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Keywords Climate change • Hydrology • Lakes • Satellite altimetry • Water management

Abbreviations

AO	Antarctic Oscillation
AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic data
CNES	Centre National d'Études Spatiales

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CTOH	Centre de Topographie des Océans et de l'Hydrosphère
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño/Southern Oscillation
ESA	European Space Agency
GCM	Global Climate Model
GDR	Geophysical Data Record
GFO	Geosat Follow-On
IOD	Indian Ocean dipole
IPCC	Intergovernmental Panel on Climate Change
ITCZ	InTertropical Convergence Zone
NAO	Northern Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NCEP	National Center for Environmental Prediction
PDO	Pacific Decadal Oscillation
PODAAC	Physical Oceanography Distributed Active Archive Center
RMS	Root Mean Square
SO	Southern Oscillation
SST	Sea Surface Temperature
T/P	TOPEX/Poseidon
UNESCO	United Nations Educational, Scientific and Cultural Organization
USDA	US Department of Agriculture

19.1

Altimetry Over Lakes

So far, the measuring of water levels using satellite altimetry has been developed and optimized for open oceans. Nevertheless, numerous studies have been already published in different fields of continental hydrology based on coupled satellite altimetry/*in-situ* gauge measurements, from a general point of view (Birkett 1995; Calmant and Seyler 2006; Crétaux and Birkett 2006) or to be more specific with respect to lakes (Cazenave et al. 1997; Birkett 2000; Mercier et al. 2002; Aladin et al. 2005; Coe and Birkett 2005; Crétaux et al. 2005; Medina et al. 2008; and Kouraev et al. 2009; Chapter by Kouraev et al., this volume). These studies show that radar altimetry is currently an essential technique for different applications: assessment of hydrological water balance (Cazenave et al. 1997; Crétaux et al. 2005), prediction of lake level variation (Coe and Birkett 2005), studies of anthropogenic impact on lake water storage (Aladin et al. 2005), and correlation of interannual fluctuations of lake levels on a regional scale with ocean-atmosphere interaction (Mercier et al. 2002).

Several satellite altimetry missions have been launched since the early 1990s: ERS-1 (1991–2000), T/P (1992–2005), ERS-2 (1995–present), GFO (2000–2008), Jason-1 (2001–present), Jason-2 (2008–present) and Envisat (2002–present). ERS-1, ERS-2, and Envisat have a 35-day temporal resolution and an 80 km inter-track spacing at the Equator. T/P, Jason-1 and Jason-2 have a 10-day temporal resolution and 350 km inter-track spacing at

the equator. GFO has a 17-day temporal resolution and 170 km inter-track spacing at Equator. The combined global altimetry historical data set now span more than a decade and is intended to be continuously updated in the coming decade. Combining altimetry data from several in-orbit altimetry missions also increases the spatiotemporal resolution of the remotely-sensed hydrological variables. Radar altimetry has, however, a number of limitations over land because radar waveforms (e.g., raw radar altimetry echoes reflected from the land surface) are complex and multi-peaked due to interfering reflections from water, vegetation canopy, and rough topography. These effects result in data having decreased validity, compared to data collected over oceans. Moreover, the instruments can only operate in a *profiling mode* and do not have a true global view. Large numbers of lakes are thus not seen by current altimetry satellites. Stage accuracies are also dependent on target size, which will limit worldwide surveying and limnological applications. However, there is adequate scope for systematic monitoring at continental scales and the provision of new stage information where gauge data are absent. Typically, altimetry measurements can range in accuracy from a few centimeters (e.g., Great Lakes, USA) to tens of centimeters depending on size and wind conditions. Minimum target sizes depend on a number of factors including footprint size, topography complexity, and instrument-tracking logic. Table 19.1 summarizes the expected accuracy for each satellite mission depending on the target characteristics (taken from Crétaux and Birkett 2006). Summing the squares of the individual RMS values gives the total height error. The range precision will be improved, as mean lake heights (across the profile) are determined, effectively averaging all valid height measurements (N) from coastline to coastline.

The derivation of time series of surface height variations involves the use of repeat track methods. This methodology employs the use of a mean (Crétaux and Birkett 2006) lake height profile. This is derived from averaging all height profiles across the lake expanse within a given time interval, effectively smoothing out the varying effects of tide and wind setup. The height differences between the reference pass and each repeat pass enable the time series of lake height variation to be created.

The accuracy of a single lake height measurement will vary depending on the knowledge of the range, the orbit and the various corrections. Range precision will vary, according to surface roughness and the selected satellite mission, as more complex tracking logic and algorithms try and maximize the quantity of data collected over continental surfaces. The precision of the measurement will then strongly depend on the capability to retrieve the time that corresponds to the actual height at the nadir of the antenna. Smith (1997) stated that the major difficulty in retrieving ranges over continental waters results from the variability in the shape of the return waveforms when onboard trackers

Table 19.1 Summary of satellite altimetry general characteristics

Satellites	Operation period	Orbital cycle (days)	Accuracy (cm RMS)	Minimum target area and width
ERS-2	1995–2002	35	>9	>100 km ² > 500 m
Envisat RA-2	> 2002	35	>9	>100 km ² > 500 m
T/P	1992–2005	10	>3	>100 km ² > 500 m
Jason-1	>2002	10	>3	>100 km ² > 500 m

are designed for a typical ocean waveform. Regular “ocean-type” trackers expect long tail shapes of energy distribution while echoes bouncing off rivers are often specular (Guzkowska et al. 1990) or a combination of specular echoes. Thus, in the best case, energy is received but the range estimate may be erroneous; in the worst case, the altimeter loses tracking and subsequent echoes are lost. The antenna-reflector range is determined by fitting the waveform with a predefined analytical function (so-called waveform “tracking”). If the analytical function is not well suited to the waveform, shape tracking leads to wrong estimates of the height value (or even no estimate at all). Here, it is worth noting that the radar altimetry data collected by the ongoing Envisat mission are nominally retracked with four algorithms.

The most widely used for all missions since Geosat is the “OCEAN” tracker (Rodriguez and Chapman 1989), tuned for deep ocean surface. Because the shape of the echoes that is reflected by other surfaces such as ice caps and continental waters can be very different from the ones reflected by the oceanic surface, other trackers have been developed and applied to retrack the radar waveforms. The OCOD/ICE-1 (Wingham et al. 1986) and ICE-2 (Legresy and Remy 1997) trackers have been developed to recover heights over sea ice; SEA-ICE (Laxon 1994) to recover heights over the sea ices too. Envisat is the first mission for which ranges are provided nominally with more than one tracker.

Based on a study made over the Amazon River, Frappart et al. (2006) have established some quality assessment of each tracker available with Envisat data by comparison with *in-situ* data. They have demonstrated that ICE-1 is the most suitable one for lakes and rivers among all algorithms of retracking.

The air density, the amount of water vapor and the content of free electrons in the ionosphere also modify the travel time of radar waves throughout the atmosphere. The electronic content in the ionosphere and air pressure is given by independent data sets. However, the amount of water vapor is estimated using microwave radiometers embarked onboard together with the radar altimeters. The current microwave radiometers fail to estimate the atmospheric content of water vapor over continents because the signature of the atmospheric water vapor is mixed with that of ground wetness. Thus, this effect ranging from a few centimeters to tens of centimeters cannot be accurately corrected for over land waters and corrections can only be estimated from large-scale global data sets such as ECMWF or NCEP. Yet, these model-based corrections – although satisfactory in most cases – can suffer large errors, in particular in the case of mountain lakes. Crétaux et al. (2009a) have shown in the case of Lake Issykul that the dry troposphere corrections delivered in the T/P, Envisat, Jason and GFO GDRs were wrong either because the altitude of the lake was not accounted for to compute the reference air pressure or this altitude varies within the lake surface, producing an artificial variation of the correction along the tracks crossing the lake. In this case, the largest difference between corrections at a given day exceeds 60 cm. Such an error is particularly impacting when merging stages from different missions in order to increase the time sampling.

Finally, the quality of the orbit directly enters into the error budget of the water height. Yet, orbit modelling did progress during the last decade and the orbital errors can be considered of second order for continual waters.

The techniques are now so well validated that lake and reservoir altimetry measurements can be found in several web sites:

Hydroweb: Developed at the LEGOS laboratory in Toulouse, this web database contains time series over water levels of large rivers, lakes and wetlands at the global scale. The lake levels are based on merged T/P, Jason-1, Envisat, ERS-2 and GFO data freely available through the NASA and the CNES data services (PODAAC and AVISO). The monthly level variations deduced from multi-satellite altimetry measurements for almost 150 lakes and reservoirs are freely provided. Potentially, the number of lakes monitored could be significantly increased. These lake and reservoir level time series are available at: <http://www.legos.obs-mip.fr/en/soa/hydrologie/hydroweb/>

The USDA has developed a database of water level variations on a 10-day basis for almost 100 lakes monitored in a near real time from the satellite missions T/P and Jason-1. The data are freely available directly on the web site: <http://www.pecad.fas.usda.gov/>

River&Lakes database: The European Space Agency, in cooperation with the De Montfort University in UK has developed an algorithm for altimetry wave form retracking, which is now operating automatically. They have set up a database which provides instantaneous water level products on a near real time basis, over the whole Earth. This database does not provide historical altimetry data that can, however, be obtained on demand from ESA. The web site is at the following address: <http://earth.esa.int/riverandlake/>

19.2

Lakes and Climate Change

The volume of water stored within lakes and reservoirs is a very special and sensitive proxy primarily for precipitation; secondly, for other climatic parameters through evaporation, temperature, surface pressure, wind stress, radiation (both short and long waves); and thirdly, for hydrologic parameters such as groundwater and runoff. Lakes, thus, may be used to study the combined impact of climate change and water resources management. *Climate change* affects several aspects of the hydrological cycle. Water management generally directly affects the water balance parameters of a lake, through irrigation or hydro-power industry, while climate change alters the water balance of a lake through long-term changes in temperature and precipitation.

A lake system represents complex interactions between the atmosphere, surface and underground water, a system that responds to climatic conditions, yet is tempered by upstream water uses for agriculture, industry or human consumption. Thus, the overall water volume (a function of surface area and lake level) depends on the balance between the water inputs and outputs. The inputs are the sum of direct atmospheric precipitation over the lake and surface runoff of the surrounding areas. Underground seepage can also provide inflow. Volume outputs are the sum of the direct evaporation from the lake's surface in addition to river outflow and groundwater seepage. Some of these water balance components can be, generally, easily measured (river runoff, precipitation, lake level), depending on the availability of *in-situ* measurements while others can only be deduced globally from hydrological or climatic models (evaporation, underground water) or partially from local field campaigns. To close the water budget of a lake, the measurement of

level/volume variations with time is a key parameter, as this can provide estimates of volume variation (when the relation between level and volume is known).

The assessment of lake water balance could provide better knowledge of regional and global climate change, while a *quantification* of the human stress on water resources across all continents is also an important factor. Moreover, this assessment can be of particular interest for all these regions where human habitation is still highly dependent on water variability, whether as direct water consumption or as a source of hydropower. In many Sub-Saharan African countries, water resources are one of the major limiting constraints on development. The region's electricity supply is dependent largely on hydropower; inland fisheries and navigation are also often dependent on the hydrological regime in lakes and rivers; a reliable supply of good quality water is required for human consumption, industry, and irrigation. The hydrological regime of the major lake and river systems in these regions is, therefore, of particular interest.

Indeed, in this regard, the choice of lake is of particular importance. One has to distinguish between closed (endorheic) lakes with no outflow, and open lakes (exorheic) that have one or more outflowing rivers. The first class of lakes depends closely on the balance of inflows (precipitation and runoff of rivers) and evaporation. They, hence, could be considered as good proxies of climate change, since a small change in the temperature or precipitation in the lake basin can have a direct consequence on the lake water level.

Moreover, Hostetler (1995) noted that deep lakes with steep shore topography are good proxies for high amplitude-low frequency changes, while shallow water basins are better indicators for rapid low-amplitude changes. The latter are extremely sensitive for revealing decreased water input and rising evaporation.

Observations of many lakes in different climatic and regional zones can be used to discriminate between regional and global climates as well as help in assessing the impact of anthropogenic forcing occurring on different spatial and timescales:

- The Southern Andean lakes (Chilean and Argentinean lakes on both sides of the Andes): the Chilean lakes (Ranco, Villarica, Panguipugui, Rupanco, etc.); lakes on the limit between Chile and Argentina (Carrera-Buenos-Aires, Cochrane, San-Martin-Ohiggins, etc.); the Argentinean lakes (Argentino, Viedma, and some smaller lakes) and finally, the world's southernmost lake (excluding Antarctica), Lake Fagnano.
- The African lakes of the Eastern Rift (Tanganyika, Victoria, Malawi, Mweru, Kyoga, Albert, Tana, Kiwu, Bangweulu, and Edouard).
- The central Asian lakes (Aral Sea, Issykkul, Balkhash, and some large reservoirs along the Syr Darya and Amu Darya rivers).

In its great majority, lake oscillations from one year to the next are associated with the local climatic regimes that govern the precipitation variability over the watershed of a given lake. In many parts of the world, interannual variations in rainfall and runoff are strongly influenced by the ENSO (New et al. 2001), which are characterized by anomalous and large deviations from mean annual levels of precipitation. Lake level variability depends on the magnitude and frequency of ENSO events given that, in many parts of the world, peak discharges occur during ENSO years. However, other climatic oscillations do also play a role: PDO, NAO, and SO.

In this regard, the first two lake groups are interesting because their level variation is closely associated with climatic forcing. The El Niño-Southern Oscillation as the main

driver worldwide of interannual climate variability (New et al. 2001) imprints lake level variability at these timescales. However, through ocean-atmosphere couplings and climate tele-connections, lake levels are subject to different climate oscillations: African lake levels are influenced by the African monsoons, the North Atlantic Oscillation and the Indian Oceanic Dipole. Lake level in South America is affected by the North Atlantic Oscillation, the southern annular mode (also called the Southern Antarctic Oscillation) as well as the southern American monsoon. Across Central Asia lakes are influenced by a mix of direct human factors (through irrigation) and climate change and variability.

In the following part of this chapter, we will show some recent results obtained over these groups of lakes in order to illustrate the potential uses of radar altimetry for the monitoring and study of these kinds of water bodies.

19.3 Andean Lakes

The large inland water bodies of South America are of crucial importance for the complex and diverse economical environments in several countries: tourism in Altiplano and Argentina, fish breeding in Chile (Fig. 19.1), water consumption and hydropower in most of these countries. Lakes and reservoirs also form high-altitude aquatic ecosystems, including ecological interaction with the surrounding terrestrial areas that are highly dependent on the water cycle and interannual variability of water storage of the lakes themselves.

Some lakes located in the Altiplano Andean regions (e.g., Titicaca, Poopo) are highly receptive to ENSO (Garreaud and Aceituno 2001; Zola and Bengtsson 2006). Associated with the PDO (Garreaud and Battisti 1999), ENSO drives interannual and decadal variations of precipitation, which has a direct impact on lakes of this region. Consequently, they are also indirectly influenced by global climate change, which strongly interacts with and modifies the climatic oscillations. For South America, the IPCC change scenarios predict an increase of temperature going up from 1°C to 6°C degrees, and an increase of precipitation anomalies by about 20% before the end of the twenty-first century (Bates et al. 2008). More precisely, the projected mean warming for Latin America for 2100, according to different climate models, ranges from 1°C to 4°C for the B2 emissions scenario and from 2°C to 6°C for the A2 scenario.¹ Most GCM (Global Climate Model) projections indicate larger (positive or negative) rainfall anomalies for the tropical region, and smaller-to-diminished ones for the extra-tropical part of South America. In the case of the tropical regions, the increase of anomalies will severely impact the runoff of the rivers that feed the lakes in the Altiplano, especially Lake Titicaca. Confidence in model estimates is higher for some climate variables (e.g., temperature) than for others (e.g., precipitation). Models still show significant errors although these are generally greater at smaller scales. Despite such uncertainties, there is considerable

¹A2 and B2 are two different scenarios, though not extremes, of what Earth might be like by the end of the twenty-first century. B2 scenario emphasizes environmental preservation and social equity while A2 scenario anticipates higher CO₂ concentrations, larger human population, greater energy consumption, more changes in land use and scarcer resources, and less diverse applications of technology.

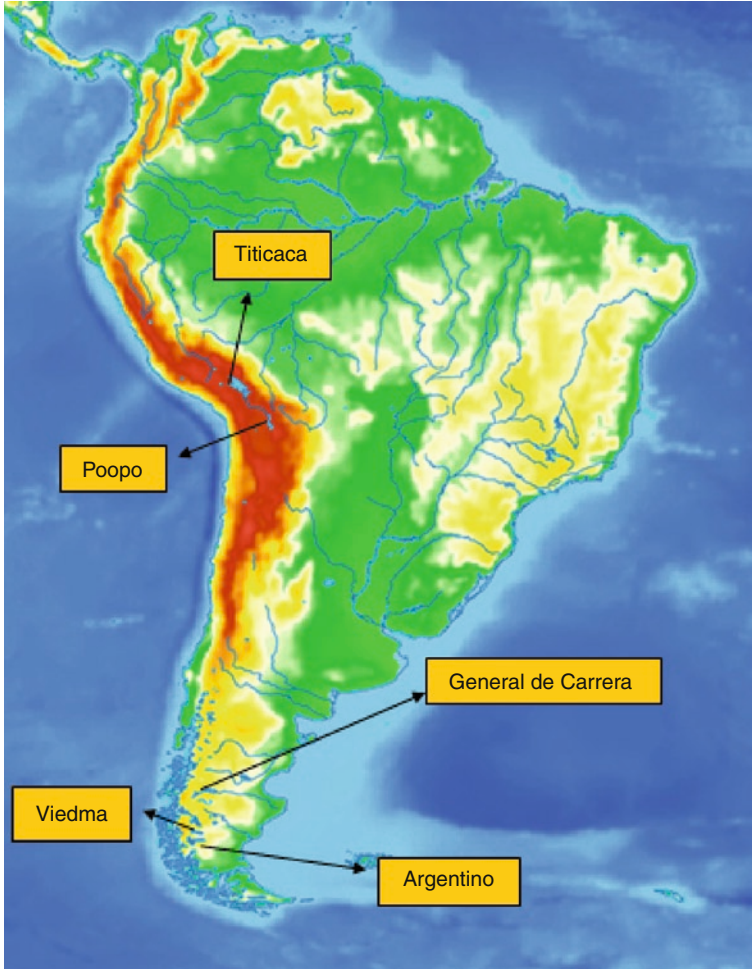


Fig. 19.1 Map of South America with the biggest lakes of the Andean Mountains

confidence that climate models do provide credible quantitative estimates of future climate change, particularly at continental scales and above (Randall et al. 2007).

However, despite these predicted high precipitation anomalies, no one can ascertain whether the lakes in the Altiplano will ultimately rise or shrink during the next decades, given that in addition to the precipitation uncertainties, other climate parameters must also be taken into account. The predicted higher temperature will enhance the role of evaporation in the water balance of those lakes. Nowadays, Lake Titicaca is well monitored by satellite altimetry (Fig. 19.2b), with the availability of very high precision data (Fig. 19.2a). Even in the case where *in-situ* gauges are operational, data are, in most of the cases, not freely available to the scientific community due to national data policies. Continuous monitoring of this lake from radar altimetry in the future (with the next mission: Jason-2, Jason-3, Sentinel-3, AltiKa, etc.) will contribute to better understanding of its water balance under the influence of diverse climatic forcing.

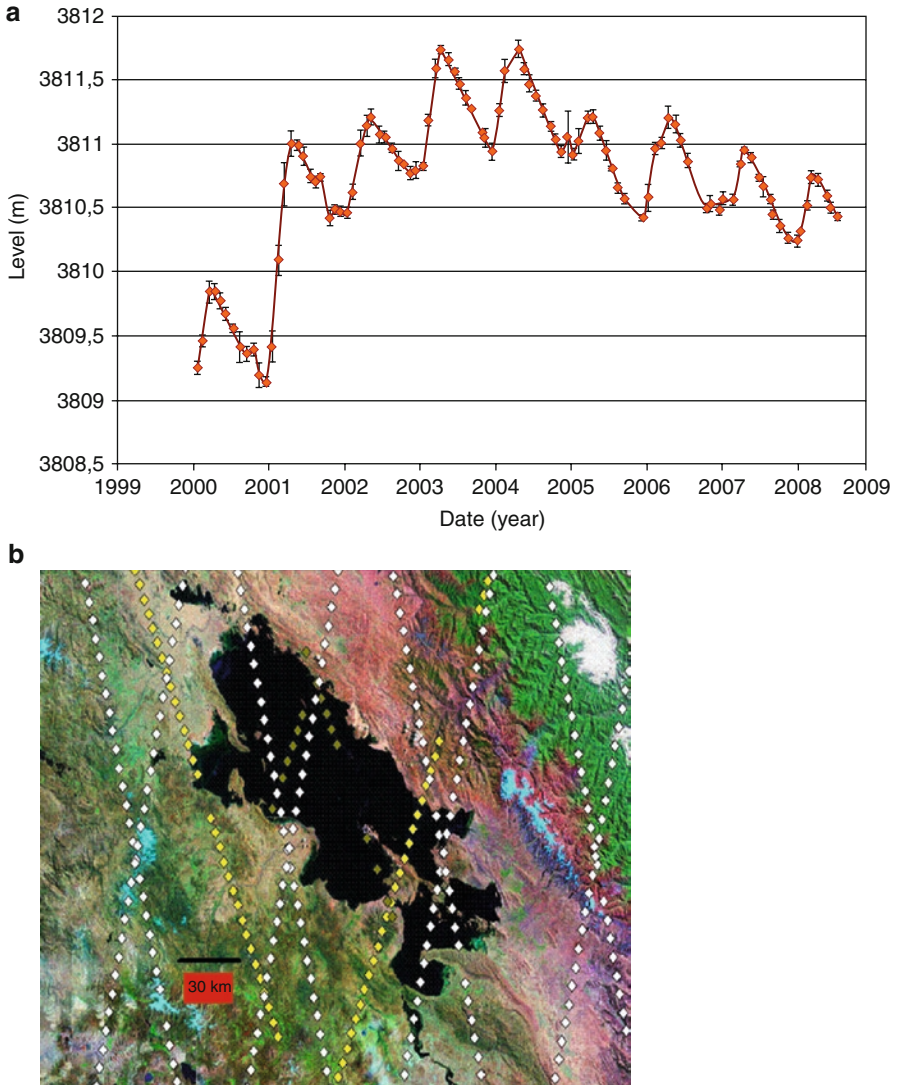


Fig. 19.2 (a) Lake Titicaca level variations from 1 Hz radar altimetry data. (b) Altimetry satellite tracks over the Lake Titicaca (Envisat: *white dots*, GFO: *green dots*, T/P interleaved orbit: *yellow dots*)

In the case of extratropical climate in South America, even though precipitation is thought to change little or even diminish in terms of anomalies, it is already the case with several lakes that are affected by global warming in the form of changing glacial feed. Examples include lakes Argentino and Viedma located on the border of Chile and Argentina (Depetris and Pasquini 2000; Coudrain et al. 2005). All of these lakes are also well monitored by altimetry (Fig. 19.3a and b).

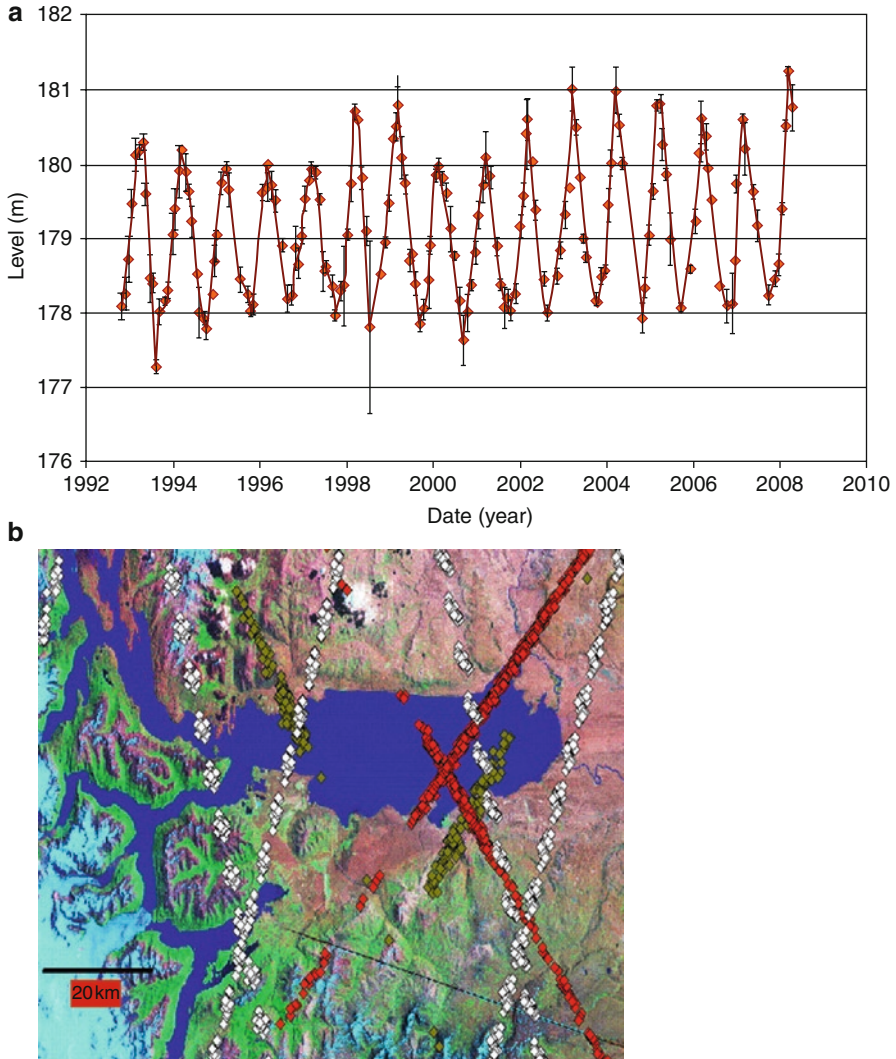


Fig. 19.3 (a) Lake Argentino level variations from 1 Hz radar altimetry data. (b) Altimetry satellite tracks over the Lake Argentino (Envisat: white dots, GFO: green dots, T/P initial orbit and Jason-1: red dots)

Ongoing research provides an example of the complexity of the diverse sources affecting lakes variability over southern America. The General Carrera/Buenos Aires Lake, a Chilean/Argentinean lake located in Patagonia ($46^{\circ}30'S$ $72^{\circ}0'W$), is recognized as representing the second greatest hydrologic lake basin for South America (after that of Lake Titicaca). Although the river inputs to the lake are driven by direct rainfall, large portions of river discharges come only from snow accumulation on different mountains of the Andean cordillera and its subsequent melting 3 months later. In addition, part of the water inflow also arises from some of the melting glaciers belonging to Northern Patagonian Ice

fields. Its glaciers are largely in retreat and with only an area of 4,200 km²; it is still the largest continuous mass of ice outside of the Polar regions. Also, it is suspected that direct input through groundwater plays an important role in the water balance. Further, the climatic regimes affecting the western and eastern sides of the lake (mainly represented by the precipitation amounts) are different. To the west, in the Andes portion of the watershed, precipitation is affected directly by ENSO regimes with moisture transported by the south westerly winds, while over its eastern part, in the Pampa catchment's region, the regimes present a complex signature where ENSO is not the leading mode. In addition to these complexities, *in-situ* measurements are necessary for completing the water balance. Unfortunately, the current *in-situ* monitoring of lake level variability involving river inflow and outflows and meteorological variables is intermittent at best, which precludes a complete and correct establishment of the water balance. Models and *in-situ* campaigns are also necessary.

Therefore, once again it is essential to have accurate water level measurements in order to understand the water balance of these lakes as well as others in the region, and thereby quantify the impact of climate change on the water resources represented by the major lakes of the Andean chain.

In particular, in the case of South Andean lakes, the combined effect of ENSO and global warming on the lake level has not been studied as yet. First of all, the cause of long-term variability of precipitation at the boundary between Chile and Argentina has just recently been understood to represent a combination of ENSO and AO on interannual timescales, as well as the direct effect of the PDO for decadal timescales (Fogt and Bromwich 2006; Gillett et al. 2006; and Fagel et al. 2008). Moreover, in this region, global warming is likely to cause decreasing precipitation and increasing temperature (Bates et al. 2008) with consequently increasing runoff from glacier thawing on the one hand, and decreasing direct precipitation over the lakes on the other. Lakes, thus, may be considered as very sensitive proxies for determining the balance between those two opposite impacts. The level variations of a lake like Argentino (Fig. 19.3a) thus reflect those different phenomena.

19.4 East African Lakes

19.4.1 Climate Change and the East African Lakes

Understanding the climate variability of Africa, and therefore tropical variability and its prominent role as the heat engine of the global climate system is one of the key goals in climate research. Also, African lakes themselves modify the local climate to a large extent: Nicholson and Yin (2002) showed that precipitation over Lake Victoria is more intense than over its catchment area by more than 30%. In addition, African lake managers and all those who are dependent economically and socially (fisheries, water availability, etc.) on lake resources, wish to understand the potential long-term controls that climate exerts on lake level and productivity (Stager et al. 2005). From short instrumental records it is evident that, as over the seas, climate variability can impact primary production through, for example, changes in wind-driven upwelling or seasonal intensification and weakening of stratification linked to temperature variability (Plisnier and Coenen 2001; Cohen et al. 2006).

In addition to understanding present climates with modern measurements (in situ, or satellite), one has to try to reconstruct the historical climatology (i.e., interannual–decadal–centennial timescale, beyond instrumental records). However, scarcity of instrumental and documentary records prior to the colonial period (Nicholson 2001) coupled with the limited potential of traditional high-resolution climate-proxy archives such as tree rings or ice cores in Africa, impedes a correct reconstruction of past climates (Verschuren 2003). Fortunately, sedimentary climate records accumulating at the bottom of Africa's climate-sensitive lakes demonstrated a great potential to document the continent's patterns of past climate change.

But for understanding these sedimentary records, on seasonal timescales at least, a correct understanding of the complexities of the water balance of a given lake is required, as well as validation of the proxy indicators. However, although a dense network of natural lakes covers the East African Rift region, only the greatest lakes of the region have been monitored by ground gauges (Lake Victoria, Lake Tanganyika) up to the present moment. This suggests that some of the water balance mechanism may still be poorly understood.

Thanks to satellite altimetry, most of the lakes of Africa are now being monitored. Study of 7-year satellite radar altimetry data from the T/P mission and the utilization of precipitation data over East Africa and the Indian Ocean, (Mercier et al. 2002) show evidence of hydro-meteorological linkages between the Indian Ocean SST and precipitation over the East African continent, and changes in lake levels. However, the main components of the water balance (precipitation and evaporation) over the East African lakes are still very uncertain and its connection with regional climate variability is an ongoing debate (Nicholson and Yin 2002).

For example, analyses of level records of the Great East African Lakes such as Victoria, Tanganyika, and Nyassa-Malawi, and regional climatic variability (precipitation amount) show synchronicity, which can only be explained by large-scale mechanisms (Ogallo 1988; Nicholson 1996; Ropelewski and Halpert 1996), associated initially with ENSO cycles. Sharp increase in the water levels of Lake Victoria (Fig. 19.5a), Lakes Tanganika, Kariba, and Turkana in 1998 may reflect this ENSO impact on lakes in the African Rift (Mercier et al. 2002). However, some studies (Beltrando and Cadet 1990; Hastenrath et al. 1993; Richard 1994; and Becker et al. 2010) have shown already that these could also be related to the Indian oceanic variability. Only recently the stronger relationship with the IOD, a particular oceanic circulation system taking place in the Indian Ocean (Saji et al. 1999) has been explained thanks to equatorial zonal atmospheric circulation (Bergonzini et al. 2004). The IOD is partly responsible for driving climate variability of the surrounding landmasses, and therefore, over eastern Africa (Marchant et al. 2006). Also, episodically or non-linearly, ENSO modulates the climate in eastern Africa and therefore, lake level variability (Mistry and Conway 2003). However, whether (and how) the IOD is an artifact of the El Niño–Southern Oscillation (ENSO) system, or it is a separate and distinct phenomenon is not the subject of this chapter.

For decadal to centennial timescales a strong and significant link between lake levels and solar activity (possibly amplified by sea surface temperature, ENSO and PDO) has been found for most of the great lakes of eastern Africa over much of the last millennia (Stager et al. 2005; Garcin et al. 2007; and Stager et al. 2007). In addition, it has also been shown that the Indian monsoon and the migration of the ITCZ² do play a role (Tierney and Russell 2007).

²The location of the inter-tropical convergence zone (ITCZ) varies over time. Over land, it moves back and forth across the equator following the sun's zenith point. Over the oceans, where the convergence zone is better defined, the seasonal cycle is more subtle, as the convection is constrained by the distribution of ocean temperatures.

Fig. 19.4 Lakes of East African Rift



Considering now the anthropogenic role, General Circulation Models (GCM) have shown that one of the consequences of global warming could be significant changes in precipitation and surface air temperature (Xu et al. 2005; De Wit and Stankiewicz 2006). This would have an impact on regional hydrology and ultimately affect lake and reservoir levels, especially in a region like the East African Rift, which is covered by a variety of lakes of different sizes and morphologies.

Current satellite radar altimetry missions (Jason-1/2, GFO, and Envisat) have increased the number of lakes observable over East Africa (around 15 big lakes, in these regions (Fig. 19.4 and 19.5f) are monitored currently from satellite radar altimetry with an accuracy of a few centimeters in the best cases, up to 10–20 cm in the worst ones). This would be a valuable tool to look carefully at climate variability impact on those water bodies.

19.4.2

Lake Victoria

Lake Victoria is the world's second largest lake in terms of surface area (68,000 km²), and is very shallow (Mean depth of 40 m with maximum of 84 m), which makes it sensitive to sudden and even relatively small changes in the water balance parameters, such as precipitation, evaporation, or surface runoff. Lake Victoria can hence be considered as a good indicator of climate change in this region. It is located in an arid to semiarid region which is, however, subjected to a high a mean annual precipitation of 1,200–1,600 mm, while evaporation is estimated at around the same order of magnitude (Nicholson and Yin 2002). Lake Victoria has exhibited very high level fluctuations over the last 15 years (Fig. 19.5a). Since

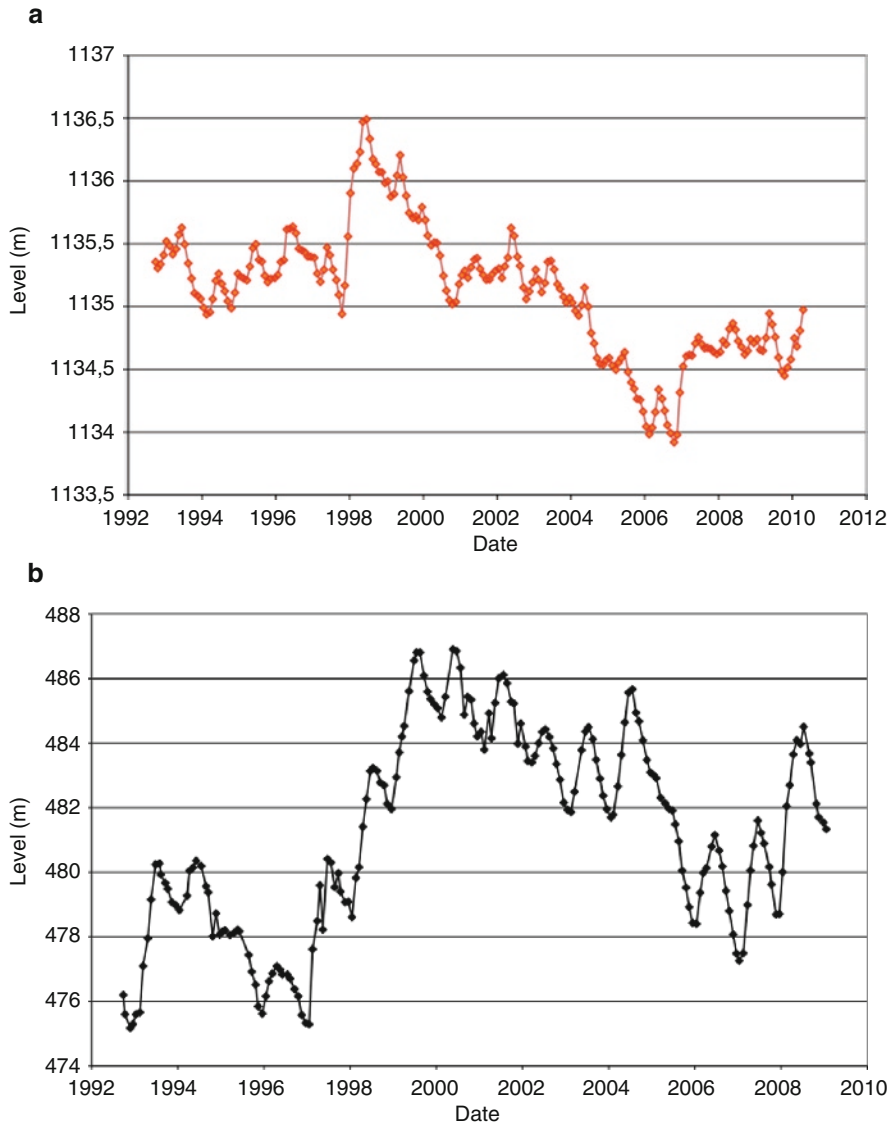
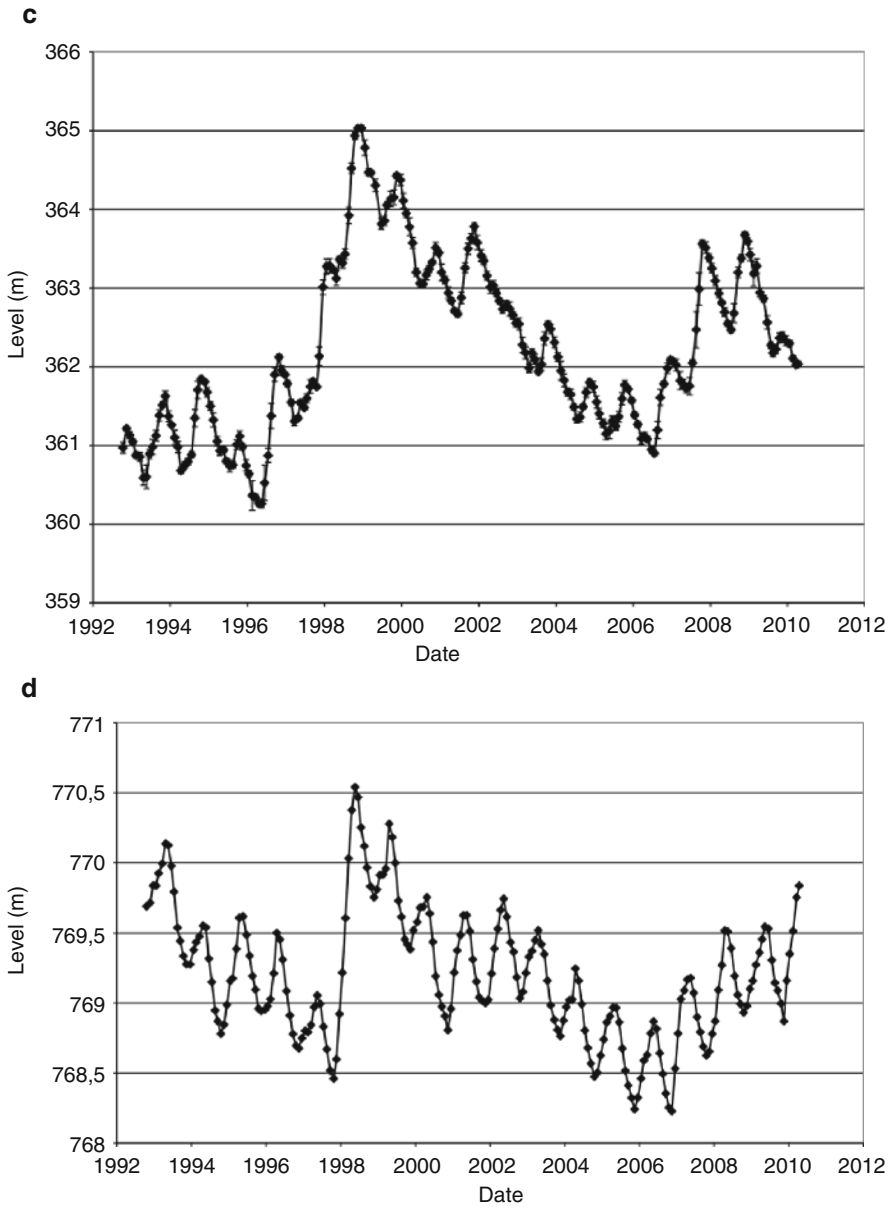


Fig. 19.5 (a) Lake Victoria level variations from 1 Hz satellite altimetry data. (b) Lake Kariba level variations from 1 Hz satellite altimetry data used in a multi-satellite processing mode. (c) Lake Turkana level variations from 1 Hz satellite altimetry data used in a multi-satellite processing mode. (d) Lake Tanganyika level variations from 1 Hz satellite altimetry data used in a multi-satellite processing mode. (e) Lake Malawi level variations from 1 Hz satellite altimetry data used in a multi-satellite processing mode. (f) Altimetry satellite tracks over the East African Lakes (Envisat: *white dots*, GFO: *green dots*, T/P initial orbit and Jason-1: *red dots*, T/P interleaved orbit: *yellow dots*)

**Fig. 19.5** (continued)

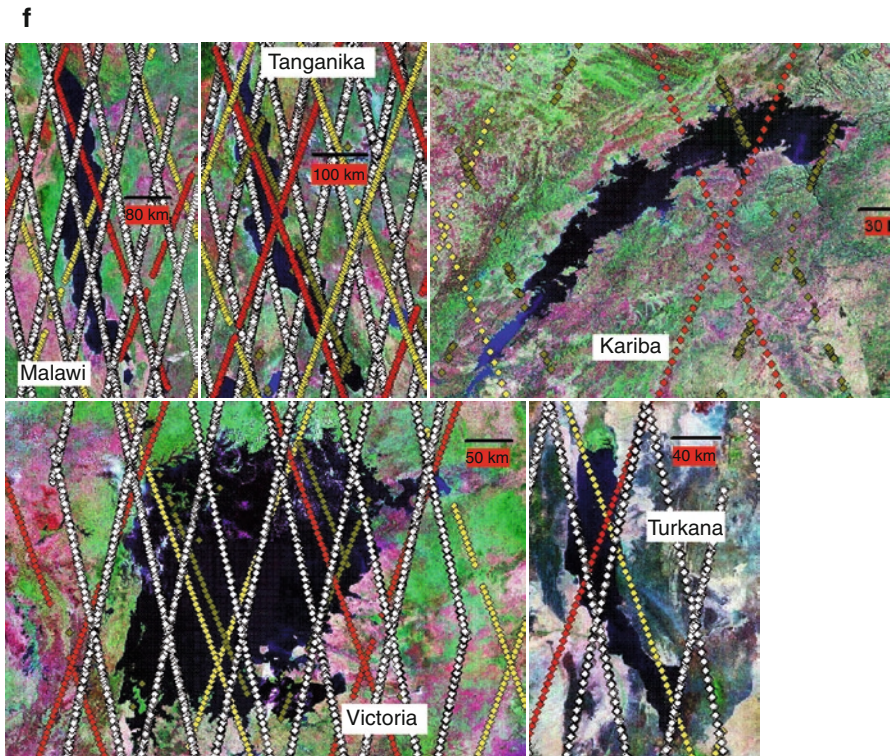
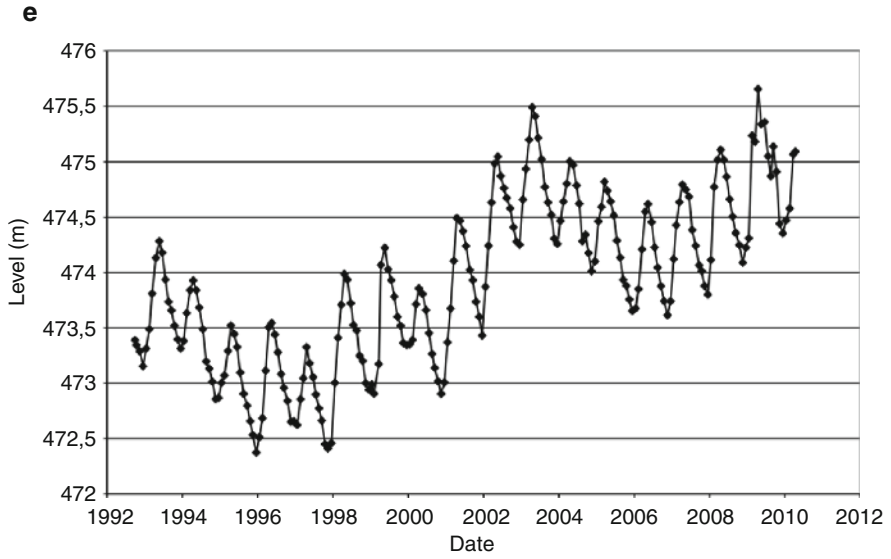


Fig. 19.5 (continued)

water from Lake Victoria flows into the Nile River, this high water level variability can also seriously alter the water uses for downstream countries. From 1999 to 2007, the level of Lake Victoria has declined around 2.5 m (Fig. 19.5a). This represents a loss of water of 20 km³ per annum. During the same period, for the other large lakes of the region, water level variations deduced from altimetry measurements (Fig. 19.5b–e) can provide interesting information on the regional hydrology: Lake Tanganyika level time series is very similar to that of Lake Victoria, which reveals regional climate forcing on water storage. For lakes Kariba and Turkana, the patterns are also similar to that of Lake Victoria but an increase of the level in 1998 is less abrupt and longer in duration, while for Lake Malawi, water level variations followed a totally different pattern. The combinations of different factors (natural and anthropogenic) that could explain these observations would be a valuable source for understanding the lake hydrological regime within the Eastern African Rift (Swenson and Wahr 2009). Moreover, they are excellent proxies of tropical climate variability.

19.5

Central Asian Lakes

The major central Asian lakes are in the drainage basins of two large rivers, the Amu Darya and the Syr Darya, shared by five different countries: Uzbekistan, Kazakhstan, Tajikistan, Kyrgyzstan, and Turkmenistan. Irrigation water is extracted on a large scale from the rivers that drain into the remnants of the Aral Sea. Consequently, water management in this region has a transboundary dimension which has political and societal ramifications. A political agreement was signed in the mid-1990s for a rational use of the water resources across the region. Through the use of large reservoirs, both Kyrgyzstan and Tajikistan agreed to retain upstream water over the winter period for later use by Kazakhstan and Uzbekistan which require a large amount of water downstream for irrigation in the dry season. As compensation, Kazakhstan, and Uzbekistan agreed to provide gas and electricity to Kyrgyzstan and Tajikistan. The agreement is a source of contention, which highlights the need to reinforce the collaboration between the water management agencies, as well as the maintenance of the water resources monitoring and sharing of the river runoff, reservoir storage, and hydro climatologic data. In fact, UNESCO, NATO, and other international organizations aim to strengthen this agreement by providing the framework for enhancing the collaboration among political managers, hydrologists and scientists in general.

In this context, the information given by altimetry data can be very useful for water management monitoring in a large area like Central Asia, since all large reservoirs (Chardarya, Karakul, Sarykamish, and Toktogul) are well monitored by this technique (Fig. 19.5a–d). This is particularly interesting when *in-situ* data are also available. In fact, several of these lakes are monitored by ground-based gauges, though access to current information (post 2001) is still restricted. When there is an overlap period between gauge and altimeter observation, validation exercises reveal the typical accuracy of the satellite measurements. For example, an accuracy of 5 cm RMS (Fig. 19.6d, Lake Issykkul), to 10 cm RMS (Fig. 19.6b, Lake Chardarya), is obtained. In some other cases, one does not have a common period of

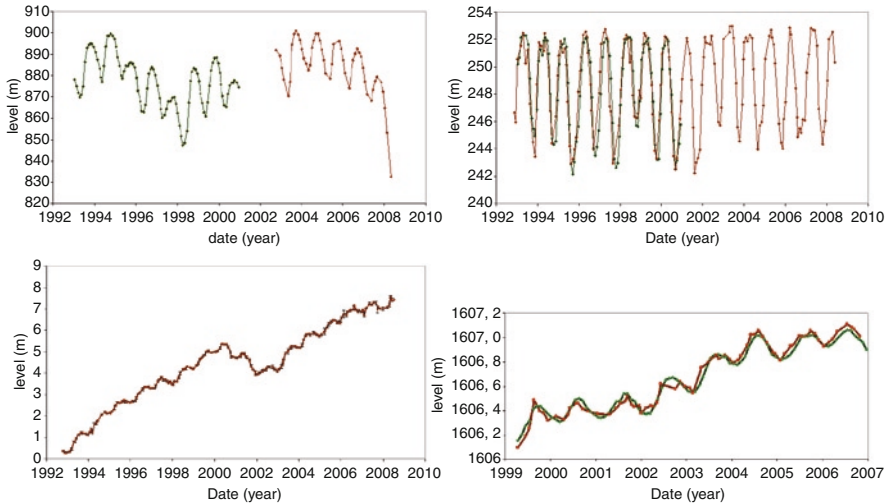


Fig. 19.6 (a) Toktogul reservoir (Kyrgyzstan) level variations from altimetry (*red*) and in-situ data (*green*). (b) Chardarya reservoir (Kazakhstan) level variations from altimetry (*red*) and in-situ data (*green*). (c) Sarykamish reservoir (Turkmenistan) level variations from altimetry. (d) Lake Issykkul (Kyrgyzstan) level variations from altimetry (*red*) and in-situ data (*green*)

observation as in the case for the Toktogul reservoir (Fig. 19.6a). Due to political restriction, *in-situ* data are not available after 2001, while altimetry provides continuous monitoring of this reservoir from the launch of Envisat in 2002. One can see that for this reservoir the level variation is very high (it has lost 50 m in less than 1 year). Due to political issues (transboundary water management of the Syr Darya River) information on the water level monitoring of reservoirs is quasi nonexistent, but one can suspect that Kyrgyz Republic have provoked water release from the Toktogul reservoir for hydropower generation during winter 2007–2008.

For another reservoir of the region, the Sarykamish, there are no gauge data available at all. Lake Sarykamish is located in Central Asia, south of the Aral Sea, in the territory of Turkmenistan. It is filled by diverted water from the Amu Darya River, through ancient natural channels, with a continuous increase since the beginning of the 1990s. Every year the lake receives approximately 5–6 km³ of drainage water (Aladin et al. 2005). Thanks to altimetry measurement one can easily see the consequences of diverting the flow of the Amu Darya River (Fig. 19.6c). This political decision, made by Turkmenistan Republic in the early 1990s has contributed, with the enhancement of irrigation in the Amu Darya river basin, to the shrinking of the Big Aral Sea.

It is therefore evident that altimetry provides a source of important independent information complementary to that produced by the ground-based networks and perhaps more critically, can provide hydrological information where gauges are lacking. In this respect it provides an additional tool for decision-makers in the field of water management.

In parallel to the issues of transboundary water management, the Central Asian lakes (Aral Sea, Balkhash, Issykkul, and many artificial reservoirs) are extremely sensitive to global change and are exposed to growing anthropogenic pressure; some of them have

already suffered severe ecological modifications. Monitoring their level variations thus also helps to infer the impact of climate change on the lakes and reservoirs, though a complete understanding would enable an interpretation of the many other complexities involved. Lake levels may drop due to potential increases in evaporation, but levels may increase due to the increase in thaw rates of the surrounding glacier and mountain snow. In the case of Issykkul Lake, located in Kyrgyzstan, the water level has continuously decreased in the twentieth century up to 1998 at a rate of around 4 cm/year. During the past 8 years, the level has considerably increased at a rate of 10 cm/year (Fig. 19.6d). Perhaps this increase can be attributed to the more rapid rate of recent high glacier melt linked to regional warming (Romanovski 2002). The Aral Sea which mainly loses water through evaporation is also affected to a lesser extent by global warming. Studies made by (Small et al. 2001) showed that global warming has accelerated the shrinking of the Aral Sea by around 10 cm/year from 1960 to 1990. With altimetry monitoring it is possible to quantify the impact of global warming on the Aral Sea during the last 15 years.

Several articles have already been published about the Aral Sea crisis, and a few of them specifically about water level monitoring from satellite altimetry (Aladin et al. 2005; Crétaux et al. 2005; Crétaux et al. 2009b; and Kouraev et al. 2009). Since the separation of Aral Sea in two independent basins in 1989, the Big Aral in the south and the Small Aral in the north, the Big Aral has continuously shrunk, varying from 20 cm/year to 1 m/year (Fig. 19.7b). The Small Aral has evolved in a different way during the same period. As the runoff of the Syr Darya River has more or less compensated the evaporation on this small water basin, its level has oscillated around a mean level value (Fig. 19.7a). The high water stage has even been enhanced through the construction of a dam in Berg's Strait (Fig. 19.8a), in particular in 1997 and in 2005.

Using a combination of a precise digital bathymetry map (DBM) of the basin with level variation deduced from altimetry, Crétaux et al. (2005) computed the resulting volume variation of the Big Aral Sea for the period 1993–2004. They showed that the reduction of lake volume as measured by T/P, GFO, and Jason is smaller than that deduced from examination of the hydrological budget; they assume that possible significant underground water inflow

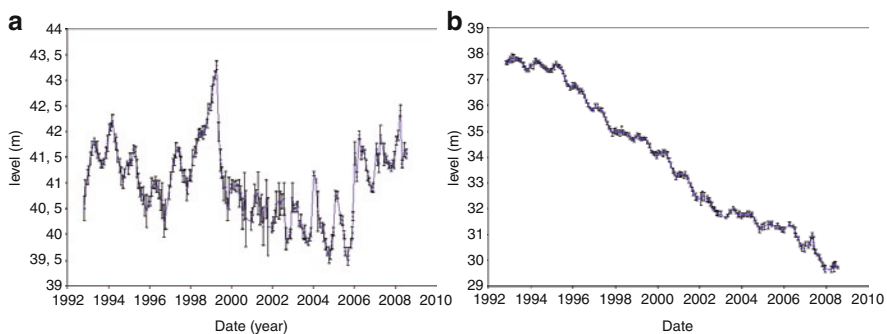


Fig. 19.7 (a) Small Aral Sea level variations from satellite altimetry. (b) Large Aral Sea level variations from satellite altimetry

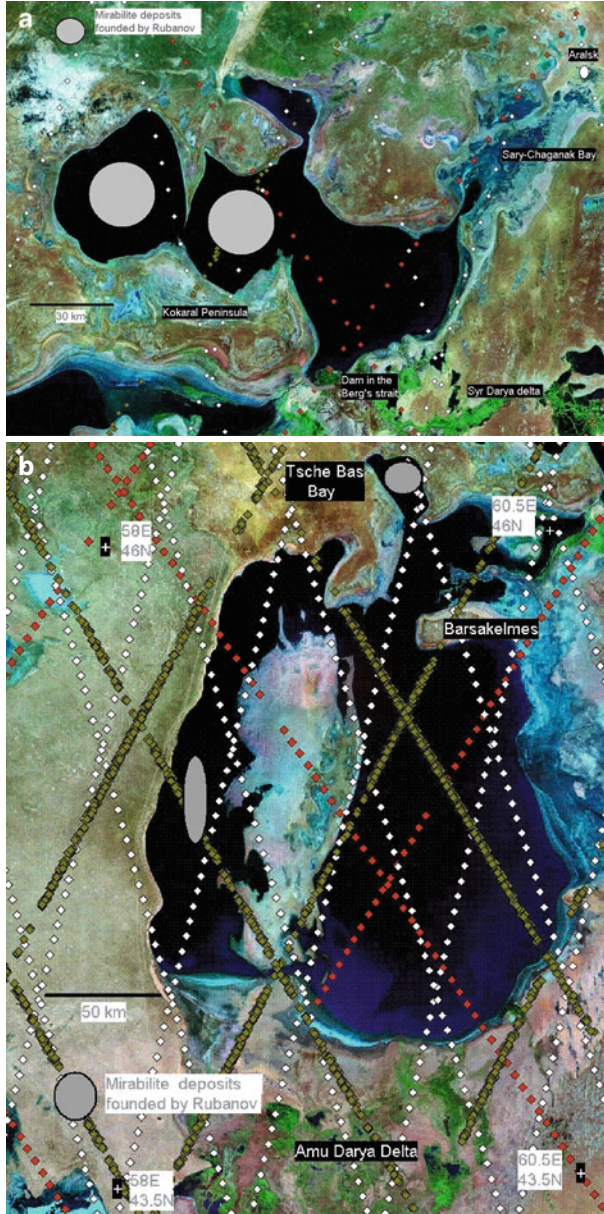


Fig. 19.8 (a) Altimetry satellite tracks over the Small Aral (Envisat: white dots, GFO: green dots, T/P initial orbit and Jason-1: red dots). The mirabilite deposits location found by I.V. Rubanov is also marked on the figure (gray circle). The satellite image is from Landsat image taken in 2000. (b) Altimetry satellite tracks over the Large Aral (Envisat: white dots, GFO: green dots, T/P initial orbit and Jason-1: red dots). The mirabilite deposits location found by I.V. Rubanov is also marked on the figure (gray circle). The satellite image is from Landsat image taken in 2000

cannot be ignored. This conjecture needs to be further assessed by hydrogeological modelling and more accurate data collected on the evaporation and precipitation rates in the region.

Even if this can be accurately established, the groundwater flow will likely only slow the desiccation of the Big Aral. To reverse the process or even to stabilize the sea level to that of the mid-1990s would require more underground flow than could be supplied in even the most optimistic scenario (Crétaux et al. 2005).

In Aladin et al. (2005), the impact of the construction of a dam in Berg's Strait in the water balance of the Small Aral as well as on the aquatic ecosystem has been precisely quantified. In Crétaux et al. (2009b), a new water balance of the Big Aral Sea based on altimetry data has been calculated. It was shown that the very narrow strait between the western and the eastern parts of the Big Aral is probably transporting water from East to West, which could explain some of the observations made 30 years ago by a Russian scientist (I.V. Rubanov³) regarding deposits of mirabilite on the bed of the Aral Sea in the Middle Ages and which has been found in very specific locations in both the Big and Small Aral seas (Fig. 19.8a and b). Mirabilite is an indicator of the advancement of evaporation of confined waters. Most endorheic lakes, in arid or semiarid areas, precipitate salts such as mirabilite when the water salinity rises above a given value (Rubanov et al. 1987³; Crétaux et al. 2009b). A review on Mirabilite can also be found in Aqué 1995.

Recently, a study of the Aral Sea level variation has been performed from a multi-satellite point of view, and an assessment of the quality of the retracking mode made with Envisat has highlighted the effects of ice cover over the Aral Sea on the mode of calculation of the water level from satellite altimetry (Kouraev et al. 2009; Chapter 13 by Kouraev et al., this volume).

Inland sea and lake level variations can presently be measured with great precision. This information, coupled with historical *in-situ* data, should help to further understanding of the responses of central Asian lakes to global climate changes and human economical activities, and perhaps serve to build coherent future scenarios for the sustainable development and protection of these large inland lakes.

19.6 Conclusions

Radar altimetry can contribute to the measurement of lake height variability over the lifetime of the satellite. The measurements can be acquired along the position of the satellite ground track with accuracy ranging from a few centimeters to tens of centimeters RMS. Altimetry measurements are not dependent on cloud cover, and may provide surface heights with respect to a common reference frame. They also are capable of providing water level variation due to continuous satellite operation since 1992 (Launch of T/P) in remote areas where no other information exists. New missions are already programmed by

³I.V. Rubanov is a Russian scientist who did core drilling of the Aral Sea bottom in the 1980s in order to study the past regressions and transgressions of the Aral Sea. He provided a map of salt deposits in his different core, some of them including Mirabilite.

space agencies to enable this system to continue lake monitoring over the whole Earth (Jason-3, AltiKa, and Sentinel-3), thereby allowing a pluri-decadal survey of lake levels. The altimetry community has made considerable efforts to ensure that the calibration of the products and the corrections used are delivered in a standardized form to the user community. However, the altimetry technique suffers from some limitations with respect to lake studies: it cannot be used to monitor all lakes on the Earth because it is a profiling system. This means that the measurements may be altered by the surrounding terrain of lakes, rendering geophysical correction less precise than over oceans. Moreover, effects such as wind, seiches, high precipitation, or the presence of ice may also degrade the accuracy of the data. Despite these limitations, the combination data sets from different altimetry missions provide a high degree of temporal and spatial resolution. Compilation of data from the Jason-1 (10-day repeat), GFO (17-day), and Envisat RA-2 (35-day) missions can provide a repeat measurement at a frequency better than a single mission alone. While Jason-1 may only view approximately 300 lakes, Envisat can augment this with potentially an additional target of 700 lakes. Such measurements can also be combined with bathymetry and image-derived areal extent to further deduce changes in storage volume. For remote lakes, altimetry can indeed be the *unique* system to determine accurate water balance.

Acknowledgments Authors acknowledge the CTOH in Legos for providing altimetry data in a standard and useful form. Authors thank the ECOS-SUR program, which allocated funds for cooperation between France and Chile for the study of Andean lakes. Authors thank INTAS and NATO science program for supporting research on lakes in Central Asia, which has been used as case studies presented in this manuscript.

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