MONITORING SNOW PARAMETERS ON THE ANTARCTIC PENINSULA USING SATELLITE DATA: A NEW METHODOLOGICAL APPROACH

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ABSTRACT

Ongoing climatic change on the Antarctic Peninsula is well documented in numerous scientific publications. Nevertheless, spatial and temporal distribution of glacier changes on the Antarctic Peninsula remain largely unknown. To analyse regional patterns and trends of changes in snow cover parameters on the Antarctic Peninsula north of 70° S, we propose a geostatistical approach based on the analysis of data derived by remote sensing methods. A time series of radar (ERS-1/2 SAR, Envisat ASAR and Radarsat SAR) and optical data (Landsat TM, Landsat ETM+ and Terra ASTER) enables the compilation of a multi-temporal database of glacier parameters for the last two decades. In this paper, we propose a method to facilitate the pre-processing and classification of remotely sensed data from several sources, and describe a sampling method used for selecting a representative set of glaciers for evaluation of classification algorithms. The so-called *centreline approach* facilitates pre-processing and classification of remote sensing data for monitoring glacier zones. In addition, the approach enables the integration of data from different sources, and minimizes the need of high resolution digital elevation models (DEM) for terrain correction.

Keywords: Glacier monitoring, Antarctic Peninsula, glacier zones, multi-temporal.

INTRODUCTION

Recent studies indicate a changing climate on the Antarctic Peninsula (1,2). For this region, a climatic change has been documented through various observations and facts such as a significant warming trend has been detected here over the last several decades (2,3), disintegration of ice shelves (4,5,6), retreat of glacier fronts (7,8), changes in precipitation patterns (9), and reduction of seasonal sea ice (10). Figure 1 summarizes the main indicators of climate change observed on the Antarctic Peninsula. There is evidence that some glacial processes are influenced by the detected changes. For instance, glacier tributaries from Larsen Ice Shelf A and B accelerated and thinned after the ice shelves' disintegration (11,12,13). However, due to the lack of consistent systematic observations (e.g., multi-year observations covering a statistically representative set of glaciers on the Antarctic Peninsula), it is difficult to predict further responses of glaciers to climate change.

Although several indicators of climate change on the Antarctic Peninsula were recorded, the spatial and temporal distribution of glacier changes for this region remain unknown. Remote sensing data enable the compilation of a multi-temporal database of glacier parameters for the last two decades. It will allow deducing and testing hypotheses of altering spatial patterns of glacier changes on the Antarctic Peninsula. This paper describes a method proposed in order to facilitate pre-processing and classification of remote sensing data from several sources. Furthermore, we discuss a sampling method used for selecting a representative set of glaciers to validate classification algorithms.

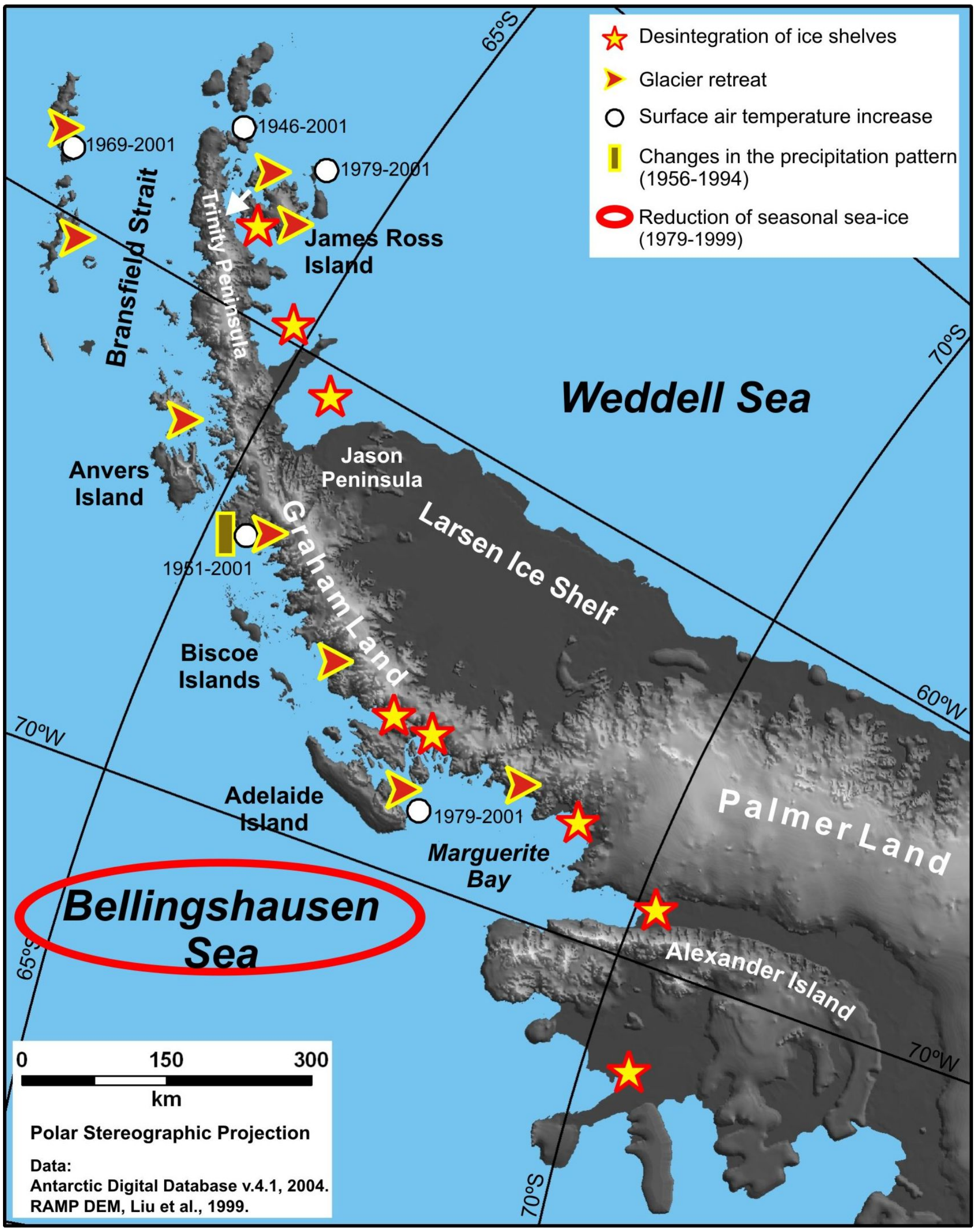

Figure 1: Indicators of climate change on the Antarctic Peninsula. Modified after (14) and (15). The white circles show the location of weather stations and time period analysed by (2), and the white arrow shows the location of Victory Glacier.

Conceptual framework

The evolution of glacier zones is greatly influenced by local and regional climatic and meteorological settings. Their variations as response to changes in energy or mass balance are considered as good indicators of climatic changes (16). In addition, several authors demonstrate the potential of remote sensing data from optical (17,18,19,20,21,22) and radar (16,21,23,24) sensors to identify distinct zonal boundaries within the glacier.

To analyse spatial and temporal patterns of glacier changes on the Antarctic Peninsula, we propose the monitoring of limits between glacial zoning (i.e., snow line, wet snow line, and dry snow line) and their altitudinal variations in the last two decades. The concept of superficial zones or facies on glaciers was first presented by (25) and (26), and reviewed by (27, p. 9). In this work, we use the reviewed concept from (27) illustrated by Figure 2. The analogous radar glacier zones (Figure 2) correspond to the classification scheme proposed by (16), and the optical glacier zones (Figure 2) are based on (17,18,20,22).

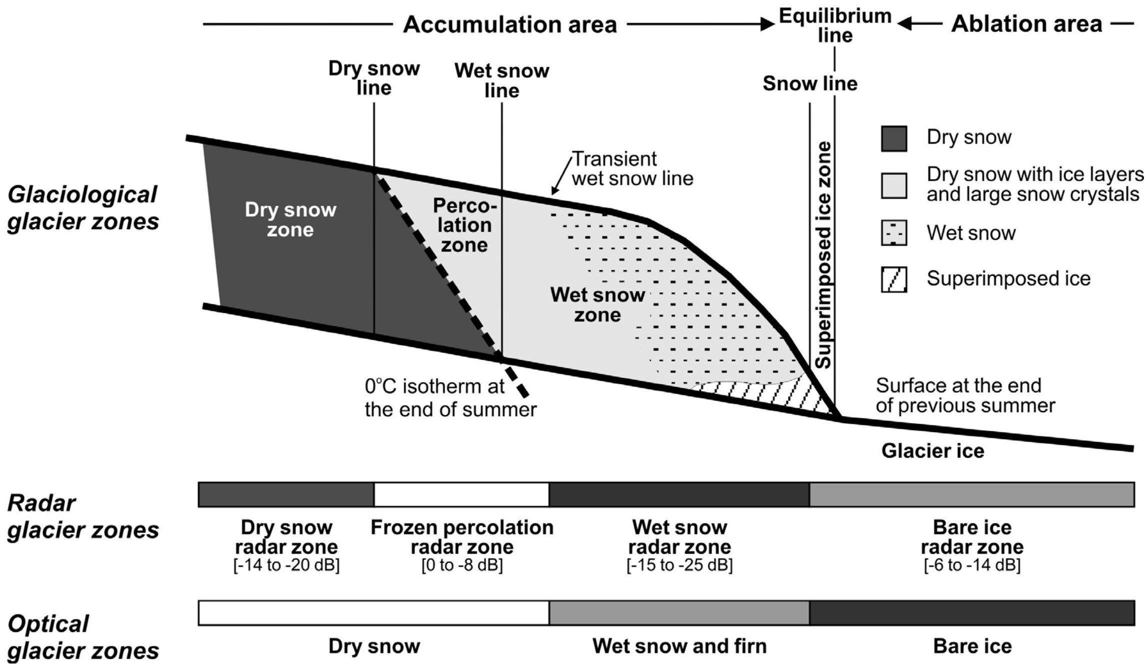

Figure 2: Classical glacier zones as described by (27) and corresponding glacier zones as detected by SAR and optical sensors. Modified after (28).

DATA AVAILABLE

Within the framework of the international project Global Land Ice Measurements from Space (GLIMS), approximately 820 glaciers are catalogued in the Antarctic Peninsula glacier inventory. 560 of them are located north of 70°S and form the data for our statistical analyses. Each glacier is represented in a geographic information system (GIS) as a point feature related to attributes holding glacier static information (i.e., morphological glacier parameters: primary classification; form; frontal characteristics; longitudinal characteristics; major source of nourishment; tongue activity; moraine code; and debris coverage of tongue). (29) describes the glacier parameters used by the GLIMS Regional Center Antarctic Peninsula. A relational database is used to manage the glacier attributes and other information regarding GLIMS analyses.

A multi-temporal dataset from optical and radar sensors forms the basis of this study. Optical data consist of about 170 scenes from the sensors Landsat Thematic Mapper (TM), Landsat Enhanced Thematic Mapper Plus (ETM+) and Terra Advanced Spaceborn Thermal Emission and Reflection Radiometer (ASTER), acquired in the time period 1986 to 2005. Radar data consist of around 250 images acquired from 1991 to 2005 by the sensors ERS 1/2 Synthetic Aperture Radar (SAR), Radarsat SAR and Envisat Advanced Synthetic Aperture Radar (ASAR). Almost all scenes from the above-mentioned datasets were acquired for north of 70°S. Furthermore, the Landsat TM mosaic from the Geoscientific Information System Antarctica (GIA; 30) was used for digitalisation of glacier centrelines. The GIA Landsat TM mosaic is comprised of more than 40 Landsat TM scenes acquired in the period 1986 to 1990.

For this work, the DEM from the Radarsat Antarctic Mapping Project (RAMP) is used. The RAMP DEM was created from various datasets with the objective of orthorectifying Radarsat images used in RAMP (31). At the Antarctic Peninsula, data from the Antarctic Digital Database (ADD) and ERS altimetry were used on land and ice shelves respectively, resulting in a product with a spatial resolution of 200 m, having a root mean square error (RMSE) of ±1 pixel (200 m) of positional accuracy and 100-130 m of vertical accuracy on rough terrain and 2 m on ice shelves. Furthermore, DEM with better spatial resolution (15 m), as well as positional (15 m) and vertical accuracies (60 m RMSE on rough terrain and 15 m on smooth terrain) can be generated from Terra ASTER scenes (32). However, the incomplete coverage of cloud-free scenes on the Antarctic Peninsula is the major restriction to the use of ASTER DEMs in this study.

THE CENTRELINE APPROACH

To monitor a great number of glaciers in a regional context for the Antarctic Peninsula, an automatic procedure is required. Due to geometric distortions and the topographic effects of snow and ice reflectance and backscattering, the analysis of complete glacier catchments in an automatic workflow is complicated. Therefore, it is necessary to simplify the current methodology based on the analyses of entire glacier surfaces.

We propose to limit the classification of remotely sensed data to a small, more manageable area along the glaciers centreline (Figure 3). A glacier's centreline is the analyst-interpreted line that approximately follows the main flow line of the glacier (see Figure 3 and Figure 5b). The approach consists of using the glacier centreline to select a buffer zone (centreline image) which is used for image analyses. After classification, the centrelines are then used to extract the classes (glacier zones) from the raster file and to incorporate it in the glacier relational database.

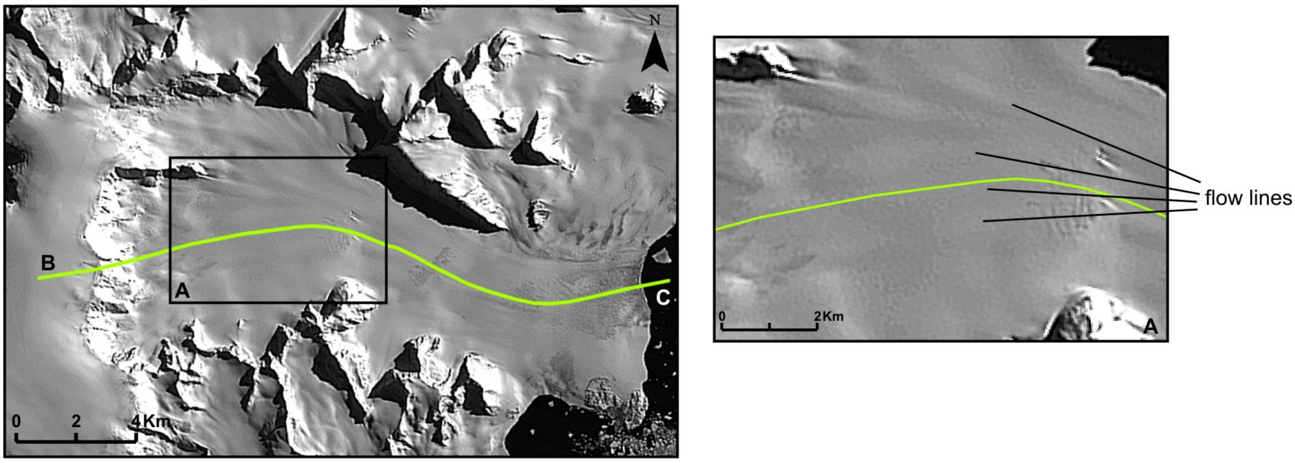

Figure 3: Subset of the GIA Landsat TM mosaic (Landsat TM original scene acquired on 1st March 1986). The green line is the glacier centreline of Victory Glacier (Figure 1). The flow direction is from B to C.

Selection of a representative sample of glaciers

Due to morphological characteristics of the glaciers, it is not possible to monitor superficial zones in the complete population (i.e., all 560 glaciers). To define the glaciers for investigation, we made our selections based on practicality of analysis. We selected glaciers wide enough so as to minimise classification errors due to relief displacements occurring in SAR data, while always attempting to maintain the representative spatial distribution. A sample of 240 glaciers resulted from this process (Figure 4). It corresponds to 43% of the glaciers catalogued on the Antarctica Peninsula north of 70°S. Using the GIA Landsat TM mosaic, glacier centrelines were digitised for each selected glacier. We determined the centrelines location by selecting a glacier-flow line located approximately at the centre of each glacier (Figure 3).

To evaluate existing algorithms for automatic classification of glaciers zones, we do not need all samples. It is sufficient if a sub-sample represents the data variability of the main sample. So, we decided on a stratified sampling. In a stratified sample, the glaciers in study are divided into homogenous groups, before simple random sampling (33). It ensures the representation of each stratum in the sample, and reduces sampling variation due to possible dominance of some strata in the sample. The strata were based on geographic localisation and GLIMS glacier classification parameters (29). The steps were as follows:

- (a) the Antarctic Peninsula was divided in eastern and western sides;
- (b) application of coarse filter to define the strata. For this, we used a matrix of glacier frontal characteristics and longitudinal profiling;
- (c) glaciers were divided into 18 strata (9 strata on each side of the Antarctic Peninsula;
- (d) definition of the sub-sample size. We defined the sub-sample size, by using Eq. (1) (33):

$$n = \frac{N\pi(1-\pi)}{(N-1)D^2 + \pi(1-\pi)} \quad (1)$$

where n is the sub-sample size, N the population, π is the proportion of glaciers estimated to be classified precisely, $1 - \pi$ is the proportion of glaciers estimated to be misclassified, $D = c/Z$, c is the confidence level, and Z is the Z value for the confidence level required. We supposed the algorithm classifies accurately 90% of the sub-samples, and we defined the confidence level 90% and confidence interval ±6%. Thus, the size of the sub-sample is 53 glaciers; and

(e) simple random sampling inside each stratum. Using proportionate allocation, we selected a sampling fraction in each of the strata which is proportional to that of the total population. For this, we used the following Eq. (2):

$$ns_i = \frac{n}{N} Ns_i \quad (2)$$

where ns_i is the number of sub-samples per stratum i, and Ns_i is the number of glaciers in each stratum.

Figure 4 shows the glaciers selected to test and validate algorithms of image classification.

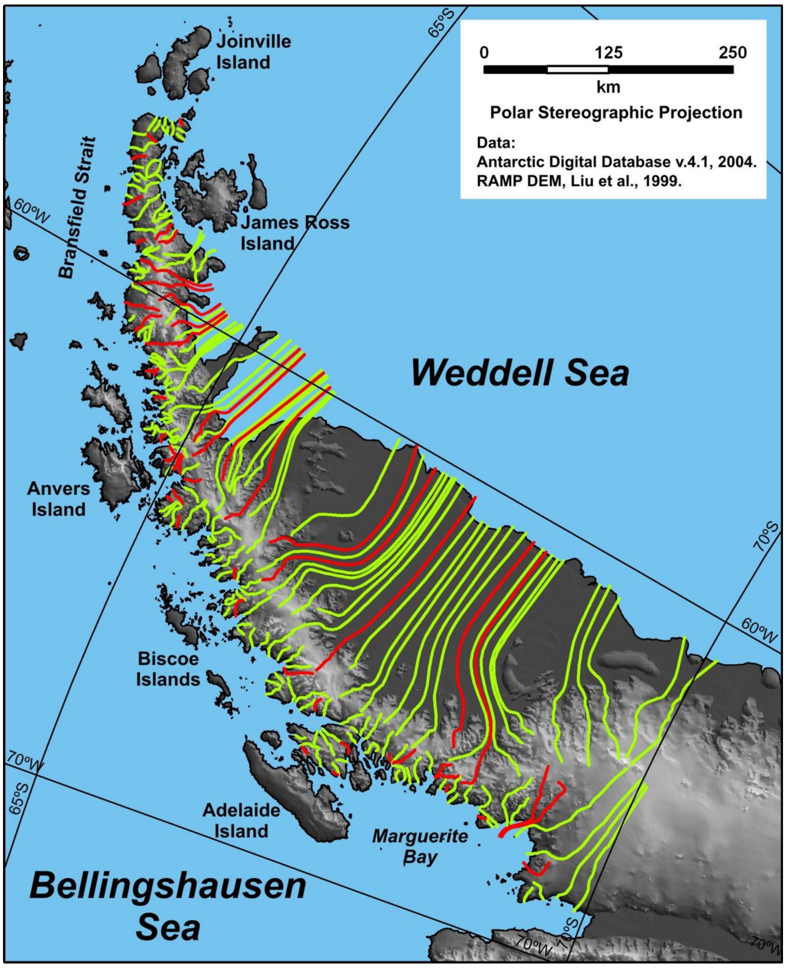

Figure 4: Centrelines digitised on the 240 glaciers selected for this study. Red centrelines represent a sub-sample of glaciers selected for validation of algorithms for classification of glacier zones. The length of the centrelines corresponds to the maximum extent of the glaciers during the time period of analysis.

FACILITATION OF CLASSIFICATION PROCESS

SAR data

SAR images have characteristic relief displacements (Figure 5a, see (34) or (35) for a description about SAR geometry and inherent distortions) which causes problems to occur during the interpretation and classification of the data. These relief-introduced geometric distortions are grave in areas with rough topography, like the Antarctic Peninsula, where typical images look similar to Figure 5a. Hence, the use of SAR images without terrain correction limits the integration of this data as well as the optical imagery.

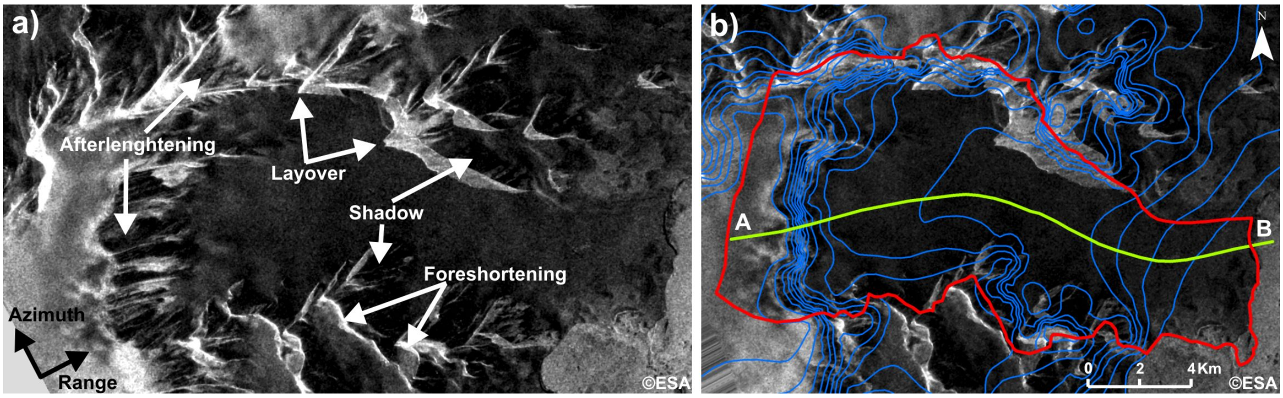

Figure 5: Subset of a ERS-2 SAR image acquired on 18 January 2002. a) Examples of relief displacements occurring in SAR data due to the rough topography of the Antarctic Peninsula, b) Image subset orthorectified using the RAMP DEM. The red lines are boundaries of the Victory Glacier (Figure 1), the blue lines are contour lines at intervals of 100 m, and the green line is the glacier centreline. The flow direction is from A to B.

To correct for relief displacements, a DEM containing a spatial resolution and accuracy compatible with terrain features is necessary. As stated above, a high resolution DEM is not available to be used in a productive workflow of orthorectifying SAR images on the Antarctic Peninsula. By using the RAMP DEM, the results are not satisfactory if we consider the whole glacier catchment area. Figure 5b depicts remaining distortions at the north and south divisors of the Victory Glacier. However, the terrain slope along the glacier centreline is smooth (less than 10 degrees, Figure 5b). An exception is the stepped transition between the plateau and the glacier valley. Thus, using the centreline of images to analyse altitudinal changes of boundaries between glacier zones, positional errors resulting from the use of RAMP DEM will not be a problem at the regional scale of the Antarctic Peninsula.

Besides dependence on sensor parameters and sensor-target geometry, the backscatter signal recorded on glaciers and ice sheets depends on snowpack parameters (e.g., liquid water content, snow density, stratigraphy, grain size, and surface roughness) (36). These parameters drive backscatter mechanisms such as volume scattering (dry snow radar zone and frozen percolation radar zone), low surface scattering with radar signal almost completely absorbed by liquid water (wet snow radar zone), and surface scattering of a rough and dense surface (bare ice glacier zone) (24). It results in different backscatter values for each glacier radar zone (Figure 2). As the backscatter values of dry snow and frozen percolation radar zones are resulting from volume scattering, small changes in terrain slope and aspect along the centrelines will not affect the classification of these zones. The adjacent wet snow radar zone and bare ice radar zone, whose thresholds in backscatter values are relatively near (Figure 2), will profit from the restriction of the analysis to areas with smooth slopes near the centreline.

Optical data

Geometric distortions in optical images are dependent on the distance to the nadir line and altitudinal variations. (37) showed a good numerical example of horizontal displacements in a Landsat TM scene covering an area with an altitudinal gradient of about 3000 m. According to the authors, the highest RMSE values range between 176-252 m and are found in areas of high topographic variation which occur mainly near the borders of the scene. On the Antarctic Peninsula north of 70°S, the highest areas on the plateau are lower than 2500 m a.s.l., with exception of some peaks in northern Palmer Land (Figure 1). So, expected positional errors by not considering topographic effects are about 1 pixel of the RAMP DEM (200 m) in the worst cases. Furthermore, by limiting the analysis to the central area of the glaciers, terrain distortions on ridges and peaks are eliminated.

The radiation reflected by glacier surfaces and detected at satellite level is strongly affected by the sun-surface-satellite geometry (38). Figure 6a depicts two main effects resulting from the terrain influence: (a) saturation; and (b) shadowed illumination. Saturation and high values of reflectance (Figure 6a, red arrows) are detected on sun-oriented surfaces with steep slopes, due to the forward component of the anisotropic reflectance on snow surfaces (38). Shadowed illumination is a characteristic from surfaces without direct solar illumination (Figure 6a, blue arrows), and is considered a challenge in the classification of glacier surfaces (20,22). Nevertheless, (39) showed that the variability in the hemispherical-directional reflectance factor (HDRF) for near-nadir sensors is negligible. As Landsat TM and ETM+ are nadir viewing sensors, and Terra ASTER data for this study are being selected within an angular range of ±10° from nadir (Terra ASTER has an off-nadir scan of ±24°), we are able to neglect the anisotropic reflectance by analysing areas with smooth slopes near the centreline.

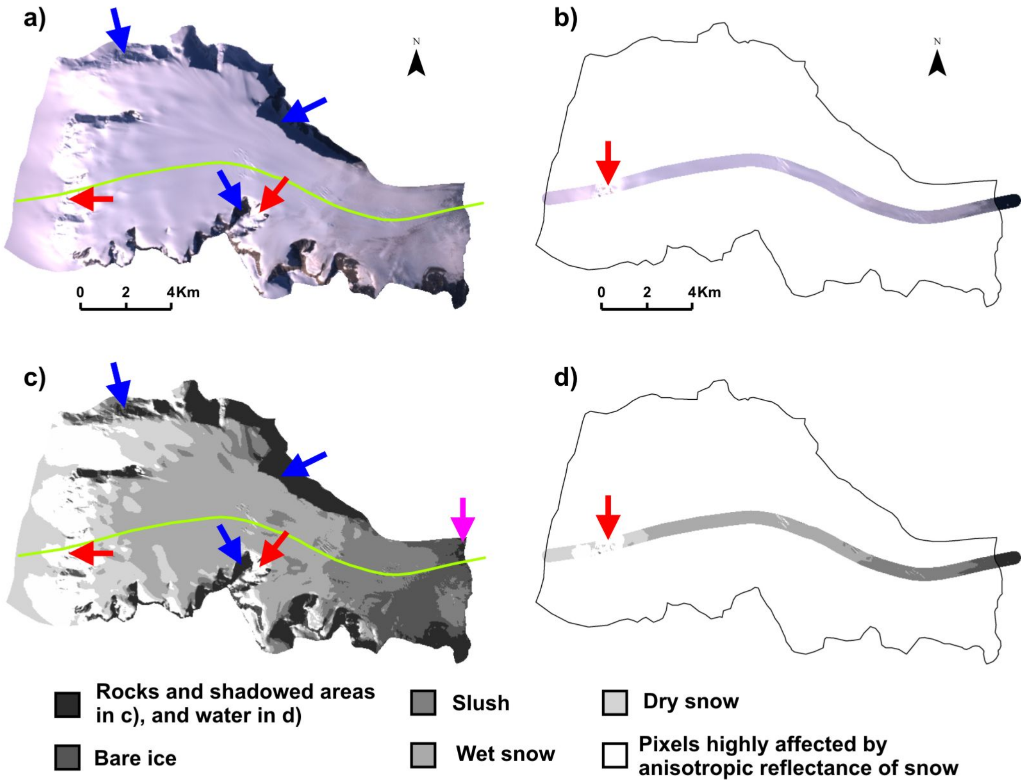

Figure 6: Subsets of the Landsat ETM+ scene acquired on 21 February 2000 (sun elevation angle 26.5°, solar azimuth 56.5°) and respective products of unsupervised classification. a) Subset of the ETM+ scene covering the whole Victory Glacier (Figure 1), the green line is the glacier centreline, b) Subset of the ETM+ image covering a buffer area of 300 m around the glacier centreline on Victory Glacier, c) and d) Products of the isodata algorithm applied on a and b respectively. The red arrows show areas of pixel saturation resulting from topographic effects (a and b), and misclassification due to topographic effects on snow reflectance (c and d); the blue arrows show areas shadowed (a) and misclassified (c) because of topographic effects; and the magenta arrow shows some pixels of the bare ice zone misclassified as rock.

Simply by using the centreline image, many areas affected by topographic effects are not considered in the analysis (Figure 6b). Figure 6c,d show products from unsupervised classification (ISODATA algorithm, 6 classes) performed on the image subsets depicted in Figure 6a,b respectively. Two classes correspond directly to the bare ice and dry snow zones, whereas the last one represents the freshly-fallen and slightly-metamorphosed snow. As found by (18), the wet snow zone was further classified as two distinct zones (Figure 6c,d): (a) a zone of snow supposed to be saturated with water (slush zone); and (b) snow highly metamorphosed by melting and refreezing cycles. Some pixels of the bare ice zone were misclassified as rock using the whole glacier basin, but accurately classified as bare ice with the centreline image. Areas affected by the topography or classification errors correspond to 26.18% of the glacier basin in Figure 6c, while it corresponds to only 9.12% of the centreline image in Figure 6d.

Besides visual interpretation and simple statistical measures, scatter diagrams (Figure 7a,b) yield a two-dimensional representation of the spectral classes. The scatter diagram of the centreline image (Figure 7b) shows better delimitation among classes in comparison with the diagram generated from the whole basin area (Figure 7a). It indicates the reduction of pixels located on the boundaries or in overlapping regions between classes.

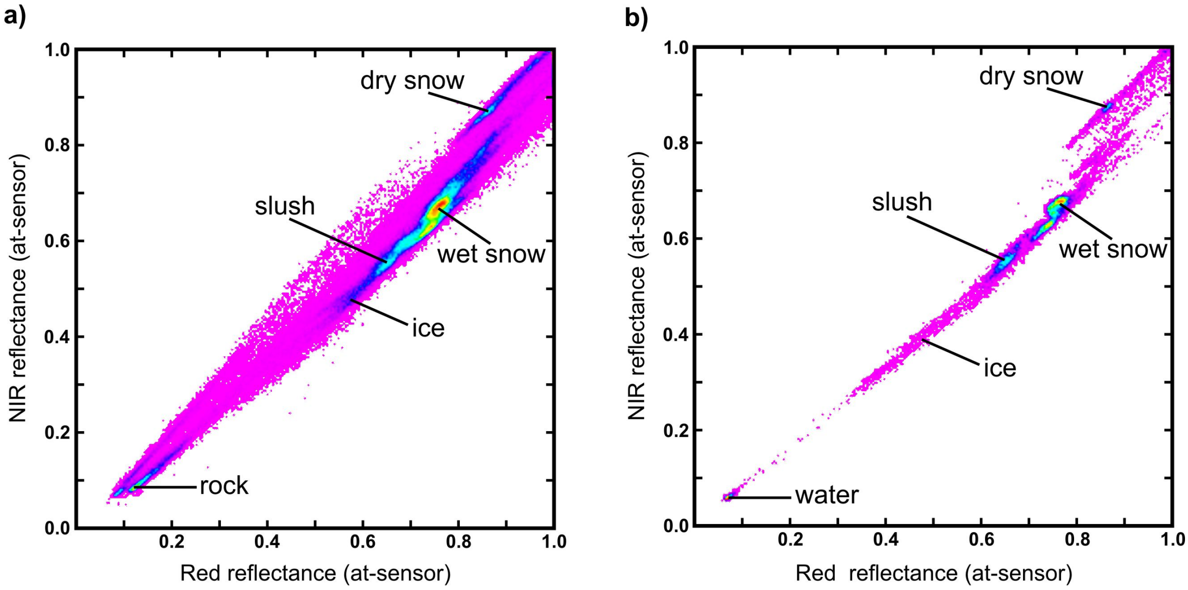

Figure 7: Scatter diagrams showing the delineation of spectral classes using the red and near infrared bands of the images depicted in Figure 6a-b. a and b correspond to 6.a and 6.b respectively. Hot colours represent higher concentration of pixels. The clusters of pixels with low values of reflectance correspond to different classes in each diagram. It occurs because the centreline approach exclude rock outcrops from the analyses, but to detect changes in glacier frontal positions, this approach analyses areas beyond glacier fronts.

DISCUSSION

The digitalisation of the glacier centrelines was strongly depending on the analyst. However, as analyses for each glacier are always realised on the same centreline, any change detected will be related to the same reference. Furthermore, the use of the GIA Landsat TM mosaic as base for digitalisation of the glacier centrelines contribute to include the maximum extension of the glaciers in study during the last two decades. It is ensured by the fact that the oldest images to be analysed correspond to GIA's original scenes and the Antarctic Peninsula had a general pattern of glacier-front retreat in the time period considered (8,40).

By reducing the glacier area to be analysed to areas along the centrelines, we minimised the need of a high resolution DEM for orthorectification of SAR and optical data, and contributed to reduce topographic effects on glacier reflectance. It facilitates pre-processing and analysing the multi-temporal image database available for this study. However, a comprehensive evaluation of classification methods has to be carried out in order to select the most appropriated algorithm for mapping of glacier zones using the centreline images.

On the other hand, due to relief-introduced geometric distortions on SAR and optical images, glaciers flowing through narrow valleys (up to 1000 m wide) will not be analysed. It corresponds to

57 % of the glaciers catalogued on the Antarctica Peninsula north of 70°S, and could mask or bias the geostatistical analysis to be carried out.

Glacier zones resulting from analyses of centreline images will consist of documented digital data to be incorporated in the Antarctic Peninsula glacier database. However, these products correspond only to a small area along glacier centrelines, and do not meet the requirements to contribute to international projects (e.g., the GLIMS project) based on analyses of complete catchment areas. We expect that the methods developed in this study can be extended and adapted in order to contribute to international projects of glacier inventorying and monitoring.

CONCLUSIONS

We proposed a method for monitoring spatial and temporal changes in glacier parameters using satellite imagery. The centreline approach facilitates the pre-processing and classification of remote sensing data acquired on glaciers. Furthermore, this approach enables the integration of remote sensing data from different sources, and minimises the needs of high resolution DEMs for terrain correction. Analyses resulting from the centreline approach will generate data for testing the initial hypothesis of spatial and temporal patterns of changes in glaciers zones in the Antarctic Peninsula.

A sampling method has also been described. It helps to select a representative subset of glaciers for evaluation of algorithms for classification of remote sensing data. If the algorithm classifies accurately 90% of the 53 selected glaciers, we can say the algorithm will classify 90% ± 6% of the 240 glaciers selected for this study, with a confidence level of 90%. If the classifier results in a different accuracy, we can use Eq. (1) to recalculate the probability of a glacier being classified accurately.

Further work will be concentrated on developing algorithms for semi-automatic classification of SAR and optical imagery along the glacier centrelines. It will enable the analysis of a time series of satellite images covering the time period 1986 to 2005. In the future, high-resolution SAR and optical sensors (e.g., TerraSAR-X, QuickBird, IKONOS) should expand the amount of glaciers possible to be analysed using the centreline approach.

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