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The Cryosphere Discussions

Interactive comment on "Investigating the dynamics of bulk snow density in dry and moist conditions using a one-dimensional model" *by* C. De Michele et al.

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Dear Colleague,

We would like to thank you for the comments, which are really very interesting and accurate. We will surely address them while revising the manuscript. Here we would like to take the occasion to provide some explanations to your comments.

1. Concerning the model's novelty, we would like to make clear that, according to our opinion, an additional element is the attempt to directly characterize the relation between liquid water content and the evolution of the mean snowpack density, adopting a theoretically and computationally simple one-dimensional model. The model is

intended to stress the difference between snow density as a dry continuum and snowpack density in dry and wet conditions. We think that this distinction let the users to obtain a more reliable and physically based simulation of snowpack density with a simple approach, improving the "very simple parameterizations of snow density" which you quoted in your comment, in which the bulk density evolution is often function of compression and atmospheric variables. To achieve this aim, we fixed an evolution law of dry snow density function of compaction and of new events and an evolution law for the total liquid water content, which directly influences the bulk snowpack density dynamics. Besides, we would like to thank you for the other novelty elements you have recognized in our work.

2. Concerning the model purposes, we intend to develop and test a simple snowpack model which has to be useful for regional hydrology considerations. As a consequence, we work with few input data, but, at the same time with a solid physically based model to reply to forcings modifications. We believe that this approach could help scientists in developing and interpreting future predictions of water resources dynamics and availability, since it is a mechanistic physically based model, which is able to reply to different climatic scenarios. This aim is here reached by simulating the mass content of a snowpack with a simple one-dimensional approach which bases on the contemporaneous simulation of snow depth and snow density, a state variable which is more physical than SWE, since its evolution obeys directly to mechanical and thermal forcings. Besides, we think that a correct prediction of bulk snowpack density could help engineers in many fields, such as civil engineering applications, and that the simultaneous simulation of snow density, SWE and snow depth could offer many new information for snow remote sensing interpretation. We agree with the Reviewer that this formulation could help interpreting snow hydrology measured data, or make predictions in areas where meteorological data are insufficient to apply more sophisticated models based on energy balances.

3. We do agree with the importance of comparing model results with other simpler

descriptions. We will surely insert some of these comparisons in the revised version of the manuscript, while a comparison with complex physical based models will be study and inserted in further developments of this work. Besides, we will clarify also the position of our model among the available snow models.

4. As for snow metamorphisms dynamics, we tried to test the model including this type of phenomenon, following a formulation derived by Zhang et al. (2008, cited in the paper). Anyway, we noticed that this term had few influence on mean dry snow dynamics since it turns out to be influential only for low densities. Furthermore, snow metamorphism presents local effects which are conceptually difficult to be predicted with a one-layer model.

5. As for the choice of sites, we did appreciate your suggestion about European sites which have liquid water content measures. Surely we will ask the availability of Davos and Col de Porte data and test our model there, near soon. According to our opinion, SNOTEL sites present the important advantage of the wide availability of stations (more than 700) and data series, which could let us to spread the analysis throughout the Western United States and deeply back in the past, for regional hydrology purposes. This generalization will be the main topic of our next contribute, which is in preparation. Investigating this huge number of sites could give us the possibility to draw considerations at regional scale, and deal with poorly instrumented and ungauged sites. Moreover, the choice of using SNOTEL sites could demonstrate that good results in simulating snowpack typical state variables can be reached even adopting few input data. Anyway, the present work has to be considered as a first step in our research, since the analysis of the applicability of the model in other environments (where direct liquid measures are available) is for us mandatory for the future;

6. Currently we assume that the evolution law for the snow density considers uncoupled mechanical and hydraulic forcings. As first attempt, we tried to model dry density only starting from mechanical forcings. We are aware that many rheological formulations are available, which characterize the evolution of snow density as also function

of liquid water content (as highlighted also by, for example, Marshall et al., 1999, in addition to Vionnet et al. 2012), but the different contributes of pore saturation and wet compaction on snow density dynamics are hardly noticeable with this kind of measured data. Anyway, future developments of this work are intended to precisely characterize the mechanical contribute of liquid water;

7. Concerning the manuscript structure, we preferred to firstly illustrate the model formulation, since it is quite general and independent from the origin of input data. As expressed before, SNOTEL data as validation data series are just one of the possible applications of this model. We preferred to not strictly "bind" the model to them;

Other comments:

- As for the 0°C threshold in section 2.1, we would like to specify that it is not a model assumption, but just a general and conceptual separation, part of an introductive description of snow dynamics. It has no effect on the model formulation. As visible in the development of the model, no temperature threshold is imposed to the existence of hw , which can exist even if air temperature is below 0°C, and which is bound to snow melting and direct outflow. We are going to fix this misconception;

- As for mass variables, volumetric V variables are cited to generalize. As for the difference between h and hS, it is important to note that "h" is the height of the volume domain (at any time), while "hS" is the height of the ice structure. As a consequence, they coincide, except for the last few hours (or days) of the melting season, during which the ice component completely melts. In this situation, pores saturate and the ice structure collapses, forcing bulk density to increase. As a borderline case, the outflow term can accumulate a little "delay" which corresponds to the instant in which the last elements of ice are disappearing, creating a liquid water domain, a pool, doomed to a quick direct outflow. This distinction is necessary to model the conceptual transition from ice to liquid water. The insert of the Maculay brackets are needed to interpret these last instants of the season without returning incorrect domain densities, and to let the model to be completely general (since it is therefore not forced by any existence condition);

- Concerning the comparison between SNOTEL measurements considered and Swiss measurements considered by Techel and Pielmeier (2011), we would like to point out that the comparison is only qualitative. According to our opinion, this comparison is reasonable because: 1) the duration and timing of the accumulation season (October-March) and melting season (April-July) are the same, 2)Mean winter air temperatures in the considered SNOTEL sites are respectively of -0.6 °C for S1 and -3.5 °C for S2 (on the considered periods), which seem to be of the same order of magnitude of Alpine sites as cited in Marty and Meister (2012) and as reported by MeteoSwiss sites at the same heights.

References

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