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Simulating cold regions hydrological processes using a modular model in the west of China

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SUMMARY

The Cold Regions Hydrological Model platform (CRHM), a flexible object-oriented modeling system, was devised to simulate cold regions hydrological processes and predict streamflow by its capability to compile cold regions process modules into purpose-built models. In this study, the cold regions hydrological processes of two basins in western China were evaluated using CRHM models: Binggou basin, a high alpine basin where runoff is mainly caused by snowmelt, and Zuomaokong basin, a steppe basin where the runoff is strongly affected by soil freezing/thawing. The flexibility and modular structure of CRHM permitted model structural intercomparison and process falsification within the same model framework to evaluate the importance of snow energy balance, blowing snow and frozen soil infiltration processes to successful modeling in the cold regions of western China. Snow accumulation and ablation processes were evaluated at Binggou basin by testing and comparing similar models that contained different levels of complexity of snow redistribution and ablation modules. The comparison of simulated snow water equivalent with observations shows that the snow accumulation/ablation processes were simulated much better using an uncalibrated, physically based energy balance snowmelt model rather than with a calibrated temperature index snowmelt model. Simulated seasonal snow sublimation loss was 138 mm water equivalent in the alpine region of Binggou basin, which accounts for 47 % of 291 mm water equivalent of snowfall, and half of this sublimation loss is attributed to 70 mm water equivalent of sublimation from blowing snow particles. Further comparison of simulated results through falsification of different snow processes reveals that estimating blowing snow transport processes and sublimation loss is vital for accurate snowmelt runoff calculations in this region. The model structure with the energy balance snowmelt and blowing snow components performed well in reproducing the measured streamflow using minimal calibration, with R^2 of 0.83 and NSE of 0.76. The influence of frozen soil and its thaw on runoff generation was investigated at Zuomaokong basin by comparing streamflow simulated by similar CRHM models with and without an infiltration to frozen soil algorithm. The comparison of simulated streamflow with observation shows that the model which included an algorithm describing frozen soil infiltration simulated the main runoff events for the spring thawing period better than that which used an unfrozen infiltration routine, with R^2 of 0.87 and NSE of 0.79. Overall, the test results for the two basins show that hydrological models that use appropriate cold regions algorithms and a flexible spatial structure can predict cold regions hydrological processes and streamflow with minimal calibration and can even perform better than more heavily calibrated models in this region. Given that CRHM and most of its algorithms were developed in western Canada, this is encouraging for predicting hydrology in ungauged cold region basins around the world.

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1. Introduction

Many of the major rivers in China, such as the Yellow River, the Yangtze River, and the Lancang River originate from the Qinghai-Tibet Plateau (QTP) and other high altitude mountains in western China. Permafrost, seasonally frozen soils and snowcover are widely distributed over this region (Zhang et al., 2003a, 2008). The high altitude and cold winters result in substantial water storage as the seasonal snowpack, seasonally or perennially frozen ground, and glacial geomorphology. Spring snowmelt and thaw of frozen soils along with the rise of air temperature are generally considered the most important hydrological events in western China. Snow ablation and frozen soil thawing processes provide a reliable and substantial spring runoff (Peterson et al., 2002; Woo et al., 2008; Yang et al., 2002; Zhang et al., 2003b), which is important to water supply for irrigation, ecological protection, and flood control (Zhao and Gray, 1999). Concerns are being raised about the maintenance of this water supply under warming climate conditions (Adam et al., 2009; Gao and Shi, 1992). However, the classical hydrological concepts of rainfall–runoff response cannot be used in cold regions to describe hydrological behavior. In order to forecast runoff in these regions, it is necessary to understand snow redistribution, snow ablation, meltwater generation and soil freezing–thawing processes, and their interactions (Pomeroy et al., 2007; Fang et al., 2013).

In the last 20 years, simulation of cold regions hydrology has received much attention in many international organizations and research projects. The Climate and Cryosphere (CliC) Project Science and Coordination Plan (http://ipo.npolar.no/reports/archive/wcrp_114.pdf) declared in 2000 that cold regions hydrological processes and their corresponding impacts are important research items for global warming research. The Predictions in Ungauged Basins (PUB) decade (http://pub.iahs.info/index.php) operated by the International Association of Hydrological Sciences (IAHS) focused on predicting streamflow for ungauged or poorly gauged basins, including the effect of snow ablation and ice-melt to streamflow processes in cold regions throughout the decade of 2003–2012. The Improved Processes and Parameterization for Prediction in Cold Regions (IP3) Network (http://www.usask.ca/ip3/index.php), funded by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS), operated from 2006 to 2011 as a research network with a prime objective of improving understanding of cold regions meteorological and hydrological processes.

Computer models of basin hydrology are important technology to help understand cold regions hydrological processes and their role in basin-scale hydrological response to precipitation and snowmelt. Numerous studies have been conducted to describe water flow and heat transport in thawing and frozen soils (Flerchinger and Saxton, 1989a,b; Hansson et al., 2004; Jansson and Moon, 2001). Since the first successful demonstration of snowmelt simulation using an energy-balance approach by Anderson (1976), numerous such snowmelt models have been developed, e.g. EBSM (Gray and Landine, 1988), SNTHERM (Jordan, 1991), Snobal (Marks et al., 1999), SNOWPACK (Lehning et al., 2002a,b; Bartelt and Lehning, 2002). Due to the differing objectives specific to each energy balance model, there is considerable variation in the detail to which snow energetic processes may be described, as well as forcing data and parameterization requirements. For instance, EBSM has a single layer, operates at a daily time-step and has no parameters to set but is only appropriate for shallow snowpacks, whilst Snobal has two layers, operates at hourly or finer time steps, requires few parameters to set, but is appropriate for a wide range of snow depths and thermal conditions. SNTHERM and SNOWPACK have many layers and many parameters but presumably a wide range of applicability. For infiltration into thawing and frozen soils, several one-dimensional numerical codes currently exist for simulating water and heat transport, including freezing and thawing, such as SHAW (Flerchinger and Saxton, 1989a,b), HAWTS (Zhao and Gray, 1999; Zhao et al., 1997) and Coupmodel (Jansson and Moon, 2001). Models that simulate cold regions hydrological processes at basin scale have also been developed in the last years and include models such as ARHYTHM (Zhang et al., 2000), GEOtop (Rigon et al., 2006) and VIC (Liang et al., 1994). Many models have been used to describe cold regions hydrological processes in the west of China (e.g. Jia et al., 2009; Wang et al., 2010; Zhang et al., 2012). The more sophisticated models generally have parameter and driving meteorological requirements that may prohibit their successful employment in many environments, such as where forcing data and parameter information is typically lacking or poorly approximated. It is recognized that it is inappropriate to run detailed distributed models where meteorological data is sparse or parameter and hydrological uncertainty are so great as to make the operation of these models physically unrealistic. However, models with unidentifiable parameters or overly simplistic treatment of cold regions mass and energy exchange processes are also physically-unrealistic and do not have transferable parameterisations due to uncertainty caused by physical unrealism. Therefore, simulating and forecasting streamflow face great challenges in the cold regions, because of the lack of appropriate information at the basin scale and the lack of hydrological models that are appropriate for cold regions applications.

An urgent need in hydrology is to apply models to predict in ungauged basins where traditional calibration of models is not possible (Sivapalan et al., 2003). This need is not at odds with the need for models that have a physical complexity matching available parameter and meteorological information, but adds further constraints as the algorithms in physically based models must be able to operate with minimal or no calibration. Solutions to this problem have been sought using the Cold Regions Hydrological Model (CRHM) platform, which was developed as a modular object-oriented modeling framework to simulate the cold regions hydrological cycle over small to medium sized basins by a multidisciplinary research group from various institutions in Canada (Pomeroy et al., 2007). Many of the algorithms were derived from field investigations of cold regions processes in western and northern Canada, and most algorithms have a strong physical basis and extensive field testing. CRHM is fundamentally different from most hydrological models, because it is a modeling platform from which models can be created, based on a good physical understanding of the principles and characteristics of hydrology in a basin, with an appropriate structure and appropriate spatial resolution and parameter selection given information that is available. Logical selection and design of model strategy, structure, and their inherent assumptions are governed by local problems and local hydrology. This is not just parameter selection but involves selection of an appropriate model structure. By offering a range of spatial complexity from lumped to distributed, of physical realism from the conceptual to physically based approaches and by offering a wide selection of process modules, CRHM permits the user to tailor the model to the appropriate complexity that is warranted by the modeling objective, scale, and available information on the basin (Pomeroy et al., 2007, 2012). Models created using CRHM have been used to study blowing snow redistribution in sub-arctic and mid-continental mountains and sub-humid prairies (Fang and Pomeroy, 2008, 2009; MacDonald et al., 2009, 2010; Kort et al., 2011), mountain snow ablation (Pomeroy et al., 2012; DeBeer and Pomeroy, 2010; Dornes et al., 2008; Ellis et al., 2010; Lopez-Moreno et al., 2012; Fang et al., 2013), runoff generation over permafrost soils (Dornes et al., 2008), runoff over seasonally frozen soils (Pomeroy et al., 2012; Fang and Pomeroy, 2007; Fang et al., 2010; Guo et al., 2012) and evapotranspiration and soil moisture dynamics in boreal forest and semi-arid steppe environments

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