DERIVATION OF STATISTICAL SNOW LINE FROM HIGH RESOLUTION SNOW COVER MAPPING

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ABSTRACT:
The snow line has been defined as a line delimiting an area with complete snow cover from an area free of snow. In the Alps, the snow cover is dispersed in snow patches due to the rugged relief and does not allow such definition. The snow line is therefore drawn within a belt of about 50% coverage. Recent advances in high resolution snow cover mapping using Landsat-TM and SPOT enable the snow line to be evaluated by statistical objectivity. In the basin of the Rhône at Sion (3371 km², 491-4634 m a.s.l.) the snow line was determined by dividing the basin into zones with 100 m altitude steps and interpolating its position within the zone nearest to the 50% snow coverage. The snow line on glaciers was found to be lower than in the adjacent areas.

KEY WORDS: Snow Line, Snow Cover Mapping, Remote Sensing

1. Introduction
The snow line is frequently considered to be a dividing line between complete snow cover and a snow free area. When various runoff models were adapted to snowmelt runoff computation, such a line was produced by simulating the snow cover from precipitation in a number of elevation zones. The snow line was set at the altitude between a zone with no simulated snow cover and the next higher zone with a complete simulated snow cover. In the Alps, such conditions exist only for short periods after snowfall during the snowmelt season. Normally, the seasonal snow cover is too scattered due to the rugged relief to allow such a straightforward distinction. Therefore, another definition (WMO, 1970) states that the snow line is drawn within a belt of 50% coverage. Recent progress in high resolution snow cover mapping (e.g. Haefner, 1990) makes possible to determine a statistical snow line, above which the snow cover is more than 50% and below which it is less than 50%.

2. Description of the test basin
The Rhône-Sion basin (3371 km², 491 - 4634 m a.s.l.), shown in Fig. 1, is characterized by a great elevation range and by a considerable glacier area (580 km²). For snowmelt runoff modelling, mountain basins are usually divided into elevation zones with an altitude range of about 500 m, enabling the snow coverage to be evaluated over sufficiently large areas. To determine the position of the snow line, a finer division using 100 m steps is needed which was made possible by the improved spatial resolution of snow cover mapping. Furthermore, the basin was also divided into 12 partial areas (subbasins or parts of subbasins) which are shown in Fig. 1, in order to determine the snow lines separately. Special attention was paid to the behaviour of the snow line on several glaciers. The areas and elevation range of the partial areas are given in Table 1.

3. Method of snow cover mapping
Accurate mapping of the patchy alpine snow cover requires a high spatial resolution which is provided by Landsat-TM and SPOT. In order to follow the position of the snow line during the snowmelt season, periodical snow cover mapping must be carried out with a sufficient frequency.

In the period of April - September 1985, six Landsat satellite images (TM and MSS) were available. The snow coverage of areas obscured by clouds was found using a refined method of extrapolation in order to maintain an adequate evaluation accuracy (Ehrler et al., 1997). The snow coverage was determined for zones with 100 m altitude steps, separately for glaciers and for partial areas of the Rhône basin as illustrated in Fig. 1.

With regard to snow and ice mapping the analysis of remote sensing data in mountainous areas, espe-
particularly in order to distinguish snow from bare glaciers or snow from other cover types, has to take into account the
effect of illumination as described elsewhere (Ehrler and Seidel, 1995). We utilize a Digital Elevation Model (DEM) and compute the local orientation of the terrain surface relative to the light source and to the sensor position. The Landsat images were segmented into four illumination classes depending on the local incidence angle. Each illumination class has been separately classified into bare ice, snow, transition zone and snowfree (=aper) using supervised multivariate statistics.

4. Seasonal rise of the statistical snow line

The gradual rise of the snow line in the partial area Goms during the snowmelt season is illustrated in Fig. 2. In April - May, the progress is slow because the temperature and solar radiation are not yet at maximum. Also, intermittent snowfalls delay the ablation of the seasonal snow cover. At this point, it should be noted that the evalua-

<table>
<thead>
<tr>
<th>Name</th>
<th>Area [km²]</th>
<th>Glacierized</th>
<th>Elevation range [m a.s.l.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gletsch</td>
<td>41</td>
<td>45%</td>
<td>1800 - 3600</td>
</tr>
<tr>
<td>Goms</td>
<td>420</td>
<td>10%</td>
<td>700 - 4200</td>
</tr>
<tr>
<td>Sierre</td>
<td>1403</td>
<td>6%</td>
<td>500 - 4500</td>
</tr>
<tr>
<td>Zermatt</td>
<td>239</td>
<td>51%</td>
<td>1500 - 4600</td>
</tr>
<tr>
<td>Stalden</td>
<td>342</td>
<td>13%</td>
<td>700 - 4500</td>
</tr>
</tbody>
</table>

Table 1: Partial areas of the basin Rhône-Sion

Fig. 1: The Rhône-Sion basin showing partial areas and glaciers
tions of the snow line refer only to the seasonal snow cover. To this effect, satellite images showing a short-lived snow cover following a summer snowfall event have been disregarded. In June - July, the snow line rises more rapidly due to intensive snowmelt. This progress is slowed down towards the end of the snowmelt season because snowmelt rates decrease with altitude and more snow has to be melted in order to remove the snow cover. Fig. 2 also shows that there is a considerable altitude range between a 5% and a 80% snow coverage. The statistical snow line is approximately in the middle of this belt.

Fig. 3 illustrates the same evaluation for the partial area Zermatt. On the same dates, the snow line is about 250 m higher in the Zermatt area due to lower initial snow accumulation, as evaluated elsewhere (Ehrler et al., 1997). The average altitude range of the belt with 5% to 80% snow coverage is about 500 m as compared with nearly 700 m in the partial area Goms.

5. Snow line in partial areas

The elevations of the statistical snow line in selected partial areas at the respective stages of the snowmelt season are shown in Fig. 4. The lowest elevations refer to the partial area Gletsch which has the greatest initial accumu-
lation of snow and 45% of glacier area. The highest elevations refer to the partial area Stalden which has a low accumulation of snow and only 13% glacier area.

It appears that a high initial snow accumulation as well as the presence of glaciers keep the snow line low. However, the snow line in the partial area Zermatt is nearly as high as in the partial area Stalden although Zermatt has 51% glacier area and Stalden only 13%. The explanation may be that the snow lines in Fig. 4 rise to an elevation of up to 3400 m a.s.l. while considerable glacier areas, particularly in the Zermatt sub-basin, are situated higher. This comparison demonstrates that the elevation of the snow line in a mountain basin of about 3000 km² may differ by as much as 600 m. This corresponds to a temperature difference (assuming a lapse rate of 0.65°C/100m) of 4°C and casts further doubts on producing the snow coverage without remote sensing by simulating a snow cover from precipitation and melting in zone by zone, in order to compute snowmelt runoff.

6. Snow coverage and snow line on glaciers

Glaciers originate in localities where the seasonal snow cover has the best chance of surviving the summer melt. Snow is also conserved on glaciers because heat flux from the ground is intercepted by the ice. Similarly, new snow in the summer stays longer on existing snow fields than on bare ground.

Fig. 5 shows depletion curves of the snow coverage evaluated from periodical mapping separately for the glacier-free areas and for the glaciers in the elevation range of 2600 - 3100 m a.s.l.. The irregular shape of the depletion curves (as opposed to the usual smooth curves interpolated from measured points) results from cold spells being taken into account. Whenever temperatures indicate no melting conditions, the snow coverage is kept unchanged. If temperatures at the mean hypsometric elevation of a zone are used as criterion for melting, the snow coverage may be occasionally assumed to stay unchanged although snow ablation occurs in the lower parts of the zone. This results in a sharp drop to the next measured point as happened in April 1985 with the glacier-free curve.

The delayed decline of the snow coverage on glaciers confirms that the snow line during the snowmelt season is lower than in the adjacent glacier-free areas. Therefore it must be determined separately. This is done in Switzerland on selected glaciers approximately at the end of the snowmelt season by analysing air photos (Aellen and Herren, 1994).

As listed in Table 2, there is a good agreement between the altitudes of the snow line on the Aletsch glacier determined by air photos and of the statistical snow line determined in 20 m altitude steps from satellite snow cover maps. The table also shows additional results for other glaciers from satellite snow cover mapping.
7. **Assessment of results**

High resolution snow cover mapping by satellites confirms that the snow line in the Alps and even in basins of only several thousand km$^2$ can generally not be set at a certain altitude. In the Rhône-Sion basin the belt with a 5% to 80% snow coverage has an elevation range of about 600 m. Furthermore, the altitude of a statistically evaluated snow line for 50% snow coverage varies by as much as 600 m in different parts of the basin. As could be also confirmed, the snow line on glaciers is lower than in the adjacent area and must be determined separately. Of particular interest is the snow line on glaciers at the end of the snowmelt season which becomes the firm line. The position of this line as compared with its average altitude from the past is an indicator of the mass balance of a glacier and, in the long run, of the effect of a climate change on glaciers. The gradual rise of the statistical snow line during the snowmelt season, as evaluated for the Rhône-Sion basin in 1985, characterizes, together with snow covered areas, snow conditions at present times. It is of interest for winter tourism and for climate change studies. The spatial resolution of snow cover mapping in the range of 10 to 30 m, as provided by Landsat-TM (or by Landsat-MSS with 80 m), appears to be sufficient to determine the statistical snow line for these purposes with an adequate accuracy and objectivity.

### Table 2: Snowline on glaciers

<table>
<thead>
<tr>
<th>Satellite Acquisition Date</th>
<th>Gr. Aletsch</th>
<th>Oberaletsch</th>
<th>Mittelaletsch</th>
<th>Findeln</th>
<th>Gorner</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.9.84</td>
<td>2890 m a.s.l.</td>
<td>2870 m a.s.l.</td>
<td>2840 m a.s.l.</td>
<td>2970 m a.s.l.</td>
<td>3120 m a.s.l.</td>
</tr>
<tr>
<td>12.9.85</td>
<td>2900</td>
<td>2929</td>
<td>3020</td>
<td>3040</td>
<td>3240</td>
</tr>
<tr>
<td>10.9.90</td>
<td>3030</td>
<td>3070</td>
<td>3150</td>
<td>3130</td>
<td>3380</td>
</tr>
<tr>
<td>15.9.92</td>
<td>cloudy</td>
<td>cloudy</td>
<td>2950</td>
<td>3140</td>
<td>3080</td>
</tr>
</tbody>
</table>

a. statistical snowline determined in 20 m altitude steps from satellite snow cover maps

b. analysis based on air photos (for the Jungfrau Firn): Glaciers of the Swiss Alps, Yearbook of the Commission of the Swiss Academy of Natural Sciences, Editor: VAW, ETH, Zürich

**Fig. 5: Depletion curves of the snow coverage in the basin Rhône-Sion, 1985, referring to glacier-free and glacier areas**
8. References


