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Short-lived ice speed-up and plume water flow captured by a VTOL UAV give insights into subglacial hydrological system of Bowdoin Glacier

Guillaume Jouvet[a,*], Yvo Weidmann[a], Marin Kneib[a], Martin Detert[a], Julien Seguinot[a,c], Daiki Sakakibara[b], Shin Sugiyama[b]

[a] ETHZ, VAW, Zurich, Switzerland
[b] Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan
[c] Arctic Research Center, Hokkaido University, Sapporo, Japan

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ABSTRACT

The subglacial hydrology of tidewater glaciers is a key but poorly understood component of the complex ice-ocean system, which affects sea level rise. As it is extremely difficult to access the interior of a glacier, our knowledge relies mostly on the observation of input variables such as air temperature, and output variables such as the ice flow velocities reflecting the englacial water pressure, and the dynamics of plumes reflecting the discharge of meltwater into the ocean. In this study we use a cost-effective Vertical Take-Off and Landing (VTOL) Unmanned Aerial Vehicle (UAV) to monitor the daily movements of Bowdoin Glacier, north-west Greenland, and the dynamics of its main plume. Using Structure-from-Motion photogrammetry and feature-tracking techniques, we obtained 22 high-resolution ortho-images and 19 velocity fields at the calving front for 12 days in July 2016. Our results show a two-day-long speed-up event (up to 170%) – caused by an increase in buoyant subglacial forces – with a strong spatial variability revealing that enhanced acceleration is an indication of shallow bedrock. Further, we used the Particle Image Velocimetry (PIV) method to analyze water flow from successive UAV images taken while flying over the main plume of the glacier. We found that PIV successfully captures the area of radially diverging flow of the plume, and provides information on spatial and time variability as no other remote sensing technique can. Most interestingly, the active part of the plume features pulsating water jets at the time scale of seconds, and is 1 to 5 times smaller than its visual footprint defined by the iceberg-free area. Combined with an ice flow model or a non-steady plume model, our approach has the potential to generate a novel set of input data to gather information about the depth of the bedrock, the discharge of meltwater, or the subglacial melting rate of tidewater glaciers.

1. Introduction

Atmospheric warming in recent decades has caused glaciers and ice sheets to shrink substantially worldwide, and thus contribute to the observed global sea level rise (Pritchard et al., 2009; Joughin et al., 2010). Our ability to predict its future evolution depends not only on the accuracy of climate change projections, but also on our understanding of the combining of processes such as ice thermodynamics, mass balance, iceberg calving, ice-ocean interaction and subglacial hydrology. Among these processes, the last one is a crucial but poorly constrained process as it is extremely difficult to monitor the interior of a glacier. As an alternative, information on subglacial hydrology can be inferred from surface ice flow – whose the sliding component of fast flow is driven mostly by englacial water pressure (Sugiyama et al., 2011) – or glacier runoff.

In the case of tidewater glaciers, the discharge of meltwater into the ocean is often characterized by proglacial “plumes” (Mankoff et al., 2016) at the ocean surface next to the calving front. As the plume rises from the bottom of the glacier front, turbulent entrainment dilutes the plume with salty ocean water, decreasing their density difference until plume and fjord waters reach the same level (called neutral buoyancy), see Fig. 1. Due to the vertical momentum, the water thus mixed can continue to rise past this level and reach the ocean surface, but then plunges back downwards to regain the neutral buoyancy level as it flows away from the glacier (Carroll et al., 2015). The turbulent and turbid water flows visible at the ocean surface directly reflect the intensity of the plume. Plumes are key components of the glacial system, not only because they reflect the glacier runoff, but also because they

* Corresponding author.
E-mail address: jouvet@vaw.baug.ethz.ch (G. Jouvet).

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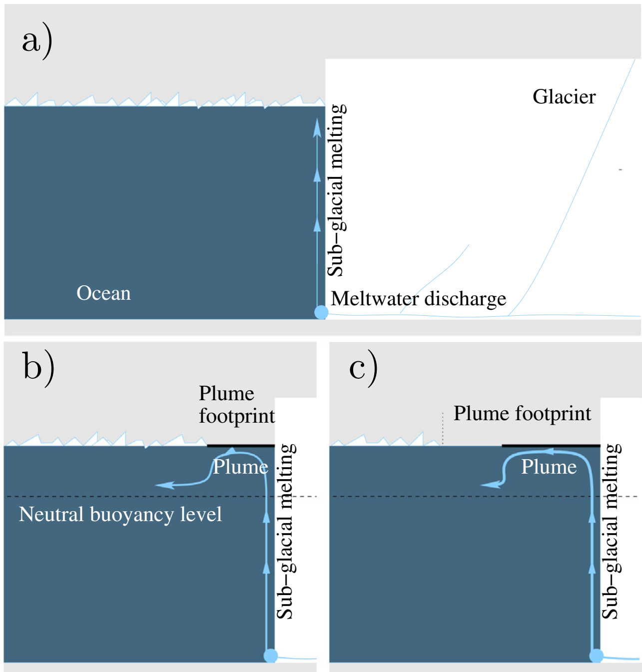

Fig. 1. Schematic description of plume mechanisms at three different stages: a) the meltwater discharge is low, remains under the sea ice, and is invisible from the surface; b) the discharge is sufficient to collapse the sea ice, but only the 'active' part of the plume is free of sea ice; c) the discharge collapses further the sea ice, leaving a footprint which is larger than its 'active' part.

can strongly enhance submarine melting (Rignot et al., 2010; Motyka et al., 2013), and subsequently amplify calving (Slater et al., 2017a).

Thanks to high-performance computing, and the substantial efforts made by the scientific community, the accuracy of ice flow models (along with subglacial hydrology) such as Elmer/Ice (Gagliardini et al., 2013) have taken a significant step forward in the last ten years. In the meantime, parallel efforts to physically model the interaction between the ice and the ocean were made (Dinniman et al., 2016), including the modelling of plumes (Jenkins, 2011; Carroll et al., 2015; Slater et al., 2017b). The increasing sophistication of models requires new variables to be determined, and this automatically increases the need for input data, such as surface ice flow velocities in inverse ice flow modelling (Morlighem et al., 2013).

Observations of ice motion reveal variations at different time scales (*e.g.*, Bartholomew et al., 2012). These range from minute-scale velocity responses to large iceberg calving events (*e.g.*, Murray et al., 2015), to hourly scale variations induced by tide (*e.g.*, Sugiyama et al., 2015), to weekly scale ice speed-ups caused by the drainage of supraglacial lakes (Joughin et al., 1996), to multi-year-scale variations in response to glacier thinning (*e.g.*, Pfeffer, 2007). Weekly or monthly ice flow changes can be tracked by repeated satellite images (Heid and Kääb, 2012). Orbital periods of observation satellites are usually too long to capture variations at daily or subdaily resolution. Minute-scale monitoring of the ice displacement can be done by means of expensive laser scanning (Pętlicki and Kinnard, 2016), interferometric radar (Riesen et al., 2011), or *in situ* GPS (Sugiyama et al., 2015). However, the ground-based remote sensing instruments have to be installed well above the glacier surface in order to obtain optimal coverage. Moreover, when this condition is fulfilled, it is a tedious task to access the site and maintain the equipment for a significant time period. The same obstacles apply to the monitoring of meltwater plumes. Due to their signature left on the ocean surface, a plume can be surveyed at a global scale by means of satellite images (Chu et al., 2009; Bartholomaus et al., 2016), or more frequently and more locally using interferometric radar or automatic cameras. For instance, Slater et al. (2017a) have tracked the visibility of a surfacing plume to infer subglacial hydrology. Conversely, How et al. (2017) determined the footprint of meltwater plumes from time-lapse imagery in order to estimate the subglacial discharge. To our knowledge, no one has ever attempted to use aerial imagery to track the flow of a meltwater plume at the ocean surface. In contrast, plumes can be monitored below the surface by conducting hydrographic *in-situ* measurements, *i.e.*, conductivity-temperature-depth (Motyka et al., 2013; Mankoff et al., 2016; Stevens et al., 2016). However, this implies using heavy and costly logistics.

Unlike satellite remote sensing or *in-situ* observation with grounded instruments, Unmanned Aerial Vehicles (UAV) can generate frequent and high-resolution aerial glacier images with relative minor effort and at a low cost (Immerzeel et al., 2014; Ryan et al., 2015; Jouvet et al., 2017). In their review article, Bhardwaj et al. (2016) elaborate the advantages of UAVs over conventional remote sensing platforms in glaciology and examine the applications already performed in polar and alpine environments. The flight range of UAVs is a limiting factor for reaching and mapping remote and large glacial areas. Multicopter UAVs like the DJI Phantom are easy to fly without prior experience, can take off and land in confined areas. However, they have a limited operational range – usually under 10 km assuming low altitude flights. Small fixed-wings, such as the Ebee (sensefly.com), can double this range while remaining relatively easy to operate. On the other hand, large fixed-wing UAVs (Ryan et al., 2015; Jouvet et al., 2017) can fly higher and over much longer distances (over 100 km), but require special flight training and are difficult to land in mountainous environments. For this reason, the latter are more suitable for mapping vast glacier areas (typically over 10 km^2) more often found in polar regions. Thanks to the latest technological developments, a new generation of UAV, based on the Vertical Take-Off and Landing (VTOL) principle, is now emerging. VTOL UAVs are hybrid platforms of multicopters and fixed-wings, which combine the advantages of both since they can take off and land smoothly and accurately as a multicopter, while benefitting from the long range offered by fixed-wings. Therefore, recent progress in the use of VTOL UAVs is expected to extend the flight range for non-expert UAV users in coming years, allowing even more remote and much larger areas than ever before to be surveyed. Thus this technology is clearly suitable for glacier monitoring. To our knowledge, VTOL UAVs have never before been used for this purpose.

For this study, we used a VTOL UAV to monitor Bowdoin glacier, north-west Greenland, twice a day. More precisely, we surveyed an ice surface area of approximately 3 km^2 near the calving front for 13 days in July 2016, with the aim of capturing both the glacial motion and water flow velocities of Bowdoin's main plume. This paper is organized as follows: After providing some key facts about Bowdoin Glacier, we describe the instruments and methods employed to conduct this study. Then, we present our results with regard to ice flow velocity, calving, and meltwater plume activities. In the final section, we discuss the interaction between these processes and subglacial hydrology.

2. Study site

Bowdoin Glacier (77°41′ N, 68°35′ W) is an ocean-terminating glacier, which belongs to a network of outlet glaciers located in the north-west sector of the Greenland ice sheet. The glacier ends in the Bowdoin fjord through an approximately 3 km wide calving front, see Fig. 2. At the center of the calving front, the glacier is approximately 250 m thick, grounded, and nearly at floatation (Sugiyama et al., 2015). As a consequence, the ice flow at the glacier front is highly influenced by buoyant forces, which counteract the ice weight and favour basal sliding. Ice flow is slower further upstream where the ice is thicker and thus undergoes further basal friction. Thus, the ice speed increases with proximity to the ocean, reaching 1 to 2 $m\,d^{-1}$ at the calving front (Sugiyama et al., 2015). Since 2013, the front of Bowdoin Glacier has experienced only minor seasonal fluctuations, *i.e.*, its advance has been compensated for by iceberg calving at the multiyear scale (Sakakibara