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Difference between near-surface air, land surface and ground surface temperatures and their influences on the frozen ground on the Qinghai-Tibet Plateau

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ABSTRACT

Surface temperature is critical for the simulation of climate change impacts on the ecology, environment, and particularly permafrost in the cryosphere. Virtually, surface temperatures are different in the near-surface air temperature (T_a) measured at a screen-height of 1.5–2 m, the land surface temperature (*LST*) on the top canopy layer, and the ground surface temperature (*GST*) 0–5 cm beneath the surface cover. However, not enough attention has been concentrated on the difference in these surface temperatures. This study aims at quantifying the distinction of surface temperatures by the comparisons and numerical simulations of observational field data collected in a discontinuous permafrost region on the northeastern Qinghai-Tibet Plateau (QTP). We compared the hourly, seasonal and yearly differences between T_a, *LST*, *GST*, and ground temperatures, as well as the freezing and thawing indices, the *N*-factors, and the surface and thermal offsets derived from these temperatures. The results showed that the peak hourly *LST* was reached earliest, closely followed by the hourly T_a. Mean annual *LST* (*MALST*) was moderately comparable to mean annual T_a (*MAAT*), and both were lower than mean annual *GST* (*MAGST*). Surface offsets (*MAGST-MAAT*) were all within 3.5 °C, which are somewhat consistent with other parts of the QTP but smaller than those in the Arctic and Subarctic regions with dense vegetation and thick, long-duration snow cover. Thermal offsets, the mean annual differences between the ground surface and the permafrost surface, were within − 0.3 °C, and one site was even reversed, which may be relevant to equally thawed to frozen thermal conductivities of the soils. Even with identical T_a (comparable to *MAAT* of − 3.27 and − 3.17 °C), the freezing and thawing processes of the active layer were distinctly different, due to the complex influence of surface characteristics and soil textures. Furthermore, we employed the Geophysical Institute Permafrost Lab (GIPL) model to numerically simulate the dynamics of ground temperature driven by T_a, *LST*, and *GST*, respectively. Simulated results demonstrated that *GST* was a reliable driving indicator for the thermal regime of frozen ground, even if no thermal effects of surface characteristics were taken into account. However, great biases of mean annual ground temperatures, being as large as 3 °C, were induced on the basis of simulations with *LST* and T_a when the thermal effect of surface characteristics was neglected. We conclude that quantitative calculation of the thermal effect of surface characteristics on *GST* is indispensable for the permafrost simulations based on the T_a datasets and the *LST* products that derived from thermal infrared remote sensing.

1. Introduction

The research on the permafrost-climate relationship has received extensive and continuous attention since the establishment of geocryology (Yershov, 2004; Zhou et al., 2000). It aims at quantifying the combined interplay of macroscopic factors and the local surface characteristics on the thermal regime of the active layer and permafrost. The macroscopic factors generally consist of climatological and geographical elements, including latitude, elevation, the contrast of ocean-land distribution, general atmospheric circulations, and so forth (Zhang et al., 2008). These factors radically determine the geographical distribution of the magnitude and amount of solar radiation balance on the globe. The local surface characteristics primarily consist of microtopography, surface cover that contains vegetation and snow cover, local hydrology and lithology, and so on (Cheng, 2004). These factors in combination result in a complex energy exchange on the ground

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surface, which characterizes the temperature regime and freezing/thawing processes of the ground and the heterogeneity of the occurrence of permafrost.

It is generally believed that permafrost originates and is retained only when the mean annual surface temperature is below 0 °C (Muller et al., 2008), while exactly what threshold is adopted for delineating the continuous, discontinuous, sporadic or isolated permafrost varies globally and regionally (Smith and Riseborough, 2002; Zhou et al., 2000). During the past several decades, especially with the recent prevalence of employing the near-surface air temperature (T_a) datasets from the reanalysis datasets and the land surface temperature (*LST*) products from thermal infrared remote sensing, surface temperatures are increasingly used alone or incorporated together with other factors to correlate or simulate the areal distribution and dynamics of permafrost. However, there is little emphasis among the geocryological communities on the distinction of surface temperatures and the varied simulation results driven by contrasting surface temperatures, which may lead to great bias compared to the reality. Overall, there are three kinds of surface temperatures related to the thermal regime of permafrost: the T_a measured at a screen-height of 1.5–2.0m above the ground surface, the ground surface temperature (*GST*) 0–5 cm beneath the surface cover, and the *LST* at the top of the surface cover. Obviously, these three surface temperatures are very different though connected closely to each other through the complex heat exchange processes at the ground surface.

T_a has a long history of being applied to represent the thermal state of permafrost (Yershov, 2004; Zhou et al., 2000). Different mean annual T_a (*MAAT*) and its vertical lapse rate have been employed to detect the spatial distribution of permafrost and to diagnose the response of permafrost to climate change, either regionally or globally (*e.g.*, Cheng et al., 2012; Førland et al., 2004; Gruber, 2012). The reason why different *MAAT* isotherms are employed to delineate the continuity of permafrost is the thermal effect of surface characteristics and substrates (Cheng, 2004; Smith and Riseborough, 2002). *MAAT* is only one of the important factors influencing the existence and dynamic of permafrost (Muller et al., 2008). The proxy of *MAAT* indicating the occurrence of permafrost should also be taken into full consideration cautiously because of other key factors, such as the snow cover and vegetation at local scales.

GST is measured at the atmosphere-lithosphere interface and is not substantially influenced by wind and shortwave radiation. Due to the thermal effects of all canopy elements, mean annual *GST* (*MAGST*) varies with a wide range within a short distance, even though the *MAAT* is identical (Hasler et al., 2015; Smith, 1975). Thermal influences of these factors on a yearly basis are manifested as the surface offset, the difference between the *MAAT* and the *MAGST* (Smith and Riseborough, 2002). Recently, the field investigation of permafrost assisted by monitoring of *GST* with inexpensive miniature data loggers has been increasing greatly in mountainous areas (*e.g.*, Etzelmüller, 2013; Hasler et al., 2015).

The land surface or skin temperature is assumedly regarded as the temperature coming from the top canopy layer (Bense et al., 2016). *LST* has been successfully retrieved from the satellite-infrared sensors such as the Advanced Very High-resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard satellites. A methodological approach that fits a sinusoidal model over the daily product is usually adopted to smooth the temporal average of *LST* (Tedesco, 2015). This facilitates the investigation of mountainous permafrost, especially for sparsely and unevenly monitored remote areas (Hachem et al., 2009; Ran et al., 2015). However, in comparison to the difference between *GST* and T_a, the difference between *GST* and *LST* result not only from the influence of the soil/litter layer and surface characteristics but also from the periodicity of shortwave radiation emitted by the sun. Therefore, a significant deviation or bias could be brought when using the *LST* products, due to the insufficient consideration of the buffering effects of vegetation, snow cover, and upper soil layers (Tedesco, 2015).

The ground surface is considered to be a thermal boundary, in addition to a physical boundary of permafrost, on which complex heat and water exchange occurs between the atmosphere and lithosphere (Riseborough et al., 2008; Smith and Riseborough, 2002). The complex interplay between *GST* and T_a is simplified as surface offset and N-factors (Lunardini, 1978; Riseborough et al., 2008). *N*-factors are the ratios between the ground surface freezing index (or thawing index) and air freezing index (or thawing index), which is fundamental to physical or empirical permafrost models (Riseborough et al., 2008). Studies showed that the incorporation of *N*-factors in a standard solution for thaw depth significantly improved the estimation of the active layer thickness (*ALT*) throughout the study areas (Karunaratne and Burn, 2004). However, a number of model practices, especially when applied in vast regions, define the upper boundary conditions with the easily obtained T_a. Moreover, few practices had been conducted to compare the results from different models or simulations based on varied upper boundary conditions. Therefore, there is a pressing need that the surface temperatures undergo an inspection of comparisons before being applied at a finer or local scale.

The Qinghai-Tibet Plateau (QTP) is well known as "the roof of the world" and "the Third Pole", due to its average altitude exceeding 4000 m above sea level. It is the most vastly distributed elevational permafrost not only at the mid-latitudes but also in the world (Zhou et al., 2000). However, the inhospitable and frigid weather, poor logistical accommodations, and unfavorable transportation conditions confine extensive field investigations of the permafrost. Therefore, the exploration of the quantitative relationship between the surface temperatures and ground temperatures are expected to be employed prior to modeling the spatial distribution and temporal dynamic of permafrost. In this study, we aim at comparing the difference in surface temperatures and providing some implications for simulating ground temperature, further contributing to the quantitatively accurate mapping of permafrost in the rugged topographical environments of the QTP.

2. Materials and methodologies

2.1. Study region

The study region is located in the central part of the source area of the Yellow River (SAYR), northeastern QTP (Fig. 1). The SAYR encompasses a catchment area above Duoshixia (34°34.7′ N, 98°19.5′ E, 41,97 m) along the Yellow River (Jin et al., 2009). As it is located at the fringe of predominantly continuous northeastern QTP and a mosaic transition zone of the discontinuous, sporadic, and isolated permafrost and the seasonally frozen ground, the permafrost in the SAYR is warm and thin. Elevation rapidly increases northwards to 4600 m on the Buqing Mountains and southwards to 5000 m on the Bayan Har Mountains from the central floodplains, where the altitudes are generally within 4350 m. Elevation appears to be the leading factor that controls the spatial differentiation of permafrost. A rapid increase in permafrost temperature was observed with the decrease in elevation on the north slope of the Bayan Har Mountain, until the moderately large area of the seasonally frozen ground with occasionally isolated permafrost in the river valleys and basins. Previous studies showed that permafrost is characterized by the temperature at the depth of zero annual amplitude decreased at a vertical lapse rate of 6 °C/km on the north slope of the Bayan Har Mountains (Luo et al., 2013). In the intermontane depressions and basins at the elevation ranging from 4300 m to 4600 m; however, permafrost temperature varies greatly within a small spatial distance (Li et al., 2016). At a local scale, soil moisture content, surface hydrology, and soil texture together play a decisive role in controlling the thermal regime of permafrost. In this way, the relationship between permafrost and climate is rather complicated.