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Impact of soil freeze-thaw mechanism on the runoff dynamics of two Tibetan rivers

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ABSTRACT

Soil freeze-thaw is typically not fully considered in quantifying the hydrology of seasonally frozen catchments located, for instance, on the Third Pole. We investigate the role of soil water content and freeze-thaw state on the runoff dynamics of the headwaters of the Yellow and Yangtze rivers, both situated on the eastern Tibetan Plateau. A version of augmented Noah land surface model (LSM) allowing reliable simulation of key hydrometeorological processes over the Tibetan Plateau is employed and further validated using measured monthly discharge records. From measurements supported by the Noah LSM simulations for more than thirty years (1979–2010), we deduce an annual hysteresis loop, viz. a time lag between measured/simulated runoff and precipitation for both catchments. Our simulation results with the augmented Noah LSM further demonstrate that annual anticlockwise (or clockwise) hysteresis loops are also observed for the liquid soil water (or soil ice). We infer from the LSM simulations that the amount of water stored in the soil is the factor driving the hysteresis between runoff and precipitation, whereby the state of the stored water plays a crucial role in the seasonality of the runoff regime. Further analyses illustrate that inclusion of soil freeze-thaw model physics effectively increases the thermal inertia of the soil column that dampens large variations of soil temperature and turbulent heat fluxes. These findings highlight the importance of soil freeze-thaw for the hydrology and runoff regime across the High Asia's rivers as well as the need for a thorough understanding of this process to generate reliable projections.

1. Introduction

For the High Asia's rivers (e.g. Yellow, Yangtze and Mekong rivers) originating from the Third Pole centered on the Tibetan Plateau and the Himalayas, a large variability among runoff projection exists (Immerzeel et al., 2010; Lutz et al., 2014; Su et al., 2016), demonstrating the absence of a consensus on the understanding of the present-day hydrological processes. Almost half of the world's population depend on water supply from these river basins (Bookhagen, 2012), it is thus vital to quantify how climate change will affect the individual hydrologic components as well as available water resources. Yet this task can only be accomplished once the present-day hydrological processes are better understood.

The runoff regime and water budget across the High Asia's river basins were generally investigated via utilizing hydrological models (e.g. Zhang et al., 2003; Bookhagen and Burbank, 2010; Andermann et al., 2012; Zhou et al., 2014), whereby precipitation, snow- and glacier-melt are thought to control the runoff regimes of these rivers. Bookhagen (2012) suggested that precipitation and melt-water can be further delayed by transient water stored in the soil and groundwater reservoirs before traveling into rivers, adding immense complexity to the hydrological regime. Andermann et al. (2012) reported an annual anticlockwise hysteresis loop between discharge and precipitation for the central Himalayan rivers and hypothesized that the main mechanism accounting for this hysteresis effect is linked with the existence of a transient groundwater storage.

The hydrological models adopted by the above studies do not consider the soil freeze-thaw process that may affect the surface energy and

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water budgets across the Tibetan Plateau as substantial parts are subject to frozen ground (Guo and Wang, 2013). The coexistence of unfrozen water and ice in the frozen soil dramatically alters the thermal and hydraulic characteristics of the soil (Zhao et al., 1997; Zhang et al., 2010; Decharme et al., 2016) that influence the exchange of water and energy between land and atmosphere (Viterbo et al., 1999; Stevens et al., 2007). Additionally, the seasonal freeze-thaw cycle also changes the magnitude and temporal patterns of runoff through modifying the soil permeability (Wang et al., 2009; Koren and Smith, 2014; Wang et al., 2017). The omission of the soil freeze-thaw process forms thus a crucial source of uncertainty in the above modeling studies.

Land surface models (LSMs), on the other hand, have been widely used to quantify the runoff regime across domains with frozen ground (e.g. Cherkauer and Lettenmaier, 1999; Slater et al., 2007; Finney et al., 2012) using rigorous characterization of freeze-thaw mechanisms (Ek et al., 2003; Dankers et al., 2011; Oleson et al., 2013). LSMs have been employed by Xue et al. (2013) and Zhang et al. (2013) to quantify the runoff dynamic on the Tibetan Plateau, but these studies have ignored key findings on the governing hydrometeorological processes observed over the Plateau. For instance, the diurnally varying thermal roughness length (z_{0h}) and vertical soil heterogeneity related to organic matter have been widely recognized as a necessity for reliably simulating water and energy exchanges between land and atmosphere (van der Velde et al., 2009; Yang et al., 2009, 2014; Su et al., 2013). Moreover, the hydrologic dynamics associated with the seasonal freeze-thaw cycle on the Tibetan Plateau have hardly been investigated (Cuo et al., 2015; Qin et al., 2016). Recently, the above key findings have been incorporated into the structure of the Noah LSM (Zheng et al., 2016), which indicated that complete descriptions of physical processes associated with both warm and cold seasons are necessary for correctly representing the runoff regime in the seasonally frozen Yellow River source area. Further, Zheng et al. (2017a) have investigated the performance of various runoff parameterizations currently adopted by Noah, Noah-MP (Niu et al., 2011), CLM (Oleson et al., 2013) and CLM-VIC (Li et al., 2011) and confirmed the suitability of default Noah runoff parameterization for representing the Yellow River source area within the period 2001–2010.

In this study, we investigate the role of soil water content and the effect of soil freeze-thaw state on the seasonal runoff pattern of the headwaters of both Yangtze and Yellow rivers. The version of the augmented Noah LSM allowing reliable simulation of key hydrometeorological processes over the Tibetan Plateau (Zheng et al., 2016) and its default runoff parameterization (Zheng et al., 2017a) is employed to simulate the soil water and ice contents as well as the runoff for the period 1979–2010, which are assessed using the measured monthly discharge records.

The structure of this paper is as follows: Section 2 provides the description of the study area and discharge measurements. The default model physics and augmentations of the Noah LSM, as well as the model setup is provided in Section 3. Section 4 presents the combined analysis of measurements and Noah simulations. Finally, the findings of this study are summarized in Section 5.

2. Study area

Both source regions of the Yellow (SRYR) and Yangtze (SRYZ) rivers are located in the northeastern part of the Tibetan Plateau (Fig. 1), which is a transition area from continuous/discontinuous permafrost to seasonally frozen soil (Jin et al., 2009). The SRYR covers an area of 122,000 km^2 above the Tangnag discharge station constituting of 16.2% of the total area of the Yellow River watershed and contributing to about 35% of the river flow (Zheng et al., 2007). The annual average daily temperature ranges from −4 °C to 2 °C decreasing from east to west, and the temperature generally remains below 0 °C from October to April. The mean annual precipitation varies from 800 mm in the southeast to 200 mm in the northeast, with more than 75% falls between June and September, while the snowfall accounts for less than 10% of the annual precipitation according to measurements collected from 15 weather stations managed by China Meteorological Administration (CMA) (Hu et al., 2011). Alpine grassland and loamy soil dominate the land cover and soil types, both of which cover more than 85% of the SRYR basin size, and the coverages of glaciers and lakes are about 1.01% (Zhang et al., 2013).

The SRYZ consists of an area of 137,700 km^2 above the Zhimenda discharge station comprising 7.6% of the total area of the Yangtze River basin, while contributing to about 1.33% of the total streamflow (Zhang et al., 2013). The annual average daily temperature varies between −2 °C and −5 °C from east to west, and the mean annual precipitation ranges from 520 mm to 290 mm, whereby the snowfall accounts for about 10% of the annual precipitation according to measurements taken from 9 CMA managed weather stations (Du et al., 2017). The dominant land cover is alpine grassland and shrubland, both of which cover more than 90% of the SRYZ basin area, and the coverages of glaciers and lakes are about 0.95%. Loamy soil covers more than 90% of the region as well (Zhang et al., 2013). For this study, the monthly discharge measurements collected at the Chinese Ministry of Water Resources managed Zhimenda and Tangnag stations are available for the periods of 1984–2009 and 1984–2005, respectively.

3. Methods

3.1. Noah land surface model and augmentations

The Noah LSM has a long history of development (Chen et al., 1996; Schaake et al., 1996; Koren et al., 1999; Ek et al., 2003) and has been largely adopted by the land surface modeling community to quantify water and energy exchanges between land and atmosphere and generate global products (Xia et al., 2014, 2015). The model structure represents the entire land surface system as a single water/energy source, for which the surface water and energy cycles are calculated. The evapotranspiration is computed with an atmospheric stability-dependent Penman method associated with a simple canopy parameterization that quantifies the transpiration (Chen et al., 1996), and the runoff is simulated using the water balance method (Schaake et al., 1996). The model implements a 2 m column with four-layer (i.e., 0–0.1, 0.1–0.4, 0.4–1.0, 1.0–2.0 m) soil scheme to simulate water and heat flows, and gravitational free drainage is assumed as bottom boundary condition. Koren et al. (1999) further included the cold season physics like freeze-thaw and snow processes in the model structure.

The Noah LSM has recently been thoroughly investigated and enhanced to better represent the water and energy exchange processes for an eastern Tibetan ecosystem (Zheng et al., 2014, 2015a,b, 2016). A scheme of diurnally varying thermal roughness length for heat transfer has been implemented to ameliorate soil temperature and turbulent heat flux simulations. The vertical soil heterogeneity associated with the root system and organic matter has been incorporated into the model to improve the simulations of soil heat and water transport (Zheng et al., 2015a,b). The parameterization of frozen ground permeability has been updated to increase water flow (e.g. infiltration and drainage) in case soil ice exists. Zheng et al. (2016) thoroughly investigated the above augmentations and demonstrated the model's skill in simulating runoff at catchment scale. Hence, the augmented Noah LSM is adopted for this study, and Appendix A provides a detailed description of the model physics associated with the freeze-thaw and snow processes. Readers are referred to existing literature (e.g., Ek et al., 2003; Zheng et al., 2015a,b, 2016, 2017b) for additional information.

3.2. Experimental design and model implementation

The meteorological inputs for driving the Noah LSM are produced by the Institute of Tibetan Plateau Research, Chinese Academy of