On the Hydrometeorological Changes of a Tropical Water Basin in the Caribbean and Its Sensitivity to Midterm Changes in Regional Climate

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ABSTRACT

Global climate change manifests in the Caribbean basin as increased SSTs, precipitation anomalies, and changes in atmospheric moisture content, among other effects. These regional climate changes have a profound impact on the local human, flora, and fauna populations. Such is the case of the Enriquillo basin, a highly sensitive ecosystem located in the southwestern region of the Caribbean island of Hispaniola. The major bodies of water in the basin, Lake Enriquillo and Lake Azuéi, show a shrinking and expanding pattern since the early 1980s. The surface area of Lake Enriquillo was observed to reach minimum values in 2004 (170 km^2), shifting to a rapid expansion to its current levels (>350 km^2 as of late 2013). Lake Azuéi is observed to grow at similar rates. This lake expansion could be attributed to regional climate change. Long-term regional climate data reflect increasing SSTs (~1°C), air temperatures (~0.37°C decade^{-1}), dewpoint (~0.66°C decade^{-1}), and precipitation (~30%); no reliable local precipitation records were found. Furthermore, local governments are being forced to issue evacuations, prompting one of the first cases of environmental refugees not caused by an extreme event (e.g., a hurricane or tsunami). The hypothesis of lake expansion in the Enriquillo basin as a regional response to climate change is further investigated with the use of an integrated regional atmospheric modeling system. Model results from simulations performed for years during the lakes' lowest water levels (2003–04) and during their continued growth (2012–13) show increased total accumulated surface precipitation, atmospheric liquid water content, and an enhanced positive feedback system that produces orographic cloud cover in the surrounding tropical montane cloud forests as a consequence of the changing atmospheric and oceanic conditions.

1. Introduction

Enriquillo (Dominican Republic) and Azuéi (Haiti) are saltwater lakes located in the Neyba rift valley, a former marine strait isolated from the Caribbean Sea around 5000–2800 BP by tectonic uplift and river sediments

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(Mann et al. 1984). They are located in southwestern Hispaniola in the border region between the 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 m below mean sea level). 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 m above mean sea level (MSL)] and south (Bahoruco, ~2700 m MSL), providing a large catchment area while isolating the watershed from the ocean and, along with the mountain shadow effects of the much higher Central Range, the approaching northeasterly trade winds. The lakes have been experiencing dramatic changes in total lake surface area coverage during the period 1982–2013 (Figs. 1, 2). The size change of the lakes was determined using remote sensing images (NASA's Landsat) at different times during the available record for the Caribbean, and then surface area calculations were performed and analyzed with a geographic information system (GIS; Fig. 2). Remote sensing, GIS, and their integration are commonly applied in monitoring dynamic changes of lakes' size around the globe (Du et al. 2001; Wei et al. 2005; Zhang and Zhu 2007). The comparison of historical maps and sediment analysis from lakebeds that experience surface area fluctuations allows the generation of a larger temporal dataset of lake sizes (Currey et al. 1984; Tartari et al. 2008). Lake-level models, based on lake water balance calculations, where evaporation is derived from the lake energy balance and runoff from the soil moisture balance, are developed to study lake surface area and levels of prehistoric and present-day lakes on geological time frames (Vassiljev 1997, 2007).

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 experienced constant growth, reaching its 1984 size (280 km^2) during 2007–08, and exceeding 350 km^2 in 2013, 30% larger than in 1984 and almost double that in 2003. During the same period, 2003–13, Lake Azuéi's area increased by 22% (from 114 to 140 km^2). Recent bathymetry measurements, combined with surface area calculations and a digital elevation model of the area, revealed a 4 times increase of volume for Lake Enriquillo (from 1.2 to 4.7 km^3) in that period while Azuéi grew by ~1.35 times (from 1.7 to 2.3 km^3). The salinity of the lakes also showed dramatic changes over the same period of time. Field readings by the authors of this

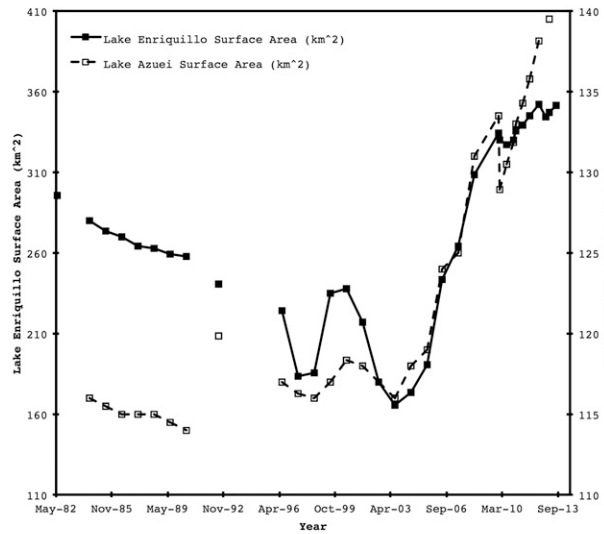

FIG. 1. Time series of surface area coverage (km^2) for Lake Enriquillo (solid line with closed squares) and Lake Azuéi (dashed line with open squares) calculated from Landsat images analyzed with a GIS.

work, using a National Industrial Supply handheld salinity refractometer with automatic temperature compensation, are the most recent recorded values of salinity in these lakes. Lake Enriquillo went from a hypersaline lake (102–105 ppt in 2003; Buck et al. 2005) to a brackish one (20–25 ppt in 2013), while Azuéi went from brackish (8–13 ppt; Perrisol and Lescoulier 2011) 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, with Enriquillo at 3000 km^2 and Azuéi at 700 km^2. Changes in salinity indicate a large influx of freshwater to the lakes, eliminating in large part the possibility of seawater intrusion to the bodies of water. Because the lakes are restricted topographically in the north and south directions, most of the size changes occur on the southeastern side of both lakes (especially on Lake Enriquillo) with some growth to the west (Fig. 2).

Determining the causes of lake surface area changes is of extreme importance because of the ecological, social, and economic impacts. In 2009 more than 18 865 ha of agricultural land around the lake was flooded, impacting 16 communities and some 10 000 families (Medrano 2009), while flooding the highway connecting the two countries at the Malpasse–Jimani border crossing, affecting the commercial traffic and associated economic activity (Pierre et al. 2009). Total lake surface area has been used as an indicator of climatic and environmental change (Benson and Paillet 1989; Carpenter et al. 2011). In this case, all lake hydrologic variables have reflected

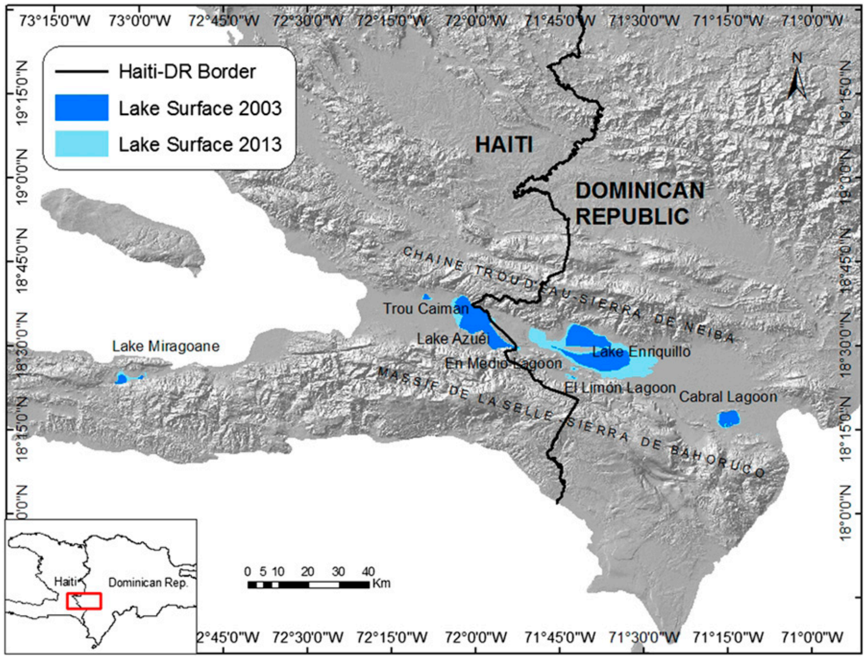

FIG. 2. GIS analysis of surface area coverage based on satellite images for 2003 (dark blue) and 2013 (light blue) for the larger southwestern Hispaniola region showing the size change of Lakes Enriquillo and Azuéi along with other bodies of water outside of the Enriquillo basin. Also shown is the location of the lake basin relative to Hispaniola (insert). Prepared by the Remote Sensing Laboratory of INTEC.

changes, including lake volume, lake surface area, and salinity, with surface area as the most evident from ground and satellite observations. The most widely accepted hypothesis for the cause of the lake surface area changes is that it is related to natural climate variations at geological time scales (Benson 1978; Benson and Paillet 1989; Digerfeldt et al. 1997; Daut et al. 2010). At shorter scales, however, most specifically during the twentieth century, changes in lake area are attributed to variations in precipitation patterns; anthropogenic-induced hydroclimatic changes, such as diversion of water for agricultural purposes; and land cover and land use (LCLU) changes. Since global mean air temperature increases have different effects at regional as compared to local spatial scales (IPCC 2007), effects on lake surface area are specific to how global warming impacts characteristics of local water basins (Wei et al. 2005; Croley and Lewis 2006; Yu and Shen 2010; Troin et al. 2010). Additional factors contributing to the lake growth are LCLU changes, most specifically deforestation and use of land and water agriculture, which affect the lake surface area in two ways: 1) via increased runoff for lake growth and 2) through increased sedimentation that contributes to reduction of lake volume (Crapper et al. 1996; Su and Jassby 2000; Du et al. 2001; Legesse and Ayenew 2006; Sidle et al. 2007).

Another factor that may play a role is the catchment mechanisms that originally formed the lake (Tartari et al. 2008). It was reported that 96% of the lakes in Sagarmatha National Park, Nepal, whose surface area increased are located in glacial basins, whereas the majority of the lakes without glacial cover in their catchment showed a reduction in surface area, with 83% of them disappearing. This behavior, observed over a short period of time, would appear to be consistent with the consequences of temperature increases recorded from the end of the 1970s on a global and regional scale. Since Lakes Enriquillo and Azuéi did not have glacial cover in their catchment, 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 lakes have no permanent natural surface inputs except for a series of seasonal streams. Other inputs include direct rainfall over the lakes' surface, groundwater, and a series of intricate man-made channels used for agriculture and domestic purposes that at some point

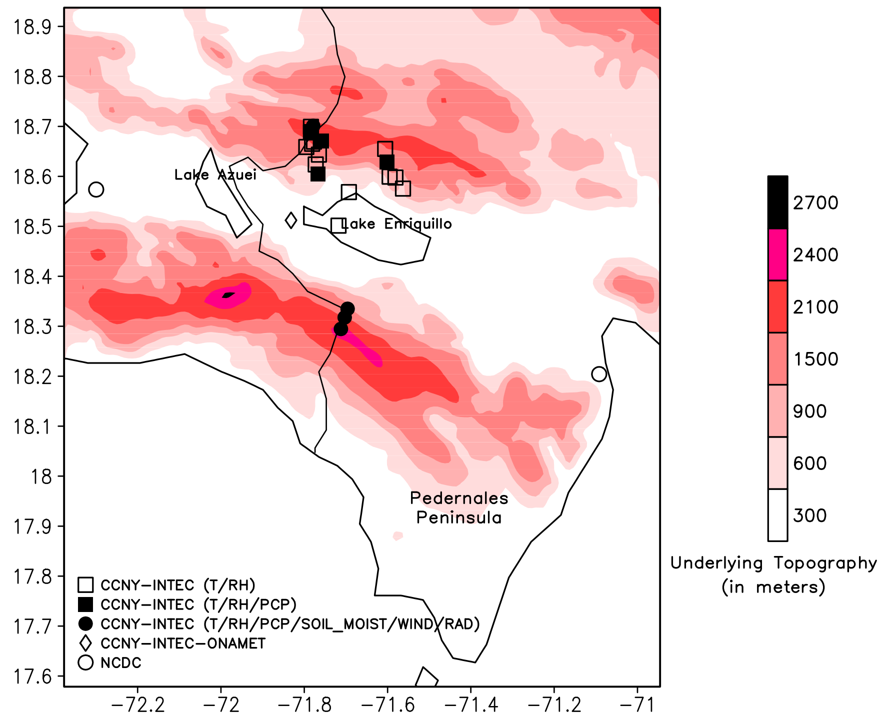

FIG. 3. Location of surface weather stations used in this study. Shaded contours represent the underlying topography (contour interval is 300 m) used in grid 3 of the modeling exercise.

flow into the lakes. There are no surface outputs, and it is believed that the only water outputs are direct evaporation off the lakes' surfaces and underground flows. Determining underground flows and water production in the surrounding sierras, whether by precipitation, fog catchment, and other sources, is extremely difficult because of the lack of data and knowledge regarding the geology and groundwater dynamics in the region. Several groups have studied some of these aspects individually, but a comprehensive hydrological analysis of the Enriquillo basin is pending; thus, we only consider the atmospheric freshwater production component of the system.

The hydroclimate change hypothesis postulates that a change in the water balance of the Enriquillo basin is the main cause of the changes in the surface area of the lakes. It is presumed that higher regional SSTs increased evaporation from the surrounding ocean water, which in turn increases relative humidity, convective and orographic cloud formation, and accumulated surface precipitation while reducing evaporation off the lakes' surfaces because of the air being saturated. This, in combination with possible LCLU changes along the sierras north and south of the lakes, would increase surface runoff to the base of the closed basin where the lakes are located and to the subterranean aquifers that feed them.

Preliminary studies performed analyzing historical data obtained from satellites and surface weather and hydrological stations appear to support the hydroclimate change hypothesis. These climate datasets include sea surface temperatures (SSTs) of waters surrounding the Pedernales Peninsula, air temperature, dewpoint temperature, and precipitation from the Cooperative Observer (COOP) station in Barahona, as archived by the National Climatic Data Center (NCDC), and several weather stations managed by the authors of this work (Fig. 3). A detailed analysis of these data sources is given in the next section. Given the lack of long-term observational data within the catchment area itself, an integrated atmospheric modeling approach is used to further explore the hydrological changes theory as the main cause of lake size variations during key shrink and growth periods over ~20 years (section 3). Also given in section 3 is a brief LCLU change analysis, as this can affect hydrological cycle variables like runoff, precipitation, soil moisture, evapotranspiration, and fog catchment, among others. A summary and conclusions are presented in section 4.

2. Regional and local climate data

a. 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 is reflected in

TABLE 1. Dataset and station identification and location. ONAMET is the Oficina Nacional de Meteorología.

No.	Station ID	Network	Lat (°N)	Lon (°W)	Elev (m MSL)	Variable	Dates
1	Cabritos Island	CCNY–INTEC	18.495	71.721	−5.5	T and RH	2012–13
2	La Descubierta	CCNY–INTEC	18.562	71.697	−19	T and RH	2012–13
3	Los Pinos	CCNY–INTEC	18.598	71.770	544	T, RH, and P	2012–13
4	Flag Point 1	CCNY–INTEC	18.617	71.776	765	T and RH	2012–13
5	Angel Felix	CCNY–INTEC	18.636	71.768	1139	T and RH	2012–13
6	Sabana Real	CCNY–INTEC	18.652	71.798	1301	T and RH	2012–13
7	Park Ranger Post 1	CCNY–INTEC	18.658	71.784	1461	T and RH	2012–13
8	Flag Point 2	CCNY–INTEC	18.662	71.780	1546	T and RH	2012–13
9	Flag Point 3	CCNY–INTEC	18.664	71.762	1720	T, RH, and F	2012–13
10	Flag Point 4	CCNY–INTEC	18.681	71.787	1882	T and RH	2012–13
11	Flag Point 5	CCNY–INTEC	18.681	71.787	1883	T, RH, and F	2012–13
12	Pyramid 204	CCNY–INTEC	18.692	71.788	1960	T and RH	2012–13
13	Military Control	CCNY–INTEC	18.694	71.782	1874	T, RH, P, and F	2012–13
14	Flag Point A	CCNY–INTEC	18.593	71.600	576	T and RH	2012–13
15	Flag Point B	CCNY–INTEC	18.591	71.586	860	T and RH	2012–13
16	Flag Point C	CCNY–INTEC	18.569	71.568	1156	T and RH	2012–13
17	Higo de la Cruz	CCNY–INTEC	18.621	71.606	1339	T, RH, and P	2012–13
18	Road Intersection	CCNY–INTEC	18.648	71.610	1285	T and RH	2012–13
19	El Aguacate	CCNY–INTEC	18.330	71.700	1078	T, RH, and P	2013
20	Zapotén	CCNY–INTEC	18.312	71.707	1537	T, RH, P, and F	2013
21	Loma del Toro	CCNY–INTEC	18.290	71.716	2355	T, RH, P, and F	2013
22	Jimaní	CCNY–INTEC–ONAMET	18.505	71.835	56	T, RH, and P	2012–13
23	Barahona	NCDC	18.200	71.100	3	T, RH, and P	1973–2013
24	Port-au-Prince	NCDC	18.567	72.300	34	T, RH, and P	1973–2013
25	2.5° reanalysis	NCEP	Gridded		17 levels	T and RH	1973–2013
26	OISST	NOAA	Gridded		Surface	SST	1982–2012
27	ERSST	NOAA	Gridded		Surface	SST	1900–2005

the region of interest, atmospheric and oceanic conditions were analyzed. Atmospheric gridded fields for the last 50 years are provided by the NCEP–NCAR reanalyses (2.5° × 2.5° resolution; Kalnay et al. 1996). SSTs are derived from two NOAA products: the Extended Reconstructed SST, version 3b (ERSST.v3b; Smith et al. 2008), and the daily Optimum Interpolation SST (OISST; 0.25° resolution; Reynolds et al. 2007). Surface weather data were obtained for Barahona (18.2°N, 71.1°W) and Port-au-Prince (18.57°N, 72.3°W) from COOP stations. Table 1 and Fig. 3 summarize the observational and reanalysis data sources used in this study.

Recent reports using the NCEP–NCAR reanalyses indicate that large-scale temperature changes at times of local overnight low and daytime high temperatures over the Caribbean region show moderate temperature increases on the order of 1.0°–1.8°C, respectively; these values increase toward the North Atlantic (Comarazamy and González 2011). There is also a reported general increasing trend of the 1900–2005 ERSST.v3b, associated with differences between Caribbean and North Atlantic near-surface pressures (Jury and Winter 2010; Angeles et al. 2007), with periods of more pronounced change (from 1920 to 1940 and from 1975 to present). Around the Greater Antilles, SST differences peak at 0.1°–0.2°C and increase to the northeast of the islands, reaching values of 1°C toward the northern tropical Atlantic (Comarazamy and González 2011). The difference in warming rates between near-surface air temperatures and SSTs has been previously associated with an accelerated Hadley circulation, with sinking motions over the Caribbean corresponding with increasing rising motion over the Amazon (Jury and Winter 2010). These changes in turn result in accelerated surface winds near Puerto Rico, disrupting the climatological rain-producing mechanism over the island, producing a dramatic reduction in atmospheric liquid water content and accumulated precipitation at high topography (Comarazamy and González 2011; Comarazamy et al. 2013). In Hispaniola, on the other hand, mountain shadow effects from the Northern (~1200 m MSL) and Central Ranges (~3100 m MSL) isolate the Enriquillo basin from the approaching northeasterly trade winds and the effects that any changes may produce over time. The Neyba and Bahoruco sierras further isolate the basin from regional-scale wind patterns.

The ERSST.v3b for the open waters surrounding the Pedernales Peninsula show that SSTs have increased 1°C during the past 30 years, the period of lake surface area measurements based on satellite images (Fig. 4, top; solid black line). The higher-resolution OISST

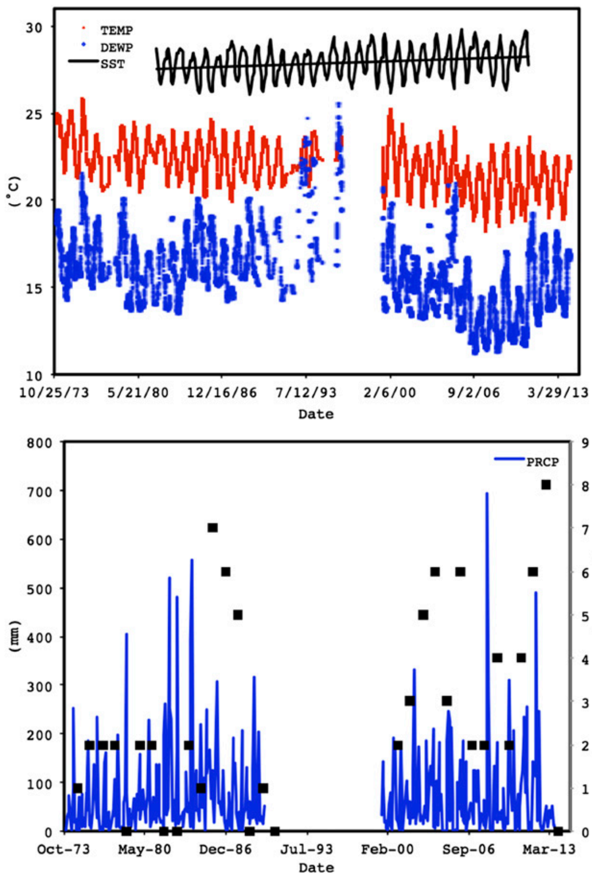

FIG. 4. Climate data recorded at the Barahona station, as archived by the NCDC. (top) Monthly SST (with linear regression trend line), daily mean air temperature, and dewpoint temperature (°C). (bottom) Monthly accumulated precipitation (mm) and yearly count of days recording >50 mm of precipitation.

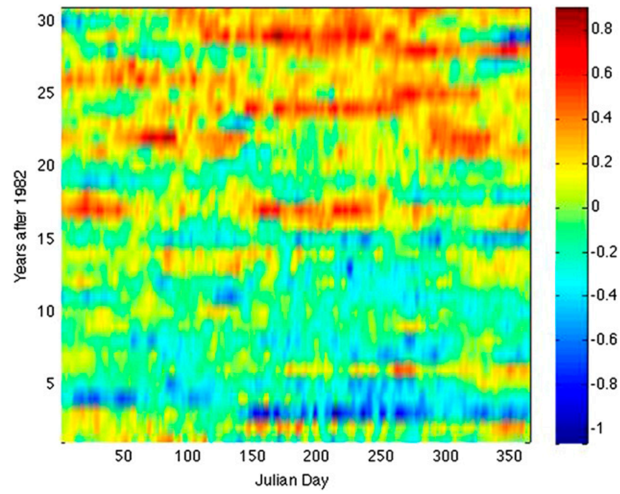

FIG. 5. Regional-scale OISST anomalies (°C) for the period 1982–2012.

product shows a clear SST increase pattern over the region between 5°N, 100°W and 31°N, 55°W, and for the same time frame, with much of the warming occurring during 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 (Fig. 5). As indicated before, this increase in SST could produce an increase in atmospheric relative humidity in the region. The COOP station located in Barahona shows an indication of this possible increase in dewpoint (Fig. 4, top; air and dewpoint temperatures are indicated by red and blue lines, respectively). As the relative humidity of an air parcel increases, its dewpoint temperature approaches the current air temperature and the air parcel is saturated. Figure 4 (top) shows how dewpoint decreased, on average, by 2.5°C in the early 1980s, a time when the surface area of the lakes was decreasing at the start of the satellite-derived measurements. It is also seen that from the mid-to-late 1990s to early 2000s, humidity increased considerably, resulting in periods of transition and growth of lake surface area; unfortunately, the large amount of missing data during this period in the station's temperature time series prevents the calculation of meaningful statistics. At the end of the time series period presented, dewpoint temperature increased by ~3.5°C from 2005 to 2013, a faster rate than dry-bulb temperature. There appears to be a trending relationship between temperature and dewpoint with the lake surface area at specific periods, but not throughout the entire time series, except in the recent growth trends. This could be because there is no such relation between the datasets, or that the lake surface area responds to specific events, or that this response has a time lag to be determined and studied in further detail. Figure 4 (bottom) shows the monthly accumulated surface precipitation recorded by the Barahona station; here it is seen how precipitation has increased since the year 2000, after the period of missing data, in relation to the period 1980–95. There is also an increase in precipitation events recording 50 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. All of these changes in climate variables recorded by the Barahona COOP station were found to be statistically significant at the 95% confidence level after applying a two-tailed Student's t test to the different datasets for the entire time series (1973–2013).

b. Local-scale weather and climate data

To compensate for the fact that the NCDC stations are located outside the Enriquillo basin and the catchment area of the lakes and for the relative lack of surface

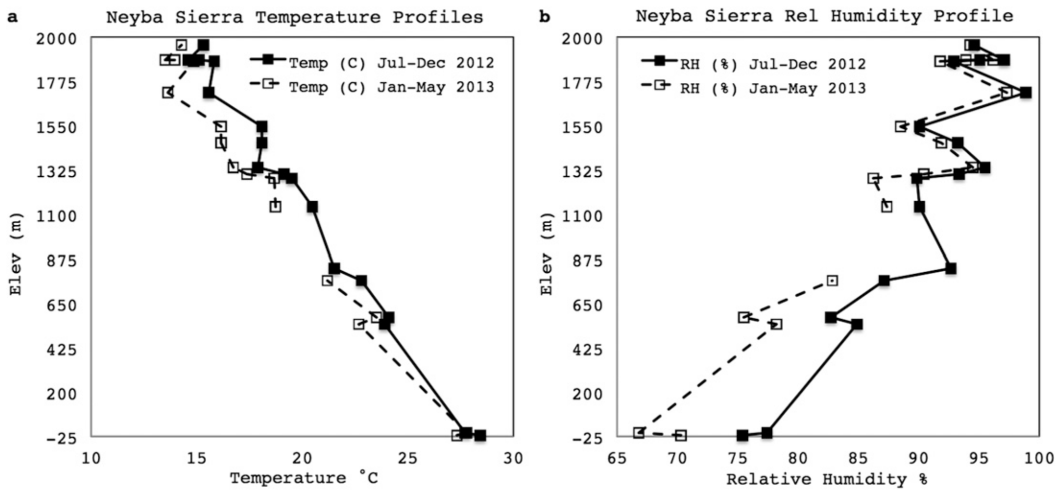

FIG. 6. Vertical profiles constructed with data from weather stations of the CCNY–INTEC network in the Neyba sierra. Presented are (a) average temperature (°C) and (b) relative humidity (%) for each location during July–December 2012 (summer months and LRS; solid line with closed squares) and January–May 2013 (dry months and ERS; dashed line with open squares).

data sources within the basin, a series of weather stations with sensors for temperature T and relative humidity RH were deployed along the sierras surrounding the lakes to the north and south and at lake level, between February 2012 and March 2013, referred to as the City College of New York–Instituto Tecnológico de Santo Domingo (CCNY–INTEC) network. The CCNY–INTEC network consists of 21 T and RH sensors, six precipitation P gauges, and five fog F gauges, all deployed across 18 locations in the Neyba sierra and three locations in the Bahoruco sierra (Fig. 3, Table 1). Other variables recorded by the CCNY–INTEC network include soil moisture, wind speed, wind direction, and solar radiation. It is acknowledged that this new network of stations and sensors will not serve to make long- or medium-term climate assertions; however, they do provide a baseline 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 because of the remoteness of the area.

Figure 6 shows data from the temperature and relative humidity sensors along the Neyba sierra, where the first set of deployments occurred, for one full year of recordings (12-month period, from July 2012 to June 2013). The vertical profiles shown for temperature and relative humidity against altitude were calculated by averaging the data for each location over two different periods of time, to account for relatively dry and wet periods according to precipitation seasons on the island. These periods are specified as July–December 2012 [summer months and late rainfall season (LRS)] and January–May 2013 [dry season and early rainfall season (ERS)]. The Caribbean annual precipitation follows a bimodal pattern, where each mode divides the annual variability in two distinct seasons: the ERS (April–July with a peak in May) and the LRS (August–November with a peak in October). The low rainfall peak between the ERS and LRS defines the Caribbean bimodal behavior and is often referred to as the midsummer drought (MSD; Magaña et al. 1999; Taylor et al. 2002; Chen and Taylor 2002; Mapes et al. 2005; Gamble and Curtis 2008; Angeles et al. 2010; Comarazamy et al. 2013). For temperature, values for the late season profile are slightly shifted accounting for the temperatures being a few degrees cooler (Fig. 6a). For relative humidity, it is shown that the environment is much drier at lake level and low mountain elevations, whereas starting at about 1325 m MSL and within the tropical montane cloud forest (TMCF; >1550 m MSL) humidity values are similar for both climate periods (Fig. 6b). This is an indication of the TMCF maintaining its capacity to produce freshwater and releasing it to the ecosystem. It is hypothesized that this freshwater 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 freshwater is further evidenced by the fact that measurable water from fog gauges installed in both sierras shows that fog events are of the same order of magnitude as precipitation events and that they can occur even when little or no precipitation is recorded (Fig. 7). It is worth noting that the fog gauge equipment is a novel

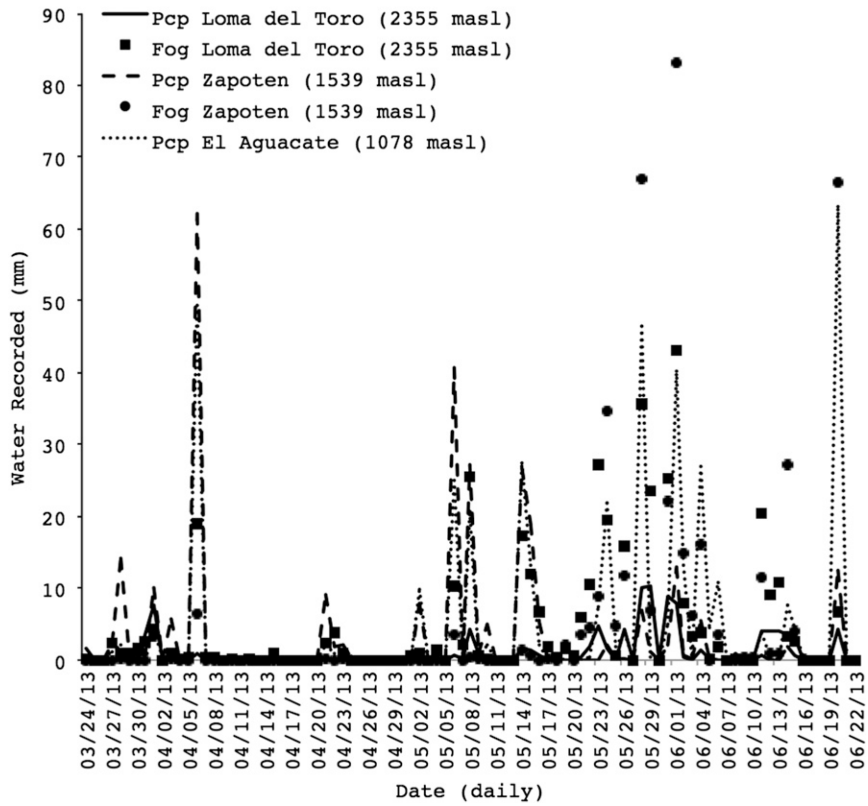

FIG. 7. Accumulated precipitation (solid, dashed, and dotted lines) and fog catchment (squares and circles) data from the weather stations in the Bahoruco sierra (mm).

design that needs to be further tested in the field and in controlled laboratory experiments in order to produce calibration curves and to be able to interpret the measurements appropriately. However, it was evident from the gathered observations that a large amount of freshwater was being produced from the mountain clouds.

3. Regional atmospheric modeling and sensitivity analysis

a. General descriptions and experimental setup

To further validate the hydroclimate hypothesis and to complement the observations, an integrated atmospheric modeling and remote sensing approach was used. The atmospheric model chosen for the study is the Regional Atmospheric Modeling System (RAMS; Pielke et al. 1992; Cotton et al. 2003), which has been used extensively to study different phenomena at various temporal and spatial scales in the Caribbean basin (Lawton et al. 2001; Nair et al. 2003; Comarazamy et al. 2006, 2010, 2013, 2015; Velazquez-Lozada et al. 2006; Ray et al. 2006; Angeles et al. 2007, 2010; Comarazamy and González 2008, 2011). The main goal of the numerical study is to investigate changes during key periods of lake shrinking and growth. The simulations are configured to integrate remote sensing information, surface weather observations, and 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.

It is believed that water cycle balance and LCLU changes are among the main causes for the recent rise in lake levels and surface area changes. To incorporate these hypotheses, satellite images, similar to those used in the calculations presented in Figs. 1 and 2, have been used to study the LCLU specifications of the Enriquillo watershed and surrounding sierras (Romero and Ponteau 2011) and are incorporated in the present modeling study. Romero and Ponteau (2011) performed a land cover specification comparison for the years 1986 and 2010 and found that only slight changes in LCLU have occurred during the period analyzed. Among the vegetation and land classes that have experience changes are developed/residential (0.9% of total area in 1986 versus 3% in 2010) and small subsistence agriculture (15.7% versus 8.3%), the latter a possible consequence of the flooding

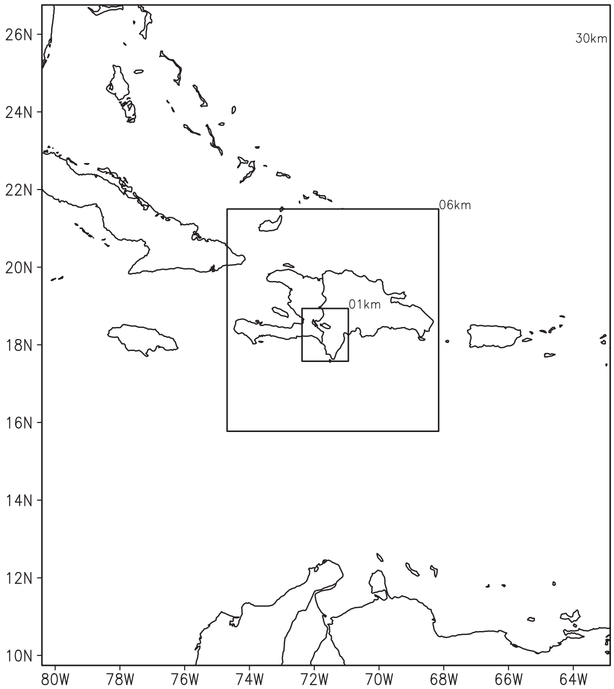

FIG. 8. Model grids used in the atmospheric modeling exercises; the horizontal resolution of each grid is shown.

and displacement of farming communities. Forested areas, with emphasis on the Neyba and Bahoruco TMCFs, appear to remain relatively unchanged in the images analyzed (just over 2% in both years), whereas conifer forest showed a marked decrease (5.9% versus 3%), possibly due to deforestation for burn wood in Bahoruco. As expected, inland bodies of water have experienced large surface area increases (8.6% versus 9.3%) that are not limited to the two large lakes but also include numerous smaller lakes, such as Cabral Lagoon and Lake Miragoane, and this is a possible indication of a regional phenomenon (Fig. 2; Romero and Ponteau 2011). The LCLU specifications of 2010 (from Romero and Ponteau 2011), along with other USGS land class maps to account for areas in the modeling grids not covered by this, NCEP–NCAR reanalyses, and OISST data for the appropriate periods, are all incorporated to the atmospheric model configuration.

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 and Bahoruco sierra–Massif de la Selle, Pedernales Peninsula, and the surrounding ocean (Fig. 8). The use of a regional atmospheric model allows the incorporation of different climate (given by NCEP–NCAR reanalyses), SST, and LCLU change effects, and the analysis of variables and phenomena for which no observations exist (i.e., atmospheric liquid water content, orographic cloud formation, and cloud-base height and depth). According to the hydroclimate change hypothesis, the growth in lake surface area is, for the most part, a consequence of increased regional humidity, surface accumulated precipitation, and cloud/fog formation due to regional climate changes and of increased surface runoff due to local LCLU changes. The atmospheric model simulations during key periods of lake surface area decrease and increase will allow for the study of the relation between atmospheric variables during such times. Simulations include yearlong runs from April 2003 to March 2004 and from April 2012 to March 2013. The 2012–13 time frame was chosen to match the data period generated by the CCNY–INTEC network to validate model results, and also because 2003–13 represents the growth period for the lakes in the Enriquillo basin. An additional month-long simulation was executed for April 1995, when the lakes were shrinking before a period of high variability before reaching the period low in 2003 (oscillating between 238 and 165 km^2), to test model sensitivity to different inputs. Because of the lack of real land surface state values, first guess values were used for the soil model module of the atmospheric modeling system, and an appropriate spinup time of 10 days for the yearlong simulations and 4 days for the month-long simulations was used to allow the model to stabilize and produce satisfactory results. The spinup time was determined after trial and error iterations during the model validation–calibration process (see the next section for the end results).

b. Regional atmospheric modeling results

1) MODEL VALIDATION

After all input information and parameters presented in the previous section were incorporated into the atmospheric model as initial and boundary conditions and as surface characteristics, and after simulations were performed, the 12-month-averaged temperature and relative humidity and individual values of daily minimum and maximum air temperatures at 2-m above ground level and surface accumulated precipitation from the 2012–13 simulation were validated and compared with corresponding observed values from Table 1 and Fig. 3, following procedures developed for the same model applied to similar regions in the Caribbean (Comarazamy and González 2011; Comarazamy et al. 2013, 2015). Results for the relative humidity vertical profile along the Neyba sierra show that the model generated a smooth profile with high levels of agreement with observations (Fig. 9, right). The observed variability

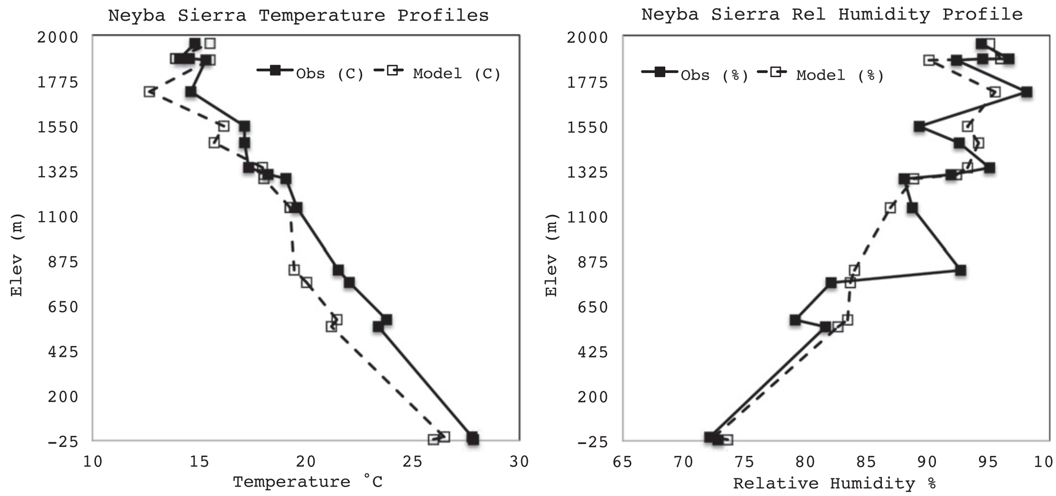

FIG. 9. Vertical profiles of (left) temperature (°C) and (right) relative humidity (%), constructed with data from weather stations of the CCNY–INTEC network in the Neyba sierra (solid line with closed squares) and atmospheric model results at grid points closest to the stations (dashed line with open squares).

in humidity at high elevations might be due to the fact that the different vegetation characteristics of the Neyba sierra tropical montane and premontane forests are affecting humidity levels and its variability, and that at 1-km horizontal resolution the atmospheric model is not capturing these individual variations while still reproducing the overall pattern very closely. A similar pattern emerges when comparing the vertical temperature profile in the Neyba sierra. While the overall pattern for temperature is replicated, values are between 1° and 2°C cooler, especially at the base of the profile, while the values match better at higher elevations (Fig. 9, left). This cold bias in the model results might be explained by looking at the comparison between daily minimum and maximum temperatures individually instead of a daily average for each location.

Figure 10 shows scatterplots for model-produced maximum and minimum temperatures at lake-level NCDC locations. Results for maximum temperatures present a high level of correlation (Fig. 10, red circles), while results for minimum temperature, on the other hand, show that the model produced cooler temperatures (Fig. 10, blue circles). The underprediction of minimum temperatures at lake level could be an indication of the model overcompensating for the drier conditions locally and producing more sensible heat flux as opposed to latent heat flux. Figure 11 shows the comparison of model-produced daily accumulated precipitation with the values recorded by the stations in the Bahoruco sierra (south of Lake Enriquillo). Here it is seen that the model performed well at the lower- and midelevation locations, El Aguacate (1078 m MSL) and Zapoten (1537 m MSL), respectively. At the higher elevation in this sierra (Loma del Toro; 2355 m MSL), however, the comparison reflects an overprediction by the model for precipitation. Given these results, we conclude that the atmospheric mesoscale modeling methodology used in this work may not fully account for the effects of humidity and soil moisture at lake level, which includes all urban/built-up areas in the domain. Surface and air temperatures, on the other hand, correlate well with previous research for the Caribbean (Comarazamy et al. 2013). In the forested regions at higher elevations, the model does, however, account for the full effects of relative humidity and volumetric soil moisture content, therefore producing more accurate temperature and precipitation results.

In general, acknowledging slight tendencies for the underprediction of minimum temperatures and overprediction of precipitation at Loma del Toro, 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 of medium-term changes in climate conditions on the hydrological balance of a closed tropical lake basin.

2) SENSITIVITY TO MEDIUM-TERM CLIMATE CHANGES

A key objective is to test the sensitivity of the model's ability to simulate atmospheric water production (i.e., cloud formation, rain development, and surface precipitation) to different input parameters and driving conditions. This is done to quantify the effects of medium-term climate change and variability on the water balance of the Enriquillo basin and what role they play in the increase of lake surface area. The simulations

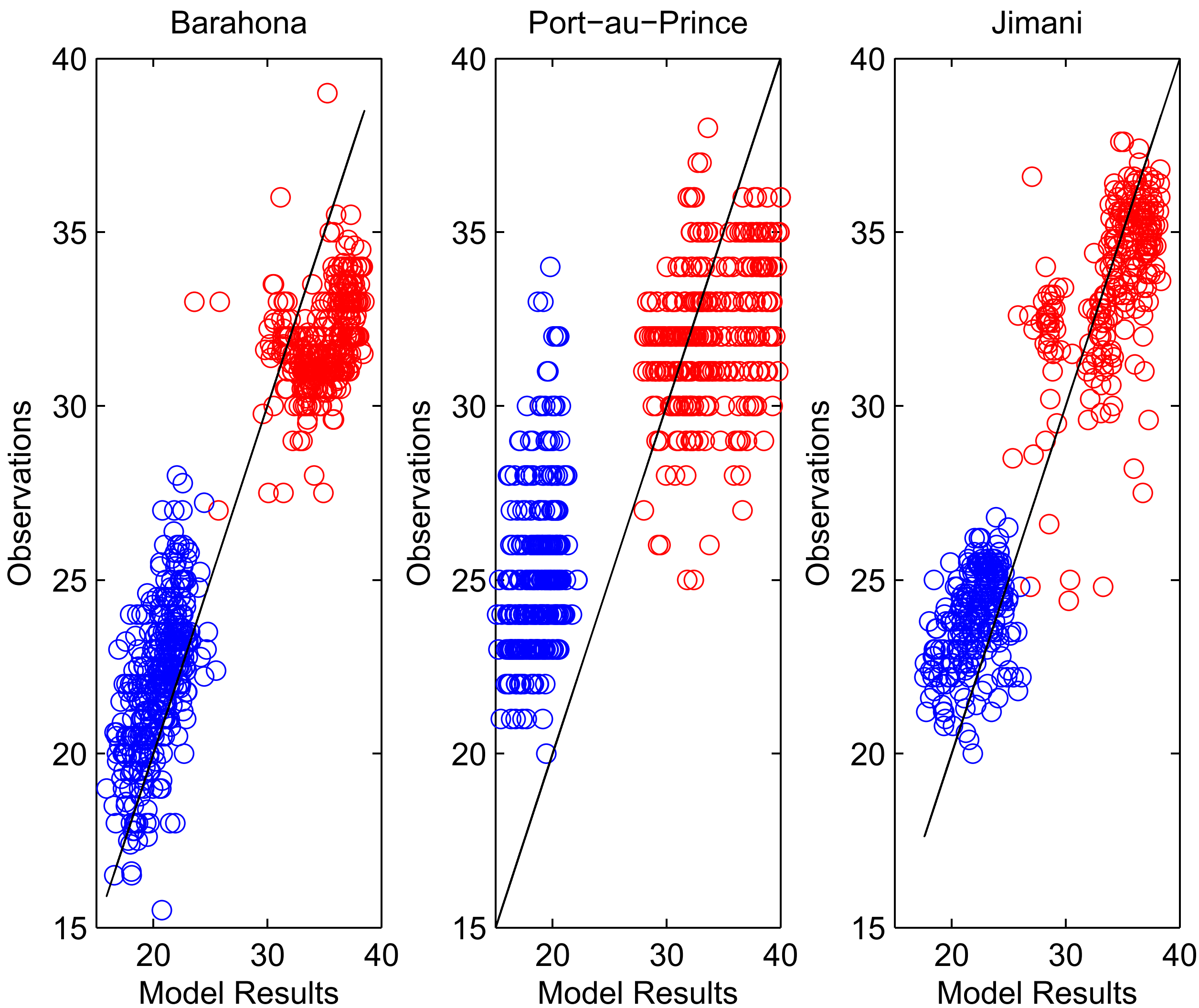

FIG. 10. Scatterplots of observations vs model results for average daily min (blue) and max (red) temperatures (°C) from April 2012 to March 2013. Stations presented are (left) Barahona, (middle) Port-au-Prince, and (right) Jimani.

span two yearlong periods from April to March 2003–04 and 2012–13, as well as an additional month-long simulation for April 1995. These time periods were chosen as they represent the period of sudden growth of Lakes Enriquillo and Azuéi during the past 10 years; 1995 represents a period of transition between shrinking and growth and lake area fluctuations before reaching satellite-record low levels in 2003.

The yearlong simulations show that differences in monthly accumulated surface precipitation, averaged over the grid points closest to the 24 observation sites (Fig. 3) between the periods 2012–13 and 2003–04, are larger at the beginning of the modeling period and remain positive during the Caribbean ERS and then diminish steadily until the summer months (Fig. 12, left). Precipitation differences continue to turn negative, indicating 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. It would appear that the opposite effects of increased and decreased precipitation during the different rainy seasons, and relatively small changes during the summer months, would produce a net neutral difference in accumulated precipitation throughout the year. However, when examining the daily precipitation difference, we noticed a pattern where most of the differences found for the ERS are produced over much of the period spanning from April to mid-June, whereas the precipitation differences over the summer and LRS are produced by single events over 1 or 2 days at a time for 4–5 extreme events (Fig. 12, right). The 2003 hurricane season was more active than 2012, but 2012 had more category 1–5 storms. The four

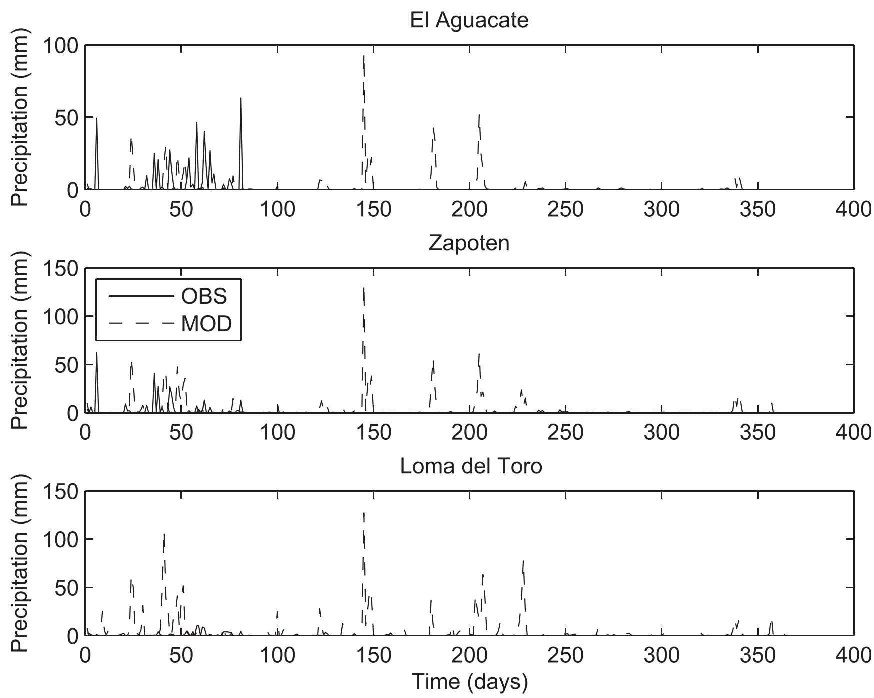

FIG. 11. Time series of daily accumulated precipitation (mm) produced by the regional atmospheric model and recorded by the weather stations from April 2012 to March 2013. Stations presented are (top) El Aguacate, (middle) Zapoten, and (bottom) Loma del Toro.

main precipitation difference spikes in Fig. 12 (right) during the period from 1 July to 31 December could be related to Hurricanes Isaac (category 1; from 21 August to 1 September 2012) and Sandy (category 3; from 22 to 29 October 2012) for the positive spikes and Tropical Storms Mindy (from 10 to 14 October 2003) and Odette (from 4 to 7 December 2003) for the negative spikes. While it would be desirable that the atmospheric model and data assimilation system reproduce tropical storm activity and its associated rainfall amounts, it would be misleading to compare precipitation differences between the two periods during the LRS, when precipitation is dominated by synoptic systems and differences are biased by them. Hence, a more in-depth study into the historical impact of tropical storms on the lake size fluctuations should be conducted for such specific events. Moreover, during the ERS, precipitation in the Caribbean is dominated by local and regional factors such as orographic rain and cold fronts, respectively, 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, for key periods of lake size shrinking and growth supports the hypothesis that freshwater is being produced as a result of changes in local and regional climate conditions.

Modeling results for the month of April during the years 1995 and 2003 are shown in Fig. 13. This represents a period of lake-level fluctuations before reaching the lowest point on record in 2003. Monthly accumulated precipitation difference (Fig. 13a) shows that April 2003 produced more precipitation than April 1995, ~260–360 mm, especially over the higher elevations of the sierras, with added emphasis over the Bahoruco sierra, south of Lake Enriquillo. In the atmospheric column over the same sierra locations, the model produced larger amounts of liquid water content integrated between 700 and 1500 m over the highest elevation (Fig. 13b). There is, however, significantly less liquid water content over much of the slopes along the Bahoruco sierra, a result better visualized along an east–west vertical cross section at 18.25°N as shown in Fig. 13d. 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. 13c). This wind pattern supports a positive feedback mechanism that transports heat and moisture up the slopes of the surrounding sierras and maintains high moisture and liquid condensate levels in the TMCFs, which in turn produce freshwater via total precipitation (horizontal, vertical, and potential) that feeds into the system closing the loop.

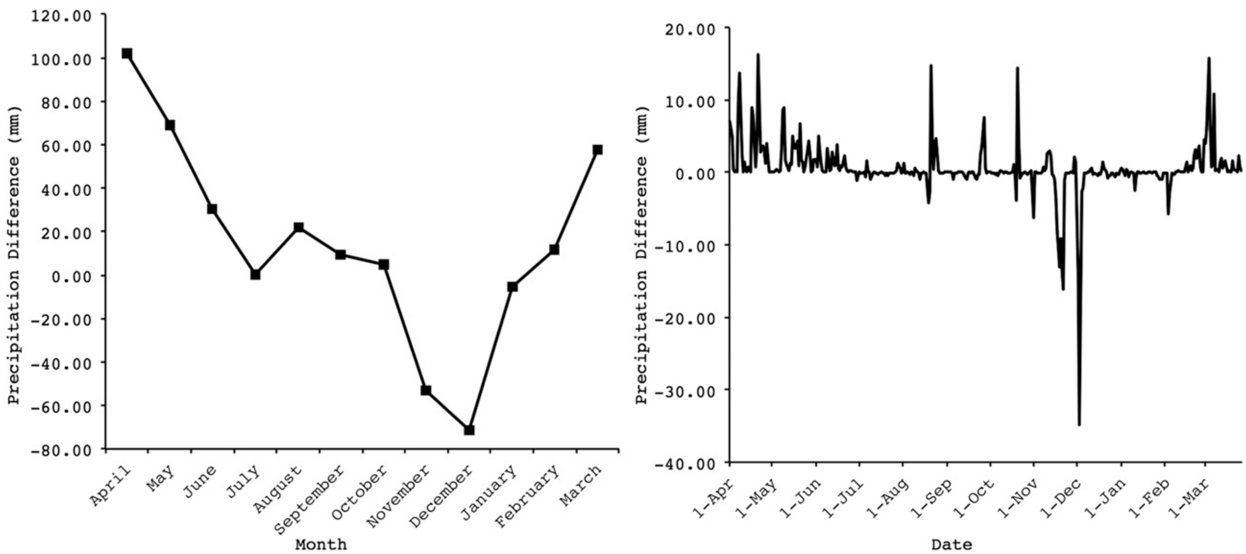

FIG. 12. (left) Monthly and (right) daily accumulated surface precipitation difference (mm) from April to March 2003–04 and 2012–13.

Results for April during the years 2003 and 2012 are shown in Fig. 14. They represent a growing period with 2003 being the lowest point in the recent record and 2012 showing the lakes in their continued expansion in the Caribbean early rainfall season. Monthly accumulated precipitation difference over the Bahoruco sierra (Fig. 14a) 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. 14b). 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. 14d). In this scenario of increased humidity, atmospheric liquid water content, cloud cover, and surface accumulated precipitation, along with stronger surface winds (Fig. 14c), the mechanism that maintains a healthy TMCF and freshwater production system is also enhanced.

4. Summary and concluding remarks

The historical data analysis presented in this document, complemented with integrated regional atmospheric modeling results, LCLU data, and regional atmospheric–oceanic conditions, have shown that regional climate and hydrological cycle changes play an important role in producing increased freshwater flows in the Enriquillo basin. We reason that these are responsible for the surface area increase observed for Lakes Enriquillo and Azuéi, as well as other smaller bodies of water in southwestern Hispaniola. The long-term regional climate data analysis reflects increasing SSTs over a 30-yr period (1982–2013) and increasing air temperatures, dewpoint, and precipitation during 1973–2013. The CCNY–INTEC network of weather stations and sensors does not provide a dataset long enough for long- or medium-term climate assessments, but it does provide valuable insights into the current climate conditions of the region, especially the TCMFs in the sierras to the north and south of the lakes and their role in producing freshwater, as well as serving for modeling result validation and calibration.

The atmospheric model simulations were executed for two yearlong periods spanning the recent period of lake surface area growth in the Enriquillo basin (2003–04 and 2012–13). An additional month-long simulation was configured for April 1995, a key period of lake surface area decrease before a short period of fluctuations and subsequent growth. The yearlong simulations showed that precipitation increases during the Caribbean ERS when comparing monthly accumulated results between 2012–13 and 2003–04, remains relatively unchanged in the summer months, and decreases in the LRS. A close look at the daily accumulated results shows that the increase during the ERS is produced by daily differences throughout the season, whereas the change in the LRS is marked by a few extreme rainfall events occurring during the hurricane season in each year. For this reason, and for the importance of the onset of the ERS in the yearly precipitation pattern, the month of April was chosen for further analysis of different variables that lead to cloud formation and rain development. Model

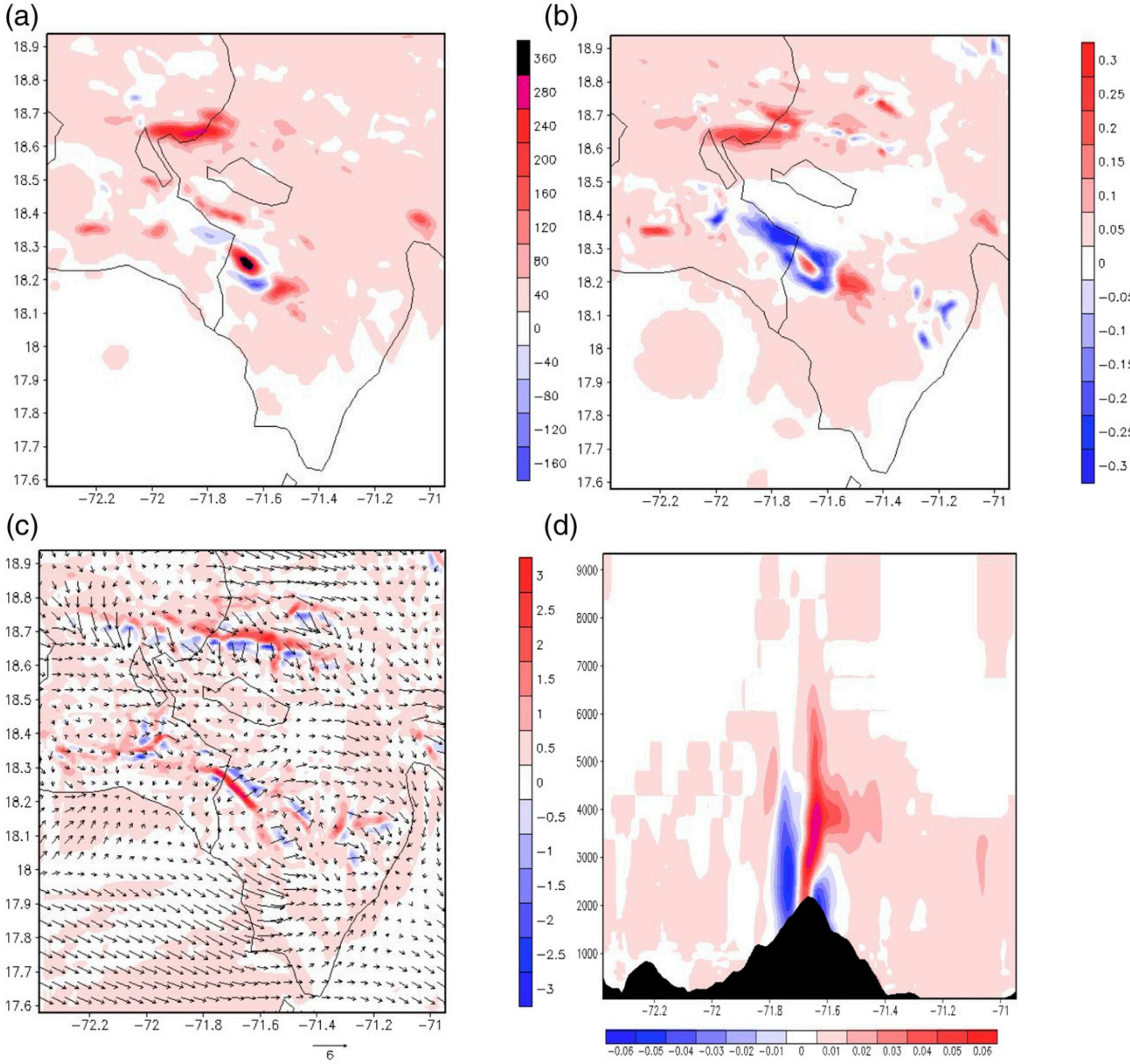

FIG. 13. Model-based differences between April 1995 and April 2003 for (a) accumulated surface precipitation (mm), (b) atmospheric liquid water content integrated between 700 and 1500 m ($g\,kg^{-1}$), (c) horizontal wind (vectors) and vertical motion ($m\,s^{-1}$), and (d) atmospheric liquid water content differences ($g\,kg^{-1}$) on a vertical cross section at 18.25°N. Black shading in (d) represents the underlying topography.

results for the month-long simulations show increased total accumulated surface precipitation, atmospheric liquid water content, and an enhanced positive feedback system that produces orographic cloud cover in the surrounding tropical montane cloud forests at specific times during the lakes' growth period (1995, 2003, and 2013) as a consequence of the changing atmospheric and oceanic conditions. A land cover change analysis for the southwestern region of Hispaniola shows that deforestation and other types of land class changes have not been significant enough to affect the hydrological balance of the area. The synthetized information from long-term regional observational records in addition to our recently deployed sensors along the sierras, and also from the midterm atmospheric processes simulations, partially validate the hydroclimate change hypothesis as playing a key role in the observed sudden change in Lake Enriquillo and Lake Azuéi surface areas. The hypothesis postulates that regional increases in SSTs motivate horizontal moisture advection to the enclosed watershed, increasing humidity levels and decreasing the lakes' ability to evaporate. These higher moisture levels

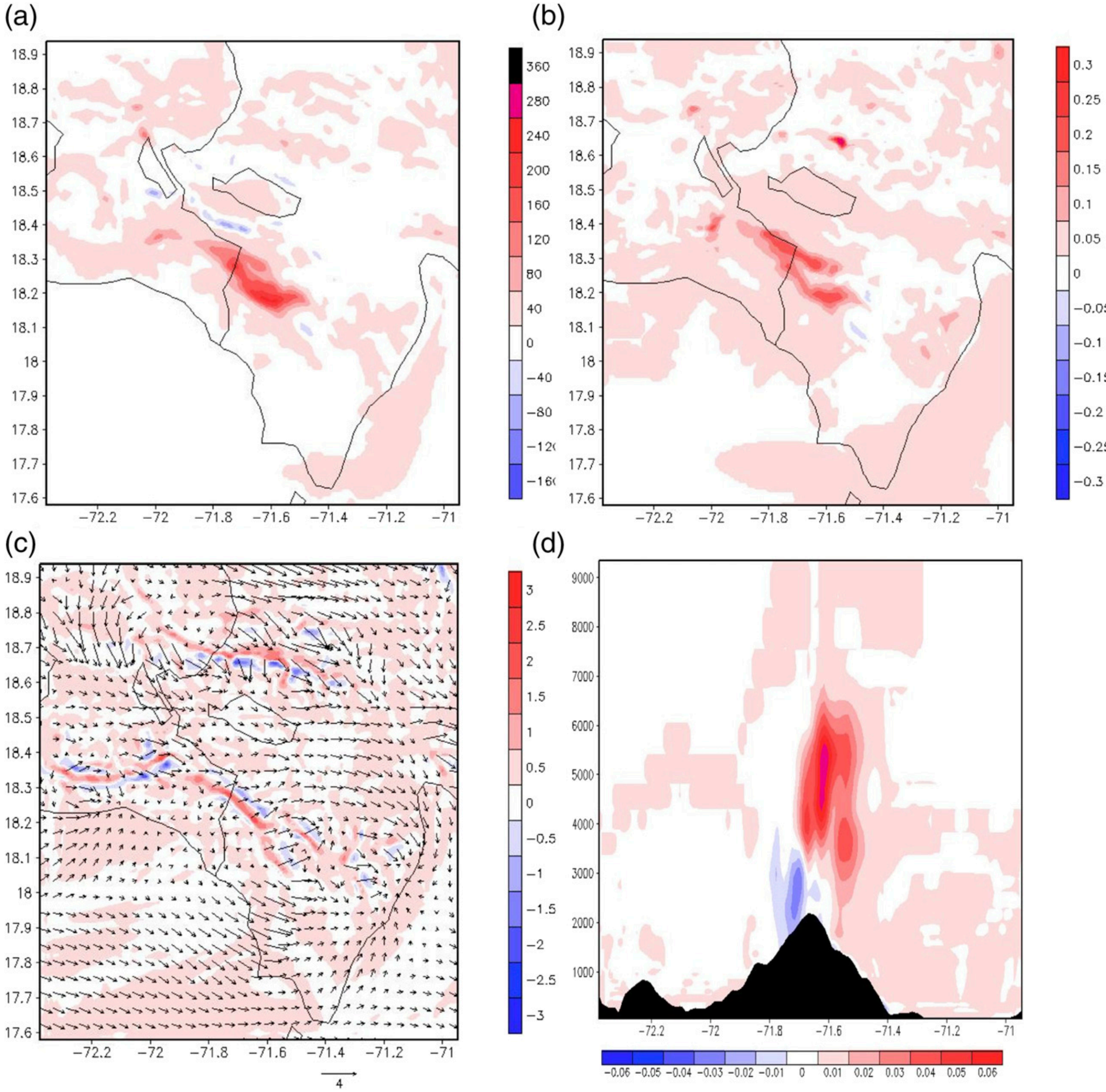

FIG. 14. As in Fig. 13, but for differences between April 2003 and April 2012.

also increase total precipitation in the surrounding sierras (surface accumulated precipitation, fog/cloud catchment, and wind-driven precipitation).

The research presented in this document not only highlights the importance of medium-term regional climate changes in affecting the hydrological balance of a tropical water basin, but also how the occurrence of extreme precipitation events in different years (e.g., tropical storms and hurricanes) produce a large volume of water. The full effects of these extreme events on lake surface area are not fully understood yet and will need more research. Other aspects, such as tectonic movements, continued deforestation, and different water management policies may need to be included in future research as additional factors affecting the hydrological balance of the Enriquillo basin. It is also of importance to constantly monitor and observe lake water levels, river and stream flows, climate information, and other lake characteristics (e.g., salinity and water temperature). Future research will include coupling of this hydrometeorological analysis to a watershed modeling to aid in quantifying more specifically changes at the surface level of the lakes. Ensemble simulations are common not only in interannual to decadal-scale experiments using general circulation models, but also in seasonal- to month-scale experiments using regional climate models (Wang et al. 2004); thus, it would be useful to introduce ensemble simulations in future modeling exercises.

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