Remote Sensing of Environment 169 (2015) 1–19

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

A processing system to monitor Greenland outlet glacier velocity variations at decadal and seasonal time scales utilizing the Landsat imagery

R. Rosenau *, M. Scheinert, R. Dietrich

Institut für Planetare Geodäsie, Technische Universität Dresden, 01069 Dresden, Germany

ARTICLE INFO

Article history:
Received 29 September 2014
Received in revised form 7 July 2015
Accepted 16 July 2015
Available online xxxx

Keywords:
Landsat
Greenland
Marine-terminating glacier
Flow velocity
Surface displacements

ABSTRACT

In this paper we present a monitoring system for area-wide flow-velocity fields of the outlet glaciers of the Greenland Ice Sheet (GrIS) utilizing the freely available Landsat archive. In order to process this large amount of satellite images an almost automatic monitoring system was developed. With the Global Digital Elevation Map V2 (GDEM-V2) of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) an improved orthorectification was applied which, in combination with a destriping correction of the Landsat 7 products with Scan Line Corrector (SLC) failure, leads to more precise flow-velocity information. In addition, outliers were removed using an adaptive, recursive filter approach. For the time span 1972–2012 more than 100,000 flow-velocity fields were derived from over 16,000 optical multi-sensoral Landsat scenes (Landsat 1 to Landsat 7) allowing the determination of the long-term flow-velocity trend. Moreover, the high temporal resolution facilitates the analysis of seasonal flow-velocity variations of numerous outlet glaciers. For many of the major outlet glaciers the results show an acceleration pattern that is consistent with most of the previously published analyses. However, the flow-velocity changes do not have a uniform pattern in their temporal and spatial distribution. This study provides both a high temporal densification and an extension of existing flow-velocity information of the GrIS margin. Finally, this processing chain in its generality allows for the determination of various types of surface displacements and can be applied to other glacier regions.

1. Introduction

Over the last decade the Greenland Ice Sheet (GrIS), the second largest ice sheet in the world, has exhibited an increasing ice-mass loss. The analysis of monthly observations from the Gravity Recovery and Climate Experiment (GRACE) revealed a linear trend of the ice-mass balance of (-230.4 ± 23.6) Gt yr^{-1} (2003–2012) superimposed by a large seasonal amplitude of (162.7 ± 17.1) Gt (Groh et al., 2014). This is consistent with the recent results obtained by other groups (Harig & Simons, 2012; Sasgen et al., 2012; Sutterley et al., 2014). Several studies show that most of the GrIS's major outlet glaciers show a recent acceleration in flow velocity and ice discharge (Enderlin et al., 2014; Joughin, Smith, Howat, Scambos, & Moon, 2010; Moon, Joughin, Smith, & Howat, 2012) as well as increased frontal thinning (Csatho et al., 2014; Ewert, Groh, & Dietrich, 2012; Thomas, Frederick, Krabill, Manizade, & Martin, 2009). Along with these changes a significant frontal retreat has predominantly been identified (Joughin et al., 2010; Moon & Joughin, 2008). Based on the results of the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) the GrIS contribution to the global sea-level rise amounts to (0.33 ± 0.08) mm yr^{-1} between 1993 and 2010 (Stocker et al., 2013).

The increased ice-mass loss is mainly caused by enhanced calving and increased meltwater runoff (Rignot, Box, Burgess, & Hanna, 2008; Sasgen et al., 2012; van den Broeke et al., 2009). While the latter is likely caused by changing atmospheric conditions, the increased calving is presumably driven by changes at the ice-ocean boundary (Straneo et al., 2012). Several mechanisms have been identified as controls of ice-mass loss at the ice-ocean boundary. Firstly, increased submarine melting because of warmer ocean water may lead to a destabilization of the glacier front and in consequence to frontal retreat (Holland, Thomas, Ribergaard, & Lyberth, 2008; Motyka et al., 2011). Secondly, ice mélange concentration in the proglacial fjord buttresses the glacier front and, hence, influences the advance and retreat of the terminus position (Amundson et al., 2010; Sohn, Jezek, & van der Veen, 1998). Thirdly, geometry changes due to frontal thinning and retreat may trigger acceleration of both the frontal and upstream glacier flow (Joughin et al., 2012) and in turn may cause grounding line migration (Motyka et al., 2011; Vieli & Nick, 2011). Along with these mechanisms, attention has been drawn to the importance of hydrological processes on ice flow control (Bartholomew et al., 2011; Sole et al., 2013; van de Wal et al., 2008; Zwally et al., 2002). From both, observation and modelling, numerous studies concluded that rapid flow-velocity changes are

* Corresponding author.
E-mail address: ralf.rosenau@tu-dresden.de (R. Rosenau).

http://dx.doi.org/10.1016/j.rse.2015.07.012

connected to the amount of surface meltwater lubrication to the bed in combination with the efficiency of the glacial–hydrological drainage system (Bougamont et al., 2014; Hewitt, 2013; Schoof, 2010; Shepherd et al., 2009; Zwally et al., 2002). It has been shown that diurnal surface melt variations and precipitation events can trigger short-term flow-velocity changes varying from minutes to several hours (Bartholomaus, Anderson, & Anderson, 2008; Sundal et al., 2011). But also lake drainage events could be identified concurrent to flow-velocity changes (Das et al., 2008; Hoffman, Catania, Neumann, Andrews, & Rumrill, 2011; Joughin et al., 2013). Specifically for fast-flowing marine-terminating outlet glaciers, it is assumed that the influence of surface meltwater lubrication on flow-velocity variations plays only a minor role (Andersen et al., 2010; Joughin et al., 2008). In general, model predictions suggest that variations in surface melting and runoff will dominate future sea-level changes (Goelzer et al., 2013; Nick et al., 2013; Price, Payne, Howat, & Smith, 2011), while ice-dynamic changes make a smaller contribution than previously assumed (Moon et al., 2012; Pfeffer, Harper, & O'Neel, 2008). In conclusion, the problem of quantifying the impact and interplay of each of these different processes on ice-mass loss is still unsolved (Joughin et al., 2012; Straneo et al., 2013).

The flow velocity regime along the GrIS margin follows a complex pattern with numerous fast-flowing marine-terminating outlet glaciers in the northwest, central west and southeast (Joughin et al., 2010; Rignot & Mouginot, 2012) and land-terminating glaciers with considerably slower flow velocities concentrated in the southwest and a few in the northeast (Moon et al., 2012). A third group comprises ice-shelf-terminating glaciers, which are located predominantly in the north and northeast (Rignot, Gogineni, Joughin, & Krabill, 2001). A long-term velocity monitoring of more than 200 outlet glaciers between 2000 and 2010 revealed a steady flow velocity increase in the northwest and southeast and a comparably steady flow in the remaining parts of the GrIS (Moon et al., 2012). Some glaciers could even double their frontal flow velocity during the last decade (Dietrich et al., 2007; Joughin, Smith, Shean, & Floricioiu, 2014), while others decelerate together with advancing front positions (Moon et al., 2012; Walsh, Howat, Ahn, & Enderlin, 2012). In addition, the observed variations in flow velocity of marine-terminating outlet glaciers were often accompanied by changes in their terminus position (Howat, Box, Ahn, Herrington, & McFadden, 2010; Moon et al., 2014).

In general, the observed long-term changes in flow velocity occur on a wide range of temporal scales and amplitudes with a complex and non-uniform distributed spatial pattern (Enderlin et al., 2014; Joughin et al., 2010; Moon et al., 2012, 2014). For example, a synchronous widespread acceleration and subsequent slowdown was identified for many major outlet glaciers in southeast Greenland between 2000 and 2008 (Howat, Joughin, Fahnestock, Smith, & Scambos, 2008; Murray et al., 2010). However, more recent observations in this region could not confirm this synchronous regional ice discharge after 2008, indicating a complex relationship between local and regional forcings (Csatho et al., 2014; Enderlin et al., 2014; Moon et al., 2012). These findings underline the difficulty in the prediction of future changes.

In addition to long-term flow-velocity trends different groups derived seasonal, intra-annual and short-term velocity variations for numerous outlet glaciers (i.e. Bartholomaus et al. (2008), Howat et al. (2010), Bevan, Luckman, and Murray (2012), Podrasky et al. (2012), Ahlstrøm et al. (2013), Moon et al. (2014)). Based on observations for 55 major outlet glaciers between 2009 and 2013 Moon et al. (2014) identified three groups of different temporal patterns of seasonal flow variability, with individual groups not restricted to a specific region. In general, the non-uniform spatio-temporal distribution of individual glaciers also applies to both dynamic thickness changes (Csatho et al., 2014) and ice-discharge variations (Enderlin et al., 2014).

Although time series of seasonal flow-velocity variations exist for many major outlet glaciers of the GrIS, these are either restricted to a period of just a few years, have a sparse temporal sampling or a limited spatial coverage (i.e. Howat et al. (2010), Bevan et al. (2012), Joughin et al. (2012), Ahlstrøm et al. (2013), Moon et al. (2012, 2014)). However, for a better decoupling of seasonal flow variations from the long-term trend of individual outlet glaciers, both a high temporal densification and an extension of existing velocity time series along the GrIS margin are preferable.

We used feature tracking on repeated optical Landsat imagery recorded mainly between 1999 and 2012 to determine area-wide flow-velocity fields during the melt season for the majority of the marine-terminating outlet glaciers with a frontal width of more than 1 km. In addition, at some locations we could infer flow velocities back to 1972 using early Landsat data, which in turn enable the estimation of long-term velocity variations over more than four decades. The accuracy of the flow velocities could be strongly improved by incorporating the high-resolution digital elevation model ASTER-GDEM-V2 (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Map V2) during the orthorectification. Moreover, we developed a destriping scheme in order to reduce the stripe pattern which was caused by small scan line shifts in Landsat 7 (L7) data acquired after 2003. Finally, to avoid a manual filtering of outliers in the final velocity product, we developed an automatic, adaptive and recursive filter approach. In comparison to previous studies (e.g. Rosenau, Dietrich, and Baessler (2012)), this paper gives a detailed description and a thorough error assessment of the implemented algorithms.

In the following section we give an overview of the Landsat data used and their related sensor characteristics. Section 3 comprises the methodology for the determination of glacier flow-velocity fields with a focus on the improved orthorectification and coregistration of Landsat standard products. Subsequently, the results of area-wide flow-velocity measurements and their changes for more than 300 outlet glaciers of the GrIS are presented in Section 4. Section 5 discusses the temporal velocity changes and their spatial distribution. Conclusions are given in Section 6.

2. Data

The analyses to determine flow-velocity fields along the GrIS margin are based solely on the freely available optical imagery of the Landsat mission (Woodcock et al., 2008). As shown in Fig. 1, the used Landsat data show a nearly complete coverage of the GrIS margin except for regions north of 82°. We incorporated over 16,900 Landsat scenes, which were automatically selected from the global Landsat metadata catalogue. A pre-filtering on the basis of the cloud coverage index was not applied, since this index is likely to work with reduced accuracy in ice-covered regions (Irish, 2000).

More than 12,000 scenes with a ground resolution of 15 m originated from the Enhanced Thematic Mapper Plus (ETM+) aboard L7. This large amount of ETM+ scenes enables to determine seasonal flow-velocity variations of numerous outlet glaciers in Greenland. In addition, satellite imagery with a ground resolution of 30 m of the Thematic Mapper (TM) aboard L4 and L5 as well as Multispectral Scanner System (MSS) imagery with a ground resolution of 60 m from L1 to L3 were used to extend the velocity time series back to 1972. However, compared to the acquisition frequency of L7 data relatively few scenes are available for the pre-L7 period between 1972 and 1999. Therefore, the temporal coverage of the Landsat scenes is heterogeneous as illustrated in Fig. 2a. Moreover, because of the Landsat acquisition strategy, orbit parametrization as well as limited sunlight during the polar night, the number of Landsat acquisitions exhibits large seasonal and latitudinal variations (Fig. 2b).

All imagery is consistently distributed in GeoTIFF format by the U.S. Geological Survey (USGS), but with different Level 1 Product Generation System (LPGS) versions (9.4.0–12.1.3). For the area of the GrIS, Landsat scenes were provided in Universal Transverse Mercator (UTM) projection with different zones ranging from 18N to 28N. Hence, horizontal