Estimating bulk snow density with models of different complexity

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Abstract
This report deals with the results of a Short Term Scientific Mission carried out by Dr. Francesco Avanzi at the WSL Institute for Snow and Avalanche Research SLF (team Snow cover and Micrometeorology) during June 2016. The STSM aimed at strengthening the collaboration between Politecnico di Milano and the WSL - SLF on the investigation of the performance of models of different complexity in estimating bulk snow density. The models involved in this comparison are a simple T-index one-layer model (HyS) and a complex physics-based multi-layer model (SNOWPACK). During the STSM, three SNOTEL sites were chosen to perform multi-year pilot simulations. In this way, Dr. Avanzi familiarized himself with the snow-cover model SNOWPACK. During the STSM, the collaborators also discussed future steps of this research.

Keywords
Bulk snow density — SWE — SNOWPACK – SNOTEL – HyS – Modeling - Intercomparison

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Purpose of the STSM

In this report, we present the results of a Short Term Scientific Mission (STSM) carried out by Dr. Francesco Avanzi at the WSL Institute for Snow and Avalanche Research SLF (team Snow cover and Micrometeorology) during June 2016. The STSM was used to promote a joint collaboration between Politecnico di Milano and the WSL - SLF on the investigation of the performance of different modeling frameworks in predicting bulk snow density.

The STSM primarily aimed at facilitating the exchange of knowledge and at establishing a shared framework for our investigation, including data pre-processing, model run, and post-processing. As we selected a multi-layer physically-based model, SNOWPACK [1], and a simple one-layer conceptual model, HyS [2, 3, 4], for our analysis, the STSM also enabled Dr. Avanzi to become familiar with the SNOWPACK model (how to prepare input data, how to set up a simulation, how to run it, how to manage post-processing). Moreover, the STSM aimed at promoting additional discussions with other researchers at the host institution. Finally, we took this opportunity to design future tests.

Work carried out

The STSM lasted two weeks (June 6 - June 17 2016). First, Dr. Avanzi was introduced to SNOWPACK code, to the preparation of a simulation, and to the management of post processing. Then, he selected a sample of three test sites and collaborated with Dr. Fierz and Dr. Bavay to initialize the model and to run multi-year simulations using both SNOWPACK and HyS. During the entire STSM, the collaborators promoted ad hoc discussions with other colleagues at the host institution to get additional feedback on this research.

Data

Our case study includes three sites from the SNOTEL network. We chose this network because it provides all necessary data to run both models as well as hourly time-series of SWE and snow depth, which can be used to evaluate model predictions. Furthermore, SNOTEL sites cover a broad latitudinal and longitudinal range across western US and provide standardized data-sets. Both features favor the comparison between different models and data. SNOTEL data are available at http://www.wcc.nrcs.usda.gov/snow/.

The first site considered is Granite Crk in Alaska (ID 963, Lat. 63° 57' N, Long. 145° 24' W, Elev. 378 m ASL), where we selected the period from 15/10/2008 to 13/06/2016. The second site is Lost Horse in Washington (ID 599, Lat. 46° 21' N, Long. 121° 5' W, Elev. 1561 m ASL). Here, we selected the period from 15/10/2002 to 08/06/2016[1]. The third site is Happy Jack in Arizona (ID 969, Lat. 34° 45' N, Long. 111° 25' W, Elev. 2326 m ASL). Here we selected the period from 15/10/2009 to 04/05/2016.

All sites are flat clearings surrounded by forest. The height over the terrain of all instruments is ~ 5 m. Thus, all instruments measure local conditions that are representative of input fluxes into the snowpack. A total of 28 snow seasons were simulated. A picture of each site is reported in Fig. 1.

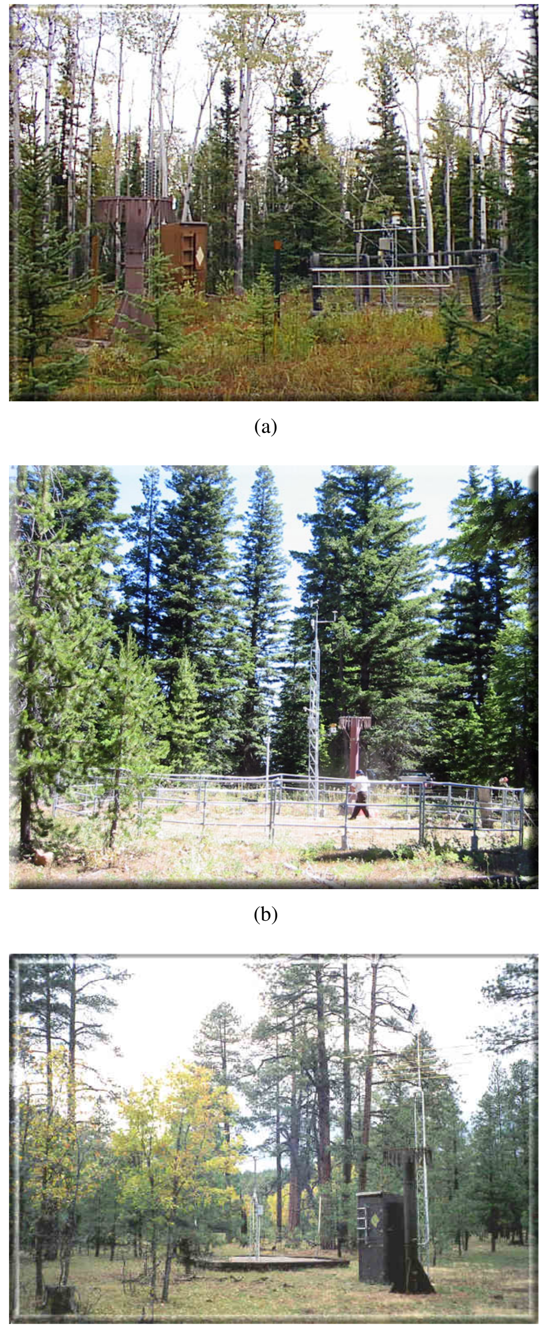
Model settings

SNOWPACK is a complex 1D multi-layer physics-based snow model. It solves energy, mass, and momentum conservation for all the phases of snow and reconstructs the vertical profile of snow properties, including grain shape and size, liquid water content, density, or temperature. Exhaustive information about the model may be found in [1, 5, 6]. Recently, a solver for Richards equation has been implemented in the model, which improves the prediction of various aspects of liquid water flow (hence, density) in snow [7]. Minimum input data are air temperature, incoming solar radiation, humidity, precipitation, and wind speed. The model is freely available at http://models.slf.ch/.

HyS is a simple one-layer T-index snow model. It solves mass conservation for ice and liquid water and momentum conservation. The tree prognostic variables are the thickness of the ice matrix (h_S), the thickness of liquid water (h_W), and the dry density of the snowpack (ρ_D). Bulk snow density as well as SWE can be calculated once the temporal evolution of these three state variables is known. Moreover, the model simulates the temporal evolution of bulk liquid water content. Input data needed are air temperature and precipitation (hourly resolution). Snow depth data are needed for calibration. Additional information about this model may be found in [2, 3, 4]. The code of this model is not publicly available.

After a preliminary introduction to SNOWPACK source, we focused on data preparation. Data from the same site were arranged in an unique input file in order to launch uninterrupted multi-year simulations. The run of SNOWPACK needs the preparation of two separated files: 1) a .smet file containing all weather and evaluation data [8], and 2) a .sno file containing all information about initial snow and soil profiles. Because detailed information about the stratigraphy of each site were lacking, we chose to run simulations using the same, generic, soil profile (Table 1). As hourly precipitation data from SNOTEL sites are often very noisy [9], measurements from the rain gauge were not considered and snow depth data were used to estimate snow events, i.e., SNOWPACK was run in snow-height-driven mode [10]. After each simulation, SNOWPACK-calculated snow events were used to force HyS.

[1] The period 01/10/2007 - 30/09/2008 was neglected due to missing data.



(a)

(b)

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Figure 1. SNOTEL sites considered: Fig. 1(a): site 963; Fig. 1(b): site 599; Fig. 1(c): site 969. Photo credits: SNOTEL.

Table 1. Initial soil properties. θ_W, θ_I, θ_V, and θ_S are the initial volumetric fractions of liquid water, ice, voids and soil particles, respectively. ρ_S is soil density.

Parameter	Value
Soil depth	5 m
Initial temperature	274.161 K
θ_W	0.1
θ_I	0
θ_V	0.2
θ_S	0.7
ρ_S	2700 kg/m^3

During this first phase, we also prepared a flexible pre-processing routine for SNOTEL input data, as these are usually unprocessed [9]. For this purpose, we used the MeteoIO library. The steps of our pre-processing routine include filters for air temperature, height of snow (HS, in m), relative humidity, incoming shortwave radiation and wind speed, gap-filling interpolations, and data generators for longwave radiation.

The second step was the set-up of the simulations. The configuration of SNOWPACK needs the definition of a standard .ini file containing all relevant parameters. This .ini underwent a trial-and-error procedure to find the optimal combination of parameters. The set-up of SNOWPACK was fully supported by daily discussion between Dr. Avanzi, Dr. Fierz and Dr. Bavay. SNOWPACK was run using either a simple bucket scheme, SNOWPACK B [1], or an advanced resolution of Richards equation, SNOWPACK RE [7], for liquid water movement.

The set-up of HyS needs continuous-time data-series of air temperature and precipitation. These were created using the MeteoIO library (data converter) and pre-processing input data exactly as they are pre-processed by SNOWPACK. Two different parametrizations for snow viscosity were considered. The first one (Visc. Dry) depends on snow density and snow temperature [2]; the second one (Visc. Wet) also depends on liquid water content [3].

Model intercomparison

SNOWPACK and HyS were finally run over the three sites. HyS is a calibration-based model and it therefore needs the preliminary evaluation of a T-index parameter [4]. This parameter was calibrated on a yearly basis. Then, the median value was chosen to perform comparative simulations with SNOWPACK. As an index of performance, the Root Mean Square Error RMSE was calculated. We calculated both a global RMSE using the entire available time-series and a monthly RMSE. The latter was obtained by aggregating observations and predictions of ρ on a monthly basis.

Main results

We report some examples of the simulated seasonal evolution of bulk snow density in Fig. 2 (site 963, Alaska) and in Fig. 3 (site 599, Washington). An example of the temporal

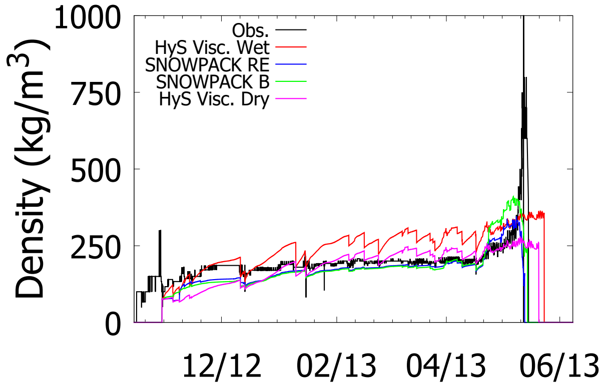


Figure 2. An example of simulation results for density at Granite Crk (site 963), snow season 2012 / 2013.

Table 2. Root Mean Square Error of HS, density, and SWE for different modeling setups (site 963).

Model	ρ kg/m^3	HS m	SWE mm
SNOWPACK B	58.11	0.04	14.10
SNOWPACK RE	51.84	0.04	12.22
HyS Visc. Dry	68.64	0.06	18.21
HyS Visc. Wet	87.98	0.06	19.63

Table 3. Root Mean Square Error of HS, density, and SWE for different modeling setups (site 599, snow seasons from 2001/2002 to 2006/2007).

Model	ρ kg/m^3	HS m	SWE mm
SNOWPACK B	66.00	0.044	33.33
SNOWPACK RE	73.44	0.045	33.33
HyS Visc. Dry	93.57	0.13	53.48
HyS Visc. Wet	88.22	0.09	48.33

Table 4. Root Mean Square Error of HS, density, and SWE for different modeling setups (site 599, snow seasons from 2008/2009 to 2015/2016).

Model	ρ kg/m^3	HS m	SWE mm
SNOWPACK B	82.53	0.04	42.63
SNOWPACK RE	79.02	0.04	33.38
HyS Visc. Dry	97.62	0.018	71.24
HyS Visc. Wet	82.53	0.16	59.95

evolution of the profile of snow density using SNOWPACK B or SNOWPACK RE is reported in Fig. 4. Fig. 5 reports a comparison between data and simulations by SNOWPACK RE and HyS Visc. Wet over the entire study period at the three sites. The RMSE for density and different modeling setups are reported in Tables 2 - 5. For the sake of completeness, these Tables also report RMSE for snow height (HS) and SWE. Figure 6 shows monthly RMSE at the three sites.

The global RMSE for SNOWPACK are generally consis-

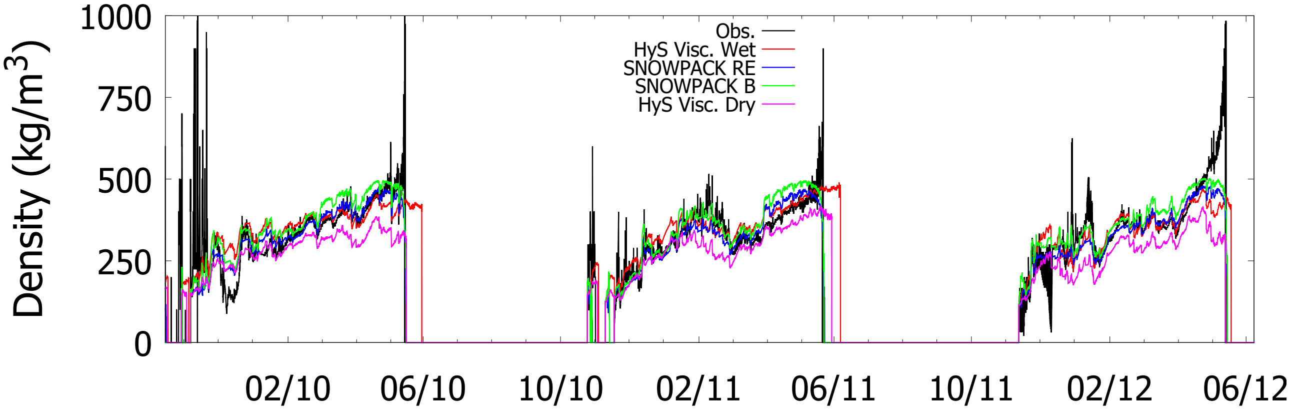
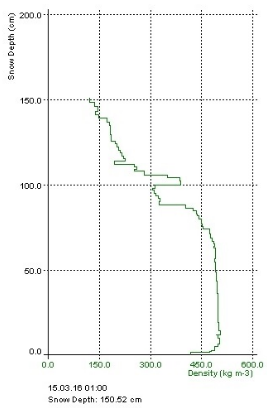


Figure 3. An example of simulation results for density at Lost Horse (site 599), snow seasons from 2009 / 2010 to 2011 / 2012.



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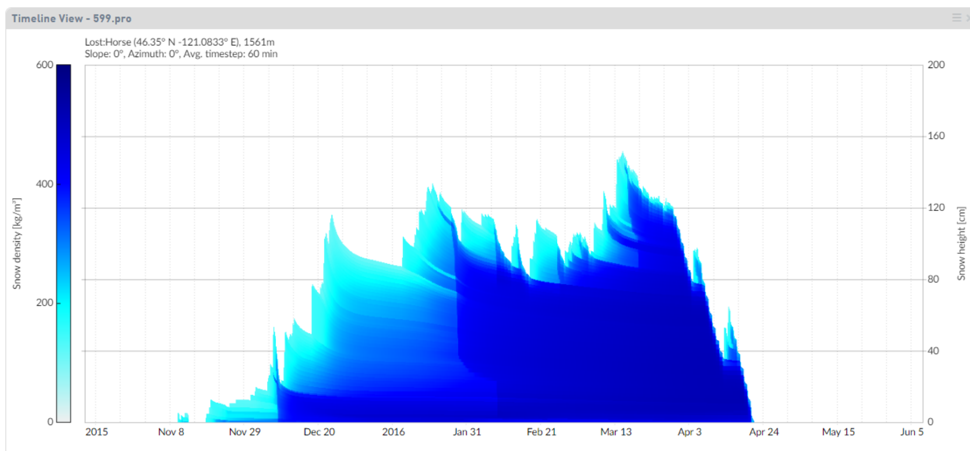

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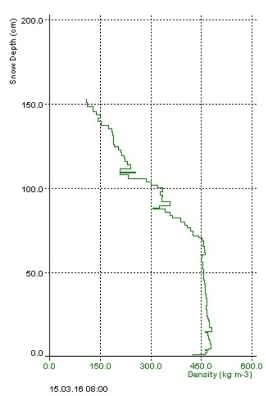

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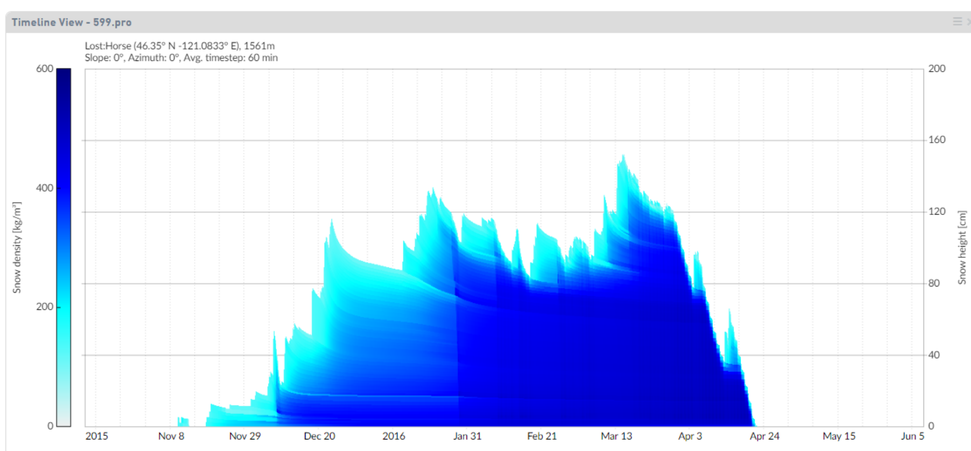

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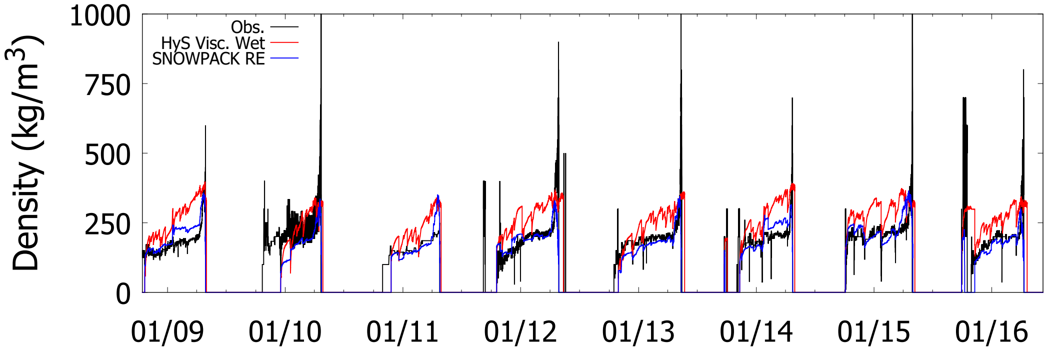
Figure 4. An example of snow density profile at peak accumulation and seasonal evolution of snow density from Lost Horse (site 599, 2015/2016 snow season). Fig.s 4(a) and 4(b): SNOWPACK B; Fig.s 4(c) and 4(d): SNOWPACK RE.



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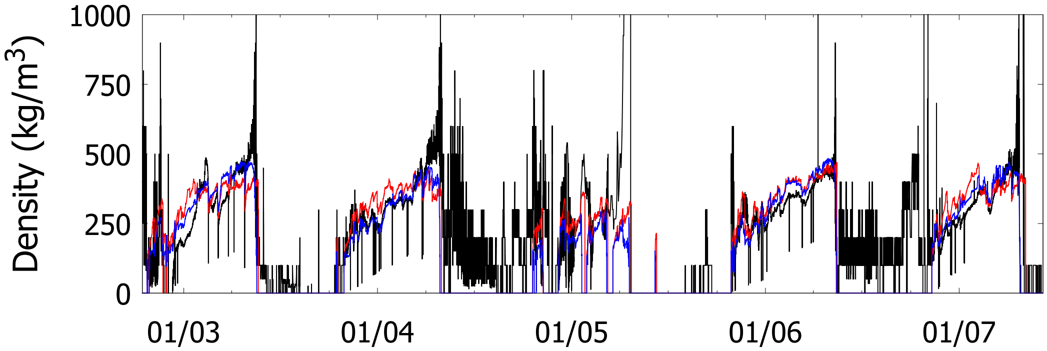

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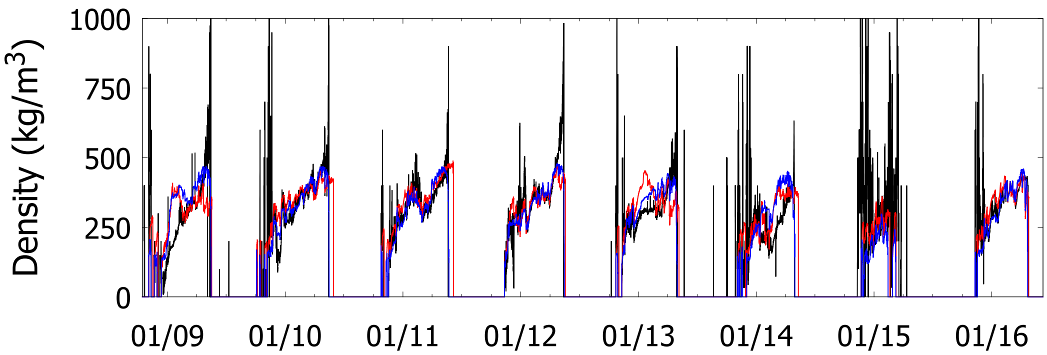

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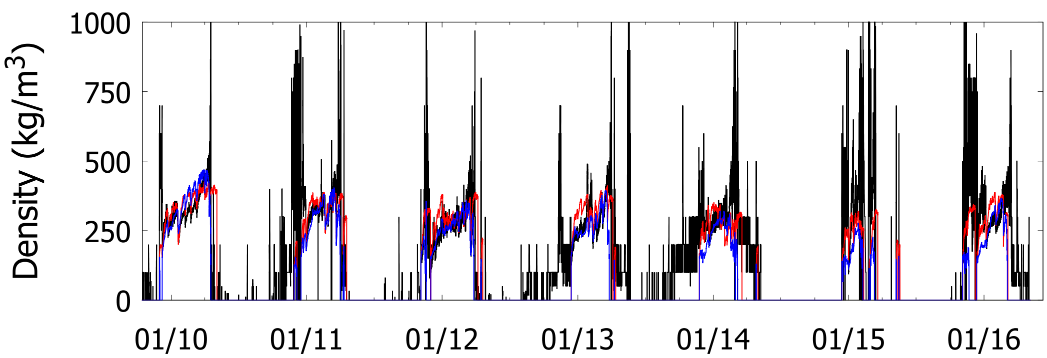
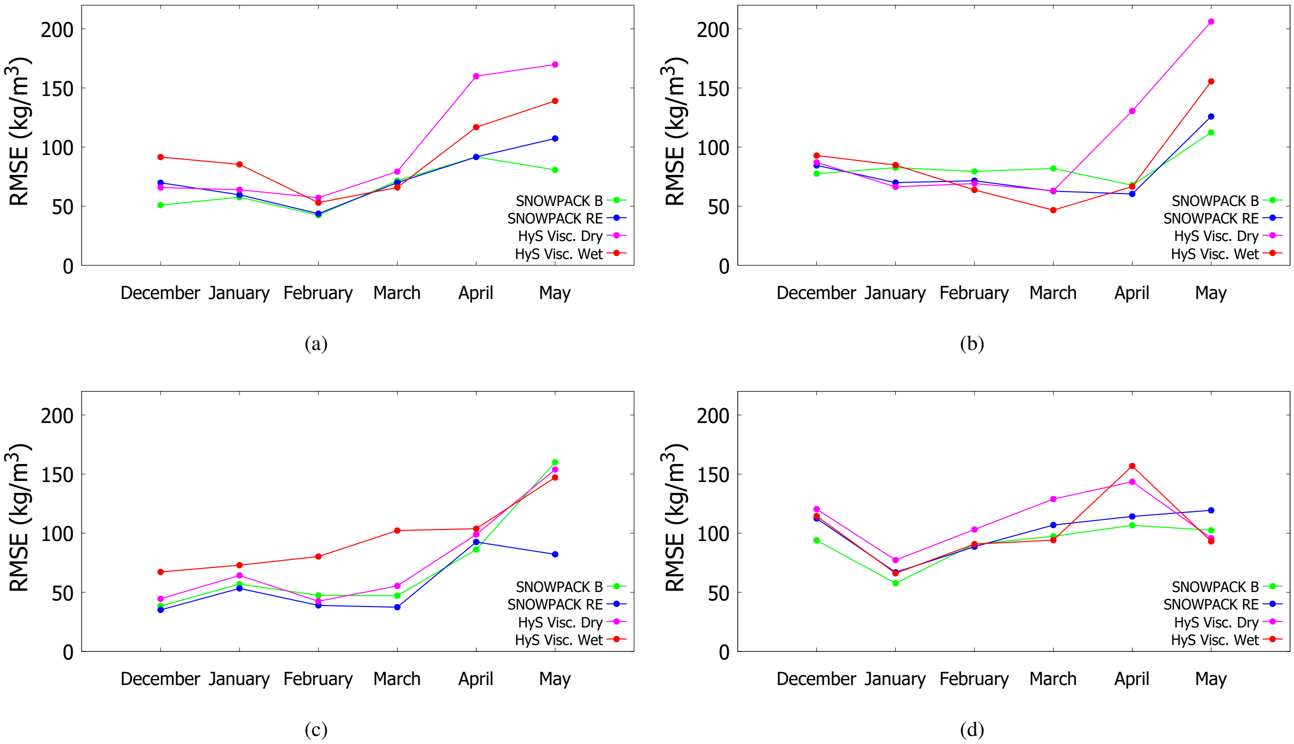


(d)

Figure 5. Complete comparison between observed bulk snow density and simulation results by SNOWPACK RE and HyS (Visc. Wet) at site 963 (Fig. 5(a)), site 599 (Fig. 5(b) and 5(c)), and site 969 (Fig. 5(d)).



(a) (b) (c) (d)

Figure 6. Monthly RMSE at site 599, snow seasons from 2002/2003 to 2006/2007 (Fig. 6(a)), site 599, snow seasons from 2008/2009 to 2015/2016 (Fig. 6(b)), site 963 (Fig. 6(c)), and site 969 (Fig. 6(d))

Table 5. Root Mean Square Error of HS, density, and SWE for different modeling setups (site 969).

Model	ρ	**HS**	**SWE**
	kg/m^3	m	mm
SNOWPACK B	88.2	0.06	23.82
SNOWPACK RE	97.20	0.06	20.55
HyS Visc. Dry	112.6	0.09	26.59
HyS Visc. Wet	98.84	0.09	22.87

tent with those obtained at alpine sites, e.g., Weissfluhjoch near Davos [10], although these evaluations were performed in western US, where SNOWPACK has been never evaluated extensively, to our knowledge. In 2 out of 4 study periods, SNOWPACK RE returns a smaller (global) RMSE than SNOWPACK B, although discrepancies are generally close to instrumental uncertainty (i.e., ≤ 10 kg$/$m^3). The simulated density by SNOWPACK RE is generally smaller than that by SNOWPACK B: this might be related to a faster routing of liquid water in SNOWPACK RE [10].

The global RMSE by HyS is generally larger, although the performance of this simple model in predicting density is promising. Indeed, the difference between a benchmark SNOWPACK run (SNOWPACK B) and HyS (Visc. Wet) ranges between ~ 0 and 30 kg$/$m^3, which is a reduced range compared with the seasonal range of variation of density. Including a parametrization of wet viscosity improves the global performance of HyS in 3 out of 4 cases. The only exception is site 963 in Alaska, where, according to Fig.s 2 and 5(a), Visc. Wet overestimates the settling rate. Weather conditions in this site are generally very cold and snow is dry during most of the season: indeed, observed bulk snow density only increases in spring, whereas it keeps constant during mid-winter. However, neglecting melt-freeze dynamics and implementing a melt-only T-index approach may overestimate liquid water content, hence settling rate [3]. This supports the use of an additional melt-freeze term.

Monthly RMSE are generally smaller during mid-winter than at the beginning and at the end of the season, when both, instrumental noise and modeling uncertainty are high. For example, it is well known that a melting snow cover over a snow pillow is often affected by bridging [11], which causes frequent oscillations in hourly/daily data of SWE; a clear example is reported in Fig. 5(b)). Furthermore, measuring SWE is more problematic when the snow cover is shallow. On the other hand, the beginning and the end of the season often experience quick alternations of snowfalls and snowmelt events, i.e., an overlap between settlement, metamorphism, and liquid water percolation, which complicates the simulation. A counterexample is again site 963, where RMSE only increases in spring, as snow is usually dry even at the beginning of the season. The general temporal pattern observed at these three sites is again in agreement with results at Weissfluhjoch [10]. Monthly RMSE either by HyS Visc. Dry or HyS Visc. Wet are alternatively the largest ones at all sites. However, the RMSE by Visc Wet. are often comparable to those by SNOWPACK (see, e.g., Fig. 6(a) or 6(d)).

During the final part of this STSM, these results were fully discussed. Additional discussions with colleagues at SLF were promoted. The established framework will be now extended to other sites and snow climate classes all around the world.

Future collaboration and publications

The aims of this STSM were fully achieved, as briefly reported here. A ISI publication is anticipated dealing with the final results of this extended intercomparison.

Acknowledgments

Authors acknowledge fruitful discussions about this work with Tobias Jonas, Christoph Marty, and Nander Wever. LaTeX template from http://www.latextemplates.com/.

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