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The glaciers climate change initiative: Methods for creating glacier area, elevation change and velocity products

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ABSTRACT

Glaciers and their changes through time are increasingly obtained from a wide range of satellite sensors. Due to the often remote location of glaciers in inaccessible and high-mountain terrain, satellite observations frequently provide the only available measurements. Furthermore, satellite data provide observations of glacier characteristics that are difficult to monitor using ground-based measurements, thus complementing the latter. In the Glaciers_cci project of the European Space Agency (ESA), three of these characteristics are investigated in detail: glacier area, elevation change and surface velocity. We use (a) data from optical sensors to derive glacier outlines, (b) digital elevation models from at least two points in time, (c) repeat altimetry for determining elevation changes, and (d) data from repeat optical and microwave sensors for calculating surface velocity. For the latter, the two sensor types provide complementary information in terms of spatio-temporal coverage. While (c) and (d) can be generated mostly automatically, (a) and (b) require the intervention of an analyst. Largely based on the results of various round robin experiments (multi-analyst benchmark studies) for each of the products, we suggest and describe the most suitable algorithms for product creation and provide recommendations concerning their practical implementation and the required post-processing. For some of the products (area, velocity) post-processing can influence product quality more than the main-processing algorithm.

1. Introduction

Glaciers are considered key indicators of climate change due to their sensitive reaction to even small climatic changes (e.g. Lemke et al., 2007). This is mainly a result of the ice being at pressure melting point (under terrestrial conditions and for temperate glaciers), i.e. any surplus energy melts the ice. Glaciers adjust their geometry (extent and surface elevation) to equilibrate with the prevailing climatic conditions that largely control mass gain and loss. Thereby, glacier flow transports the mass gained in the accumulation to the ablation region where it melts.

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The determination of changes in glacier geometry that occur as a reaction to climate change thus involves the measurement of change in glacier surface elevation, flow velocity and size/length, among others (e.g. snow covered area at the end of the melting period). Variations in these parameters are related to each other at varying time scales. For example, the annual mass budget is a direct reaction to the prevailing meteorological conditions over a year, whereas changes in flow velocity result from a more long-term change in the nourishment of a glacier (Span & Kuhn, 2003). Also changes in glacier length and size follow more long-term climatic changes, so that a direct cause and effect relation is difficult to resolve (e.g. Johannesson, Raymond, & Waddington, 1989).

Due to the often remote location and large areal extent of glaciers, satellite-based measurements of glacier changes complement field-based surveys. Satellite data can largely extend the number of glaciers measured, the time period covered and the parameters that can be assessed. The wide range of available sensors (e.g. imaging sensors and altimeters working in both the optical and microwave regions of the electromagnetic spectrum) and archives from ongoing and historic missions combined with already existing geospatial information like digital elevation models (DEMs) or former glacier outlines as available from GLIMS (Global Land Ice Measurements from Space), allows measurement of a wide range of glaciologically relevant parameters (IGOS, 2007; Kargel et al., 2005; Malenovsky et al., 2012). The Glaciers_cci project focuses on three of these parameters: glacier area, elevation changes (from DEM differencing and repeat altimetry), and surface velocity fields (from optical and microwave sensors). Numerous algorithms are available for product retrieval from each of the input data sets and sensor combinations. They differ in complexity (from simple arithmetics such as division or subtraction of raw data to rather complex calculations and processing lines) and in the required operator interaction (e.g. from manual control and editing to almost fully automatic processing), but a pre-, main- and post-processing stage is common to all of them. In general, only the main processing stage is automated while the other stages require operator interaction. The consistency of the manual corrections applied in the post-processing stage is critical when products are derived in a globally collaborative effort such as for GLIMS (Kargel et al., 2005; Raup et al., 2007).

Accordingly, a major objective of the Glaciers_cci project is to find the most suitable algorithms for data processing and an improved error characterisation of the generated products. For this purpose we performed an analysis of various existing algorithms along with their specific post-processing and editing operations in four round robin experiments (one for glacier area and surface velocity, and two for elevation change). In each of the following product-related sections we provide a short overview of the algorithms applied based on earlier studies and either summarise (if already published) or illustrate in detail the set-up and results of the round robin experiments for each product. We also describe the challenges and main pitfalls that might occur during the pre- and post-processing stages by operators, as this always involves some subjectivity and has an impact on the quality of the final product. The study regions for the product-specific round robin experiments are located in different mountain ranges around the world (Fig. 1). These regions were selected for a range of criteria such as availability of validation data or satellite data from different sensors, typical challenges, clear identification of the target, and glacier size.

2. Glacier area

2.1. Background and previous work

Satellite data have been used to study glaciers from the very beginning of their availability. Starting with the mapping of different ice and snow facies using the ca. 80 m resolution Landsat Multi Spectral Scanner (MSS) sensor in the 1970s (Østrem, 1975; Rott, 1976) and the 30 m Landsat Thematic Mapper (TM) sensor a decade later (e.g. Hall, Ormsby, Bindschadler, & Siddalingaiah, 1987; Williams, Hall, & Benson, 1991), the 1990s saw mapping of glacier extent and first studies on change assessment with TM data (e.g. Aniya, Sato, Naruse, Skvarca, & Casassa, 1996; Bayr, Hall, & Kovalick, 1994; Jacobs, Simms, & Simms, 1997). A wide range of methods were applied in these and other studies to map glacier extents. They range from full manual on-screen digitisation (e.g. Rott & Markl, 1989; Williams, Hall, Sigurdsson, & Chien, 1997), to the segmentation of ratio images (e.g. Bayr et al., 1994; Paul, 2002; Rott, 1994) and various supervised (Maximum-Likelihood) and unsupervised (ISODATA clustering) algorithms (e.g. Aniya et al., 1996; Sidjak & Wheate, 1999). All methods utilise the very low spectral reflectance of ice and snow in the shortwave infrared (SWIR) versus the high reflectance in the visible spectrum (VIS) to identify glaciers (e.g. Dozier, 1989).

Several methods have been compared in regard to their performance (e.g. computation time, accuracy) in a relative sense (e.g. Albert, 2002;

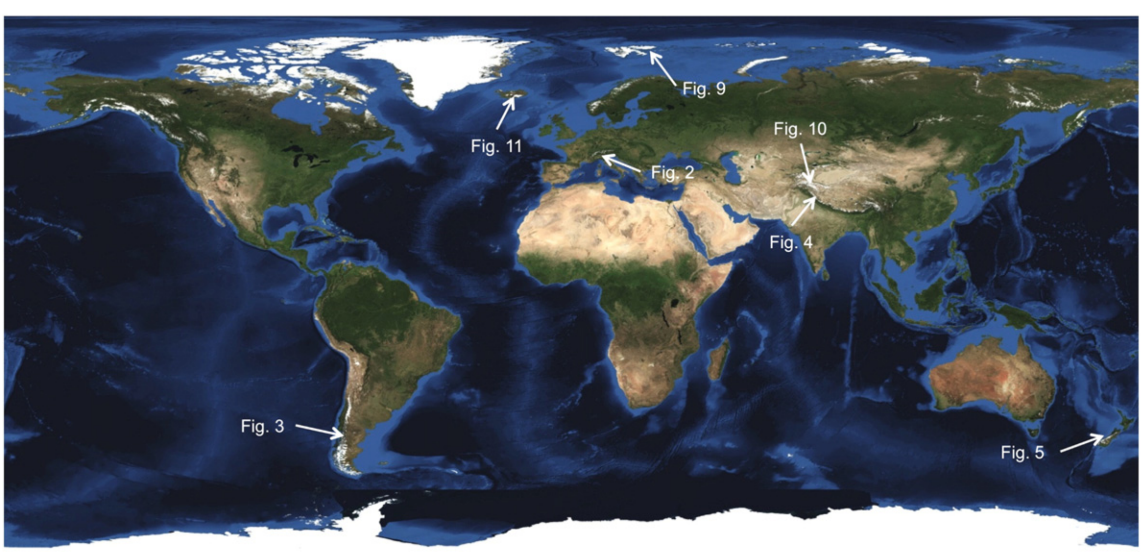

Fig. 1. Global map showing the approximate location of the test regions described in this study. Geographic coordinates are: Fig. 2: 46.53 N, 8.2 E; Fig. 3: 42.25 S, 72.15 W; Fig. 4: 34.15 N, 75.75 E; Fig. 5: 43.65 S, 170.25 W; Fig. 9: 79.8 N, 22.1 E; Fig. 10: 35.9 N, 75.9 E (left) and 35.75 N, 76.4 E (right); and Fig. 11: 64.2 N, 16.4 W.