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Characterizing C-band backscattering from thermokarst lake ice on the Qinghai–Tibet Plateau

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ABSTRACT

On the basis of weather observations and field measurements of lake ice, this study investigates multi-temporal C-band VV-polarized radar backscattering values from the thermokarst lakes and alpine meadow on the QTP during the period 2003–2010. In order to understand the scattering mechanism of lake ice, a scattering model is developed for lake ice that updates some assumptions adopted in previously developed models, including the roughness of the ice–water interface and the shape of vertically stacked centimeter-sized bubbles in the lake ice. We conclude the following: First, with a incidence angle range near 24°, the backscattering intensities of C-band VV-polarized ENVISAT–ASAR data exhibit a strong dependence on time, which is related to the processes of ice growth and decay on the QTP. Some unique backscattering characteristics of lake ice in this high-altitude region, as compared to those for high-latitude regions, are also discussed and documented in the paper. Secondly, the timing of lake ice-on in fall and ice-off in spring for this region can be identified in radar images by using a threshold of −12 dB for the backscatter intensity of the surrounding alpine meadow. Finally, the results of applying the scattering model indicate that surface scattering from the ice–water interface and volume scattering from gas bubbles embedded in the lake ice are the dominant scattering mechanisms for C-band VV polarized SAR and that the roughness of the ice–water interface and also bubble size are the most sensitive factors.

1. Introduction

Thermokarst lakes are common features of ice-rich permafrost landscapes. Such lakes are widespread in tundra and boreal lowland regions as a result of thermal degradation of the permafrost or melting of massive amounts of ground ice (Kokelj and Jorgenson, 2013; Niu et al., 2011). Changes in the spatial distribution and depth of permafrost resulting from global warming may be indicated by the occurrence of active thermokarst lakes (Smith et al., 2005). To understand these features of thermokarst lakes and the energy-related processes controlling the regional geomorphology and environment, numerous studies of high-latitude lakes have been undertaken (Kokelj and Jorgenson, 2013).

The Qinghai–Tibet Plateau (QTP), the highest and the most extensive plateau in the world, is identified as one of the most sensitive regions to climate change (Kang et al., 2010). There are more than 1500 lakes distributed across the permafrost regions of the QTP and the majority of these lakes are thermokarst features (Ling et al., 2012; Liu et al., 2009). During the past 30 years, permafrost has been persistently degrading, the permafrost table has been lowering, the active layer has been deepening, the supra-water table lowering, and the ground surface drying (Yang et al., 2010b). The shrinking or disappearance of lakes has been continuous across in the whole source region of the Yellow River and also the southeastern source region of the Yangtze River (Huang et al., 2011); however, in the continuous permafrost region along the Qinghai–Tibet Railway (QTR), the number of thermokarst lakes and ponds has been increasing under the influence of recent climate warming and accelerated surface disturbance (Lin et al., 2010; Niu et al., 2011). So far, in comparison with the high-latitude lakes in other regions, the characteristics and impacts of the high-altitude thermokarst lakes on the QTP have received relatively little attention from researchers (Lin et al., 2011; Pan et al., 2014). This has been due to the scarcity of meteorological stations, the vast numbers of lakes found on the plateau, and the harsh

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environment imposing logistical difficulties for extensive and continuous field observations. These are all good reasons for the use of remote sensing on the QTP (Song et al., 2014).

Lake ice formation, growth and decay are the result of either a surplus or a deficit in the energy balance of the ice cover, which is in turn determined by the air temperature, precipitation, wind and radiation (Brown and Duguay, 2010). Thus the ice phenology, including the date of freeze-up, length of ice duration and date of break-up, has been shown to be a good proxy indicator for local and regional climate variability and, therefore, useful in climate change investigations (Howell et al., 2009; Kropáček et al., 2013). Of particular interest in permafrost research is, whether the lake bottom is frozen completely or not (with grounded or floating ice present) by the end of the cold season as this determines the absence or presence of a talik beneath the lake (West and Plug, 2008), which plays a key role in the ecological, land surface and geomorphological process occurring on the ground and around lakes (Arp et al., 2011; White et al., 2008). It has been shown that radar remote sensing, which is not limited by weather and solar illumination conditions, has the capability to obtain significant information about lake ice characteristics and processes because of the capability of microwaves to penetrate ice (Jeffries et al., 2005). SAR images acquired by the ERS-1/2 (Jeffries et al., 1994; Morris et al., 1995), ASAR (Arp et al., 2012), Radarsat-1/2 (Duguay et al., 2002; Geldsetzer et al., 2010; Geldsetzer and van der Sanden, 2013), PALSAR (Engram et al., 2013) and TerraSAR (Jones et al., 2013) have been successfully applied for characterizing the backscattering from lake ice and classifying ice types. Great progress has been also made in quantitatively extracting these geophysical parameters using SAR imagery. Using the intensity information contained in multi-temporal SAR images acquired during the cold season to determine when lakes freeze to the bottom and also which lakes do so, ice thickness, water availability and lake bathymetric profiles can be determined (Duguay and Lafleur, 2003; Grunblatt and Atwood, 2014; Hirose et al., 2008; Kozlenko and Jeffries, 2000). SAR interferometry provides another possible method of determining lake depth and ice thickness (Wegmuller et al., 2010), although it is limited by the low coherence due to the increase in ice thickness during the relatively long revisit period of SAR satellites (Li et al., 2000). Recently, (Engram et al., 2012; Walter et al., 2008) investigated the potential use of SAR data to detect and estimate the potential release of large stocks of carbon in the thermokarst lakes. However, these studies only focused on radar signature from lake ice on the high-latitude region.

The present paper aims to investigate the temporal characteristics of backscattering from thermokarst lake ice in the northern QTP, China. Weather observations and field measurements of lake ice are used to support the interpretation of the temporal evolution of backscattering in multi-temporal SAR data sets. A microwave scattering model is also used to study the radar responses to these ice phenomena by simulating the effects of different ice parameters on the dominant scattering mechanism. To our knowledge, this is the first time radar remote sensing has been used to study thermokarst lakes on the QTP with low-latitude and high-altitude, where lake ice differs significantly from these high-latitude lakes.

2. Study area and data

2.1. Study area

The Beiluhe Basin, which includes the Xiushuihe valley and the Beiluhe beach lands and terraces, is located on the central QTP about 350 km southwest of the city of Golmud and surrounded by the Hoh Xil Mountain in the north and the Fenghuo Mountain in the south (see Fig. 1). In spite of the high altitude (4600 m on average), the terrain in the selected study area is relatively flat, with rolling hills varying only some tens of meters in elevation. The ground surface is covered by fine sands with gravels (0.5–2.1 m in thickness) and the vegetation is generally sparse, consisting of short prairie grasses and mosses. The thermokarst lakes in the Beiluhe Basin are relatively large, with a mean area of 8500 m^2, the biggest one is over 60,000 m^2 and the smallest is 1200 m^2. Some of the lakes are isolated while others are linked together and they are found in the lower parts of the terrain where ice-rich permafrost or masses of ground ice exist (Niu et al., 2011). According to a bathymetric survey, the depth of the lakes varies from 0.5 m to 2.5 m and the mean ice thickness in January is 0.5 m. The maximum thickness which has a range of 0.6–0.8 m occurs at the end of March and about 80% of the lakes do not freeze to the bottom (Lin et al., 2010; Niu et al., 2011).

According to the field observations, the lake ice in the Beiluhe basin may be classified (Huang et al., 2012) as either frazil or columnar ice: frazil ice forms first, followed by columnar ice. From late October to December, when the air temperature falls to below the freezing point of water and undergoes a slight super-cooling, the surface water starts to freeze rapidly (Kirillin et al., 2012). At the same time, a strong northwest wind prevails in the Beiluhe Basin, the surface layer is disturbed and small ice crystals do not have enough time to congeal, and then frazil ice forms and progressively joins together to form a solid sheet that consists of tiny granular crystals on the surface. However, vigorous ablation and evaporation of surface ice was sustained during the period of ice growth and decay, principally due to a low relative humidity (~30% in winter), a powerful prevailing northwest wind and strong solar radiation (Shenbin et al., 2006; Yang et al., 2010a). Therefore, if the air temperature during the day is high, a thin granular crystal layer that existed at the very start will gradually evaporate and ablate. After lakes have frozen over, columnar ice begins to form. As the ice thickness increases, ice crystals have enough time to grow but are confined by surrounding crystals. A preferred growth orientation appears for some crystals and causes the formation of vertical columnar crystals. The mean size of this columnar crystals increases with depth until it reaches a fixed level of about 20 mm.

Two types of gas bubbles have been observed in field ice samples, dot-line-shaped bubbles (DBs) found in the peripheral lake ice cover (Fig. 2(a) and (b)) and larger rachis-shaped bubbles (RBs) found in the ice cover at the center of the lake (Fig. 2(c) and (d)). In contrast to the tubular bubbles in other regions previously reported by (Jeffries et al., 1994; Li et al., 2011), DBs are made up of tiny spherical pockets with diameters of 0.3–2.5 mm that are arranged vertically in the direction of the ice growth. If the vertical spherical bubble strings are classified as 'cylindrical bubbles', the slenderness ratio will be within 100–200. The porosity ranges from 2% to 3%, and decreasing rapidly with depth until a constant value is reached where the distribution of DBs is uniform. An individual RB is relatively large and has a regular pattern of oblate round cakes or quasi-spheres 1–5 cm in diameter and 1–2 cm in height, with a flat top and a circular bottom. The individual units are vertically connected with pronounced horizontal banding, similar to "kotenoks" described by (Walter et al., 2006; Wu et al., 2014). Both the porosity of the ice and the mean size of these bubbles increase with depth and thus the density of the ice is also depth-dependent.

2.2. Data

Meteorological data recorded at the Wudaoliang Reference Climate Station at 35°13′N, 93°05′E (http://cdc.cma.gov.cn/home.do), located approximately 30 km north of the study area, includes daily average temperature, maximum temperature, minimum temperature, daily total water equivalent precipitation, and daily