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Detection of land surface freeze-thaw status on the Tibetan Plateau using passive microwave and thermal infrared remote sensing data

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ABSTRACT

The freeze/thaw (F/T) cycle plays an important role in climate change and ecology research. Currently, soil F/T monitoring is restricted by low satellite spatial resolution or a relative long revisit cycle, which is one of the main problems in improving F/T monitoring resolution using available satellite data. Because temperature is a key parameter in determining soil F/T status, in this study, relatively high-resolution merged land surface temperature data were obtained using the Bayesian Maximum Entropy (BME) method by blending LSTs retrieved from passive microwave and infrared remotely sensed data. The merged temperature data were then used to downscale the passive microwave brightness temperature from 0.25° to 0.05°. Finally, the merged temperature and downscaled brightness temperature data were applied to discriminate the surface freeze/thaw status. A comparison with *in situ* data turned out that the downscaled brightness temperature could be used to determine soil F/T status with a total classification accuracy higher than 80%. The total freeze/thaw classification accuracy using merged temperature data was only 59.7%, which can be attributed to the temperature difference between the land surface and soil. After the adjustment with a relationship between soil temperature and land surface temperature, the classification accuracy reached 89.7%.

1. Introduction

The region where soil is either permanently or seasonally frozen occupies almost 52.5% of the total global land area, which is approximately 66 million km^2 (Kim et al., 2011; McDonald and Kimball, 2005). Most of these zones undergo a seasonal transition between frozen and thawed (F/T) landscape conditions. The F/T process has a major influence on the surface moisture and energy balance, which in turn impacts hydrology and terrestrial ecology, hence impacting weather and climate. For example, at high northern latitudes, seasonal freezing limits evapotranspiration and photosynthesis because biological processes are constrained as a result of the water in plants being frozen. In addition, the timing of seasonal snowmelt (Rawlins et al., 2005), the length of the growing season (Kimball et al., 2004), vegetation productivity (Nemani et al., 2003) and the release of nutrients in a form available to plants (Grogan and Jonasson, 2003), the associated land–atmosphere trace gas exchange (Kurganova et al., 2007) and other factors are closely linked to the landscape F/T status. Given that it is a strong indicator of climate change, surface F/T status is gaining attention in the scientific community.

Over the past few decades, a number of studies have focused on the issue of soil F/T status detection. Initially, high northern latitude weather station networks were established to monitor permafrost, but the application of these data was restricted by sparse spatial distributions, inconsistent monitoring, limited funding and embargoes on national data (Karl et al., 1995; Lanfear and Hirsch, 1999). Satellite optical remote-sensing methods provide spatially explicit regional information on snow-covered areas, albedo and temperature, which can be used to infer the surface freeze–thaw state. However, these methods are generally limited to coarse, 8 to 16-day temporal-scale composites for boreal and Arctic regions due to low solar illumination effects and cloud contamination (Running, 1998). In contrast, satellite microwave remote sensing is well suited for global F/T monitoring due to its insensitivity to atmospheric contamination and solar illumination effects and its strong sensitivity to the relationship between landscape dielectric properties and predominantly frozen and thawed conditions. Many algorithms have been constructed to monitor landscape F/T states using different sensors. For passive microwave sensors, the corresponding methods include a dual-index algorithm (Judge et al., 1997; Zhang and Armstrong, 2001; Zuerndorfer et al., 1990; Zuerndorfer and

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England, 1992), a decision tree algorithm (Jin et al., 2009), a discriminant function algorithm (Zhao et al., 2011), a seasonal threshold method (Kim et al., 2011), a standard deviation method (Han et al., 2015) and a polarization ratio(PR)-based on algorithm (Roy et al., 2015; Rautiainen et al., 2016). Though these methods and F/T data products have been validated with *in situ* data, monitoring of landscape F/T dynamics is restricted by current global operational satellites, which are at relatively coarse (~25 km resolution) spatial scales (Jin et al., 2009; Kim et al., 2011; Zhao et al., 2011; Chai et al., 2014; Han et al., 2015). For active microwave sensors, methods include a FT threshold value method (Way et al., 1997; Kimball et al., 2004; Kim et al., 2012; Du et al., 2015), a change detection algorithm (Frolking et al., 1999), and an edge detection algorithm (Canny, 1986; McDonald et al., 2004). Compared with passive microwave sensors, active sensors have higher spatial resolution and a stronger capacity to monitor landscape F/T states; however, the revisit period is longer, which may inhibit the detection of surface F/T processes. Seasonal F/T transitions are spatially heterogeneous and occur frequently throughout a season; both high spatial resolution and a high revisit rate are necessary to capture these characteristics (Running et al., 1999). New capabilities for F/T monitoring were made possible by the NASA Soil Moisture Active Passive (SMAP) mission, which was launched in January 2015 and provided global operational F/T products determined from lower frequency (L-band) radar backscatter measurements with 1- to 3-day temporal fidelity and a 3-km spatial resolution (Entekhabi et al., 2010). However, the radar sensor failed after operating for less than three months, which is inadequate for climate change and ecological research. Thus, one of the main challenges is finding alternative approaches to enhance F/T monitoring ability and spatial resolution using the available satellite data.

Frozen soil refers to all types of rock and soil containing ice when the temperature is below zero degrees Celsius (Xu et al., 2010). In this context, temperature is a key parameter in determining the soil F/T state. Land surface temperature (LST) products derived from passive microwave (PMW) and thermal infrared (TIR) remote sensing sensors provide spatial estimates of near-surface temperature values (Gillespie et al., 1998; Holmes et al., 2009; Li et al., 2013; Mcfarland et al., 1990; Qin et al., 2001; Royer and Poirier, 2010; Surdyk, 2002; Wan and Dozier, 1996). However, these values are usually either incomplete or have low accuracy because of cloud contamination (Chen et al., 2011) and coarse spatial resolution (Zhou et al., 2015). In the present study, the PMW and TIR remote sensed LST products were integrated using the Bayesian Maximum Entropy (BME) method to obtain high-resolution temperature information, which was used in two ways: to directly detect the landscape F/T state and to downscale the brightness temperature (TB) from the PMW sensor. The goals of this study were to (1) investigate the feasibility of using temperature information only to achieve land surface F/T monitoring and (2) use the downscaled TB to distinguish landscape F/T state for finer spatial resolution, finally satisfying the requirements for application in climate change and ecology research.

2. Study area and data

2.1. Study area and validation data

The Tibetan Plateau (TP), which has been called the “Third Pole” (Qiu, 2008), has a considerable impact on the surrounding climate and environment through atmospheric and hydrological processes (Wu et al., 2007; Yang et al., 2011). As the highest plateau in the world, the TP is covered by permafrost and seasonally frozen ground with an average elevation of 4000 m above sea level and an area of approximately 2.5×10^6 km^2. Our study area is on the central TP near the town of Naqu (as shown in Fig. 1). This is a seasonally frozen soil dominated region, with an average elevation of 4650 m and an area approximately matching 16 AMSR-E grid boxes. In this region, the annual precipitation is 400–500 mm, and three-quarters of the precipitation occurs during the monsoon season (June to August) due to the influence of the South Asian summer monsoon. The terrain is relatively flat with rolling hills and hummocks. The area is typically characterized by short and sparse grasses. The soil primarily comprises sand and silt, and the clay content is low with a value <10%. In addition, the organic carbon content is high at the top soil layer and gradually decreases with depth. More details about this area can be found in previous study (Yang et al., 2013). In addition, a few water bodies are located near the western edge of the study area, and Naqu City lies in the center of the area.

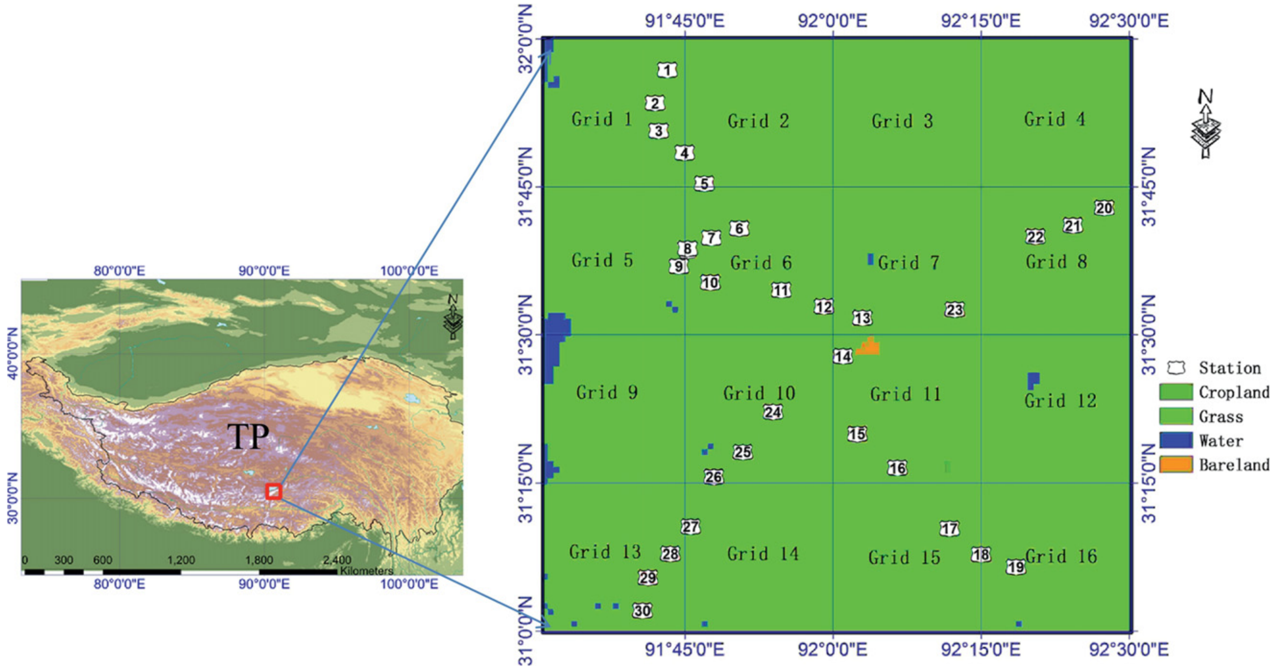

Fig. 1. Overview of the study area: land cover map and station distributions around Naqu on the central TP.