MODELING SNOW WATER EQUIVALENT EXCLUSIVELY FROM DAILY SNOW DEPTHS

Michael Winkler[1,*], Harald Schellander[1]

[1] *ZAMG – Zentralanstalt für Meteorologie und Geodynamik, Innsbruck, Austria*

ABSTRACT: Many applications and studies, like climate and extreme value analyses, are seeking for long-term records of snow water equivalent (SWE). Measurements of SWE are principally scarce; SWE data older than 50 years hardly exist at all. However, there are many observation sites with long-term snow depth records.

In order to assign SWEs to snow depths, different models have been developed. On the one side there are process-based snowpack models. They depend on meteorological input which often is not available for old snow records. On the other side there are parametrizations of snow density based on its statistical relations to snow depth, date, altitude and climate region. These often fail to model seasonal maxima of SWE and are unsuited to provide SWE of a certain day.

A new semi-empirical snow model is presented, bridging the gap between above mentioned models. It is a layer model addressing basic settlement mechanisms as well as rain-on-snow events and ablation. Preliminary results show a clear improvement in SWE modeling compared to statistical models, whereas computational efforts stay small and necessary input is limited to snow depth only.

Keywords: snow depth, snow water equivalent, snow density, semi-empirical model, long-term snow data

1. INTRODUCTION

Sophisticated, physical snow models like SNOWPACK (e.g. Lehning et al., 2002), Crocus (e.g. Vionnet et al., 2012) and others depend on meteorological input. Since many long-term or historical snow depth records do not come along with measurements of temperature, radiation etc. these models cannot be used to gain more insights from those snow depth data. That's a pity because measurements of daily snow depths covering many decades — sometimes even more than 120 years — do exist for many places, e.g. in Austria, and hydrological, climatological and extreme value analyses would benefit if, at least, snow water equivalent (SWE) could be derived from these historical data. Certainly, there are statistical approaches which assign SWEs to pure snow depths series using parametrizations of bulk snow density based on location, altitude and time of year (e.g. Mizukami and Perica, 2008; Jonas et al., 2009; Sturm et al., 2010; McCreight and Small, 2014; Pistocchi, 2016). However, the transferability of their results to different sites is questionable since physical mechanisms are ignored and it is not at all reasonable to use those models for estimating SWE of certain days (see e.g. Jonas et al., 2009, who honestly acknowledge this circumstance).

To bridge the gap between process-based and statistical snow models a semi-empirical snow model was developed (Gruber, 2014, chap. 4). Revisting Martinec and Rango (1991), it encompasses actual snow depth, seasonal snow depth evolution and basic settlement mechanisms as well as possible rain-on-snow events and periods of ablation. It is independent from geographical parameters and time of year and, therefore, better transferable to different sites. Furthermore, respecting basic physical processes provides the possibility to derive SWE of certain days. The model does not depend on meteorological information and is therefore especially valuable for deriving SWE-series from long-term and historic observations of snow depth.

2. METHOD

The new semi-empirical layer-model-approach assesses different settlement properties of individual snow pack layers by a decision tree. Each day-to-day change in measured snow depth is analyzed and compared to the model's expectation due to settlement. The model's expectation depends on layer ages and layer thicknesses basically based on Martinec and Rango (1991). At this point the decision tree strategy is applied:

(1) A new snow layer is modeled if the discrepancy between expected and measured day-to-day change indicates a fresh snow event. This is either

*Corresponding author address:
Michael Winkler
ZAMG – Zentralanstalt für Meteorologie und Geodynamik
Fürstenweg 180, 6020 Innsbruck, Austria;
tel: +43 512 285598
email: michael.winkler@zamg.ac.at

the case if the measured snow depth increases in absolute values from one day to the following, or if the snow depth stays constant or declines less than hypothetical settlement would expect. A certain value of SWE is allocated to the new snow layer, depending on the fresh snow amount and an estimated fresh snow density, and added to the bulk SWE. Underlying, older snow layers get compressed and their densities increase. The rate of compression and densification depends on the mass (SWE, respectively) of the superimposed layer and follows an exponential function.

(2) If the following day's measurement and the model expectation for the following day resemble each other within certain threshold bounds, bulk SWE is conserved. All layers densify at rates, which depend on individual layer thickness, age and their previous day's density.

(3) If the following day's measurement is lower than a decisive threshold, a rain-on-snow event is assumed by the model. Depending on the strength of the signal an adequate increase in SWE is modeled for the uppermost layers, leading to an increase in bulk SWE as a function of hypothetic rain amount stored in the snowpack.

(4) Ablation of the snowpack and a respective decrease in SWE are modeled if there are several successive days with a significant decline of snow depth and snow layer densities are high enough.

Multiple linear regression analyses were carried out by Gruber (2014) to find the best set of thresholds etc. The model was calibrated with weekly SWE and daily snow depth measurements from six weather stations in the Tyrolean Alps representing different climatic settings and spanning an altitudinal range from 590–1650 m. The model performed best with fresh snow density set to 85 kg/m^3 and a threshold for maximum density of 450 kg/m^3, both values being surprisingly reasonable assumptions given the simplicity of the approach.

For publication in the conference proceedings at hand the new semi-empirical model was tested with series of snow depths and SWEs modeled by the detailed snowpack scheme Crocus (e.g. Vionnet et al., 2012) and compared to the performance of the statistical models by Jonas et al. (2009), Sturm et al. (2010) and Pistocchi (2016).

3. RESULT AND DISCUSSION

The snowpack of 2014/15 at Chartreuse (2100 m), French Alps, should serve as an example of model performance and act as basis of discussion of advantages and problems of the semi-empirical approach versus the statistical ones.

Figure 1 shows daily values of snow depth and different model results for SWE. Note that ”CROCUS” (e.g. Vionnet et al., 2012) is a process-resolving snowpack model depending on a variety of meteorological input and therefore being computationally expensive. ”Jonas” (Jonas et al., 2009), ”Pistocchi” (Pistocchi, 2016) and ”Sturm” (Sturm et al., 2010) represent typical statistical models to parametrize snow density and allow the efficient calculation of SWE solely from snow depth, date, altitude and region. The semi-empirical model (”NEW APPROACH”) presented here resolves different layers within the snowpack and only needs a gapless record of daily snow depths to model SWE, while keeping the computational effort very small. Given the well-established, well-validated and highly sophisticated character of ”CROCUS” it can be regarded as the benchmark model for SWE in this case.

Looking at the behavior of the statistical models (”Jonas”, ”Pistocchi” and ”Sturm” in Figure 1) one recognizes their strong dependence an snow depth. Not least Jonas et al. (2009) showed that high (low) snow depth is by far the most important reason for high (low) SWE, however, the statistical models erroneously assume decreasing SWEs when snow depths decline by pure settlement. As a consequence artificial peaks of SWE are modeled at the beginning of a settlement phase and — as the statistical models are typically trained to perform best in modeling mean seasonal SWE — they often underestimate SWE at the end of settlement periods (see end of April in Figure 1). In this respect the semi-empirical model behaves much more reasonable and keeps SWE constant during these periods, quite similar as Crocus does, which makes SWE values of distinct days much more reliable when modeled with the semi-empirical model than with the statistical models.

Many applications (e.g. hydrological studies focusing on potential runoff from snow covered areas, climate studies investigating changes in winter precipitation and water availability, extreme value analyses fitting appropriate distributions to SWE data) rely on good assumptions of maximum SWE. Figure 1, as a representative example of model behavior, shows that the semi-empirical model outperforms statistical approaches.

The new semi-empirical model at this stage shows problems when only small settlement rates occur. For example around New Year of 2015 in Figure 1 one can see that SWE is increased by the ”NEW

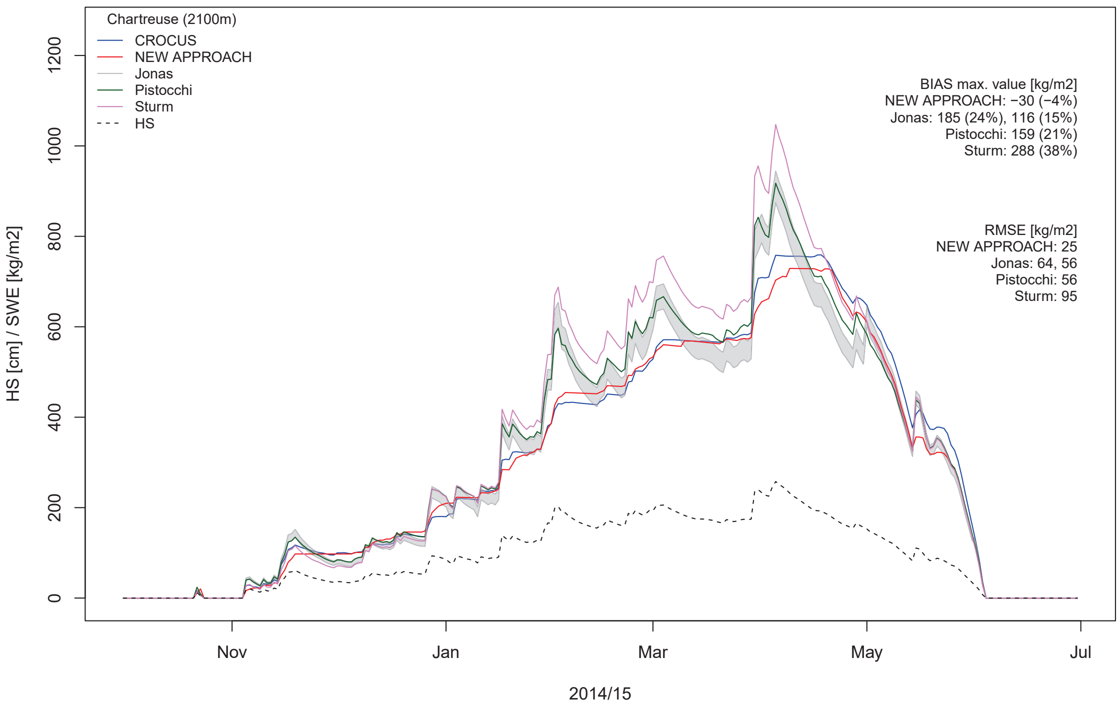

Figure 1: Snow depth HS [cm] and snow water equivalent SWE [kg/m^2] at Chartreuse (2100 m), French Alps, in 2014/15 as modeled by the snowpack model Crocus "CROCUS" (e.g. Vionnet et al., 2012), the new semi-empirical model "NEW APPROACH" (based on Gruber, 2014) and three models, that statistically parametrize snow density: "Jonas" (Jonas et al., 2009, gray shaded area shows spread due to different region offsets), "Pistocchi" (Pistocchi, 2016) and "Sturm" (Sturm et al., 2010). Numbers in the upper right corner indicate bias of the maximum SWE as well as RMSE of the whole season with respect to "benchmark-model" Crocus.

APPROACH" whereas it stays constant in Crocus. Furthermore there are occasional problems with too low fresh snow density in the semi-empirical model (strong snowfall event at the beginning of April in Figure 1) and sometimes also with too high fresh snow density (not obvious in 2014/15 at Chartreuse in Figure 1). Another problematic field for the semi-empirical model are melt phases in mid-winter, which it cannot distinguish from phases of pure settlement (mid to end of November in Figure 1). All these problem areas, which are to be improved in the semi-empirical model, should not hide the fact that its performance is fundamentally better than that of the statistical models, although transferability to other sites is higher (no dependence on altitude and region) and computational efficiency is only marginally worse.

4. CONCLUSIONS AND OUTLOOK

A new approach to model snow water equivalent (SWE) from snow depth series without the need of further meteorological input is presented. It is a semi-empirical snow layer model deriving SWE from gapless records of daily snow depths.

Of course, not all events influencing a snowpack during a winter season are ascertained correctly by the new model, and as it still is at a developmental stage some parts are to be optimized. However, results show a much better behavior of the new semi-empirical model compared to statistical models like Jonas et al. (2009), Sturm et al. (2010) and Pistocchi (2016) while computational efforts stay very small. Undoubtedly the model is a valuable tool for many studies and applications, e.g. climate studies and extreme value analyses, longing for SWE data from long-term and historical snow depth data that do not come along with additional meteorological information on temperature, radiation etc.

The new semi-empirical snow model can fill the gap between statistical parametrizations of snow density and sophisticated, computationally expensive, process-based snow models. The authors are looking forward to presenting more insights, verifications and details on the coding of the model as a peer-reviewed article in the near future.

ACKNOWLEDGEMENT

We want to acknowledge Samuel Morin (Météo-France, Centre d'Etudes de la Neige) for providing Crocus data and the Tyrol Hydrographic Service for preparing snow depth and snow water equivalent measurements.

REFERENCES

Gruber, S. (2014). Modelling snow water equivalent based on daily snow depths. Master's thesis, University of Innsbruck.

Jonas, T., Marty, C., and Magnusson, J. (2009). Estimating the snow water equivalent from snow depth measurements in the Swiss Alps. *Journal of Hydrology*, 378:161–167.

Lehning, M., Bartelt, P., Brown, R., Fierz, C., and Satyawali, P. (2002). A physical SNOWPACK model for the Swiss Avalanche Warning Services. Part II: Snow Microstructure. *Cold Regions Science and Technology*, 35(3):147–167.

Martinec, J. and Rango, A. (1991). Indirect evaluation of snow reserves in mountain basins. In *Snow, Hydrology and Forests in High Alpine Areas*, number 205, pages 111–120.

McCreight, J. L. and Small, E. E. (2014). Modeling bulk density and snow water equivalent using daily snow depth observations. *Cryosphere*, 8(2):521–536.

Mizukami, N. and Perica, S. (2008). Spatiotemporal Characteristics of Snowpack Density in the Mountainous Regions of the Western United States. *Journal of Hydrometeorology*, 9:1416–1426.

Pistocchi, A. (2016). Simple estimation of snow density in an Alpine region. *Journal of Hydrology: Regional Studies*, 6:82–89.

Sturm, M., Taras, B., Liston, G. E., Derksen, C., Jonas, T., and Lea, J. (2010). Estimating Snow Water Equivalent Using Snow Depth Data and Climate Classes. *Journal of Hydrometeorology*, 11(6):1380–1394.

Vionnet, V., Brun, E., Morin, S., Boone, A., Faroux, S., Le Moigne, P., Martin, E., and Willemet, J. M. (2012). The detailed snowpack scheme Crocus and its implementation in SURFEX v7.2. *Geoscientific Model Development*, 5(3):773–791.