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Impact of spatial, spectral, and radiometric properties of multispectral imagers on glacier surface classification

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ABSTRACT

Using multispectral remote sensing, glacier surfaces can be classified into a range of zones. The properties of these classes are used for a range of glaciological applications including mass balance measurements, glacial hydrology, and melt modelling. However, it is not immediately evident that multispectral data should be optimal for imaging glaciers and ice caps. Thus, this investigation takes an inverse perspective. Taking into account spectral and radiometric properties, *in situ* spectral reflectance data were used to simulate glacier surface response for a suite of multispectral sensors. Sensor-simulated data were classified and compared. In addition, airborne multispectral imagery was classified for a range of spatial resolutions and intercompared in three different ways. In these analyses, the most important property which determined the suitability of a multispectral imager for glacier surface classification was its radiometric range (i.e. gain settings). Low resolution imagery (250 m pixels) is too coarse to represent the true complexity present on a glacier while medium resolution imagery (60 m, 30 m, or 20 m) accurately represented the results derived from high resolution airborne imagery. Of those studied here, the satellite imagers currently in use that are most suitable for glacier surface classification are Landsat TM/ETM+ and ASTER (each with particular gain settings). Both Sentinel-2 and the OLI on Landsat 8 are also expected to be similarly qualified. Landsat MSS is also found to be radiometrically well-suited for glacier surface classification, but its lower spatial resolution makes it a secondary selection.

1. Introduction

The world's glaciers and ice caps (GIC), which respond much more quickly to shifting climate than the continental ice sheets, provide information about past and present climate variability, are central parts of the world's hydrological cycle, and are key to understanding regional and global climate changes (e.g. Cogley et al., 2011; Oerlemans, 1994). In addition, glaciers contribute to local biodiversity (Jacobsen, Milner, Brown, & Dangles, 2012), mediate the hydrology and flooding of some mountain systems (Dahlke, Lyon, Stedinger, Rosqvist, & Jansson, 2012), and provide crucial water resources for large populations of the world (Baraer et al., 2011; Barry, 2011; Björnsson & Pálsson, 2008; Bolch et al., 2012; Hopkinson & Demuth, 2006).

Glacier surface properties are integral to the behaviour of GIC. The division of GIC into accumulation and ablation areas is just the beginning of classification of glacier facies, or zones (Benson, 1960; Williams, Hall, & Benson, 1991). The equilibrium line altitude (ELA) and accumulation area ratio (AAR; Cogley et al., 2011) can be used as proxies for glacier mass balance (Braithwaite, 1984; Dyurgerov, 1996). In addition, the glacier surface controls much of a glacier's energy balance (Cuffey & Patterson, 2010). Energy balance models both assimilate remotely sensed data about glacier surfaces to improve their results (Machguth, Paul, Kotlarski, & Hoelzle, 2009; Van Angelen et al., 2012), as well as validate their results (Braun, Schuler, Hock, Brown, & Jackson, 2007; De Woul et al., 2006).

Multispectral imagery is often the best tool for studying glacier surfaces (Pellikka & Rees, 2010). Reflectance information over a range of wavelengths, good spatial resolution, frequent repeat imaging, an extensive image archive, and often cost-free data access are all important. However, multispectral sensors were not designed by glaciologists. Satellites like the original Landsat were (and continue to be) designed for a range of tasks including agricultural, oceanographic, and atmospheric monitoring (Markham & Helder, 2012). Therefore, it is not self-evident that they should be optimal for imaging GIC. Thus, the roles that the various spectral, spatial, and radiometric properties of each sensor play in the success and output of resulting classifications remain unquantified.

1.1. Research aims

Multispectral imagers are powerful tools, and with the increasing availability of a range of high quality multispectral data including the recently launched Landsat 8 (Irons, Dwyer, & Barsi, 2012) and upcoming Sentinel 2 (Drusch et al., 2012), it is increasingly crucial that they are

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fully understood. This investigation therefore takes an inverse perspective; it aims to start with *in situ* data to investigate the extent of information available from full-spectrum data and what that means for efficient and consistent application across multispectral sensors with different band capabilities and combinations. We ask the questions: How do the spectral and radiometric properties of these sensors limit or enhance their performance in glacier classification? Because sensors are characterised by both spatial and spectral properties, how does the spatial resolution of these various sensors impact the resultant surface classification? And what does this mean for glaciological applications?

2. Background

2.1. Glacier facies

Glacier surfaces exhibit a range of zones — wet and dry, snowy and icy, clean and dirty. In order to understand better the changing conditions of a glacier's surface, the area can be considered to be divided into a set of systematic, idealised facies that are characterised by a particular set of properties relating to the metamorphosis of the snow or ice surface; facies range from dry snow at colder, higher elevations through to melting ice near the glacier terminus (Benson, 1960; Williams et al., 1991). Although there is a wide range of glacier facies, a glacier can be divided into two larger regions: the accumulation zone and the ablation zone. The transition between these two areas is the line of net zero annual mass change known as the equilibrium line (Cogley et al., 2011; Cuffey & Patterson, 2010). Each different configuration of facies is evidence of a different metamorphic history. Facies distributions vary across glaciers both within seasons and across years, and not all facies are necessarily present on all glaciers.

In addition, beyond these zones which are considered 'facies,' further surface classes can be identified *in situ* and remotely. For example, there are extensive areas of wind glaze and sastrugi in Antarctica (Kuchiki, Aoki, Niwano, Motoyoshi, & Iwabuchi, 2011; Orheim & Lucchitta, 1987; Scambos et al., 2012). The presence of snow algae imparts a reddish tinge to an evolving wet-snow facies (Takeuchi, 2009), and dust or black carbon will darken the snow surface (e.g. Painter, 2011). Debris cover on the glacier can be considered another type of surface class (e.g. Casey, Kääb, & Benn, 2012; Shukla, Gupta, & Arora, 2009), as can volcanic ash deposited on glacier surfaces from a nearby eruption. In this study, 'facies' are considered to be the idealised zones of glacier surfaces which relate directly to accumulation and melt, while 'surface classes' are the zones which can be distinguished from the surface.

Identification of accumulation versus ablation classes (through the ELA or the AAR) can be used as a proxy for a glacier's mass balance, often in combination with further data such as a digital elevation model (e.g. Braithwaite & Müller, 1978; Dyurgerov, Meier, & Bahr, 2009; Rabatel, Dedieu, & Vincent, 2005; Shea, Menounos, Moore, & Tennant, 2013). Also, glacier facies can be related to mass balance in other ways. Snow is bright (i.e. highly reflective in much of the visible and near-infrared) and ice is darker, therefore as the melt season progresses the glacier as a whole gets darker overall — specifically in proportion to the relative contributions of different glacier facies. In this way, it is possible to monitor glacier albedo as a tool for monitoring glacier mass balance (Dumont et al., 2012; Greuell & Oerlemans, 2005; Greuell et al., 2007).

Shortwave radiation is crucial to the energy balance of a glacier. Glacier facies meaningfully contribute to this radiation balance and therefore to the surface energy balance of GIC. A clear example of the interrelated nature of energy balance and glacier facies can be seen in the simple parameterization of the degree-day melt model where ice and snow have different degree day factors (e.g. Hock, 2003). Information about the interannual and intra-annual evolution of glacier surfaces is also a key parameter in building energy balance models. Fuller consideration of glacier facies in glacier melt modelling is gaining increasing traction within the glaciological community (e.g. Dumont et al., 2010; Machguth et al., 2009). This is true not just for GIC, but also for the larger ice sheets, where better classification and description of the unique properties of different facies improve melt model behaviour (e.g. Van Angelen et al., 2012).

Snow and ice reflectances are heavily wavelength-dependent (e.g. Wiscombe & Warren, 1980). In particular, the NIR (near infrared, ~700–1400 nm) has been seen as containing quantitative information about snow and ice surfaces (Kokhanovsky & Zege, 2004; Li, Stamnes, Chen, & Xiong, 2001; Nolin & Dozier, 1993). Glacier facies classification, too, has focused on the NIR to the exclusion of the visible, although snow studies have highlighted both ranges (Zeng et al., 1983). Sidjak and Wheate (1999) and Braun et al. (2007) cited some saturation in the visible and enhanced performance in the NIR as reasons for choosing linear combinations of input multispectral bands which contained large contributions from the NIR and SWIR (shortwave infrared, ~1400–2500 nm) and minimal contributions from the visible.

Based on these examples, it is natural to hypothesise that sensors with enhanced capabilities in the NIR will be able to classify glacier facies better than their counterparts. This belief will be investigated below.

2.2. Multispectral remote sensing, classification, and glacier facies

Multispectral remote sensing images are some of the most prevalent, easily available, and versatile forms of data available for the Earth Observing glaciologist. There are a variety of factors which must be weighed in choosing an appropriate multispectral sensor; each separate investigation or task requires an imager which is fit for purpose. Major considerations include spatial resolution, spectral resolution (i.e. band wavelengths), radiometric resolution and range, temporal resolution (i.e. revisit time), data cost and ease of access, length of data archive, data availability, and availability of pre-processed products. From the range of different options, it is highly unlikely that any one sensor will be optimal for all studies. Nevertheless, sensors were chosen to span a wide range of properties (i.e. spatial scales, spectral bands, and gain settings) and priority was placed on wide use and easy data access. Although many imagers could have been included, those not included (e.g. SPOT, WorldView, etc.) will be able to find analogous properties in those considered here. Fig. 1 includes the range of popular and prominent multispectral imagers that are considered in this study.

Glaciological uses of multispectral imagery include glacier maps and inventories (Albert, 2002; Hendriks & Pellikka, 2008; Kargel et al., 2005; Paul, 2000; Paul & Kääb, 2005), albedo calculation (Greuell, Reijmer, & Oerlemans, 2002; Knap, Reijmer, & Oerlemans, 1999), distinguishing snow from cloud (Hall, Riggs, & Salomonson, 1995), identification of surface and basal crevasses (Luckman et al., 2012), feature tracking (Heid & Kääb, 2012), interpolating digital elevation models (Pope, Willis, Rees, Arnold, & Pálsson, 2013), identifying ice sheet grounding lines (Bindschadler et al., 2011), and much more (Pellikka & Rees, 2010; Rees, 2006).

Classification, the process that takes quantitative information from every pixel and places each into one of a group of discrete categories, is crucial for image interpretation. Many different techniques have been applied to multispectral data to identify glacier surface classes. It should be noted that (automated) classification of glacier extent is considered to be a separate problem, one which has been largely solved, with the exception of debris-covered areas (Paul et al., 2013). Unsupervised classifications have had significant success in classifying glacier facies not only because they are easily reproducible but also because they are often able to exploit subtle features within data sets. ISODATA (Iterative Self-Organizing Data Analysis; e.g. Aniya, Naruso, Skvarca, & Casassa, 1996; De Angelis, Rau, & Skvarca, 2007; Nolin & Payne, 2007; Sidjak & Wheate, 1999; Wolken, Sharp, & Wang, 2009) and k-means classification (e.g. Barcaza, Aniya, Matsumoto, & Aoki, 2009; König, Winther, Kohler, & König, 2004) are the most widely and easily implemented clustering algorithms for glacier surface