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SATELLITE ALTIMETRY FOR MONITORING LAKE LEVEL CHANGES

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ABSTRACT

Accurate and continuous monitoring of lakes and inland seas is possible since 1991 thanks to the recent missions of satellite altimetry (Topex-Poseidon, ERS-1, ERS-2, Jason-1 and Envisat). Global processing of the data of these satellites could provide temporal and spatial times series of lakes water level from 1991 to 2003 on the whole Earth with a decimeter precision. The response of water level to regional hydrology is particularly marked for lakes and inland seas of semi-arid regions. Altimetry data can provide an invaluable source of information in hydrology sciences, but in-situ data (rivers runoff, temperature, precipitation etc.) are still strongly needed to study the evolution of water mass balance of each lake. Moreover, sea level variations that result from variation of hydrological parameters such as river discharge, precipitation and evaporation, are very sensitive indicators of regional climate variations. Recent results obtained on Aral Sea and Issykkul Lake are presented here. Inter - annual changes of water level have been obtained over these lakes that must be interpreted in term of hydrological water balance. Since 1960 the Aral sea has been drying and since 1989 it is divided into two lakes that follow different evolution, the Big Aral in the south which continuously dried up the last 10 years, while the so-called Small Aral in the north presented large inter-annual fluctuations related to constructions and destructions of a dam in the Berg's strait retaining the water from the Syr Darya. For Issykkul, a slow decrease of the level has been observed over the last hundreds years (4 cm / year), followed by an abrupt and bigger increase of the level of around 10 cm/yr since 1998. The impact on local populations and infra-structures of these fluctuations are dramatic in the case of Aral, much less in the case of Issykkul, but comparative study of both water bodies may help in the future to understand the respective consequences of human-induced activities from the natural changes. It is also the task of a new project recently submitted and accepted by the NATO with scientists from Uzbekistan and Kyrgyz Republic.

INTRODUCTION

In August 1992, the TOPEX/Poseidon (T/P) satellite has been launched on a 66° inclined orbit at 1336 km altitude with objective of measuring ocean height at a very high accuracy of few centimeters. The

orbit repeat period is 10 days which corresponds to an inter track spacing of 250 km at equator. Altimetry, although designed to study open ocean, has been immediately used over continental lakes (for exhaustive details on application of altimetry to lake studies, see Birkett 1995). The satellite carries a dual frequency radar altimeter operating in C and Ku bands (5.3 and 13.6 GHz respectively for T/P), which transmits a short pulse in the nadir direction, which is then reflected by the sea surface. The measurement of the time for pulse to be reflected back to the altimeter corresponds to the distance between satellite and sea surface (Fu & Cazenave 2001). Little correction must be applied to these measurements, due to atmospheric refraction, various electromagnetic bias, tides, and then, instantaneous sea surface height (SSH) is simply obtained from the difference between the radial component of the orbit and the corrected altimeter measurement. For previous altimeter missions, uncertainty in the radial orbit component was the largest source of error affecting SSH. For T/P, the orbit precision is currently 2-3 cm rms (Nouel et al., 1994) and thus it allows a high precision altimetry. This technique can be used on all water surfaces, ocean as well as lakes, inland seas, flooding plains, or rivers. It is just requested that the projection of the orbit of the satellite cross the surface of the water body and that this intersection is large enough to generate the return radar signal. The spatial resolution along the ground track is of about 6 km for 1-second measurement. This technique has been already applied to some large lakes since the last 5-6 years (Ponchaut & Cazenave 1998). Results have been obtained on Caspian Sea (Cazenave et al., 1997), on Mediterranean and Black Sea (Cazenave et al., 2002), African lakes (Mercier et al., 2002), and recently on Aral Sea (Aladin et al., 2003). In this article, we present results obtained recently on Big and Small Aral Sea and Issykkul lake.

ARAL SEA

The Aral sea, which was one of the world's largest inland water-bodies, with a surface of 66000 km² and a volume reaching more than 1000 km³, started to shrink at the beginning of the 1960's when anthropogenic demands for agricultural needs led authorities to increase irrigation intake of the 2 inflow water contributors: Amu Darya and Syr Darya rivers. In 1960, the level of the sea was 53 m above the Baltic Sea level (taken as usual reference of zero sea level). Amu Darya and Syr Darya provided around 60 km³ of fresh water runoff per year, which represents approximately half of the total runoff capacity flow of both rivers. The other half was lost by evaporation, underground infiltration lost and irrigation along the 3000 km length of the rivers. When withdrawal water for irrigation increased in 1960, the equilibrium of the water was broken, the level declined very rapidly and reached 39 meters in 1989 at the time of separation of Aral Sea into two parts: Small (northern part) and Big (Southern part) Aral Seas. During this period from 1960 to 1989, salinity of the sea has increased from 10 g/l to 28 g/l. Since 1989, both lakes have evolved differently. The Small Aral, which continued to receive water

inflow from Syr Darya River, and suffer less from evaporation due to the small size of the lake, has fluctuated around the level 40 m, with highest level in 1998 when a dam has retained water from the river within the lake. The Big Aral received less water from Amu Darya, and due to its larger water surface, it has suffered from a high rate of evaporation during the last ten years. Using the T/P data, we have computed the variation of level and volume of both lakes (figures 1 and 2). In a first step we have averaged the level of the lakes deduced from all measurements made by T/P each ten days (Aladin et al., 2003). Then we used a dedicated Digital Bathymetry Map (DBM) of Aral Sea to compute time series of volume of Small and Big Aral with temporal resolution of 10 days.

In the same time we have computed their variations of volume taken into account of the in-situ hydrological data available through Internet and publications. For the runoff of Amu Darya and Syr Darya, we used data provided by Internet web site (<http://water.freenet.uz>) thanks to research made in the frame of an INTAS program (Ivan Stavitsky, personal communication). These corresponded to monthly average flow of Amu Darya (1993 to 2000) and Syr Darya (1993 to 1998) made at few dozens of kilometres upstream from the Big and Small Aral (In Kyzylgda and Kazalinsk, respectively). For evaporation and precipitation we have considered the values given in Small et al. (1999), that are based on outputs of a coupled regional climate-lake model (regCM2) for evaporation, and on Legate and Wilmott climatology data (Legates and Wilmott, 1990) for precipitation.

For Small Aral we have also taken into account that a dam has been built several times between 1993 and 1999 (Aladin et al., 2003). We have separated the period of treatment in 6 parts, 3 for the times when there was a dam in the Berg's strait, 3 for the times when the dam was destroyed. Comparing the time series of volume deduced from altimetry with variation of volume deduced from the hydrological budget (Precipitation plus Runoff minus Evaporation), we have estimated that the dam allow to retain 80 % of the Syr Darya river runoff passing the gauges of Kazalinsk. For the period of time without dam, we have estimated that only 20 % of river runoff reaches the sea. The rest is lost in evaporation in the delta and in the desert, as well as to underground infiltration. This computation allows quantifying the positive effect on water budget of the Small Aral. For the Big Aral, we have made the same computation. It first showed, that the volume of the lake measured by T/P measurements decreases slower than deduced from hydrological budget. To make both computations in agreement, we should consider an additional positive water inflow within Big Aral of around 5 km³/year. This can be interpreted in different ways: errors of altimetry measurements, in the hydrological parameters we have used (Precipitation, Evaporation and Amu Darya Runoff), or lack of information about underground water flow. We have assessed the quality of altimetry measurement by comparing the surface of the lake (which can also be deduced from combination of altimetry and DBM) with satellite images of the Big Aral at different times between 1993

and 2003. This presented a very close agreement, which indicated that altimetry and DBM were accurate enough, and are not the source of disagreement within the hydrological budget.

Among the 2 other sources of errors (hydrological parameters, and possibility of non negligible underground inflow) it is up to now impossible to come to a definitive conclusion. This needs further analysis on each of these parameters. For evaporation, we need to take into account the high salinity of the lake (actually more than 80 g/l) which influences the rate of evaporation, as well as climate change since the time when the evaporation measurements were made (Small et al., 1999, 2001). For the runoff, there are possible errors, as we don't know how much water is lost between the gauge site used to compute Amu Darya runoff and the mouth of the delta. For possibility of underground water supply, this assumption needs hydro-geological investigations actually made, among other groups at the University of Neuchatel in Switzerland (Benduhn et al., 2003). This issue is far to be clear and solved.

LAKE ISSYKKUL

Lake Issykkul is an endorheic mountain lake located at 1608 m above the sea level in the northern Tian Shan, in the Kyrgyz Republic. It has an area of 6236 km², a length of 180 km, a width of 60 km, and a maximum depth of 668 m making it the fifth deepest lake in the world.

Rivers that flow into the lake are fed by melt-water from glaciers and snow, located above 3,300 meters altitude. The supply of river water into the lake result in the mean annual oscillation of lake level about 20 cm. The lake level progressively increases from February until beginning of September, decreasing afterwards progressively to the next February.

Historical sources (Holocene terraces, abrasion benches) point out that the lake level has strongly fluctuated. Thus, between the 11th BC and the 1stAD centuries the lake level was 12 - 13 m higher than today, whereas between the 10th AD and the 12th AD centuries the lake level was lower than today. The 18th AD and the 19th AD centuries were also characterized by higher water levels than the present day (Mamatkanov et al., 2002).

During the last 75 years, the water level has progressively declined by about 4cm/year, and several factors have been invoked for explaining this phenomenon although the exact mechanism that trigger such oscillations remain unknown: the progressive increase of the intensive agricultural use of the lake shores together with the enlargement of the population inhabiting its shores (with consequent increase of the water consumption for domestic purposes) and the increase of the regional aridity conditions, are the main factors invoked for explaining the present day lake level drop (Mamatkhanov et al.,2002). From 1972 up to now, about 4 km³ of glaciers have been thawing. For the period 1993 to 2003, as for Aral Sea, we have computed the variation of Issykkul with T/P altimetry data. As this lake is located in mountainous area, this decreases the accuracy of the altimetry measurements, mainly due to bigger errors made in the

tropospheric correction applied to the range measurements, and the lost of many data due to the influence of surrounding topography of the lake region on the radar return signal. These limitations of altimetry for mountain lake have been described in Birkett et al., 1995, and possible source of improvements could be obtained through accurate atmospheric model used to compute the tropospheric correction, and retracking of the waveform of the altimetry radar echo that we didn't make for this analysis (Birkett et al., 1995).

However, since the last 4-5 years, measurements deduced from T/P altimetry mission have shown that the lake level of Issykkul increased with a rate of around 10 cm /year instead of dropping. In ten to twenty years, if lake Issykkul level continues to increase, damages on the shore infrastructure could be high. It can be the consequences of recent higher glacial melting. This could be connected to regional warming, which may also be registered in level variations of other neighbouring lakes like Karakul and Chatyrkul lakes.

PERSPECTIVES

In the scope of a NATO project, in coordination with Uzbek and Kyrgyz colleagues, we plan to investigate the inter-annual variability of Aral Sea and Issykkul Lake.

The main goal of the project is to precisely monitor variations of level and volume of both water bodies and to discriminate between global effect (consequences of climate changes on precipitation, evaporation, and glacier melting and regional or local effect (consequences of human activities: mainly withdrawal of water for agricultural consumption).

To outline natural and anthropogenic contribution to fluctuation of lake Issykkul, it is also proposed to study the level variations of other lakes, located in other parts of Holocene terraces that have different hydrological regime and different chemical composition. Lakes Karakul and Chatyrkul will be considered as proxies for this analysis. For example, Chatyrkul Lake is a mountainous lake, which is influenced only by climatic changes. Analysis of sediments, measurements of rivers runoff into these lakes and data of precipitation and lake temperatures will be used for the establishment of accurate current and historical water balance.

We plan to use various sources of information: in situ data of lake temperature, river runoff (from Amu Darya as well as rivers feeding Kyrgyz lakes), precipitation, evaporation, lake level measurement, etc.)and satellite altimetry data. This technique will allow to measure on a very short time scale the variations of average levels of lakes. Combination of different altimetry missions will also provide high temporal resolution of the mean sea level variations (10 days with T/P and Jason-1) and high spatial resolution of these variations (with ERS-1/2 and ENVISAT). It has been already applied to Aral Sea and Issykkul, with reliable results as shown above, that confirms and precisely measures the drying up of the Aral sea, and also provided continuous level decrease of Issykkul since 1998, followed by abrupt increase of its level. We also plan to use the

ERS1&2 data that provides a better density of measurements over the lakes and in case of Issykkul will help to not only consider average lake level variations, but also geographical distribution of water level fluctuations, that should give better estimates of currents and water redistribution within the whole lake.

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