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Water level fluctuations derived from ENVISAT Radar Altimeter (RA-2) and *in-situ* measurements in a subtropical waterbody: Lake Izabal (Guatemala)

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ABSTRACT

The use of remote sensing techniques in monitoring inland waters has become a powerful tool, considering the amount of ungauged waterbodies all over the world. The water mass balance is an essential subject to take into account in water management activities. The level changes of a lake surface are an indicator of the water mass balance of a basin since they reflect the water storage variations. Space borne altimeters have been successfully used in the last decade to measure lakes, rivers and wetland stages. This study presents the first analysis of Lake Izabal — the biggest lake of Guatemala (Central America) — water level fluctuations using altimetry data and *in-situ* measurements. Water level variations were obtained from Envisat Radar Altimeter (RA-2) Geophysical Data Records coupled with *in-situ* measurements. The analysis period included three complete years (2004 to 2006). The rainfall and temperature records over the catchment were analyzed considering that the amount of water feeding the lake, either by the tributaries and/or the groundwater, is driven by the climatic conditions over the lake's catchment. The results obtained show a good agreement between both, altimeter and *in-situ* datasets (correlation coefficient: 0.83 and rms error: 0.09 m). Lake Izabal water level fluctuations have a seasonal signal forced by the rainy and dry climate seasons in the region. An abrupt lake level rise was found in July 2006 which is correlated to abnormal precipitations in June. We found a connection between the higher/lower extreme values in the lake level variations with rainfall anomalies produced by regional climate changes forced by El Niño Southern Oscillation and the Tropical North Atlantic anomaly.

1. Introduction

Lakes water levels have a dynamic behaviour and its variations are an essential subject for water resources research and management. These variations have a wide range of time scales from short-term (daily) to long-term (yearly) scales. Most of the physical and ecological processes in a lake are directly related with its water level fluctuations. Among others, the lake level variations might affect the residence time of the water, nutrients concentration, heat content, circulation patterns, wind-driven resuspension, biologic activities and changes in the trophic chain. In addition, the water mass balance of the lake watershed depends on level fluctuations also, since they reflect volume variations of the storage water.

The ecosystem on a lake shows a complex interaction between weather conditions, surface and underground waters. Lakes water level variations are generated by: fluctuations of the water volume, pressure changes over the lake surface, circulation processes, wind events and tides. From all of them, the water volume fluctuations are the main responsible of the water level variations (Mercier et al., 2002). Volume changes in the water are driven by precipitation and evaporation over the lakes surface, rivers inflow and outflow, and underground inflow and ground seepage. The amount of water that fed the lake depends on climatic conditions over the hydrologic basin, its geomorphology and level of human activities, such as irrigation and drainage systems (Birkett, 1995; Birkett, 2000; Crétaux et al., 2005; Mercier et al., 2002). The latter found that the time difference between the strongest rainfall over 12 African basins and their corresponding lake level variations was about 1–3 months. Part of this delay corresponds to the time necessary for water to saturate the soils and to reach the lakes. In addition, lakes are known to be sensitive to local and regional climate changes since these changes affects the amount of precipitation, temperature, winds, humidity and evaporation (Crétaux & Birkett, 2006; Mercier et al., 2002).

Water stages of lakes have been traditionally gauged *in-situ*. Nevertheless, field measurements need human and economic resources. Considering that most of the lakes around the world are remotely located, a broad number of them are not being routinely gauged especially in developing countries. Although, radar altimetry technique was developed to measure over ocean surfaces, it has recently provided new means for monitoring inland water stages (Birkett, 1995). Radar altimetry has been, successfully, used in deriving the water level of ungauged inland waterbodies such as rivers, lakes and wetlands. Previous studies have combined *in-situ* measurements

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with altimetry to monitor the water stages of a broad variety of such kind of waterbodies. Birkett (2000) combined lake level variations derived from Topex/Posseidon (T/P) with inundated area variations observed from NOAAs AVHRR satellites to determine water volume variations of Lake Chad. Mercier et al. (2002) used T/P data to evaluate the lake level fluctuations of 12 African lakes, and their relationship with climate changes. More recently, Frappart et al. (2006) evaluated the performance of the ENVISAT (ESA) mission Radar Altimeter (RA-2 henceforth) for continental water height measurements. Crétaux and Birkett (2006), showed in their study the potential of altimetry in this particular matter by reviewing several test case studies on a diverse waterbodies selection.

Lake Izabal (Guatemala) has a great importance to the country, and its physical features are poorly known (URL, 2002). Besides scientific and ecological points of view, the knowledge of its level fluctuations has social effects because the lake resources support the economy of communities settled around the lake. The main objective of this study is to estimate water level fluctuations of Lake Izabal using derived water levels from the Radar Altimeter RA-2 on-board ENVISAT and *in-situ* water level measurements. We will analyze the relationship of these variations with local weather conditions and regional climate changes. Although Lake Izabal is being already monitored by *in-situ* measurements (ground gauge), radar altimetry information is useful to have precise budget errors giving the order of magnitude of confidence for waterbodies with same geomorphologic characteristics in some other remote areas. The paper is organized as follows: Section 2 delineates the Lake Izabal settings. Section 3 describes both datasets and methodology used to estimate the lake level fluctuations. The results obtained, including the seasonal and interannual fluctuations observed are presented in Section 4. The discussion concerning the fluctuations found based on a climatologic–geographic analysis (relationships with the local climate conditions) is in Section 5. We will also discuss the relationship between the fluctuations with regional climate changes produced by El Niño Southern Oscillation (ENSO) and the Tropical North Atlantic anomaly. Finally, the main conclusions are presented in Section 6.

2. Lake Izabal settings

Lake Izabal is the biggest lake in Guatemala (Fig. 1). It is located in the Northwest side of the country, at 15°30′ N and 89°10′ W. It surface extents over 717 km^2, and it is a lowlands water body since its surface height is, approximately, 10 m above the Caribbean Sea mean sea level (Arrivillaga, 2002). Lake Izabal main tributary is the Polochic River, which discharges around 70% of the lakes water input (Basterrechea, 1993). The water outlet is Dulce River, which connects Lake Izabal with the Caribbean Sea through a longitude of 42 km. The lake, its tributaries and outlet, constitute the biggest aquatic ecosystem of Guatemala, named as Lake Izabal–Dulce River System. The ecosystem works as habitat of a broad diversity of wildlife species. The appropriate knowledge of the Lake Izabal water level variations would contribute to improve its management, which is of great importance to the country because of its ecologic and social benefits. The whole system plays a key role in tourism and economic activities, food security, maritime transport and biodiversity conservation.

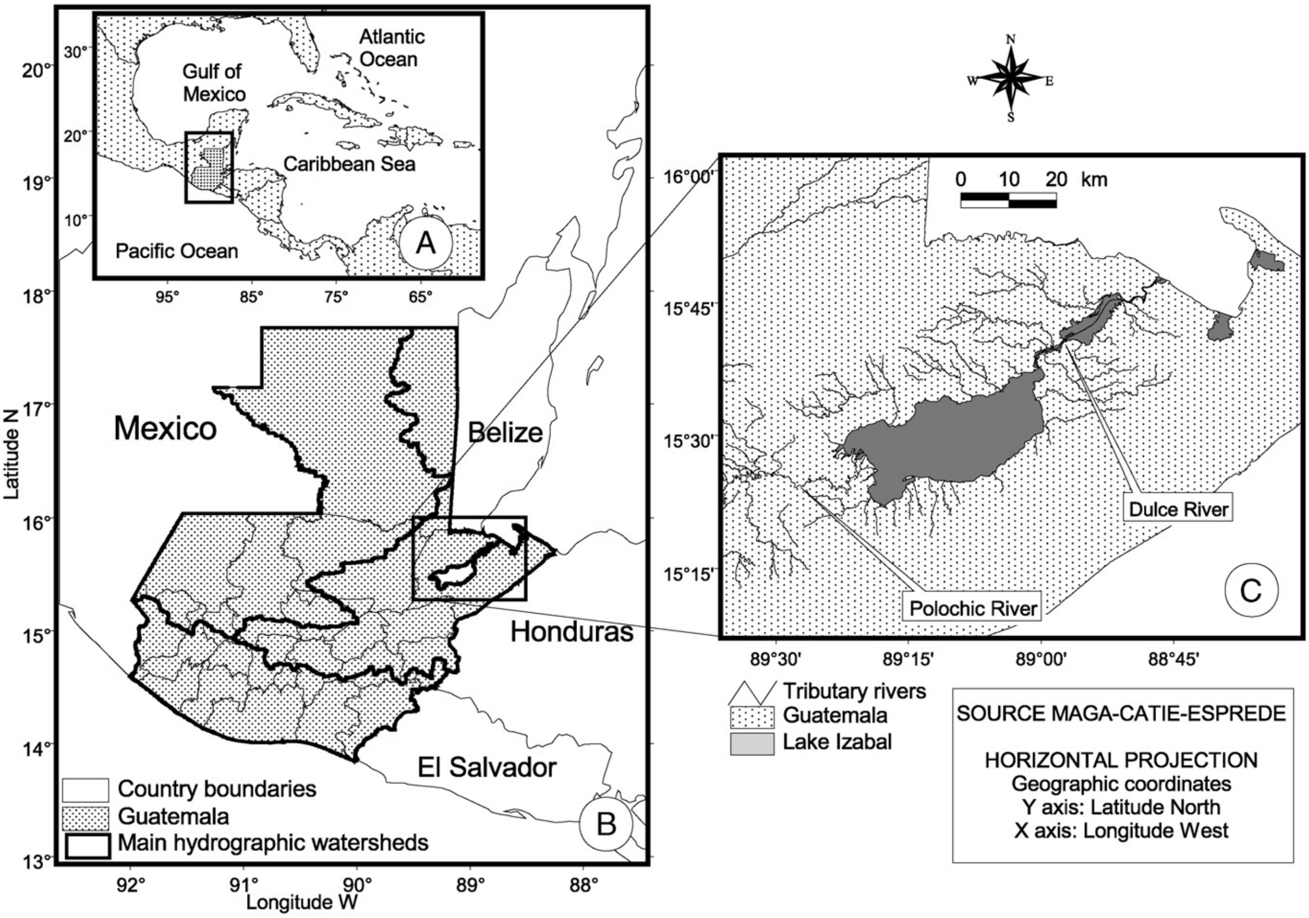

Fig. 1. A) Localization of the Republic of Guatemala in Central America, showing the three main hydrologic watersheds: Gulf of Mexico, Pacific Ocean and Caribbean Sea. B) Geographical situation of Lake Izabal within the country. C) Map of Lake Izabal, its affluent, the Polochic River and outlet (Dulce River).

Climate conditions in the region are influenced by ocean–atmosphere circulation in the Eastern Pacific and North Atlantic (Restrepo & Kjerfve, 2000; Thattai et al., 2003). Controls on local weather conditions (temperature and rainfall) of the zone include, as well, topography, altitude, land use, and basin geology (Thattai et al., 2003). The study area has a climate seasonality related with rainfall, temperature and humidity changes. The rainy season is from May to December, whereas dry season is from December to April. The mean rainfall is about 2000 mm/yr and the mean yearly temperature is about 25.2 °C with 4.4 °C variations (Brinson & Nordlie, 1975; URL, 2005). Lake Izabal is sensitive to climate changes because of its large extension and low depth (Arrivillaga, 2002).

The mean depth of the lake is 12 m and the maximum 18 m. Because of the lake surface height, most of the lake's water volume is below the Caribbean mean sea level (Brinson & Nordlie, 1975). Hence, Lake Izabal level dynamics have a close relationship with the basins upstream and with the marine environment downstream. For that reason, the Dulce River is influenced by the salty water intrusion from the Caribbean Sea, especially during the dry season with low fresh water discharge and high Northwest wind events.

The lake's catchment area is about 6862 km^2; this yields an extension rate of 1:10 among the lake surface and its catchment area (Dix et al., 1999). The estimated living population in Lake Izabal catchment area is around 900,000 habitants with a density of 225 inhabitants/km^2 (INE, 2002; URL, 2002). The anthropogenic activities in the catchment such as settlements, irrigation systems, deforestation, agriculture and cattle, may affect the lake water level dynamics since they affect the water cycle and yield to soils compacting. Anthropogenic factors have reduced the water absorption capacity of the basin and effective rainfall over the catchment is converted easily in direct runoff instead of groundwater (Arrivillaga, 2002).

Lake Izabal water level variations are mainly driven by hydrologic conditions over the Polochic River basin, since it contributes with up to 70% of the lakes water volume (Basterrechea, 1993). Between 1994 and 2002 the Polochic River has reduced its dry season mean annual water discharge in about 40% (INSIVUMEH, 2002). The reason for that might be in the increasing number of irrigation systems constructions built since 1996. Note that this activity derives water from the river to agriculture production areas during the dry season, enhancing evapotranspiration and infiltration and reducing the surface runoff. Seasonal and interannual fluctuations of Lake Izabal water level have ecological and social implications. The lake level plays a key role in the ecosystem water balance affecting the groundwater availability in the surrounding areas (FDN, 1997). Furthermore, those fluctuations affect the lake relationships with the downstream marine environment. Lake Izabal level variations might affect the salty water intrusion from the Gulf of Honduras, modifying the ecologic processes in the water column.

3. Datasets

In order to estimate the Lake Izabal water level fluctuations two datasets were used: water levels from *in-situ* measurements provided by the Guatemalan Authority for Sustainable Management of Lake Izabal Basin (AMASURLI); and derived water levels from ENVISAT RA-2 Geophysical Data Records (GDR) provided by the European Space Agency (ESA). The analyzed period spans three complete years from January 2004 to December 2006. Note that radar altimetry was initially developed for open ocean oceanographic purposes, but in the recent years has been successfully used in the monitoring of inland water stages, together with *in-situ* measurements (Birkett et al., 2002; Crétaux & Birkett, 2006; Frappart et al., 2006) or as the sole source of information (Birkett, 2000; Mercier et al., 2002; Berry et al., 2006). Thus, Radar Altimeter data has arisen, in the last decades, as a powerful tool in monitoring inland water stages such as rivers, lakes and wetlands.

3.1. In-situ dataset

The gauge station used in this work was a moored rule operated by AMASURLI. The gauge station is located in the Northwestern part of Lake Izabal, in the dock called INDE, at 15°31′25″ N and 89°19′46″ W (Fig. 2) and it is located near the main tributary river mouth: Polochic River. The *in-situ* water level measurements are being carried out since 2004 in a daily basis. From the analysis of the dataset two problems were found: some gaps in the observations and the lack of a reference system. The study proposed here is focused on seasonal and interannual fluctuations so the small number of daily gaps observed did not significantly affect the final results. Regarding the reference system, the instrument measures the lake surface height from the bottom of the lake in the moor location and is not referenced to any international reference system. In the RA-2 validation study over inland waters made by Frappart et al. (2006), the gauge stations used were levelled with GPS being the unlevelled stations discarded. That gauge stations selection criteria was applied because it was a validation study on absolute water stages rather than relative level fluctuations. Our study makes use of the aforementioned not referenced *in-situ* dataset because the objective was not to validate absolute altimeter derived data.

3.2. RA-2 derived dataset

Radar altimetry technique allows the estimation of the surface height based on a fundamental principle. The altimeter provides the range by measuring, with great accuracy, the time in which a radar pulse goes to the Earth's surface and comes back to the instrument. The altitude of the satellite above the reference ellipsoid is computed with a precise orbit determination system. The surface height above the ellipsoid is calculated by subtracting the corrected range from the satellite altitude. The RA-2 on-board ENVISAT was originally developed to derive surface heights over the ocean, but it was also designed to monitor changes in height over land targets (Berry et al., 2006; Crétaux & Birkett, 2006; Frappart et al., 2006). One of the regional objectives of the ENVISAT mission covers hydrological research and applications where continental water level monitoring is the RA-2 application (ESA, 2002). The mode switching capability allows the instrument to maintain lock over rapidly varying topography and enhances the suitability of RA-2 to retrieve lake level heights (Berry et al., 2006). The RA-2 is a nadir-pointing instrument providing 20 range measurements at 1.1 s interval. The along-track distance between each range measurement is approximately 400 m. The range value provided in the GDR product is the average of 20 measurements covering around 8 km over the track segment. The mission has a repeat cycle of 35 days corresponding to a track-to-track distance of 80 km in the equator (ESA, 2002), equivalent to approximately 75 km at Lake Izabal latitude. The spatial density of RA-2 measurements offers a wide variety — but larger than Topex/Poseidon — of continental waterbodies to be potentially monitored (Mercier et al., 2002). Moreover, the 35 days frequency provides enough resolution to obtain hydrologic information related with seasonal and interannual variations.

Lake Izabal is overflown by the RA-2 descending orbit number 269 along a 23 km-long ground segment (Fig. 2). This segment provides two points with valid data over the lake surface. According to previous studies, the length of the track segment is long enough to obtain valid records. Mercier et al. (2002) reported that reliable time series using 1-Hz T/P data require a track length over water of at least 10–15 km long. Crétaux and Birkett (2006) confirmed that the minimum target area (lake) and width attainable to derive inland water heights are about 100 km^2 and 0.5 km, respectively. The procedure to select these two valid points was the following. We first selected a rectangular window covering the lake and checked the number of tracks within that frame. As mentioned, we obtained one track (descending orbit

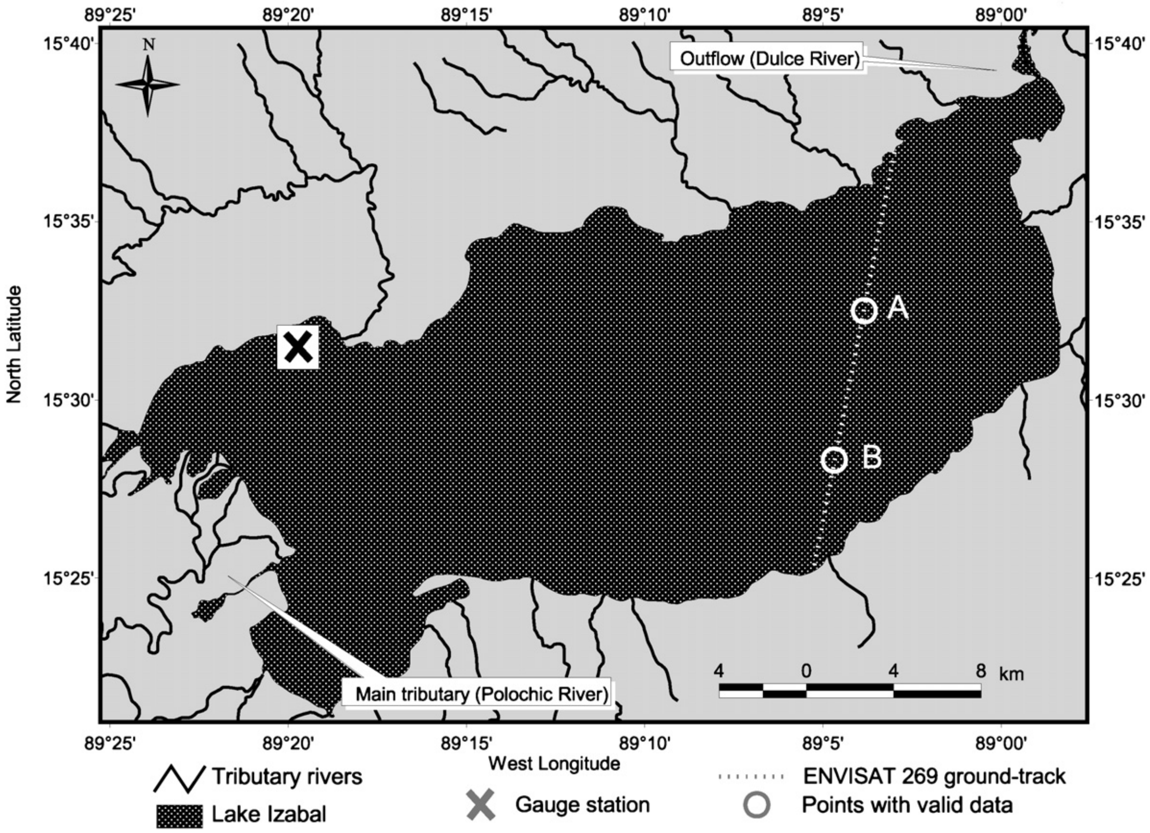

Fig. 2. Map of Lake Izabal crossed by the ENVISAT RA-2 descending ground track ~23 km-long segment. Points A and B denotes the location of the along-track range measurements. Also shown the gauge station used for *in-situ* measurements located ~25 km away from the altimeter ground track segment.

number 269) with four points within the lake. Then we used a criterion to select the number of valid points. We must note that every "1-Hz" measurement available in the GDR cycles is the average of a maximum of 20 "18-Hz" measurements. Only "1-Hz" points obtained with the average of at least 95% of "18-Hz" measurements were selected. Following this, we only had the two central points of the segment as valid as the first and the last measurements within the orbit segment did not completed the criterion. The last step in the processing was to estimate the mean of the two valid points, obtaining the dataset used in the comparison with the *in-situ* measurements.

The gauge station was located close to the Polochic river mouth, whereas the RA-2 measurements were close to the lake outflow. This geographic fact could be an error source in the comparison between both datasets (Birkett et al., 2002). Wind-driven wave events, circulation processes, depth differences or pressure variations are the main forcing factors that might produce some biases. Frappart et al. (2006) found biases between RA-2 and *in-situ* Lake Level Height (LLH) measurements, suggesting that the distance between the gauge stations and the altimeter tracks (several tens of km) could be in the origin of the bias. The differences between among both datasets might have been produced by short wavelength geoid undulations not described in the geoid used and instrumental (altimeters) bias (Faugere et al., 2006). However, in that study, the correlation coefficients between both data records were all higher than 0.95.

3.3. RA-2 data processing

The range measurements need to be corrected to account the interaction of the radar signal with the atmosphere and the ocean. Thus a set of geophysical corrections (including some instrumental corrections) were applied to the data, considering previous studies regarding inland water levels. The corrections applied were (correction source indicated here in brackets): Dry troposphere (model), wet troposphere (model), ionospheric (DORIS), solid earth tide (model) and pole tide (model). The sea state bias correction was not applied because the lake surface does not behave as the open ocean (Crétaux & Birkett, 2006; Frappart et al., 2006; Mercier et al., 2002). We did not apply the inverted barometer correction following Mercier et al. (2002), because the closed basins isostatic response to atmospheric pressure variations has not yet been investigated. Regarding the wet tropospheric correction, we used the model derived because the Micro Wave Radiometer (MWR) correction is applicable only for ocean surfaces (ESA, 2002).

The LLH was the average of the two points with valid data covering the lake (points A and B in Fig. 2), then, it was referenced by subtracting the reference geoid (EGM96) altitude to the surface height above the ellipsoid. Note that Crétaux and Birkett (2006) suggested that for continental water bodies, a low-resolution terrestrial geoid like EGM96 can be utilised as a reference system. In addition the short geoid wavelength errors were estimated using the Radar Altimeter measurements at these two points (A and B) and subtracted to the LLH time series.

There are four retracking algorithms available on the RA-2 instrument to derive the range value: Ocean, Ice-1, Ice-2 and SeaIce. Frappart et al. (2006), states that although none of the retracking algorithms for ENVISAT were designed to retrieve water heights over continental waters, the altimeter RA-2 exhibits instead a strong capability for the monitoring of these kind of targets. They found that the Ice-1 retracking algorithm provides the most suited ranges for continental hydrologic studies. In the validation study made by these authors, the Ocean retracking algorithm yielded the second better results in the root mean square (rms) discrepancies and correlation coefficients between RA-2 derived LLH and *in-situ* measured water level heights (i.e. 0.1 and 0.09 m for rms, and 0.98 and 0.98 for r^2 for Ocean and Ice-1 respectively). We compared the performance of the four retrackers available: Ocean, Ice-1,

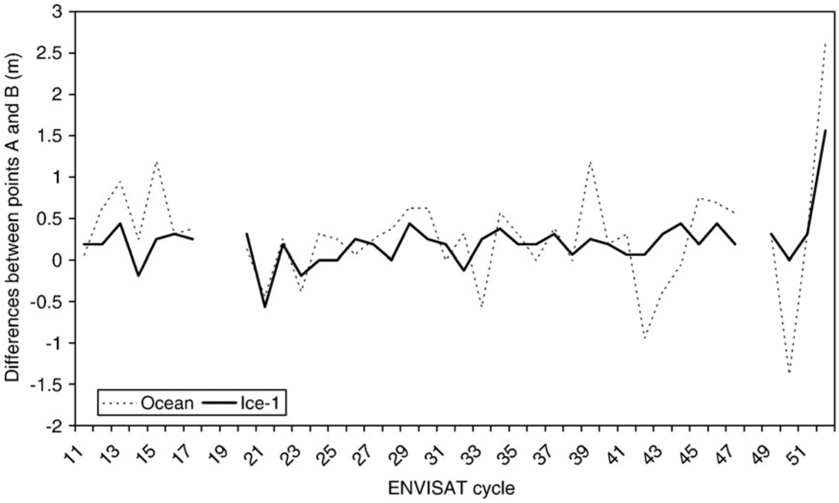

Fig. 3. Time series comparison of corrected range differences between points A and B using Ocean (dashed line) and Ice-1 (thick solid line) retrackers. Units are in m.

Ice-2 and SeaIce over the Lake Izabal surface. To do this, we obtained the range differences between the corrected ranges at point A and point B (Fig. 2). The criterion was to select the retracker with lesser corrected range differences between the two points. From the physical point of view and considering the water level behaviour of Lake Izabal, two points 8 km away from each other should not produce strong corrected ranges differences between them. The mean of the range differences for Ice-1 was found to be 0.19 m and the rms of the differences 0.35 m, whereas for the other three retrackers were 0.26 m (mean) and 0.68 m (rms) (Ocean), 0.36 m (mean) and 0.75 m (rms) (Ice-2) and 0.20 m (mean) and 1.05 m (rms) (SeaIce). The time series of differences of the two better algorithms are shown in Fig. 3 (for easy interpretation of the results only Ocean and Ice-1 retrackers are presented). Based on these results, Lake Izabal water level fluctuations (LLH) were derived using Ice-1 retracking algorithm. This result is in agreement with the retracker selected by Frappart et al. (2006).

4. Results

4.1. Comparison between in-situ and RA-2 LLH measurements

The analysis is focused on relative lake level variations. The RA-2 dataset has a 35 days time scale whereas the *in-situ* lake levels are gauged daily. For inter-comparison purposes we selected only *in-situ* measurements coincident in time with the RA-2 LLH. The number of gaps in the *in-situ* dataset was 2 (14th August 2004 and 30th July 2005) and 1 (10th June 2006) in the RA-2 measurements. These gaps were filled up using a linear regression analysis.

Fig. 4 presents the lake level comparison between the two datasets showing a similar variation pattern. The fluctuations observed along the whole time period are due to a variety of factors forcing the lake level: climate, soils, catchment morphology, human activities, and their interactions. The most unusual feature found in both time series was an abrupt water level rise in July 2006. In order to estimate the correlation between both time series in determining the Lake Izabal relative level variations, we did the following: a linear regression analysis between both, a double mass test, and the rms error of the LLH differences. The correlation coefficient obtained in the regression analysis was 0.83 (Fig. 5A). The double mass analysis yielded a correlation coefficient of 0.99, showing that both datasets have the same distribution pattern (Fig. 5B). The rms error of the differences was 0.09 m, which is the same rms error level obtained by Frappart et al. (2006) in their analysis. The slope of the double mass function (Fig. 5B) is affected by discrepancies in the reference system of both datasets. These results are in agreement with previous studies (Berry et al., 2006; Crétaux & Birkett, 2006; Frappart et al., 2006).

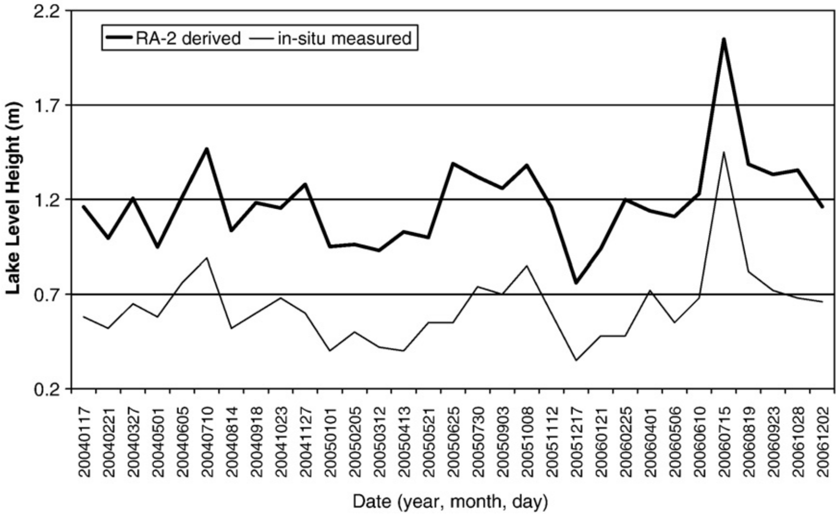

Fig. 4. Time series of water level from *in-situ* measurements (thin solid line) and RA-2 derived data. (thick solid line). Units are in m.

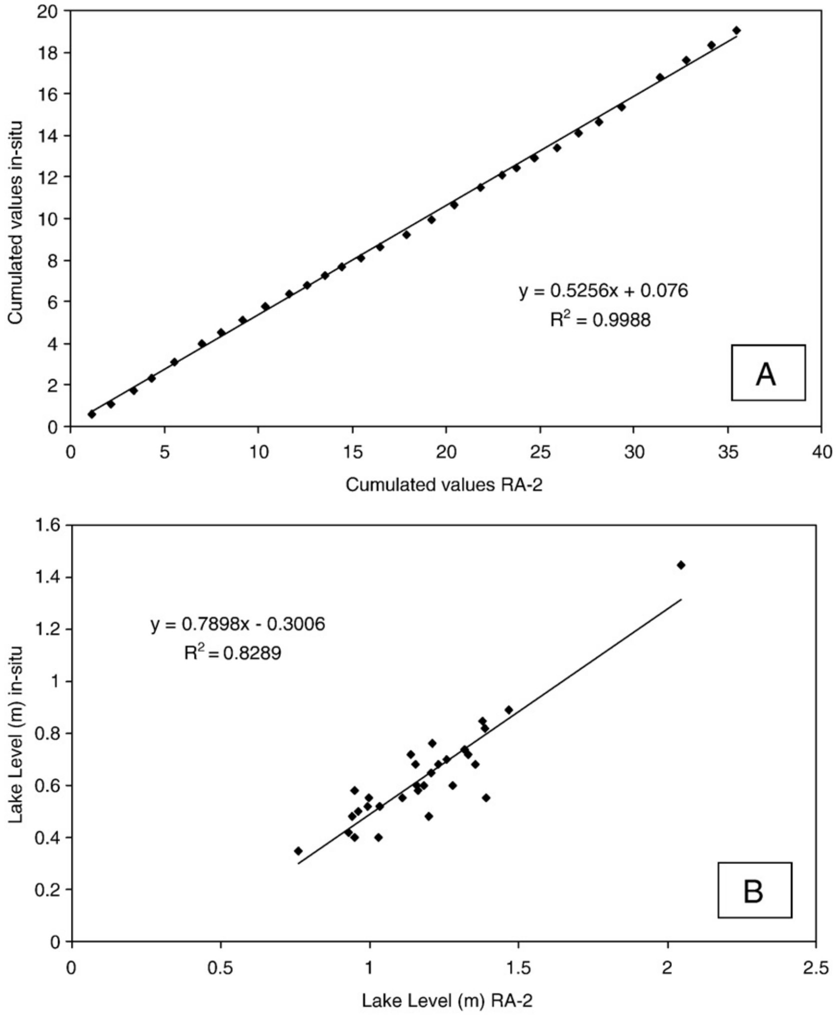

Fig. 5. A) Lake Izabal water level from RA-2 data versus *in-situ* measurements. Also shown the tendency line. B) Double mass analysis: cumulated values from RA-2 data versus *in-situ* measurements.

Fig. 6 shows the comparison between RA-2 LLH and the daily *in-situ* measurements. Some variations observed by the daily dataset are clearly unnoticed by the RA-2 LLH (lake level drop in April 2005 and the lake level rise in October 2006). The RA-2 LLH oscillations with frequencies higher than the Nyquist frequency ($f=1/[2*35]\ \mathrm{d}^{-1}$) are superimposed to the lower frequencies. Thus the oscillations with periods shorter than the ENVISAT time sampling are not observed in the RA-2 dataset.

4.2. Seasonal and interannual variability

Since we are interested in the lower frequency oscillations (seasonal to interannual), all the fluctuations with higher frequencies were removed from the time series by applying the LOWESS (Locally Weighted Regression Scatterplot Smoother) filter proposed by Cleveland (1979). LOWESS is a modelling method built on “classical” methods such as linear and non-linear least squares regression. It combines techniques for smoothing with techniques for estimation. Simplicity of linear least squares regression with flexibility of non-linear regression is merged also. This kind of curve fitting method is known as locally weighted polynomial regression. The polynomial curve is fitted to the data using weighted least squares, but it gives more weight if the value is near to the fitted curve and less weight for data far from it (Cleveland, 1979; NIST/SEMATECH, 2006). The weight function $W(d)$ is a bi-cubic weight function traditionally used in the modelling (Eq. (1)).

$$W(d) = \begin{cases} \left(1-|d|^3\right)^3 & \text{for } 0 \le |d| < 1 \\ 0 & \text{else} \end{cases} \tag{1}$$

Where:

$$d_i = |x_0 - x_i| / \max(|x_0 - x_i|) \tag{2}$$

$|d|$ denotes the absolute value of d, which corresponds with the local assignation of weight for each value according to its position. x_0 is the estimated value and x_i is each observed value. Eq. (2) will assign the maximum weight to the estimated value x_0 and the weight decreases with farther values.

LOWESS curve fitting procedure allowed us to obtain adjusted curves representing the seasonal fluctuations in Lake Izabal for RA-2 and 35-day *in-situ* datasets (Fig. 7A) and for daily *in-situ* time series (Fig. 7B). A low and a high stage of the lake level were found in each year. The first months of the three years studied (January to May) showed low water levels, whereas high water levels were found from May/June to November/December. This seasonal behaviour of the Lake Izabal level is driven by the rainy and dry season's cycle in the area. The rainy season starts around May, diminishing by the end of the year, when the dry season starts. We isolated a seasonal signal with

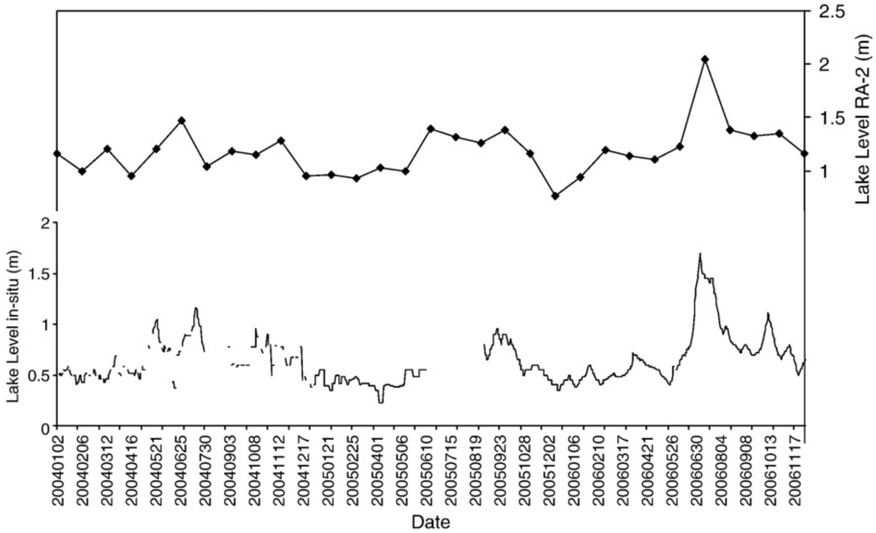

Fig. 6. Time series of RA-2 derived lake level and daily *in-situ* measurements. Solid lines indicate the exact daily data corresponding with the RA-2 value. Units are in m.

relative differences of 0.3 m in average from dry to rainy season. We found the highest lake elevations in June and July of each year in the whole time period analyzed. The reason of that is when the rainy season starts, the rainfall generates a runoff that feds the lake's bed, depending on soil moisture and other runoff modulators. Thus, the lake level response in relation to the rainfall starting date has a delay of one or two months.

Guatemalan rivers flows, including Polochic River, have also a seasonal behaviour following the rainy and dry season's cycle. Fig. 8 shows the flow time series for the hydrologic year 2002–2003 of an affluent of the Polochic River (Cahabon River). The seasonality of the river has the same time distribution of the rainy (May to November) and dry (December to April) seasons, since the weather is the main forcing factor of the water resources in the region. In addition, the lake level seasonality is driven by the climate conditions and the subsequent tributary rivers discharge.

Rainy and dry season's cycle does not have the same magnitude or time distribution every year. Almost 30% of this variability is explained by the ocean–atmosphere circulation in the Eastern Pacific and Northern Atlantic (Giannini et al., 2000). In order to extract more information about Lake Izabal water level annual dynamics we performed a year to year comparison. Note that the time period analyzed is considered too short to find a long-term trend of the lake water level, but some interesting findings were obtained regarding its seasonal and interannual variability. Fig. 9 shows the adjusted time series of the three years study period using the RA-2 dataset. The descriptive parameters used to compare statistically the three years are presented in Table 1.

The year with the highest LLH in the study period was 2006. The maximum LLH in that year was in July 2006. The minimum LLH in 2006 (January) was higher than 2005 and equal to 2004. The high stage (rainy season) and the low stage (dry season) in 2006 were also higher than 2004 and 2005. The seasonal variance in that year was higher as well, leading to high data dispersion reflected in range and standard deviation values (Fig. 9 and Table 1). 2005 was the year with the lowest stages, in mean and extreme lake level values. During this

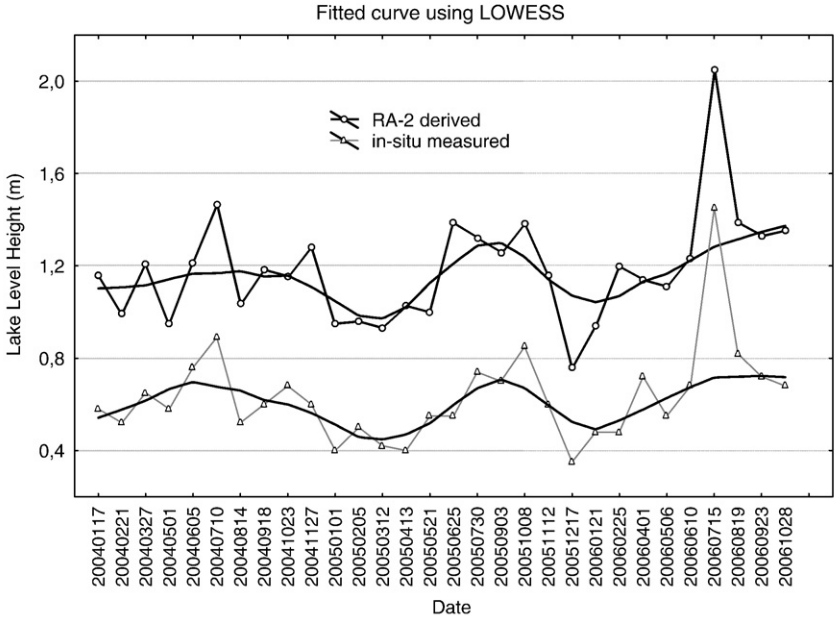

Fig. 7. Lake Izabal water level seasonal fluctuations. A) Line plot and curve fitted to the 35 days timescale dataset. B) Line plot and curve fitted to the *in-situ* daily dataset. Units are in m.

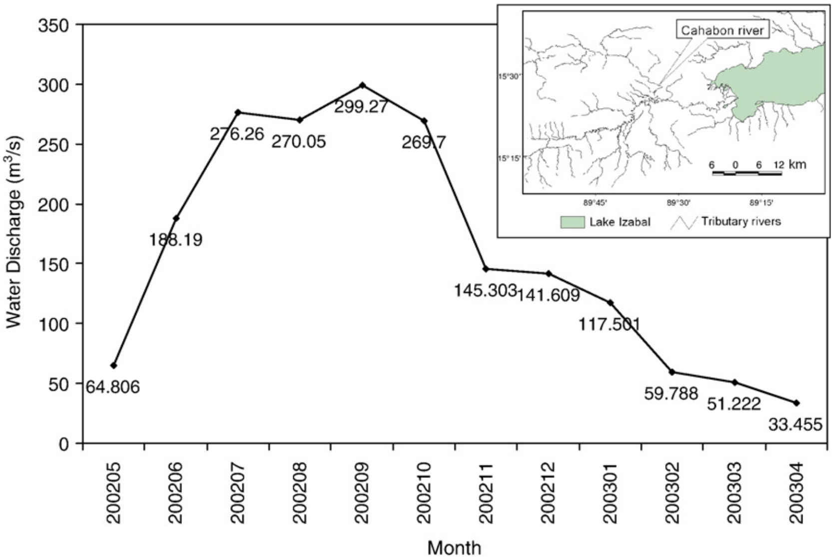

Fig. 8. Annual Cahabon River water discharge (2002–2003). In the inserted box, the location of the Cahabon River in the Lake Izabal catchment is presented. Units are in m^3/s.

year, two strong drops of the lake level were found in the dry season, the first one in April was only observed in the *in-situ* daily dataset (Fig. 7B) and the second one in December (Fig. 9). Furthermore, the 2005 high stage (rainy season) presented a lower water height than 2004 and 2006 high stages. The 2004 lake level dynamic showed average values (Table 1). Data dispersion through this year was relatively small, being seasonality the main contributor to this feature (Fig. 9). In the three years taken into account the lake high and low stages are well defined.

5. Discussion

The lake level fluctuations found using RA-2 and *in-situ* measurements presented monthly (daily dataset), seasonal and interannual (both datasets) time scales. These fluctuations are mainly driven by the climate conditions which are further driven by the ocean–atmosphere circulation in the influencing oceanic basins (Restrepo & Kjerfve, 2000; Thattai et al., 2003). Synergistic studies including climate, runoff, inundated areas and water level, contribute to obtain better ways for monitoring, forecasting and management of water resources (Birkett, 2000). The discussion of the results obtained here is focussed firstly on the relationship of the lake level fluctuations with the local climate conditions and, secondly on the correlation of the extreme lake surface height events with El Niño Southern Oscillation (ENSO) and the Tropical North Atlantic anomaly. The water balance of Lake Izabal is not computed due to a lack of data (groundwater flows, tributaries discharge and surface outflow). Thus here it is only presented the relationships of the lake level fluctuations with local climate and basin geomorphology.

5.1. Relationships with local climate and catchment geomorphology

Lakes water level fluctuations depend on climatic conditions, basin geomorphology and anthropogenic factors (Birkett, 2000; Mercier

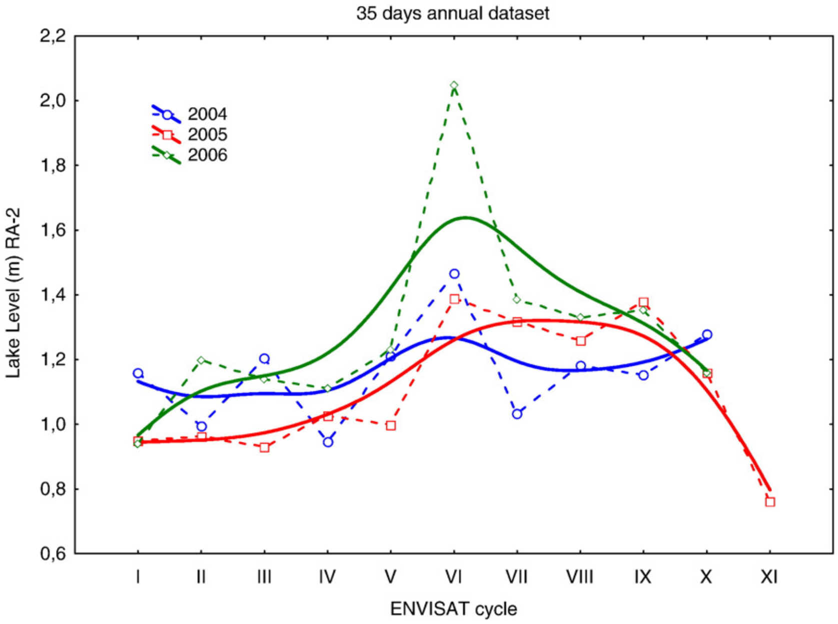

Fig. 9. Lake Izabal water level annual time series derived from RA-2. Units are in m.

Table 1
Annual statistical parameters of RA-2 derived lake level and *in-situ* measured lake level datasets

Parameter	RA-2 derived lake level			*in-situ* measured lake level		
	2004	2005	2006	2004	2005	2006
Mean	1.1635	1.1029	1.3037	0.6556	0.5159	0.7291
Standard deviation	0.14964	0.2097	0.3119	0.1812	0.1561	0.2984
Maximum	1.4665	1.3892	2.0477	1.16	0.95	1.7
Minimum	0.9475	0.7607	0.9387	0.37	0.22	0.38
Range	0.519	0.6285	1.109	0.79	0.73	1.32

et al., 2002). Climatic conditions include rainfall, temperature, winds, humidity and evaporation. Catchment geomorphology comprises soils, slope, altitude, geology, among others. Finally, anthropogenic factors are mainly land use, urban settlements and irrigation systems. We first analyze the correlation between the Lake Izabal level fluctuations with the rainfall/evaporation over the lakes surface and the rainfall/evapotranspiration over the catchment area. The data used in this analysis include: climate records and geographic information. The climate data records were taken from meteorological stations located inside or near the watershed. These meteorological stations are managed by the Guatemalan Institute of Meteorology and Hydrology (INSIVUMEH). The parameters taken into consideration were: rainfall (mm), mean temperature (°C), altitude (m), daylight (hours) and evaporation (mm) (if available from the hook gauge evaporimeter). The geographic information used was obtained from MAGA-CATIE-ESPREDE (2001). Geographic parameters comprised: catchment size, shape and altitude. The time scale used was monthly due to data availability.

The amount of water that could finally reach the lake's bed was calculated. To do this, monthly evapotranspiration was subtracted from monthly rainfall. Potential evapotranspiration was determined using the Blaney–Criddle method, which takes into account the mean temperature and percentage of daylight hours (Blaney & Criddle, 1950). Then, it was adjusted by a factor of land cover and use. The water volume feeding the lake, whether by direct runoff, base flow or underground water, depends on the difference between the rainfall and the evapotranspiration. In the study region, that difference has a seasonal behaviour (Fig. 10). Direct relationships are found when comparing the rainfall/evapotranspiration differences with the lake level from the daily *in-situ* dataset (Fig. 10). Lake surface height rises/drops correspond to positive/negative rainfall/evapotranspiration differences. Note that this relationship may have a time delay of one month. When rainfall exceeds evapotranspiration (June–November 2004, June 2005–February 2006 and June–November 2006) there is a water surplus in the area. This water will be turned into runoff or will fed aquifers, depending on soil moisture, land cover and morphology conditions. To the contrary, periods when evapotranspiration exceeds rainfall (March–May 2004, September 2004, December 2004–June 2005, April–May 2006) mean water deficit stages. In that particular case, the water feeding the lake will depend on the water storage from previous rainy seasons.

According to Restrepo and Kjerfve (2000), rainfall, temperature, runoff ratio and other hydrologic parameters may vary within a watershed. In their study concerning water discharge from Colombian Andes, each drainage basin was divided into polygons, each one with approximately uniform altitude, rainfall and temperature. Following that methodology our lake catchment area was divided in three polygons. The Polygon I represents the high basin, whereas Polygon II and III are the medium and low basins respectively. Each Polygon represents different hydrologic processes. The division criteria followed the altitude and slope features obtained from the level curves information (Fig. 11). Each meteorological station was assigned to a polygon; their main characteristics are presented in Table 2. The climate diagram presented in Fig. 10 was obtained using data averages of all four meteorological stations. It is considered that each meteorological station is enough representative of each polygon since the weather conditions in the region follows altitude patterns.

According to the hydrologic cycle dynamics, the climate conditions over the catchment area are converted to volume changes in the lake's water and hence into lake level fluctuation changes. Rainfall, evaporation and evapotranspiration are parameters directly related with water volume changes of Lake Izabal. Water inputs/outputs in the Lake Izabal ecosystem include: (i) Rainfall over the lake surface, (ii) Tributary rivers water discharge, which depend on rainfall/evapotranspiration rate, soils features, catchment morphology and human activities in the basin; (iii) Groundwater going into the lake, (iv) Evaporation from the lake surface; (v) Dulce River water discharge from the lake; and (vi) Ground seepage. (i) to (iii) are inputs, whereas (iv) to (vi) are outputs. The water input in each polygon driven by climate conditions is computed in Eq. (3).

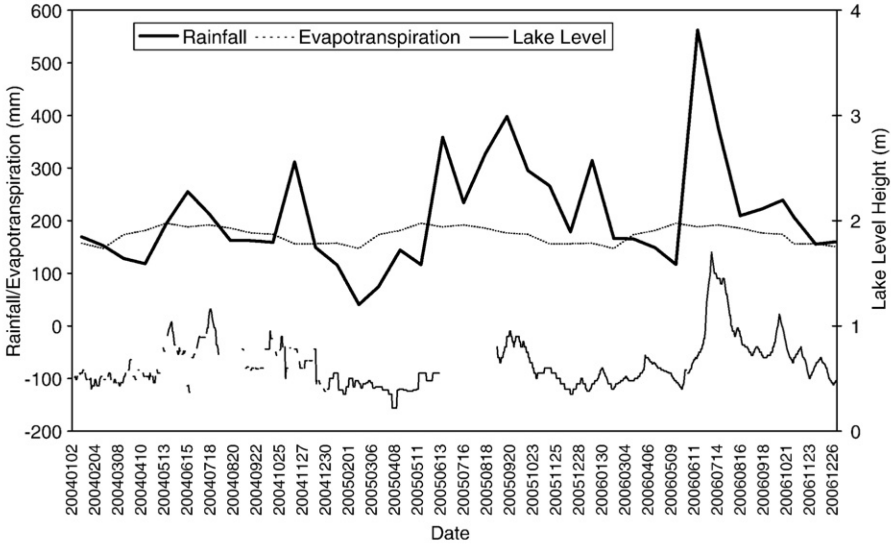

Fig. 10. Climate diagram of rainfall and evapotranspiration over the Lake Izabal catchment. Units of Rainfall/evapotranspiration are in mm and LLH are in m.

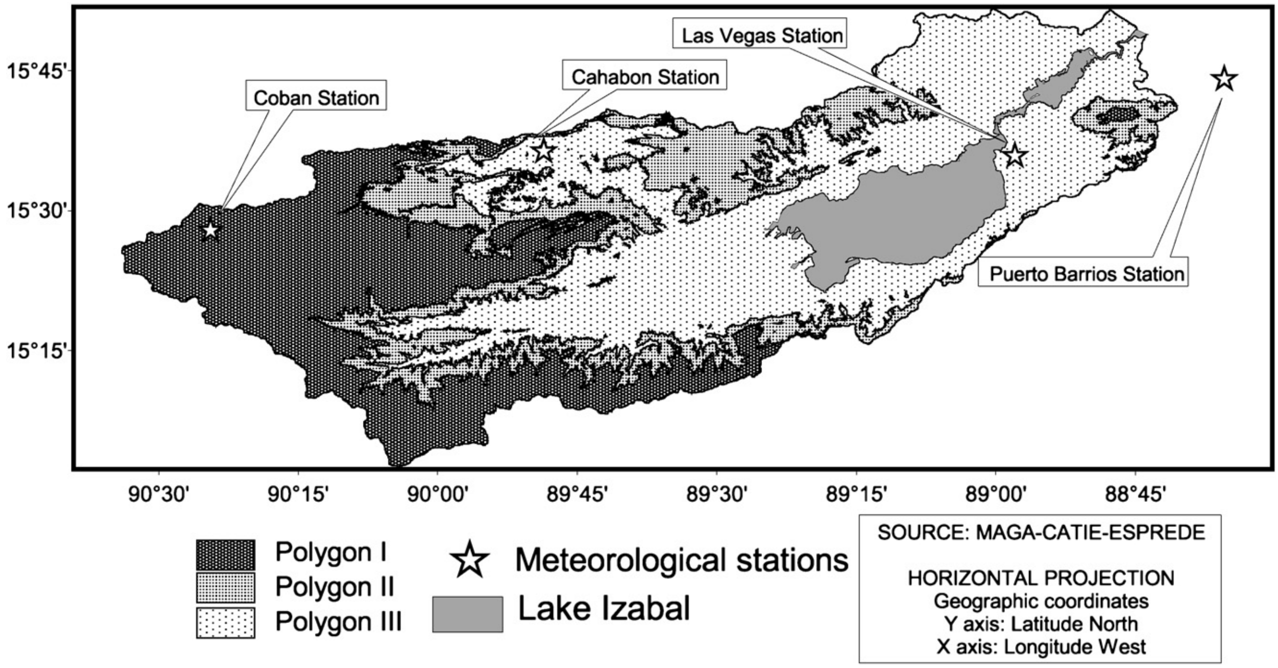

Fig. 11. Spatial distribution of the polygons used for the climatologic and geographic analysis. It is shown the location of the meteorological stations assigned to each polygon and the lake surface.

That value corresponds to the amount of water that could reach the lake bed.

$$W_i(n) = (\mathrm{PP}_i(n) - E_i(n)) \times A_i \tag{3}$$

Where:

$W_i(n)$	Water input in each polygon in the month n
$\mathrm{PP}_i(n)$	Rainfall in each polygon in the month n
$E_i(n)$	Water outlet in the month n. (Evapotranspiration over the lake catchment)
A_i	Polygon area

The climate conditions taken into consideration in Eq. (3) have closed relationships with (i), (ii) and (iv). The other inputs/outputs (iii), (v) and (vi) were not considered due to the lack of data. The annual average water input for each polygon is presented in Table 2.

Hydrographic response to rainfall of the catchment consists on two main components, the first representing the base flow and the second the direct runoff. Moreover, effective rainfall over the catchment reaches the rivers mouth following three flow ways: base flow (groundwater), rapid subsurface flow (flow through pipes and seepage zones) and saturated overland flow (surface runoff). Direct runoff is composed by the rapid subsurface flow and the saturated overland flow (Murrone et al., 1997). The base flow depends, essentially, on the water storage in the basin. The hydrologic response of base flow has monthly to annual time lags, whereas the direct runoff response has daily, weekly and monthly delays. The relationships between each flow way are non-linear because this relationship depends on the basins infiltration capacity, which is forced by soils moisture and rainfall intensity. In order to determine the total lake level variation explained by the local weather conditions, Eqs. (4) and (5) were empirically developed considering each water flow way.

$$\begin{aligned}\mathrm{Qp}(n) = [&0.1 \cdot W_1(n) + 0.2 \cdot W_1(n{-}1) + 0.2 \cdot W_2(n) + 0.3 \cdot W_2(n{-}1)\\ &+ 0.3 \cdot W_3(n) + 0.3 \cdot W_3(n{-}1)]\end{aligned} \tag{4}$$

$$\mathrm{LC}(n) = \left[\frac{(\mathrm{Qp}(n) + \mathrm{QB})}{\mathrm{As}}\right] + \mathrm{Ws} \tag{5}$$

Where:

$\mathrm{Qp}(n)$	Short-term rain generated water discharge to the lake in the month n
$W_i(n)$	Water input in each polygon, obtained in (3), in the month n
$\mathrm{LC}(n)$	Total level variation explained by climatic and geographic conditions
QB	Base flow
As	Lake surface area
$\mathrm{Ws}(n)$	Lake level variation due to rainfall/evaporation over the lake surface in the month n

Eq. (4) considers the direct runoff produced in the first two months after the rainfall event, the percentage of rainfall turned into runoff, the time lag of the water to reach the lake bed, and the distance of each polygon from the lake. Note that it is not expected the water in Polygon I to take the same time to reach the lake as water fallen in Polygon III. Then, Eq. (5) determines the level change forced by climate conditions and catchment geomorphology. First, the total volume change was computed by adding the base flow to the short-term rain generated runoff. The base flow was supposed to be the average dry season's flow from 1987–1994 when a gauge was operating. The base

Table 2
Characteristics of the divided polygons (MAGA-CATIE-ESPREDE, 2001)

Polygon	Altitude Range (mamsl)[a]	Extension (km^2)	Meteorological station	Stations Altitude (mamsl)[a]	Annual rainfall (mm)	Annual input[b] (10^6 m^3)
Polygon I	>1000	2546.97	Cobán	1323	2208	2404
Polygon II	500–1000	1767.02	Cahabón	380	2159	1904
Polygon III	10–500	3700.14	Las Vegas	10	1825	3072
			Puerto Barrios	2	3439	
Lake Surface	10	679.73	Las Vegas	10	1825	1132

[a] mamsl (metres above the mean sea level).
[b] Annual average derived from Eq. (3).

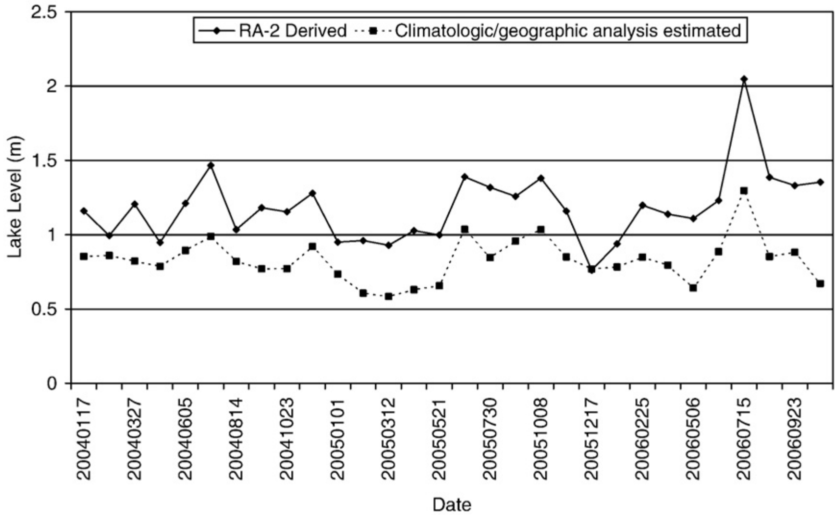

Fig. 12. LLH derived from RA-2 measurements (dashed line) and derived from the climatologic and geographic analysis (solid line). Units are in m.

flow was reduced by an assumed constant value of the Dulce river outflow. Then, the water volume changes were turned into level changes by normalizing the volume with the lake surface area. Finally, the level is adjusted by the level variation due to rainfall/evaporation over the lake surface. The rainfall/evaporation data over the lake surface were obtained from the meteorological station Las Vegas (Fig. 11). The evaporation was measured using a hook gauge evaporimeter.

The values of the coefficients used in Eq. (4) were assumed following the results obtained in Murrone et al. (1997). The time lags of each flow way were assumed based on how far is each polygon from the river mouth. The amount of the water fell in each polygon that would reach the river mouth in the "*n*" month was determined by the topography and soils distribution in the catchment. The geographic information used to obtain the Eq. (4) coefficients was found at MAGA-CATIE-ESPREDE (2001). The estimated coefficients are interpreted as follows: 10% of the polygon I water input is assumed to be transformed into runoff in the same month and 20% of that water input reaches the mouth river in the next month. Concerning polygon II, coefficients increase to 20% and 30% respectively, because this polygon is closer to the lake. Finally, in polygon III, it was assumed that 60% of water input reaches the outlet in the first two months. The analyses presented here lead to a LLH time series which was compared to the Lake Izabal water level time series. From the comparison of the two time series it is possible to determine the percentage of the lake level fluctuations explained by climatic conditions in the zone. The time series of the LLH obtained with Eqs. (3)–(5) compared with the RA-2 derived is presented in Fig. 12. The results of water inputs (Eq. (3)) and rainfall for each polygon and the LLH forced by local climate conditions (Eq. 5) are shown in Table 3. Most of the lake level rises are observed in both datasets, but this is not the case for some of the lake level drops as they appeared to have other forcing factors. The correlation coefficient between the observed LLH values and the climate driven LLH values is 0.74. The low correlation coefficients are probably caused by the influence of other factors not taken into consideration in the equations used (i.e. groundwater dynamics and the outlet discharge).

According to the results shown in Fig. 12, 2005 was the year with the lowest lake stages (rainy and dry seasons). However, 2005 rainy season reported higher precipitation values than 2004 rainy season (Figs. 10 and 12). This fact could be due to the early 2005 climate conditions, when a 6 month period of water deficit caused that 2005 rainfall events did not affected the lake level as much as they should have done it. The water deficit conditions in early 2005 left low levels of soils moisture, hence the rainfall events initially recovered the aquifers emptied in the preceding dry season.

There are two features considered as abnormal to the lake level dynamics: the lake level rise in July 2006, which is mainly driven by extremely high rainfall events in June 2006 (Fig. 10). And the abrupt lake level drop in April 2005, which is mainly driven by the water deficit conditions observed in the previous months (Fig. 10). In this

Table 3
Mean monthly rainfall and water input ($W_i(n)$) derived from Eq. (3) for each polygon and the LLH change explained by local climate from Eq. (5)

Month	Polygon I		Polygon II		Polygon III		*LC* Eq. (5)
	Rainfall (mm)	$W_1(n)$ Eq. (3)	Rainfall (mm)	$W_2(n)$ Eq. (3)	Rainfall (mm)	$W_3(n)$ Eq. (3)	
January	126.22	109.1706	132.42	66.5714	231.74	333.7689	0.791
February	100.78	48.5162	84.878	26.2174	157.079	164.5917	0.776
March	171.14	162.3437	98.66	24.6556	121.303	69.8053	0.712
April	98.88	60.3258	122.83	28.4948	120.651	42.8419	0.684
May	157.68	78.5471	193.78	119.3791	133.86	56.2585	0.698
June	306.24	444.4531	356.82	397.7259	314.783	499.4590	0.857
July	235.39	257.4365	351.06	382.9944	335.776	539.7209	0.948
August	202.998	202.6689	280.46	265.9211	193.829	191.5847	0.835
September	256.9	339.7666	281.045	222.7087	209.043	238.1470	0.841
October	216.6	241.2026	248.4075	178.8357	206.3025	180.8968	0.840
November	268.12	404.8129	215.9825	150.9762	368.235	555.2099	0.795
December	126.16	55.0704	137.1775	39.3184	202.92125	200.5151	0.777
Annual	2267.11	2404.3145	2326.998	1903.7987	2440.031	3072.7997	

condition the lake water input depended, solely, on the water storage in the catchments aquifers represented by base flow (assumed to be constant).

The results obtained here give general information about the water balance of the lake. However, it is not possible to know the contribution of each water balance component and error budgets. Some efforts are being carried out, using hydrological models and field measurements, in order to determine other water balance components. Further studies will include the water mass balance of Lake Izabal. Note also that regarding the three factors forcing lake level fluctuations: climate conditions, basin geomorphology, and anthropogenic factors (Birkett, 2000; Mercier et al., 2002) the anthropogenic factors were not taken into account in this study due to a lack of reliable data. Thus, the human activities remain as another source of error in this research.

5.2. Interactions with regional climate changes

The weather conditions in the study area are forced by ocean–atmosphere circulation in the North Atlantic and the Eastern Pacific, mainly the Tropical North Atlantic anomaly and ENSO (Fig. 13) (Enfield & Alfaro, 1999; Giannini et al., 2000; Hastenrath, 1984; Restrepo & Kjerfve, 2000). The magnitude of these oscillations might also affect to the water resources in the region (Mercier et al., 2002; Restrepo & Kjerfve, 2000; Thattai et al., 2003). Regarding the lake levels, Mercier et al. (2002) pointed out the qualitative links between an abrupt elevation in the LLH of the African lakes analyzed and an abnormal warming in the Indic Ocean forced by ENSO. The analysis presented here is focused on the relation between the lake level extremes pointed out in the relationships with local climate and catchment geomorphology, and regional climate changes forced by ENSO and the Tropical North Atlantic anomaly. The climate indexes used in this analysis were obtained from the Climate Prediction Center of the US National Weather Service: Southern Oscillation Index (SOI) related with ENSO and North Atlantic Index (NATL) related with the Tropical North Atlantic anomaly. These climate indexes were obtained at: http://www.cpc.ncep.noaa.gov/data/indices/.

Fig. 14 shows the time series of the Sea Level Pressure Anomaly (SLPA) of the two climate indexes used in this study: SOI (Fig. 14A) and NATL (Fig. 14B). La Niña and El Niño are opposite phases of the ENSO event; La Niña is referred to as the cold phase (positive SOI in Fig. 14A) and El Niño as the warm phase (negative SOI in Fig. 14A) (NOAA, 2007). In the study area, years with La Niña/El Niño conditions are correlated with high/low rivers water discharges (Restrepo & Kjerfve, 2000). Regarding the NATL index, high/low values are cooling/warming features of the ocean's upper layer. Normally, cooling/warming events in the North Atlantic generate rainfall decreases/increases in the Caribbean Sea basin (Giannini et al., 2001).

Anomalous dry summers in the study area coincide with lower (negative) SOI values, related with higher Sea Surface Temperature (SST) in the Equatorial Pacific. These, are the conditions for an ongoing El Niño event (warm phase); in addition to this, a higher NATL is observed in the North Atlantic (cold phase) with lower SST in the area. The same patterns are observed (but opposite signs), for anomalous wet summers (Hastenrath, 1984). Fig. 14A shows a strong El Niño occurrence between January and April 2005, coincident with the most important water deficit observed in the climatologic analysis (Fig. 10). In addition, the minimum LLH water stage in the whole study period was found in April 2005 (Fig. 6). During that period, the highest NATL was observed (Fig. 14B), with a very cold SST in the North Atlantic.

During early 2006 two strong La Niña events were recorded. This is observed in the higher values of SOI (positive values) in the Eastern Pacific (Fig. 14A) and the lower NATL values in the North Atlantic (Fig. 14B). According to predictions made by national and regional climate forecasting agencies: INSIVUMEH (Guatemala), and El Salvador National Service of Territory Studies (SNET), these two events might be in the origin of the early rainy season and more cumulated rainfall observed during that season. Note that when the

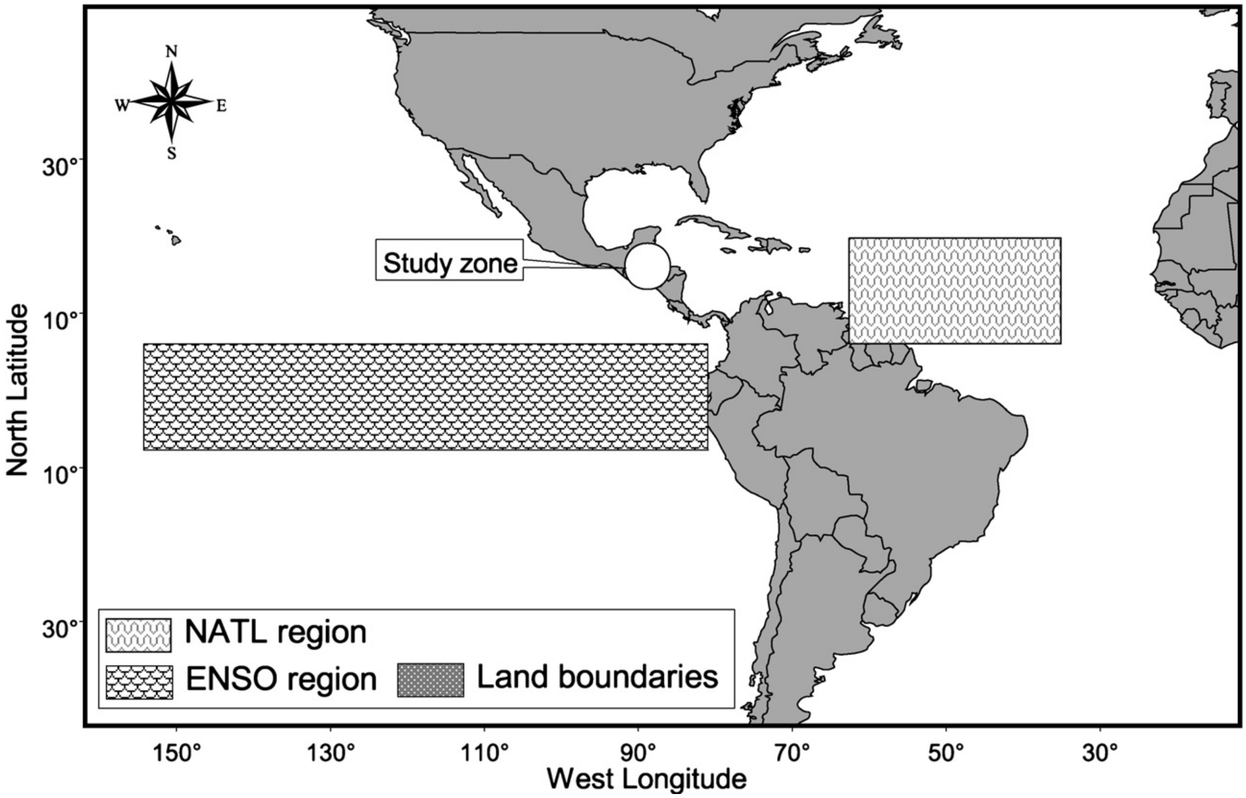

Fig. 13. Oceanographic regions that affect the weather and water resources of the study zone.

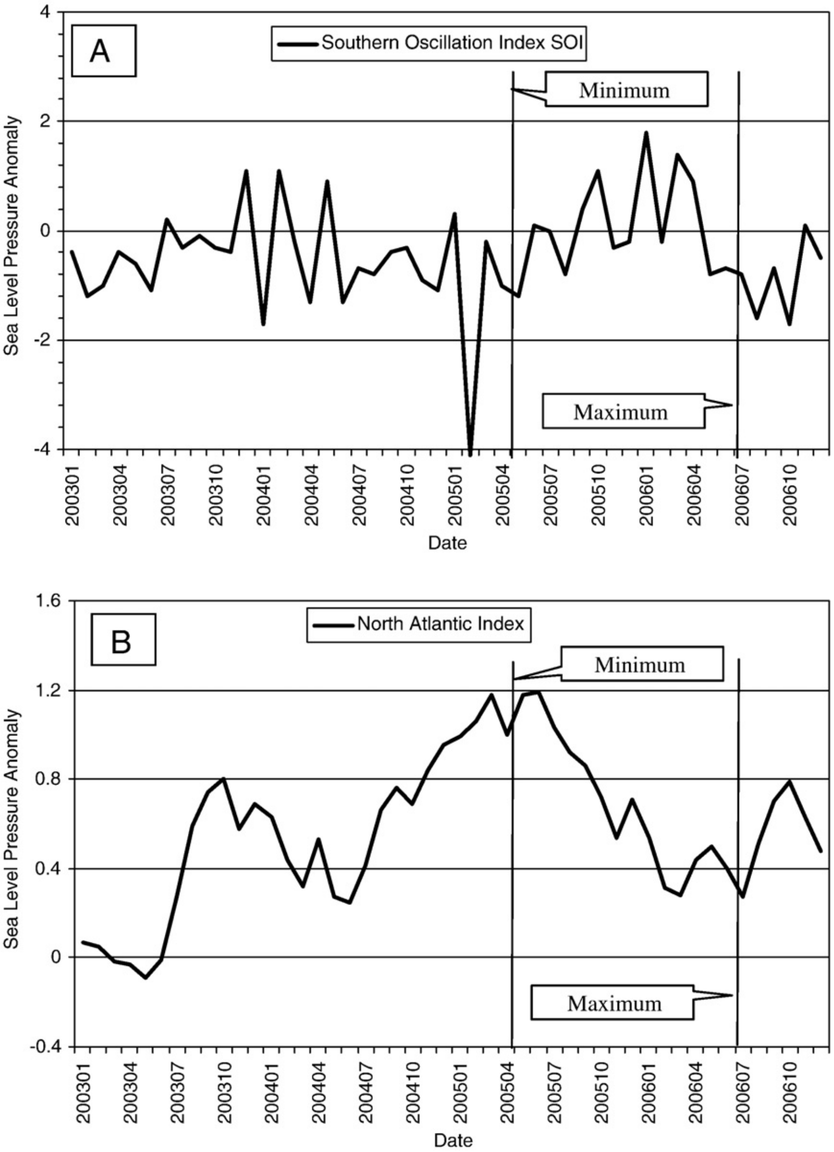

Fig. 14. Time series diagram of the Sea Level Pressure Anomaly of the Southern Oscillation Index (SOI) (A) and the North Atlantic Index (B). Solid vertical lines indicate the date of the extreme Lake Izabal water level fluctuation: minimum (April 2005) and maximum (July 2006).

Eastern Pacific is colder (La Niña event) and the North Atlantic is warmer, rainfall anomalies are positives in the region (Enfield & Alfaro, 1999; Hastenrath, 1984). As a consequence, the river water flows in the region are increased during La Niña occurrences (Restrepo & Kjerfve, 2000). Thus, the abrupt lake level rise observed in July 2006 (Figs. 4, 6 and 10) and the annual high level behaviour during 2006 (Fig. 7), could partially be explained by the two La Niña events observed in that year. However, the Lake Izabal water level variations interactions with the North Atlantic and ENSO are not well known and the shape and magnitude in which they affect are out of the scope of this study. Further works might take this matter into account.

6. Conclusions

In this work, we have estimated the water level fluctuations of Lake Izabal, the biggest lake in Guatemala, their relationship with local climate, catchment geomorphology and regional climate events. Lake level fluctuations were estimated using two datasets: lake level heights derived from RA-2 range measurements and daily *in-situ* data. In order to determine the relationship of the fluctuations observed with local weather conditions and regional climate changes, climate data records and climate indexes were used. To the light of the results obtained, we outline the following conclusions.

The comparison of the relative lake levels variations made from the two data sources showed very similar patterns, yielding to a correlation coefficient of 0.83 and a rms error of 0.09 m. Lake water level dynamics are forced by complex interactions of several factors such as climate, soils, physiography, biology, oceanography and anthropogenic influences. These interactions make the lake level to have interannual, seasonal, monthly, and daily fluctuations. From all the timescales of variations, our results show that the seasonal signal is the strongest. Our analysis show that in the time period of study, the Lake Izabal level dynamics follow the rainy and dry season's cycle in the zone. During the period from December to May the lake water height shows a low stage, whereas from June to November shows a high stage. The interannual comparisons made found that 2006 was the year with the highest lake water levels (average and extremes); and 2005 was the year with the lowest values of lake level.

Lake Izabal water level dynamics are forced by weather conditions over its surface and catchment area and they are sensitive to local and regional climate changes. Morphologic characteristics of the catchment and complex interactions with rainfall/evapotranspiration cause a delay in the time it takes the water to reach the lake bed after rainfall events. We have estimated the lake level variations derived from the climatologic and geographic analysis and compared with the RA-2 information. The correlation coefficient between both dataset was 0.62. The low correlation observed might be due to the factors not considered in the estimation of the lake levels from climatologic and geographic information. Regarding the two extreme values observed in the dataset analyzed (abrupt level rise in July 2006 and strong drop in April 2005) we conclude that they seem to have interconnections with previous occurrences of strong SST anomalies in the North Atlantic and the Eastern Pacific. However, further analysis should be done in order to confirm this.

Acknowledgments

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