Monitoring lake level changes by altimetry in the arid region of Central Asia

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Abstract. The study of lake level changes in arid region of Central Asia not only has important significance for the management and sustainable development of inland water resources, but also provides the basis for further study on the response of lakes to climate change and human activities. Therefore, in this paper, eleven typical lakes in Central Asia were observed. The lake edges were obtained through image interpretation using the quasi-synchronous MODIS image, and then water level information with long period (2002-2015) was acquired using ENVISAT/RA-2 and Cryosat-2 satellite borne radar altimeter data. The results show that these 11 lakes all have obvious seasonal changes of water level in a year with a high peak at different month. During 2002 – 2015, their water levels present decreased trend generally except Sarygamysh Lake, Alakol Lake and North Aral Sea. The alpine lakes are most stables, while open lakes’ levels change the most violently and closed lakes change diversely among different lakes.

1. Introduction

Arid/semi-arid region of Central Asian with relatively dense distribution of lakes in the world is more than 88000 km² [1]. Lake is not only a sensitive indicator of climate and environment change, but also the indispensable foundation of human survival and social progress. Many studies have indicated that the inland lakes here have changed dramatically in recent decades, causing a series of ecological disasters [2, 3]. The water level is a significant indicator of lake change. Therefore observing lake level changes in a long time of the Central Asian is necessary.

Traditionally, the lake level monitoring is mainly through gauge data for a specific lake. However, these data can’t be presented in the same reference system with inconsistent data accuracy. So, given large geographical span of Central Asia, it’s difficult to use conventional means to obtain lake level changes of long time series throughout this region. Satellite altimetry makes lakes in remote area observable, which provides convenience for water level change study with large scale and long period. Satellite altimetry was used as an alternative tool to measure lake levels since the 1990s [4]. Different altimeters have been used along with its development, from Topex/Poseidon (T/P), ERS-1, ERS-2, ENVISAT to ICEsat, Jason-2 and Cryosat-2, with an accuracy ranging from centimeters to decimeters [5, 6, 7, 8, 9].
ENVISAT/RA-2 is currently the most widely used altimeter in monitoring lake level changes with higher time resolution, while Cryosat-2 makes the lake level observation using satellite data continuous. In this paper, the 11 typical inland lakes in Central Asia were studied, and water level information with long period (2002-2015) was acquired using ENVISAT/RA-2 and Cryosat-2 radar altimeter data. Then the characteristics of seasonal and inter-annual lake level variation were analyzed.

2. Study area and data

2.1. Study area
As shown in Fig.1, the study area is the five countries in Central Asia located in the mid-latitudes of the north-western hemisphere (46°30′E – 87°30′E and 34°39′N – 56°16′N), including Kirgizia, Uzbekistan, Kazakhstan, Turkmenistan and Tajikistan. This region has a temperate continental climate with the average annual rainfall of 100 – 400 mm. Most areas are severe drought with little rain and large evaporation. This study selects 11 inland lakes as the research object.

![Fig.1. Map of study area and lakes distributions](image_url)

2.2. Data
In this paper, three datasets were used, including the image data of MODIS13Q1 from National Aeronautics and Space Administration (NASA), ENVISAT RA-2 and Cryosat-2 Geophysical Data Records (GDR) provided by the European Space Agency (ESA).

The ENVISAT RA-2 was launched in 2002 and stopped working in April 2012. It has been successfully used to monitor inland waters with accuracy about 0.3m [10, 11]. The RA-2 is a nadir-pointing instrument with a repeat cycle of 35 days. ENVISAT RA-2 GDRs provides four satellite-to-ground retracked ranges, including Ice-1, Ice-2, Ocean and Sea ice retracker. And Ice-1 was considered as the best data for lake level monitoring, which was used in this study [6, 12].

The Cryosat-2 satellite was launched in April 2010, carrying SIRAL altimeter, which is operating in three modes, including Low Resolution mode (LRM), SAR mode and SAR Interferometric (SARIn) mode. It has a 369-day repeat cycle with shifting sub-cycles of 30 days. The study area is mainly covered by LRM and SARIn observation mode. Furthermore, GDRs of LRM mode provides three different retrackers: UCL, refined CFI and refined OCOG, and the last one (OCOG) was used in this study.

3. Methods
To ensure that the data points are on the lake surface, boundary of each lake was firstly extracted by the method of density slice using NDVI (Normalized Difference Vegetation Index) image of MODIS13Q1 data, which were near the time altimeter visited.

Then, corresponding tracks of ENVISAT RA-2 passing each lake were selected. For example, there are 3 tracks (212, 425 and 969) overpassing Sarygamsh Lake before October 2010. Water Surface Height was calculated by subtracting the corrected range from the satellite altitude:

\[
\text{Water Surface Height} = \text{Altitude} - \text{Corrected Range}
\]

Where

\[
\text{Corrected Range} = \text{Range} + \text{Wet Troposphere Correction} + \text{Dry Troposphere Correction} + \text{Ionosphere Correction}
\]

The lake level was calculated above the geoid by the following formula:

\[
\text{Lake Level} = \text{Water Surface Height} - \text{Geoid} - \text{Solid Earth Tide Height} - \text{Pole Tide Height}
\]

Next, the data was further processed. **Step 1**, the points outside the boundary of the lake was deleted. **Step 2**, for all observed points of a lake, delete the obvious abnormal values using visual interpretation. **Step 3**, calculate the standard deviation ($\sigma$) and mean value ($m$) of those remaining footprints of a day, and remove those outliers which distance from $m$ more than three times of $\sigma$ ($3\cdot\sigma$ criterion). Then calculate the mean value of a day as this day's water level. **Step 4**, delete the abnormal single day water level using $3\cdot\sigma$ criterion mentioned above. **Step 5**, get a relatively clean water level sequence using Gauss filter to remove noise for the whole day water level, with a filtering window of half a year [13]. **Step 6**: average the day water level of a month as the level of that month.

For Cryosat-2 data, the process is basically the same as ENVISAT RA-2 except two different points. First, the tracks passing a lake aren’t fixed because of its shifting sub-cycles. Second, the Cryosat-2 GDRs provide geodetic height of points that have been corrected. So, lake level could be obtained by subtracting the Geoid from the given geodetic height.

Finally, combine the water level results derived from the two altimetry datasets to obtain water level time series of each lake from 2002 to 2015. Elevation system conversion is needn’t in this study, because both the datasets use WGS84 & EGM96 reference system. To remove the remaining bias between them, we calculate the mean difference between them within the same time period. Then transform Cryosat-2 to the level of ENVISAT RA-2 by adding the difference.

4. Results

This study analyzed the characteristics of seasonal and inter-annual water level variations of 11 lakes in Central Asia. The results (Fig.2) show that they all have obvious seasonal changes of water level in a year with a high peak. Balkhash Lake has a relatively early water level high peak in about March, while Issyk Lake reaches the peak in September. Others have the maximum water level during May to July.
We obtained the seasonal water level variations by calculating the mean difference between annual maximum and minimum value of water level (Fig.3). Zaysan Lake and Kapshagay Reservoir have the largest seasonal water level change, which is more than 1.2 meter, while Issyk Lake is only about 0.5 meter.

The mean temporal trends of lake level were calculated by a simple linear regression (Table.1). They show that Lake level generally decreases except three closed lakes among them: Sarygamshy Lake, Alakol Lake and North Aral Sea. Southeast Aral Sea and Southwest Aral Sea have the most
significant continuing dropping change with high $R^2$ of 0.906 and 0.969 and the mean trend of -0.245 m/a and -0.450 m/a respectively.

Table 1. Statistics of lake level change information derived from ENVISAT RA-2 and Cryosat-2 Altimetry data

| Lake name          | Longitude (°) | Latitude (°) | Start date (yyyymmdd) | End date (yyyymmdd) | Observation days | Trend (m/a) | $R^2$   | Types of lake |
|--------------------|---------------|--------------|------------------------|---------------------|------------------|------------|--------|--------------|
| Issyk Lake         | 77.3          | 42.4         | 20020714               | 20151227            | 687              | -0.014     | 0.267  | Alpine       |
| Sarygamysh Lake    | 57.4          | 41.9         | 20020616               | 20151208            | 315              | 0.111      | 0.389  | Closed       |
| Balkhash Lake      | 76.6          | 46.6         | 20020524               | 20151229            | 1825             | -0.003     | 0.004  | Closed       |
| Alakol Lake        | 81.7          | 46.1         | 20020612               | 20151208            | 258              | 0.025      | 0.149  | Closed       |
| Zaysan Lake        | 83.9          | 48.1         | 20020731               | 20151215            | 547              | -0.02      | 0.006  | Closed       |
| North Aral Sea     | 60.6          | 46.5         | 20020727               | 20160221            | 367              | 0.091      | 0.538  | Closed       |
| Southeast Aral Sea | 59.7          | 45.1         | 20020626               | 20160225            | 401              | -0.245     | 0.906  | Closed       |
| Southwest Aral Sea | 58.5          | 45.2         | 20020525               | 20160227            | 362              | -0.45      | 0.969  | Closed       |
| Kapsagay Reservoir | 77.5          | 43.8         | 20020711               | 20151218            | 325              | -0.087     | 0.333  | Open         |
| Sasyqolk Lake      | 80.9          | 46.5         | 20020615               | 20151122            | 253              | -0.059     | 0.501  | Open         |
| Aydar Lake         | 66.8          | 40.9         | 20020526               | 20151222            | 558              | -0.074     | 0.195  | Open         |

These 11 lakes are categorized into three types according to the type of basin and the source of the water supply: Alpine Lake, Closed Lake and Open Lake. As an alpine lake, Issyk Lake is the most stable one with the minimal seasonal and inter-annual water level changes. For the closed lakes, Balkhash Lake and Alakol Lake have a small change in general while they aren’t as stable as alpine lakes. Alakol Lake’s water level apparently increases in Month 2010. The water level of North Aral Sea and Sarygamysh Lake are rising, while Southeast Aral Sea and Southwest Aral Sea are dropping. North Aral Sea is tending towards stability after rising in 2006. Open lakes in arid region of Central Asia are decreasing generally. Their water levels changed most violently during 2002 – 2015, such as Kapsagay Reservoir, Zaysan Lake and Aydar Lake. Moreover, the water levels of open lakes in this area also have greater seasonal changes than others.

5. Conclusions
Monitoring water level using satellite altimeter, especially in a large scale and remote regions, is really meaningful. Water level time series of 11 main lakes in the arid region of Central Asia from 2002 – 2015 were derived from ENVISAT RA-2 and Cryosat-2 GDRs. The results show that:

(1) These 11 lakes all have obvious seasonal changes of water level in a year with a high peak at different month.
These lakes’ water levels show decreased trend generally except Sarygamysh Lake, Alakol Lake and North Aral Sea.

The alpine lakes are most stables, while open lakes’ levels change most violently and closed lakes change diversely among different lakes.

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