The Lake-level Changes in Central Asia during the Last 1000 Years Based on Historical Map

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Keyword: lake-level changes, historical map, proxy data, Central Asia

Abstract

To clarify the environmental changes in Central Asia during the past few hundred years, lake levels of three lakes, Aral Sea, Lake Issyk-Kul, and Lake Balkhash in Central Asia were reconstructed by several historical maps and SRTM DEM data. These historical maps in 17^{th}-19^{th} century were described in English, Russian, Mongolian, Manchu, and Chinese languages during Qing Dynasty for acquiring information of landscape (land, culture, and living of local people) in western country. Historical maps show lake-levels of Lake Issyk-Kul increased 14m from the present during 17^{th}−mid-19^{th} century, because lake water had overflowed to Chu river on the historical maps. These maps show three lakes, which have the same water sources in the Pamirs and Tien Shan mountains, expanded in 17^{th}-19^{th} century on the same timing. As the previous studies, Aral Sea experienced the drastic decline of the lake-level in the 12^{th}-13^{th} century, and the old settlements around Lake Issyk-Kul in the 10^{th}-12^{th} century have sunk under present lake level. According to several proxy data such as summer temperature from tree-rings, snow accumulation from ice-cores, glacier variations,

soil development, and historical documents, these lake-level decline occurred in 12th-13th under a long dry condition, and the increase of lake-level in 17th-mid-19th century under cold/wet condition in the Little Ice Age. However, drastic and large-scale decline of the Aral Sea might be related with water use of irrigation system in the 7th-12th century around Syr Darya and Amu Darya or flow change of Amu Darya to Uzboi to the Caspian Sea, including contribution of water use from Syr Darya as show in previous studies. These facts highlight the significant environmental changes that have occurred in the past millennium in Central Asia.

1. Introduction

Environmental changes in the Central Asia during the last 1000 years progress to understand by several proxy data such as lake sediments of the Aral Sea since AD2000s. Lake-level of the Aral Sea, which has shrunk since the 1960s due to large-scale irrigation projects for spread cotton fields, had also declined significantly in 12th-13th century (Sorrel *et al*., 2006; Oberhänsli *et al*., 2007; Boroffka *et al*., 2010). The drastic decline and lake-level changes during the last 2000 years were clarified by the lake terraces and analysis of lake sediments taken from the dried-up lake bottom (Oberhänsli *et al*., 2007; Sorrel *et al*., 2007; Boomer *et al*., 2009). In the dried-up lake bottom, human activities such as settlements and pottery also are confirmed (Boroffka *et al*., 2005; 2006). On the other hand, historical map on the mid-19th century shows that the Aral Sea expanded, compare with the present lake area (Kostianov *et al*., 2003; Reinhardt *et al*., 2008). Drastic shrinkage in 12th-13th century and expansion in the mid-19th century suggests large environmental changes might occur in Central Asia. In this study, we approached three lake-level changes of Aral Sea, Lake Issyk-Kul, and Lake Balkhash in Central Asia during the last 1000 years using the historical maps, and discussed about relationship with lake-level changes and climate conditions by several proxy data such as tree-rings, ice-core, glacier variations, soil development, lake sediments and historical documents.

We have several following issues. 1) Were timing in lake-level changes of the Aral Sea the same as Lake Issyk-Kul and Lake Balkhash during the last 1000 years? 2) How was climate condition under large lake-level changes in Central Asia (ex. 12th-13th and mid-19th century)? There are several reports on historical interpretation of climate change using several proxy data such as ice-cores, tree-rings, lake sediments (Solomina and Alverson, 2004; Yang *et al*., 2007; Yang *et al*., 2009).

2. Study area

The study areas are three lakes, Aral Sea (64,500 km^2), Lake Issyk-Kul (6,300km^2), Lake Balkhash (18,200 km^2) in arid and semi-arid region of the Central Asia (Figs. 1, 2). The water resources of these lakes are located at the Tien Shan and Pamirs, which a product of India-Eurasia plate convergence by distributed depormation (Burbank *et al*.,

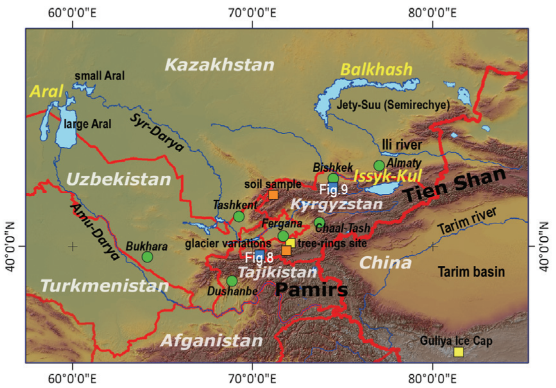

Fig.1. Study area of Central Asia.
Three large lakes, Aral Sea, Lake Issyk-Kul, Lake Balkhash have the same water resources of Tien Shan and Pamirs. Green circle: town, yellow square: Guliya Ice Cap and tree-rings sampling site, blue square: glacier variations, orange square: buried soil development in the glacier landforms.

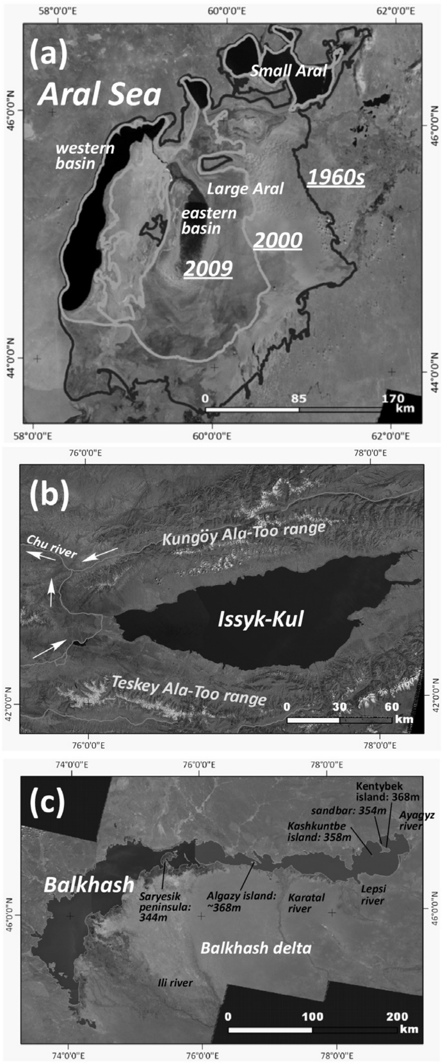

Fig. 2. Three lakes, (a) Aral Sea, (b) Lake Issyk-Kul, (c) Lake Balkhash in Central Asia.
Aral Sea has shrank since 1960s due to human impact such as irrigation system. Aral Sea and Lake Balkhash are shallow, and Lake Issyk-Kul has deep basin.

1999; Thompson *et al*., 2002). Tien Shan of the shortening rate 20mm/year (Abdrakhmatov *et al*., 2001), consist of many ranges in 4,000-5,000m asl, which runs from west to east. Pamirs is the mountainous area which lined with Karakoram, Gissar-Aray, Kunlun, and Hindu-Kush mountains. The western-central parts of the Pamirs have 6000-7000m elevations with deep valleys and steep-high peak, eastern part is plateau landforms. Many mountain glaciers are distributed in two mountain regions. Snow and glacier meltwater in these mountain parts is transported to oasis area through the river during spring/summer. However, recent mountain glaciers in the Tien Shan has shrank (Aizen, *et al*., 2006; Narama *et al*., 2006; Bolch, 2007; Kutuzov and Shahgedanova, 2009; Narama *et al*., 2010a). Its influence for river discharge is expected to be greater the western Tien Shan which has dry season during summer (Narama *et al*., 2010a), because glaciers contribute water discharge during summer of ablation season (Hagg *et al*., 2007; Narama *et al*., 2010b).

Climate environment in Central Asia has been determined by the interaction between the shifted westerly and the Siberian high that develop during the winter (Zavialov, 2005). The moisture is brought by the westerlies from the Atlantic and the Mediterranean Sea in spring, or from the Arctic Ocean in summer. Annual precipitation is strongly influenced by mountainous terrain, because moisture is blocked by outer mountain terrain (Western and Northern Tien Shan), inland mountain area (Inner and Central Tien Shan) has less precipitation (Aizen *et al*., 1995; Narama *et al*., 2010a). The lower plain parts which are distributed oasis town and agriculture field are dry condition (Bukhara: 167 mm; Fergana: 191mm). On the other hand, precipitation in mountain sites is higher (Fergana range: >1000 mm). Local people in the plains, has been used as domestic water supplied by water from the mountain sites. In Northern Tien Shan region, oasis and agriculture field developed along the foothills of the Tien Shan.

3. Method

3.1. Extraction of environment change using historical maps and SRTM DEM data

There are historical maps described Central Asia region in 17^{th}-19^{th} century (Kicengge, 2007; Nazarbaev, 2008; Kicengge, 2009). These maps were mainly created for investigation and exploration for new land, culture, and living of local people by Russia and the Qing Dynasty (China). The geographical names on the maps were written in English, Russian, Manchu, Mongolian, and Chinese languages. The historical maps include much information of landscape in 17^{th}-19^{th} century, such as lakes, islands in the lakes, rivers, towns, pasture, agriculture fields, and geographical names. We reconstructed lake-level of Aral Sea, Lake Issyk-Kul, and Lake Balkhash in 17^{th}-19^{th} century using historical maps and the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) data. The present shoreline in three lakes is shown by Corona in 1962 and Landsat 5 TM in 2009. Recent lake-level changes are shown by observational data (1960-2000) and ICESat satellite data (2003-2009). The satellite data was handled using PCI Geomatica 10.3 and data analysis was conducted with ArcGIS 9.3. The shoreline on the Aral Sea in the past has been reconstructed in several previous studies using SRTM DEM (ex. Reinhardt *et al*., 2008).

3.2. Proxy data replaced to climate changes in Central Asia

To discuss climate environment caused lake-level changes of three lakes in Central Asia, we used several proxy data, replaced to climate changes during the last 1000 years, such as tree-rings, lake-level changes, lake sediments, ice-cores, glacier variations, and historical documents. Summer temperature during the last 1000 years was reconstructed using ring width index of tree-rings in southern Kyrgyzstan (Esper *et al*., 2003) and average summer temperature (June to August) in Fergana Meteorological station (Fig. 1). As a proxy data for precipitation in the past, we used snow accumulation data from ice-core which taken at the Guliya Ice Cap in the Kunlun mountains, the western China (Thompson *et al*., 1995). We also referred to glacier variations which shown by ^{14}C dating in the Alay, Turkestan, and Kyrgyz Ala-Too ranges, Kyrgyzstan (Zech *et al*., 2000; Narama, 2002; Narama and Okuno, 2006; Narama *et al*., 2010b). In the western Tien Shan and Gissar-Alay regions, the ^{14}C ages of buried soils in the glacier lardforms shows it was warm period during glacier recession or stagnant (Savoskul and Solomina, 1996; Zech *et al*., 2000). In addition, historical document supports the climate events by writing about serious damages of livestock called as “жұт (Jyt)”, due to natural events under much snow and cold.

4. Result

4.1. Lake-level changes in the Central Asia during 17^{th}-19^{th} century

4.1.1 Lake-level changes in Aral Sea

The lake-level of the Aral Sea (66,000 km^2) was 53m asl in the early 1960s. The lake-level of large-Aral has declined till 43.5m in 1984, 40m in 1987, and 30.5m in 2002 by human influence (Fig. 2a; Reinhardt *et al*., 2008). ICESat satellite data recorded the lake level of the large-Aral since 2003, such as 31 m asl in 2003, 31 m in 2004, 31 m in 2005, 30 m in 2006, 29 m in 2007, 28 m in 2008, 27 m in 2009 (Fig. 3a). The changes of lake level in the eastern basin and western basin which Large Aral separated in 2005 were the same since 2003. At the present, the water balance of the blocked small-Aral has been maintained around 41-42 m by water from Syr Darya since 2003 (Fig. 3a). The lake-level changes of the Aral Sea have been analyzed in the last 2000 years by the lake terraces and lake sediments from dried-up lake bottom (Boomer *et al*., 2000; Oberhänsli *et al*., 2007; Sorrel *et al*., 2007). According to previous studies, the Aral Sea has drastically declined the lake-level around the 12^{th}-13^{th} century. At the period, the lake-level had declined till the lower 32m (Boroffka *et al*., 2006) or lower 30.47m at November 2002 (Reinhardt *et al*., 2008). These results show the drastic shrin-

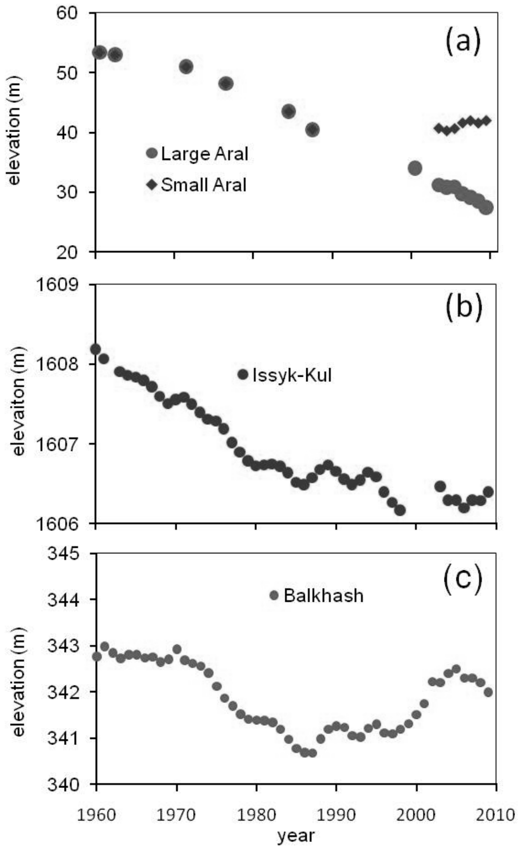

Fig. 3. The lake level of (a) Aral Sea, (b) Lake Issyk-Kul, (c) Lake Balkhash since 1960.
Large Aral has continued to decline the level at the present, and the level of Small Aral was maintained by Kokaral Dam since 2003.

described the lake in more detail were created around 1850s. Fig. 4 shows a historical map "Fragment karti kyrgyz-kaisakov; Maloi Ordi" in 1864 (Nazarbaev, 2008). In the south shoreline of Aral Sea, Tok-May-Atay island and Karaumbet Bay were drawn on the historical map. However, these landforms of the Aral Sea were not observed on Corona photographical image taken in 1st Aug 1962. To reconstruct the coastline in 1864, we investigated the shoreline of the Aral Sea in 54m asl, 55m, and 56m using SRTM DEM. The shoreline in 55m was coincided with that on the historical map in 1864 (Fig. 4). The lake-level 55m was the same level as the shoreline reconstructed using historical map in 1951 (Boroffka *et al.*, 2006; Reinhardt *et al.*, 2008). Only 2m-lake-level decline caused to kage on 12th-13th century was the same impact as current human activities since the 1960s. Although there are some reports that irrigation system developed in 7th-12th century (Oberhänsli *et al.*, 2007), the cause of the decline of the Aral Sea's surface is still unclear.

There are historical maps described the Aral Sea during 17th-19th century. However, it is difficult to compare with landscapes for older and present, because older maps around 17th-18th century show the lake shorelines and lake form are very different from the present. Historical maps

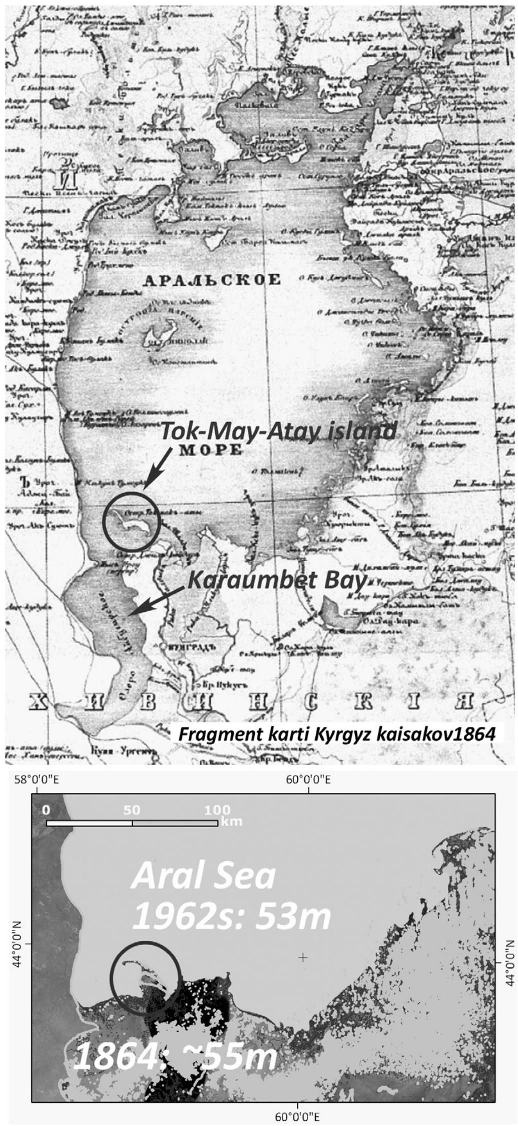

Fig. 4. Aral Sea of historical map in 1864 and lake shoreline in 55m asl using SRTM DEM data.

change the Aral Sea area largely, because the eastern part of the Aral Sea is shallow and spread gentle slope on the east shoreline. The historical maps and SRTM-DEM data showed the 2m lake-level increasing in the mid-19th century, comparing with these in the 1960s. Lake terraces and lake sediments shows the maximum lake elevation 54-55m during the Holocene (Reinhardt *et al.*, 2008), was the same as that in mid-19^{th} century.

4.1.2. Level changes of Lake Issyk-Kul (Ysyk-Köl)

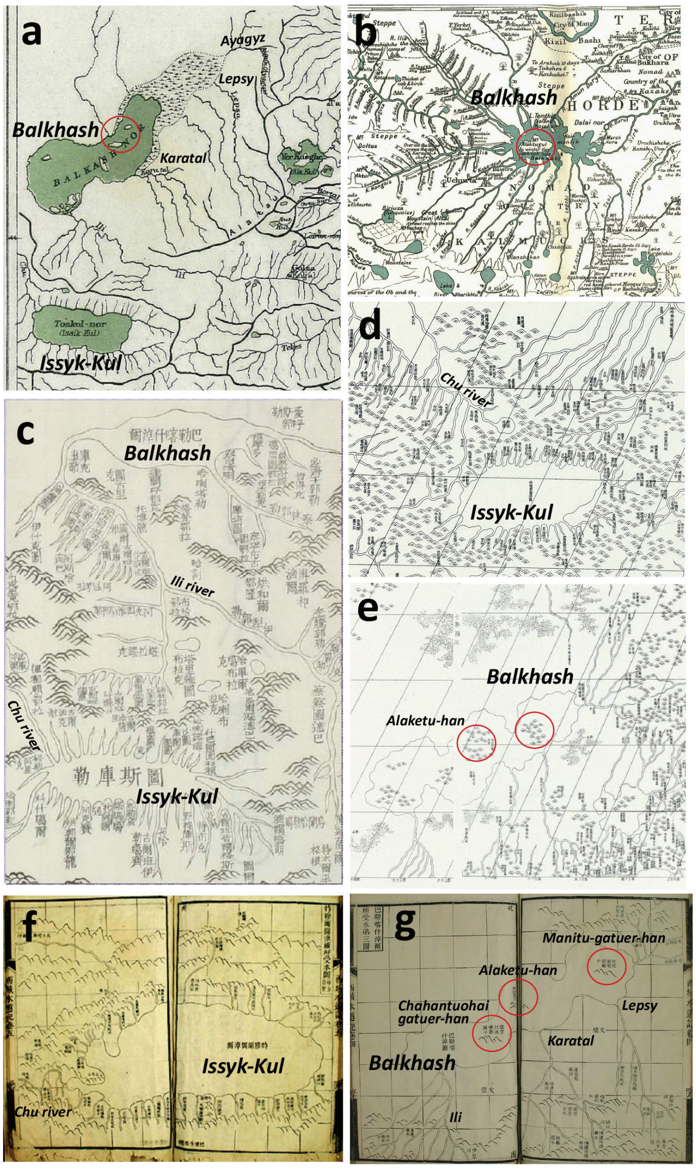

Fig. 5. Historical maps which described Lake Issyk-Kul and Lake Balkhash.
(a, b) "Map of all the waterless and difficult country of the mountain steppe" in AD1698, (c) "Qinding huangyu xiyu tuzhi [Imperially commissioned gazetteer of the western regions of the imperial domain] vol.1 in AD1756, (d, e) Lake Issyk-Kul of "Daqing yitong yutu [Comprehensive Qing period map]" was published in 1760, (f, g) "Xiyu shuidao ji [Waterways of the western regions]" vol. 1-5 was investigated in before AD1823.

Lake Issyk-Kul (6,300km^2, 1606m asl.; Ysyk-Köl in Kyrgyz language) located in the north-western Kyrgyzstan (Fig. 1), is compression basin between the Kungöy Ala-Too and Teskey Ala-Too ranges (Fig. 2b; Bowman *et al.*, 2004). Average depth of the lake is 278m (maximum depth: 668m), the water volume is about twice that of the Aral Sea. Chu river, which has origin in Naryn and Kyrgyz Ala-Too ranges, changes direction from north to west (the Chu plain) at the turning point (Kutemaldinsky threshold) near Lake Issyk-Kul. This river disconnects to the Lake Issyk-Kul (Fig. 2b). The lake level decreased in 1927-2000 and increased since 2000 (Fig. 3b; Romanovsky, 2002). ICESat satellite data in 2003-2009 shows the current lake-level of the Lake Issyk-Kul is 1606m asl. Turning point (Kutemaldinsky threshold) of the Chu river near Lake Issyk-Kul is 1620m asl, and vertical elevation is 14m difference between the present level and turning point. A distance from lake-shoreline to the turning point is 6km separately (Ferronskii *et al.*, 2003).

Fig. 5 shows historical maps described the Lake Issyk-Kul and Lake Balkhash in 17^{th}-19^{th} century.

Lake Issyk-Kul was written as "Salty Lake" or "Large and beautiful Lake" or "Hot Lake" such as the meaning of Ysyk-Köl (Ysyk: hot; Köl: lake) in Kyrgyz language (=Issyk-Kul in Russian) on 7th century in the historical document (*Da tang xiyu ji* [*An notated edition of accounts of the western lands during the great Tang*] by Xuan zang (602-664)). The introduction of the historical maps is the following. Figs. 5a, b show "*Map of all the waterless and difficult country of the mountain steppe*". The map of Fig. 5a was investigated in AD1698 by Lemezov, who was ordered about information of Central Asia (Jungar territory) by the Emperor of Russia. He researched territory, lord, pasture and agriculture fields, town, river, lake, mountain, and desert. The range of research area is from Kingdom of Altin (east) to Aral Sea (west), from Zaisan Nor (north) to Hiva (south). Lake Issyk-Kul was written as Tosköl Nor (Toskol: salt lake in ancient Turkish language; Nor: lake in Mongol). Fig. 5c shows that "*Qinding huangyu xiyu tuzhi* [*Imperially commissioned gazetteer of the western regions of the imperial domain*] vol.1 was investigated in AD1756 by Chu tingzhng. In Daichin Gurung period (1616-1911), the purpose of this map is to understand all aspects of new western country and some group, which have different lifestyle and livelihood. The maps consist of 33 maps including mountain, river, and territory in the western region of Daichin Gurung. Lake Issyk-Kul was called as Tusi Kule (salt lake) in writing of Chinese for ancient Turkish name. "*Daqing yitong yutu* [*Comprehensive Qing period map*]" was created in 1760 by Michel Beniost (Figs. 5d, e). The area of the map is from Arctic to Indian Sea, Borody Sea to East Sea. Lake Issyk-Kul was named as Temurtu nor (Lake of Iron) in writing of Manchu for Mongolian name. "*Xiyu shuidao ji* [*Waterways of the western regions*]" vol. 1-5 was investigated in before AD1823 by Xu song (Figs. 5f, g). This map was also named as Temurtu Noor (Lake of Iron) in writing of Manchu for Mongolian name. To understand new country and land as national project, Xu song investigated river system in this region for making this map. According to the report of *Xiyu shuidao ji* [*Waterways of the western regions*], the Temurutu Noor has many fishes and this area is popular with production of iron. Many domestic fowls, livestock like sheep and cow live on the good grass fields, and agriculture field spread around Lake Issky-Kul. Thus, after Mongol invasion, the name of Lake Issyk-Kul has been changed by situation of country and the ruler. Each new country was appearance, mapping and geographical names has been repeatedly remade as national project to understand new land territory. Recently, this lake has been called as Lake Issyk-Kul in Russian or Ysyk-Köl (Ysyk: warm; Köl: lake) in Kyrgyz language.

Lake Issyk-Kul described on these historic maps in 17th-19th centuries clearly has the discharge from the lake (Fig. 5). The discharge joined to the Chu river at the Kutemaldinsky threshold (1620m asl). In the case of the connection with Chu river, the lake-level of the Issyk-Kul rose by 14m (Fig. 6a). Historical maps show the lake-level during 1698-1829 was higher than the present and maintained 1620m asl. Fig. 6a shows the area change at the Issyk-Kul at the lake-level 1620m asl. The lake area does not change largely by slight lake-level rising such as Aral Sea and Lake Balkhash, because the depression basin type has been surrounded by steep mountains such as the Kungöy Ala-Too and Teskey Ala-Too ranges. The decline lake-level (1600m asl) in 15th and rising (1620m asl) in mid-19th century were also reported by ^{14}C age of lake terraces around the lake (personal communication by C. Ormukov; Romanovsky and Rasmussen, 2007). According to historical documents, the lake was close without discharge in 16th and 19th century (Romanovsky, 2002). As a result, the lake level was lower in 15th-16th century, and higher till 1620m asl during 17th-mid-19th century, after that lower again since mid-19th century. The lake-level declined 10m since 1876, 2.64m in 1927-early-1990's, increased 1.3m in 1910-1928 (Kostianov *et al.*, 2003; Giralt, *et al.*, 2004).

Sevastuanov (1991) reported the separation between the Chu river and Issyk-Kul was caused by tectonic movement during the late Pleistocene. The separation might be occurred by the tectonic movement in the past. However, the large lake-level changes for several hundred years (short period) are influenced by climate change. Koy-Sary settlement in the east part of Issyk-Kul on 10^{th}-12^{th} centuries existed until the end of the 15^{th} century or the early-16^{th} century after Mongol invasion. Tossor settlement at the southern shoreline of the Issyk-Kul has existed in 12^{th} century (Romanovsky, 2002). At the present, the two settlements had sunk by increase of the lake-level and the settlements is located below 3-6m of the current lake-level (Shnitnikov, 1979). In addition, the lake sediments show the lake level was decline during AD1180-1308, when moisture index was lower (Giralt *et al.*, 2004). These facts show the lake level of the Issyk-Kul was lower than the current level during 10-14^{th} century and the lake-level increased after 15^{th}-16^{th} century as shown by historical maps. The water discharge resulted by increased lake-level in 17^{th}-19^{th} centuries. The relationship between the lake-level and river discharge is high (Romanovsky, 2002), the change of lake-level in the past might be caused by climate change.

4.1.3. Level changes of Lake Balkhash

Lake Balkhash (18,200 km^2) located in southeastern Kazakhstan is an inland lake, which collected water in northern margin of the Balkhash delta (Figs. 1, 2c). Average depth of the lake is 5.8m shallow (maximum depth: 26.5m). Average depth is 4.6m in west part of the Saryesik peninsula and 7.6m in east part (Kostianov *et al*., 2003). Present lake-level is 342m asl. Balkhash means "width" in Mongolian language, indicating that collect many rivers. Ili river, which has origins from Tien Shan and Jungar Ala-Too range occupies 80% of inflow water into Lake Balkhash. Seven rivers such as Lepsi, Karatal and Ak-Su rivers flow to the lake. The region was called as Semirechye (seven rivers) in Russian since the 1840s, or Jety-Su in Kazakh, known as a good pasture and agriculture fields, and central region of pasture culture of central Eurasia. The lake level of Balkhash has changed in 2.3m range since 1960 (Fig. 3c).

Lake Balkhash was drawn on many historical maps as shown in Lake Issyk-Kul. We also recognize some characteristics of landforms in the Lake Balkhash on the historical maps during 17^{th}-19^{th} century (Figs. 5a, 5b, 5e, 5g). In "*Map of all the waterless and difficult country of the mountain steppe*" investigated in AD1698 and "*Xiyu shuidao ji* [*Waterways of the western regions*]" vol. 1-5 in before AD1823, the islands and its names are drawn on the historical maps. As written on historical maps in Fig.5b, local people caught fish in the island in winter. The island in the central part drawn on historical maps named as "Alaktugul or Alakehan". Present Algazy island (13.2km^2) is located at the same location and its name is similar to that on historical maps (Fig. 2c). In documents of "*Xiyu shuidao ji* [*Waterways of the western regions*]" vol. 1-5 (Fig. 5g), there are three lakes in the lake. These names are Chahantuohai gatuerhan in western part, Alakehan in central part, and Manitu gatuerhan in eastern part. There is a sandbar island Kentybek in the eastern part, connected to land. On the document, Manitu gatuerhan was located at the point which Lepsi river and Aytansu river (Ayagyz river?) inflow to the lake, Kentybek is the same location as Manitu gatuerhan. However, the highest point of the sandbar formed between the Ketybek island and land is 354.5m asl. In the case of separated Kentybek island as shown in the historical maps, lake-level needs to rise by ~13m (current lake-level of Balkhash: 342m). Lake Balkhash is three times area of Lake Issyk-Kul. In the case of the level rise ~13m, it is not clear that a significant increase in flow occurred or not in this period. The historical maps since mid-19th century show Kentybek island remains connect to the land. It is difficult to estimate that the lake level has increased ~13m during the 17th-19th centuries. On the other hand, Saryesik peninsula (highest point: 344.2 m) was not shown on the historical map during 17th-19th centuries (Figs. 2c, 6b). The lake-level of Lake Balkhash rise several meter (2~3m) during end-17th-19th century. As shown that a reconstructed shoreline of lake-level in 345m asl using SRTM DEM data, the lake area spread to south direction significantly (Fig. 6b). The area 23,464km^2 and 344.1m asl. in 1910 changed to 15,730km^2 and 340.7m in 1946 by lake-level decreasing of 3.5m (Aubekerov *et al*., 2003). As the large area-change shown in Aral Sea due to slight lake-level change, Balkhash lake, which has spread land (delta) with gentle slope, also changed the area largely (Fig. 6b). As a result, the lake-level of the Aral Sea, Lake Issyk-kul, and Lake Balkhash which has the same water resources in the Tien Shan and Pamirs, had increased in 17th-19th century.

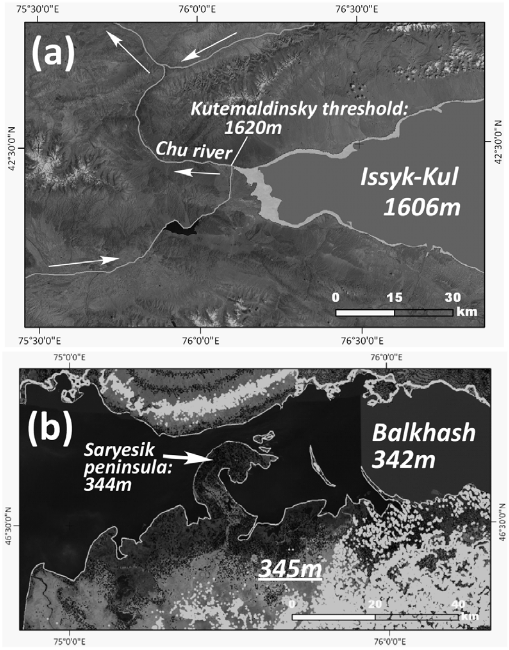

Fig. 6. (a) The area changes of Lake Issyk-Kul with lake-level in 1620m asl., (b) The area changes of Lake Balkhash with lake-level in 345m.

5. Discussion

5.1 Climate changes related with lake-level changes in Central Asia

The historical maps showed the lake-levels of the Aral Sea, Lake Issyk-Kul, and Lake Balkhash increased during 17th-19th. On the other hand, the lake-level of Aral Sea declined on 12th-13th century and that of Lake Issyk-Kul on 10th-14th century. These results show three lakes which have a water source in the Pamirs and Tien Shan, have been changes at the same timing. We discuss about the cause of lake-level change using proxy data replaced to climate change in Central Asia.

Fig. 7 shows several proxy data in Central Asia during the last 1000 years, (a) Summer temperature in Fergana reconstructed using tree rings index, (b) Snow accumulation reconstructed using ice-core of Guliya Ice Cap in the Kunlun mountain, (c) lake-level changes from historical maps and lake terraces of Lake Issyk-Kul, (d) Salinity data from lake sediments of the Aral Sea, (e) glacier changes and soil development in the Pamir-Alay and Tien Shan. Summer temperature in Fergana was reconstructed by the normalized data of ring width from tree-rings, which taken in the Alay range in southern Kyrgyzstan (Esper *et al*., 2002; 2003), and by summer temperatures (June, July, August) of the Fergana Meteorological station (1883-1998) near the sampling sites. *Juniper* sp. of tree-ring samples collected shows high correlation between ring width and summer temperature (Solomina, 1996; Esper *et al*., 2003). The temperature shows the clearly lower phase between AD mid-1400 and mid-1800 during the Little Ice Age. Tree-rings data shows coldest time was around AD1650 during the Little Ice Age (Esper *et al*., 2002). Before the Little Ice Age, summer temperature repeated to change largely during AD1000-AD1500. Medieval Warm Period (Optimal Warm Anomaly) is not clear in this data. Mann *et al*., (2009) shows that Medieval Warm Period (AD

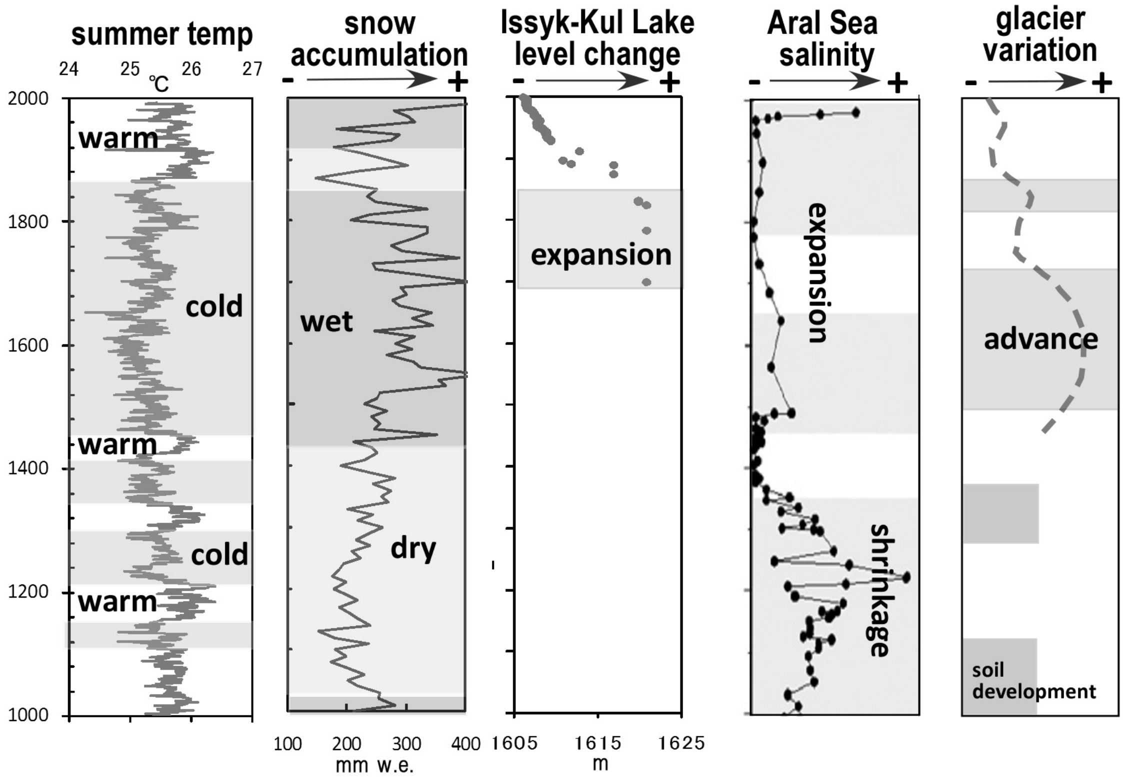

Fig. 7. Proxy data of Central Asia. (a) Fergana summer temperature, (b) snow accumulation from Guliya Ice Cap, (c) lake-level changes of Lake Issyk-Kul, (d) salinity data of Aral Sea, (d) glacier variations, including soil development in glacier landforms.

950-1250) was clear in the North Atlantic, southern Greenland, and not clear in parts of North America and northwestern Central Eurasia and North America, the tropical Pacific Ocean, related with a localized phenomenon. The climate data reconstructed from lake sediments of Aral Sea is also unclear for the Medieval Warm Period.

As proxy data of precipitation in Central Asia, we used snow accumulation reconstructed from ice-cores of the Guliya Ice Cap in the Kunlun mountain (Thompson *et al*., 1995). The data has high correlation with precipitation data from tree-rings data in upper part of the Ili river and the eastern Tien Shan region (Bao *et al*., 2006), indicating that significantly affected by the Westerlies. On the other hand, precipitation in the southern Tibet influenced by Indian Monsoon is very low correlation. Snow accumulation in AD1000-1500 was relatively lower, and increased in the Little Ice Age. Considering with temperature data, AD1000-1500 was repeated cold/warm under dry condition in this region, and the Little Ice Age was cold/humid environment. The cold/wet condition during the Little Ice Age was also reported by pollen analysis of Bosten lake sediments in the northern Taklimakan of northwest China (Chen *et al*., 2006).

Fig. 7 shows glacier chronology in Central Asia during the last 1000 years. Many glaciers in the Tien Shan region advanced during the Little Ice Age (Solomina, 2000). We suggest two main glacier advance stages during the Little Ice Age. In the Turkestan range of the Gissar-Alay region, the oldest and outside moraines during the Little Ice Age include many trees which fallen by moraine deposits at the glacier advance. ^{14}C ages of these fallen trees shows the maximum glacier advances occurred during 15-17th centuries in this region (Figs. 1, 8; Narama, 2002; Narama and Okuno, 2006). In the Ak-Say glacier front in the Ala-Archa valley, Kyrgyz Ala-Too range, two distinct moraines was formed during the Little Ice Age (Figs. 1, 9). The two moraines, which consist of fresh debris, could be classified with two glacier advance stages I and II. A calibrated ^{14}C age (OxCal4.1) of radiocarbon (^{14}C) dating for plant fossil from stage II moraine shows glacier in second stage occurred in AD1833-1880 (PLD-14664), respectively (Narama *et al*., 2010b). The result is supported by the relative age (AD1845-1865) on the stage II moraine by lichenometory (Solomina *et al*., 1994). Although many glacier advances around mid-19th century have been identified in the European Alps (Grove, 1988), maximum glacier expansions in Central Asia occurred 15-17th centuries during the Little Ice Age (Fig. 10; Solomina, 2005; Narama, 2002; Narama and Okuno, 2006). Glacier advances in stage II (mid-19 century) were smaller. As shown in temperature variations, glacier expanded at more colder/humid condition during the first half of the Little Ice Age.

There are no reports about glacier advances in AD1000-1500 by absolute dating. However, soil developments were observed at

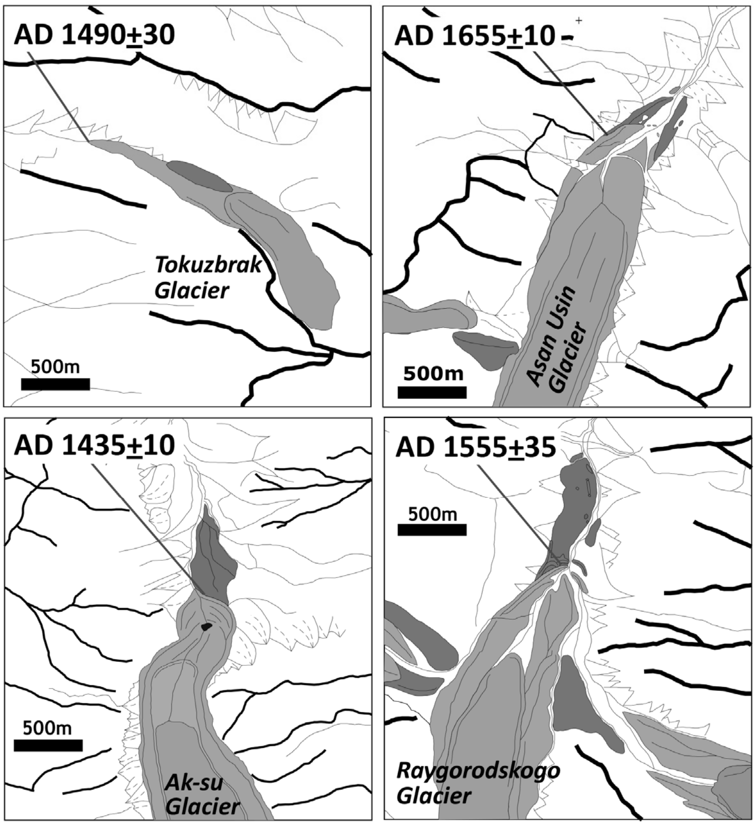

Fig. 8 Glacier advances in Turkestan range during the Little Ice Age. The maximum of glaciers advances occurred in 15th-17th century in Gissar-Alay region.

Fig. 9. The second advance stage of Ak-Say glacier, Kyrgyz Ala-Too

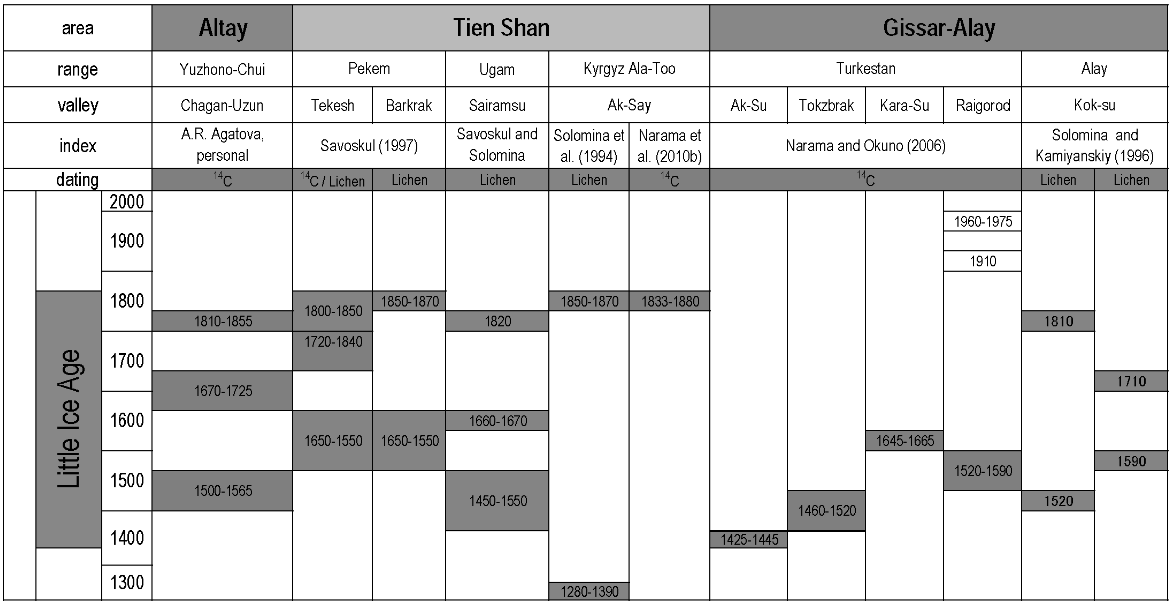

Fig. 10. Glacier advance stages in Altay, Tien Shan, and Gissar-Alay during the Little Ice Age.

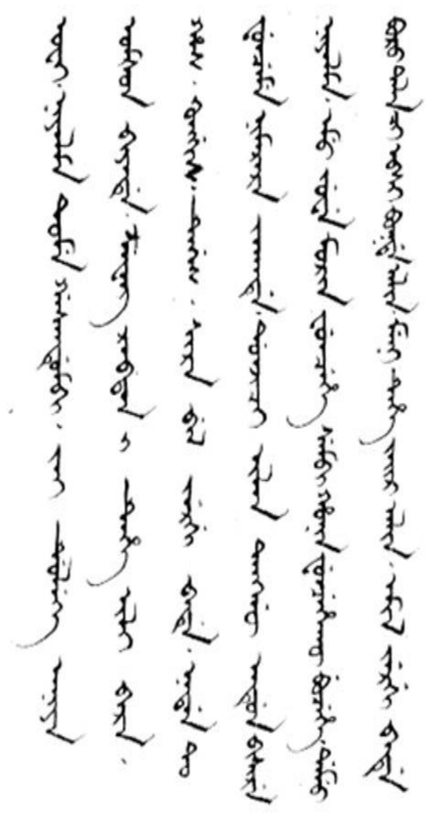

Fig. 11. "Manchu memorials of the Kangxi reign (Kangxichao manwen zhupi zouzhe)" in 1715.
Lower temperature and heavy snow events in 17th-19th century are shown in historical documents.

the moraine outcrops and riverbed at the glacier front in several mountain regions (Fig. 1). The buried soil in the lateral moraine in the Alay range, Gissar-Alay was formed in AD920-1160. This age shows the Abramov glacier was stagnant or shrinking under warm climate condition (Zech *et al.*, 2000). In Pskem and Ugam ranges in the western Tien Shan, the ^{14}C ages of the buried soil at riverbed of glacier front were AD935-1109, AD969-1023, AD1289-1383 (Savoskul and Solomina, 1996; Solomina, 1996). These ages of soil development are coincided the warm climate period on summer temperature variations of tree-rings, and glaciers might be smaller than the present area in this time (Solomina, 1996).

Historical documents in 17th-19th century were written about serious damages of livestock due to heavy snow and cold condition called as "жұт (Jyt)" in Kazakhstan. According to "Manchu memorials of the Kangxi reign (Kangxichao manwen zhupi zouzhe)" in 1715, it was snow 105cm in November 1714 and only two horses among 300 domestic animals remained around Ili river of the southern part of Kazakhstan (Fig. 11). The heavy snow in 1766 caused large livestock deaths and many emigrants from Kazakhstan to Chinese territory. Cold and wet conditions during the Little Ice Age often led to serious damage of livestock under lower temperature or heavy snow.

5.2 The lake-level changes under climate condition

Aral Sea and Lake Balkhash were expanded the area largely with slight lake-level increase. On the other hand, the change of lake area in Lake Issyk-kul was small due to lake-level change, because Lake Issyk-Kul was depression basin by uplifted Teskey Ala-Too and Kungöy Ala-Too ranges. Historical maps showed the lake-level increased during 17th-19th century in Aral Sea, Lake Issyk-Kul, and Lake Balkhash. According to previous studies, the lake-level of Aral Sea declined in 12th-13th century and that of Isskyk-Kul also declined in 10th-14th century. Three lakes, which have the same water resources in the Pamir and Tien Shan might change at the same timing. According to several proxy data, lake-level rising in the 17th-19th century occurred under cold/wet condition during the Little Ice Age. Historical documents around 1782 also show Rope-Noor in Tarim basin expanded in this period (Chen *et al.*, 2006). Other lakes in Central Asia were also reported about lake-level rising during this period (Solomina and Alverson, 2004). Nam lake of central Tibet has also expanded AD1600-1800 during the Little Ice Age (Wrozyna *et al.*, 2009). Lake evaporation was lower and glacier melt-water also decreased significantly under cold period. Changes in lake-level of Lake Issyk-Kul correlated with the inflow from rivers (Romanovsky, 2002), the change of precipitation might cause increase of the lake-level. Giralt *et al.*, (2001) also estimated the repeated lake-level rising occurred under wet condition using lake sediments.

On the other hand, the lake-level decline of the Aral Sea in the 12th-13th century and that of Isskyk-Kul also declined in 10th-14th century might be caused under a long dry condition, because lower snow accumulation in Guliya Ice Cap and high salinity condition of Aral sediment had continued in 11th-13th century. The lake-level decline on the 12th-13th century was caused by the decrease in inflow under the long arid condition and decreasing temperature, including decrease of glacier melt-water and lower evaporation. The impact of glacier meltwater might be not significant on the lake-water balance. However, the level decline of the Aral Sea was quiet drastic and large-scale, compare with Lake Issyk-Kul. There are some reports that the large lake-level decline on the 12th-13th century caused by the development of irrigation system in the 7th-12th century around Syr Darya and Amu Darya related with human impact or water flow changes to Uzboi to the Caspian Sea, including contribution of water use from Syr Darya (Oberhänsli *et al.*, 2007; Boroffka *et al.*, 2010). It is difficult to estimate that the same impact of current human activity occurred on the 12th-13th century under climate change. Water flow of Amy Darya changed from Aral Sea to Caspian Sea during the Holocene (Ferronskii *et al.*, 2003; Boroffka, 2010), the flow change might be related to the decline of lake level during 12th-13th century.

6. Conclusion

Aral Sea, Lake Issyk-Kul, and Lake Balkhash caused lake-level rising in 17th-19th century. The Aral Sea had experienced a rapid decrease of lake-level in the 12th-13th century. The settlements which had developed in 10th-12th century around Lake Issyk-Kul had sunk under present lake-level. Thus, the lake-level in Central Asian lakes might change in the same timing during the last 1000 years. The decline of the lake-level caused under a long dry condition in 12th-13th century, and the increase of lake-level caused under cold/wet condition in 17^{th}-mid-19^{th} century. Precipitation might mainly lead to change lake water balance. However, the drastic level decline of the Aral Sea might be caused by human impact such as irrigation system or water flow changes to Caspian Sea as shown in previous studies. In this study, we used the historical maps in 17^{th}-19^{th} century which described for investigation by Qing Dynasty and European explorers. These maps include information on geographical information such as mountains, rivers, lakes, and human activities (town, pasture land, and agriculture field) at that period. Using these multiple historical maps, we can extract much information about environmental changes in the past and present different views.

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