ESTIMATION OF ACCUMULATION AREA RATIO OF A GLACIER FROM MULTI-TEMPORAL SATELLITE IMAGES USING SPECTRAL UNMIXING

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ABSTRACT

The snowline altitude (SLA) and the accumulation area ratio (AAR) of the Morteratsch glacier, Switzerland are derived using Landsat images over a period of 20 year. To draw the SLA, multitemporal Landsat images are first calibrated to surface reflectance using 6S [1]. A linear spectral unmixing algorithm is applied with accumulation and ablation end-members. Transects best representing the morphology of the glacier are drawn and the SLA is defined using the shifts between the end-member profiles of snow and ice. The results of two mass balance characteristics, SLA and AAR, show that the Morteratsch glacier has changed substantially during the period between 1985 and 2005. The average SLA of the glacier has risen by 131 m and the AAR decreased from 66.2 % to 52.5 % during this period. Comparatively, the eastern part of the Morteratsch glacier has a smaller increase (94m) in the altitude of the snowline, as compared to that of the western part (183 m).

Index Terms— Glacier, accumulation area ratio, snowline, spectral unmixing

1. INTRODUCTION

Close monitoring of glaciers can provide hints of climate change. A direct measurement of the change in mass balance of glaciers over time is a straightforward method to relate glacier fluctuations and climatic variations. The mass balance of a glacier is defined as the difference between accumulation and ablation. Accumulation means the amount of snow accumulated during the winter. Ablation refers to the amount of snow and ice melted during the summer. Net mass balance is positive if the melting of snow and ice is less than the accumulation, and it becomes negative if the former is larger than the latter. Inferences of mass balance can be achieved by finding the altitude of the transient snowline of each year, and monitoring their change over time. The altitude of the transient snowline is defined as the lower boundary of last year's snow at the time of the image acquisition [2]. The altitude of the transient snowline approximately coincides with the altitude of the equilibrium line which is the elevation where the mass balance is zero. The altitude of the equilibrium line is inversely related to the annual net balance of the glacier. A lower equilibrium line represents a higher net mass balance. A higher equilibrium line represents a lower net mass balance. If the transient snowline is delineated over successive years, and the area-elevation relationship of a glacier is known, then the accumulation area ratio (AAR) can be determined.

It has been suggested that recently available satellite image can be exploited to find the transient snowlines and AAR [3]. In [4], the visible and near-infrared bands of Landsat images have been shown to be useful to define the snowline. The distinction is possible because reflectance of snow is always high and that of the ablation zone with melting snow and ice is usually low. Either single bands or a combination of bands in the form of band ratios can be used to define the snowline. MSS7 (0.8-0.11μm) and TM4 (0.76-0.90μm) have been found individually useful, and band ratio TM4/TM5 can enhance the contrast between the accumulation and ablation zones. However, to finally map the snowline, manual delineation or some forms of classification have to be employed. In [5], spectral mixture analysis is applied to multi-spectral Landsat images to delineate the snowlines. Comparing with conventional band ratio methods, the spectral mixture analysis provides a more accurate delineation of the transient snowline. Some results from [5] also show the possibility of using endmembers selected from one glacier for unmixing of another glacier. In this study, we gather multitemporal Landsat images of Morteratsch glacier in the south-east of Switzerland between 1985 and 2005. Linear spectral unmixing is used to delineate the snowline altitude (SLA) with the help of a DEM image. Then the accumulation area ratio (AAR) is calculated to give a perspective of the change in mass balance of the Morteratsch glacier over the years between 1985 and 2005.

2. DATA AND PREPROCESSING

Landsat images between 1985 and 2005 are made available for this study. The images, however, have to be cloud free over the Morteratsch glacier and there should not have been recent snowfalls as that would cover both the accumulation and ablation zones entirely making separation impossible. After examined all the available images, only ten images are found to be useful.

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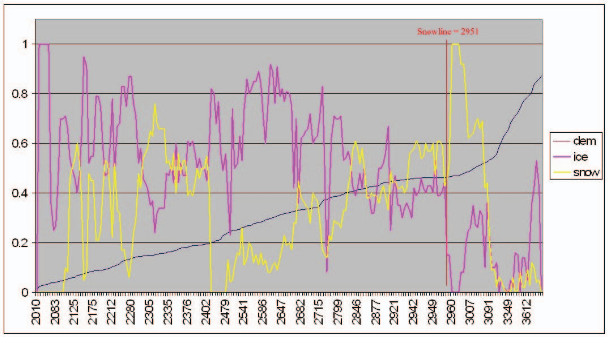


Fig 1. An example of finding the snowline altitude through the spectral unmixing method. The pink and yellow represent the variations of the end-members of ice and snow respectively along a transect from around 2,000 to 4,000m, in the year 1999. The blue line shows the profile of a digital elevation model (DEM). The snowline altitude is estimated at the substantial shift at 2951m.

The selected images are then calibrated to surface reflectance using 6S. The use of 6S for a glacier has been well-documented in [6]. While the process of reflectance calibration might not lead to significant improvement on the results of spectral unmixing, it can improve contrast in shades and make comparison more feasible when the same method is applied to other satellite images such as ASTER. A DEM is available and is used to mask out the glacier area from all the images.

3. SPECTRAL UNMIXING

Since a pixel can contain different land covers, its value is actually an averaged reflectance of a mix of land covers. Spectral unmixing is a technique to measure the proportion of an endmember within a pixel using multispectral images. The result of the fraction of a land cover within a pixel is important in many applications. Following the notations in [5], a linear unmixing is modelled as follow:

$$R_{measured,b} = \sum_{em=1}^{N} (F_{em,b} R_{em,b}) + \varepsilon_b$$

where $R_{measured,b}$ is the measured reflectance in band b, $R_{em,b}$ is the reflectance of the endmember, $F_{em,b}$ is the fraction of each pixel covered by each endmember in band b., and ε_b is the residual errors. N is the number of bands. For each pixel, the summation of endmember fractions always equals one. While spectral unmixing is usually employed to estimate the proportion of a pixel that is belonging to certain endmembers, its application in this study is to delineate the transient snowline, or to separate the accumulation and ablation zones. As suggested in [5], a linear spectral unmixing method is used. In order to delineate the snowline, accumulation and ablation endmembers are defined and applied in the spectral unmixing.

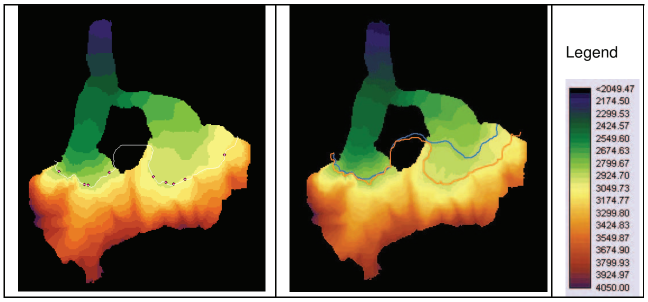
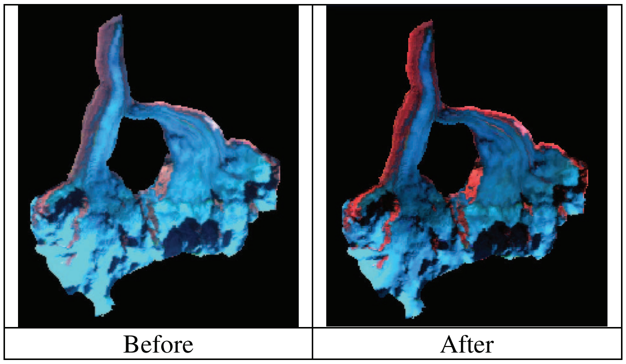


Fig 2. Left: A 2D snowline in 1999 is drawn on the DEM by combining the snowline altitudes estimated from all nine transects. Right: the comparison of the transient snowline in 1985 (blue) and 1999 (orange) using the spectral unmixing method.



Before After

Figure 3. A comparison of the 1999 Landsat image before and after atmospheric corrections. The figures represent the false color composites of band 5,4 and 2.

A transect which runs from the highest point to the lowest point of the glacier has to be carefully chosen. Then, both the profiles of the accumulation and ablation endmembers are plotted on the same chart. The transient snowline can be approximated at the altitude where the profiles of both endmembers have an abrupt and substantial shift but in the opposite directions: in ascending altitude, the accumulation endmember has a sudden jump while the ablation endmember has a sudden drop in their endmember fractions. These abrupt changes signal the altitude of the transient snowline. Figure 1 is an example of how a SLA is being found from the unmixed images of 1999. But this only gives a point of the snowline on one transect. In order to present a two dimensional snowline, many transects are needed and their estimated snowline altitudes are then connected. In this study, nine transects are carefully drawn to best represent the morphology of the glacier (Fig 2, left figure).

Since a net radiometer was installed on the glacier only since 1995 [7], ground measurement for the calibration of surface reflectance for image acquired before that was not available and consequently the application of unmixing was not possible. Manual estimation was made on the 1985 image (Fig 2. right).

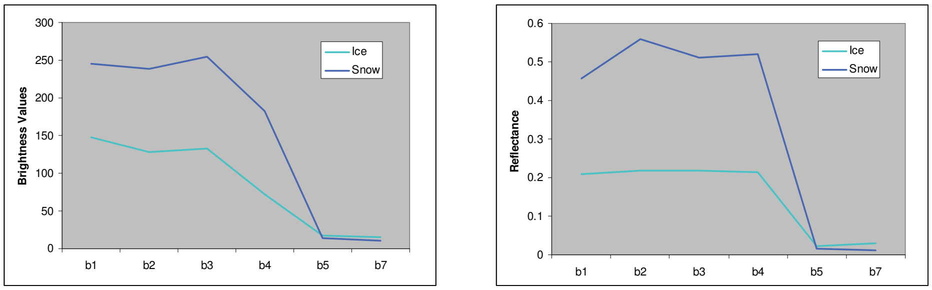


Figure 4. A comparison between ice and snow spectral profiles before (left) and after (right) atmospheric correction.

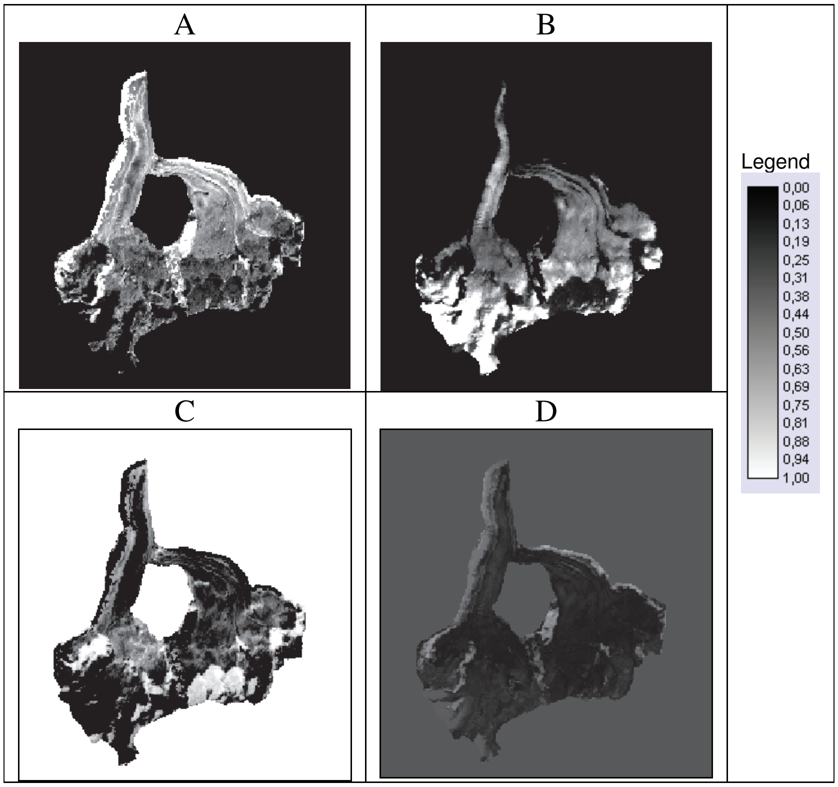


Figure 5. Unmixed images of 1999 A) ice, B) snow, C) shadow, and D) residuals.

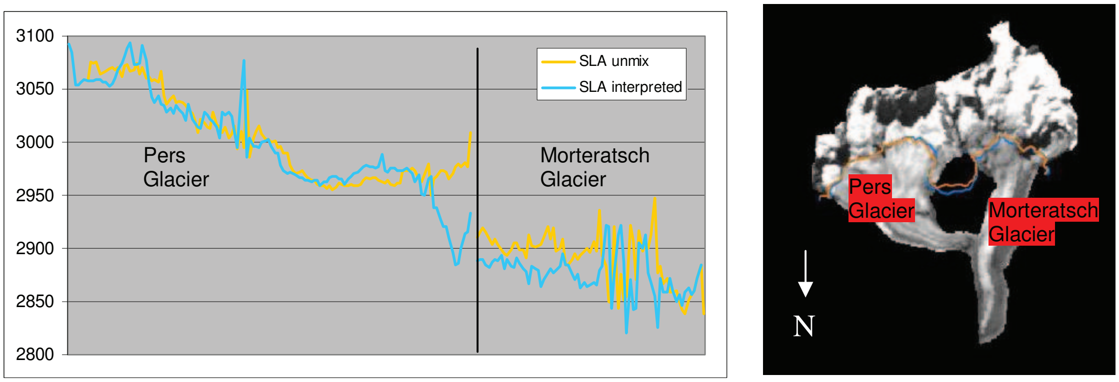


Fig 6. A comparison between visually interpreted snowline in blue and the snowline delineated by spectral unmixing in orange from the 1999 Landsat image. The two snowlines are overlaid on the Landsat image to show their location.

	SLA average over glacier (m)	Surface accumulation area (km^2)	AAR
1985	2885	11.89	66.2
1995	2912	11.18	62.3
1997	2924	11.0	61.2
1998	2915	11.28	62.8
1999	2961	10.06	56.0
2000	2964	10.12	56.3
2005	3026	9.42	52.5

Table 1. The SLA and AAR calculated from the snowlines delineated with the unmixing method. Figures for the years 1985 and 2005 are manually interpreted.

4. RESULTS AND DISCUSSION

Figure 3 shows the false color composites of the 1999 Landsat image before and after atmospheric correction. While the calibration is not expected to have significant effects on our final results, reflectance image provide a physical meaning of the image and it is observed that the contrast at certain parts of the image are marginally enhanced. Figure 4 shows the change of signature profiles of snow and ice after atmospheric correction. After all the images are calibrated into reflectance images, spectral unmixing is applied using all the bands. Figure 5 shows the results from the year 1999. The results of spectral unmixing method were compared with other snowline delineation methods such as direct classification of snow and ice, the Normalized Difference Snow Index and image thresholding. Our results show that the unmixing method gives the most satisfactory estimates on the snowline. Endmembers used for the unmixing are snow, ice and shadow. Table 1 shows the calculated SLA and AAR. Manual interpretation of images from 1985 and 2005 are used together for our analysis. The results of two mass balance characteristics (SLA and AAR) show that the Morteratsch glacier has changed substantially during the period between 1985 and 2005. The average SLA of the glacier has risen by 131 m and the AAR decreased from 66.2 % to 52.5 % during this period. Comparatively, the eastern part of the Morteratsch glacier has a smaller increase in the altitude of the snowline. The rising of the snowline is 94 m in the eastern part compared to 183 m at the western part.

The use of multi-year reflectance images can be an important tool for long term assessment of the change in mass balance of a glacier which in turn indicates the possible effect of climate change. In this study, we examine the use of spectral unmixing approach for the delineation of the transient snowlines. The method shows some potentials but it is also not straightforward when the shifts between the endmembers of ice and snow are not obvious, or in some cases more than one significant change are observed. Certain manual interpretations are necessary in those cases. Figure 5 shows a comparison between a manual interpreted snowline and a snowline derived from the unmixing method. There is a good proportion of the snowline with certain agreement, but there are clear disagreements at the transition between Pers and Morteratsch glaciers. It is suspected that the surrounding topography of the glacier could be a factor. In our case, heightened peaks have shadowed certain portions of the glacier which makes it impossible to obtain a good delineation. This problem with the shadowing can not be solved entirely even with advanced techniques.

The unmixing method, however, provides better results and is a better alternative than conventional methods such as band ratios and thresholding from individual bands. The use of a reflectance image for the method also provides a physical meaning to the result. While human interpretation is still needed for deciding the SLA, it gives a better guidance to the delineation. The method can easily be applied on images acquired by other sensors.

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