Science of the Total Environment 607–608 (2017) 120–131

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Monitoring ice variations in Qinghai Lake from 1979 to 2016 using passive microwave remote sensing data

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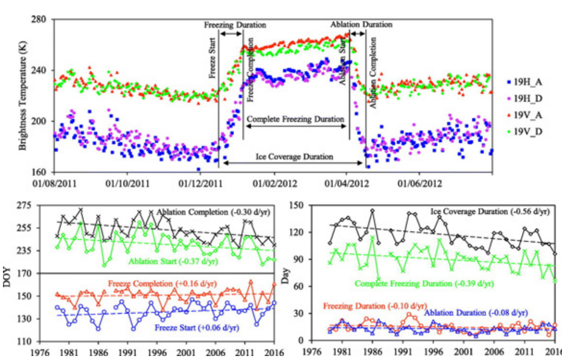
HIGHLIGHTS

- SMMR & SSM/I data are capable of extracting lake ice freeze-thaw dates of Qinghai Lake.
- The freezing dates have been delayed and the ablation dates have advanced.
- Ice coverage duration of Qinghai Lake has shortened by 21.21 days from 1979 to 2016.
- Ice coverage duration is significantly negatively correlated with air temperature in winter.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 21 April 2017
Received in revised form 28 June 2017
Accepted 3 July 2017
Available online 27 July 2017

Editor: Simon Pollard

Keywords:
Lake ice
Freeze-thaw dates
Climate warming
Passive microwave remote sensing
MODIS
Qinghai Lake

ABSTRACT

Lake ice is a sensitive indicator of climate change. Based on the disparities between the brightness temperatures of lake ice and water, passive microwave data can be used to monitor the ice variations of a lake. With focus on the analysis of long time series variability of lake ice, this study extracts four characteristic dates related to lake ice (the annual freeze start, freeze completion, ablation start and ablation completion dates) for Qinghai Lake from 1979 to 2016 using Scanning Multichannel Microwave Radiometer (SMMR) and Special Sensor Microwave Imager (SSM/I) passive microwave brightness temperature data. The corresponding freezing duration, ablation duration, complete freezing duration and ice coverage duration are calculated. Applying Moderate Resolution Imaging Spectroradiometer (MODIS) daily snow products, the accuracy of the results derived from passive microwave data is validated. The validation analysis shows a strong agreement (R^2 ranges from 0.70 to 0.85, mean absolute error (MAE) ranges from 2.25 to 3.94 days) in the freeze start, ablation start, and ablation completion dates derived from the MODIS data and passive microwave data; the ice coverage duration also has a small error (relative error (RE) = 2.95%, MAE = 3.13 days), suggesting that the results obtained from passive microwave data are reliable. The results show that the freezing dates of Qinghai Lake have been delayed and the ablation dates have advanced. Over 38 years, the freeze start date and freeze completion date have been pushed back by 6.16 days and 2.27 days, respectively, while the ablation start date and ablation completion date have advanced by 11.24 days and 14.09 days, respectively. The freezing duration and ablation duration have shortened

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http://dx.doi.org/10.1016/j.scitotenv.2017.07.027

by 3.89 days and 2.85 days, respectively, and the complete freezing duration and ice coverage duration have shortened by 14.84 days and 21.21 days, respectively. There is a significant negative correlation between the ice coverage duration and the mean air temperature in winter.

1. Introduction

Some lakes produce a seasonal ice sheet, and changes in air temperature can be inherently reflected in the freeze-thaw dates of lake ice for a given year (Marszelewski and Skowron, 2006). In the context of global climate change, information such as the freeze-thaw dates of lake ice and the duration of ice coverage can serve as effective indicators for monitoring the actual impact of climate change (Ke et al., 2013). Previous studies have shown that the freeze-thaw dates of lake ice are clearly correlated with climate change (Williams, 1971; Livingstone, 1997; Weber et al., 2016). Climate change directly or indirectly affects the freeze-thaw cycle of lake ice (Adrian et al., 2009), and the duration of ice coverage over lake surfaces determines the time for heat exchange between lakes and the atmosphere, thereby affecting the chemical and biological processes of lake ecosystems and influencing the amount of annual evaporation from lakes. These changes provide feedback to the regional and global climate systems and may generate further climate change (Latifovic and Pouliot, 2007). Therefore, the study of lake ice changes can provide important insights into climate change.

The earliest research on lake ice dates back to the 1860s (Palecki and Barry, 1986). The traditional methods for collecting data on lake ice include aerial surveys, field observations and meteorological and hydrologic observations. However, these types of observations are often influenced by regional conditions, and only limited data can be collected; thus, it is difficult to obtain complete information from these traditional methods (Chaouch et al., 2014). Remote sensing methods can obtain images at various spatial and temporal resolutions and can compensate for the shortcomings of traditional observation methods; therefore, these methods have been widely used in studies on lake ice (Wei and Ye, 2010). To date, operational methods to distinguish lake ice and lake water have largely relied on the visual (or semi-automated) interpretation of optical and microwave imagery. In addition, few automatic algorithms have been developed, such as Snowmap designed for Moderate Resolution Imaging Spectroradiometer (MODIS) snow data products. The threshold algorithm is also commonly used in extracting lake ice (Duguay et al., 2015). For example, Latifovic and Pouliot (2007) used Advanced Very High Resolution Radiometer (AVHRR) data to extract the freeze-thaw dates of Canadian lakes from 1985 to 2004 by setting a threshold value of the reflectance. Their results showed that remote sensing data are highly consistent with ground observation records. Kropacek et al. (2013) used MODIS eight-day synthesis products (MYD10A2) to analyse variations in the freeze-thaw dates of lake ice for 59 large lakes on the Tibetan Plateau from 2001 to 2010. The aforementioned AVHRR and MODIS data are generated by optical remote sensing, which has advantages such as high temporal and spatial resolution and richness in multispectral information (Latifovic and Pouliot, 2007; Chaouch et al., 2014). However, the quality of optical remote sensing data is greatly limited by the presence of cloud cover and is influenced by winter solar altitudes at high latitudes. Microwaves can penetrate clouds and are less affected by weather conditions and illumination; thus, microwave remote sensing is more suitable for the dynamic monitoring of lake ice, particularly for areas where cloudy days often occur and for areas at high latitudes (Dörnhöfer and Oppelt, 2016; Duguay et al., 2015). Algorithms used to monitor lake ice that utilize microwave data are based on backscatter (scatterometry and altimetry) and brightness temperature. Compared with those of water, the backscattering coefficient and brightness temperature of ice are higher (Duguay et al., 2015). Geldsetzer et al. (2010) used RADARSAT-2 data at different polarizations to monitor ice cover on lakes located in the Old Crow Flats, Yukon, Canada. The available active microwave technologies are limited by a narrow frame width and hence low temporal resolutions (5–6 days), which limits their ability to monitor daily freeze-thaw variations of lake ice and study long-term climate change (Latifovic and Pouliot, 2007; Chaouch et al., 2014). However, the combination of two types of satellite observations can compensate for the shortcomings of both. For example, combining RADARSAT and Landsat Thematic Mapper (TM)/Enhanced Thematic Mapper Plus (ETM+), Cook and Bradley (2010) obtained a dataset with a 1–2 day revisit cycle, which was also free from the influence of weather. Using these data, they analysed the melt period of lake ice in the Upper and Lower Murray Lakes on Ellesmere Island from 1997 to 2007. Passive microwave technology has generated long-term time series of observation records and generally has a high frequency revisit cycle (at times twice daily or better). Although the spatial resolution of passive microwave data is often low (several km to tens of km), these data present considerable advantages for monitoring the ice coverage of oceans and large lakes (Chaouch et al., 2014; Duguay et al., 2015). Using QuickSCAT/SeaWinds data, Howell et al. (2009) set different thresholds for the Ku-band backscattering coefficients to extract freeze start, ablation start and ablation completion dates for Great Bear Lake and Great Slave Lake in Canada. Similarly, Kang et al. (2012) used the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) daily brightness temperature to extract the freeze-thaw dates as well as the duration of lake ice.

Studies have shown that lakes in the Tibetan Plateau are experiencing trends of later ice freezing and earlier ice ablation, which shortens the duration of lake ice coverage (Ke et al., 2013; Che et al., 2009; Yao et al., 2016). Located in the northeastern part of the Tibetan Plateau, Qinghai Lake lies at the intersection of the East Asian monsoon, the Indian monsoon and the westerly jet stream, and it is sensitive to climate change (Zhang et al., 2011). Since the 20th century, rising air temperatures have increased the amount of evaporation from Qinghai Lake to levels beyond the precipitation recharge rate such that the water level dropped by 2.75 m and the lake area decreased by 227.5 km^2 between 1959 and 2010 (Dong and Song, 2011). After 2004, however, the impact of glacier melt from the Qilian Mountains and increases in precipitation led to increases in the water level and an expansion of the water surface of Qinghai Lake (Yuan et al., 2012; Dong and Song, 2011; Wan et al., 2014). Based on the projected trends in global warming, the water level of Qinghai Lake may continue to rise (Dong and Song, 2011; Jin et al., 2013). Qinghai Lake experiences limited impacts from human activities; thus, it is a good indicator of natural climate change (Li et al., 2007), and its huge water body plays a significant regulatory role in the regional climate. Qinghai Lake has a long and stable period of lake ice coverage every year. Using optical remote sensing data (e.g., MODIS and AVHRR), some studies have extracted freeze-thaw dates for Qinghai Lake to validate the feasibility of using remote sensing data to monitor the variability of lake ice (Yin and Yang, 2005; Chen et al., 1995). However, there has been little research on long time series. Che et al. (2009) extracted the ice freezing dates and ablation dates of Qinghai Lake from 1978 to 2006 using passive microwave data, but the freezing and ablation of lake ice are components of a process of change, which is difficult to explain using only two specific days.

Thus, to analyse the complete characteristics of long time series variability, the objective of this study is to extract four lake ice dates (the annual freeze start, freeze completion, ablation start and ablation completion dates) and ice durations for Qinghai Lake from 1978 to 2016 using passive microwave Scanning Multichannel Microwave