Remote Sensing of Environment 191 (2017) 389–401

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Snow depth from ICESat laser altimetry — A test study in southern Norway

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ARTICLE INFO

Article history:
Received 20 April 2016
Received in revised form 23 December 2016
Accepted 20 January 2017
Available online xxxx

Keywords:
ICESat
Altimetry
Snow depth

ABSTRACT

Direct snow depth measurements are sparse, especially in remote areas. In this study, we assess the potential of ICESat laser altimetry for providing snow depths for its operational period 2003–2009 on the example of the Scandinavian Mountains in southern Norway. Snow cover during ICESat campaigns typically results in positive elevation differences (dh) between ICESat GLAH14 elevations and reference elevations from Digital Elevation Models (DEMs). Three DEMs are used: the Norwegian national DEM for the entire study area, and the SRTM DEM and a high-resolution airborne lidar DEM for a spatial subset on the Hardangervidda mountain plateau. To account for uncertainty in elevation data, ICESat samples are grouped into spatial subsets, elevation bands, and over time (e.g. all winter campaigns together). We find that ICESat has the potential to provide regional-scale snow depths for the years 2003–2009 for its winter (March) and late spring (June) campaigns. ICESat-derived snow depth time series for different elevation bands agree well with measured (RMSE 0.47 m) and modelled (RMSE 0.61 m) snow depths in the study area. Annual differences in snow amounts and the increase of snow depths with elevation and coastal proximity over the study area are correctly reproduced. Uncertainties in reference elevations exceed ICESat elevation uncertainty and good control over errors and biases in reference DEMs turn out essential. Spatially varying vertical offsets between ICESat and the reference DEMs make it necessary to bias-correct March/June snow depths with autumn dh per spatial unit or elevation band. Best results are achieved when samples are summarised per season over the entire observation period. After correction of local DEM biases, the spatial pattern of ICESat 2003–2009 March dh matches spatially distributed modelled snow depths in southern Norway with decimeter-scale accuracy. In the western part of Hardangervidda, ICESat-based March snow depths agree better with measurements (RMSE ≤0.15 m for all DEMs) than modelled snow depths do (RMSE 0.61 m). In eastern Hardangervidda, the coarse resolution SRTM DEM (RMSE 0.41 m) performs better than the 10 m Norwegian DEM (RMSE 0.64 m) which is based on a less consistent mosaic of elevation data. Using the high-resolution lidar DEM, even single footprints show good agreement (R^2 0.59, RMSE 0.94 m) with measured snow depths from the same year. Snow depth estimates could be further improved by using full waveform ICESat data or elevation measurements from ICESat-2 once this satellite is operational. Good quality reference DEMs may still be acquired in the future even in areas where no such data exists today.

1. Introduction

Snow plays a key role for the hydrology, ecology and energy balance of large areas on Earth. In Norway, snow is directly important for society e.g. through its role in hydropower production and winter recreation, but it also bears risks for floods or avalanches and affects transportation and accessibility (Engeset et al., 2004). Snow and its spatial distribution govern cryospheric processes such as glacier mass balance, permafrost distribution and surface energy balance, and also determine mountain ecology and habitats (Dietz et al., 2012). Consequently, snow is a driving factor in models for many different aspects of our environment, worldwide. Yet, the amount of snow in remote areas is not well known due to a lack of measurements. Its estimation in mountainous terrain is possibly the most important unsolved problem in snow hydrology (Dozier et al., 2016; Lettenmaier et al., 2015). In rough terrain the snow cover varies highly both in space and with elevation due to orographic effects and wind-driven redistribution in combination with small-scale topography. Spatially distributed information on snow over large areas is

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http://dx.doi.org/10.1016/j.rse.2017.01.022
0034-4257/

Table 1
ICESat sample numbers and operational periods in southern Norway, and dates of lidar reference snow depth measurements. Modelled snow depths are available for every day of the ICESat operational periods. SN stands for Southern Norway, i.e. the entire study area, HV for the Hardangervidda subset. Sample numbers are after filtering and smaller for the lidar/SRTM reference DEM datasets due to the limited spatial extent of the lidar stripes and data gaps in the SRTM DEM respectively. The campaign lengths in days (# d) are slightly shorter for HV as not all SN orbits cross that spatial subset.

Laser	Dataset	Sample # SN	HV	SRTM	lidar	First – last day SN	# d	HV
1AB	March	4901	512	512	28	24 Feb – 29 Mar 2003	34	32
2A	Autumn	7298	626	625	33	28 Sep – 17 Nov 2003	51	50
2B	March	3866	541	541	29	23 Feb – 20 Mar 2004	27	26
2C	June	2135	553	551	32	24 May – 19 Jun 2004	27	26
3A	Autumn	2548	225	225	10	09 Oct – 05 Nov 2004	28	27
3B	March	4684	652	651	39	17 Feb – 23 Mar 2005	35	34
3C	June	2036	373	373	17	26 May – 20 Jun 2005	26	9
3D	Autumn	1246	124	124	5	27 Oct – 22 Nov 2005	27	26
3E	March	4102	446	446	23	28 Feb – 26 Mar 2006	27	17
3F	June	2692	568	568	27	30 May – 25 Jun 2006	27	26
3G	Autumn	2354	401	401	28	31 Oct – 26 Nov 2006	27	16
3H	March	2761	613	611	31	17 Mar – 13 Apr 2007	28	27
3I	Autumn	3251	583	583	27	08 Oct – 03 Nov 2007	27	26
3J	March	1943	222	222	13	23 Feb – 20 Mar 2008	27	9
	April 2008 lidar DEM					3 Apr – 21 Apr 2008		19
	lidar reference DEM					21 Sep		1
3K	Autumn	716	226	226	9	09 Oct – 18 Oct 2008	10	9
2D	Autumn	1781	173	173	11	28 Nov – 16 Dec 2008	19	8
2E	March	2005	362	362	14	14 Mar – 09 Apr 2009	27	17
	April 2009 lidar DEM					21 Apr – 23 Apr 2009		4
2F	Autumn	444	178	178	11	06 Oct – 07 Oct 2009	2	1
total Autumn		19638	2536	2535	134			
total March		24262	3348	3345	177			
total June		6863	1494	1492	76			

typically a product of modelling or interpolation based on sparse in-situ measurements, remotely sensed data, or climate reanalyses. The former method is how Norwegian national snow maps are produced: a snow model is forced by precipitation and temperature maps that are interpolated from spatially distributed, point-based station measurements (Saloranta, 2012).

Different metrics are used to express the amount of snow on the ground: the extent of the snow-covered area, snow depth and snow density, and snow water equivalent (SWE). The parameter of choice depends on the application (e.g. SWE for hydrological studies, snow-covered area for albedo, snow depth for heat transfer). On per-point basis, SWE can be measured in an automated way by snow gauges on meteorological stations, or snow pillows. Similarly, local snow depths are measured automatically with the use of e.g. a sonic ranger mounted on a meteorological station. On the scale of small catchments, SWE measurements are traditionally done manually, following a standardised protocol (snow course) where snow depth and density are measured at multiple, pre-defined locations several times throughout the winter. Direct measurements from meteorological stations or snow courses are mainly available for inhabited areas at lower elevations (stations) and/or catchments with hydropower generation (snow courses) and may be unrepresentative of conditions at higher altitude (e.g. Rasmussen, 2013; Dozier et al., 2016).

For larger areas, remote sensing techniques are used to derive snow metrics in a spatially distributed way. Terrestrial or airborne lidar (light detection and ranging) systems are currently the best providers of snow depths and distribution at catchment scale with decimeter-scale vertical accuracies (Deems et al., 2013) — but they require specifically planned campaigns and have considerable costs (airborne systems). Increasingly, camera systems using structure from motion (SfM) photogrammetry techniques are used to map snow depth and snow cover area (e.g. Nolan et al., 2015; Vander Jagt et al., 2015). Photogrammetric techniques require good image contrast which is not necessarily given on bright snow-covered areas, and advances in their application for snow depth retrieval with decimeter-scale accuracy have been made only recently (Bühler et al., 2015). A recent study by Marti et al. (2016) shows that also very-high-resolution optical satellite stereo imagery may be used for snow depth measurements at catchment scale — the swath width of such sensors is below 20 km. The method is limited to areas with significant snow accumulation due to decimetric systematic and random errors.

Optical space-borne remote sensing data is commonly used to map snow cover extent at coarser spatial resolutions (Dietz et al., 2012; Lettenmaier et al., 2015). Numerous satellite-derived snow cover maps are available as ready-made products (e.g. the MODIS global snow cover products; Hall et al., 2002). However, optical satellite imagery does not provide information on snow depth and SWE of the snow-covered area. SWE has been successfully estimated from passive microwave sensors for dry snow packs <1 m (Dietz et al., 2012; Clifford, 2010). Unfortunately, products from passive microwave sensors are only available at a coarse spatial resolution of tens of kilometres which leaves large uncertainties at regional scales, in particular in mountainous regions (Rango, 1994; Vikhamar and Solberg, 2003; Lettenmaier et al., 2015). For applications where precipitation amounts are important, reanalysis data provides plausible values also at high altitudes (Rasmussen, 2013; Immerzeel et al., 2015) but only at even coarser spatial resolutions.

To the best of our knowledge, no method is available so far to measure snow depth on regional scales and from space. For certain applications or model assimilations, direct regional snow depth measurements would be useful. Additionally, the combination of regional snow depth measurements with the above methods for retrieval of, for instance, snow cover extent or SWE could open up important synergies (Dozier et al., 2016; Lettenmaier et al., 2015).

In contrast to the above methods or models, the NASA Ice, Cloud and land Elevation Satellite (ICESat) directly measured surface elevations during 18 campaigns (Table 1) between 2003 and 2009 in northern autumn, winter and late spring, and thus has the theoretical potential to provide information on snow depths. Data from ICESat's Geoscience Laser Altimeter System (GLAS) consists of point samples of surface elevation along near-repeat ground tracks. By using double-differencing techniques, i.e. comparing ICESat elevations with a reference Digital Elevation Model (DEM) and their subsequent evolution over time, Kääb et al. (2012) successfully detected glacier surface elevation change trends even in the rough Himalaya Mountains. The method relies on spatial grouping of samples to average out uncertainties, and has subsequently been applied successfully to other glacierised mountain areas and even globally (Kääb et al., 2015; Ke et al., 2015; Kropáček et al., 2014; Neckel et al., 2014; Treichler and Kääb, 2016; Gardner et al., 2013). The limits of this method were found to be the elevation accuracy of the reference DEMs rather than ICESat's vertical accuracy (Treichler and Kääb, 2016). On Norwegian glaciers, Treichler and Kääb (2016) found clear indications of yearly varying snow depths that correspond well with measured winter mass balances in the area. On the Antarctic ice sheet, Bindschadler et al. (2005) used elevation differences of intersecting ICESat orbits before and after a snow fall event to validate snow event detection from microwave data. To the best of our knowledge, explorations of seasonal ICESat-derived elevation variations to analyse snow depths have not been published, even though a few authors mention this possibility (Jasinski and Stoll, 2012; Jasinski and Neumann, 2013; Stoll and Jasinski, 2012; Fassnacht et al., 2012).

In this study, we extend the glacier analysis of Treichler and Kääb (2016) to assess ICESat's potential in providing snow depths also on the non-glacierised areas of the mountains in southern Norway.