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On water vapor transport in snowpack models: Comparison of existing schemes, numerical requirements and the role of non-local advection

Konstantin Schürholt (1), Julia Kowalski (2), and Henning Löwe (1)

(1) WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland (konstantin.schuerholt@slf.ch), (2) Aachen Institute for Advanced Study in Computational Engineering Science (AICES), RWTH Aachen University, Aachen, Germany (kowalski@aices.rwth-aachen.de)

The incorporation of a mass-conserving treatment of vapor transport has become a key requirement for snowpack modeling to capture various effects emerging particularly under persistent temperature gradient conditions. Though different schemes for the upscaled vapor diffusion undergoing phase changes with the ice matrix are available, none of them are presently included in common snowpack models. This is mainly due to difficulties of faithfully integrating the equations into the numerical core of existing models. To shed further light onto the mathematical and numerical nature of the non-linear problem we have revisited the numerical treatment for the macroscopic, one-dimensional continuity equations of energy, ice mass and vapor mass in snow modelling. We focus on a comparison between two established, homogenized models that only differ in the presence or absence of a local thermodynamic equilibrium of the vapor phase. As a compromise between minimizing programming overhead and keeping access to low-level modifications of the numerical scheme, we have implemented a finite element model of the coupled problem using the FENICS framework. For numerical cross validation, we used a finite difference solver as well as analytical solutions of reduced problems. Then, we conducted numerical experiments for idealized, initial density profiles which are either smooth (Gaussian) or non-differentiable (piece-wise linear). As a main result, we observe clear differences between the two schemes with regard to i) absolute values of simulated mass transfer, ii) the response to non-smooth initial conditions and the iii) onset of numerical instabilities emerging in the the same, fully coupled, non-stabilized, non-linear solver for both problems. Differences are at least partly related to the assumption of a strict equilibrium of the vapor phase imposing different numerical requirements related to the separation of time scales. To further understand the nature of the numerical instabilities, we have derived an analytical approximation of the fully coupled problem. This reveals the ice-phase dynamics as a non-linear and non-local advection problem with associated gradient steepening of physical origin. Based on this insight we discuss remedies for a stable and robust numerical solution of vapor transport in snow.