Past hydrological variability in the Moroccan Middle Atlas inferred from lakes and lacustrine sediments

Laurence Vidal, Ali Rhoujjati, Rachid Adallal, Guillaume Jouve, Edouard Bard, Abdel Benkaddour, Emmanuel Chapron, Thierry Courp, Laurent Dezileau, Marta Garcia, et al.

The Mediterranean Region under Climate Change

La méditerranée face au changement climatique

A Scientific Update

État des lieux de la recherche

Abridged English / French version with chapter summaries

Version bilingue (anglais/français) abrégée avec résumés des chapitres

AllEnvi

Alliance nationale de recherche pour l'Environnement

Sub-chapter 1.1.3

Past hydrological variability in the Moroccan Middle Atlas inferred from lakes and lacustrine sediments

Laurence VIDAL
Aix-Marseille University, France

Ali RHOUJJATI
Laboratoire Géoressources, Morocco

Rachid ADALLAL
Aix-Marseille University, France,
Laboratoire Géoressources, Morocco

Guillaume JOUVE
Aix-Marseille University, France

Edouard BARD
Aix-Marseille University, France

Abdel BENKADDOUR
Laboratoire Géoressources, Morocco

Emmanuel CHAPRON
University Toulouse-Jean Jaures,
Toulouse 2, France

Thierry COURP
Perpignan University, France

Laurent DEZILEAU
CNRS, Géosciences Montpellier, France

Marta GARCIA
Aix-Marseille University, France

Bertil HEBERT
Perpignan University, France

Anaëlle SIMMONEAU
Orléans University, France

Corinne SONZOGNI
Aix-Marseille University, France

Florence SYLVESTRE
Aix-Marseille University, France

Kazuyo TACHIKAWA
Aix-Marseille University, France

Christine VALLET-COULOMB
Aix-Marseille University, France

Elisabeth VIRY
Aix-Marseille University, France

Introduction

The challenge is to implement research that can estimate the consequences of climate changes in terms of impact on terrestrial environments and resources. Emphasis should be placed on regions dependent on natural resources and for which demographic pressure is strong. Simulations obtained from climate model projections (using different Representative Concentration Pathways (RCPs)) predict that the Mediterranean basin and its southern periphery are particularly vulnerable to water resources and environmental impact (IPCC, AR5, 2013). An annual rainfall decrease by 30% is found for the projection period 2070-2099 (IPCC, AR5, 2013) associated with a decrease in water resources by 30 to 50% (Milano, 2012). In addition, several studies using regional atmospheric models indicate an increase in the precipitation inter-annual variability with extreme events and a spatial heterogeneous signature, superimposed on a decrease in the total precipitation amount (Giorgi and Lionello, 2008; Raible et al. 2010). Currently, regional climate projections are highly sensitive to the climate model used. In particular, spatial resolution as well as local climate conditions seem to impact significantly on the simulations (Jacob et al. 2014).

The Mediterranean region, at the interface between arid and temperate climates with several mountainous areas, is a complex climate system affected by the interactions between mid-latitude and sub-tropical processes. In this context, Morocco, located at the transition between a temperate climate to the North and a tropical climate to the south constitutes a key area for an impact and sensitivity study to global climate changes. The climate is influenced by the Atlantic Ocean, the Mediterranean Sea and the Sahara, together with a very steep orography in the Atlas region. The precipitation distribution is therefore characterised by great spatial variability, and exhibits a marked seasonality, a strong inter-annual variability (Ouda et al. 2005) and in general a pronounced gradient from north to south and west to east. At a broader scale, Morocco is located on the subtropical subsidence path and between the Acores High and the Saharan Low (Agoussine, 2003). Several studies have also identified strong links with inter-annual precipitation variability and NAO index (Knippertz, 2003) as well as remote climate modes (Esper et al. 2007).

Continental climate variability at a local/regional scale, if it is to be integrated in climate predictions, needs to be supported by long-term observation. Meteorological stations in Morocco provide climatic data mainly for the last 40 years with only a few stations located in the mountainous region (Tramblay et al. 2012; 2013; Driouech et al. 2010). This climate database is also supported by the IAEA network providing stations for which isotope tracers have been applied to daily/monthly rain and water vapour samples over 2 to 3 years between 2000 and 2004. Besides the poor coverage of instrumented areas, lacustrine systems can provide a climatic data set that offers access to short and long-term time series of climate parameters when knowledge of modern lake water balance is combined with lacustrine sedimentary-climate records. Lake sediment records ideally provide high resolution climate/environmental information of the last 10,000 years (Magny et al. 2013). This time interval (corresponding to the Holocene) is a key period to investigate short and long-term climate variability and to improve prediction in a warming climate.

In this study we present an integrated approach focusing on a mountainous lake (Aguelmam Azigza). The modern lake system study is based on site monitoring (2012-2016) and available regional hydro-climatic data. These data show that lake level changes during the instrumented period were mainly driven by precipitation following the high inter-annual variability. These data are then compared with accurately dated short sediment cores retrieved in the same lake. Micro-scale geochemical and sedimentological analyses of these sequences enable us to identify various sedimentary facies that can be linked with periods of high (low) lake levels over the past decades.

Study area

The Moroccan Middle Atlas is an intra-continental mountain range belonging to the Atlasic system (Choubert and Marcais, 1952). It comprises two morpho-structural units: the tabular Middle Atlas in the Northwest and the folded Middle Atlas in the southeast separated by the Northern Middle Atlas fault (Martin, 1981). The study area is located in the Ajdir plateau of the tabular Middle Atlas. Its structure consists of landscapes of elevated Jurassic limestone and dolomite lying over Triassic argilites and Paleozoic basement units (Lepoutre and Martin, 1967). It is close to the Oum R'Bia springs and belongs to the Oum R'Bia watershed, one of the most important fluvial system in Morocco with a catchment area of about 48000 km^2 (Figure 1a).

The climate in the Middle Atlas is of a Mediterranean sub-humid type, characterised by wet winters and dry summers (Martin, 1981). This particular climate results essentially from its altitudinal position, its geographical position and its exposure to marine influences (Atlantic and Mediterranean). Mean annual temperature (MAT) in the area is about 13°C (with maximum daily values of 35°C and minimum of -4°C). Mean annual precipitation (MAP) is about 900 mm, most of which falls between October and April (Martin, 1981). It is assumed that 20 to 40% of the total rainfall infiltrates. The numerous lakes, caves, rivers and springs that feed the Oum R'Bia river, make the region one of the most important water reservoirs in Morocco.

Long-term daily precipitation and temperature series (Figure 1b) were obtained from the governmental hydrological services of Morocco (ABOER, Tamchachate station, 33°4N, 5°16W, 1685 m asl) in charge of dams and water regulation structures. Most of these stations were installed during the sixties. The raw data

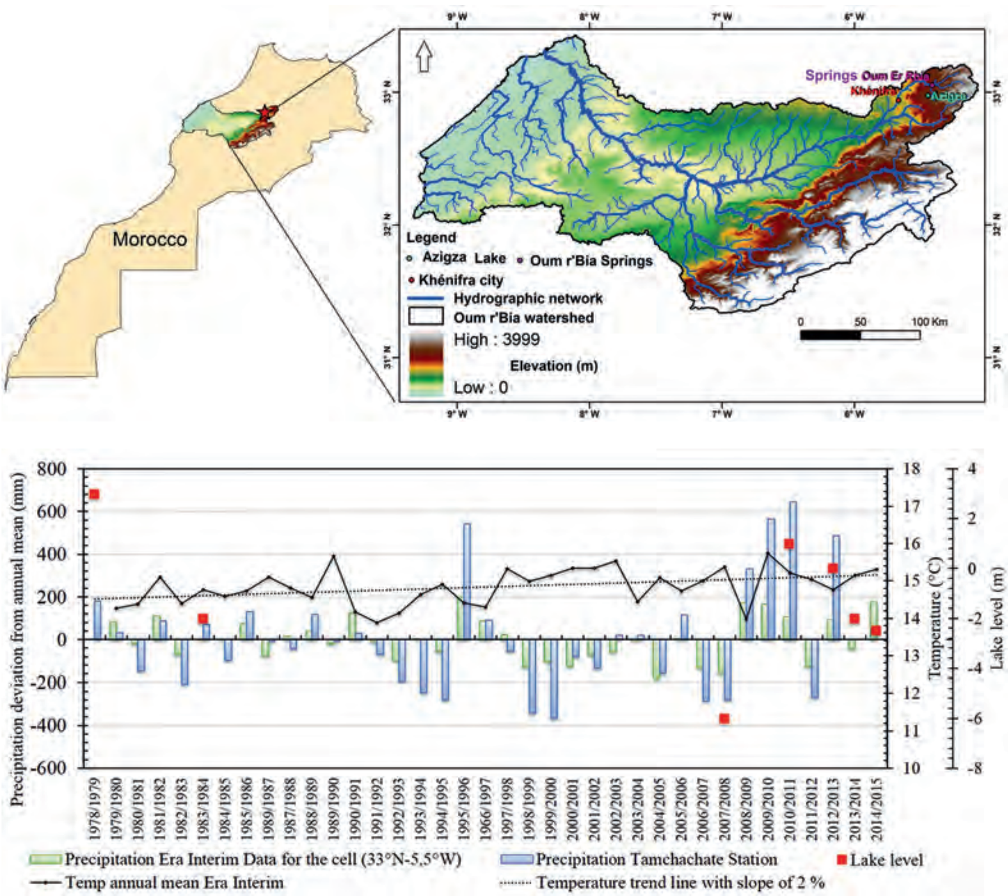

Figure 1

Hydro-climatic context of the study. a: Watershed of the Oum R'bia area.
b: Times series of mean annual temperature (MAT) and precipitation (MAP) close to the study area (Tamchachate station, ABOER data; ERA-Interim re-analyses data).
Data are expressed as standard deviation to the mean (calculated for the whole period, 1979-2015).
Symbols (red) indicate lake levels observed at the study site (Lake Azigza) (compared to our reference level of 2013).

of the precipitation record have been checked for quality control. For comparison, ERA-Interim re-analyse precipitation and temperature data provided by the ECMWF were used (Dee et al. 2011). The data are available every 3 hours and cover the period from January 1979 to the present with a projected horizontal resolution grid of 0.5°*0.5°. The mean annual air temperature series obtained close to the study site between 1979 and 2015 is about 14.5°C. A long-term trend in the temperature record can be detected toward increasing values (about 2% increase per decade). This has been already documented for several regions in Morocco since 1960's (Driouech et al. 2010). For precipitation, both data sets (ABOER and ERA-Interim) reveal a strong inter-annual variability

(Figure1b), which is one of the most important feature of the Mediterranean climate (Lionello, 2012). Higher average precipitation is recorded at Tamchachate, linked to the orographic influence. Similar inter-annual trends are observed between both sets, despite a smoothing effect for ERA-INTERIM re-analyses data which are based on few stations. The precipitation variability is also marked by extreme hydrological events. Some of them had a large regional impact like in 1995 (violent flood episode in the Ourika valley).

Hydrological context of Lake Azigza

Aguelmam Azigza Lake (32°58N, 5°26'W, 1544 m asl) is a natural lake, in a tectono-karstic depression along a NW oriented fault line, located at about 30 km east of the city of Khenifra.

The lake has been studied intermittently since 1940. Previous works noticed the relative pristine nature of the lake environment (particularly the Cedar forest) and the low level of human activity in the catchment area. The local vegetation is dominated by Cedar *(Cedrus Atlantica)* and Oak *(Quercus)* woodland formed on calcareous red soils. Physical parameter measurements (temperature profiles) have shown that the lake is monomictic with a winter overturning period (Gayral et Panouse, 1954). This has been confirmed with recent temperature profiles indicating a thermocline at about 8 m water depth during stratification periods (spring, summer and autumn). The lake is fed by diverse springs and sub-surface inflows. Despite the absence of surface outflows, chemical and isotopic signatures of water samples suggest an open system, with a short residence time and diluted water (Benkaddour et al. 2008). Ample evidence of significant lake level changes have been observed (Gayral et Panouse, 1954; Flower et al., 1992; Benkaddour et al. 2008) (Figure 1b). It was suggested that variation in annual rainfall significantly affects the magnitude of water level fluctuations (Flower et al. 1992), although the contribution of groundwater processes in modulating the lake response needs to be considered. Precise information about the timing and causes of these variations is still missing, mainly due to poor data availability.

For this study, a high resolution digital elevation model (DEM) of the lake and its watershed was produced (Adallal, Thesis) (Figure 2a). The lake's surface is $0.48*10^6$ m^2 and its volume is $6.91*10^6$ m^3. The watershed (automatically delineated from the DEM using the ArcHydro extension of ArcMap) has a surface of $10.16*10^6$ m^2, about twenty times the lake surface. The morphometry of the lake shows a mean depth of 26 m and a maximum depth of 42 m in the eastern part of the basin characterised by steep slopes compared to the western part (Figure 2a). Today, the lake has no surface outflow but evidence for a former outlet has been observed on the NW shore, probably linked to past high lake level periods.

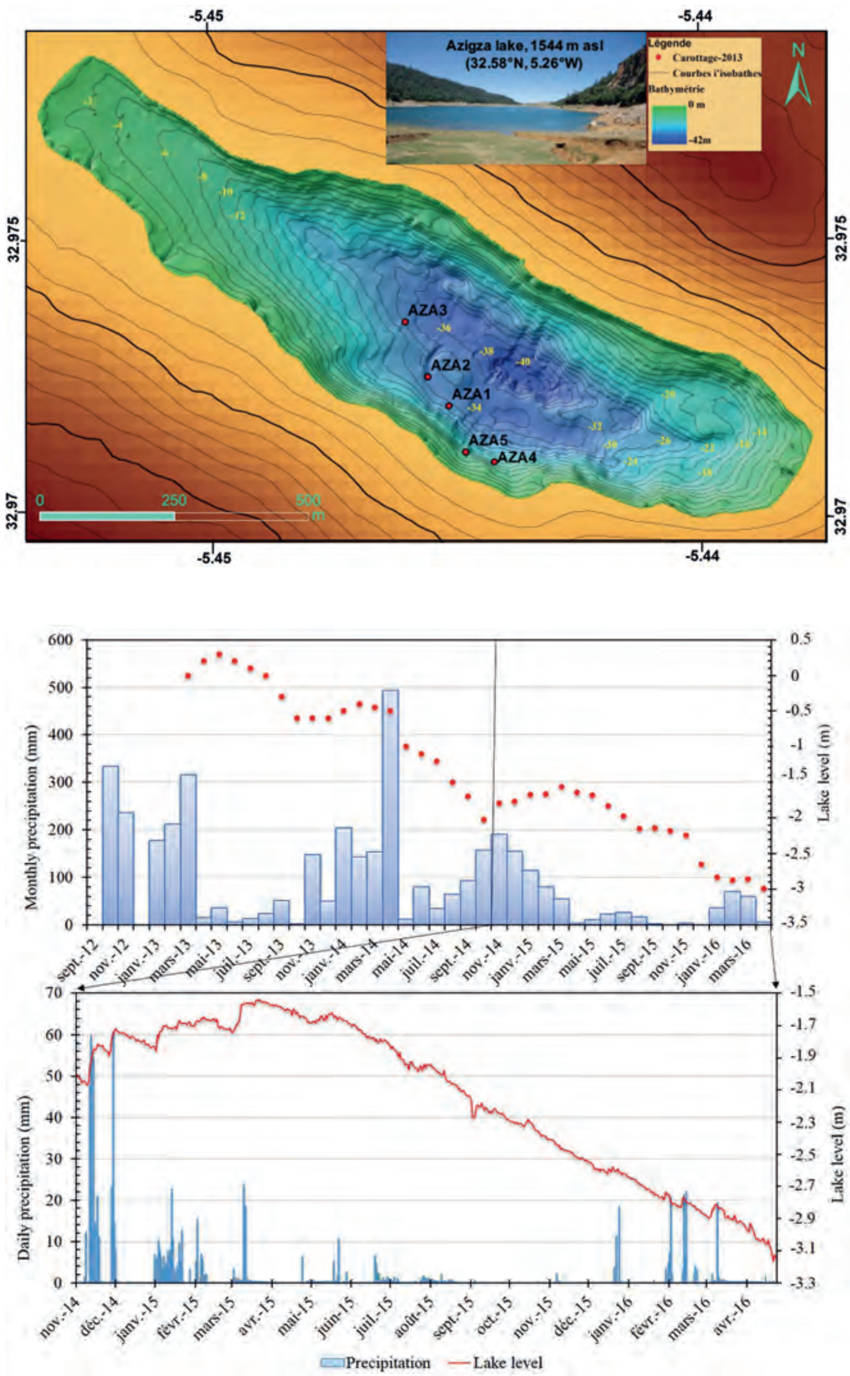

Figure 2
Hydro-climatic data from Lake Azigza.
a: High-resolution digital elevation model (DEM) of the lake watershed and bathymetry.
b: Monthly and daily precipitation (2012-2016) and lake level (2013-2016) monitoring.

Since October 2012, a monthly sampling of precipitation (using a rain gauge), lake and spring waters has been undertaken for hydro-chemical and isotopic analyses. In April 2013, monthly measurements of Azigza lake level have been manually measured using a reference gauge (Figure 2b). After November 2014, the installation of a data logger and a meteorological station at Lake Azigza enabled us to collect daily measurements. The data logger was anchored in the eastern part of the basin in order to measure water pressure, temperature and conductivity at 2.6 m under the water surface. Lake level is obtained by correcting the water pressure data from the atmospheric pressure measured at the same place. Other atmospheric parameters were measured with the meteorological station (precipitation, temperature, evaporation, humidity, solar radiation and wind speed) (Figure 2b).

For the instrumented period, the MAP is estimated at about 1100 mm/yr**.** The daily data reveal a strong link between precipitation and lake level over an annual cycle, which increases during the rainy season (November to February) and decreases during the dry period, with an annual amplitude of 0.5 m. In addition, the lake level responds rapidly to precipitation events with, for example, a mean increase of about 0.15 m (in a few days) followed by a relaxing period when rainfall stops mainly controlled by evaporation and groundwater outflow.

Over and above these changes, we also observed a long-term trend with a lake level decline of about 3 m since April 2013. As already mentioned, lake level fluctuations of several meters have been documented from the survey of former lake level terraces. These results found that low lake level for the early 50's coincided with a sharp decline in annual rainfall (Flower et al. 1992). Historical aerial photographs (obtained from Direction de Cartographie, Rabat, Morocco) and historical lake level observations (Flower et al. 1992; Benkaddour et al. 2008) have been compared to our reference lake level (between 1979 and the present). The data suggest that the lake level fluctuations follow inter-annual variations of precipitation (Figure 1b). It is noticeable that the high lake level reported in 1979-1980 (Figure 1b) follows a rainy period in 1977, 1978 and 1979 as recorded at Tamchachate Station (not shown). Our monthly monitoring of the physico-chemical properties of the lake system (lake, wells, springs) (2012-2014) indicate a significant contribution of groundwater flows in the lake water budget. For example, conductivity data (not shown) do not record any trend apart from the seasonal variability despite the lake level decline. Indeed, the lake water remains fresh even in the absence of surface outflow, in line with previous results (Benkaddour et al. 2008). However, the contribution of this groundwater outflow to the long-term lake level fluctuations still needs to be estimated.

Hydro-sedimentlogical context

In spring 2013, several short sediment cores from Lake Azigza were retrieved using the UWITEC gravity recovering system. Cores from shallow (16 m water depth) and deep water (30 m water depth) locations were obtained (Figure 2a). The cores were split longitudinally into two halves and after lithological description were used for multi proxy analyses. In general, the sedimentary sequences were composed of unconsolidated light-brown to dark, partly laminated clastic sediments and endogenic carbonates and few transition metal oxides. The cores AZA-13-3 (90 cm long) and AZA-13-1 (78 cm long) retrieved in the deeper basin were first imaged and measured for chemical composition in an X-Ray fluorescence (XRF) ITRAX core scanner (Cox Analytical System) at CEREGE. Using a Molybdenum X-ray source, a suite a chemical element was semi-quantitatively determined (at 40 kV, 30 mA, and an exposure time of 15s). This method provides high-resolution (1mm step) records of six elements (Ca, Fe, Ti, K, Si, Mn).

Thin sections performed at CEREGE for core AZA-13-3 allow for micro-scale observations of the sedimentary facies using a microscopic approach and semi-quantitative analysis of elements using energy dispersive technique (EDS) coupled with a scanning electron microscope (SEM). The elemental mapping of each facies is then linked to the mineralogy and sedimentary characteristics of the sample in order to improve interpretation of XRF signals (Jouve et al. 2013).

The chronological framework of core AZA-13-3 was derived using the ^{210}Pb and ^{137}Cs activity- depth profiles. The radionuclides content of the bulk sediment was measured for 13 samples (for the uppermost 40 cm of core AZA-13-3) by gamma spectrometry at Géosciences, Montpellier. Concentration of ^{137}Cs clearly identifies the AD 1963 peak due to atmospheric nuclear tests and the associated radionuclides fallout (Cambray et al. 1989) (Figure 3a). Sediment accumulation rates estimations using ^{210}Pb-excess and/or ^{137}Cs concentrations give similar results of about 5 mm/year. Considering a continuous sedimentation rate we tentatively estimate that the deep basin sedimentary sequences cover approximately the last 150 years, given that the age model needs to be improved.

Micro-scale analyses of thin section of sediments revealed three main facies in core AZA-13-1. The first is a mixing of clastic (quartz) and authigenic (calcite) sediments with thin laminations of calcitic shells of ostracods and bivalves, and wood fragments (Facies 1) (Figure 3b). The second is composed of a mixing of clastic and authigenic sediments with few millimetric calcitic shells of ostracods and bivalves without wood fragments (Facies 2). Facies 1 and 2 repeated several times along the sequence while Facies 3 is only present in the upper part of the sequence. It is composed of a mixing of clastic and authigenic sediments that integrate a critical amount of authigenic minerals, such as gypsum, pyrite and phosphates, inconsistently deposited on Facies 1.

Facies 1 is interpreted as a proxy of higher superficial runoff during high lake levels. During increased runoff activity, and when the shoreline is close to the cedar forest, calcitic shells and wood fragments can be mobilized from the littoral zone. Facies 2 reflects reduced runoff activity associated with low lake levels. Indeed, when the shoreline is closer to the coring site, coarser

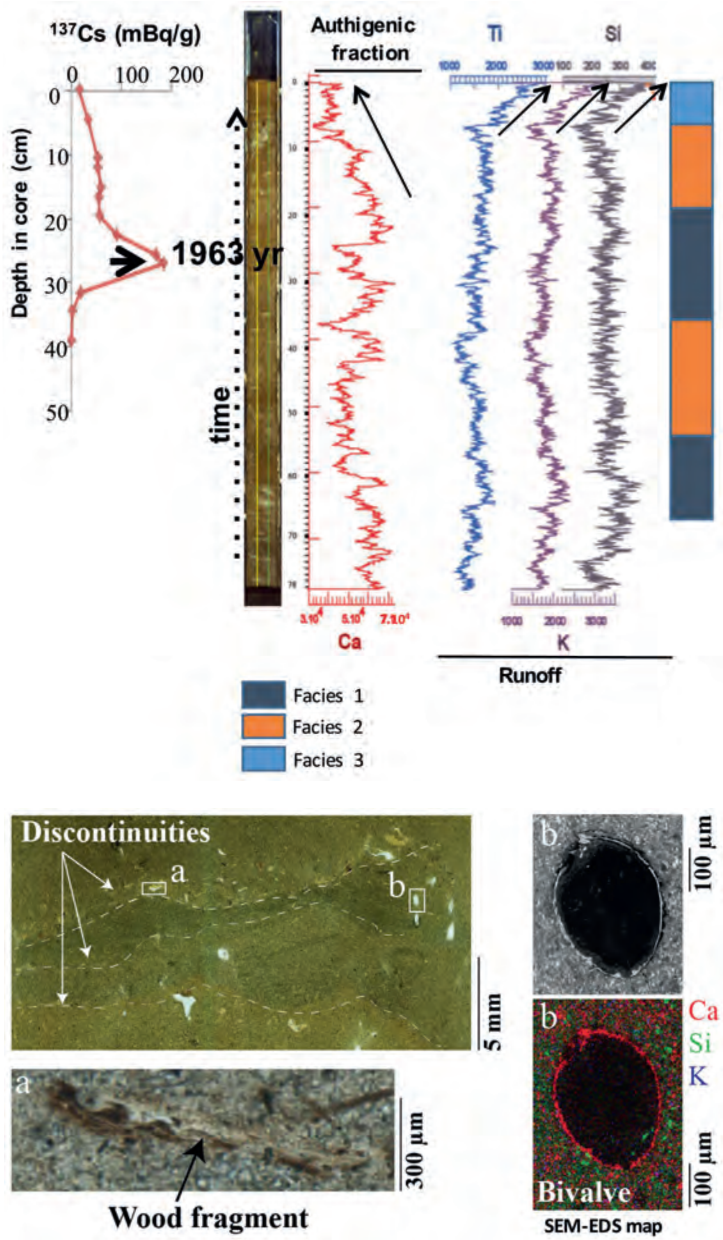

Figure 3
Geochemical composition and sedimentary structures of Azigza lake sediment cores.
a: Age model and XRF measurements (Ca, Ti, K, Si)
for core AZA-13-3 (N32°58,418; W5°26,708; 32 m water depth).
b: Micro-facies structures of facies 1 at 34 cm in core AZA-13-1
(N32°58,332; W5°26,659; 30 m water depth) corresponding to a high lake level period
(derived from SEM-EDS measurements on indurated blocks of sediment).

calcitic shells can be moved from the littoral zone to the deep basin. In this case, less intense superficial runoff prevents the transport of wood fragments to the basin.

In agreement with the sedimentation rate derived from the age model, Facies 3 is interpreted as the sedimentary deposit derived from the refilling period of the shallow basin in 2009, following a period of low rainfall (Figure 1b). When the lake level was rising, the superficial runoff carried authigenic particles from the shallow to the deep basin throughout small rivers (visible in the bathymetry, Figure 2a and Jouve et al. in prep). A fast lake level rise could have led to water column stratification and suboxic/anoxic conditions at the water/sediment interface and thus the precipitation of pyrite.

These interpretations are consistent with XRF data, since elemental proxies of superficial runoff (Si, Ti, K and Fe) are higher/lower associated with Facies 1 and 3/Facies 2 (Figure 3a). Moreover, using the age model, periods of high/low lake levels are coeval with periods of higher/lower annual precipitation close to our study area (Figure 1b). Since 1963, two periods of high (from the 60s to the 70s, and since 2009) and one period of low lake level stand (from the 80's to 2008) seems to be synchronous with the appearance of Facies 1/2 respectively.

Conclusion and perspectives

Several studies have already highlighted the significant impact of human and climatic factors in the Middle Atlas lake systems at various spatio-temporal scales (Lamb et al. 1995; Cheddadi et al. 1998; Rhoujatti et al. 2010; Damnati et al. 2012 among others). These approaches, while indicating the vulnerability and sensitivity of these lakes suffer from poor current characterisation of these hydro-systems needed for a better interpretation of sedimentary records in term of past hydrological variability. Long-term site survey is essential to conduct research dealing with the environmental impact of global climate change in vulnerable remote areas.

At Lake Azigza, our site monitoring (2012-2016) confirmed the strong link between lake level fluctuations and precipitation variability at daily, monthly and annual steps. This data set will definitively help to understand the long-term decreasing trend of the lake level as observed during the instrumented period. Indeed, the understanding of the hydrological behaviour of the lake requires the quantification of the groundwater contribution to the lake water balance. This is an ongoing study in which a water balance model is coupled with water isotopes (Adallal et al. in prep.). The simulation of the lake level and lake isotopic composition at daily and monthly steps compared to the measured data set will provide a quantified relation between climate, groundwater inflows and outflows, and lake level variations. Finally, our approach has the potential to provide quantitative past lake level reconstructions using the hydrological model forced by historical precipitation times series. The same approach should be tested with precipitation simulations obtained from high resolution regional climate model projections.

The micro-scale studies of the sedimentary lake deposits revealed that sedimentary structures and geochemical composition can be interpreted as a proxy for runoff intensity. The improvement of the dating of the cores will allow for the extension of the sedimentary record over the last 150 years. A calibration of the proxy with the climatic data will be tested and used to reconstruct runoff intensity changes (linked to precipitation extreme events) over the last 150 years, beyond the instrumental period. Interestingly, Flower et al. (1992) did not find obvious records of the recent lake fluctuations in deep-water sediment cores (from coarse grain size measurements) and concluded with fairly stable soil erosion rates. The approach conducted in this project shows that micro-scale observations can bring valuable additional sedimentary information linked to the hydro-sedimentary behaviour of the lake.

The integration of modern lake system knowledge (through site instrumentation and modelling) with lacustrine sedimentary climate records from the same site will provide new insights into the study of continental hydrological variability at various time scales. It will enable us to evaluate the imprint of human activities *vs* climate factors at decadal scale for the last millennia and provide keys to future environmental management and preservation purposes.

Acknowledgements

This research project has been funded by several structures and programmes: the research federation “ECCOREV”, LABEX OT-Med (ANR-11-LABEX-0061) “Investissements d’Avenir,” French Government project of the French National Research Agency (ANR) and MISTRALS-Paleomex. LABEX OT-MED provides RA PhD thesis fellowship. The contribution of the CNRST-Maroc to the RA fellowship is also acknowledged. The data from Tamchachate station were provided by the Agence du Bassin Hydrolique de l’Oum R’Bia (ABOER). The support of the LMI-TREMA-Marrakech for the meteorological station installation at Lake Azigza site is acknowledged and appreciated. LV thanks IRD for providing her with a long stay (MLD) at the University Cadi Ayyad (2014). Our warm thanks are also extended to SETEL-CEREGE and IRD-Rabat, who provided logistic support during the field trip (2013).

References

Agoussine, M. (2003)
Les divers aspects de l'hydrologie en régions arides et semi arides : cas du sud-est marocain. *Terre & Vie*, Rabat, 70 p.

Benkaddour, A., Rhoujjati, A., Nourelbait, M. (2008)
Hydrologie et sédimentation actuelles au niveau des lacs Iffer et Aguelmam Azigza (Moyen Atlas, Maroc). *Le Quaternaire marocain dans son contexte méditerranéen. Actes de la 4e rencontre des quaternaristes marocains (RQM4, 2007)*, *1*, 108-118.

Cambray, R.S., Playford, K., Lewis, G.N.J., Carpenter, R.C. (1989)
Radioactive fallout in air and rain: results to the end of 1987 (AERE-R--13226). UK.

Cheddadi, R., Lamb, H. F., Guiot, J., Van Der Kaars, S. (1998)
Holocene climatic change in Morocco: a quantitative reconstruction from pollen data. *Climate Dynamics*, 14(12), 883-890.

Choubert, G., Marcais, J. (1952)
Aperçu structural. In Géologie du Maroc. *Notes et Mémoires du Service géologique du Maroc*, 100, 9-76.

Damnati, B., Etebaai, I., Reddad, H., Benhardouz, H., Benhardouz, O., Miche, H., Taieb, M. (2012)
Recent environmental changes and human impact since mid-20th century in Mediterranean lakes: Ifrah, Iffer and Afourgagh, Middle Atlas Morocco. *Quaternary International*, 262, 44-55.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S.,... Bechtold, P. (2011)
The ERA Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553-597.

Driouech, F., Déqué, M., Sánchez-Gómez, E. (2010)
Weather regimes-Moroccan precipitation link in a regional climate change simulation. *Global and Planetary Change*, *72*(1), 1-10.

Esper, J., Frank, D., Büntgen, U., Verstege, A., Luterbacher, J., Xoplaki, E. (2007)
Long-term drought severity variations in Morocco. *Geophysical Research Letters*, *34*(17).

Flower, R. J., Foster, I. D. L. (1992)
Climatic implications of recent changes in lake level at Lac Azigza (Morocco). *Bulletin de la Société géologique de France*, *163*(1), 91-96.

Gayral, P., Panouse, J. B. (1954)
L'Aguelmame Azigza, Recherches physiques et biologiques. *Bull. Soc. Sci. Nat. & Phys. du Maroc*, *36*, 135-159.

Giorgi, F., Lionello, P. (2008)
Climate change projections for the Mediterranean region. *Global and Planetary Change*, *63*(2), 90-104.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M.,... Georgopoulou, E. (2014)
EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change*, *14*(2), 563-578.

Jouilil, I., Bitar, K., Salama, H., Mokssit, A., Tahiri, M. (2013)
Sécheresse météorologique au bassin hydraulique OUM ER RBIA durant les dernières décennies. *Larhyss Journal, ISSN 1112-3680*, 12, 109-127.

Jouve, G., Francus, P., Lamoureux, S., Provencher-Nolet, L., Hahn, A., Haberzettl, T.,... Team, T. P. S. (2013)
Micro-sedimentological characterization using image analysis and μ-XRF as indicators of sedimentary processes and climate changes during Late glacial at Laguna Potrok Aike, Santa Cruz, Argentina. *Quaternary Science Reviews*, *71*, 191-204.

Knippertz, P., Christoph, M., Speth, P. (2003)
Long-term precipitation variability in Morocco and the link to the large-scale circulation in

recent and future climates. *Meteorology and Atmospheric Physics*, *83*(1-2), 67-88.

Lamb, H. F., Gasse, F., Benkaddour, A., El Hamouti, N., van der Kaars, S., Perkins, W. T.,... Roberts, C. N. (1995)
Relation between century-scale Holocene arid intervals in tropical and temperate zones. *Nature*, *373*(6510), 134-137.

Lepoutre, B., Martin, J. (1967)
Le causse moyen atlasique. *Les cahiers de la recherche agronomique*, 24, 207-226.

Lionello, P. (2012)
The Climate of the Mediterranean Region: From the Past to the Future, Elsevier, 502 p.

Magny, M., Combourieu Nebout, N. (2013)
Holocene changes in environment and climate in the central Mediterranean as reflected by lake and marine records. *Climate of the Past*, *9*(4), 1447-1454.

Martin, J. (1981)
Le Moyen Atlas central : étude géomorphologique. *Notes et Mémoires du Service géologique du Maroc*, 285, 447 p.

Milano, M., Ruelland, D., Fernandez, S., Dezetter, A., Fabre, J., Servat, E. (2012)
Facing climatic and anthropogenic changes in the Mediterranean basin: What will be the medium-term impact on water stress?. *Comptes Rendus Acad. Geosciences*, *344*(9), 432-440.

Ouda, O., El Hamdaoui, A., Ibn Majah, M. (2005)
Isotopic composition of precipitation at three Moroccan stations influenced by oceanic and Mediterranean air masses. *TECDOC*, *1453*, 125-140.

Raible, C. C., Ziv, B., Saaroni, H., Wild, M. (2010)
Winter synoptic-scale variability over the Mediterranean Basin under future climate conditions as simulated by the ECHAM5. *Climate Dynamics*, *35*(2-3), 473-488.

Rhoujjati, A., Cheddadi, R., Taïeb, M., Baali, A., Ortu, E. (2010)
Environmental changes over the past c. 29,000 years in the Middle Atlas (Morocco): a record from Lake Ifrah. *Journal of arid environments*, *74*(7), 737-745.

Stocker, T. F., Qin, D., Plattner, G. K., Tignor, M., Allen, S. K., Boschung, J.,... Midgley, B. M. (2013)
IPCC, 2013: climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change.

Tramblay, Y., Badi, W., Driouech, F., El Adlouni, S., Neppel, L., Servat, E. (2012)
Climate change impacts on extreme precipitation in Morocco. *Global and Planetary Change*, *82*, 104-114.

Tramblay, Y., Ruelland, D., Somot, S., Bouaicha, R., Servat, E. (2013)
High-resolution Med-CORDEX regional climate model simulations for hydrological impact studies: a first evaluation of the ALADIN-Climate model in Morocco. *Hydrol. Earth Syst. Sci*, *17*(10), 3721-3739.