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Spatiotemporal characteristics of Qinghai Lake ice phenology between 2000 and 2016

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Abstract: Lake ice phenology is considered a sensitive indicator of regional climate change. We utilized time series information of this kind extracted from a series of multi-source remote sensing (RS) datasets including the MOD09GQ surface reflectance product, Landsat TM/ETM+ images, and meteorological records to analyze spatiotemporal variations of ice phenology of Qinghai Lake between 2000 and 2016 applying both RS and GIS technology. We also identified the climatic factors that have influenced lake ice phenology over time and draw a number of conclusions. First, data show that freeze-up start (FUS), freeze-up end (FUE), break-up start (BUS), and break-up end (BUE) on Qinghai Lake usually occurred in mid-December, early January, mid-to-late March, and early April, respectively. The average freezing duration (FD, between FUE and BUE), complete freezing duration (CFD, between FUE and BUS), ice coverage duration (ICD, between FUS and BUE), and ablation duration (AD, between BUS and BUE) were 88 days, 77 days, 108 days and 10 days, respectively. Second, while the results of this analysis reveal considerable differences in ice phenology on Qinghai Lake between 2000 and 2016, there has been relatively little variation in FUS times. Data show that FUE dates had also tended to fluctuate over time, initially advancing and then being delayed, while the opposite was the case for BUS dates as these advanced between 2012 and 2016. Overall, there was a shortening trend of Qinghai Lake's FD in two periods, 2000–2005 and 2010–2016, which was shorter than those seen on other lakes within the hinterland of the Tibetan Plateau. Third, Qinghai Lake can be characterized by similar spatial patterns in both freeze-up (FU) and break-up (BU) processes, as parts of the surface which freeze earlier also start to melt first, distinctly different from some other lakes on the Tibetan Plateau. A further feature of Qinghai Lake ice phenology is that FU duration (between 18 days and 31 days) is about 10 days longer than BU duration (between 7 days and 20 days). Fourth, data show that negative temperature accumulated during the winter half year (between October and the following April) also plays a dominant role in ice phenology variations of Qinghai Lake. Precipitation and wind speed both also exert direct influences on the formation and

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melting of lake ice cover and also cannot be neglected.

Keywords: lake ice; phenology; freeze-up and break-up; MODIS; Qinghai Lake

1 Introduction

The global climate change has been profoundly influenced by both human development and survival and is one of the major challenges currently faced by the international community (Vaughan *et al*., 2013). It is well known that there is a strong link between climate change and the phenology of lake ice (Weber *et al*., 2016); as freeze-up and break-up durations accurately record changes in regional climate, lake ice phenology is considered to be a significant indicator of regional climate change (Johnson *et al*., 2006; Marszelewski *et al*., 2006; Qin, 2012; Benson *et al*., 2012; Vaughan *et al*., 2013). As lake ice is also an important component of the cryosphere, annual changes in this variable also influence the regional heat and energy balance and are also of important ecological and economic value (Weyhenmeyer *et al*., 2004; Duguay *et al*., 2006; Xin *et al*., 2008; Qin, 2012). The uplift of the Tibetan Plateau has also had a significant influence on the natural environmental evolution of the plateau and its adjacent areas, while regional climate change is known to be closely related to global climate change. Indeed, more local variations are often referred to as "the driver and amplifier of global climate change" (Pan, 1996). It is also the case that the Tibetan Plateau encompasses both the largest number of plateau lakes at the highest altitudes globally (Duguay *et al*., 2006); there are 1055 such lakes on the plateau that cover an area of 41,831.7 km^2 (Ma *et al*., 2011). As most areas on the Tibetan Plateau are inaccessible because of the harsh environment of this region, lakes are rarely influenced by human activities and largely remain in their natural states. This also means that the phenology of lake ice can be used as an accurate proxy for natural regional climate change. Analyses that address the spatiotemporal characteristics of lake ice phenology on the Tibetan Plateau in the context of global warming are therefore of great significance, not only to develop more accurate picture of these variations locally, but also to promote a deeper understanding of climate change in this region. The phenology of lake ice on the Tibetan Plateau has therefore attracted considerable national and international research attention in recent years (Kropáček *et al*., 2013).

At present, the research on the lake ice phenology has mostly extracted time and attribute parameters (Wei *et al*., 2010), which are usually collected using ground observations and remote sensing (RS) monitoring. The first of these approaches is high-precision but is also time-consuming and laborious, while RS monitoring can encompass a larger range of observations and has a higher update speed. These attributes compensate for the drawbacks inherent to ground-based observations including the potential use of artificial samples, weather stations, and other unevenly distributed data. As the development of RS techniques has enabled researchers to obtain lake ice phenology using automatic (or semi-automatic) approaches, this suite of methods has gradually become the most common for lake surface ice observations (Hall *et al*., 2002; Lenormand *et al*., 2002; Latifovic *et al*., 2007). Research around the world on lake ice phenology has so far mainly been carried out in central and northeastern North America and in northern Europe (Magnuson *et al*., 2000; Benson *et al*., 2012; Wang *et al*., 2012) and has focused on establishing datasets in this area, simulating the evolution of ice using mathematical models, and assessing the responses of these surfaces to global climate change (Wang *et al*., 2010; Dibike *et al*., 2012; Oveisy *et al*., 2014). Research in this area has therefore contributed important international data to the Intergovernmental Panel on Climate Change. In contrast, research on lake ice phenology within China has mainly focused on the great Tibetan Plateau lakes; previous research in this area has shown that reductions in lake freezing durations on the Tibetan Plateau are due to delayed freeze-up times and the advance of break-up times (Che *et al*., 2009; Ke *et al*., 2013; Yao *et al*., 2015). One example, Qinghai Lake, is located at the junction between the East Asian and Indian monsoons and the westerlies (Ma *et al*., 2011) and so is very sensitive to climate change; the phenology of lake ice at this site has gradually attracted more and more attention from researchers. In early work, Chen *et al*. (1995) investigated changes in Qinghai Lake ice phenology using an inversion between 1958 and 1983 based on AVHRR satellite images, while Ying *et al*. (2005) later performed a water surface temperature inversion using EOS/MODIS satellite images to establish a monitoring model for this site. Che *et al*. (2009) developed a complete sequence for Qinghai Lake ice phenology between 1978 and 2006 using SSM/I data, revealed that ice cover duration has decreased by between 14 days and 15 days over this time, and showed that the date of ice break-up is most sensitive to changes in regional temperature. Although Cai *et al*. (2017) attempted to analyze ice phenology on Qinghai Lake between 1979 and 2016 using both SMMR and SSM/I data, the low spatial resolution and discontinuities in these data limited the extraction of relevant information. Thus, as the area of this lake is expanding and its water level is rising, it is increasingly important to determine how changes in the phenology of lake ice respond to climate change. We therefore established a series of Qinghai Lake ice phenology datasets for the period between 2000 and 2016 using both RS and GIS technology; these datasets enable us to provide references for winter tourism, lake navigation, and ice thickness inversions as we analyze Qinghai Lake freeze-melt processes in detail.

2 Study area

Qinghai Lake (36.53°–37.25°N, 99.60°–100.78°E) is located on the northeastern Tibetan Plateau within the Tibetan Autonomous Prefecture of Hainan in Qinghai Province. This waterbody is the largest inland saltwater lake within China (Figure 1), and was formed as a result of a stratigraphic fault depression which means that its northwestern part is at a higher elevation than the southeastern. The Haixin Mountain and Three Stone islands are in the center of this lake, and the whole feature is surrounded by a series of sub-lakes, including Gahai, Haiyan Bay, and Shadao on the eastern shore and Erhai Lake on the southeastern margin. Data collected in 2013 shows that Qinghai Lake encompasses an area of 4294 km^2 (Figure 1) and has an elevation of approximately 3200 m; this feature is slightly "convex" in overall shape, measuring about 109 km east-to-west and 65 km north-to-south with an average water depth of about 18.3 m. The water level of Qinghai Lake has been rising in recent years as the volume of glacial melt water from the Qilian Mountains has increased alongside precipitation within the Qinghai Lake Basin; these factors have also increased the area of the lake (Dong and Song, 2011; Wan *et al*., 2014). Measurements made over many years show that the lake basin is characterized by a cold and arid continental climate including a low annual temperature but large variations in daily average values that range between –1.4℃

and 1.7℃, gradually decreasing from southeast to northwest (Sun *et al*., 2007). Mean annual precipitation within the lake basin tends to be concentrated in the summer and is between 319 mm and 395 mm; these data also reveal that rainfall in the southwestern part of the basin is less than in the northeastern and that precipitation gradually is increasing from the center to the ambitus of the lake (Li *et al*., 2008). The major rivers that fed into the Qinghai Lake Basin include the Buha and Shaliu; these systems form an obviously asymmetric distribution such that the flow in the northwest is larger than that in the southeast. Alpine meadows and steppe are also widely distributed within the Qinghai Lake Basin; this region comprises an important biological center within the Tibetan Plateau because of an abundance of species and unique natural conditions, often referred to as the "Gene Pool of Tibetan Plateau".

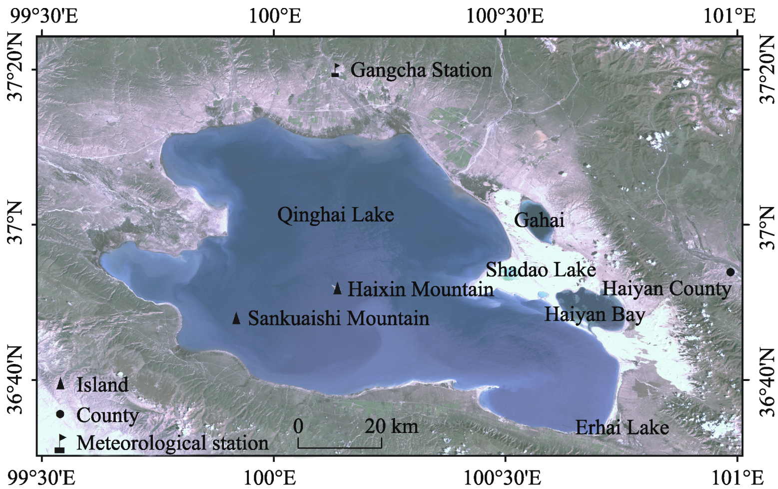

Figure 1 A Landsat TM image base map showing the study area discussed in this paper

3 Data and methods

3.1 Data

In order to accurately obtain data on the timing of Qinghai Lake ice formation and decay, MODIS MOD09GQ products at high temporal (one day) and moderate spatial resolutions (i.e., 250 m on bands 1 and 2 and 500 m on bands 3 and 4) were utilized in this study. A total of 12,410 scenes for the period between 2000 and 2016 were therefore downloaded from the website (https://data.giss.nasa.gov) of the National Aeronautics and Space Administration Land Surface Distributed Data Center and used to monitor Qinghai Lake freezing-ablation processes. We wrote a batch script in Python to perform geometric corrections of MODIS 1B data in order to deal with a large number of images, selected UTM projections and the WGS84 coordinate system, and calculated the area ratio between lake and ice by inputting multi-scene images. We statistically analyzed all images that were cloudless via visual interpretation one-by-one, focusing in particular on a series of 34 Landsat TM/ETM+ image scenes that had a spatial resolution of 30 m to verify the accuracy of lake ice phenology data extracted from MODIS MOD09GQ and Landsat data provided by the USGS and NASA (http://earthexplorer.usgs.gov).

In the absence of more widespread information, we utilized wind speed and temperature data collected at Gangcha meteorological station relatively close to Qinghai Lake as a reference for the regional climatic background. Because of the complexity of the Tibetan Plateau both in terms of terrain and changeable climate, we employed 0.5°×0.5° temperature and precipitation grid data as a supplement generated from observational records collected at all national meteorological stations and via a GTOPO30 digital elevation model. All these data were downloaded from the website of the Chinese Meteorological Information Center (http://data.cma.cn).

3.2 Automated lake ice extraction

Identifying lake ice using RS is dependent on the spectral characteristics of ice and water and is mainly assessed via artificial visual interpretation and use of the threshold and index methods (Reed *et al*., 2009; Choinski *et al*., 2010; Wei and Ye, 2010). The last of these, the index method, is an indirect approach that applies band calculations to distinguish the two, while the threshold method is more direct and synthetically takes into account reflectivity, temperature, the backward scattering coefficient, as well as other characteristics of lake ice and water. This approach can therefore provide a higher precision result by eliminating atmospheric influences and system errors (Wei and Ye, 2010). We therefore used the threshold method to extract lake ice phenology information in this study by defining a threshold between the red and near-infrared bands. The calculation equation used in this analysis is as follows (Yin and Yang, 2005):

$$\text{Results} = \begin{cases} \text{lake ice}, & \text{if } \rho_{red} - \rho_{NIR} > a \text{ and } \rho_{red} > b \\ \text{no lake ice}, & \text{if } \rho_{red} - \rho_{NIR} < a \text{ or } \rho_{red} < b \end{cases} \quad (1)$$

In this expression, ρ_{red} and ρ_{NIR} denote the reflectance of the red and near-infrared bands, respectively, and correspond with MODIS MOD09GQ Band 1 and Band 2. We combined with artificial visual interpretations and histogram distributions to determine appropriate thresholds using repeated human-computer interaction tests. Thus, two thresholds (a and b) were used to distinguish lake ice from surrounding water, 0.028 and 0.05, respectively.

The Landsat ETM+ and MODIS images presented in Figure 2 show the status of Qinghai Lake on February 22nd, 2014. These images estimated for ice cover area at this time of 4125.66 km^2 (based on artificial visual interpretation of the Landsat ETM+ image) (Figure 2a) and 4092.17 km^2 (using the threshold method applied to MODIS MOD09GQ data (Figure 2b). As the error of the latter estimate was only 0.8%, it is clear that the threshold method performed much better in this case.

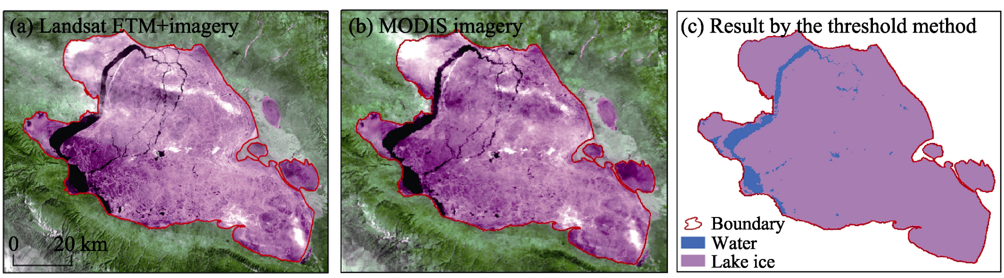

Figure 2 Images showing ice cover on Qinghai Lake on February 22nd, 2014

3.3 Automated identification of lake ice phenology

The ice coverage duration (ICD) over time period of this research was defined as the number of days between lake freeze-up start (FUS) and ice break-up end (BUE). Thus, ice ablation duration (AD) encompasses the period between break-up start (BUS) and BUE. As discrepancies exist in the definition of variables used to describe the duration of lake ice cover, comparisons between phenology records for different regions are often biased (Reed *et al*., 2009; Kropáček *et al*., 2013; Gou *et al*., 2015); we therefore used freezing duration (FD, between FUE and BUE) and complete freezing duration (CFD) to describe ice phenology on Qinghai Lake in this study. The former (FD) is defined as the time interval between lake freeze-up end (FUE) and ice BUE, while CFD refers to the time between lake FUE and ice BUS. As the lake generally freezes in the autumn or winter, and begins to melt during the following spring or summer each year (Che *et al*., 2009), these dates reflect changing trends in ice phenology. Thus, in order to accurately obtain the timing of formation and decay in ice cover, the freeze-up date was defined as the time point when ice cover is greater than, or equal to, 90% of lake area, while break-up date was defined as the time point when ice was less than, or equal to, 10% of total cover (Reed *et al*., 2009). These assumptions mean that lake ice phenology parameters could be automatically extracted, as follows:

$$\text{Results} = \begin{cases} FUS, \text{ if } IA \geqslant 0.1 * LA \\ FUE, \text{ if } IA \geqslant 0.9 * LA \\ BUS, \text{ if } IA \geqslant 0.9 * LA \\ BUE, \text{ if } IA \geqslant 0.1 * LA \end{cases} \tag{2}$$

In this expression, *LA* and *IA* refer to lake and ice areas, respectively. *IA* value was calculated using GIS software from automatically extracted lake ice data (see above), while *LA* value was based on annual lake boundary results for the period between 2000 and 2016.

4 Results and discussion

4.1 Temporal characteristics of lake ice phenology

The ice phenology of Qinghai Lake between 2000 and 2016 are presented in Table 1. These data show that the temporal characteristics of lake ice phenology include a few diurnal scale inaccuracies for some years because of the influence of cloud cover; the maximum error over the period of this research was 3 days in the worst case. Dates for FUS were relatively concentrated over the study period, and mainly occurred in mid-December each year; while the average FUS date was December 16th each year (the 350th day of the year) this phenomenon occurred earliest on December 6th, 2005 (the 340th day of the year), and latest on December 28th, 2004 (the 362nd day of the year). The average time between FUS and FUE was about 20 days; the date of FUE was either at the end of December or in early January of the following year, while the average FUE date was January 5th (the 5th day of the year), and the earliest and latest FUE dates, respectively, occurred on December 23rd, 2005 (the 357th day of the year) and January 23rd, 2009 (the 23rd day of the year). Data show that BUE occurred in late March after two or three months CFD, the average BUS date was March 23rd (the 82nd day of the year), and the earliest and latest BUS dates, respectively, were on March 2nd, 2015 (the 62nd day of the year) and April 7th, 2008 (the 97th day of the year). The termination of lake ice break-up usually occurred between late March and early April within about ten days of AD, while the average BUE date was April 11th (the 93rd day of the year) with the earliest and latest dates occurring on March 24th, 2014 (the 83rd day of the year) and April 14th, 2011 (the 104th day of the year), respectively. Data also reveal considerable variation in the dates of both FD and CFD on Qinghai Lake between 2000 and 2016 as well as relatively little change in FUS times. The average lengths of FD and CFD recorded in this study were 88 days and 77 days, respectively; the longest FD was 108 days while the shortest was 69 days, and corresponding CFD values were 96 days and 55 days, respectively. It is noteworthy that the longest and shortest values for both FD and CFD were between 2010 and 2011 and between 2008 and 2009, respectively, while the average ICD for Qinghai Lake was 108 days between FUS and BUE. The longest ICD recorded was 125 days between 2005 and 2006, while the shortest was just 90 days between 2004 and 2005 and between 2015 and 2016. Data show an average AD of 10 days between BUS and BUE each year; the longest recorded AD was 26 days between 2014 and 2016, while the shortest was just four days between 2012 and 2013.

Table 1 The ice phenology of Qinghai Lake between 2000 and 2016

Year	FUS	FUE	BUS	BUE	ICD	AD	FD	CFD
2000/2001	343	6*	85	92*	114	7	86	79
2001/2002	351	5	92*	98	112	6	93	87
2002/2003	355	4	85*	89*	99	4	85	81
2003/2004	359*	12	79*	88	94	9	76	67
2004/2005	362*	10	69*	87*	90	18	79	59
2005/2006	340	357	86*	100*	125	14	108	94
2006/2007	348	7	90*	96	113	6	89	83
2007/2008	353	4*	97*	102*	114	5	99	93
2008/2009	344	23*	78*	92	113	14	69	55
2009/2010	351	365	78	84*	98	6	84	78
2010/2011	347	361	91*	104	122	13	108	96
2011/2012	350	5*	95	103	118	8	98	90
2012/2013	342	361	88	92	115	4	97	92
2013/2014	350	8	65	83	98	18	75	57
2014/2015	346	3	62*	88*	107	26	85	59
2015/2016	359	12	71*	84*	90	13	72	59
Average	350	5	82	93	108	10	88	77
Range	22	31	35	21	35	22	39	41
Slope (d/a)	–0.12	–0.08	–0.86	–0.29	–0.16	0.58	–0.22	–0.78

Notes: *, denotes error date (the maximum error in this study was 3 days); FUS, FUE, BUS, and BUE times are denoted in this table by the number of days in the year (e.g., December 9th is the 343rd day of the year).

4.2 Changes in lake ice phenology

The data collated in this study reveal significant variations of ice phenology on Qinghai Lake between 2000 and 2016, in particular relatively little change in the timing of FUS; this phenomenon usually occurred on the 350th day of the year apart from between 2003 and 2005 and between 2015 and 2016. Variation in FUE dates can be characterized by an initial advance in time followed by a subsequent trend towards delays with the largest variation recorded approximately one month. In contrast, BUS dates tended to show the opposite trend over the course of this study; the average BUS date recorded was the 85th day of the year subsequent to 2012 but fell on the 72nd day of the year prior to this point. Although the date of BUE fluctuated little between 2005 and 2012, this date advanced within the year between 2000 and 2005 (apart from between 2001 and 2002) and between 2012 and 2016. Changes in ICD, FD, and CFD all remained basically consistent over the time period of this study; these dates all tended to initially extend within the year before falling back between 2005 and 2010, and gradually shortening in duration between 2000 and 2005 and between 2010 and 2016. Values for AD also tended to fluctuate over the course of this study, initially reducing in length before extending between 2000 and 2012. It is noteworthy that these values were always larger than average durations over the 17 years between 2012 and 2016 and they tended to advance in the year overall.

Although the results of this study are consistent with previous research, there are some differences. Trends of ice phenology in Qinghai Lake reported by Cai *et al*. (2016) are similar to those presented here, but the detailed dates recovered for FUS, FUE, BUS, and BUE vary for some years up to maximum differences of 9 days (between 2008 and 2009), 19 days (between 2008 and 2009), 14 days (between 2014 and 2015), and 6 days (between 2006 and 2007), respectively, because of disparity in data sources and methods. Because Cai *et al*. (2016) used passive microwave SMMR and SSM/I data with low spatial resolution and the artificial visual interpretation method (their results are both difficult to verify and to some extent inconsistent due to the different experience of researcher). Data show that both the FD and CFD of Qinghai Lake have been shortened over time compared with other waterbodies on the Tibetan Plateau (Ke *et al*., 2013; Kropáèek *et al*., 2013; Yao *et al*., 2016); these changes were especially obvious subsequent to 2012 and are characterized by a lower rate of reduction than is the case for other high-altitude lakes in the plateau hinterland, including Nam Co and other examples in the Hoh Xil region. These results may be related to the geographical location of Qinghai Lake as well as other unique attributes such as its area, shape, water depth, and salinity.

4.3 Spatial characteristics of lake ice freeze and break processes

Spatial patterns in lake ice freeze-up and break-up can reflect differences in depth and salinity as revealed by the fact that ice begins to form in Nam Co and in the seven other lakes in the northern Hoh Xil region in shallow-water shoreline areas before gradually expanding into deep-water areas (Qu *et al*., 2012; Yao *et al*., 2016). The processes of ice freeze-up and break-up on Qinghai Lake follow a similar pattern; Figure 3 illustrates these changes between 2015 and 2016. Observations show that Qinghai Lake begins to freeze along its eastern edge close to Haiyan Bay (Figure 3a) before ice begins to form in the northeast and northwest; at the same time, lake ice gradually expands out from the shore into the center of this waterbody (Figures 3b, 3c and 3d) before a complete freeze is seen by around January 24th 2016 (Figure 3e). Observations show that the freezing process is relatively slow overall, and that the main component of Qinghai Lake ice has melted from the northeast and northwest by early March 2016 (Figures 3f and 3g); at the same time, ice is gradually ablated from the lakeshore to the center such that the bulk of surface coverage has completely melted (Figures 3h and 3i) by March 31st, 2016, at a faster speed compared to the freezing process. The spatial pattern of lake ice freeze-up was generally uniform over this period compared to break-up; in other words, the region in which ice first freezes also tends to be the region where it also melts first, a distinct difference from the patterns seen in Nam Co (Ke *et al.*, 2013) and other lakes in the northern Hoh Xil region (Yao *et al.*, 2016). Processes of lake freeze-up and ice break-up are known to be closely related to the spatial distribution of lake ice thickness (Zaikov, 1963), another key factor which should be taken into account, especially in the context of RS-based inversions of lake ice thickness and the future initiation of winter tourism on Qinghai Lake.

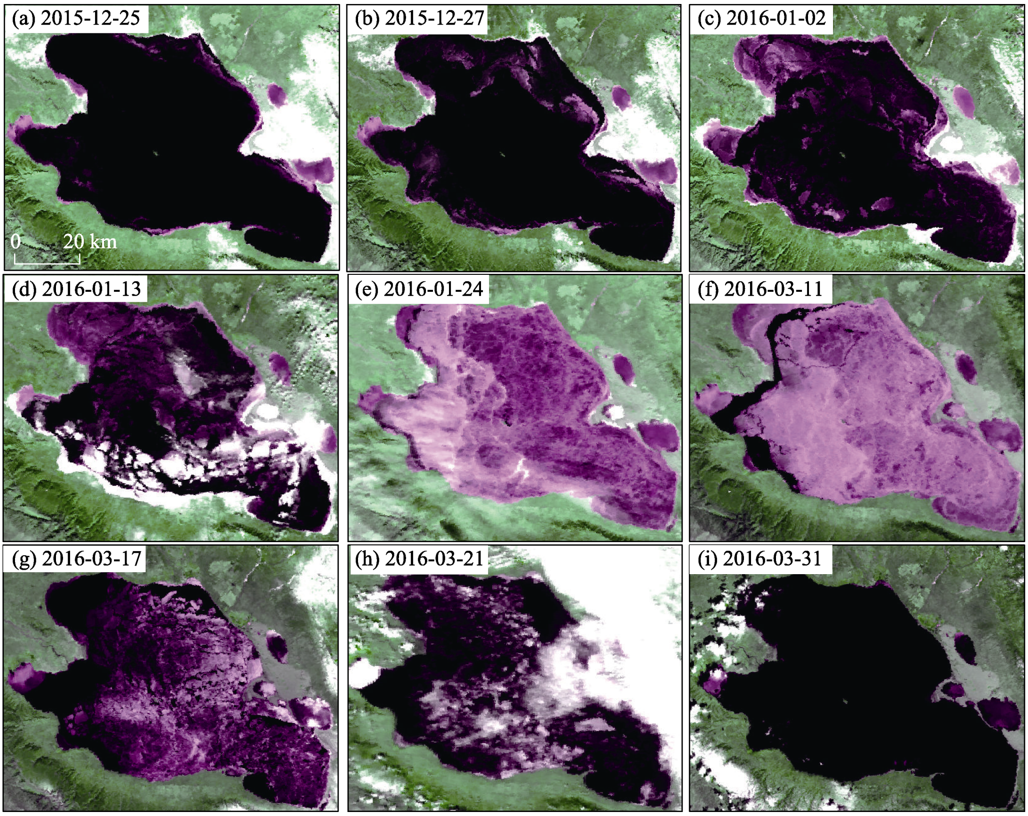

Figure 3 Images to illustrate freezing and melting processes on Qinghai Lake over time (the purple and white regions on these images are lake ice, while the black areas are water)

Observations show that the duration of lake freeze-up (between 18 days and 31 days) tends to be about 10 days longer than the duration of ice-break up (between 7 days and 20 days) overall (Figure 4). However, the lake freeze and break process were repeating and irregular in individual years. In one example, abnormal values for the ratio between ice and water areas were recorded on the 78th day of the year (Figure 4b) between 2004 and 2005; meteorological records (Figure 5a) for the same period show wind speeds of 8.8 m/s and 10.0 m/s on March 18th, 2005, and March 19th, 2005 (the 77th day of the year and the 78th day of the year), respectively, and reveal that temperatures began to decrease from March

18th 2005 onwards. We therefore conclude that abnormal values may have occurred in this year due to the re-freezing of already melted lake ice as temperatures suddenly dropped and wind speeds increased. This phenomenon was also seen between 2009 and 2010 when abnormal values for the area ratio of lake ice were recorded on the 359th day, including on the 362nd day in 2009 and on the 84th day in 2010 (Figure 4c); these discrepancies can be explained by either the re-melting (or re-freezing) of already melting (or frozen) lake ice due to fluctuations in temperature or wind speed (Figures 5b and 5c). In terms of physical freezing and ablation processes, ice crystals and new thin ice surfaces first appear initially in shallow water around the shore of Qinghai Lake. Observations show that wind also plays an important role in lake freeze-thaw processes to the exclusion of ice surface layer optical properties and the heat of bottom waterbodies.

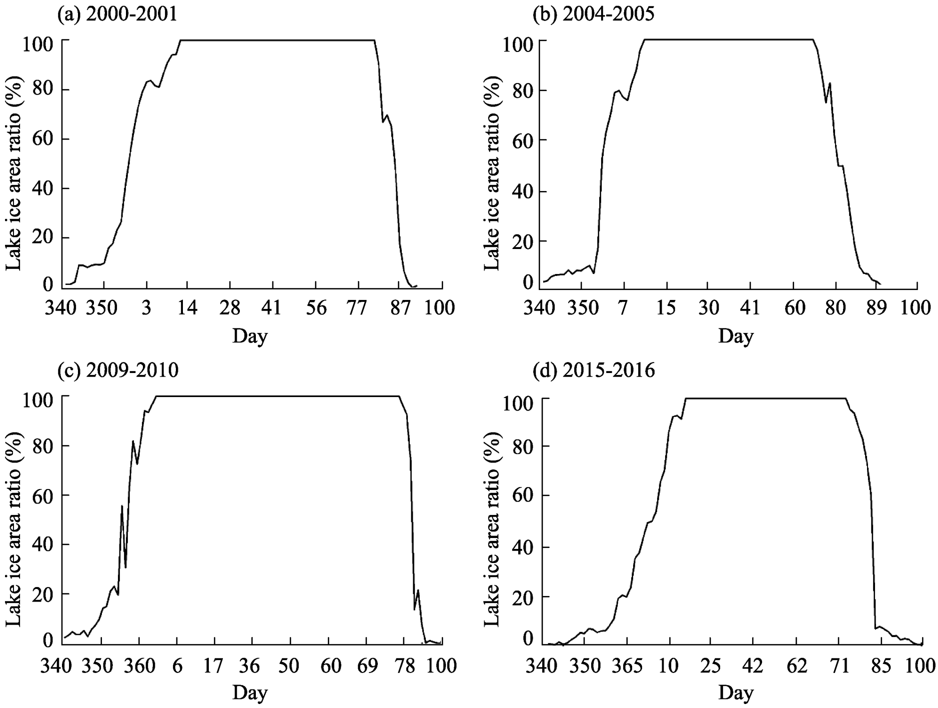

Figure 4 Qinghai Lake freeze-melt processes between 2000 and 2016

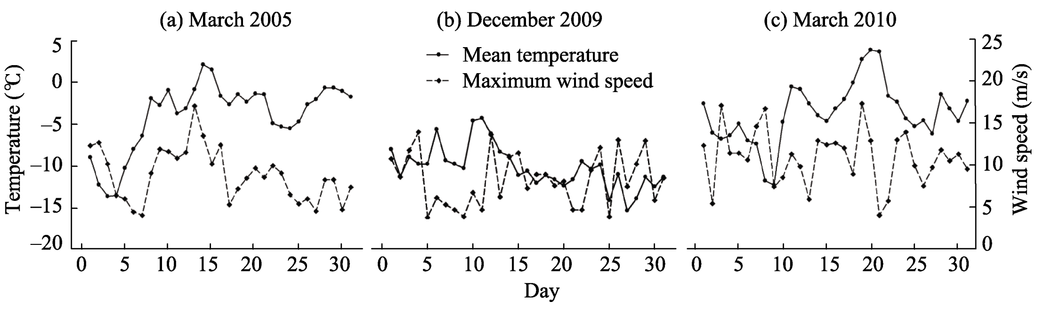

Figure 5 Daily variations in air temperature and wind speed measured at Gangcha meteorological station

As Qinghai Lake continues to cool, storms cause thinner ice to quickly crack and blow towards the shore as thin and transparent ice belts, called Shore Ice, form along the bank. The timing of continuous fixed ice formation along the margins of the lake is mainly related to the shape of the lakeshore and the local prevailing wind direction (Lei *et al.*, 2011). Thus, as heat dissipation increases and fixed Shore Ice continues to form, this layer starts to extend out into the open water area of the lake; as the surface area of the open lake decreases, the formation of Shore Ice continues towards the center of the waterbody while the influence of surface wind is weakened and a continuous ice cap forms. The lake then starts to freeze in a stable fashion from the surface downwards via thermal conductivity if a constant low temperature is maintained and both ice thickness and freezing rate therefore also increase. As an ice cap forms, complete freezing of the lake is initiated even though this process is relatively slow and requires a sustained low temperature. Data show that the average temperature of Qinghai Lake remained continuously higher than 0℃ at the end of the March and into early April; at this point, the possibility of maintaining lake ice coverage is largely determined by existing heat storage within the waterbody. Lake ice subsequently begins to melt because of the influence of heat flow, while other key factors such as water level rise and wind driven ice layer breakup and increase of the contact surface area between the ice and the surrounding environment, accelerating the melting process (Duan *et al.*, 2016; Weber *et al.*, 2016). Observations show that wind speed and temperature at the water surface of Qinghai Lake gradually increase in March and April and also accelerate the melting process.

4.4 The influence of climatic factors on ice conditions

The data collated in this study reveal that the characteristics of lake ice phenology are influenced by both meteorological (e.g., temperature, solar radiation, humidity, and snow) and geographical (e.g., lake shape and location) factors. Observations show that temperature is the main factor underlying these changes over longer time scales (Dibike *et al.*, 2012), an important result because the Tibetan Plateau is experiencing marked warming (Duan *et al.*, 2016; You *et al.*, 2016) at a significantly higher level than the average global rate (Kang *et al.*, 2010). Data from 6 meteorological stations within the Qinghai Lake Basin also show that average temperature has risen significantly over the last 50 years (Sun *et al.*, 2007); thus, changes in lake ice phenology provide a good indication of negative accumulated temperature over the course of the winter half year. In order to further discuss these changes, we defined the winter half year in the Qinghai Lake Basin as the time interval encompassing the period between October and April of the following year; as data show that daily average temperature over this time starts below 0℃ in mid-to-late October and then rises above this point in mid-April, we calculated the sum of daily mean temperatures below freezing throughout this period and used this value as negative accumulated temperature for the winter half year. We then analyzed correlations between accumulated negative temperature and the FD of Qinghai Lake between 2000 and 2016 (Figure 6); results show a negative correlation coefficient of –0.632 when a confi-

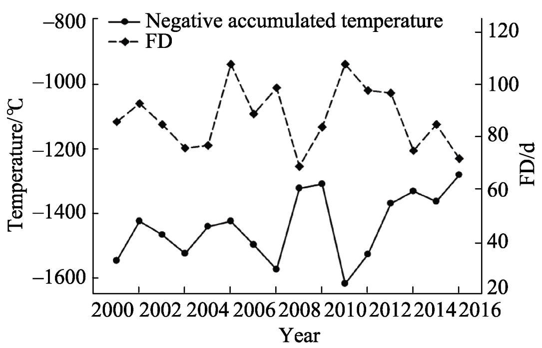

Figure 6 The relationship between winter half year negative accumulated temperature and the FD of Qinghai Lake ice between 2000 and 2016

dence level of 0.01 was applied. This implies that Qinghai Lake has a long FD when the level of negative accumulated temperature remains small during the winter half year and a short duration when the latter variable is large. Data show that the ice phenology of Qinghai Lake responds significantly to regional climate warming and that changes in FD are a good indication for temperature during the winter half year.

Analysis of ice phenology on Qinghai Lake between 2000 and 2016 reveals clear correlations between the timing of FUS, FUE, BUS, BUE, and wind speed (Figure 7). As discussed above, we investigated these correlations by selecting average wind speeds that were measured during the week prior to lake freeze-up and break-up; the results of these comparisons reveal covariance values of –1.57, 0.57, –1.49, and –0.93 between the four wind speed time nodes and lake ice phenology, respectively. A non-zero covariance value indicates the presence of a correlation between two variables, while negative and positive signs are indicative of corresponding relationships according to the definition of covariance (Tao, 2014). Results show that average wind speed over a week exerts an important influence on variation in Qinghai Lake ice phenology and that onset of FUS was most sensitive to changes in regional speeds; data reveal that FUS advanced when the average wind speed during a week was larger and vice versa (Figure 7a). Higher speeds accelerate convection between the air and water surface during the initial stages of ice formation and cause the heat dissipation intensity of the lake to quickly reach freezing, promoting the formation of lake ice (Lei *et al.*, 2011). Data also show that ice BUS date was most sensitive to changes in regional wind speeds (Figure 7c), especially between 2004 and 2015; this variable was also closely related to

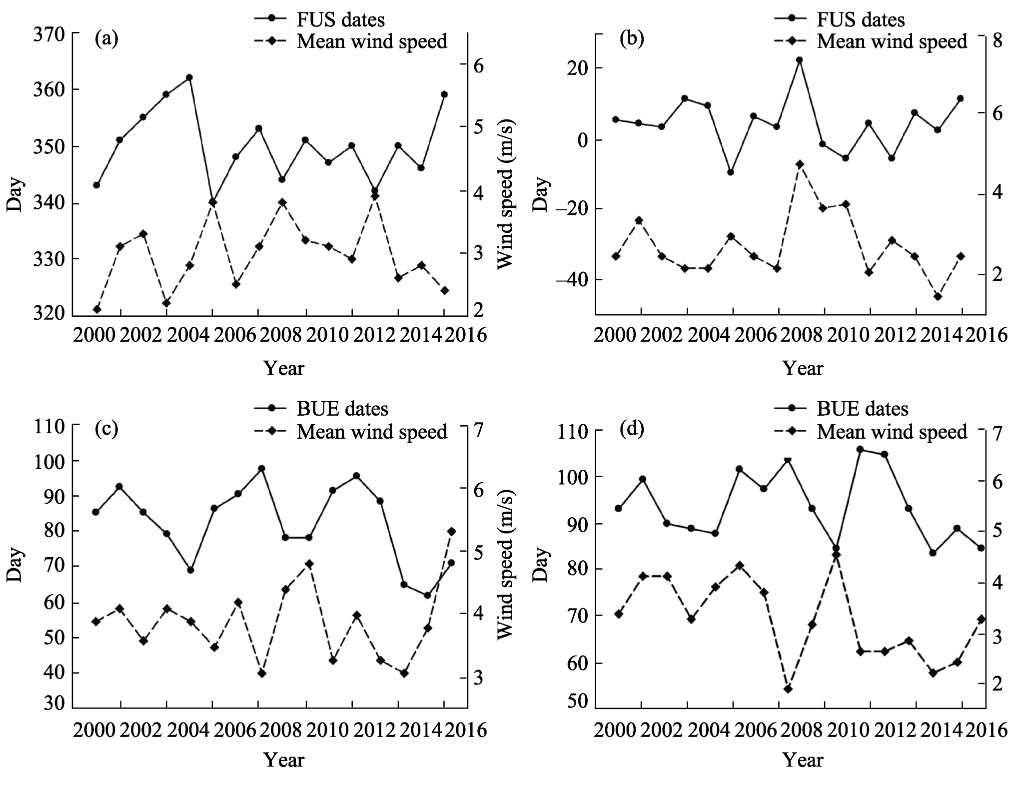

Figure 7 Graphs showing the relationship between mean weekly wind speed measured at Gangcha meteorological station and ice phenology on Qinghai Lake between 2000 and 2016

changes in mean wind speeds within a week which shows that when average speeds were larger, ice break-up started earlier and vice versa. Indeed, because larger wind speeds can more effectively mix the water surface and hotter deeper layers, this effect slows lake surface temperature reduction to freezing while also dynamically disturbing or destroying existing ice and accelerating break-up processes (You and Kang, 2016). Analyses also show that FUE and BUE dates were not very sensitive to mean wind speeds variations within a given week, but were very responsive to variation in this factor over different time periods. In particular, FUE date responded very significantly to changes in mean wind speeds between 2003 and 2008 and between 2011 and 2016; FUE dates shifted earlier when wind speeds increased over these periods (Figure 7b). Similarly, the BUE date proved more sensitive to changes in mean wind speed between 2007 and 2016; the dates shifted to earlier in the year when wind speeds were larger and vice versa (Figure 7d).

Changes in precipitation also play a key role in the formation and ablation of lake ice in addition to other weather conditions (e.g., air temperature and wind speed). We also analyzed correlations between timings of ICD, AD, and precipitation over the same time period as part of this study. This analysis yielded correlation coefficients of –0.31 and 0.36 for ICD and AD versus precipitation, respectively, and data that the latter exerted a different level of influence on the two former variables. These results show that ICD was shorter during years when precipitation was larger (Figure 8a) while AD was longer (Figure 8b) and vice versa; this is likely because the temperature of the water surface remained continuously below 0℃ between FUS and BUS while precipitation causes surface cooling and the development of crystal nuclei which are the basis of ice formation (Lei *et al*., 2011; Oveisy *et al.*, 2014). As precipitation increased, ICD was shortened as faster nucleation accelerated the lake freezing process; however, the temperature of the water surface nevertheless remained lower between BUS and BUE because of increased precipitation and snowfall while the lake ice melting rate fell and ablation was prolonged.

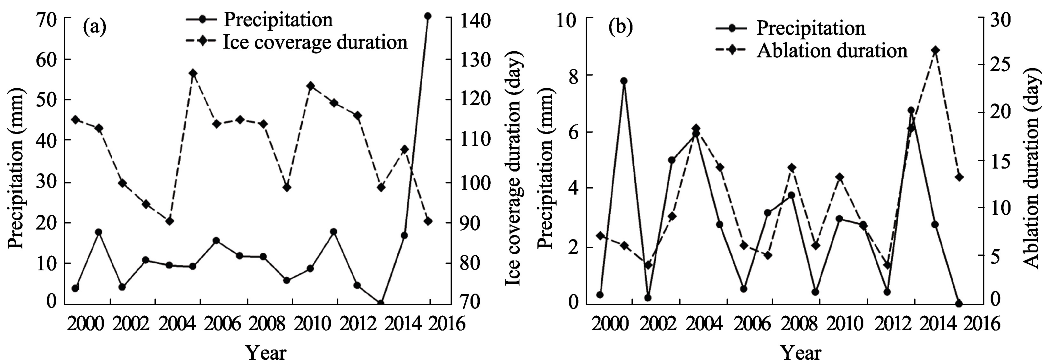

Figure 8 Graphs showing the relationship between precipitation and ice variation (coverage and ablation) on Qinghai Lake between 2000 and 2016

5 Conclusions

The results of this study reveal spatiotemporal variations of ice phenology on Qinghai Lake and relationships with climatic variables between 2000 and 2016.

(1) The lake ice phenology datasets presented here for the period between 2000 and 2016

are based on MODIS MOD09GQ products. Comparisons suggest that FUS tended to occur in mid-December each year while BUS occurred in mid-to-late March of the following year. Data also show an average of 20 days between FUS and FUE with BUE occurring in early April. Average values for FD (between FUE and BUE), CFD (between FUE and BUS), ICD (between FUS and BUE), and AD (between BUS and BUE) were 88 days, 77 days, 108 days, and 10 days, respectively.

(2) Data reveal a great deal of diversity in the spatial characteristics of Qinghai Lake ice phenology between 2000 and 2016. The overall date of FUS changed relatively little over the time period of this study, while the dates of FUE and BUS trended in opposite directions. Results also show that the date for BUE between 2000 and 2005 (apart from between 2001 and 2002) and between 2012 and 2016 tended to advance within the year. Changes in ICD, FD, and CFD all remained basically consistent, these dates were initially advanced within the year but then fell back between 2005 and 2010. The durations of these periods also all gradually shortened between 2000 and 2005 and between 2010 and 2016, and AD has increased slightly over the last five years.

(3) Qinghai Lake is characterized by similar spatial patterns in freeze-up and break-up processes; observations show that ice begins to form from the eastern edge of the lake close to Haiyan Bay before the northeastern and northwestern sections of this waterbody start to freeze. At the same time, ice gradually expands out from the lakeshore into the center of lake and begins to melt from the northeast and northwest after 77 days of CFD and is gradually ablated in the same direction. Observations show that areas of the water surface that froze earlier also started to melt first on Qinghai Lake, a distinct difference from other similar waterbodies on the Tibetan Plateau. An additional feature of Qinghai Lake ice phenology is that the duration of freeze-up (between 18 days and 31 days) is on average about ten days longer than the duration of break-up (between seven days and 20 days).

(4) The data presented in this study clearly show that the ice phenology of Qinghai Lake depends on a range of climatic factors. Winter negative accumulated temperature determines the length of lake FD, for example, Qinghai Lake is characterized by a long FD when winter half year negative accumulated temperature is smaller, while wind speeds and precipitation also exert significant effects on the formation and ablation of lake ice. Higher wind speeds can promote the formation of lake ice during early stages and can also accelerate melting at this time. The effect of precipitation on lake ice is most evident during years with high rainfall; lake ice coverage duration is shorter at these times while ablation durations are longer, and vice versa.

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