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Calculation of river discharge and prediction of lake height from satellite radar altimetry: Example for the Lake Chad basin

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[1] The application of satellite radar altimetry to the determination of lake and river elevations has been used in numerous projects, and is well validated. Here we show that with the aid of ground-based information, this technique can be extended to determine river discharge and predict downstream lake and marsh height. The Lake Chad basin provides an ideal case study due to its well-known hydrology and complex lake and marsh morphology and because prediction of lake and marsh height has been identified as potentially useful to people living in the region. Altimetric stage measurements from the TOPEX/Poseidon satellite, at the Chari/Ouham confluence, estimate river discharge about 500 km downstream at N'Djamena 10 days in advance (r^2 = 0.9562). Via simple linear correlation methods, the stage measurements successfully estimate the height of the permanent waters of the lake (600 km downstream) 39 days in advance (r^2 = 0.9297). Predicting the water height on the western marshes of the lake bed is poorer (r^2 = 0.7958) due to a change in response time of the local stage to the seasonal floods coincident with an observed increase in mean water level in the latter half of the 1990s. Before 1997 a 96-day phase lag results in the best fit (r^2 = 0.6463). After 1997 the best fit is obtained with a 66-day phase lag (r^2 = 0.8139). The excellent river discharge and lake height predictions show that altimetry is a useful tool where ground-based data are difficult to obtain and where rapid water resource assessment is desirable. *INDEX TERMS:* 1860 Hydrology: Runoff and streamflow; 1884 Hydrology: Water supply; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; *KEYWORDS:* altimetry, discharge, Lake Chad

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1. Introduction

[2] It is becoming increasingly clear that water resources represent one of the most important issues facing humans [e.g., *Postel et al.*, 1996; *Rosengrant*, 1997], as water is the building block of all societies. However, because of increasing population, industrialization, and dependence on irrigation, infrastructure deficiencies, and the inherent high variability of precipitation and discharge, water resource scarcity (from occasional to chronic) is already common in many regions of the world, and can be expected to become more acute [*Biswis*, 1993; *Falkenmark*, 1994; *Gleick*, 1998; *Ashton*, 2002]. As a result, quantifying regional water resource pools and their modes of variability (both short- and long-term) have become important research topics [e.g., *Vörösmarty et al.*, 1996].

[3] Ground-based data are most commonly and accurately used for water resource analysis. However, the decrease in the number of hydrometerological monitoring stations [*World Meteorological Organization* (*WMO*), 1991; *Vörösmarty et al.*, 2001] and difficulties in obtaining data consistently and accurately from remote regions make the use of ground-based data impractical in some cases. As a result, remote sensing of rivers, wetlands, and lakes is recognized as an additional useful source of water resource information [*Alsdorf and Lettenmaier*, 2003]. In the last 2 decades a number of studies have demonstrated the capabilities of satellite radar altimeters [e.g., *Koblinsky et al.*, 1993; *Morris and Gill*, 1994; *Birkett*, 1995, 1998; *Dalton and Kite*, 1995; *Cazenave et al.*, 1997; *Campos et al.*, 2001; *Mercier et al.*, 2002; *Maheu et al.*, 2003] and passive and active microwave sensors [*Giddings and Choudhury*, 1989; *Alsdorf et al.*, 2000] to monitor river, lake, and wetland level and extent and, further, to derive river discharge from a combination of passive microwave data, ground-based data, and numerical model simulations [*Vörösmarty et al.*, 1996]. Further, *Birkett* [2000] demonstrated the application of satellite radar altimetry to monitor water height variations across the Lake Chad basin where she found that under good conditions data from the satellite radar altimeter could be used to predict fluctuations of lake level several months in advance.

[4] The purpose of this paper is to expand on the previous work of *Birkett* [2000] described above. In this study we use upstream measurements of surface water height from the

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TOPEX/Poseidon radar altimeter, calibrated through simple empirical regression techniques with ground-based gauge height and discharge data, to estimate the mean monthly river discharge of the Chari River at N'Djamena, Chad (about 500 km downstream of the altimetric measurements), and predict the wet season height of the surface waters within the Lake Chad basin (more than 600 km downstream). The prediction of the wet season water height on the lake and marshes is of particular interest because the seasonal maximum level determines the success of people who farm and fish on the southern shore of the basin [*Sarch and Birkett*, 2000].

[5] A study by *Guganesharajah and Shaw* [1984] presented a statistical model to predict the seasonal minimum levels of Lake Chad. Minimum lake level was of interest in that study, because the water intake structures of irrigation facilities (since abandoned due to permanently low water levels) were dependent on exceeding a minimum water level. Their model used ground-based river discharge and lake gauge data to describe the probability of variations in the minimum level of Lake Chad in the coming dry season and predict the minimum lake level one season in advance.

[6] In this study we calibrate upstream water height measurements with local lake and water height measurements to develop a statistical model that directly predicts wet-season water height at the location where it is needed (on the lake or marsh). Typically, a hydrologic study of the changes in lake and marsh height would involve calculations of the volume changes as a function of the river input, precipitation on the lake, the output via evaporation and outflow, and the volume of water in the lake basin from the previous season. However, for this basin a calculation of water height directly from satellite height is more instructive than an analysis of volume change for two reasons: (1) The local population of the lake basin are dependent on lake level fluctuations for their livelihood and satellite altimetry can provide that directly. (2) Conversion of lake basin volume changes to water height changes is inaccurate because of the complex combination of shallow permanent water and wetlands that occupy this basin and the enormous seasonal fluctuations in the lake and marsh area (from roughly 2000 km^2 to about 15,000 km^2 between dry and wet season). Therefore upstream height directly predicts water height without an intermediate step to introduce additional error.

[7] Using satellite observations rather than ground-based observations in this case is advantageous because (1) altimeter data are received continuously and are potentially available within a few days of measurement and therefore provide data on water resources where traditional gauge data can be irregular and difficult to obtain quickly, (2) the time lag between upstream and downstream points provides an opportunity to predict, as much as 1–2 months in advance, the downstream water resources, and (3) development of general techniques for water resource quantification or prediction from satellite altimetric data may be potentially useful in other regions of the globe.

2. Study Region

[8] We have chosen the Lake Chad basin to develop and test our techniques of estimating discharge and predicting lake level because of our previous experience in satellite applications and numerical model development in this region [*Birkett*, 2000; *Coe and Foley*, 2001; K. Y. Li et al., Investigation of hydrological variability in western and central Africa using land surface models, submitted to *Journal of Climate*, 2004, hereinafter referred to as submitted manuscript, 2004] and because of the challenging physical, climatic, and social characteristics of this basin.

[9] The Lake Chad drainage basin is an approximately 2.5×10^6 km^2 hydrologically closed drainage system in the central Sahel region of northern Africa (Figure 1). It has a monsoon climate, with the majority of the rainfall occurring in the southern one third of the basin (as much as 1500 mm/yr falling during the months of June, July, and August) and semiarid and arid conditions in the north. Runoff and river discharge are generated predominantly in the southern portions of the drainage basin and transported via the Chari/Logone River system to the town of N'Djamena, Chad, and thereafter to Lake Chad.

[10] Lake Chad is the terminal lake of the drainage system. It is currently a shallow lake (<7 m) comprising a region of permanent water of about 2000 km^2 surrounded by seasonally inundated marshlands, which may occupy greater than 10,000 km^2 during the wet season (Figures 1a and 1b). The Chari/Logone River system transports to Lake Chad greater than 90% of the discharge generated within the drainage basin, with the remaining coming from the Komadougou-Yobe, the El Beid, and the Yedseram [*Famine Early Warning System* (*FEWS*), 1997]. Therefore the discharge of the Chari River measured at N'Djamena represents the greatest portion of the discharge input to Lake Chad.

[11] The river input to Lake Chad and modest precipitation on the lake surface (<5% of the annual discharge input) are balanced by evaporation, seepage to groundwater (perhaps as much as 15% of the water budget [*Isiorho et al.*, 1996]), and interannual storage in the lake. As a result, under the current climatic conditions the lake and marsh level shows strong seasonal variability, fluctuating by about 1.5 m each year as the flood wave arrives and is subsequently removed in large part by evaporation. Because of its dominance of the water budget, interannual variations in the peak lake level are mostly determined by variations in the amount of discharge to the lake from the Chari River. Therefore, as suggested by *Birkett* [2000], upstream measurements of water height are capable of accurately predicting the water height of the lake more than 600 km downstream.

[12] In addition to the physical and climatic conditions listed above, the social conditions of the region suggest that a predictive tool would be useful. The large and increasing population (about 20 million people in 2000) of the Lake Chad basin depends on a limited water resource. The fraction of the precipitation available as runoff is very small (<10%) [*U.N. Food and Agricultural Organization*, 2000; *Ashton*, 2002; K. Y. Li et al., submitted manuscript, 2004], and the precipitation, and therefore runoff, are highly variable and anomalies show extreme persistence [*Hulme*, 1992; *Nicholson*, 2000]. For example, in the Sahel, every year since 1970 has been anomalously dry compared with the climatological period 1931–1960 [*Olivry et al.*, 1996; *Nicholson*, 2000]. The persistent drought since the early 1970s has led to a drastic reduction in water

resources and hardship for many people in the Lake Chad basin [*Hutchinson et al.*, 1992; *FEWS*, 1997].

[13] Despite this, around the shores of Lake Chad itself some people have been able to take advantage of the increased seasonal fluctuation of the marshlands and lake for agriculture and fishing [*FEWS*, 1998; *Sarch and Birkett*, 2000]. Local people fish as the floods arrive in the early winter and then farm emergent lands after the winter flood recedes. This combination of fishing and farming has provided an important economic boost to some residents of the lake [*Sarch and Birkett*, 2000]. However, the population is still vulnerable to interannual fluctuations in the timing and height of the flood. Dry years lead to reduced yields in both fishing and farming; wet years result in village flooding and the spoiling of crops. *Sarch and Birkett* [2000] showed that information on the height of the coming flood, even 1–2 months in advance, may be a valuable tool in aiding water management decisions.

[14] This combination of the complex physical/climatic conditions and the potential for useful application of the results make the Lake Chad basin an ideal location to develop and test techniques for quantification of water resources from satellite altimeter data.

3. Data Sets and Validation

3.1. Ground-Based Data

[15] Ground-based data of mean monthly gauge height (January 1990 to December 1998) at N'Djamena and Sarh, Chad, and river discharge (January 1990 to December 1994) at N'Djamena (provided by Y. Nelngar of the Lake Chad Basin Commission) are used to (1) derive a discharge rating curve and (2) calibrate and validate the altimeter products.

[16] To derive a rating curve, the reported discharge at N'Djamena is regressed against the reported gauge height for the period January 1993 to December 1994 (r^2 of 0.9703, Figure 2a). To validate this rating curve, the fit is applied to the remaining months in the gauge height series (January 1990 to December 1998). As expected, the rating curve ($D = 81.809H^{1.9487}$, where D = discharge, H = ground observed stage height) is extremely accurate; the discharge derived from the gauge height and regression equation compares very well with the reported discharge (r^2 for the 24 months 1990–1992 = 0.99). This indicates that changes to the rating curve are small in time and discharge can be accurately estimated from it.

3.2. Satellite Data

[17] In this study, archived radar altimetric range measurements for the period 1992–2002 (archived in the

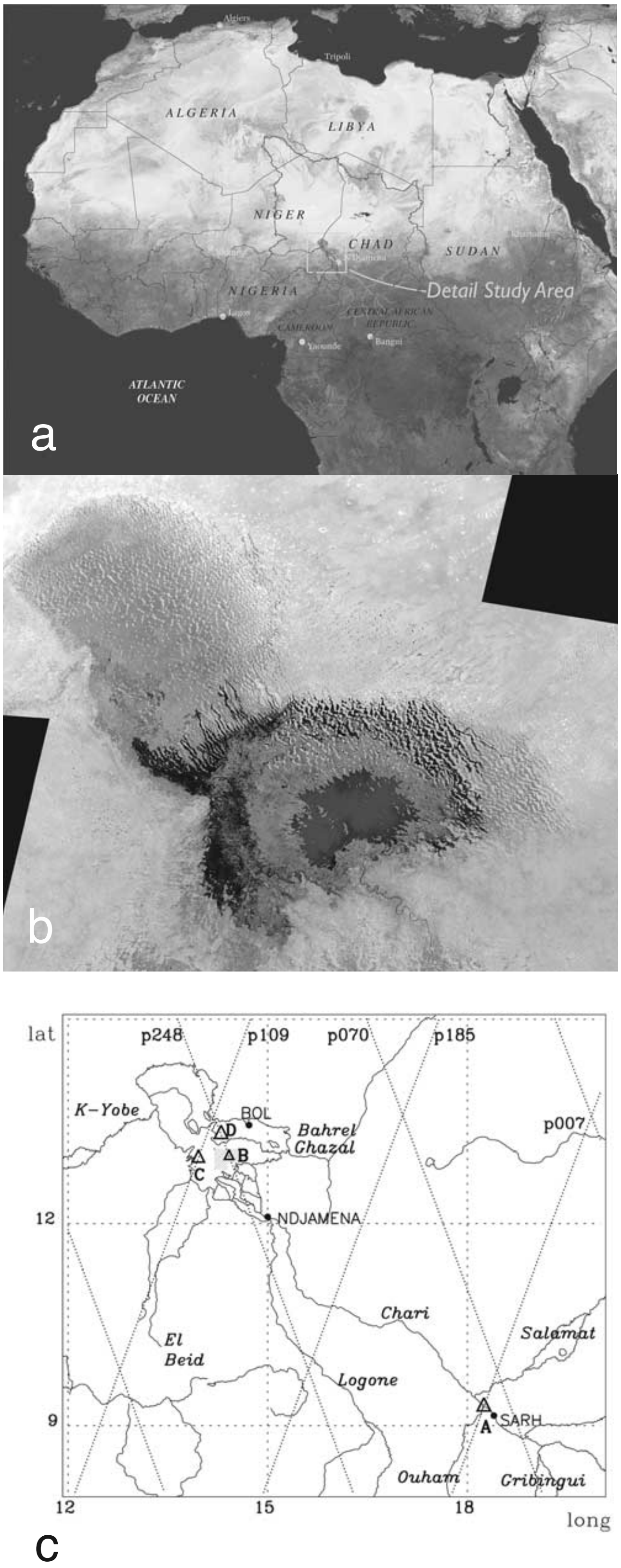

Figure 1. (a) The geographic location of the Lake Chad basin, (b) a close-up of the lake, and (c) Chad basin with TOPEX/Poseidon ground paths. The extent of the basin in Figure 1a is revealed in dark blue, and the inflowing rivers are in pale blue. Figure 1b is a Landsat mosaic using ETM scenes from October 1999 and October 2000. The remaining permanent waters of the lake (deep blue) can be seen as well as the inflowing Chari River. Dune systems which become seasonally inundated can be seen across the lake bed. Both figures courtesy of UNEP GRID Sioux Falls. Figure 1c shows the TOPEX/Poseidon ground paths (dashed lines) and the four sites used in this study: A, Chari/Ouham confluence; B, open lake; C, western marshes; and D, northern marshes. Historical lake coastlines are also shown, as is the approximate location of the current permanent lake (shaded area in vicinity of site B). See color version of this figure at back of this issue.

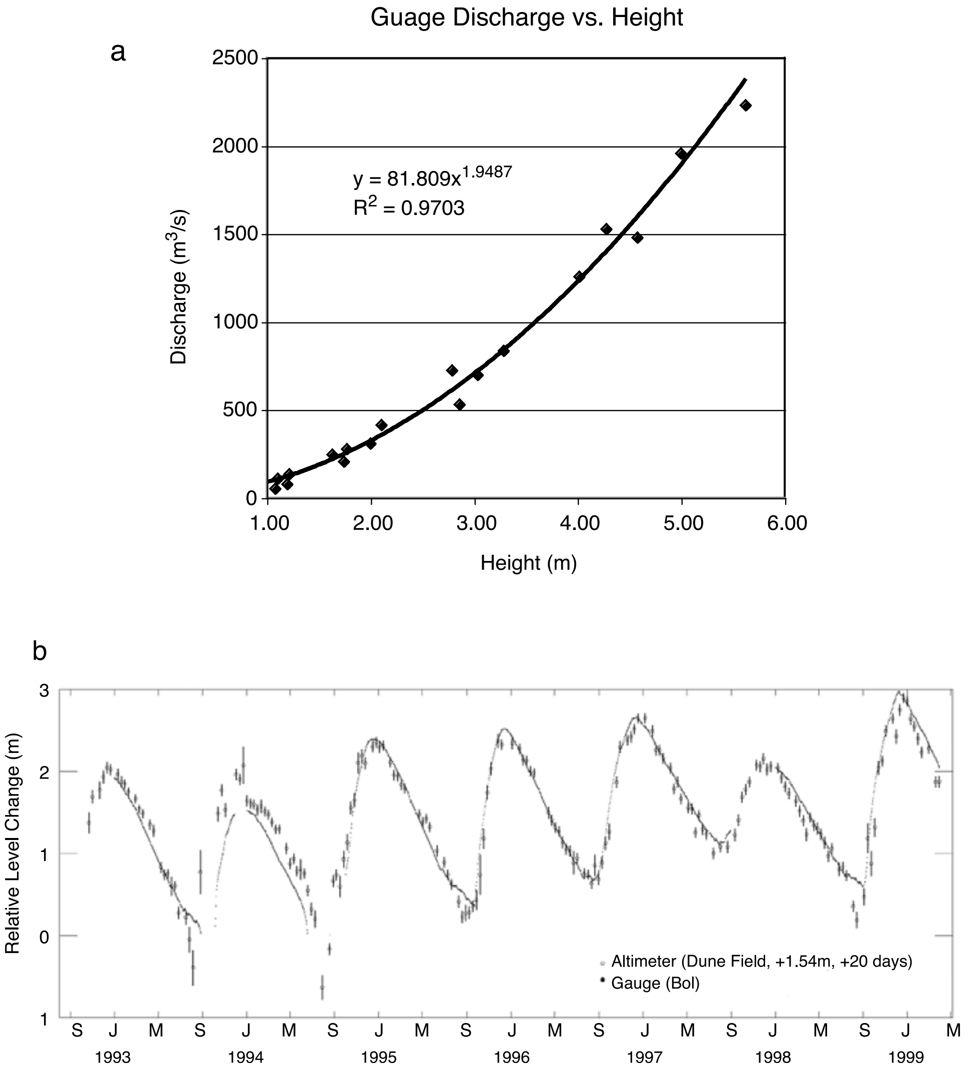

Figure 2. (a) Discharge rating curve from gauge height and discharge data at N'Djamena, Chad. The rating curve is developed from the 24 months of data between January 1993 and December 1994. (b) Comparison of the relative lake height in the northeast quadrant of Lake Chad as measured by the gauge at Bol, Chad (black dots), and the radar altimeter (open triangles). For the comparison, the altimeter measurements have been shifted 1.54 m vertically and a 20-day phase lag has been applied. The latter reflects variations in timing of peak stage across the lake bed.

Geophysical Data Records) from the TOPEX/Poseidon satellite together with various geophysical corrections are used to make a full reconstruction of altimetric water heights at selected locations in the basin. A detailed explanation of this data set and the repeat-track technique that is used can be found elsewhere (e.g., *Birkett* [1995, 1998] and in particular for Lake Chad, *Birkett* [2000]). To summarize, this satellite orbit has a 10-day repeat period, with a number of ground tracks passing over the lake basin (Figure 1). Altimetric height measurements can be potentially retrieved every ~580 m along the ground tracks wherever water is detected by the instrument. These values represent the average height within the altimeter footprint, which can be a few hundred meters to a few kilometers wide, depending on the surface roughness.

[18] Certain sections of the ground tracks (defined by geographical locations; see Table 1) are used here because they cross the Chari River and Lake Chad. Along each of these sections, surface water elevations from each satellite pass are differenced relative to an arbitrarily designated "reference pass," and an average is created that represents the lake or river stage and the relative change in elevation from the date of the reference pass. The resulting time series of relative height variations therefore have a maximum temporal resolution of 10 days and are based on averaged height variations along the ground track, rather than on a spot height measurement.

[19] A validation of the altimetric water height variations within the northeast quadrant of Lake Chad is made by comparison with recently obtained daily gauge data from Bol (Figure 2b). The gauge data extend only to March 1999 and are sporadic because of operational difficulties. The altimetric measurements represent a ~30 km extent (i.e., potentially ~50 altimetric height values along the satellite ground track) of the seasonally inundated dune field, ~55 km to the southwest (site D, Figure 1) of the

Table 1. Satellite Pass Number, Surface Location (see Figure 1), and Geographic Locations of the Sections of Satellite Ground Tracks Used in This Study to Derive Altimetric Height[a]

Satellite Pass	Surface Location	Geographical Limits, Latitude/Longitude to Latitude/Longitude, deg
007/A	A, Ouham/Chari	(9.240, 18.214)–(9.320, 18.243)
248/D	B, lake	(12.92, 14.42)–(13.05, 14.37)
109/A	C, marsh	(12.80, 13.88)–(13.15, 14.01)
248/D	D, marsh	(13.20, 14.31)–(13.50, 14.20)

[a] A and D indicate ascending and descending TOPEX/Poseidon satellite overpasses.

gauge site. The error bars on the altimetric data are a combination of the total error budget (from all measurements and corrections used in constructing the altimetric height) and the standard error on the height difference ($s/\sqrt{N}$) between the reference pass and any other repeat pass. N is the number of valid data points along the pass, and s is the one sigma standard deviation in the mean height difference (see *Birkett* [1995] for details). Additionally, the RMS value, 21 cm, is only an approximation because the gauge and satellite sites compared are not in the exact same location and any differences in spatial location between altimeter and gauge sites can result in height and timing variations. Typically, validation of TOPEX/Poseidon height measurements at locations where the sites are more closely aligned [e.g., *Birkett*, 2000] show accuracies ranging from >3 cm RMS (for lakes greater than ~300 km^2) to >10 cm RMS (for rivers, wetlands, and floodplains $\geq$1 km wide).

4. Techniques

[20] Time series of altimetric height derived from TOPEX/Poseidon at three locations within the basin were taken from the previous Lake Chad study [*Birkett*, 2000] and updated to extend to May 2002. The locations, the Chari/Ouham confluence, the open water on Lake Chad, and the western marshes of the lake are described in Table 1 and shown in Figure 1.

[21] The altimeter data at the Chari/Ouham confluence (Figure 3) is used to predict the discharge at N'Djamena and the lake and marsh height. Because of the narrow width of the river channel at this upstream location, the altimeter data from the Chari/Ouham confluence are most likely representative of variations on the combined floodplain rather than within the river channels only. As a result, the altimeter does not record the lowest water levels with accuracy, and there is increased error at time of low-water periods as dry land emerges on the plain. Nevertheless, the advantages with the Chari/Ouham site are (1) it is relatively far upstream (about 500 km from N'Djamena and greater than 600 km from the Lake Chad sites) and therefore maximizes the time lag with downstream sites and the predictive capabilities, and (2) it encompasses most of the headwater tributaries of the Chari River and therefore maximizes the relationship with the discharge at N'Djamena.

[22] The TOPEX/Poseidon altimetry measurements are instantaneous values with a roughly 10-day temporal resolution (Figure 3). The altimetric heights were linearly interpolated to daily values to smooth the uneven spacing of the data and then averaged to monthly means to conform to the resolution of the gauge data. This altimetric height series from the Chari/Ouham site is used to (1) estimate the river discharge at N'Djamena (~500 km downstream) and thereby extend the time series to the present, beyond what is currently available from ground-based data; and (2) predict the height of the open lake and western marshes of Lake Chad (~600 km downstream), which is home to villages that depend directly on the lake for economic benefit.

4.1. Estimation of River Discharge

[23] As a first step to estimating the river discharge at N'Djamena, a simple linear regression is derived to relate the gauge height at N'Djamena to the altimetric height from the Chari/Ouham confluence. The linear regression for a 24-month calibration period (January 1994 to December 1995) results in an excellent coefficient of correlation (r^2 = 0.9789; Figure 4a), where a 10-day phase lag was added to the altimeter data to maximize the correlation. The 10-day phase lag represents the flow time of water between the confluence and N'Djamena and agrees reasonably well with the flow time of about 15 days between Sarh and N'Djamena derived from daily gauge data. This lag and the equation of the linear regression are then applied to the remaining months (November 1992 to December 1993; January 1996 to May 2002) to convert the entire altimetric record of the Chari/Ouham to altimetric height at N'Djamena. When compared with the gauge height, the agreement is excellent (Figure 4b; r^2 = 0.9512 for the 24 months of the validation period, January 1996 to December 1997), indicating the potential of the calibrated Chari/Ouham altimeter data to accurately predict the gauge height at N'Djamena.

[24] The final step is to estimate the altimetric discharge at N'Djamena. To do that, the newly predicted altimetric height at N'Djamena is substituted as H, into the rating curve calculated in section 3 (Figure 2a), for the period November 1992 to May 2002. The derived altimetric discharge is in excellent agreement with the gauge discharge (Figure 5; r^2 for the 48-month validation period, 1993, 1996–1998 = 0.9562), indicating that discharge can be accurately derived from the altimetric height on the Chari/Ouham 10 days in advance of the ground-based observations and provide discharge when the gauge data are intermittent.

[25] A test of the sensitivity of the results to error in the altimetric measurement is performed by recalculating the N'Djamena altimetric discharge assuming a ±10-cm error in the Chari/Ouham altimetric height observations. This results in less than a 10% change in the mean annual discharge compared with the initial calculation. The difference between monthly mean discharge for the peak flow period (August–December) is also less than 10% but rises to 15–40% in the dry season months (when altimeter measurements are poorer and discharge approaches zero). A retest assuming ±20-cm height error results in less than 20% change in the mean annual and monthly (peak period) discharge predicted for N'Djamena. Therefore the altimetric height at the Chari/Ouham confluence predicts the discharge at N'Djamena within the error bounds of the surface measurements of discharge, generally accepted as about 10–15% [*Dickinson*, 1967; *Cogley*, 1989].

4.2. Estimation of Water Height Within the Lake Basin

[26] The objective here is to use the altimetric height at the Chari/Ouham confluence to predict the water height

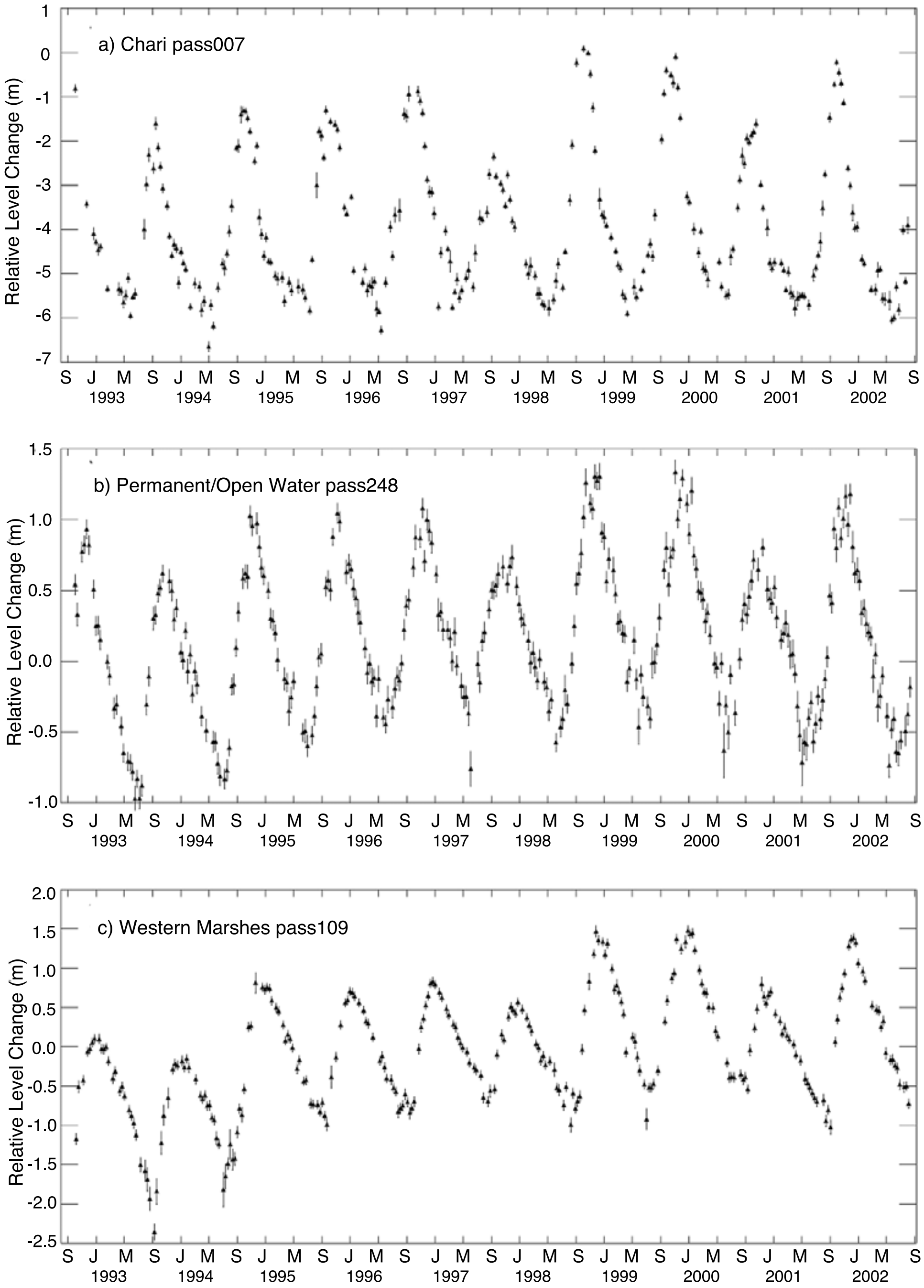

Figure 3. Raw altimeter relative height data (m) for the Chari/Ouham confluence (site A on Figure 1), the lake (site B), and the marsh (site C) with error bars.

within the open lake waters and the western marsh (Table 1). The phase lag resulting from the travel time of water in the stream is used as a prediction tool. As described earlier, there are little ground-based gauge data with which to validate the predictions, and therefore, with expected accuracies of ~10 cm RMS we will use the height series measured by TOPEX/Poseidon at the two sites as calibration and validation sources.

[27] To calibrate the Chari/Ouham height series to the open lake location, a simple linear regression of the 16 peak monthly lake heights of the 1994 and 1995 water years (August 1994 to March 1995, August 1995 to March 1996) is performed. Best agreement is achieved with a 39-day phase lag added to the Chari/Ouham height (r^2 for the 16 months = 0.9667; Figure 6a). Only the peak period height values are considered because the river flow goes to near zero during the dry season and makes direct comparison between river and lake measurements impossible.

[28] The resulting equation and time lag are then applied to the entire time series at the Chari/Ouham confluence to derive water height on the open lake from it (Figure 6b). The agreement between the lake height derived from the Chari/Ouham altimetric data and the altimetric height as directly observed on the open lake has r^2 = 0.9297 for the 56 peak-period months from August 1993 to March 1994 and August 1996 to March 2002. The excellent agreement

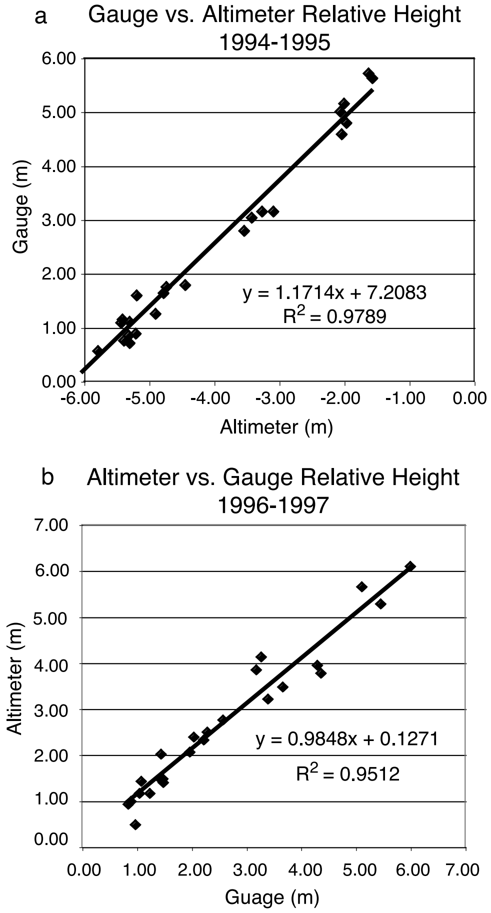

Figure 4. (a) Regression of gauge height at N'Djamena against altimetric height at the Chari/Ouham confluence for the 24-month calibration period, January 1994 to December 1995. (b) Regression of height derived for N'Djamena from the altimeter data against the gauge height at N'Djamena for period January 1996 to December 1997.

and the 39-day phase lag mean that, for this time period, the altimetric height at the upstream Chari location alone is a good predictor of the height within the permanent lake waters, 39 days later.

[29] Typically, one expects that the prediction of water height on a lake surface is a function not just of the net incoming water but also the flux out of the lake and the water stored in the lake from the previous years. However, as described in section 2, the discharge of the Chari River system so dominates the seasonal and annual fluctuation of the water balance of the lake that upstream height alone (which is a proxy for discharge) predicts future lake level accurately. To prove that this assumption is true, we also investigated adding a second independent variable to our regression. We tried using a number of different second variables, each of which is some representation of the excess of the previous season's water budget (similar to the approach of *Guganesharajah and Shaw* [1984] to simulate minimum lake height). However, in all of these attempts, previous water height showed no statistical significance in determining water height on the lake for this calibration period (1994 and1995 water years). Therefore the dependence of the lake height prediction on upstream height only (with 39-day phase lag) is appropriate for this time period. However, we do not expect it to be appropriate for all time periods; rather the regression should be routinely recalculated with single and multiple independent variables, to achieve best fit and predictive capability. In this way, a tool for the most accurate calculation of lake and marsh height can be maintained from data that are easily accessible and be of most potential use to the people of the region.

[30] The original regression technique is also used to predict the water height within the western marshes of the lake bed (Figure 1c) but with much poorer agreement. For this location, no single phase lag provides good prediction for the entire time period (Figure 7). Before 1997, a 96-day phase lag results in the best fit (r^2 for 16 peak period months from September–April 1994 and 1996 = 0.6463). After 1997, the best fit is obtained with a 66-day phase lag (r^2 for 16 peak period months from September–April 1997 and 1998 = 0.8139). A validation for the period September 2000 to April 2002 of this 66-day phase lag calibration shows relatively good agreement (r^2 for the 16 months = 0.7958).

5. Results and Discussion

[31] As indicated by the high coefficient of correlation, the altimetric height at the upstream Chari location accu-

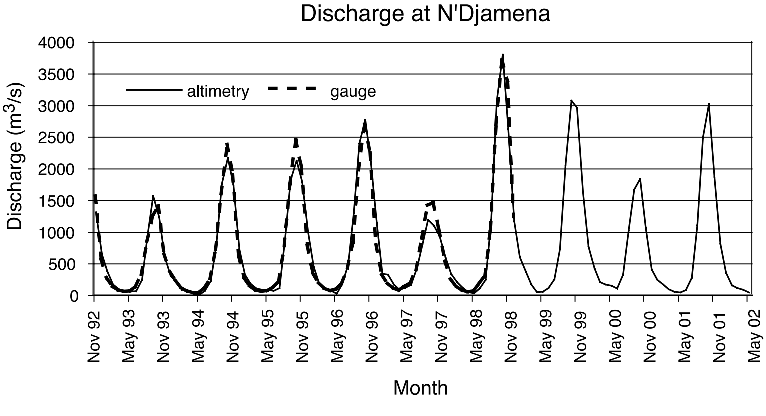

Figure 5. Discharge (m^3/s) at N'Djamena, Chad. The altimetry discharge (solid line) is developed by applying the discharge rating curve (Figure 2a) to the altimetric height for N'Djamena (described in Figure 4). The gauge discharge (dashed line) is derived by applying the rating curve to the reported gauge height at N'Djamena.

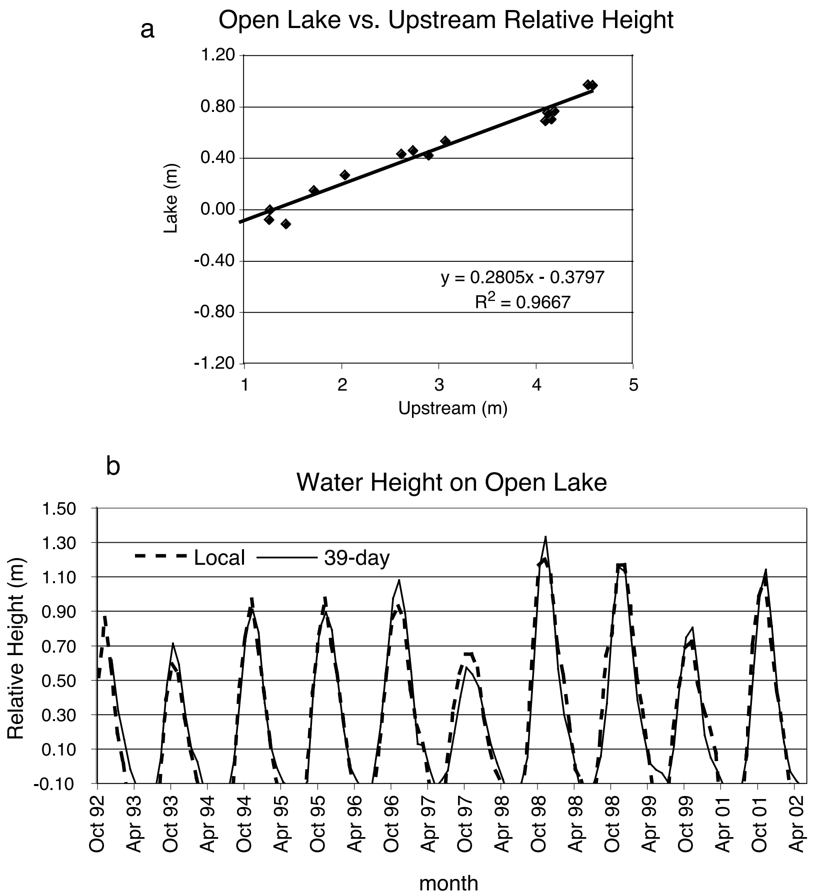

Figure 6. (a) Regression of altimetric water height (m) at the open lake location to altimetric water height (m) at the Chari/Ouham confluence with a 39-day phase lag. Regression is for the 16 months in the period August 1994 to March 1995, August 1995 to March 1996. (b) Relative lake height (m) at the open lake location (see Figure 1) as measured by the altimeter locally (dashed line) and as calculated for the open lake from the altimetric height at the Chari/Ouham confluence (solid line).

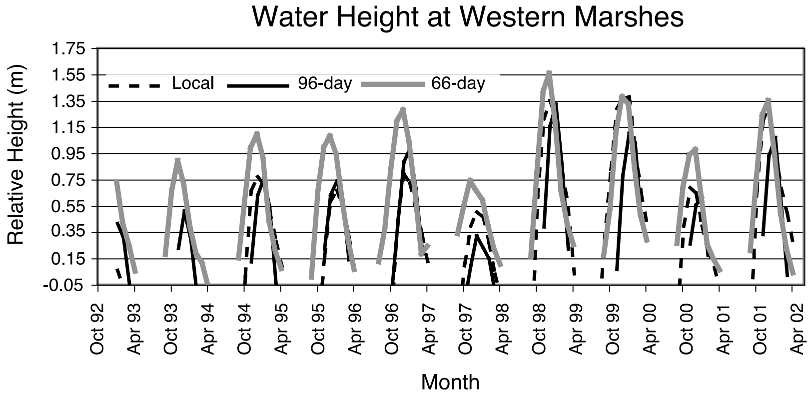

Figure 7. Relative water height (m) at the western marshes location (see Figure 1) as measured by the altimeter locally (dashed line) and as calculated for the western marshes from the altimetric height at the Chari/Ouham confluence (solid lines). The solid black line is the water height of the western marshes calculated from the Chari/Ouham altimetric data with a 96-day phase lag (calibration period is August 1994 to March 1995, August 1995 to March 1996). The solid gray line is the water height of the western marshes calculated from the Chari/Ouham altimetric data with a 66-day phase lag (calibration period of September 1998 to April 1995, September 1995 to April 1996).

Table 2. Discharge at N'Djamena, Chad, and Relative Height in the Lake Chad Basin[a]

	Discharge at N'Djamena, Site A, m^3/s		Site B Mean Annual Altimetric Height, m		Site C Mean Altimetric Height, m		
	Calculated From Gauge Height	Calculated From Altimeter Height	Measured at Site B	Calculated From Site A With 39-Day Phase Lag	Measured at Site C	Calculated From Site A With 96-Day Phase Lag	Calculated From Site A With 66-Day Phase Lag
1993	449	472	0.18	0.26	−0.68	−0.15	0.37
1994	658	653	0.40	0.41	0.27	0.00	0.54
1995	712	709	0.44	0.43	0.13	0.04	0.56
1996	816	928	0.44	0.57	0.12	0.22	0.64
1997	550	515	0.38	0.31	0.15	−0.08	0.44
1998	1079	1072	0.71	0.64	0.66	0.27	0.79
1999		998	0.70	0.61	0.89	0.22	0.75
2000		673	0.39	0.35	0.25	−0.02	0.48
2001		848	0.50	0.50	0.65	0.14	0.64
Mean	724	747	0.47	0.46	0.29	0.09	0.44
Variation	0.23	0.29	0.44	0.35	1.93	0.17	0.11

[a] The mean discharge and height for the period and the coefficient of variation (standard deviation/mean) are also shown. Years 1994 and 1995 are used for model calibration in all cases except the 66-day phase lag, which used 1998–1999 for calibration. Calibration years are not included in the statistics.

rately predicts the water height and discharge of the Chari River at N'Djamena, Chad, about 500 km downstream. The mean annual discharge calculated from the altimetric height at the upstream Chari location is within ~5% of the gauge discharge (Table 2) for the years not used in the calibration (1993, 1996, 1997, 1998). Most of that difference is attributable to the year 1996, which is about 15% greater than the surface discharge. The interannual variability, measured by the coefficient of variation of the annual mean discharge (standard deviation/mean × 100) is also in agreement for the same 4 years: about 23% for the gauge discharge and 29% for the altimetric discharge. Additionally, the variability of the monthly mean altimetric discharge is within ±20% of the observed discharge variability for 75% of the 50 noncalibration months (Figure 8).

[32] The standard error of the regression for the 50-month validation period is about 190 m^3/s, which is 25% of the mean calculated discharge. The residual error for individual months is generally less than ±25% of the calculated monthly discharge for discharge rates of greater than about 300 m^3/s (Figure 9). However, at discharge rates below about 300 m^3/s the residual error increases to greater than ±30%. The increased error at low discharge values, discussed in section 3, illustrates the inability of the altimeter to register water height at the confluence of the Chari/Ouham Rivers during the dry season. The residual error does not increase appreciably for the discharge calculated with altimetric height error ±10 cm.

[33] As a further test of the altimetry derived discharge, we also calculated the discharge at N'Djamena from the reported gauge data at Sarh, Chad (~25 km upstream of the altimeter location at the Chari/Ouham confluence), using the same technique as with the altimeter data. The mean annual discharge derived from the Sarh gauge is within about ±20% of the discharge at N'Djamena for only two of the six noncalibration years (1990–1993, 1996–1998). Similarly, the variability of the monthly mean discharge derived from the Sarh gauge data is within ±20% of the observed discharge variability for only ~55% of the 50 noncalibration months (compared with 75% for the altimetric discharge; Figure 8). The reason the discharge calculated for N'Djamena from the Sarh gauge data does not agree as well as that derived from the altimeter is most likely because the Sarh location is upstream of the confluence of the Ouham River and therefore does not include the substantial input of the Ouham River (roughly two thirds of the total at the confluence). This comparison indicates the value of using the altimeter to calculate the discharge at N'Djamena.

[34] As discussed in section 4.2, the height of the open lake is accurately predicted ~39 days in advance from the upstream Chari/Ouham altimetric measurement. The mean relative height of both the predicted and observed open water height (peak period, August through March, for 1993, 1996–2001) is ~0.45 m, while the coefficient of variation between years is ~35% for the former and 44% for the latter. Both data sets reveal the relatively high (1993, 1997)

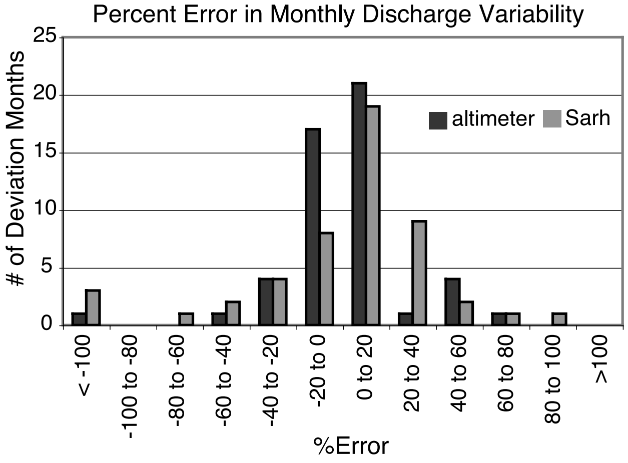

Figure 8. Frequency diagram of the percent error in the variability of the monthly mean river discharge at N'Djamena, Chad, for the discharge derived from the altimeter (black bars) and from the gauge height at Sarh, Chad (gray bars). Percent error is calculated as 100 × (sima-obsa)/obs, where sima and obsa are the monthly mean discharge anomalies (deviations from the annual mean) of the upstream and observed data, respectively, and obs is the observed annual mean discharge. Percent error is shown for all 50 months in the time series not used in the calibration (November 1992 to December 1993, January 1996 to December 1998).

and low (1998, 1999) inundation years (Table 2). The variability of the monthly mean predicted open water height is within ±20% of the local height variability for 29 of the 56 peak period months (Figure 10). The standard error of the regression for the 56-month validation period is 0.11 m.

[35] As discussed earlier, the water level fluctuations in the western marshes are not well predicted for the entire observation period due to a 30-day change in the phase lag during the period of measurement. The change in phase lag is due to a temporal shift in the timing of the peak height in the western marsh, from December/January prior to 1997 to November/December after 1997. This change is unique to this location. The anomaly is also coincident with an increase, after 1997, in the observed mean water level at all three sites and in mean annual discharge at N'Djamena (Table 2). The fact that an increase in mean and minimum water height occurs in the open lake and marsh but only the marsh has a change in the timing of the response suggests that there may be an increased hydraulic connection between the western marsh and the open lake. With increased water height after 1997, the vegetated channels connecting the western marshes to the open lake may offer less impediment to water travel or more channels may have become available to transport water.

[36] Despite the change in response of the water height in the western marshes, the predicted height for 2000–2001 appears to be relatively well represented by the 66-day phase lag from the 1998–1999 calibration (r^2 for the 16 months = 0.7958). This relatively good agreement in the last 2 years of the record suggests that it may be possible to provide information for the western marshes, where many people live, from the Chari altimetric data if the calibration period is carefully evaluated and frequently updated.

6. Conclusions

[37] The results of this study demonstrate that with the aid of in situ data, satellite radar altimetric measurements of water height can be used to estimate river discharge. This application does not replace ground-based methods but can be an aid during periods of discontinuity of gauge measurements or data availability. In addition, the spatial resolution of the satellite ground tracks across the Lake Chad basin make prediction of both the discharge at N'Djamena and the lake stage within the permanent waters of the lake bed possible.

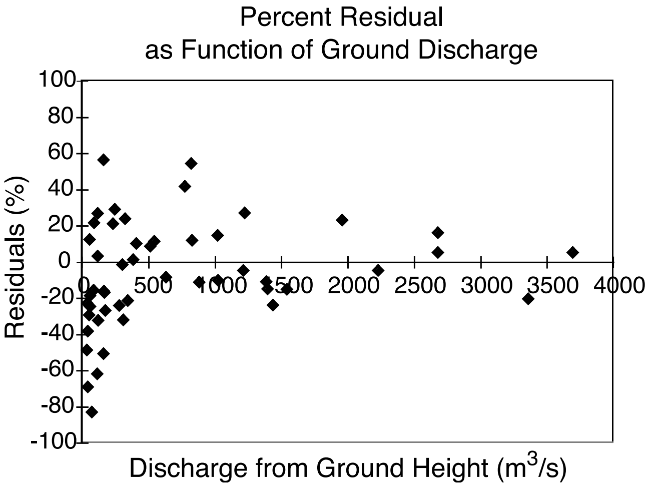

Figure 9. Scatter diagram of error residuals of the altimetric discharge (shown as a percent of the altimetric discharge) versus the gauge discharge (m^3/s) at N'Djamena, Chad.

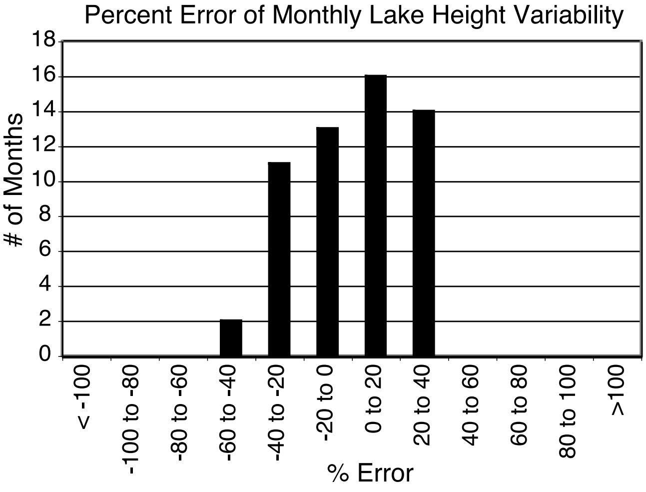

Figure 10. Frequency diagram of the percent error in the variability of the monthly mean water height on the open lake calculated from the altimetric height at the Chari/Ouham confluence (see Figure 1). Percent error is calculated as in Figure 8 and is shown for the 56 wet-season months not used in the calibration (August–March, 1992–1993, 1996–2002).

[38] The annual mean and monthly variability of the discharge of the Chari River at N'Djamena are accurately estimated, with an r^2 = 0.9562 for 48-month validation period and 75% of the months are within ±20% of the observed discharge. Additionally, the height of water in the open lake during the wet season (August–March) is predicted 39 days in advance of local observations (r^2 = 0.9297). Before 1997, the water height in the western marshes is not as well simulated (r^2 = 0.6463) due to changes in the timing of the response of the water height to the seasonal water flow into the lake. However, after 1997 the water height of the western marshes during the wet season is relatively well predicted 66 days in advance of the local measurements (r^2 = 0.7958).

[39] An advantage of calculating the downstream discharge and lake height from upstream altimetric data is that satellite data may be available very rapidly, whereas ground-based gauge data are often difficult to obtain. For example, operational difficulties such as funding shortages and civil strife can lead to data discontinuities and dissemination difficulties. Whereas data from the new follow-on mission to the TOPEX/Poseidon satellite, Jason 1, are potentially available within a few days after satellite measurement with sufficient height accuracy to enable a near-real-time monitoring system to be in place for the basin. Future research will need to include testing the direct applicability of this technique to people in the Lake Chad vicinity through outreach to working groups such as the Lake Chad Basin Commission. Outreach to local groups may help us better understand what temporal and vertical

accuracy can be useful in local agricultural and fishing decision-making.

[40] Future research will also include testing the robustness of this technique in other water-sensitive regions. The good results for the Chad Basin are due in part to the nature of this system: Most of the rainfall and runoff are generated in a distinct rainy season in the headwater regions and pass to the lake system as a fairly undisturbed flood wave. Therefore it remains to be seen how applicable this technique will be to other locations in Africa or globally. Finally, investigations will also be made into the correlation of water height and discharge using other altimeter data sets such as that from the European ERS series and the ENVISAT mission. In the latter case, the possibility of rapid delivery of data and the increased performance of the instrument during low inundation periods will also be investigated.

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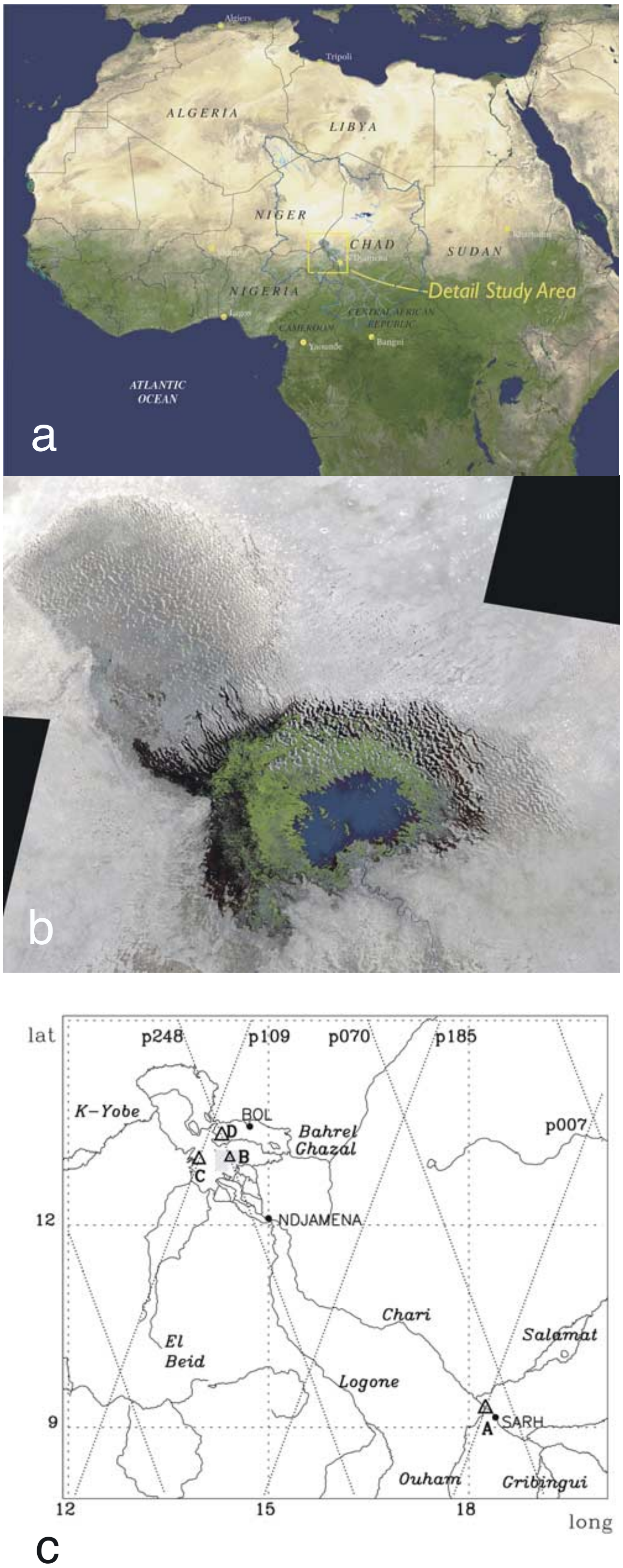

Figure 1. (a) The geographic location of the Lake Chad basin, (b) a close-up of the lake, and (c) Chad basin with TOPEX/Poseidon ground paths. The extent of the basin in Figure 1a is revealed in dark blue, and the inflowing rivers are in pale blue. Figure 1b is a Landsat mosaic using ETM scenes from October 1999 and October 2000. The remaining permanent waters of the lake (deep blue) can be seen as well as the inflowing Chari River. Dune systems which become seasonally inundated can be seen across the lake bed. Both figures courtesy of UNEP GRID Sioux Falls. Figure 1c shows the TOPEX/Poseidon ground paths (dashed lines) and the four sites used in this study: A, Chari/Ouham confluence; B, open lake; C, western marshes; and D, northern marshes. Historical lake coastlines are also shown, as is the approximate location of the current permanent lake (shaded area in vicinity of site B).