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Correlation Analysis of NINO3.4 SST and Inland Lake Level Variations Monitored with Satellite Altimetry: Case Studies of Lakes Hongze, Khanka, La-ang, Ulungur, Issyk-kul and Baikal

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ABSTRACT

Climate change can sometimes be reflected in variations in lake levels, thus understanding variations in lake levels and their relationship to climate change plays an important role in studying climate change. In this study, about 10 years of Topex/Poseidon (T/P) altimetric data and 6 years of Jason-1 data were used to compute time series of level variations of six lakes in the Central and East Asia. The study sites were Hongze, La-ang, Ulungur, Khanka, Issyk-kul and Baikal Lakes. Time series of level variations were analyzed by means of the wavelet spectrum for inter-annual (between 2 to 4 years), annual and semi-annual signals. Since 2000, water level variations of Issyk-kul, Ulungur and Khanka lakes were larger than those of Baikal and Hongze. Correlations between the NINO3.4 sea surface temperature (SST) and the level variations of the six lakes were analyzed. For Baikal and Khanka Lakes, the correlations were significant (+0.3834 and +0.3334) for 3 - 5 months after the occurrence of ENSO, while the correlation for La-ang Lake was the weakest (< 0.1), indicating that ENSO showed a lag influence on variation in lake levels in the Central and East Asia.

Key words: Topex/Poseidon, Jason-1, Lake level variation, NINO3.4 SST, ENSO

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1. INTRODUCTION

As an Earth observation technique from space with characteristics such as all-weather, high-precision, and large-scale operation, satellite altimetry can not only provide abundant oceanic information with high spatial and temporal resolution (Wang et al. 1995; Guo et al. 2010a), but also monitor variations in levels of inland waters (Fu and Cazenave 2001). Many studies have utilized satellite altimetry technique to monitor the water storage variations. For example, level variations of 24 global lakes were monitored with Topex/Posidon (T/P) altimetry (Birkett 1995), as well as the water variations of Amazon Basin (de Oliver Campos et al. 2001). These studies indicate the feasibility of monitoring the variations in inland water levels using satellite altimetry. T/P altimetric data have also been used to study the correlation between the climate and variations in water levels of 3 African lakes and 3 North American lakes (Ponchaut and Cazenave 1998), and the correlation between the climate over the Indian Ocean and variations in water levels of 12 African lakes (Mercier et al. 2002). These kinds of studies also connect climate change with changes in inland water storage. However, because data in these studies only covered a few years, long-term change and correlation between variations in lake levels and climate change cannot be interpreted. In addition, some water resources in China have also been studied using satellite altimetry (Peng 2004; Hwang et al. 2005; Li et al. 2007; Gao et al. 2008; Guo et al. 2009, 2010b). However, the relationship between variations in inland lake levels and El Niño-Southern Oscillation (ENSO) phenomenon has not been thoroughly analyzed.

ENSO often occurs in the atmosphere and the tropical Pacific Ocean. It is manifested in the atmosphere by a

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pressure difference between Tahiti and Darwin, Australia, and in the ocean by warming or cooling of surface waters of tropical central and eastern Pacific Ocean (Trenberth and Hoar 1996; Trenberth 1997). ENSO is associated with floods, droughts and other weather disturbances in many regions in the world. In this study, we studied variations in lake levels of six lakes in Central and East Asia, Lakes Hongze, Khanka, La-ang, Issyk-kul, Ulungur, and Baikal (Fig. 1). Approximately 10 years of T/P altimetric data and 6 years of Jason-1 data were used for this study. The study was focused on the relationship with ENSO and is of importance for understanding water resources and patterns in water vapor in the Central and East Asia.

2. LAKE LEVEL ALTIMETRY DATA

The geophysical data record (GDR) data for Lakes Baikal and Issyk-kul include T/P data (from September in 1992 to August in 2002) and Jason-1 data (from September in 2002 to January in 2009) with cycles of 10 days. The GDR data for the other four lakes include only T/P data due to the lack of a large number of Jason-1 data.

Lake level refers to the free surface elevation of lake. For determining lake levels from altimetric data, it is equivalent to sea surface height. For the inland lakes, the influences of ocean tide, inverted barometer effect and tidal loading are weaker than those on the open ocean, so any uncertainities caused by these factors were not considered in this study. After editing, reducing and filtering the altimetric data, the time series of water level variations were used to analyze temporal changes in lake levels (Wang et al. 1995).

Seasonal variations is the main part of lake level changes (LLC) (Hwang et al. 2005). The seasonal variations were obtained by the least squares method using the following approximation (Guo et al. 2008)

$$g(t) = a + b(t - t_0) + A_1 \sin\left[\frac{2\pi}{p_1}(t - t_0) + \varphi_1\right] + A_2 \sin\left[\frac{2\pi}{p_2}(t - t_0) + \varphi_2\right] \quad (1)$$

where a is the offset, b is the trend rate, t is time, t_0 is the initial time (1992.0), φ_1 and φ_2 are the initial phase of annual and semiannual, A_1 and A_2 are the annual and semiannual amplitudes, p_1 and p_2 and are the annual and semiannual periods. The results for each studied lake are listed in Table 1. Trends of lake level variations before 1998 and after 1998 in the least squares sense are shown in Fig. 2.

2.1 Lake Baikal

Lake Baikal is the largest lake in Eurasia, and is the deepest lake in the world. The variation in lake level contains inter-annual, annual and semiannual components. The semiannual amplitude and annual amplitudes were, respectively, 0.0222 and 0.3183 m, and the initial phases were 0.8757 rad (0.8 month) and 0.6969 rad (1.3 month). The average change was -0.0136 m a^{-1}, which indicates that the water level of Lake Baikal is decreasing. The average change was -0.0761 and -0.009 m a^{-1} before 1998 and after 1998, respectively.

2.2 Lake Issyk-kul

Lake Issyk-kul is located in the northern part of the Tianshan Mountains, and is one of the world's largest mountain lakes. The variation in Lake Issyk-kul level also contains inter-annual, annual and semiannual components. The semiannual amplitude and annual amplitudes were, respectively, 0.0101 and 0.081 m, and the initial phases were 1.1497 rad (1.1 month) and -1.5097 rad (9.1 month). The average change trend was +0.029 m a^{-1}, indicating that the water level in Lake Issyk-kul level is increasing. The trends were -0.0488 and +0.1588 m a^{-1} before 1998 and after 1998, respectively. This may be related to glacier melting under the effect of global warming.

2.3 Hongze Lake

Hongze Lake is the fourth largest fresh lake in China and is located in the lower reaches of the Huai River. Its variation in lake level includes inter-annual, annual and semiannual components. The semiannual amplitude and anual amplitudes were 0.3204 and 0.3574 m, and the initial phases were 0.3515 rad (0.3 month) and -0.9203 rad (10.2 month). The average change trend was +0.0045 m a^{-1}, which indicates the level of Hongze Lake is increasing. The trends were -0.0362 and +0.0261 m a^{-1} before 1998 and after 1998, respectively.

2.4 Ulungur Lake

Ulungur Lake is a rift lake with a north-south width of 30 km and the east-west length of 35 km. The variation in level also includes inter-annual, annual and semiannual components. The semiannual amplitude and annual amplitudes were respectively 0.1201 and 0.3546 m, and the initial phases were -0.3664 rad (2.6 month) and -0.4664 rad (11.1 month). The average change was -0.0384 m a^{-1}, which indicates that the level of Ulungur Lake is decreasing. The trends were -0.0303 and +0.0437 m a^{-1} before 1998 and after 1998, respectively.

2.5 La-ang Lake

La-ang Lake is a brackish lake, and is also known as Ghost lake. Its level variation has inter-annual, annual and semiannual components. The semiannual amplitude and annual amplitudes were, respectively, 0.0906 and 0.1796 m, and the initial phases are 1.2766 rad (1.2 month) and 1.0820 rad (2.0 month). The average change was -0.2401 m a^{-1}, which indicates that the water level of La-ang Lake is decreasing. The trends were -0.2143 and -0.2323 m a^{-1} before 1998 and after 1998, respectively.

2.6 Khanka Lake

Khanka Lake is a shallow lake on the Sino-Russian border. Its level variation includes inter-annual, annual and semiannual components. The semiannual amplitude and annual amplitudes were, respectively, 0.2488 and 0.2497 m, and the initial phases were -0.6056 rad (2.4 month) and -0.2578 rad (11.5 month). The average change was +0.033 m a^{-1}, which indicates that the water level in Khanka Lake is increasing. The trends were +0.0353 and +0.0308 m a^{-1} before 1998 and after 1998, respectively.

3. WAVELET ANALYSIS

Lake level time series can also be analyzed using a wavelet time-frequency spectrum (Torrence and Compo 1998). The Morlet wavelet as a combination of trigonometric and Gaussian functions is widely used in the geophysical and geodetic data analysis. Signals are separated from noise in a time series by wavelet filtering in the time and frequency domain, which efficiently reduces the noise. Then a clean signal is reconstructed and an ideal function is obtained (Hwang and Chen 2000). The wavelet analyses on level time series for the six study lakes are shown in Fig. 3. The detection periods are listed in Table 1. Figure 3 also shows that these periods are temporally changing.

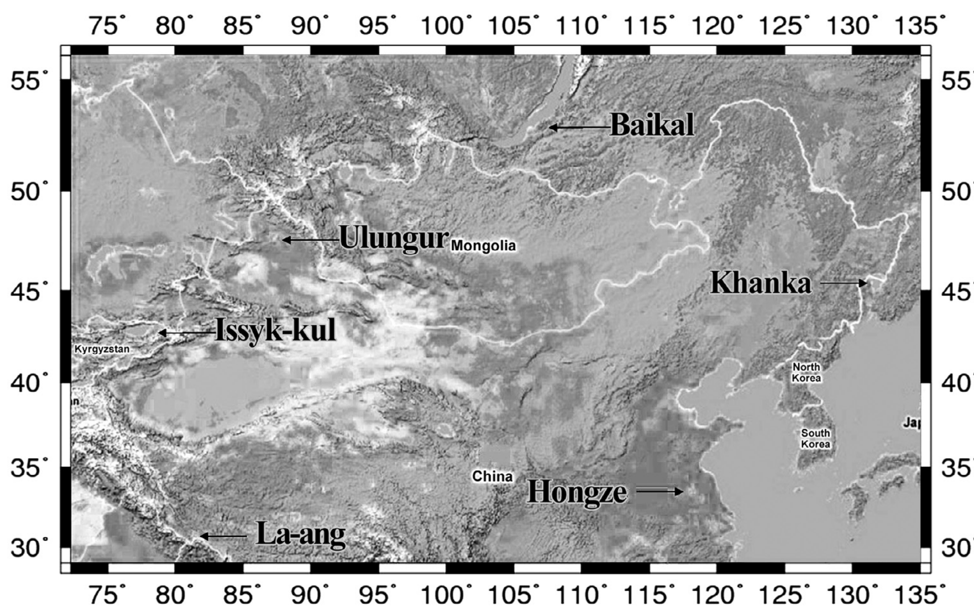

Fig. 1. Location of Lakes Hongze, Khanka, La-ang, Issyk-kul, Ulungur and Baikal.

Table 1. Parameters for annual and semiannual level for the six study lakes.

Lake	a [m]	a [m a^{-1}]	A_1 [m]	φ_1 [months]	A_2 [m]	φ_2 [months]
Baikal	0.2564	-0.0136	0.0222	0.8	0.3183	1.3
Issyk-kul	0.1885	0.0290	0.0101	1.1	0.0810	9.1
Hongze	0.7373	0.0045	0.3204	0.3	0.3574	10.2
Ulungur	0.1403	-0.0384	0.1201	2.6	0.3546	11.1
La-ang	1.5007	-0.2401	0.0906	1.2	0.1796	2.0
Khanka	-0.2239	0.0330	0.2488	2.4	0.2497	11.5

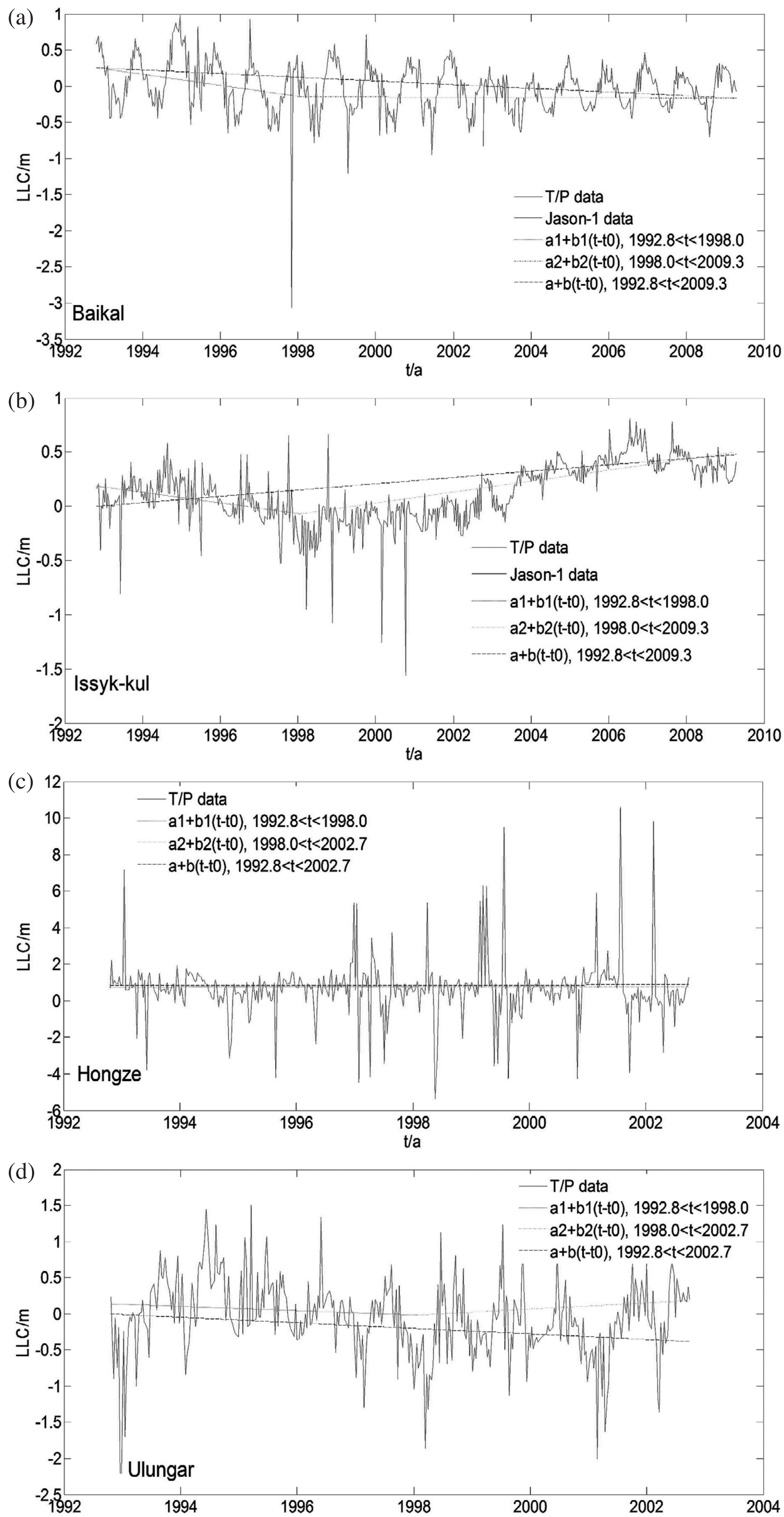

Fig. 2. Time series of level variations with T/P and Jason-1 data for the study lakes: (a) Baikal, (b) Issyk-kul, (c) Hongze, (d) Ulungur, (e) La-ang, and (f) Khanka.

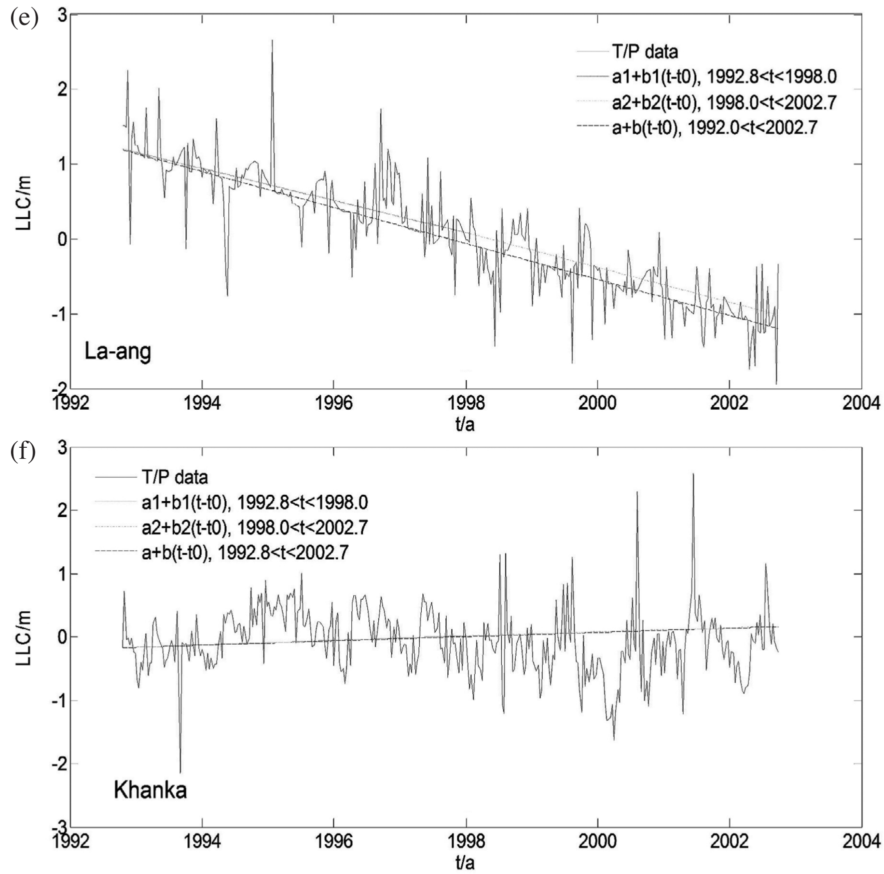

Fig. 2. (Continued)

3.1 Lake Baikal

The annual signal of this lake level variation was stronger in most years except 2003 - 2005. For the seasonal variation, the water level is lower in winter (December to next April), and higher in summer (June to August). For the inter-annual variation, the water level was lower in 1999, 2000, 2003 and 2004, and higher in 1995, 1999 and 2003. The inter-annual period of level variations is about 3.5 years.

3.2 Lake Issyk-kul

Its level annual signal was stronger in 2001 - 2005, and weaker in 1999 - 2001. For the seasonal variation, the lake level is lower in winter (November to next March), and higher in summer (June to September). For the inter-annual variation, the water level was lower in 19997, 2000 and 2002, and higher in 1995, 2005 and 2007. The inter-annual period of water level of lake is about 2.7 years.

3.3 Hongze Lake

Its periodic signals are all weaker in most years because of influence of human activities. The water level is low from November to next February, and higher from July to September.

3.4 Ulungur Lake

Its annual signal was stronger while the semiannual signal was weaker in most years. The water level was lower in 1997, 1998 and 2002, and higher in 1999 and 2001. The inter-annual period of water level is about 2.8 years.

3.5 La-ang Lake

The annual signal was stronger from 1994 to 2001, and the semiannual signal was weaker in most years. The water level was lower in 1994, 1998 and 2002, and higher in 1997 and 2000. The inter-annual period of water level of lake is about 3.8 years.

3.6 Khanka Lake

The annual signal was stronger from 1995 to 2002, and the semiannual signal was stronger from 1999 to 2002. The water level was lower in 1995, 1998 and 2001, and was

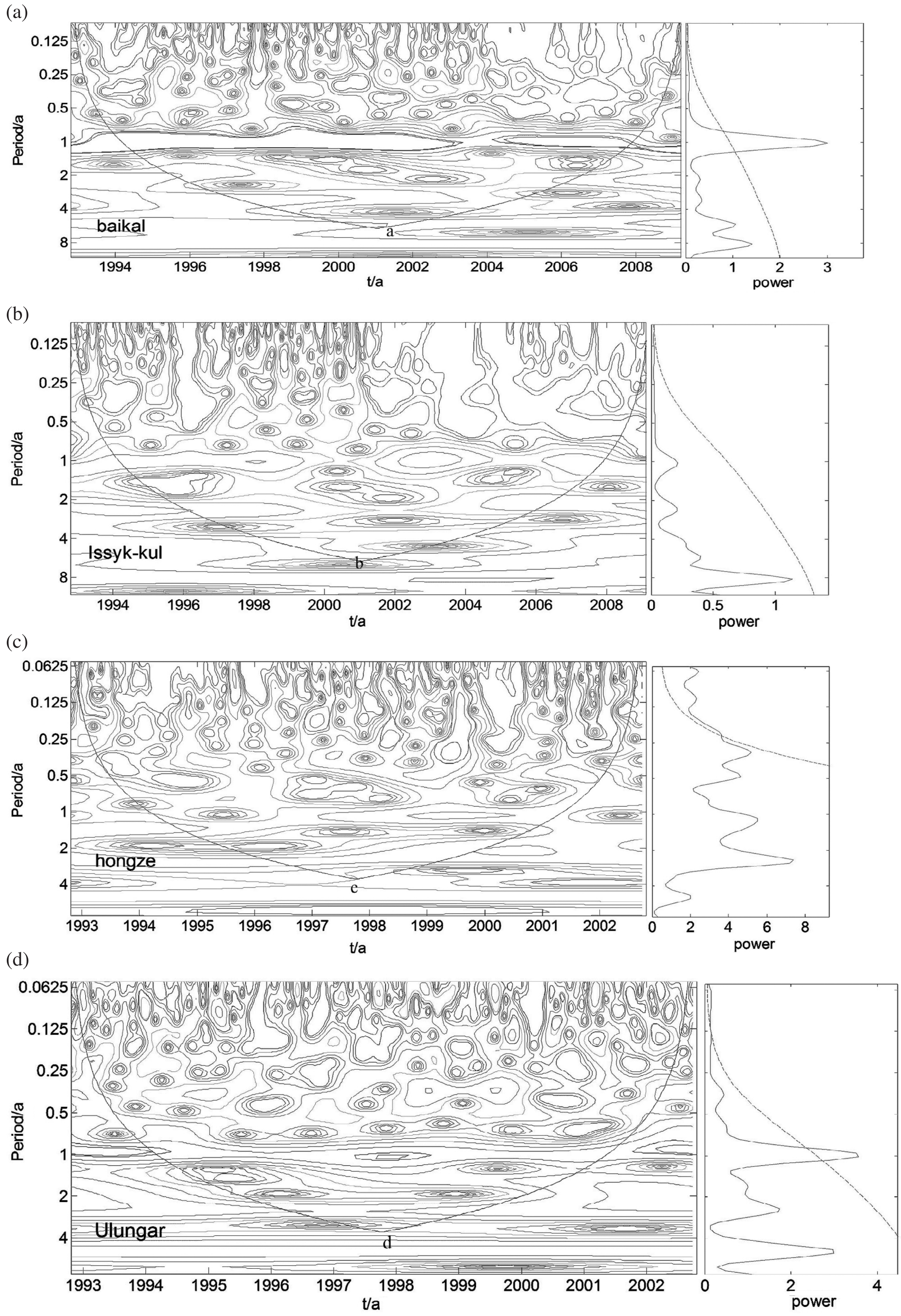

Fig. 3. Wavelet analysis for level variations of the study lakes: (a) Baikal, (b) Issyk-kul, (c) Hongze, (d) Ulungur, (e) La-ang, and (f) Khanka.

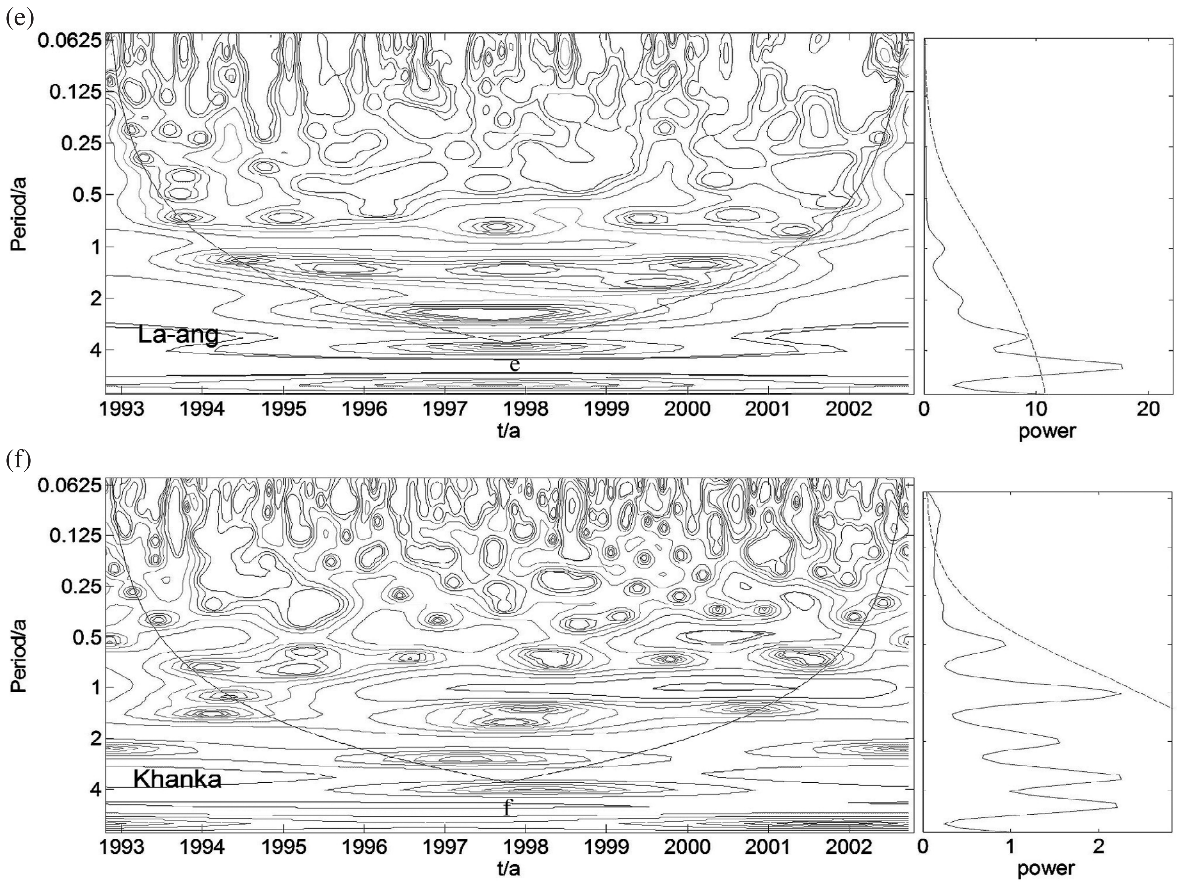

Fig. 3. (Continued)

higher in 1999 and 2001. The inter-annual period of water level is about 3.1 years.

4. CORRELATION BETWEEN LAKE LEVEL VARIATIONS AND ENSO

The Intergovernmental Panel on Climate Change (IPCC) assessments conclude that the average warming trend is 0.3 ~ 0.6°C $(100a)^{-1}$ and the average global temperature has increased by about 0.5°C $(100a)^{-1}$ (Houghton 1995). As temperatures increase, glaciers melt faster and the water levels of rivers and lakes rise (Kezer and Matsuyama 2006). The meteorological community uses a temperature difference of 0.5°C in the average sea surface temperature (SST) as a criterion for an ENSO event. NINO3.4 zone (5°S ~ 5°N, 180°W ~ 90°W) covers most of the equatorial eastern Pacific waters, where the variation of SST is a very good representation of the ENSO event (Weisberg and Wang 1997). In order to link inland lake level changes with ENSO, we analyzed the correlation between the water level variations of six lakes and NINO3.4 SST from 1990 to 2009. Because the time interval of GDR data and NINO3.4 SST are respectively ten days and seven days, it is necessary to compute the mean monthly variations. In addition, the units of measurement are different. So we have to normalize these data to conduct a better comparison. A significance test was also used to evaluate the significance of any correlations between the two sets of data. The mean monthly level variations and NINO3.4 SST are shown in Fig. 4. Correlations between lake level variation and NINO3.4 SST are listed in Table 2.

5. DISCUSSION AND CONCLUSIONS

The variation in lake levels for the six study lakes show that these lakes all contain inter-annual, annual and semiannual components in the overall variation in levels. Semiannual signals of all lakes were weaker in most years except Khanka Lake from 1999 to 2002. Annual signals of all lakes were stronger except Hongze Lake which is greatly influenced by the artificial regulation for industrial and agricultural water. Inter-annual variations were all between 2 to 4 years except for Hongze Lake.

The differences in level trends were great, as shown in Fig. 2. Variations in water levels in Lakes Baikal and Khanka were small. For Lake Baikal, Angara has a regulatory role which outflows from Baikal. Due to building many sluices, the water level in Lake Hongze is affected by

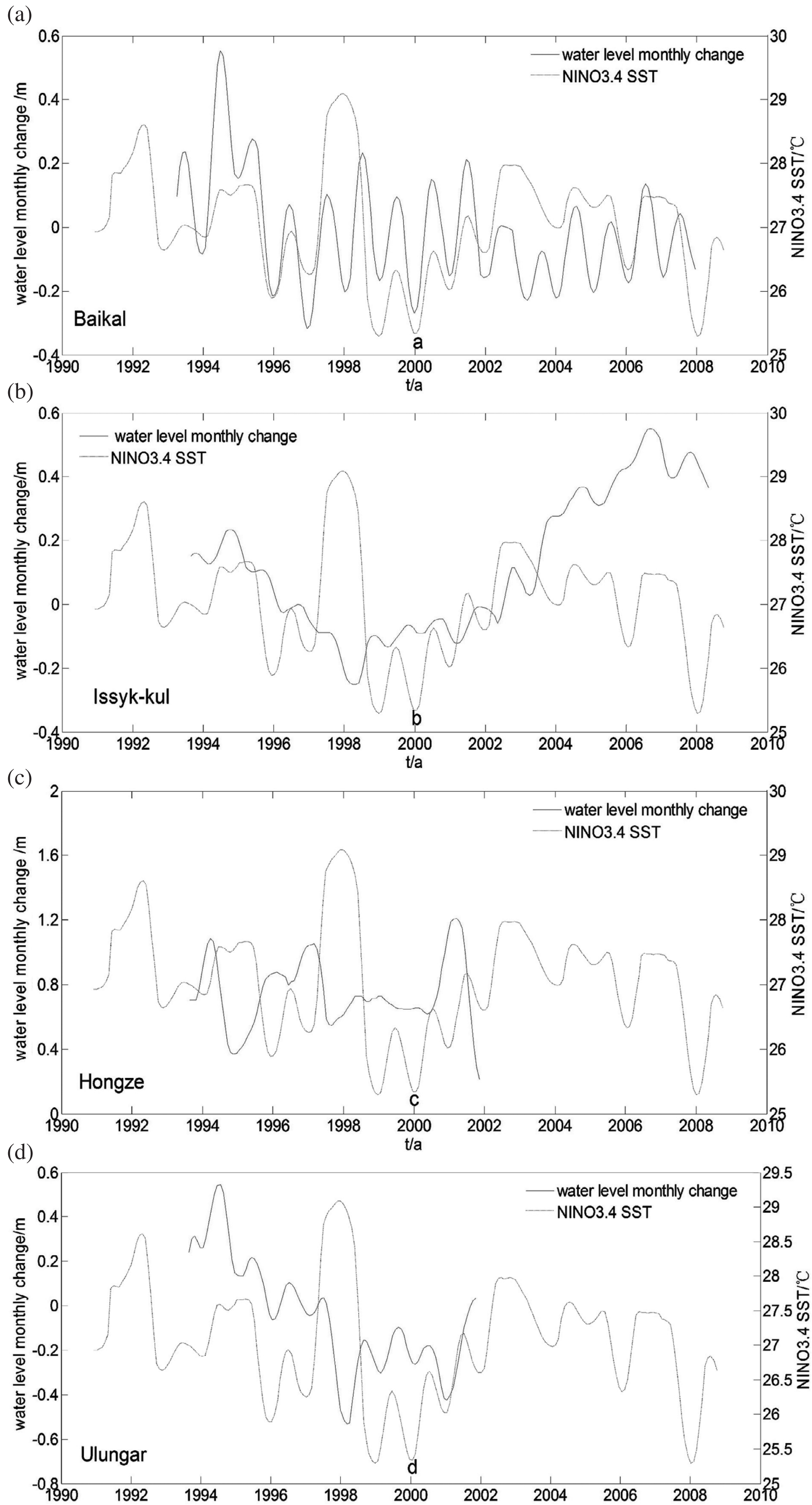

Fig. 4. Relationships between lake level changes and NINO3.4 SST.

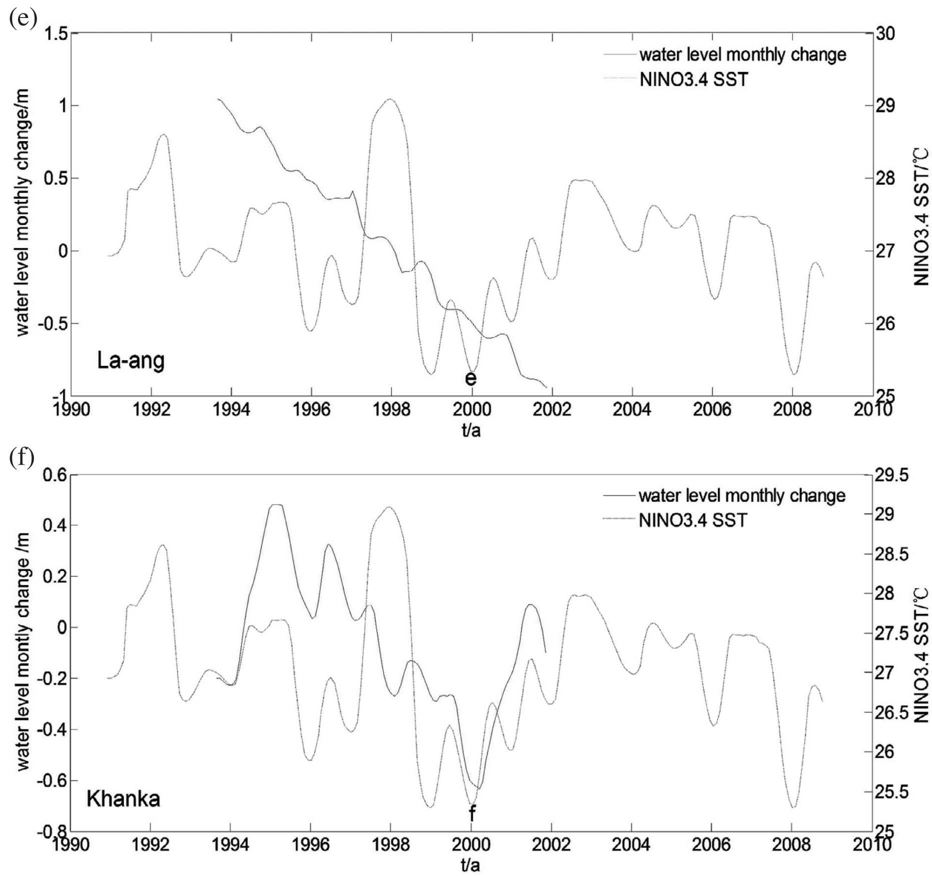

Fig. 4. (Continued)

Table 2. Correlation between lake level variation and NINO3.4 SST.

Lake	Correlation	Confidence level (%)	Lag (months)
Baikal	+0.383	99.5	4
Issyk-kul	+0.340	99.0	5
Hongze	+0.248	98.0	5
Ulungur	+0.242	99.5	7
La-ang	< 0.100	95.0	-
Khanka	+0.389	98.5	3

multiple uses. Lake levels of Lakes Issyk-kul, Ulungur and Khanka have obviously increased since 2000. Increases in temperature lead to increases in river runoff within glacial lake basins, which might be the main reason for rising lake levels in mountainous lakes. Due to low precipitation and larger evaporation, the water level in La-ang Lake has decreased since 1992 (-0.2401 m s^{-1}).

A strongly sustained East Asian monsoon plays an important role in increasing ENSO (Li 1990; Molteni et al. 1993; Weisberg et al. 1997; Yan et al. 2003). At the end of 1997, the strong East Asian winter monsoon caused an increase in average sea surface temperatures in the western equatorial Pacific, which caused the ENSO event. At this time, the stronger water vapor transport of Indian monsoon and weaker water vapor over the East Asia lead to less precipitation in the Yangtze River and in the northwest Xinjiang (Hurrell 1996; Zhao 1996; Zhou and Zhang 2002). This may have led to water levels in Ulungur Lake in northwest

Xinjiang to be lower than in previous years. However, water levels in Hongze Lake did not decrease, but were greatly affected by human needs. Precipitation in western China depends mainly on the mid-latitude westerly water vapor transport. When the East Asian winter monsoon is stronger, the East Asian summer monsoon will be stronger in the following year which results in weak mid-latitude westerly winds, so that the rainfall is decreased in western China. As a result, lake levels in Lakes Issyk-kul and La-ang were less during previous years. Precipitation in the Siberia mainly comes from the water vapor transport from the Arctic Ocean. Stronger East Asian winter and summer monsoons lead to more water vapor transport from the Arctic Ocean to Siberia, bringing more precipitation to this region. Therefore Lake Baikal showed higher water levels than in previous years. For Khanka Lake, the source of precipitation comes mainly from the western Pacific warm and humid air. In El Niño year and the following year, the East Asian winter monsoon and summer winds are stronger, which block spread of oceans warm and humid air to the land. Therefore precipitation in northeast China is lower which leads to lower water levels in Lake Khanka than during previous years.

The correlation analysis shows that Lakes Baikal and Khanka levels with NINO3.4 SST were highly correlated. On the one hand, this indicates some consistency between lake level changes and temperature changes in the equatorial eastern Pacific Ocean. On the other hand, it also reflects the fact that these two lakes are less affected by mankind. The correlation for La-ang Lake was the weakest because of its particular geographic location. There is a certain lag between the lake level variation and the temperature changes in the equatorial eastern Pacific. The reason mainly lies in the equatorial eastern Pacific Ocean temperature changes leading to changes of monsoon and the water vapor transmission rate. As Lakes Baikal and Khanka are closer from their water vapor sources (the Arctic Ocean and the Western Pacific), lag times are shortest (respectively 3 and 4 months). The lag time of Ulungur Lake is longest, about seven months because the distance from Ulungur to its water vapor source is longer.

The precision of instantaneous sea surface height in the deep sea measured by the satellite altimetry is better than ±5 cm (Wang et al. 1995). For the inland lakes with large areas, the lake surface has a similar reflective property with the ocean surface. Thus it is possible to monitor the variations in water level of freshwater lakes using satellite altimetry.

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