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Historical and future changes of frozen ground in the upper Yellow River Basin

Taihua Wang[a], Dawen Yang[a,*], Yue Qin[a], Yuhan Wang[a], Yun Chen[b], Bing Gao[c], Hanbo Yang[a]

[a] State Key Laboratory of Hydroscience and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China
[b] National Meteorological Center, China Meteorological Administration, Beijing 100081, China
[c] School of Water Resources and Environment, China University of Geosciences, Beijing 100083, China

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ABSTRACT

Frozen ground degradation resulting from climate warming on the Tibetan Plateau has aroused wide concern in recent years. In this study, the maximum thickness of seasonally frozen ground (MTSFG) is estimated by the Stefan equation, which is validated using long-term frozen depth observations. The permafrost distribution is estimated by the temperature at the top of permafrost (TTOP) model, which is validated using borehole observations. The two models are applied to the upper Yellow River Basin (UYRB) for analyzing the spatio-temporal changes in frozen ground. The simulated results show that the areal mean MTSFG in the UYRB decreased by 3.47 cm/10 a during 1965–2014, and that approximately 23% of the permafrost in the UYRB degraded to seasonally frozen ground during the past 50 years. Using the climate data simulated by 5 General Circulation Models (GCMs) under the Representative Concentration Pathway (RCP) 4.5, the areal mean MTSFG is projected to decrease by 1.69 to 3.07 cm/10 a during 2015–2050, and approximately 40% of the permafrost in 1991–2010 is projected to degrade into seasonally frozen ground in 2031–2050. This study provides a framework to estimate the long-term changes in frozen ground based on a combination of multi-source observations at the basin scale, and this framework can be applied to other areas of the Tibetan Plateau. The estimates of frozen ground changes could provide a scientific basis for water resource management and ecological protection under the projected future climate changes in headwater regions on the Tibetan Plateau.

1. Introduction

Frozen ground is an important component of the cryosphere and is vulnerable to climate warming; thus, it can serve as a sensitive indicator of climate change (Vaughan et al., 2013). Previous studies have reported that permafrost degradation is manifested by increases in the active layer thickness (ALT) and decreases in the areal extent (Frauenfeld, 2004; Li et al., 2008; Park et al., 2013; Wu et al., 2015; Luo et al., 2016), and this degradation profoundly impacts hydrological and ecological processes in high-latitude regions and alpine cold regions (Liu et al., 2011; Bense et al., 2012; Chen et al., 2012; Liu and Wang, 2012; Hayashi, 2013; Walvoord and Kurylyk, 2016; Y. Zhang et al., 2016). Similarly, the freeze-thaw cycle and thermal regimes of seasonally frozen ground are also undergoing considerable changes (Jin et al., 2015; K. Wang et al., 2015; Peng et al., 2016). Long-term changes in the maximum thickness of seasonally frozen ground (MTSFG) reflect changes in air temperature as well as the comprehensive effects of temperature seasonality, precipitation, land surface conditions and site-specific soil properties (Frauenfeld and Zhang, 2011; Peng et al., 2017). Although seasonally frozen ground is more widely distributed than permafrost (Zhang et al., 2003), long-term observations in regions with seasonally frozen ground remain limited, and the historical and potential future shifts in the soil thermal regime of seasonally frozen ground regions remain poorly understood.

The Tibetan Plateau (TP), also known as the third pole of the globe, has the largest area of alpine permafrost in the world (Qiu, 2008; Immerzeel et al., 2010; Cuo et al., 2015). Almost all of the TP is underlain by permafrost and seasonally frozen ground because of its high elevation (Guo and Wang, 2013). The source regions of several large Asian rivers, including the Yellow River, which is the second largest river in China (Hu et al., 2011), are located on the TP. Several studies have reported the degradation of frozen soil in the upper Yellow River Basin (UYRB), including an upward shift in the permafrost lower limit, shifts in the discontinuous/continuous permafrost boundary, and a decrease in the MTSFG at the point scale (Jin et al., 2009; Fang et al., 2011). These changes could generate complex interactions with wetland shrinkage, vegetation degradation and other ecohydrological changes resulting from climate change (Cheng and Wu, 2007; Jin et al.,

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* Corresponding author.
E-mail address: yangdw@tsinghua.edu.cn (D. Yang).

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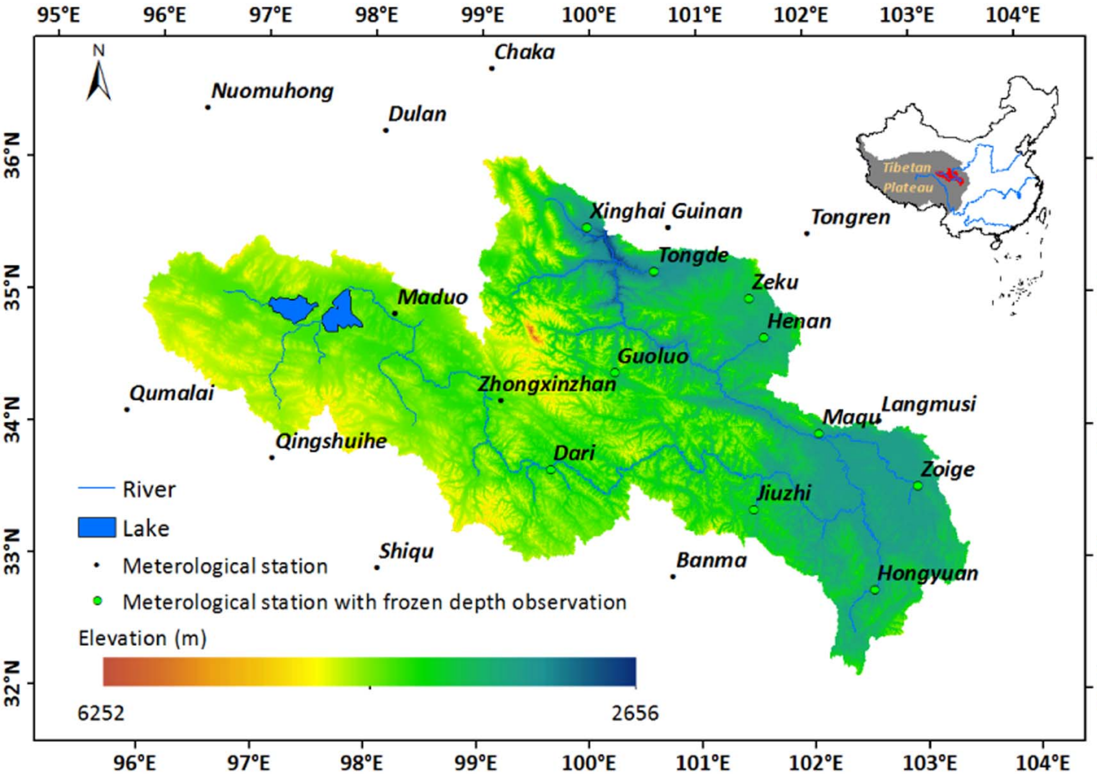

Fig. 1. Study area and locations of the meteorological stations. Ten stations have frozen depth records.

2009; Yang et al., 2010; Cuo et al., 2013; W.J. Zhang et al., 2016). Most of the previous studies focusing on changes in the frozen ground on the TP are based on point-scale borehole observations (Wu and Zhang, 2010; Xie et al., 2012; Wu et al., 2015), and few studies have focused on changes in frozen ground at the regional or catchment scale (Pang et al., 2011; Qin et al., 2016; Xu et al., 2016). Although several studies have predicted future changes in the frozen ground of the TP, they have only focused on changes in the permafrost (Nan et al., 2005; Pang et al., 2011; Guo et al., 2012), and none have projected long-term changes in regions with seasonally frozen ground.

Traditional frozen ground studies have only relied on in situ observations; however, due to the harsh climate in frozen ground regions, in situ observations are hard to obtain, very expensive, and usually restricted to the point scale (Zhang et al., 2005; Frauenfeld and Zhang, 2011; Wu et al., 2015). Therefore, freeze-thaw models can complement in situ observations, and this combination can be used to obtain long-term and spatially continuous frozen ground information at a larger scale if proper input data and parameterization methods are used (Riseborough et al., 2008; Walvoord and Kurylyk, 2016). The commonly used soil freeze-thaw models can be categorized into 2 groups: (1) analytical solution models and (2) numerical method models (Walvoord and Kurylyk, 2016). Numerical models that incorporate numerical solution schemes, such as finite element and finite difference methods, are usually more accurate in simulating ground freeze-thaw cycles if they are properly parameterized (Y.S. Zhang et al., 2008; Li et al., 2010). Nevertheless, accurate results are only obtained when a greater number of parameters are included, which requires more data input and leads to greater computational complexity (Walvoord and Kurylyk, 2016). Analytical algorithms based on certain assumptions can achieve considerable computational savings for simulations at large scales and introduce fewer parameters than numerical methods, and these algorithms include the Stefan equation, the Kudryavtsev model, and the temperature at the top of permafrost (TTOP) model (Riseborough et al., 2008; Yin et al., 2016). Due to limited data, many studies used a simplified Stefan equation that only considered the air temperature variability (Zhang et al., 2005; Q.F. Wang et al., 2015; Wu et al., 2015; Peng et al., 2017). The Stefan equation and TTOP model with physically based parameters combining multi-source data based on either ground or remote sensing observations could have the potential to better reflect the spatial variability of frozen ground.

In the headwater regions of major Asian rivers, such as the Yellow River, few studies have focused on the historical and future trends of frozen ground changes. Recently, Qin et al. (2017) used a process-based model GBEHM to simulate the frozen ground change in the UYRB, and they focused on the impacts of climate warming and consequent frozen ground changes on ecohydrology during 1981–2015. Our study uses two analytical algorithms, the Stefan equation and TTOP model, which call for fewer parameters and less computational complexity, and focuses on the long-term frozen ground changes in the UYRB both in the past (1965–2014) and in the future (2015–2050). The objectives of this study are to (1) test and verify the applicability of the Stefan equation and the TTOP model with physically based parameters, which may also be useful in the headwater regions of other major rivers originating from the TP; (2) understand the long-term changes and spatial variability in frozen ground over the past 50 years in the UYRB; and (3) project the response of frozen ground to future climate change in the UYRB.

2. Study area and data

2.1. Study area

The UYRB is located in the transitional zone between seasonally frozen ground and discontinuous and continuous permafrost on the northeastern TP (Jin et al., 2009). In this study, the UYRB refers to the catchment upstream of the Tangnaihai hydrological station, and it covers an area of 122,000 km^2 that accounts for 16% of the total area of the Yellow River Basin and yields 35% of the total runoff of the Yellow River (Hu et al., 2011). The elevation of the UYRB ranges from 2656 m to 6350 m (Fig. 1) and mainly decreases from southwest to northeast. A