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Analysis of georadar data to estimate the snow depth distribution

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ABSTRACT

We have performed extensive georadar surveys for mapping the snow depth in the basin of Breuil-Cervinia (Aosta Valley) in the Italian Alps, close to the Matterhorn. More than 9 km of georadar profiles were acquired in April 2008 and 15 km in April 2009, distributed on an hydrological basin of about 12 km^2. Radar surveys were carried out partially on the iced area of Ventina glacier at elevation higher than 3000 m a.s.l. and partially at lower elevation (2500 m–3000 m) on the gently slopes of the basin where the winter snow accumulated directly on the ground surface.

The snow distribution on the basin, at the end of the season, could vary significantly according to the elevation range, exposition and ground morphology. In small catchment the snow depth reached 6–7 m. At higher elevation, on the glacier, a more homogeneous distribution is usually observed. A descriptive statistical analysis of the dataset is discussed to demonstrate the high spatial variability of the snow depth distribution in the area. The probability distribution of the snow depth fits the gamma distribution with a good correlation. Instead we didn't found any satisfactory relationship of the snow depth with the main morphological parameters of the terrain (elevation, slope, curvature). This suggests that the snow distribution, at the end of the winter season, is mainly conditioned by the transport phenomena and re-distribution of the wind action. The comparison of the results of georadar surveys with the hand probe measurements points out the low accuracy of the snow depth estimate in the area by using conventional hand probing approach only, encouraging to develop technology for fast and accurate mapping of the snow depth at the scale of basin.

1. Introduction

The Ground Penetrating Radar (GPR) is able to give accurate estimates of mean snow depth and snow-ice interface with much less time spent in the field compared to conventional measurements (e.g. Harper and Bradford, 2003; Sand and Bruland, 1998; Godio, 2008). Pulsed and frequency modulated GPRs are promising but require great care in data processing and calibration as the snow depth is estimated from the traveltime of the radar signal (e.g. Holmgren et al., 1998; Godio, 2009); the variation of the snow density affects the snow velocity and inaccuracies in the snow depth estimation (e.g. Lundberg et al., 2000). Marchand et al. (2001) combined the ground based radar system with a differential global positioning survey to map the snow cover on a scale of basin.

The integration of snow depth and density allow one to estimate the snow water equivalent (SWE). This is the product between the snow depth and snow/water density ratio. It is usually based on punctual measures with traditional techniques, like the excavation of snow trenches and vertical density profiles. These techniques are time consuming, require a large employment of human resources when applied to the scale of basin, and provide just local measures. As SWE is a crucial component of the hydrological system in cold terrestrial environments, yet the ability to estimate SWE accurately over large areas is still limited.

We performed GPR surveys to collect snow depth data in the basin of Breuil-Cervinia in the Italian Alps. The analysis of the snow distribution on this basin has a double value: the site is an important ski-resort area, where seasonal winter sport activity can be performed from November to May; moreover the estimate of the overall quantity of water released during the snow melt is relevant for flood prevention and for estimating the recharge of the aquifers and hydroelectric plants of the valley. Data was collected during the winter period of 2007–2008 and 2008–2009, the two seasons were characterized by different climate conditions and different snowfalls distribution along the season.

The snow distribution on large area is a challenge when the hydrological model at the scale of basin is required (Bruland et al., 2000). In most cases the models are derived from statistical analysis of the snow falls and by analysis the correlation of the snow depth with the terrain morphology (e.g. Golding, 1974; Copland, 1998; Jaedicke and Sandvik, 2002), often working with limited and spatially questionable data. As the availability of large GPR data sets distributed all over the area, we analyse the probability distribution of snow depth at the scale of the basin; we focus on relationships between the snow depth and the terrain parameters such as elevation, slope and curvature. We compute semivariograms of the snow depth for evaluating the snowcover spatial variability; a comparison between the result of the

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survey on the two years is discussed. The results can be useful to estimate the snow depth statistical function (e.g. probability distribution and spatial correlation) for the hydrological modeling of the area during the snow melt.

2. The area

The area is located in the Western Alps of Northern Italy, near the border between Switzerland (Fig. 1). We performed two georadar surveys (in April 2008 and April 2009) over a wide area of the Breuil-Cervinia basin (Valtournenche, Aosta Valley). The basin is limited by Colle Superiore di Cime Bianche (2980 m a.s.l.), Plateau Rosa (3450 m a.s.l.) and Goillet Lake (2516 m a.s.l.). The valley is dominated by the Matterhorn, the gorgeous mountain in the Pennine Alps on the border between Switzerland and Italy Its peak reaches 4478 m a.s.l. At the foot of the Matterhorn the touristic village of Cervinia lies, in a valley surrounded by high, glaciated mountains and the sheer rock face of the Jumeaux.

The border between Italy and Switzerland is the main Alpine watershed, separating the drainage basin on the Rhone on the north and the basin of the Po River on the south.

The hydrological basin above the Cervinia village is characterized by slope morphologies formed by the past activities of the glaciers with pronounced gully depressions alternated with variable local reliefs.

In the period 1990–2005 the average snow depths ranges between few centimeters at the beginning of October up to a maximum value of around 170–180 cm in March; in April the trend shows a stationary value around 150 cm; the snow melt starts at the end of April and a sharp decrease of the snow thickness is usually observed during the month of May. The average temperature during the winter time in the period between 1970 and 2000, has been about −5 °C.

During the winter 2007–2008, the snowcover was characterized by an intense phase of wind transport and re-distribution with presence of ice crusts formed by the wind action. During the winter 2008–2009, a huge amount of snow falls occurred from November to April, with a total amount of cumulative snow fall of about 12 m. Particularly, the meteorological station at *Goillet Lake* (2580 m a.s.l.) recorded during the winters 2007–2008 and 2008–2009 (from November to April), respectively 52 snowfall days bringing 533 cm of fresh snow and 80 snowfall days bringing 1270 cm of total seasonal snow. The snowpack has been subjected to the snow drift for 38 (winter 2008) and 55 (winter 2009) equivalent days (data from the Avalanches Warning Service of the Aosta Valley). The snowpack presented different behaviors in the two winter seasons: in 2008 the basin had a more heterogeneous snowpack, with wide erosion and deposition areas caused by a strong snow drift due to the wind effect. On the contrary, in 2009, the presence of a more compacted and thicker snowpack with stronger inter-granular bonds hampered the wind effect on the deposited snow.

3. Methods

3.1. Background

Ground Penetrating Radar (GPR) is used to detect the snowpack properties by means of the propagation of electromagnetic waves within the snow. GPR survey for snow thickness detection was conducted since 30 years ago. In North-Europe GPR track-mounted system were employed for snow thickness evaluation and for estimating the equivalent water content of snowpack for hydrology purposes and the recharge of aquifers (Ulriksen, 1982).

In GPR survey, the snow depth is derived by the two-way traveltime (twt) of an electromagnetic wave which propagates through the snowpack. The electrical permittivity of the snow controls the wave propagation. We consider the snow as a mixture of ice crystals, liquid water and air; at very low temperatures, the presence of unfrozen water molecules can be neglected. For dry snow, an estimate of the density can be derived from the value of the electrical permittivity. The relative (to air) electrical permittivity of snow ranges from 1.5 (new snow, density

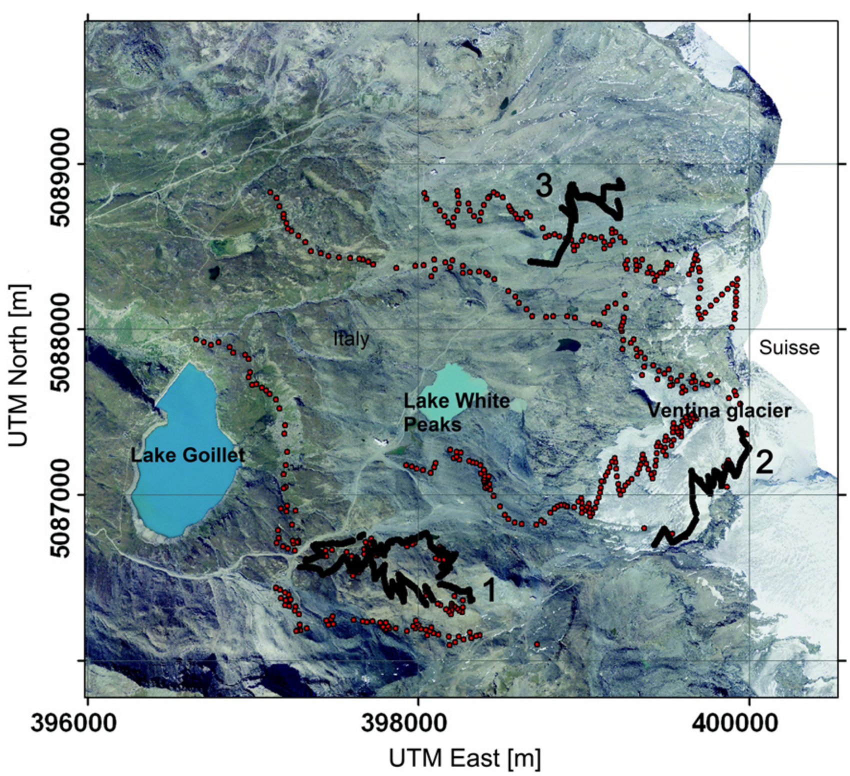

Fig. 1. Map of the basin with georadar traces (black) in three different zones of basin; areas 1 and 3 refer to the snow interface on the ground; sector 2 deals with georadar measurements on the glacialized area; red dots indicate the position of hand probing measurements.