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Characteristics of the ratios of snow, rain and sleet to precipitation on the Qinghai-Tibet Plateau during 1961–2014

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A B S T R A C T

Precipitation in different types has great influence not only on water resources and distribution of annual precipitation in cold regions, but also on the thermal regimes of frozen ground. The long-term variations of the ratios of snow, rain and sleet to precipitation were analyzed in this study. The 44 meteorological stations were selected, which are located on the Qinghai-Tibet Plateau (QTP) including permafrost and seasonal frozen ground regions. The results indicate that the monthly snow/precipitation ratio in permafrost regions is far higher than that in seasonal frozen ground regions, but the monthly rain/precipitation ratio in permafrost regions is lower than that in seasonal frozen ground regions, and the monthly variation of sleet/precipitation ratio is indistinctive. The annual ratios of snow and sleet to precipitation show decreasing trends in both regions, and annual rain/precipitation ratio shows an increasing tendency. The dropping magnitude of annual snow/precipitation ratio in seasonal frozen ground regions is larger than that in permafrost regions. The maximum and minimum annual snow/precipitation ratios in both regions occur in winter and summer, respectively, and the second is in spring, instead, the maximum and minimum annual rain/precipitation ratios appear in summer and winter, respectively. The spatial features of the ratios of snow and rain to precipitation are largely opposite, that is, the low snow/precipitation ratio stations are usually associated with the high rain/precipitation ratio, and prominent seasonal diversities of three ratios can be found from their spatial patterns. In addition, the decreasing (increasing) tendency of snow (rain)/precipitation ratio in spring and autumn is more significant than that in winter and summer, and these stations of snow/precipitation ratio with downward trends are mainly located at the edge of the QTP. The ratios of snow and sleet to precipitation will gradually decrease (increase), and the rain/precipitation ratio will increase (decrease) with the air temperature (altitude) rises, respectively, while there are significant seasonal discrepancies. Moreover, the altitude zone showing remarkable variations of the ratios of snow and rain to precipitation ranges from 3000 to 4000 m a.s.l, especially in spring and summer.

1. Introduction

Precipitation is a key meteorological factor, and it is an important part of water cycle as well (Joshi and Pandey, 2011; Trenberth, 2011). Regional water resources and distribution of annual precipitation are also influenced by different precipitation types (mainly snow, rain and sleet) to some extent, and the transformation of precipitation types from solid to liquid will immediately cause the spring runoff timing to advance and summer water resources to reduce (Hodgkins et al., 2002). Therefore, it is vital to investigate the variation characteristics of precipitation in different types, particularly the ratios of snow, rain and sleet to precipitation. At present, some studies focusing on snow/precipitation ratio are more than other two ratios, their results indicate that the snow/precipitation ratio has a decreasing trend in different regions. In the central United States and Pacific Northwest, the maximum dropping magnitude of the snow/precipitation ratio appears in March, and winter snowfall is a crucial factor on the

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decreasing tendency, but the influence of winter precipitation is weak (Feng and Hu, 2007). In winter, The decreasing trend of snow/precipitation ratio in New England is closely related to the Pacific North American index and the North Atlantic Oscillation index (Huntington et al., 2004). Under the scenarios of global climate change, if air temperature doesn't exceed the freezing point, precipitation types won't be influenced and altered (Knowles et al., 2006). What is more, the ratio of snowfall days to precipitation days can also be obtained. Under the influence of air temperature, the winter and spring ratios of snowfall days to precipitation days in Switzerland show prominent downward trends, and the decreasing magnitude is larger in lower altitude regions, where air temperature is closer to the melting point (Serquet et al., 2011). Moreover, the snowfall days in the central and western Spanish Pyrenees are usually influenced by the distance to sea, the altitude, and the frequency of weather types (Buisan et al., 2015). Guo and Li (2014) revealed the snow/precipitation ratio in Tien Shan Mountains, China exhibits a decreasing tendency owing to the increasing magnitude of precipitation is larger than snowfall, and prominent differences of change magnitude exist in different altitude zones. Between the regions whose elevation range from 1500 to 2500 m a.s.l, the decreasing tendency is quite pronounced, whereas it is indistinctive above 3500 m a.s.l by reason of the air temperature is below freezing point.

The QTP is sensitive to the climate change owing to its unique geographic position and geomorphic type, and its high altitude and cold climate are conductive to the existence and growth of frozen ground (Pan and Li, 1996; Wu et al., 2005; Schwalb et al., 2010). The plateau frozen ground is an important underlying surface feature, and it is a sensitive indicator of climate change as well (Pavlov, 1994; Wu et al., 2013; Gao et al., 2015). Frozen ground acts as a vital role in the cryosphere, and precipitation in different types, as the primary recharge resources of different water bodies (Jiang et al., 2013; Li et al., 2014), will affect the land surface water and heat balance in frozen ground regions, thus the existence of frozen ground will be altered to some extent. Significant regional and seasonal variation characteristics of precipitation can directly influence the surface vegetation condition on the QTP (You et al., 2012; Gao et al., 2014), and there is complex relationship between precipitation and the frozen ground distribution (Qiu and Cheng, 1995; Salerno et al., 2014; Kokelj et al., 2015), particularly the different precipitation types. Snowfall in winter and spring could restrict the soil freezing, while in summer and autumn, it contributes to preserving frozen ground. Rainfall is one of the most important factors which exert on the thermal-moisture dynamics of active layer. When the rainfall events occur in permafrost regions, the latent heat flux will increase, and the surface net radiation and sensible heat flux will decrease, particularly the decreasing magnitude will be more prominent when the snow cover exists in ground surface (Sun et al., 2014). In summer, continuous rainfall events could change the ground surface energy balance in frozen ground regions, and cause soil moisture to increase and subsurface soil temperature to decrease (Wen et al., 2014); but in winter, the heavy rainfall events will have strong and on-going influences on ground surface temperature because the ground surface is covered by snow cover (Westermann et al., 2011). The QTP is the predominant snow cover region in the mainland of Eurasia, and specific radiation and thermodynamics properties of snow cover will cause corresponding effects on frozen ground (Ling and Zhang, 2003; Qin et al., 2006).

Currently, some studies of snow and precipitation on the QTP can be easily found, but the long-term variation characteristic of the ratios of snow, rain and sleet to precipitation is rare. Although the snow on the QTP has aroused the wide concern, it is difficult to obtain reliable snow data. Air temperature is only used in most methods for discriminating precipitation types, but their credibility is not good, particularly in some specific regions (Kang and Ohmura, 1994; Lindström et al., 1997; Dai, 2008; Gao et al., 2010). A new scheme for discriminating precipitation types, developed by Ding et al. (2014), contains 6 meteorological indexes, such as altitude, wet bulb temperature and relative humidity, and its accuracy is better than other schemes or models, notably on the QTP. This study aims at investigating the spatial and temporal characteristics of the ratios of snow, rain and sleet to precipitation on the QTP during the period from 1961 to 2014, based on the precipitation data of different types acquired by the new scheme, with the purpose of providing useful information for detecting relevant response of frozen ground to climate change and water resources employment or management.

2. Data and methods

2.1. Data sources

According to the principles of data continuity and longer time series, 44 meteorological stations in frozen ground regions of the QTP are selected (Fig. 1). In view of the lower limit of high mountains permafrost regions in the western China agrees well with the annual average air temperature of −2 to −3 °C (Zhou et al., 2000), so these stations that annual average air temperature is under −3 °C are defined as the stations that distributing in permafrost regions, there are 4 of 44 stations distribute in permafrost regions, and other 40 stations are in seasonal frozen ground regions on the basis of this method, stations details are listed in Table 1. The data of daily average air temperature, precipitation, average relative humidity and air temperature are provided by National Meteorological Information Center (NMIC), China Meteorological Administration (CMA) (available at http://data.cma.gov.cn), and the time series is from September 1, 1961 to August 31, 2014. In the meanwhile, the data has suffered strict quality controlling procedures, including extreme value test, time synchronization test and homogenization test.

In this study, the scheme for discriminating precipitation types in the literature of Ding et al. (2014) is applied to obtain the daily data of snowfall, rainfall and sleet. The period from September 1 to August 31 next year is defined as a snowfall year, for example, the snowfall year in 1961 is from September 1, 1961 to August 31, 1962.

2.2. Method

2.2.1. The scheme for discriminating precipitation types

Most schemes or models for discriminating precipitation types are predominantly dependent on the single meteorological index (air temperature); but their reliabilities or accuracies are poor in some specific regions. Through analyzing the correlation between precipitation types and primary meteorological indexes, Ding et al. (2014) found precipitation types are not only dependent on air temperature, and wet bulb temperature, relative humidity and altitude are crucial factors as well. In the meantime, a new scheme for discriminating precipitation types based on multi-meteorological indexes was developed, and its availability evaluation report in different regions of China indicated that it is more reliable and accurate than other 11 mainstream schemes, which the reliability on the QTP is the best. Consequently, this scheme is used to discriminate precipitation types in this study, and details about its computing process are shown as follows:

In view of good relationship between precipitation types and wet-bulb temperature (T_w), two key threshold temperatures (T_{max} and T_{min}) are introduced and regarded as the optimal thresholds of daily mean wet-bulb temperature in the scheme for discriminating

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