

MYSNOWMAPS: OPERATIVE HIGH-RESOLUTION REAL-TIME SNOW MAPPING

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ABSTRACT: Snow plays a crucial role in the Alps for many human activities, like winter tourism, hydropower and water table recharge. At the same time, during extreme meteo conditions (heavy snowfall or rapid snow melt), snow may become an issue for safety and needs to be particularly observed by civil protection to manage snow related hazards (avalanches, flood or traffic jam on the roads).

At the same time, snow tourism in the last years has experienced a big increase in off-piste explorers that are interested in snow presence in open terrain. The avalanche bulletin contains a rough estimate of snow presence, based on the data collected in specific points of interest, but is not continuous in space and not convenient to use on a map.

The attempt monitor snow evolution and display snow information in a convenient way has evolved in the creation of Mysnowmaps (www.mysnowmaps.com). At our knowledge it represents the first web and app platform displaying snow depth on a daily basis all over the Alps. Furthermore, the app is designed to involve the users in crowdsourcing snow measurements, thus helping to increase the snow dataset.

Mysnowmaps may be considered as an operative snow monitoring system, continuous in time and space, that could help to manage snow related activities and anticipate possible hazardous situations.

Keywords: snow monitoring, snow crowdsourcing, physically based modeling.

1. INTRODUCTION

Snow is a crucial variable in mountain environment. The majority of precipitation during winter and early spring falls as snow in the Alps over 1500 m altitude, and there remains stored until the melting season, when it returns in the hydrological cycle. The importance of snow for many human and environmental activities requires a continuous snow monitoring during winter time.

One of the key ingredient in all monitoring systems is represented by ground measurements. In the Alps the avalanche warning offices maintain a network of stations that measures snow depth and meteorological variables at specific points. Such network is usually integrated by manual observations performed by specifically trained people. Even though fundamental, this point-scale monitoring cannot cover all the morphological heterogeneity of the terrain and budget constraints prevent local administrations to increase the number of stations. One way to increase the number of measurements is to exploit alternative solutions like snow crowdsourcing (Dall'Amico et al., 2018). One way to obtain a snow representation continuous in space is to spatially distribute the point-scale measurements.

2. SNOW SPATIAL DISTRIBUTION

Spatial snow modeling can be divided into two main approaches: statistical and physically-based.

According to the statistical approach, the target variable is correlated to some characteristics of the territory, also called explanatory variables or predictors e.g. elevation, potential radiation, mean annual air temperature ect). If the correlation is above a given threshold, then the explanatory variables are used to spatially distribute the target variable (Grunewald et al., 2013). The crucial input to the statistical models is the measures of snow depth collected at specific locations $P_k(X_k, Y_k)$ at the time stamp t^n : $HS(P_k, t^n)$ and the spatial model S :

$$HS(P, t^n) = S [HS(P_1, t^n), \dots, HS(P_k, t^n)] \quad (1)$$

The statistical model is an instantaneous approach, i.e. the model S at the time stamp t^n is not interested in the situation at the time stamp t^{n-1} but just looks for statistical similarities without arguing about the involved processes. In a sense, it evolves according to measurements and its accuracy is very much related to the availability and abundance of measurements. It is usually used together with snow covered area (SCA) maps derived from satellite images. To infer the snow water equivalent (SWE), proper campaign of snow density measurement are usually organized, or empirical formulations are used (Sturm et al., 2010). Some limitations occur when few measurements are available (e.g. in Spring), so the

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model may suffer from poor correlation and low accuracy.

According to the physically-based approach, snow depth is the result of the physical processes affecting the snow mantle. Starting from an initial condition, snow depth varies according to energy and mass balance. In each point of the domain its morphological characteristics (elevation, slope, aspect) are assigned in order to accurately derive the incoming energy fluxes (radiation, turbulent fluxes) and mass fluxes (liquid and solid precipitation). This allows to distinguish the physical processes controlling snow evolution (accumulation, compaction and melting) and eventually to estimate snow depth and snow water equivalent. Differently from the statistical approach, it uses an incremental approach: it needs an initial condition $HS(P, t^{n-1})$ and a parameterization of the fluxes F affecting the snow surface during the time interval $\Delta t = t^n - t^{n-1}$:

$$HS(P, t^n) = HS(P, t^{n-1}) + F(P, t^{n-1} : t^n) \cdot \Delta t \quad (2)$$

The physically-based approach has interesting advantages: a) it accounts for morphological heterogeneity (elevation, slope, aspect); b) it is conservative, i.e. conserves the mass and so provides also snow water equivalent; c) it is always available, i.e. it is not limited by the presence of a good satellite image or a sufficient number of snow measurements; d) it can be run in forecast modality, i.e. it provides information on snow evolution (and snow melting) in advance.

3. MODELING CHAIN

Mysnowmaps follows a physically-based approach. The modeling chain on which Mysnowmaps is based is composed by the following components: 1) pre-processing of ground meteo and snow data to estimate the solid precipitation; 2) spatial interpolation of meteo data; 3) physically-based approach to model snow evolution; 4) post-processing for results visualization.

3.1. Solid precipitation estimation

The pre-processing module analyzes the ground meteo data in order to improve the calculation of the mass flux, which is the input to the hydrological model. The precipitation in winter is very tricky to measure. Heated rain gauges are usually used, however it is recognized that they are subject to errors (undercatch) in presence of high wind speed and low air temperatures (Sevruk, 1983). Furthermore, rain gauges are usually installed on meteo stations located in the valley bottom, which means that there is a lack of precipitation measurement at

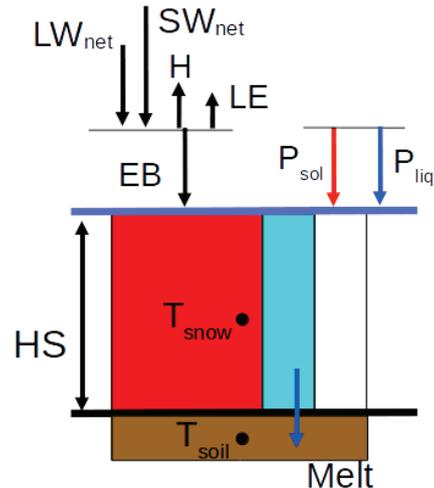


Figure 1: Representation of the 1D calculation domain. Above is the snow volume where the red part is the ice content, the cyan is water and the white is the air content. Below in brown is the representation of the soil. EB is the net energy balance on the snow surface, i.e. the algebraic sum of the longwave radiation LW_{net} , the short wave radiation SW_{net} , the sensible heat flux H and the latent heat flux LE .

higher elevations (say above 1.500 m) where the snow is most persistent.

In order to improve the estimation of precipitation in the mountains in winter time, Mysnowmaps exploits the snow gauges to derive the equivalent precipitation fallen during a snowfall event. Similar to Mair et al. (2016), the hourly data of automated snow gauge stations are filtered to remove the noise and the outliers. From filtered HS the snowfall event is detected and quantified and finally HN is multiplied by the estimated snow density calculated according to Valt et al. (2018). In this way it is possible to integrate the measurements of precipitation given by the rain gauges with an estimate of solid precipitation fallen at high elevation and thus better capture the overall precipitation field.

3.2. Spatial interpolation

The calculation of the energy components of EB in each point of the calculation grid requires the spatial interpolation of meteo variables. Mysnowmaps has been integrated with Meteolo (Bavay and Egger, 2014), a library specifically developed to handle meteorological data. Meteolo includes several methods for spatial interpolation, like inverse distance weighting (IDW) and kriging, and computes every time step the lapse rate present in the time series to capture time-varying elevation-driven effects. Meteolo is used to interpolate ground meteo variables when the system is run in quasi real-time and to downscale numerical weather predictions when the system is run in forecast modality.

3.3. Physical model

The physical model used to calculate the snow evolution is GEOtop (Endrizzi et al., 2014), a physically-based distributed hydrological model. GEOtop considers the following inputs: 1) static maps (250 m grid size) describing the morphology (elevation, slope, aspect and sky view factor) and the land cover of the domain; 2) spatially interpolated maps of meteorological variables provided by MeteolO at each time step; 3) the initial conditions from the previous simulation run where the state variables have been saved.

The model solves the mass and energy balance equations in 1D where the snow is discretized according to a multilayer scheme.

Let us suppose a control volume of snow over a soil layer as depicted in Fig. 1. SWE (mm) is defined as the equivalent mass of water present in a snow volume per unitary surface:

$$SWE := \frac{\rho_s}{\rho_w} HS \quad (3)$$

where ρ_s is the bulk snow density and ρ_w (Kg m^{-3}) the water density. Following Endrizzi et al. (2014), the mass balance of the snow volume is:

$$\frac{\partial SWE}{\partial t} + M - (P_{sol} + P_{liq}) = 0 \quad (4)$$

where M (mm s^{-1}) is the snow melt and P_{sol} and P_{liq} (mm s^{-1}) are the solid and liquid precipitation respectively. U (J m^{-3}) is the internal energy of the snow volume, a state variable that depends on snow temperature and liquid water content. It is:

$$U^* := U \cdot HS = (c_i I + c_w W) T + L_f W \quad (5)$$

where c_i and c_w ($\text{J kg}^{-1} \text{K}^{-1}$) are the heat capacities of ice and water respectively, L_f (J kg^{-1}) is the latent heat of freezing and $I = \rho_i \cdot HS \cdot \theta_i$ (mm) and $W = \rho_w \cdot HS \cdot \theta_w$ (mm) are the solid and the liquid water mass present in the snow volume respectively. The energy balance, excluding the advection fluxes, is:

$$\frac{\partial U^*}{\partial t} - \lambda \frac{\partial T}{\partial z} - EB = 0 \quad (6)$$

where T is the snow temperature ($^{\circ}\text{C}$), λ ($\text{W m}^{-1} \text{K}^{-1}$) is the thermal conductivity at the snow-soil interface, needed to calculate the conduction flux, and EB (W m^{-2}) is the net energy balance on the snow surface, i.e. the algebraic sum of all energy components impacting the snow surface. After each calculation step, the state variables are updated and the results (HS, SWE, HN) are stored and eventually printed at a desired frequency.

3.4. Results display

The results of GEOtop are given in form of maps (raster data). In order to be published, the maps are

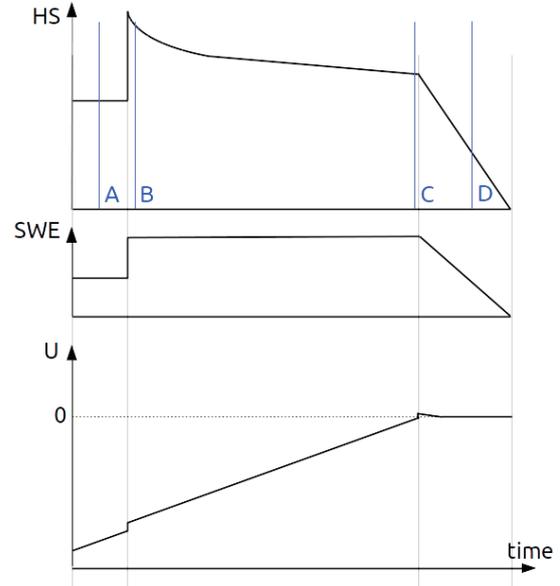


Figure 2: HS, SWE and U evolution in a simplified physical scheme. A (initial condition), B (accumulation), C (compaction) and D (melting).

later transformed into a vector format by discretizing the raster into various categories of snow depth (e.g. 10-30 cm, 31-50 cm etc.) to be nicely visualized. The final result is two shapefiles for the variables HS and HN that are eventually stored by GeoServer and ready to be displayed as reported on Fig. 5.

4. SNOW PROCESSES

Let us now review the physical processes that are simulated with the snow model. Fig. 2 reports a schematic representation of a possible snow evolution in time of the macro variables HS, SWE and U, starting from an initial condition A and subject to the following processes: accumulation (point B), compaction (point C) and melting (point D). Suppose the initial condition A is in winter time. Usually air temperature is cold and the snow is dry (i.e. very low water content $< 1\%$). Under these conditions the snow temperature is well below 0°C except close to the soil surface where it tends to 0°C , whereas the internal energy is negative and dominated by temperature. Let us investigate how the equations previously described can be used to follow the evolution of a snow volume.

Accumulation

The mass involved in the snowfall event is given by:

$$\rho_{ns} \cdot HN = \rho_w P_{sol} \quad (7)$$

where $P_{sol} = P_{tot} - P_{liq}$ is the solid precipitation and $HN := HS^{n+1} - HS^n$ is the depth (m) of the new snow

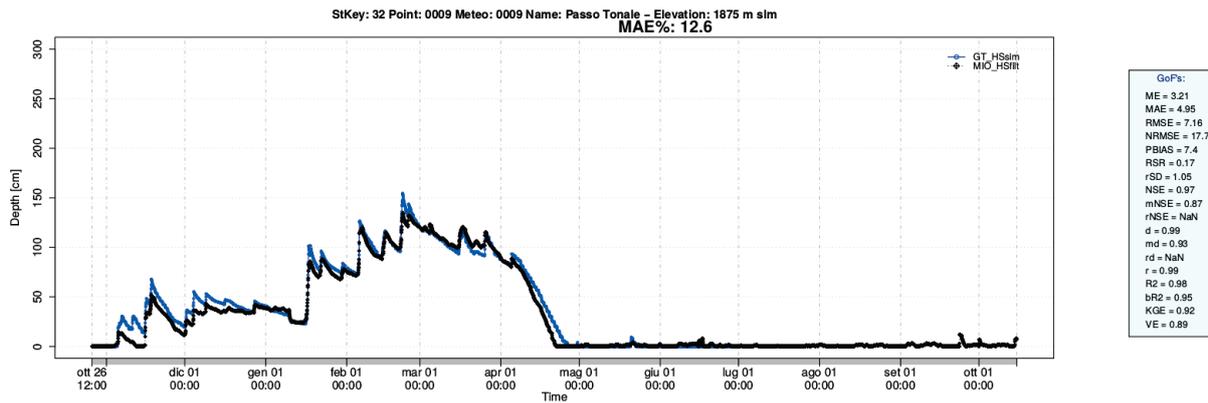


Figure 3: Measured (black) vs simulated (blue) snow depth at snow gauge Passo del Tonale (Italy) during winter 2014-2015.

event occurred in the time interval $t^{n+1} - t^n$. The density of the new snow ρ_{ns} is calculated according to Valt et al. (2018). The split of total precipitation into solid and liquid phases is done according to air temperatures, by defining two thresholds. Referring to Fig. 2, during accumulation both HS and SWE increases and so does U, supposing the snowfall occurs at temperatures near 0°C , and so it warms the snow.

Compaction

Then snow undergoes a compaction phase, due to the sintering of grains and the weight of the snow. The compaction for the new snow and old snow layer is calculated following Jordan et al. (1999) and is a function of the snow temperature, the new snow density and the snow viscosity. Referring to Fig. 2, the densification of snow reduces HS but leaves constant SWE as there is no mass loss. If air temperature is mild (positive values), U is expected to grow until the snowpack becomes isothermal. Under these conditions (point C), the thermal component of the internal energy reaches its maximum and the water component increases with the increase of the water content that may reach values up to 10-12% (humid snow).

Melting

When the snow is isothermal, the conduction flux becomes null and the thermal component of the internal energy cannot grow anymore. Eq. 6 can thus be simplified in:

$$L_f \frac{\partial W}{\partial t} = EB \quad (8)$$

It is evident that under these conditions, the incoming energy flux EB is used to melt the snow. Referring to Fig. 2, both HS and SWE decreases. The internal energy, on the other hand, cannot grow any more: so we may think the internal energy as a bank

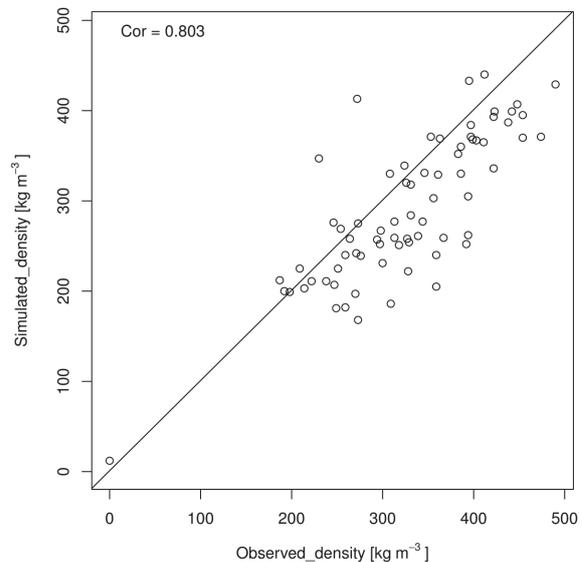


Figure 4: Snow density comparison. Observed values provided by Friuli-Venezia Giulia during winter 2015-2016 on 4 locations.

account whose size is given by the negative temperatures of the snowpack: when the weather is warming, the incoming energy flux from above is used to warm up the snow, until the isothermal state is reached.

5. VALIDATION

A continuous collaboration with several Italian avalanche offices has allowed model testing and validation on more than 200 snow gauges along the Italian Alps. Fig. 3 reports the comparison of the modeled HS (blue line) with the measured HS (black line) on a snow gauge located at Passo del Tonale (1.875 m) in central Italian Alps. The mean absolute error (MAE) for the entire winter shows a value of 12.6%. Another validation test has been conducted on a snow density comparison during the winter 2015-2016 on four locations in Friuli-Venezia Giulia (Italy). Fig. 4 shows a scatter plot of the com-

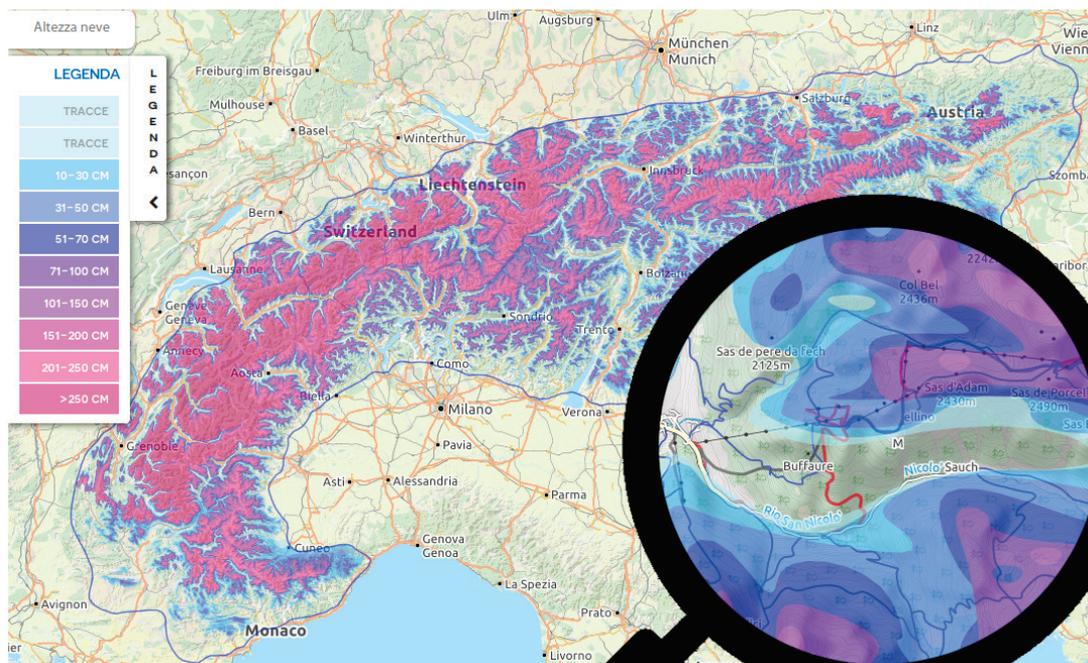


Figure 5: Map of snow depth HS (cm) updated on 9 March 2018 on Mysnowmaps with zoom on the Dolomites area.

parison: it appears that the model underestimates the snow density, however the correlation is fairly neat if we consider that the measurements correspond to different timings during the winter.

6. CONCLUSIONS

Several institutional portals, e.g. senorge.no (Saloranta, 2012) expose snow maps in real time with a national or regional scope. Mysnowmaps (www.mysnowmaps.com) represents the first commercial platform displaying high resolution snow-depth maps in real time at large scales.

The applications span from civil protection, as it allows a real-time snow monitoring at regional scale and to anticipate possible critical conditions (Dall'Amico et al., 2015), to hydropower, as it is a tool to quantify the water resources stored in a basin for energy exploitation, to tourism, as it aggregates snow information useful to plan off-piste excursions.

Furthermore it is becoming a data collector from the outdoor Community. In fact, through the App, users may share the snow conditions (depth and type of snow) experienced during the tour, together with other details about the excursions (e.g. critical situations). The crowdsourced data allow to increase the dataset of snow measurements in the terrain, to foster civic sense of people in monitoring the environment, and to highlight possible critical conditions, improving the safety of outdoor excursion planning (Dall'Amico et al., 2018).

At the moment Mysnowmaps is operative on the Alps (176.000 km²) but is potentially scalable worldwide.

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