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Numerical solution of the mass continuity equation for snowpack modeling on moving meshes: Coupling between mechanical settling and water vapor transport

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The snowpack continuously evolves due to metamorphic and mechanical processes. Understanding and quantifying these processes and in particular their complex interplay and impact on the snowpack's strength is challenging, yet of large interest to the snowpack modeling community. Due to the layer representation and the absence of an explicit numerical solution of the mass continuity equation in common snowpack models, competing effects of mechanical settling and phase changes (e.g. due to vapor transport) can hardly be assessed faithfully. Towards a remedy, we investigate the potential of a numerical scheme that treats the vapor recrystallization term on a moving mesh as imposed by the settling term of the continuity equation.
First, we introduce a continuum mechanical snowpack model that explicitly accounts for both water vapor transport induced by temperature gradients, and settling processes. Next, we describe a computational approach to solve the coupled snowpack model. Water vapor transport as a result of temperature and condensation rate evolution are solved by means of a finite difference scheme. Accounting for settling processes requires to solve an additional ice volume balance, which is done based on the method of characteristics. Its advantage is that it can exactly account for the moving upper free surface of the snowpack. Unstructured meshes enable us to track (potentially densifying) snow layers at high spatial resolution. A closure for the settling velocity is formulated in terms of stresses from the overburdened snow mass and snow viscosity. The proposed continuum-mechanical snowpack model enables us for the first time to investigate the coupled interplay and relative importance of water vapor transport and snowpack settling on time scales from minutes to several hours.
In a series of numerical examples, we present simulation results for varying snow heights (0.02 - 1 m), snow densities (100 - 917 kgm^{-3}) and temperature gradients (20, 100, 1000 Km^{-1}) to assess the effect of simultaneous snowpack settling and water vapor transport. The proposed model allows us to observe the downward propagation of a snow layer interface coupled to water vapor deposition and sublimation, at high spatial resolution. One of our major findings is that while settling might strongly increase ice densities, it also has an additional (weaker) impact on the condensation rate. Finally, we will discuss to which extent the proposed novel computational approach could be used to study and quantify the interplay of coupled mechanical and

metamorphic processes in future community snowpack models, for instance while identifying regimes that require to account for process coupling.