Remote Sensing of Environment 137 (2013) 17–30

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

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

Monitoring glacier zones and snow/firn line changes in the Qinghai–Tibetan Plateau using C-band SAR imagery

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ARTICLE INFO

Article history:
Received 29 October 2012
Received in revised form 10 May 2013
Accepted 11 May 2013
Available online 26 June 2013

Keywords:
Continental glacier
Synthetic aperture radar
Equilibrium line
Firn line
Radar glacier zones

ABSTRACT

Small glaciers and ice caps in mountainous areas are often sensitive indicators of local and global climate change. In this paper, typical continental glaciers, the Dongkemadi and its neighbouring glaciers in the central area of the Qinghai–Tibetan Plateau, are monitored using multi-sensor C-band synthetic aperture radar (SAR) imagery. The study includes analysis of the alternating processes of ablation and freezing, the glacier zones detected on SAR images, and the changing snow/firn line across different days, seasons, and years. Experiments show that in late summer the wet snow-/firn-ice boundary, which is termed the late summer wet snow/firn line (WSFL) is easily detected on SAR images and it is relatively stable over multiple days. Also, the detected late summer WSFL, and the recorded yearly equilibrium line which reflects glacier mass balance, are close in a positive mass balance year, but the detected late summer WSFL is lower than the equilibrium line in a negative mass balance year. By combining pit and SAR observations it was found that the firn can be divided into two parts on the glaciers; the thick firn that lies in the neve basin is distinct on SAR images in winter, but the firn surrounding the basin with thickness ranging from 0 to 20 cm is difficult to recognize. The thick firn line (the lower boundary of neve basin) is stable in observations eight years apart. Based on the C-band VV polarization SAR image experiments, field work, and existing records, the spatiotemporal backscatter signature specific to the typical continental glacier is identified. The spatiotemporal backscatter signature helps to understand mass balance proxies and surface melt patterns of the glaciers in SAR images.

1. Introduction

1.1. Mountain glaciers and climate

About 10% of the Earth's land surface is covered by glacier ice at present, and generally 99% of the ice is retained within the Greenland and the Antarctic ice sheets (Cuffey & Paterson, 2010). Despite the low proportion, the remaining 1% of ice in mountain glaciers plays an important role in human life. Small glaciers and ice caps are often sensitive to regional and global climate changes and they are notable indicators of these changes (Haeberli et al., 2007; König et al., 2001a). It is estimated that about 60% of sea level rise since 1900 was contributed by the retreat of global mountain glaciers (Meier, 2007; Raper & Braithwaite, 2006). In the next century, mountain glaciers will continue to contribute significantly to sea level rise (Gardner et al., 2011; Radic & Hock, 2011; Raper & Braithwaite, 2006). In many parts of the world, they are important sources of water supply. For example, the three famous rivers in Asia, the Yangtze River, the Yellow River and the Indus River, all originate from mountain glaciers on the Qinghai-Tibetan Plateau. Accurate monitoring of glaciers is required for climate change research, natural hazard forecasting and human life.

1.2. Basic concepts of glacier facies

The surface mass balance of a glacier (such as the advance or retreat of snow and ice extents) depends on the climate (Lemke et al., 2007). The surface of a glacier can be roughly divided into accumulation areas where the glaciers gain mass, and ablation areas where the glaciers lose mass. These areas are separated by the equilibrium line where the snow accumulation is balanced by ablation (Cogley et al., 2011; Pellikka & Rees, 2010).

The concept of glacier facies was first proposed by Benson in his study on the Greenland Ice Sheet (Benson, 1960), and the concept was developed and connected with remotely sensed images in the following years (Williams et al., 1991). The glacier surface can be further divided into five facies (Cuffey & Paterson, 2010): 1) dry snow facies, no melting occurs here for a whole year; 2) percolation facies, some melting occurs on the surface, and melt water percolates a certain distance into the snow before refreezing; 3) wet snow facies, in these areas, in summer, all the snow accumulated since the end of the previous summer is raised to the melting point; 4) superimposed ice facies, in these areas superimposed ice is exposed at the surface. Superimposed ice is formed when the water accumulated from surface

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http://dx.doi.org/10.1016/j.rse.2013.05.016

snow melt percolates downwards to the colder ice surface and refreezes (Fujita et al., 1996; Nicolaus et al., 2003); 5) ablation facies, i.e., bare ice facies, in this area the entire annual accumulation of snow melts, exposing bare ice at the surface. Very few mountain glaciers show this entire sequence. A dry snow facies only exists where the annual highest temperature is below the melting point, such as the Greenland and Antarctic ice sheet and on parts of the temperate glaciers at very high elevations (König et al., 2001a). At the end of the ablation season, the firn line refers to the boundary between the wet snow and superimposed ice facies, and the lower boundary of the superimposed ice facies is the equilibrium line. Moreover, facies boundaries vary from year to year (Cuffey & Paterson, 2010).

1.3. Glacier surface monitoring using remote sensing

Traditionally, glacier mass balance has been determined by the glaciological method, using labor-intensive stake and pit observations distributed over a glacier (Cogley et al., 2011). Long-term time series of mass balance measurements are taken only on a few glaciers worldwide (Kaser et al., 2006; WGMS, 2008). The mass balance of glaciers may differ greatly in different regions, or even on different glaciers in the same region depending on physical properties (e.g. size, orientation), so there is significant need for additional mass balance data (Braithwaite, 1984; Rott et al., 2007). The equilibrium lines and the evolution of glacier zones are greatly influenced by regional climate (Ohumra et al., 1992), and they can be used to estimate mass balance (Albright et al., 1998; Floricioiu & Rott, 2001). Remote sensing provides efficient tools for monitoring glacier zones and boundaries (Williams et al., 1991). It has been reported that the Multi-angle Imaging SpectroRadiometer (MISR) (Nolin & Payne, 2007), the dual-frequency European Remote sensing Satellite (ERS) microwave radiometer (Tran et al., 2008), and optical imaging sensors such as Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Thematic Mapper (TM) (Williams et al., 1997), and Satellite Pour l'Observation de la Terre (SPOT) (Rabatel et al., 2005) have been successfully used to detect glacier zones based on surface albedo, roughness, or wetness differences. However, these passive sensors are prone to the influence of weather or ground snow cover conditions. A scatterometer has also been used to detect surface zones on ice caps (Wolken et al., 2009), but it is not suitable for mountain glaciers due to its low spatial resolution. In contrast, synthetic aperture radar (SAR) is a good tool for mountain glacier monitoring because it is sensitive to subtle wetness and roughness variations of snow and ice, it is hardly influenced by cloud cover, and it can acquire data day or night (Forster et al., 1996). Physical background on the interpretation of microwave measurements of snow and ice is summarized by Rott and Mätzler (1987) and König et al. (2001b) according to airborne experiments.

1.4. Radar glacier zones

In this paper, we use “facies” to reflect the physical properties of a glacier on annual timescales and “zones” to reflect the characteristic of a glacier detected by SAR sensors that operate on a timescale closer to days and weeks (Forster et al., 1996). The radar glacier zones are not necessary consistent with the glacier facies because the definition of zones are based on seasonal conditions and radar wavelength. Among the familiar radar bands, L-band is better in detecting crevasses beneath snow and firn (König et al., 2001b); C-band and X-band are sensitive to snow wetness (Rott & Mätzler, 1987). In this study C-band is used because there are plenty of long-term achieved satellite data in this band.

Depending on the liquid water content, snow can be classified into dry or wet snow. In completely dry snow, the host medium is air and the scatterers are ice particles. For wet snow, there are water droplets that reside between ice particles (Fung, 1994). On SAR imagery, dry snow is nearly transparent in the C-band, and the lower backscatter from wet-snow is caused by increased attenuation of the incident microwaves due to the liquid water in the snow (Baghdadi et al., 1998). Firn is snow that has survived a summer melt season and recrystallized into denser and larger grains. Although this traditional definition seems narrow while referring to the transformed snow on the polar glaciers without melting (Cuffey & Paterson, 2010), it is still suitable for temperate glaciers.

The percolation facies is composed of ice pipes, lenses, layers which distributed laterally when refreezing or appear slushy when melting (Rignot, 1995). The percolation zone in frozen state in the Greenland can be distinguished on radar image (Rau et al., 2000).

The superimposed ice zone, which lies between the percolation zone and bare ice zone, plays a critical but also complicated role in determining the position of the equilibrium line. The region where superimposed ice is exposed at the surface is defined as the superimposed ice zone, and it is only a small part of the region where superimposed ice exists (Brandt et al., 2008). On temperate glaciers, most of the superimposed ice forms in the lower part of the wet snow zone where the superimposed ice is buried beneath wet snow or firn (Cuffey & Paterson, 2010). In C-band, both surface scattering and volume scattering occur in the superimposed ice area due to the air bubbles in the ice (Langley et al., 2009). Superimposed ice is detectable by using cross-polarized ground penetrating radar (Langley et al., 2008); however, whether the superimposed ice is detectable on SAR imagery is controversial. In Brandt et al. (2008) and Langley et al. (2007), the authors give the backscatter coefficient extent of superimposed ice in C-band co-polarization. However, other authors have suggested that superimposed ice is not distinguishable from the bare ice zone (Casey & Kelly, 2010; Hall et al., 2000; König et al., 2001a). The difficulty in detecting superimposed ice zones complicates the acquisition of the equilibrium line location from remote sensing, which will be discussed below.

1.5. SAR and the equilibrium line

The equilibrium line altitude (ELA) is the spatially averaged altitude of the equilibrium line (Cogley et al., 2011). The ELA is closely connected with local climate factors such as solid precipitation and air temperature. The ELA rises when snowfall decreases and/or air temperature increases, and vice versa (Benn & Lehmkuhl, 2000). Scientists try to use remote sensing to replace expensive and intensive field work, but whether SAR has the ability to detect the annual equilibrium line is also uncertain. Engeset and Weydahl (1998) and Engeset et al. (2002) reported that the equilibrium line could be derived in Svalbard from winter SAR imagery. However, when looking at an eight-year time series of SAR images on the same glacier, those authors found that it represented the firn line rather than the equilibrium line (König et al., 2001b). In our study, the snow line is defined as the transient boundary of wet snow and ice on a glacier (Adam et al., 1997). In late summer, the snow line is the equilibrium line if a superimposed ice zone is not present (Rau et al., 2000). Therefore, the maximum late summer snow line elevations acquired from frequent SAR observations have been used to estimate the equilibrium line, and the closeness of these values suggests a potential use for SAR in complementing traditional in situ equilibrium line monitoring for mountain glaciers (Casey & Kelly, 2010; Smith et al., 1997). However, in a negative mass balance year, the equilibrium line is difficult to detect on SAR images because it is obscured by older firn with similar backscatter coefficients (Hall et al., 2000; Jaenicke et al., 2006).

1.6. Glacier monitoring in the Qinghai–Tibetan Plateau

Glaciers in the Qinghai–Tibetan Plateau are especially sensitive to climatic change (Kang et al., 2010; Li et al., 1998; Thompson et al., 1989). Mountain glaciers can be categorized into maritime glaciers and continental glaciers. Continental glaciers are characterized by low precipitation, low average air temperature, and high-altitude snow lines. Most of the glaciers on the Qinghai-Tibetan Plateau are