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Imaging spectroscopy to assess the composition of ice surface materials and their impact on glacier mass balance

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ABSTRACT

Glacier surfaces are not only composed of ice or snow but are heterogeneous mixtures of different materials. The occurrence and dynamics of light-absorbing impurities affect ice surface characteristics and strongly influence glacier melt processes. However, our understanding of the spatial distribution of impurities and their impact on ice surface characteristics and the glacier's energy budget is still limited. We use imaging spectroscopy in combination with in-situ experiments to assess the composition of ice surface materials and their respective impact on surface albedo and glacier melt rates. Spectroscopy data were acquired in August 2013 using the Airborne Prism EXperiment (APEX) imaging spectrometer and were used to map the abundances of six predominant surface materials on Glacier de la Plaine Morte, Swiss Alps. A pixel-based classification revealed that about 10% of the ice surface is covered with snow, water or debris. The remaining 90% of the surface can be divided into three types of glacier ice, namely ~7% dirty ice, ~43% pure ice and ~39% bright ice. Spatially distributed spectral albedo derived from APEX reflectance data in combination with in-situ multi-angular spectroscopic measurements was used to analyse albedo patterns present on the glacier surface. About 85% of all pixels exhibit a low albedo between 0.1 and 0.4 (mean albedo 0.29 ± 0.12), indicating that Glacier de la Plaine Morte is covered with a significant amount of light-absorbing impurities, resulting in a strong ice-albedo feedback during the ablation season. Using a pixel-based albedo map instead of a constant albedo for ice (0.34) as input for a mass balance model revealed that the glacier-wide total ablation remained similar (10% difference). However, the large local variations in mass balance can only be reproduced using the pixel-based albedo derived from APEX, emphasizing the need to quantify spatial albedo differences as an important input for glacier mass balance models.

1. Introduction

Glaciers surfaces are neither clean nor homogeneous. In fact, glacier surfaces are heterogeneous mosaics of different materials and structures (e.g. Cuffey & Paterson, 2010; Oerlemans, 2001). The darkening of glacier surfaces is a phenomenon observed in various regions across the globe, for example in the European Alps (e.g. Oerlemans, Giesen, & Van Den Broeke, 2009), the Himalayas (Takeuchi, 2001), or on the Greenland ice sheet (Dumont et al., 2014). The existence of materials that are darker compared to actual bare-ice surfaces has a large impact on ablation, eventually enhancing glacier melt. This feedback becomes particularly important in the context of climate change and strong glacier retreat, since it hampers our capability to project the future of glacier ice worldwide (e.g. Flanner, Zender, Randerson, & Rasch, 2007; Painter, Bryant, & McKenzie Skiles, 2012; Xu et al., 2009).

Recent studies have shown that light-absorbing impurities, e.g. mineral dust, soot, black carbon, or other organic matter, are crucial in defining melt rates of snow and ice and influence processes across a large range of temporal and spatial scales (Alexander et al., 2014; Oerlemans et al., 2009; Pedersen, Berntsen, Gerland, & Warren, 2010). In most cases, a decrease in surface reflectance due to impurities increases the light absorbance causing enhanced snow and ice melt and therefore represents a positive feedback.

Several research activities have been carried out to investigate the feedback between ice and snow melt and light absorbance. Organisms living on snow and ice surfaces, for example, have received considerable attention while focusing on their distribution, biological activities, as well as their morphodynamics (Hodson et al., 2010; Wharton, McKay, Simmons, & Parker, 1985). Further, in-situ sampling and remote sensing was used to study cryoconite (Langford, Hodson, Banwart, & Bøggild, 2010; Takeuchi, 2002a), glacier facies (Klein & Isacks, 1999; Nolin & Payne, 2007; Pope & Rees, 2014), and debris composition on glacier surfaces (Casey, 2011). Yet other studies apply time-lapse imaging and automatic weather stations to monitor cryoconite or albedo locally (Irvine-Fynn, Bridge, & Hodson, 2011; Oerlemans & Knap, 1998). Especially in snow science, remote sensing techniques revealed important and essential information about snow

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coverage, snow properties such as grain size or liquid water content, and snow albedo (Dozier, Green, Nolin, & Painter, 2009; Joerg, Weyermann, Morsdorf, Zemp, & Schaepman, 2015; Nolin & Dozier, 2000; Painter, Seidel, Bryant, McKenzie Skiles, & Rittger, 2013; Painter et al., 2009).

Despite the various research lines and efforts related to snow, little is yet known about similar aspects considering bare ice that appears in the ablation area of glaciers after the melting of winter snow. This limits current process understanding since impurities and surface albedo are two factors crucially determining ice ablation. Bare-ice surfaces represent a large, and – in times of warmer and longer summers – growing fraction of all ice masses worldwide, thus increasingly provoking the ice-albedo feedback.

Compared to snow, bare-ice surfaces tend to be more heterogeneous across spatial scales, complicating the characterization of surface properties and quantitative assessments of light-absorbing impurities. Furthermore, liquid water present on glacier surfaces is able to efficiently reallocate and transport impurities, adding a temporal component to the complexity of respective assessments (Chandler, Alcock, Wadham, Mackie, & Telling, 2014). Concerning the ability to determine ice surface albedo, various factors such as surface roughness, presence of water, crystal size, anisotropic effects, and many others have a large influence (e.g. Cuffey & Paterson, 2010) and thus challenge the retrieval of ice surface albedo. Existing satellite-based approaches to distinguish glacier-wide albedo values (Dumont et al., 2012; Knap, Reijmer, & Oerlemans, 1999; Paul, Machguth, & Kääb, 2005) typically suffer from a scaling mismatch since sampling distances (pixel sizes) are much coarser than albedo variability of the ice surface (e.g. Azzoni et al., 2014).

The global importance of rapid and ongoing glacier melt requires dedicated research focusing on the dynamics and underlying processes of bare-ice surface albedo changes. In particular the divergence between typical spatio-temporal length scales of melting processes and state-of-the-art remote sensing or in-situ field sampling demands more suitable and interdisciplinary methodologies. In this paper we demonstrate the applicability of a combined approach using observations and models to improve current knowledge about the temporal and spatial distribution of light-absorbing impurities on bare-ice surfaces and to assess their impact on glacier albedo and the energy and mass balance of glaciers. In particular, we use in-situ and airborne spectroscopy data and a high-resolution orthoimage (i) to map the distribution of different glacier surface materials and (ii) retrieve a glacier-wide spectral albedo map. Furthermore, we apply a mass balance model to (iii) evaluate the impact of glacier surface albedo on calculated mass balance distribution.

2. Study site and data

2.1. Study site

Glacier de la Plaine Morte (46°23′N, 7°30′E) is the largest plateau glacier in the European Alps covering an area of 7.52 km^2 in 2013. The glacier is located on the main water divide between the Rhine and the Rhone River in the Bernese Alps, western Switzerland (Fig. 1). The

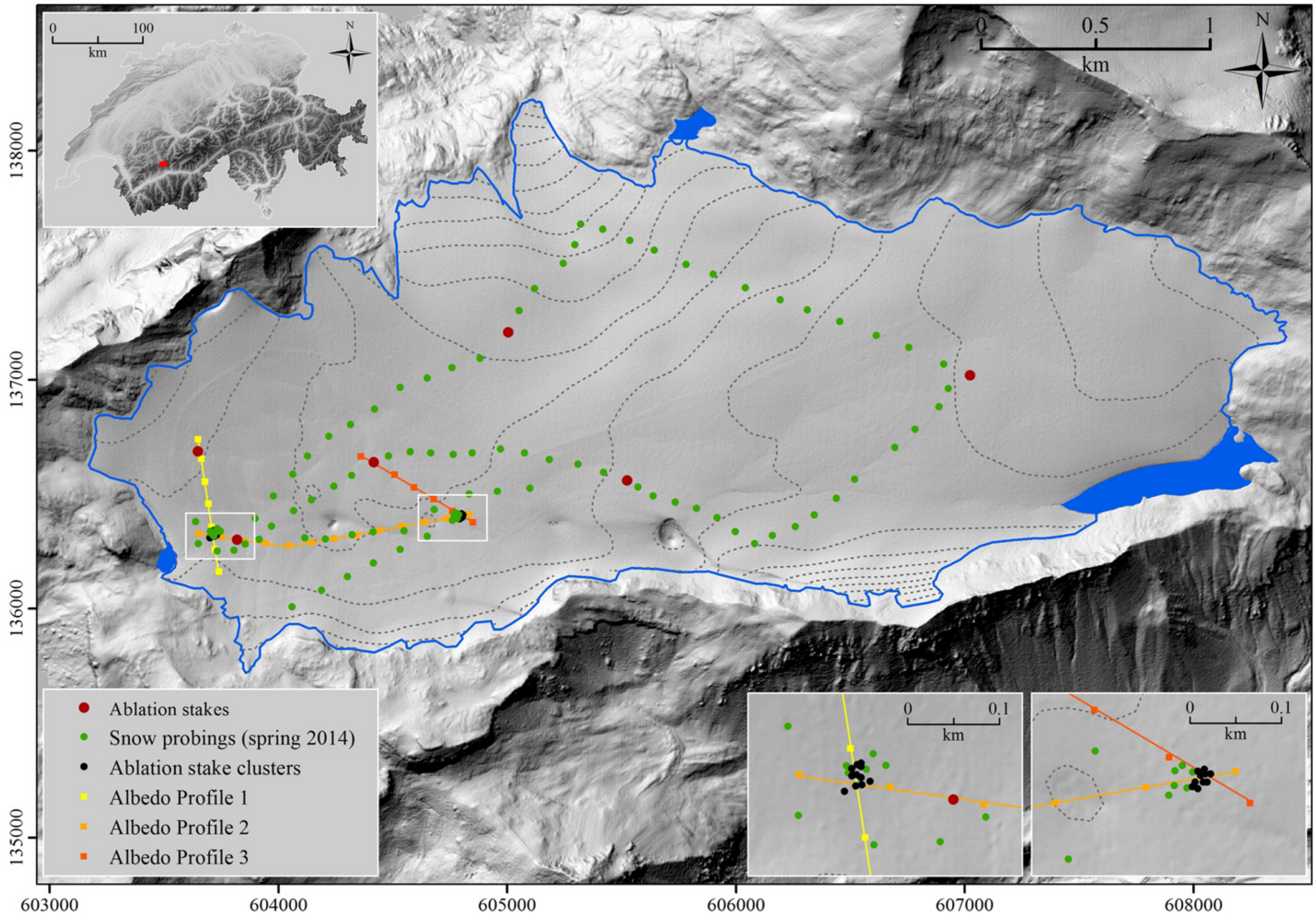

Fig. 1. Glacier de la Plaine Morte and its location within Switzerland (upper left inset). The location of various in-situ measurements of the past years are marked with different symbols and colours. The insets show the ablation stake clusters (for more explanations see Section 2.6). The blue line delineates the glacier outline in 2013 and the blue polygons represent three supraglacial lakes in 2010. Coordinates refer to the Swiss national grid (CH1903).