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Comparing snow models under current and future climates: Uncertainties and implications for hydrological impact studies

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ABSTRACT

Projected climate change effects on snow hydrology are investigated for the 2041–2060 horizon following the SRES A2 emissions scenario over three snowmelt-dominated catchments in Quebec, Canada. A 16-member ensemble of eight snow models (SM) simulations, based on the high-resolution Canadian Regional Climate Model (CRCM-15 km) simulations driven by two realizations of the Canadian Global Climate Model (CGCM3), is established per catchment. This study aims to compare a range of SMs in their ability at simulating snow processes under current climate, and to evaluate how they affect the assessment of the climate change-induced snow impacts at the catchment scale. The variability of snowpack response caused by the use of different models within two different SM approaches (degree-day (DD) *versus* mixed degree-day/energy balance (DD/EB)) is also evaluated, as well as the uncertainty of natural climate variability. The simulations cover 1961–1990 in the present period and 2041–2060 in the future period. There is a general convergence in the ensemble spread of the climate change signals on snow water equivalent at the catchment scale, with an earlier peak and a decreased magnitude in all basins. The results of four snow indicators show that most of the uncertainty arises from natural climate variability (inter-member variability of the CRCM) followed by the snow model. Both the DD and DD/EB models provide comparable assessments of the impacts of climate change on snow hydrology at the catchment scale.

1. Introduction

The main impact of recent climate change, according to the global historical climatology network observations, is an increase in surface temperature across the globe, particularly in the northern hemisphere and most especially at higher latitudes (Hartmann et al., 2013). A further acceleration of the global warming trend during the present century is projected by all Global Climate Models (GCMs) (IPCC, 2014). This will clearly affect snow accumulation, the duration of snow covered periods and snowmelt processes, with direct impacts on water resources (Pohl et al., 2007; Kay and Crooks, 2014). Thus, Nordic regions, where the water cycle is dominated by snow hydrology, are expected to be particularly sensitive to climate change, as it affects the seasonality of streamflow (Adam et al., 2009).

In Canada, the hydrology of catchments is driven by the accumulation of precipitation as snow over the winter period and the subsequent rapid release of this precipitation as meltwater during the springtime. This release leads to seasonal high flows which provide a sustained source of water for many regions in Canada (Shrestha et al., 2012a, 2012b). A disturbance of the snow-driven hydrologic regime in the catchments could have major regional implications. Therefore, to ensure continued economic development in many Canadian regions, such as Quebec, information related to future projected changes on the contribution of snowmelt runoff to streamflow generation is essential for the management and future planning of water resources.

The assessment of future climate change impacts on snowmelt runoff requires quantifying the variability inherent in seasonal snowpack evolution, usually described in four successive steps: snow accumulation, snowpack aging and thawing, and snow melting (Dingman, 2002). Many hydrological models provide a comprehensive framework to investigate the snowpack state by incorporating an additional snow hydrology component in the basic rainfall-runoff models (Neitsch et al., 2001; Martinec et al., 2008; Rango and Dewalle, 2008; Oreiller et al., 2014); these can subsequently be used with future climate change scenarios from climate models to evaluate projected changes on the snowpack dynamics (López-Moreno et al., 2013; Sproles et al., 2013; Kay and Crooks, 2014; Szczypta et al., 2015).

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The amount of water held within the snowpack waiting to be melted (referred to as the snow water equivalent or SWE) can be estimated by means of three snow model (SM) approaches, with various levels of complexity: physical energy-balance (EB) models, degree-day (DD) models, and mixed degree-day and energy-balance (DD/EB) models. The EB models explicitly simulate energy and mass exchanges between internal layers of the snowpack as well as snowpack stratigraphy. Each of the relevant energy fluxes at the snow surface is computed from physically-based calculations using simulated meteorological data; the SWE is then calculated as the sum of the individual fluxes (Pellicciotti et al., 2005). The DD models employ the air temperature as a proxy of the heat transfer process affecting snowmelt to compute the SWE (Jain et al., 2010); however, additional input variables, such as incoming shortwave radiation or albedo, may be incorporated through empirical formulas based on time and location. The DD models are widely used for hydrologically-related applications due to their parsimony in data requirements compared to more sophisticated EB models (Troin and Caya, 2014; Kay and Crooks, 2014; Panday et al., 2014). The DD models are generally interpreted at daily or coarser time scales, and in a lumped or semi-lumped manner for the calculation of the average SWE over a whole catchment.

Recently, an increasing need for high temporal and spatial resolution simulation of the SWE for hydrological modeling purposes has prompted numerous attempts to combine the accuracy of physically-based EB models with the simplicity of DD models in order to develop mixed EB/DD models (Jost et al., 2012; Tobin et al., 2013; Bormann et al., 2014). In this respect, in addition to assessing the advantages of using EB/DD models rather than DD models to obtain more robust SWE simulations over a particular Nordic catchment of interest, one pertinent issue remains for impact studies – being able to evaluate how the projected changes on the snowpack dynamics (mainly snow accumulation and melting) differ among the SM approaches at the catchment scale. Resolving this issue will allow the exploration of uncertainty associated with snow hydrology modeling, a critical step towards the understanding, quantification and reduction of uncertainty in hydrological projections.

The present study focuses on comparing a range of SMs in terms of their ability at simulating the snowpack dynamics under current and future climates. One aspect of this investigation is to evaluate how the SMs affect the assessment of the climate change-induced snow impacts at the catchment scale. Another aim is to evaluate different models within the two hydrologically-relevant types of snow modeling approaches (DD *versus* DD/EB models). This assessment allows us to investigate the variability of snow processes caused by the choice of the models within the two SM approaches, and to show how this choice can produce different future projections of snow hydrology conditions at the catchment scale.

The above aspects are addressed through a complete snow hydro-climate model chain which is applied over three seasonally snow-covered catchments in Canada: the Chaudiere and Yamaska Basins both located on the south shore of the St-Lawrence River and the Mistassini Basin situated on the north shore of the St-Lawrence River in Quebec. Snowmelt processes dominate the surface hydrology of these basins. Fig. 1 shows the location of each basin and Table 1 lists some of their main features. For each of the three basins, daily climate variables are derived from the high-resolution ensemble of simulations from the Canadian Regional Climate Model (CRCM-15 km) forced by the Canadian (CGCM3) GCM. Each simulation in the ensemble is used to calibrate the SMs. The SM simulations' are evaluated under current (1961–1990) and future (2041–2060) periods by comparing daily simulated SWEs with the pseudo-observations from the virtual world based on the CRCM. The virtual world offers a fully coherent dataset with no missing data or inconsistencies in time and space (Maraun, 2012; Arsenault and Brissette, 2014; Minville et al., 2014; Velázquez et al., 2015). Along with the significant reduction of these usually noteworthy uncertainties associated with the real world, the approach has the advantage of providing predictions of snow hydrology on ungauged sites under climate change conditions. The SMs are also evaluated over a short period in the real world based on the Gamma MONitor (GMON) observations dataset (Choquette et al., 2008). Given the nature of the CRCM ensemble simulations used in the study, it is possible to explore the uncertainty associated with the natural climate variability of the driving GCM combined with the internal variability of the CRCM, and to evaluate how this uncertainty affects the response of snow hydrology over the study catchments. Other uncertainties in climate change assessment such as inter-model variability, driving GCM

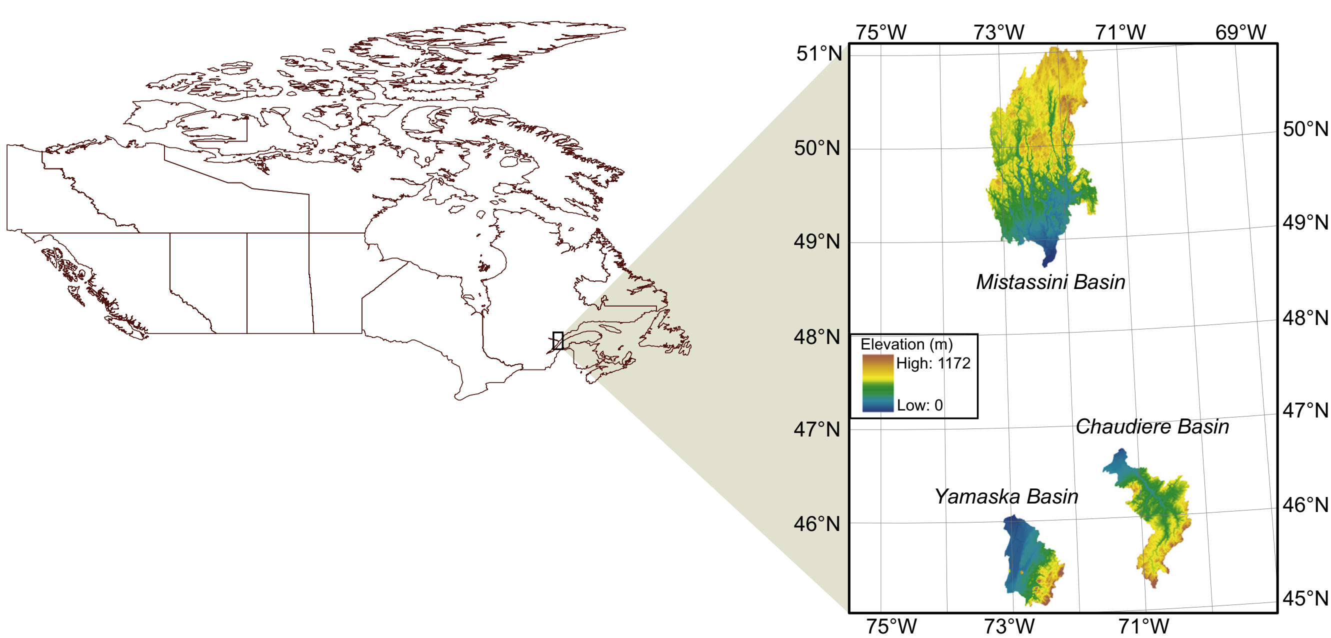

Fig. 1. Location map of the study basins.