Geophysical Research Abstracts
Vol. 16, EGU2014-14452, 2014
EGU General Assembly 2014

Seasonal and diurnal cycles of liquid water in snow

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The combination of upward-looking ground-penetrating radar (upGPR), automatic weather station (AWS) and lysimeter allows for continuous monitoring of bulk volumetric liquid water content (θ_w) within the snowpack and direct comparison with measurements of the corresponding outflow. The AWS data can be utilized to calculate energy fluxes between atmosphere and snowpack at the location of the station. While combining all data sets, we were able to quantify diurnal and seasonal changes in residual water content and relate modeled energy fluxes to water outflow. Since upGPR is a non-destructive monitoring technique, it is possible to continuously observe the snowpack and results are not biased through spatial variability of pit locations. Data analysis conducted for three consecutive years at the flat test site Weissfluhjoch, Davos, Switzerland showed that diurnal θ_w variations never exceeded 2%. Without regard to days with new snow accumulation or refreezing, the diurnal patterns in θ_w were very similar, with always daily peaks in the late afternoon (at about 17:00h) at the site. Although θ_w values varied during a day up to 2%, the gradients during the season were very small. In 2012, for the whole melting period (>100 days), increases in θ_w from day to day were 0.4% liquid water content on average. After the snowpack has become isothermal, positive energy fluxes result in outflow and increase the residual water content (θ_r). Our data showed that as long as potential melt - calculated for the determined energy fluxes - was exceeding measured outflow, θ_r values were increasing but only until reaching a certain threshold. For all three years, the thresholds were similar at about θ_r=4–5%. Only shortly before full ablation, these thresholds were surpassed. In two sloped test sites (about 22 degree slope angle) in Boise, Idaho, USA and above Davos, we installed upGPR systems as well. AWS data and energy-flux calculations for both slopes were extrapolated for the respective aspect and slope angle. Our data showed that snow stratigraphy highly influences θ_r in slopes. As long as e.g. crusts ponded the vertical water flow, residual θ_w of the whole snowpack was fairly low (<1%) over weeks. Diurnal variations in θ_w were in accordance with values observed at the flat site. Once the ponding capabilities of the stratigraphy disappeared, residual θ_w values were in a comparable range to the ones of the flat site. The applied measurement setup is able to monitor continuously the behavior of liquid water in snow and record almost exactly the date when θ_r thresholds are reached or surpassed. Data thereof can be used to assimilate model outputs and may help to better predict water outflow and storage capacities.