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Climatic physical snowpack properties for large-scale modeling examined by observations and a physical model

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Abstract

Here we have conducted an integral study using site observations and a model with detailed snow dynamics, to examine the capability of the model for deriving a simple relationship between the density and thermal conductivity of the snowpack within different climatic zones used in large-scale climate modeling. Snow and meteorological observations were conducted at multiple sites in different climatic regions (two in Interior Alaska, two in Japan). A series of thermal conductivity measurements in snow pit observations done in Alaska provided useful information for constructing the relationship. The one-dimensional snow dynamics model, SNOWPACK, simulated the evolution of the snowpack and compared observations between all sites. Overall, model simulations tended to underestimate the density and overestimate the thermal conductivity, and failed to foster the relationship evident in the observations from the current and previous research. The causes for the deficiency were analyzed and discussed, regarding a low density of the new snow layer and a slow compaction rate. Our working relationships were compared to the equations derived by previous investigators. Discrepancy from the regression for the melting season observations in Alaska was found in common.

Keywords: Snowpack; Physical property; Arctic; Large-scale climate models; Observations; Snow dynamics model

1. Introduction

Seasonal snowcover is a cryospheric phenomenon that exerts extensive and significant eco-climatic impacts in high-latitude/high-altitude regions and in mid-latitudes (Armstrong and Brun, 2008; Jones et al., 2001). Large-scale changes in snowcover influence energy and water exchange between the atmosphere and the ground in winter, amount and timing of spring peak stream flow of rivers, and water storage (soil moisture content) within these regions. Snow conditions and variability are physically, ecologically, and economically important issues relating to natural vegetation and agriculture, wildfires, infrastructure

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construction, and indigenous subsistence and culture. Seasonal snow shows different characteristics under different ambient conditions (such as temperature, precipitation amount, wind, and radiation) in different climatic regions (such as Arctic, or tundra; continental interior, or taiga; mountainous; coastal; and mid-latitudinal, or ephemeral). Many classification systems and distribution maps have been presented (cf. Table 1 of Sturm et al., 1995), e.g., Benson (1982) for Alaska, and Ishizaka (2008) for Japan. In this study, climatic difference or gradient refers to abrupt or gradual changes in the characteristics of snowpack (e.g., snow depth or water equivalent, snow type, wetness, density, thermal property, viscosity, and microstructure) spanning the different climate regions.

Large-scale climate models, such as global climate models (GCMs), Earth System Models (ESMs), or regional climate models (RCMs), are useful tools for large-scale snow studies, including interactions between snowcover and climate over different climate regions (Essery, 2003; Liston, 1999, 2004; Pomeroy et al., 2002; Marshall et al., 1994). Global or regional climate models (G/RCMs) provide quantitative information on snow water equivalent and snowcover percentage at a grid scale (ranging from 100 to 300 km in current major integrations, depending on the choice of horizontal resolution of the model's discretization). One of the advantages of these modeled values is their physical consistency in time and space, in comparison to the compiled data from different climatic regions, which entail different observation practices and standards. The simulated results are physically constrained to the conditions of current, future, or hypothetical climate over the entire integration period and area.

However, terrestrial snow models (numerical modeling of the physics and dynamics of a snowpack) implemented in the current G/RCMs vary considerably with respect to the complexity of the resolved processes, and are in general not good at reproducing the sub-grid scale heterogeneity (e.g., Randall et al., 2007). The Snow Model Intercomparison Project phase 2 (SnowMIP2) (Rutter et al., 2009) demonstrated that both the complex snow-physics models and those models designed for large-scale climate simulations produced offline simulations that varied greatly in terms of depth, stratigraphy, amount, and duration of a snowpack. In general, snow parameterizations used in G/RCMs can be very coarse. For example, a constant value is often used for snow density and/or thermal property (conductivity or diffusivity), important snow physical properties at all points and through seasons (e.g., Takata et al., 2003). Heat transfer is one of the essential physical processes of the snowpack, controlling heat balance between the atmosphere and the subsurface ground. Vertical heat conduction of ice and air through the snowpack is implemented largely in the physically-resolved snow model in the current G/RCMs, whereby other possibly important processes, such as convection by air and transport of water vapor and associated latent heat, may be neglected. An effective relationship between thermal conductivity and other physical variables that can be easily determined or quantified has been sought (Yen, 1981; Sturm et al., 1997; Kaempfer et al., 2005; Calonne et al., 2011). The thermal conductivity of snow is determined through different processes and by complex factors that involve ambient meteorological conditions, metamorphism, and microstructure of the snowpack. Sturm et al. (1997) argue that a temperature–conductivity relationship is not simple. One of the practical choices proposed by previous investigators is to study snow density. This research follows those works and seeks to derive a simple but effective relationship between snow density and vertical snow thermal conductivity, applicable to the different climatic regions used in large-scale climate modeling and studies.

When developing a numerical model, it is a common, and occasionally essential, strategy while targeting processes to presume the lowest-order approximations for relevant physical properties. This is especially true when the basic variability of the value, such as spatial distribution or the nature of temporal changes, is only poorly known or lacks observational evidence. Besides, it is not always a successful strategy for G/RCMs to implement the physical model of the same complexity as the detailed process models used for localized studies, from the viewpoints of numerical stability, computational economy and efficiency, and practicality. Therefore, there should be an optimized range of complexity levels in the implemented processes that suits the G/RCMs (although levels might be different for different horizontal or temporal resolutions). Sturm et al. (1995) conducted a pioneering observation-based investigation, aimed at large-scale climate study applications, to classify snow characteristics over different climatic regions (i.e., tundra, taiga, alpine, maritime, prairie, and ephemeral). The proposed classification is simple but extracts essential information on the snow's textural and stratigraphic characteristics from climate variables such as wind, precipitation, and air temperature. Sturm et al. (2010) further attempted to draw