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Rigorous 3D change determination in Antarctic Peninsula glaciers from stereo WorldView-2 and archival aerial imagery

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ABSTRACT

This paper presents detailed elevation and volume analysis of 16 individual glaciers, grouped at four locations, spread across the Antarctic Peninsula (AP). The study makes use of newly available WorldView-2 satellite stereo imagery to exploit the previously untapped value of archival stereo aerial photography. High resolution photogrammetric digital elevation models (DEMs) are derived to determine three-dimensional glacier change over an unprecedented time span of six decades with an unparalleled mean areal coverage of 82% per glacier. The use of an in-house robust surface matching algorithm ensured rigorous alignment of the DEMs to overcome inherent problems associated with processing archival photography, most notably the identification and correction of scale error in some datasets. The analysis provides insight into one of the most challenging and data-scarce areas on the planet by expanding the spatial extent north of the AP to include previously un-studied glaciers located in the South Shetland Islands. 81% of glaciers studied showed considerable loss of volume over the period of record. The mean annual mass loss for all glaciers yielded 0.24 ± 0.08 m.w.e. per year, with a maximum mass loss of up to 62 m.w.e. and frontal retreat exceeding 2.2 km for Stadium Glacier, located furthest north on Elephant Island. Observed volumetric loss was broadly, though not always, correlated with frontal retreat. The combined mass balance of all 16 glaciers yielded − 1.862 ± 0.006 Gt, which corresponds to − 0.005 mm sea level equivalent (SLE) over the 57 year observation period.

1. Introduction

The Antarctic Peninsula (AP) is one of the most inaccessible regions on Earth, with its remoteness and extreme weather conditions limiting human understanding of this fragile mountain glacier system. The AP is a complex system comprised of > 1590 glaciers (Cook et al., 2014) that drain a narrow and high mountain plateau. The average mountain height is 1500 m, with the highest peaks rising to > 3000 m above sea level. As such, the region can be considered as a glaciated mountain range that differs fundamentally from the ice sheets covering East and West Antarctica. Most of the glaciers on the west and north-east coasts of the AP are marine-terminating, either as tidewater glaciers or with a short floating portion. The AP occupies < 1% of the entire grounded Antarctic ice sheet, but has the potential to significantly contribute to sea-level change (Meier et al., 2007; Pritchard and Vaughan, 2007; Radic and Hock, 2011). The AP ice sheet itself accounts for 25% of all ice mass losses from the Antarctic region, despite comprising only 4% of the continental area (Shepherd et al., 2012). Simulations of future sea level change in the AP suggest that omission of tidewater glaciers could lead to a substantial underestimation of the ice-sheet's contribution to regional sea level rise (Schannwell et al., 2016).

Similar to other large mountain near-polar glacier systems such as Alaska and Patagonia (Barrand et al., 2013a), the AP is most likely influenced by both atmospheric and oceanic changes (Cook et al., 2016; Vaughan et al., 2001). Its sensitivity to warming has manifested in many ways, one of the signs being the progressive retreat and subsequent collapse of numerous ice shelves such as Larsen A in January 1995, Wilkins in March 1998, and Larsen B in February/March 2002 (Cook and Vaughan, 2010; Scambos et al., 2004). In total, seven out of 12 ice shelves around the AP have either almost completely disappeared or retreated significantly in the second half of the 20th Century (Cook and Vaughan, 2010; Fox and Vaughan, 2005). Increased ice

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velocities (Pritchard and Vaughan, 2007; Scambos et al., 2004; Seehaus et al., 2015; Wang et al., 2016), as well as the retreat and thinning of glaciers and ice caps (Cook et al., 2005; Ferrigno et al., 2006; Scambos et al., 2014) have also been reported.

Atmospheric warming of the AP in the second half of the 20th Century is well documented. Vaughan (2006), for example, reported a 74% increase in the number of positive degree days at the Faraday/Vernadsky Station (65° 15′ S, 64° 16′ W) between 1950 and 2000. According to Sobota et al. (2015) the air temperature on King George Island increased by 1.2 °C between 1948 and 2012. The mean temperature trend for AP stations between 1949 and 2002 was reported by Jacka et al. (2004) to be approximately + 4.4 °C per century. However, according to Turner et al. (2016), this warming process has reversed in the 21st Century. Turner et al. (2016) identified mid-1998 to early-1999 as the turning point between warming (+ 0.32 ± 0.20 °C per decade, 1979–1997) and cooling periods (− 0.47 ± 0.25 °C per decade, 1999–2014) and attributed the decadal temperature changes to the extreme natural internal variability of the regional atmospheric circulation, rather than to the drivers of global temperature change. This does not necessarily mean that the retreat of glaciers will slow down or stop. Another recent study by Cook et al. (2016) argues that the primary cause of glacier retreat in the AP is ocean-led rather than atmospheric-driven.

Due to a lack of detailed observations, many global mountain glacier mass balance inventories either do not include the AP (Dyurgerov, 2002) or use proxy values, such as the global average, instead (Leclercq et al., 2011). A recent glacier basin inventory by Cook et al. (2014) provides information on 1590 AP glacier basins in the form of frontal and areal changes. The study showed a north-south gradient of increasing ice loss across the AP, with 90% of 860 marine-terminating glaciers shown to have reduced in area. This study was, however, compiled based on a relatively coarse 100 m ASTER DEM. A recent surface mass balance study of the AP over the period 1979–2014 by van Wessem et al. (2016) estimated mass change at 5.5 km resolution based on the regional atmospheric climate model RACMO2.3 and a firn densification model (Ligtenberg et al., 2011). The average AP icesheet-integrated surface mass balance, including ice shelves, was estimated at 351 Gigatonnes/year with an inter-annual variability of 58 Gigatonnes/year, and the western AP dominating the eastern AP. However, to this day, there remains a lack of detailed and high resolution measurements relating to almost all AP glaciers, and in particular there is limited information on mass balance change. Radic and Hock (2011) estimated the total sea-level rise from global mountain glaciers by 2100 as 0.124 m ± 0.037 m, with the most significant contribution from glaciers in Arctic Canada, Alaska and Antarctica (excluding ice sheets). Schannwell et al. (2016) predicted a contribution to sea level rise from AP tide water glaciers and ice-shelf tributary glaciers (split equally) in the order of 0.028–0.032 ± 0.016 m by 2300. Pritchard and Vaughan (2007) assessed that the annual sea level contribution from the AP region increased by 0.047 ± 0.011 mm between 1993 and 2003. Shepherd et al. (2012) reported ice sheet mass balance of the AP between 1992 and 2011 as − 20 ± 14 Gigatonnes/year. Hence, while the AP is believed to be a considerable component of the overall Antarctic ice imbalance (Shepherd et al., 2012), denser spatial sampling is required to better understand its contribution to sea-level rise.

The validation of predictive ice-loss models, and the consequent potential contribution to sea-level, requires accurate understanding of historical change and its drivers. It is therefore crucial to accurately estimate mass loss, to identify temporal and spatial patterns, and establish whether changes may be counter-balanced by increased snowfall and snow accumulation (Kunz et al., 2012a; Nield et al., 2012). Due to the rough terrain and inaccessibility to ground-based survey, the only practical source of information that can provide data over extended regions of the AP with relatively high temporal resolution is remote sensing. However, despite the increasing ubiquity of satellite observations, spatio-temporal records are generally too sparse and recent to enable the identification of long-term trends and variations (Fox and Cziferszky, 2008).

This study improves existing records by presenting new information for sixteen glaciers distributed across the western coast of the AP. This is carried out by utilising modern-day stereo satellite images and aerial photographs dating back to the 1950s from largely unexplored archives of > 30,000 frames held by British Antarctic Survey (BAS) and the United States Geological Survey (USGS) (Fox and Cziferszky, 2008). The study builds on existing literature that has attempted to quantify changes in individual AP glaciers (Cook et al., 2005; Fox and Cziferszky, 2008; Kunz et al., 2012a; Kunz et al., 2012b; Seehaus et al., 2015). These previous studies have focussed largely on observations made at the glacier fronts (Cook et al., 2005; Kunz et al., 2012a), primarily as a result of limited coverage of archival photography as well as poor image texture and contrast, or were time-limited to the last two decades (Seehaus et al., 2015). This research quantifies elevation changes across more complete glacier extents, at higher resolution than before (sub-metre image pixels of WorldView-2 and aerial photography) and over a time span of almost six decades. Furthermore, the spatial extent of the studied changes has been expanded to the north of the AP to include glaciers located in the South Shetland Islands.

In contrast to Kunz et al. (2012a) and Miller et al. (2009), both of which used Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) 30 m gridded DEMs, this study utilised sub-metre resolution WorldView-2 imagery (DigitalGlobe, 2016). In the long-term, sub-metre spatial resolution satellite imagery such as that provided by WorldView-2 has the potential to independently shift understanding of the processes taking place in the AP. Although at this moment temporal records are too recent to allow such imagery to be the only source for reliable long-term change studies, the data can facilitate the accurate registration of datasets from alternative sources. A recent study by Wang et al. (2016) presented the use of WorldView-2 for registration and ortho-rectification of declassified ARGON images. WorldView-2 images have been successfully used in several studies of glacier change around the world (Chand and Sharma, 2015; Karimi et al., 2012; Osipov and Osipova, 2015; Racoviteanu et al., 2015; Wang et al., 2016; Yavaşlı et al., 2015), however, in most cases only planimetric observations were used in analysis rather than rigorous 3D photogrammetric observations from stereo-imagery, as presented here. A full photogrammetric workflow allows for a high degree of quality control in the process of image orientation, as well as provides the opportunity for 3D validation of results e. g. manual verification and editing of DEMs in a stereovision environment. Such opportunity is eliminated in the case of 2D ortho-imagery as the third dimension is suppressed.

This study follows the proof-of-concept research presented in a pilot study by Fieber et al. (2016), where surface matching techniques were used to demonstrate elevation changes in three glaciers around Lindblad Cove, AP. DEMs were generated from 2014 stereo WorldView-2 data and a corresponding block of 1957 aerial archival imagery. Here, further results following a refined methodology are presented for 16 glaciers and additional problems encountered in the processing of archival imagery, and their solutions, are discussed.

2. Study sites and data

2.1. Study areas

Sixteen glaciers selected for this study are grouped in four sites: Elephant Island (EI), King George Island (KGI), Lindblad Cove (LC) and Anvers Island (AI). The glaciers are spread across latitudes of 61° to 64° South and longitude of 54° to 63° West. The fact that the glaciers are clustered at four locales limits their spatial extent compared with 16 glaciers at different locations, but at the same time allows observation of whether glaciers of similar size in very similar topographic settings exhibit the same behaviour. Fig. 1 shows the location of the study sites