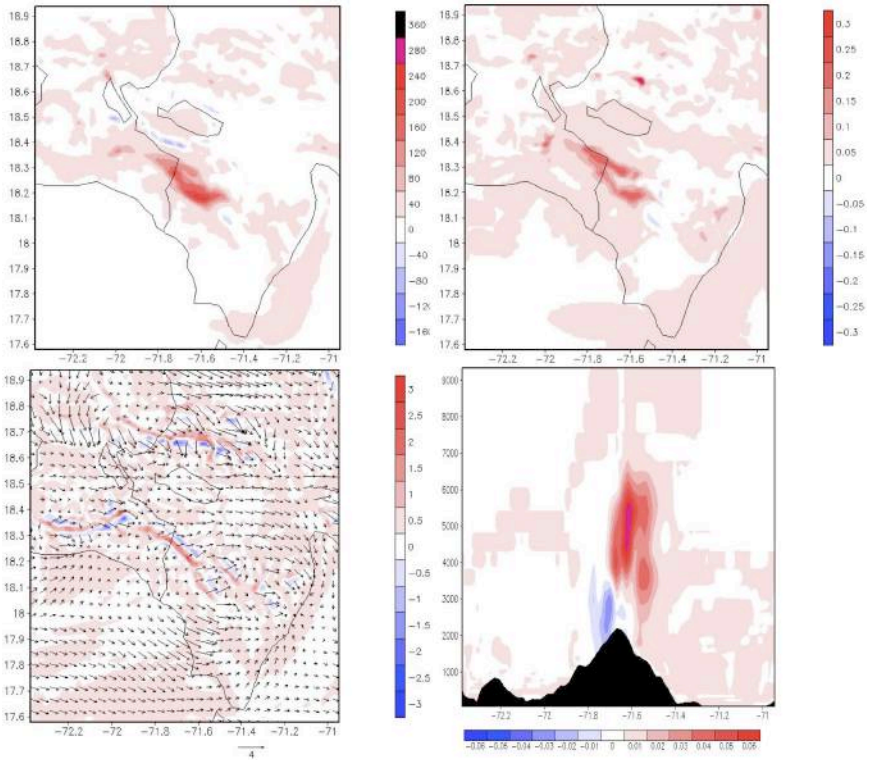

Figure 6. Model based differences between April 2003 and April 2033 for accumulated surface precipitation, mm (a, upper left); atmospheric liquid water content integrated between 700 and 1500 m, g kg^{-1} (b, upper right); horizontal wind (vectors) and vertical motion, m s^{-1} (c, lower left); and atmospheric liquid water content differences, g kg^{-1}, on a vertical cross section at 18.25N, black shading represent the underlying topography (d, lower right).

SUMMARY

The historical data analysis presented, complemented with regional atmospheric modeling results, show that regional climate changes play an important role in producing increased fresh water flows in the Enriquillo basin. Climate data analysis over the 1982-2013 period reflects increasing SSTs, air temperatures and precipitation. The CCNY-INTEC network provides valuable insights into the current climate conditions of the region, especially the TCMFs in the surrounding sierras and their role in producing fresh water. The atmospheric model simulations showed that precipitation increases during the Caribbean ERS when comparing monthly-accumulated results between 2012-13 and 2003-04. Furthermore, the month-long results for April show increased total accumulated surface precipitation, atmospheric liquid water content, and an enhanced positive feedback system that produces orographic cloud cover in the surrounding TMCFs during the lakes' growth period as a consequence of a changing climate.

Acknowledgements

This study was supported and monitored by NOAA CREST Grant #NA11SEC4810004, FONDOCYT of the Dominican Republic, and by NSF Grant # 1264466. We also extend our gratitude to Yolanda M. León and Cándido Quintana of INTEC for providing the GIS data of the lakes and lake water data, and to Equisha Glenn of CCNY for the SST data and analysis.

REFERENCES

[1] Mann P., Taylor, F.W., Burke, K., Kulstad R. (1984), Subaerially exposed Holocene coral reef, Enriquillo Valley, Dominican Republic, *Geol. Soc. Am. Bull. 95,* 1084–1092.

[2] Buck, D. G., Brenner, M., Hodell, D. A., Curtis, J. H., Martin, J. B., and Pagani, M. (2005), Physical and chemical properties of hypersaline Lago Enriquillo, Dominican Republic, *Verh. Internat. Verein. Limnol., 29,* 725-731.

[3] Perrisol, M. and Lescoulier, C. (2011), Étude Hydrologique et Hydrogéologique de la montée des eaux du lac Azueï Rapport de Mission. March 2011. Egis International

[4] Sheller, M., and León, Y. M. (2014), Assessing citizen understanding, bi-national state action, and capabilities for adaptation to the rising waters of Lake Azuéi (Haiti) and Lake Enriquillo (Dominican Republic), *Geoforum, Under Review.*

[5] Smith, T. M., Reynolds, R. W., Peterson, T. C., and Lawrimore, J. (2008), Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880-2006), *J. Clim., 21*, 2283-2296.

[6] Reynolds, R. W., Smith, T. M., Liu, C., Chelton, D. B., Casey, K. S., and Schlax, M. G. (2007), Daily High-resolution blended analyses for sea surface temperature, *J. Clim., 20*, 5473-5496.

[7] Pielke, R. A. et al. (1992), A comprehensive meteorological modeling system-RAMS, *Meteorol. Atmos. Phys,, 49*, 69-91.

[8] Comarazamy, D. E. and González, J. E. (2011), Regional Long-Term Climate Change (1950-2000) in the Mid Tropical Atlantic and its Impacts on the Hydrological Cycle of Puerto Rico, *J. Geophys. Res.,* doi:10.1029/2010JD015414.

[9] Comarazamy, D. E., González, J. E., Luvall, J. C., Rickman, D. L., and Bornstein, R. D., (2013a) Climate Impacts of Land-Cover and Land-Use Changes in Tropical Islands under Conditions of Global Climate Change, *J. Clim.,* doi: 10.1175/JCLI-D-12-00087.1.