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Accelerating glacier mass loss on Franz Josef Land, Russian Arctic

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ABSTRACT

The glaciers of the Franz Josef Land (FJL) archipelago in the Russian Arctic are subjected to rapidly-warming temperatures but are small contributors to sea level. We analyze ice surface elevation data derived from satellite stereo imagery (WorldView and SPOT), radar altimetry (CryoSat-2), and a digitized 1953 cartographic map to calculate elevation change rates $\left(\frac{dh}{dt}\right)$. Mass loss from FJL doubled between 2011 and 2015 compared to 1953–2011/2015, increasing from a rate of -2.18 ± 0.72 Gt yr^{-1} to -4.43 ± 0.78 Gt yr^{-1}. This 2011 − 2015 rate indicates an acceleration in ice loss from that observed in 2003–2009 by multiple studies using ICESat and GRACE. Glacier thinning rates are spatially highly variable. We observe glacier thinning rates of up to 10 m per year, and in general we see a trend of increased thinning from the NE towards the SW. Glacier retreat is widespread and has led to the creation of at least one new island. Historically, ice wastage from FJL is thought to have been relatively small, but accelerating ice loss may be the new normal for this archipelago in a warming Arctic.

1. Introduction

Arctic air temperatures have increased at double the average global rate over the past few decades (e.g., Serreze and Francis, 2006; Pithan and Mauritsen, 2014). This has led to a corresponding loss of Arctic sea ice and warming of the ocean (Screen and Simmonds, 2010). Land ice in the Arctic is thought to be vulnerable to atmospheric warming and marine-terminating glaciers are affected by changes in ocean temperatures. Arctic air temperatures have increased unevenly (e.g., Walsh, 2009; Cohen et al., 2014) with warming in the Russian Arctic outpacing rates everywhere else except northern Alaska, particularly in winter (DJF) (Walsh, 2009). Although the Russian Arctic accounts for about 14% (51,800 km^2) of Arctic land ice (e.g., Radić et al., 2014), this region only contributed 8% of the entire Arctic land ice mass loss (-11 ± 4 Gt yr^{-1}) between 2003 and 2009 (Moholdt et al., 2012; Gardner et al., 2013). Numerical model simulations suggest that the glaciers and ice caps of the Russian Arctic islands may contribute 20–30 mm to global sea level rise by 2100 (Radić et al., 2014). Glaciers in the western hemisphere portion of the Arctic, including Greenland, the Canadian Arctic and Alaska, had higher ice loss rates than the Russian Arctic between 2003 and 2010 (e.g., Jacob et al., 2012; Gardner et al., 2013).

Ice mass changes across the Russian Arctic are spatially variable. Novaya Zemlya has the largest glacierized area (42.9% of the Russian Arctic ice) with an ice mass change rate of -340 ± 50 kg m^{-2} yr^{-1} between 2004 and 2009 (Moholdt et al., 2012), -320 ± 50 kg m^{-2} yr^{-1} between 2011 and 2014 (Sun et al., 2017), and -300 ± 60 kg m^{-2} yr^{-1} between 2012 and 2014 (Melkonian et al., 2016); Severnaya Zemlya in the east (32.4% of the Russian Arctic ice) has a lower rate of -78 ± 48 kg m^{-2} yr^{-1} between 2003 and 2009 (Moholdt et al., 2012). Franz Josef Land (abbreviated as FJL), the northernmost archipelago in the Russian Arctic (Fig. 1), consists of around 200 islands between 79 and 82°N, and has a total surface area of 16,135 km^2 (Barr, 1995), roughly the same as the U.S. state of Hawaii. It is generally classified as a polar desert with an average annual precipitation of 228 mm w.e. (Moholdt et al., 2012; Sharov, 2010), a mean annual air temperature of

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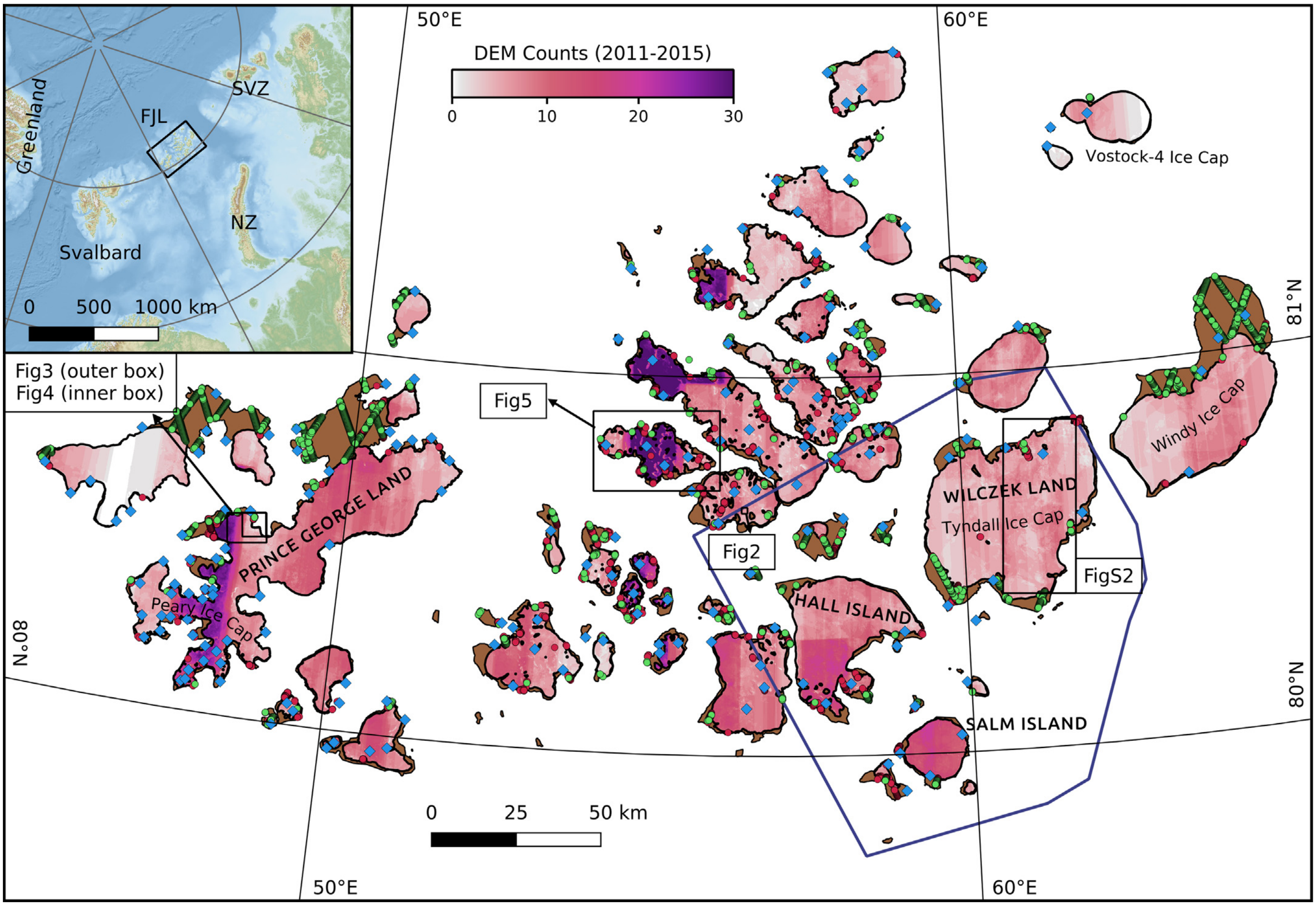

Fig. 1. The coverage map of WorldView-derived DEMs over glacierized areas of Franz Josef Land (FJL), with names of islands (bold) and ice caps mentioned in this paper. Off-ice area is highlighted in brown. 18,447 ICESat points (red + green) are used for coregistering WorldView DEMs, and only 10,398 points (green) are used for the cartographic DEM. 185 ground control points (blue diamonds) are also used in georeferencing the cartographic DEM. The data coverage of 2007 SPOT-5 DEM is outlined by the blue polygon. The outline of 1953 cartographic DEM is not shown since it covers the whole area of FJL. The inset map shows the location of FJL and other islands in the Eurasian Arctic (NZ: Novaya Zemlya; SVZ: Severnaya Zemlya). The figure also serves as a reference map of the location of Figs. 2, 3, 4, 5, and S2.

-12.4°C, and summer air temperatures that hover around 0°C (Barr, 1995). Regional climate variation at each island is unknown due to a lack of weather stations. Land ice covered over 85% of the archipelago in 1957–59, equivalent to 13,735 km^2 (Grosswald et al., 1973); however, ice cover was recorded as 12,700 km^2 (24.7% of the Russian Arctic ice) in 2000–2010 by Moholdt et al. (2012). In contrast to the shrinkage of ice cover, past measurements suggest that FJL has been close to neutral in ice mass budget over the past decades. The mass budget derived from GRACE data was 0 ± 2 Gt yr^{-1} (0 ± 160 kg m^{-2} yr^{-1}) between 2003 and 2010 (Jacob et al., 2012) and -0.8 ± 1.3 Gt yr^{-1} (-63 ± 102 kg m^{-2} yr^{-1}) between 2004 and 2012 (Matsuo and Heki, 2013). The ICESat analysis by Moholdt et al. (2012) gives a slightly more negative value of -0.9 ± 0.7 Gt yr^{-1} (-71 ± 55 kg m^{-2} yr^{-1}) between 2004 and 2009, but the rate of loss is much lower than its nearest neighbors, Novaya Zemlya and Svalbard; the latter has an ice mass change rate of -130 ± 60 kg m^{-2} yr^{-1} between 2003 and 2009 (Gardner et al., 2013).

To better understand mass loss from the glaciers and ice caps of FJL and the change of mass loss rate since 2010, we produce a high-resolution map of ice elevation changes across the archipelago. We highlight similar variability to Sharov (2008) who found that elevation changes at adjacent glaciers could be very different. We produce our digital elevation models (DEMs) from along-track stereo optical satellite imagery collected as a time series, and resolve the details of FJL mass loss on a glacier-by-glacier basis across the entire region over 60 years. Our WorldView-derived DEMs are 2-m posting and have reduced errors on steep and rugged terrains compared to lower resolution techniques. This new method features comprehensive measurements on ice elevation, thus is more capable of detecting changes in a small region, e.g. ice loss rate variations between two adjacent glaciers. We additionally stack DEMs derived from SPOT-5, CryoSat-2, and cartographic data with our DEMs in order to examine and extend the time series of elevation changes.

2. Data

2.1. Elevations from WorldView satellite series

DEMs from multiple sources are compared in this study. The ArcticDEM (https://www.pgc.umn.edu/data/arcticdem/) is used as our primary data source. This is an initiative to provide open access 2-m DEMs across the entire Arctic (e.g., Noh and Howat, 2015). The DEMs were created from DigitalGlobe's WorldView-1, WorldView-2, and WorldView-3 optical stereo imagery using the software Surface Extraction with TIN-based Search-space Minimization (SETSM), and the details are described in Noh and Howat (2015). In the second release in late 2016, 564 strips were available for FJL. In this study, we use only 385 strips for which an "ICESat transformation vector" is provided within the metadata. We use the transformation vector to correct the DEMs with the best fit ICESat measurements (see Section 3.1). All the