Trend analysis of snow density and water equivalent in the Alpine region

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ABSTRACT: Snow density is an important property for the characterisation of a snow cover. It is also a key factor for retrieving the snow water equivalent (SWE), which plays a critical role in the water cycle in any mountainous region. Both, snow density and SWE are important parameters when assessing snow models used e.g. in hydrology or avalanche forecasting.
In this study we analyse changes of snow density and SWE measurements from roughly 30 snow stations in the Alps in the last 50 years. The measurement sites are located between 500 and 2600 m asl in four Alpine countries. We show that missing values can be successfully parameterised. The hereby induced error for SWE decreases from about 30% at lowest stations to about 15% only at the highest stations. The long-term time series reveal slightly increasing mid-winter snow density at altitudes below 1000 m but decreasing SWE at all altitudes.

KEYWORDS: snow density, snow water equivalent, alpine region, variability

1 INTRODUCTION

There are three basic properties used to describe a snow cover: snow depth, snow density, and SWE – and they are all interconnected with each other by the fact that the snow pack density together with the snow depth determines the SWE or vice versa (Armstrong and Brun, 2010). Snow depth is by far the easiest and therefore most frequent measured and analysed parameter. Measurements of snow density or SWE on the other hand are either costly or time consuming and therefore only sparse. However, these parameters influence the thermal, mechanical and optical properties of snow layers. They are therefore important parameters for snow related research and its applications, including snow hydrology, snow load estimation, avalanche hazard assessment, numerical weather prediction and climate modelling.
First, this study demonstrates how missing values of snow density/SWE can be parameterised. Second, we show an analysis of the annual variability of snow density and SWE in the Alpine region and investigate if there have been obvious trends in the last few decades since the beginning of the measurements. We focus on index dates of January 1 and April 1 in order to check if there are season dependent changes.

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2 DATA & METHODS

The used snow parameters in this study are: SWE, snow density, daily snow depth and daily height of new snow. The data were provided by the national services for weather, hydrology, avalanche warning and private hydropower related companies from Austria, France, Germany and Switzerland. The procedure to measure snow density or SWE varied between the different countries. The measurements were accomplished by either manually weighting a snow probe in the case of Switzerland, Germany and Austria or by automatically measuring the attenuation of cosmic rays through the snow pack as it is done in France. The data were available weekly, bi-weekly or monthly. The sites are located between 500 and 2600 m asl. However, the majority of the measurements started at the beginning of the 1960's and are located around 1500 m asl, only two stations are above 2500 m asl. We therefore focus on the last 50 years between 1963 and 2012.

Eventually, 27 stations for snow density and 38 for SWE fulfilled the above criteria. To assess the performance of the different parameterisations we used the index of agreement (IOA) and absolute and relative (to the mean) error measures like root mean square (RMSE) and mean bias (MBE). Significance and strength of long-term trends were analysed with the Mann-Kendall test and Theil-Sen slope estimator.

3 PARAMETERIZATION OF MISSING VALUES

For this study we tested two basic parameterization approaches: The first method consists of a set of equations which describes the settling of new snow and the associated increase of snow density (Rohrer and Braun, 1994). The second method is based on a statistical (climatological) connection between snow density and total snow depth, whose parameters are dependent on season and altitude (Jonas et al. 2009). As we also tested modified versions of these two basic approaches, we finally compared five different SWE parameterizations (Figure 1). All methods showed smaller (larger) absolute (relative) errors at low altitude stations and larger (smaller) absolute (relative) at high altitude stations. Relative RMSEs were similar for the best version of both approaches. We finally decided to apply the best parameterization (called "Jonas Spline") based on the second approach, because absolute MBEs were much smaller. Moreover, this method is more generally applicable because solely snow depth is used as input. The chosen method is able to parameterize SWE with relative RMSE which decreases from about 30 % at altitudes below 1000 m asl to about 15% at altitude above 1200 m asl.

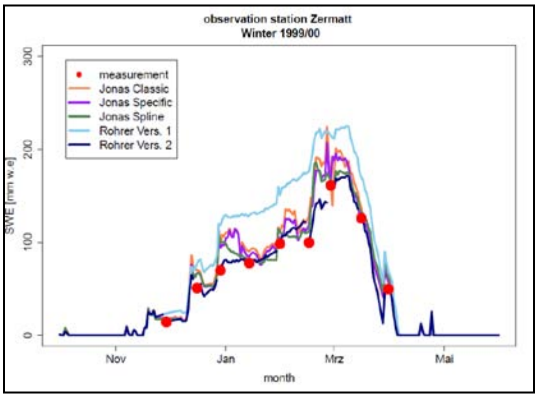

Figure 1. Five different SWE parameterizations and bi-weekly SWE measurements as example at the station Zermatt (1620 m asl) in Winter 1999/2000.

4 TREND ANALYSIS

4.1 Snow density changes

The analysis of the long-term snow density data revealed no clear trend towards larger or smaller observed values. However, for January 1 and altitudes below 1000 m asl the majority of stations show an increasing slope (Figure 2). For April 1, on the other hand, the number of stations with a decreasing trend is much larger at all altitudes.

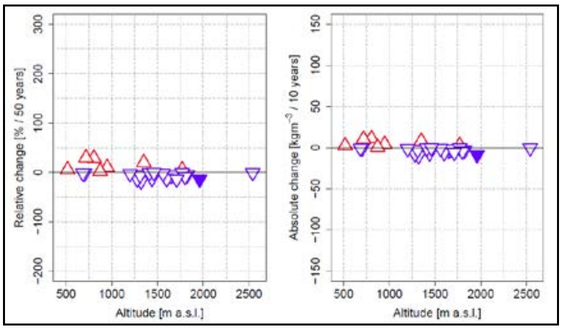

Figure 2. Relative (left) and absolute (right) density changes of the individual stations at January 1. Red (purple) triangles show increasing (decreasing) trends. Filled triangles indicate significant (p<0.05) changes.

4.2 Snow water equivalent changes

In contrast to snow density the trend analysis of the long-term SWE data revealed clear trends towards smaller SWE for both index dates. 15 % of the stations showed a significant ($p < 0.05$) decrease at January 1. This number increased to 40 % at April 1, where all stations observed a negative trend (Figure 3). With the exception of the two uppermost stations absolute changes are increasing with altitude. Relative changes however are more or less constant and definitely larger than the corresponding density changes.

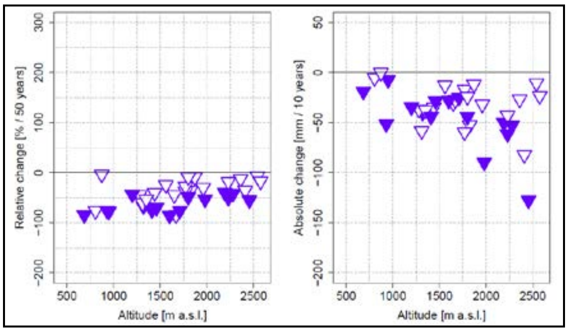

Figure 3. Relative (left) and absolute (right) SWE changes of the individual stations at April 1. All stations show decreasing trends. Filled triangles indicate significant (p<0.05) changes.

5 CONCLUSION

This study demonstrates that snow density shows no clear trend in the last 50 years. In contrast, SWE measurements demonstrate clear decreasing trends at all altitudes, especially for April 1. A correlation analysis between density and SWE changes reveals that significantly decreasing SWE is mostly accompanied by decreasing snow density. Stations with increasing snow density despite significantly decreasing SWE showed only weak positive trends. The decreasing SWE trends can probably be explained by less snowfall (Serquet et al. 2013) and more intensive snowmelt (Marty and Meister, 2012) due to the climate change induced temperature increase.

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