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Derivation and validation of supraglacial lake volumes on the Greenland Ice Sheet from high-resolution satellite imagery

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A B S T R A C T

Supraglacial meltwater lakes on the western Greenland Ice Sheet (GrIS) are critical components of its surface hydrology and surface mass balance, and they also affect its ice dynamics. Estimates of lake volume, however, are limited by the availability of in situ measurements of water depth, which in turn also limits the assessment of remotely sensed lake depths. Given the logistical difficulty of collecting physical bathymetric measurements, methods relying upon in situ data are generally restricted to small areas and thus their application to large-scale studies is difficult to validate. Here, we produce and validate spaceborne estimates of supraglacial lake volumes across a relatively large area (1250 km^2) of west Greenland's ablation region using data acquired by the WorldView-2 (WV-2) sensor, making use of both its stereo-imaging capability and its meter-scale resolution. We employ spectrally-derived depth retrieval models, which are either based on absolute reflectance (single-channel model) or a ratio of spectral reflectances in two bands (dual-channel model). These models are calibrated by using WV-2 multispectral imagery acquired early in the melt season and depth measurements from a high resolution WV-2 DEM over the same lake basins when devoid of water. The calibrated models are then validated with different lakes in the area, for which we determined depths. Lake depth estimates based on measurements recorded in WV-2's blue (450–510 nm), green (510–580 nm), and red (630–690 nm) bands and dual-channel modes (blue/green, blue/red, and green/red band combinations) had near-zero bias, an average root-mean-squared deviation of 0.4 m (relative to post-drainage DEMs), and an average volumetric error of <1%. The approach outlined in this study – image-based calibration of depth-retrieval models – significantly improves spaceborne supraglacial bathymetry retrievals, which are completely independent from in situ measurements.

1. Introduction

The acceleration of mass loss from the Greenland Ice Sheet (GrIS) over the last two decades is of great significance when considering its potential contribution to sea level rise (Wouters, Chambers, & Schrama, 2008; van den Broeke et al., 2009; Schrama & Wouters, 2011; Rignot, Velicogna, van den Broeke, Monaghan, & Lenaerts, 2011; Shepherd et al., 2012). Accurate projections of Greenland's contribution to sea level rise require an improved understanding of ice dynamic responses to hydrologic processes, which is currently lacking (Bartholomew et al., 2012; Bartholomew et al., 2011; Das et al., 2008; Hoffman, Catania, Neumann, Andrews, & Rumrill, 2011; Palmer, Shepherd, Nienow, & Joughin, 2011; Zwally et al., 2002; Phillips, Rajaram, Colgan, Steffen, & Abdalati, 2013; Tedesco et al. 2013a). Supraglacial lakes and streams play a crucial role in the ice sheet's hydrological system by storing large quantities of meltwater, which can promote hydrofracturing events (i.e. propagation of water-filled cracks to the base of the ice sheet). A sudden influx of meltwater to the ice-bed interface, as a result of hydrofracturing events, can increase basal water pressures and therefore overwhelm existing drainage systems, leading to pronounced yet short-lived enhancements of ice flow (Das et al., 2008; Catania, Neumann, & Price, 2008; Hoffman et al., 2011; Selmes, Murray, & James, 2011; Selmes, Murray, & James, 2013). This process, however, is largely controlled by the rate of meltwater delivery to the subglacial environment. Slow vs. rapid drainage events appear to impact ice dynamics differently (Tedesco et al., 2013b; Stevens et al., 2015). Thus, to advance the coupling between hydrological and ice dynamics models, it is important to quantify how much meltwater is stored on the ice sheet in supraglacial lakes and ponds, how much

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drains from the ice sheet surface through supraglacial streams and rivers, and how much drains into the ice sheet through crevasses and moulins (Smith et al., 2015). Making assessments of water volumes, however, is quite challenging, as it requires knowledge of bathymetry over supraglacial water bodies, which is very difficult to measure especially over large areas. Given the distribution of supraglacial lakes across large areas of the ice sheet, data from spaceborne optical sensors offer great potential for this purpose.

The fundamental concept behind spaceborne bathymetry is to build depth-reflectance relationships in order to isolate the effects of depth, water column optical properties, and bottom albedo on measured reflectance. Several physically-based and empirical passive remote sensing techniques have been used to derive bathymetric information over supraglacial lakes using the Moderate Resolution Imaging Spectroradiometer (MODIS), the Advanced Spaceborne Thermal Emission and reflection Radiometer (ASTER), Landsat 7, Landsat 8, or WorldView-2 (WV-2) measurements (Sneed & Hamilton, 2007; McMillan, Nienow, Shepherd, Benham & Sole, 2007a; Box & Ski, 2007; Georgiou, Shepherd, McMillan & Nienow, 2009; Tedesco & Steiner, 2011a, 2011b; Legleiter, Tedesco, Smith, Behar & Overstreet, 2014; Banwell et al., 2014; Pope et al., 2016). Though providing valuable insight into supraglacial bathymetry, previous efforts have been hindered by the paucity of co-located remote sensing and in situ observations of water depth and spectral reflectance. Most of the techniques reported in the literature rely solely upon sparse point measurements to calibrate reflectance to depth, or to validate estimated water depths (e.g. Tedesco & Steiner, 2011a, 2011b; Legleiter et al., 2014). Therefore these studies were confined to small areas and to a limited number of lakes out of necessity. Furthermore, some of these techniques have been applied across large portions of the ablation region, despite not being validated at large spatial scales (e.g. Fitzpatrick et al., 2014; Arnold, Banwell & Willis, 2014).

The main goal of our study is to explore the capability of the WV-2 sensor in retrieving validated supraglacial lake depths over large areas that are independent from in situ measurements. Although this study primarily focuses on the use of WV-2 measurements, we also estimate lake depths from data collected by Landsat 7's Enhanced Thematic Mapper (ETM^+). Given the vast archive of Landsat 7 imagery, developing models for the ETM^+ sensor will be useful for expanding lake volumes assessments, which are required for large-scale studies of ice sheet surface hydrology.

2. Study area and data description

The primary study area (50 km × 25 km) is located in the ablation region of the GrIS, centered at 67° 16′ 33″ N, 49° 35′ 15″ W and approximately 1200 m above sea level (a.s.l) (Fig. 1), over which imagery from WV-2 and Landsat 7 ETM^+ sensors was available. We used two WV-2 multispectral images (~2 m resolution) covering the area from early in the melt season (June 12, 2011) and six stereo panchromatic WV-2 pairs (~0.5 m resolution) over the same area at the end of the melt season (August 30, 2011). WV-2 instrument acquires data in eight spectral bands, namely coastal blue (400–450 nm), blue (450–510 nm), green (510–580 nm), yellow (585–625 nm), red (630–690 nm), red edge (705–745 nm), Near InfradRed-1 (770–895 nm), and Near InfraRed-2 (860–1040 nm). However, the multispectral WV-2 images over our study area were acquired with just four of the 8 available spectral bands, notably blue, green, red, and Near InfraRed-1.

The Landsat 7 image over the study site was acquired on the same day as the WV-2 scenes (within ~1 h). Of the total twenty-two lakes visible in Fig. 1, we used measurements over fourteen large lakes for which we were able to acquire stereo image pairs following their drainage later in the season.

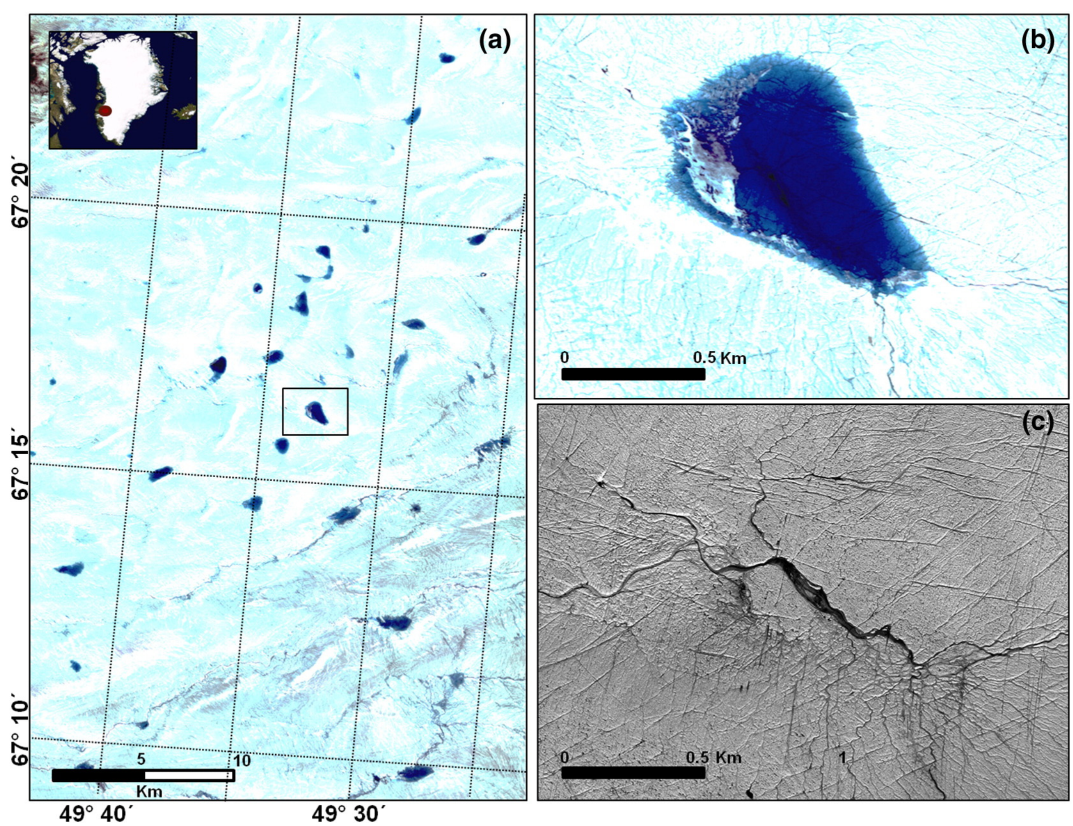

Fig. 1. (a) Enhanced true-color composite mosaic of WV-2 images acquired over the primary study area. Visible in the composite are twenty-two large lakes with an average areal extent of 1.5 km^2. (b) The enlarged boxes show WV-2 snapshots of a lake pre-drainage on June 12, 2011 and (c) post-drainage on August 30, 2011 included in the black box shown in the left panel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)