Remote Sensing of Environment 191 (2017) 168–178

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Characterizing global patterns of frozen ground with and without snow cover using microwave and MODIS satellite data products

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ARTICLE INFO

Article history:
Received 31 August 2016
Received in revised form 12 December 2016
Accepted 18 January 2017

Keywords:
MODIS
MEaSUREs Freeze/Thaw data records
Snow cover
Frozen ground
Frozen season
Subnivium

ABSTRACT

How organisms respond to climate change during the winter depends on snow cover, because the subnivium (the insulated and thermally stable area between snowpack and frozen ground) provides a refuge for plants, animals, and microbes. Satellite data characterizing either freeze/thaw cycles or snow cover are both available, but these two types of data have not yet been combined to map the subnivium. Here, we characterized global patterns of frozen ground with and without snow cover to provide a baseline to assess the effects of future winter climate change on organisms that depend on the subnivium. We analyzed two remote sensing datasets: the MODIS Snow Cover product and the NASA MEaSUREs Global Record of Daily Landscape Freeze/Thaw Status dataset derived from SSM/I and SSMIS. From these we developed a new 500-m resolution dataset that captures global patterns of the duration of snow-covered ground (D_{ws}) and the duration of snow-free frozen ground (D_{wos}) from 2000 to 2012. We also quantified how D_{ws} and D_{wos} vary with latitude. Our results show that both mean and interannual variation in D_{ws} and D_{wos} change with latitude and topography. Mean D_{ws} increases with latitude. Counter-intuitively though, D_{wos} has longest duration at about 33°N, decreasing both northward and southward, even though the duration of frozen ground (either snow covered or not) was shorter than that at higher latitudes. This occurs because snow cover in mid-latitudes is low and ephemeral, leaving longer periods of frozen, snow-free ground. Interannual variation in D_{ws} increased with latitude, but the slopes of this relationship differed among North America, Europe, Asia, and the Southern Hemisphere. Overall, our results show that, for organisms that rely on the subnivium to survive the winter, mid-latitude areas could be functionally colder than either higher or lower latitudes. Furthermore, because interannual variation in D_{wos} is greater at high latitudes, we would expect organisms there to be adapted to unpredictability in exposure to freezing. Ultimately, the effects of climate change on organisms during winter should be considered in the context of the subnivium, when warming could make more northerly areas functionally colder in winter, and changes in annual variation in the duration of snow-free but frozen conditions could lead to greater unpredictability in the onset and end of winter.

1. Introduction

Winter is a key driver of species distributions through its effects on individual performance, community composition, and ecological interactions (Williams et al., 2014). Thus, differences in the distributions of species often reflect differences in their susceptibility to resource scarcity and energy deficits during winter (Kreyling, 2010; Pauli et al., 2013). Discussions of the effects of climate change on ecological systems are often centered around the growing season, where climate warming will affect flowering phenology, the length of the growing season, droughts, fire regimes, etc. However, winter is also subject to climate change (Williams et al., 2014) through changes in snow cover, soil freeze/thaw cycles, and lake and river ice (Fountain et al., 2012; Kim et al., 2012; Peng et al., 2013). These changes may strongly influence biophysical conditions and biogeochemical processes (Fountain et al., 2012; Makoto et al., 2013), and hence organisms (Kreyling, 2010; Pauli et al., 2013). Winter as a distinct season attracts less scientific attention by biologists than other seasons, at least partly due to the perception that there is little biological activity and to the inherent difficulties of field work during winter (Campbell et al., 2005).

Whether or not an area is covered by snow during winter can greatly affect the condition and survival of organisms because snow cover affects microclimates (Decker et al., 2001; Isard and Schaetzl, 2007; Williams et al., 2014). Beneath the snow there is an insulated and thermally stable refugium – the subnivium (Pauli et al., 2013). The subnivium forms when heat is released from the soil, and warm, moist air is trapped by the snow (Petty et al., 2015). Areas with a

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http://dx.doi.org/10.1016/j.rse.2017.01.020

subnivium generally have higher overwintering success of plants, animals, and microbes (Aitchison, 2001; Pauli et al., 2013; Williams et al., 2014). The higher temperatures in the subnivium can reduce root damage and plant death during winter by alleviating frost penetration into the soil (Kreyling, 2010; Starr and Oberbauer, 2003). Animals that overwinter in surface soils, including reptiles, amphibians and insects, may require the thermally stable subnivium for survival (Aitchison, 2001; Bale and Hayward, 2010; Jones, 1999; Williams et al., 2014). Furthermore, the subnivium can also keep soil temperatures above the threshold required for microbial respiration (Pauli et al., 2013; Sullivan et al., 2008), causing rates of soil microbial activity to be sufficiently high in winter to comprise a significant percentage of annual activity (Campbell et al., 2005). High rates of microbial activity can also result in increased mineralization of organic matter and trace gas concentrations during winter (Campbell et al., 2005; Pauli et al., 2013; Schimel et al., 2004). However, despite its ecological importance, the subnivium has not been mapped globally (Pauli et al., 2013; Williams et al., 2014).

Mapping the subnivium requires information on frozen ground and snow cover, yet most research has focused on only one of these two attributes. As a result, there are excellent remote sensing datasets of freeze/thaw cycles in terms of the date of spring thaw, the date of fall freeze, and the duration of the frozen/non-frozen season (Kim et al., 2012; Smith et al., 2004; Zhang et al., 2011), as well as assessments how these dates have shifted in recent decades, causing earlier spring thaw and shorter frozen seasons. Similarly, there are excellent remote sensing datasets of the length of the snow season, the maximum snow depth, the maximum snow extent, the timing of snowmelt, etc. (Déry and Brown, 2007; Dye, 2002; Kim et al., 2015; Peng et al., 2013). Trends in recent decades have been earlier spring snowmelt, longer snowmelt periods, and decreased snow cover duration (Kim et al., 2015; Peng et al., 2013). However, to our knowledge, few studies have combined freeze/thaw status and snow cover (Kim et al., 2015), even though the combination of these two attributes determines the duration of the subnivium.

Satellite remote sensing data have greatly advanced the scientific understanding of snow cover, soil freeze/thaw status, and other winter-specific variables at regional to global scales. Ground-based meteorological networks have been monitoring snow for a long time, but the discrete distribution of stations cannot capture spatial variability, especially in remote areas (Pu et al., 2007). A number of digital snow products based on remote sensing observations are available (Frei et al., 2012), and the longest NOAA snow cover extent (SCE) climate record (CDR) has been widely used for regional-scale climate studies, monitoring, and model validation (Estilow et al., 2014). A suite of MODIS snow cover products available since 2000 have been generated using MODIS sensor measurements (Hall et al., 2002). The advantage of the MODIS data is their higher spatial resolution. In particular, the 8-day composite product of MOD10A2 minimizes the effect of cloud contamination (Liang et al., 2008), and its global availability at 500-m resolution is ideal for broad-scale research on winter ecology.

Microwave remote sensing is well suited for freeze/thaw monitoring due to its relative insensitivity to atmospheric contamination and solar illumination effects, and strong sensitivity to changes in the predominant frozen/thawed state of water (Kim et al., 2011; Kim et al., 2012). One of the NASA MEaSUREs Global Record of Daily Landscape Freeze/Thaw Status datasets from Scanning Multichannel Microwave Radiometer (SMMR), Special Sensor Microwave/Imager (SSM/I), and Special Sensor Microwave Imager/Sounder (SSMIS) provides a consistent long-term global record available daily since 1979 of land surface freeze/thaw state dynamics for all vegetated regions where low temperatures are a major constraint on ecosystem processes. Prior analyses of this dataset have revealed close biophysical linkages between several freeze/thaw-associated variables and the duration of seasonal snow and frozen ground, the timing and length of the growing season, and vegetative productivity and water cycling (Kim et al., 2012, 2015; Zhang et al., 2011). The microwave satellite-based dataset is thus an ideal option for monitoring ground freeze/thaw status given its long duration.

Here, we characterize global patterns of frozen ground with and without snow cover to assess the duration of the subnivium; this provides baseline data to understand current and forecast future winter conditions that affect overwintering organisms. We combined two datasets, the MODIS Snow Cover product and the NASA MEaSUREs Freeze/Thaw dataset from SSM/I and SSMIS, and developed a new 500-m resolution dataset from 2000 to 2012 which shows global patterns of the duration of snow-covered ground (D_{ws}) and the duration of snow-free frozen ground (D_{wos}). We defined the timing and length of the frozen season based on the daily freeze/thaw records. To illustrate the potential use of our new dataset, we investigated latitudinal patterns in the mean and variation of D_{ws} and D_{wos}. These patterns show both nonlinear latitudinal gradients and differences in latitudinal gradients among continents, emphasizing the value of our dataset.

2. Data and methods

2.1. Data

We used the NASA MEaSUREs Global Record of Daily Landscape Freeze/Thaw Status dataset (Version 3) from SSM/I and SSMIS to determine frozen/thawed status, and the timing and duration of the frozen season. The dataset is available on a daily basis with 25-km spatial resolution from 1979 to 2012. It applies a seasonal threshold approach to the continuous daily (A.M. and P.M.) radiometric brightness temperatures (Kim et al., 2011). Thus, four discrete categories are distinguished on a daily basis: frozen (A.M. and P.M.), thawed (A.M. and P.M.), transitional (A.M. frozen and P.M. thawed), and inverse transitional (A.M. thawed and P.M. frozen) ground. Mean annual classification accuracies at P.M. and A.M. are approximately 92.2 and 85.0%, respectively (Kim et al., 2011). The retrieved status represented predominant frozen or thawed conditions within the satellite footprint and does not distinguish individual landscape elements, including soil, vegetation, and snow cover (Kim et al., 2015). The dataset excludes non-vegetated areas, and those areas which are not constrained by seasonal cold temperatures detected by a simple cold temperature constraint index (Kim et al., 2015). The daily dataset is available at the National Snow & Ice Data Center (NSIDC) (http://nsidc.org/).

We analyzed the 8-day composite MODIS Snow Cover product (MOD10A2) to determine ground snow-cover status. The dataset is available globally, at a spatial resolution of 500 m, from 2000 to present. The snow-cover algorithm is based on a grouped-criteria technique, which applies band ratio and a suite of threshold-based criteria to determine snow or no snow status on different land-cover types (Hall et al., 2002). The MODIS snow cover products have been assessed at both global and regional scales, and the overall accuracy is generally >80% but varies by land-cover type, snow conditions (e.g., snow depth), and the number of days used to make the composite (Hall and Riggs, 2007; Klein and Barnett, 2003; Liang et al., 2008; Pu et al., 2007). Compared to the daily MODIS snow cover product (MOD10A1), the 8-day composite effectively reduces cloud contamination and thereby provides more consistent coverage (Liang et al., 2008; Pu et al., 2007). Because MODIS sensors cannot receive optical information effectively in high-latitude areas during winter due to the effect of polar night, we were not able to analyze areas above 62°N. The MODIS snow cover data that we used were also downloaded from the NSIDC.

2.2. Methods

We defined the timing and duration of the frozen season annually on a pixel basis, and calculated D_{ws} and D_{wos} within the pre-defined frozen season (Fig. 1). For each pixel, we calculated the freeze frequency, which we defined as the number of occurrences of frozen ground (A.M. and P.M. frozen, A.M. frozen and P.M. thawed) at the same day-of-year