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Influence of canopy shading and snow coverage on effective albedo in a snow-dominated evergreen needleleaf forest

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ABSTRACT

The presence of a forest canopy above highly reflective snow results in overall lower surface albedo, even when snow is intercepted by the forest canopy. The effective forest snow albedo (FSA) explains the overall upwelling radiation from the forest relative to the incoming radiation. FSA is strongly influenced by the complex pathways of radiation as it travels through the 3D canopy structure. Current errors in calculations of FSA arise due to uncertainties in how models should treat masking of snow by vegetation. Improvement of distributed models is currently limited by a lack of measurements that demonstrate both spatial and temporal variability over forests. We present above-canopy measurements of winter-time effective forest snow albedo using up- and down-looking radiometers mounted on an octocopter UAV for a total of fifteen flights on eight different days. Ground-view fractions across the flight path were between 0.12 and 0.81. Correlations between FSA and both ground-view fraction and maximum canopy height were statistically significant during 14 out of 15 flights, but correlation strength varied between flights as a function of solar angle and snow cover. Measured effective albedo across the flight path differed by up to 0.33 during snow-on canopy conditions. A subsequent comparison between maximum interception and no interception showed effective albedo differed by up 0.27. A similar variation (0.26) in effective FSA was measured during low (44°) and high (67°) solar zenith angles. This study therefore demonstrates that temporal and spatial variations in effective albedo caused by canopy shading of the snow surface are therefore as important as temporal variations caused by interception of snow by the canopy. Calculation of effective albedo of forested areas requires careful consideration of canopy height, canopy coverage, solar angle and interception coverage. The results of this study should be used to inform snow albedo and canopy structure parametrizations in local and larger scale land surface models.

1. Introduction

Approximately 19% of the Northern Hemisphere seasonal snow covered area overlaps with boreal evergreen forest (Rutter et al., 2009). This overlap of highly reflectant snow and absorbent forests creates strong heterogeneity in the surface energy budget and overall reduces the reflectivity of the land surface compared with forest-free snow covered surfaces (Betts and Ball, 1997; Loranty et al., 2014). Overall, boreal and subalpine forests have been shown to have a warming effect on the global climate through the reduction in effective surface albedo (Brovkin et al., 2009; Abe et al., 2017), although uncertainty remains in how this effect will continue with projected land use and land cover changes (Bright et al., 2015). These variations greatly influence local ecohydrological processes and regional and global climate due to the snow albedo feedback, altering the incident energy reflected by the surface (Betts, 2000; Thackeray et al., 2014). Changes in the extent of seasonal snow cover, deforestation, and the northern migration of the boreal vegetation are all direct consequences of a changing climate, driving changes in the strength of the snow albedo feedback (Loranty et al., 2014).

At the local scale, accurate representation of effective forest snow albedo (FSA) can lead to better estimations of absorbance of shortwave radiation, which subsequently can give indications of canopy temperature and the sub-canopy energy budget for input into ecological and hydrological models (e.g. Nakai et al., 1999; Stähli et al., 2009; Bartlett and Verseghy, 2015). At regional and global scales, accurate estimation of FSA is required to improve models of the effects of climate change in the vulnerable northern latitudes and further understand the feedback processes in the boreal forest in relation to snow cover and climate change (Bartlett and Verseghy, 2015). Development of characterizations of FSA at distributed scales is currently hampered by the limitations of point measurements driving model development and validation. At larger land-surface and global scales, errors in calculations particularly arise due to uncertainties in how models should treat

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masking of snow by vegetation (Qu and Hall, 2014; Essery, 2013; Thackeray et al., 2015). Winter-time observations over vegetated surfaces are therefore required to improve understanding of FSA and constrain modelled albedo in the different parametrizations employed in land surface models (Qu and Hall, 2014) as well as validate certain assumptions on which surface reflectance models depend (Vikhamar and Solberg, 2003).

Surface albedo in forests is theoretically composed of two components, the albedo of the ground (α_g) and the canopy (α_c):

$$\alpha_{tot} = F_g\alpha_g + F_c\alpha_c \tag{1}$$

where F_g is the fraction of ground and F_c is the fraction of canopy (1 - F_g). Measured albedos of these individual surfaces can vary between 0.95 (snow-covered ground) to 0.09 (trees) (Bartlett and Verseghy, 2015), thus α_{tot} is dependent on forest density, tree species, canopy interception and the characteristics of the snow surface. Albedo described in Eq. (1) is an idealized concept, while the effective surface albedo is what is typically measured, determined as the ratio between incident and upwelling shortwave radiation measured above the canopy. The effective FSA, therefore, describes the overall reflected radiation from the land surface, which is strongly dependent not only on the albedo of the different surfaces, but is influenced by multiple reflections of radiation as it travels through the 3D canopy structure. Overall effective surface albedo of the ground is thus comprised of more than just two components. The pathway of incident radiation through the canopy results in sun-lit and shaded areas of the snow surface, which have different effective albedos given that the above-canopy incident radiation remains spatially consistent. Partitioning of the land surface for calculation of FSA therefore requires the addition of a shaded and a sun-lit snow surface fraction:

$$\alpha_{eff} = F_g\alpha_g + F_c\alpha_c + F_s\alpha_s + F_{sh}\alpha_{sh} \tag{2}$$

where g, c, s and sh denote ground (no snow), canopy, sun-lit snow and shaded snow, respectively. The spatial arrangement of these four variables are controlled primarily by the solar position and the forest size and distribution, however current understanding is limited by an availability of spatially distributed measurements.

Forest distribution descriptor variables have been shown to correlate with effective forest snow albedo. For example, effective FSA exhibits greater variability between different tree species compared to variations in leaf area index (LAI), which is often used to describe forest density in land surface models (Kuusinen et al., 2014). Effective FSA decreases with increasing LAI or forest density (Amiro et al., 2006; Manninen et al., 2012; Kuusinen et al., 2014) and decreases with increasing forest age, both in summer and winter conditions (Amiro et al., 2006). Used together, information on both tree species and forest structure can improve albedo prediction in summer months compared to using tree structure or species alone (Kuusinen et al., 2016). These relationships have not been investigated during winter snow-on conditions.

Data of FSA in snow-dominated areas are sparse, and only a limited number of research sites worldwide feature suitable instrumentation. Bartlett and Verseghy (2015) summarized albedo values measured at various sites worldwide and concluded that the change in albedo from snow covered to snow free canopy varies with stand properties. For example, most studies have demonstrated that winter albedos increase following snowfall due to snow being intercepted by the canopy (e.g. Betts and Ball, 1997; Arain et al., 2003; Suzuki et al., 1999; Stähli and Gustafsson, 2006; Wang and Zeng, 2010; Kuusinen et al., 2012). Measured values were varied, with wintertime FSA ranging between 0.07 and 0.43, depending on location, species and canopy or ground snow cover. Point-based measurements have facilitated detailed assessment of temporal variations in FSA, for example Kuusinen et al. (2012) demonstrated that FSA of a boreal Scots pine stand is greatest in midwinter and Stähli et al. (2009) used four years of continuous above-canopy measurements to show that FSA increases with increasing interception during cloudless days. A lack of studies using spatially distributed measurements of FSA present an ongoing challenge in understanding how these measured albedo values represent forests across larger spatial scales particularly in heterogeneous forest environments where forest structure and shaded-view fraction exhibit strong spatial and temporal variability.

Essery (2013) highlighted that some climate models employ unrealistic vegetation parameters or distributions, leading to errors in estimation of FSA. The necessary improvements in these land surface models cannot be made without detailed measurements of effective FSA across different vegetation structures and densities. Satellite images can offer information regarding spatial variations of FSA, however variability in FSA affected by fragmentation, gaps, clearings, and canopy shading in forests at spatial resolutions < 30 m are not well identified in available satellite products. Details regarding spatial variations in FSA have so far eluded the modelling community, relying instead on bulk albedo values based on point measurements applied to varying plant functional types within land surface models (Loranty et al., 2014). Available data from ground-based point measurements or satellites are limited in spatial and temporal coverage and resolution. There is currently a data gap between station measurements at the point scale with high temporal but low spatial resolution and coarse resolution satellite data products that fail to demonstrate effects of discontinuous canopy structures and have low return times limiting the temporal resolution. Airborne measurements from manned and unmanned aerial vehicles (UAVs) are currently the only method available to fill this data gap.

High flying heights of manned vehicles over forest cover limit the utility of remotely sensed data due to an increase in the sensor's ground footprint, decreased imaging resolution and the reduction in viewable gap fractions, especially when sensors have a high range of scanning angles (Liu et al., 2004). Manninen et al. (2012) partially solved this issue through attaching radiometers to a manned helicopter, which allowed slower flight speed for increased measurement accuracy. While good areal coverage was reached in this study, the large cost, lack of repeatability of measurements and the relatively fast flying time of manned aerial vehicles limits the utility of results for input into radiative, hydrological and other land surface models.

More recently, higher resolution estimates of albedo have been obtained using unmanned aerial vehicles, which are comparatively low cost and can still cover large surface areas with relatively high spatial resolution (Ryan et al., 2017a). These new methods have helped provide insights into the spatial variability of albedo of the Greenland Ice Sheet, revealing that in-situ point measurements can overestimate the albedo of ice by up to 0.1 (Ryan et al., 2017b). This new measurement technique reveals information regarding the spatial variability that was previously unknown based on satellite and point measurements. The utilization of a UAV for data acquisition has introduced a relatively cost- and time-efficient method with fast turn-around times for repeatability that are not available from manned aerial vehicles or satellites. This new data acquisition method through UAVs is particularly suitable for forested environments where view of the top of the canopy has previously only been available through the installation of a tower.

Moving radiometer platforms have previously been successfully employed below-canopy to measure net radiation (Chen et al., 1997) and incoming shortwave and longwave radiation at the understory surface (Blanken et al., 2001; Stähli et al., 2009; Webster et al., 2016). This method has so far been limited to the sub-canopy as installation difficulties restrict its usefulness for above-canopy measurements. In this study, we develop a moving net shortwave radiation platform installed on a rotocopter to relate the albedo of a coniferous forest to canopy structure and solar position during different snow and meteorological conditions.

This study aims to determine controls on effective FSA through the deployment of a pair of moving net shortwave radiometers on a rotocopter across a discontinuous forested environment during the 2017 snowmelt period (March and April). A range of canopy characteristics,