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Temperature and precipitation changes over the Loess Plateau between 1961 and 2011, based on high-density gauge observations

Qiaohong Sun [a,b], Chiyuan Miao [a,b,*], Qingyun Duan [a,b], Yafeng Wang [c]

[a] State Key Laboratory of Earth Surface Processes and Resource Ecology, College of Global Change and Earth System Science, Beijing Normal University, Beijing 100875, PR China
[b] Joint Center for Global Change Studies, Beijing 100875, PR China
[c] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-environmental Sciences, Chinese Academy of Sciences, P.O. Box 2871, Beijing 100085, PR China

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ABSTRACT

The Loess Plateau has the most serious soil erosion in China and is the main source of sediment in the Yellow River. In this study, we systematically analyzed the changes in the mean and extreme values for temperature and precipitation over the Loess Plateau between 1961 and 2011, using a gridded dataset with high-density gauge data. Statistically significant positive trends ($p < 0.05$) in the mean, maximum, and minimum temperature values (TM, TX, and TN) were identified in almost all regions. Warming rates increased from the southeast to the northwest of the Loess Plateau for both TM and TN; however, for TX, the greatest warming increases were observed in the southeast region. We also found general decreases in the diurnal temperature range and the number of cold nights and cold days, and increases in the length of the growing season and the number of warm days and warm nights. Moreover, relatively intense changes occurred in the high percentile ranges for both TX and TN. The total amount of precipitation on wet days decreased over a large area of the Loess Plateau, particularly in the southeast region. The inequality in the spread of precipitation over the year (temporal inequality) increased extensively over the past fifty years in the wet region. Approximately 37.60% of the total area with a reduced amount of precipitation had concurrent decreases in both the frequency and intensity of rainfall. However, approximately 37.20% of the area with a reduced amount of precipitation had decreases in the frequency but increases in the intensity of rainfall. The proportion of days with light or moderate precipitation was decreased in the wet region which mainly located in the southwest of the Loess Plateau, but there were only minor changes in extreme precipitation events. Overall, when both temperature and precipitation changes were combined, we observed that the southwest of the Loess Plateau has undergone the largest degree of climate change. Consequently, both the ecological environment and local agriculture on the Loess Plateau will suffer increased challenges: the decline in water availability will lead to more frequent droughts, yet the risk of flood and soil erosion from extreme precipitation events will not be reduced.

1. Introduction

The Loess Plateau (35–41°N, 102–114°E) is situated in the upper and middle reaches of the Yellow River in the People's Republic of China, and covers a total area of about 628,000 km^2 (Fig. 1). This region has a distinctive landscape where the main geomorphic landforms are "yuan" (cliff-edged plains), ridges, hills, and gullies of various sizes (Wang et al., 2011a). Most of the Loess Plateau is covered by loess deposits ranging from 30 m to 80 m in thickness; loess is a highly erosion-prone soil that is susceptible to the forces of wind and water (Chen et al., 2008; Wang et al., 2010). The Loess Plateau generally has a sub-humid and semi-arid climate, with extensive monsoonal influence (Chen et al., 2014). The average annual precipitation ranges from 200 mm in the northwest to 750 mm in the southeast, and the rainy season (June–September) accounts for 60% to 70% of the total precipitation (Li et al., 2012; Gao et al., 2014). Rainfall is mainly from high-intensity storms (Wang et al., 2012). The combined effects of frequent heavy rainfall, steeply sloping landscapes, low vegetation cover, and highly erodible soils have made the Loess Plateau one of the most seriously eroded areas in the world, with an average annual soil loss of 2000 to 2500 t/km^2 (Shi and Shao, 2000). The Loess Plateau is the main source of sediment in the Yellow River, and the amount of earth and sand flowing out from the Loess Plateau to the Yellow River can reach 1.6 billion tons/year (Wang et al., 2015). Soil loss from the Loess Plateau constitutes more than 90% of the total sediment entering the Yellow River (Chen et al., 2007).

With global warming, many regions have experienced changes in both the mean climate and climate extremes (Gao et al., 2013; Miao et al., 2013; Sun et al., 2014). A changing climate can lead to changes

* Corresponding author at: State Key Laboratory of Earth Surface Processes and Resource Ecology, College of Global Change and Earth System Science, Beijing Normal University, Beijing 100875, PR China. Tel./fax: +86 10 58804191.
E-mail address: miaocy@vip.sina.com (C. Miao).

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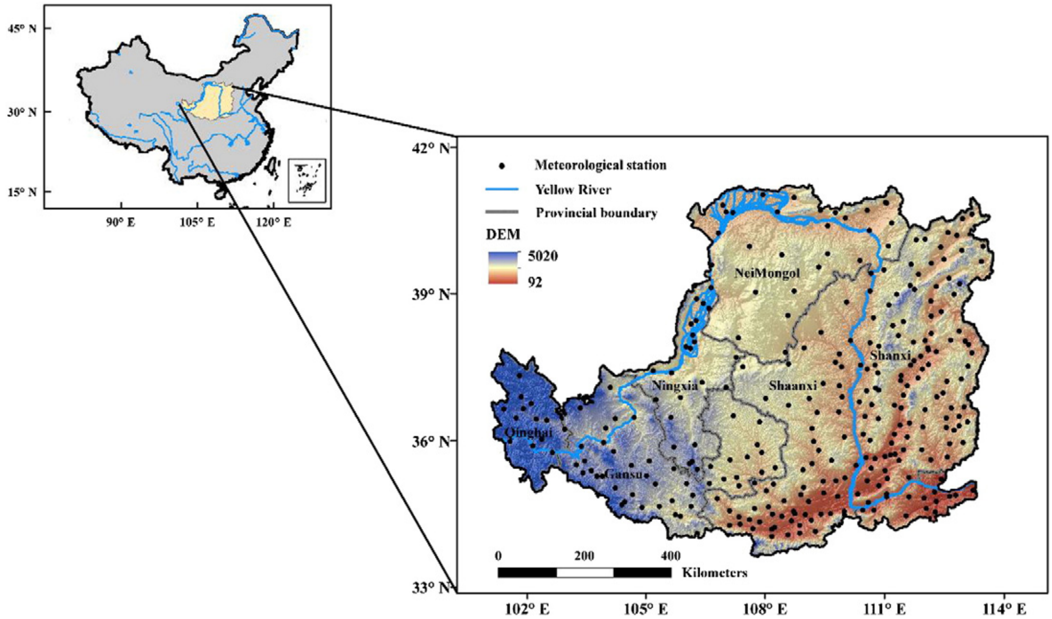

Fig. 1. Location of the Loess Plateau and the meteorological stations.

in the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events, and can result in unprecedented extreme climate events (IPCC, 2012). The Loess Plateau has a fragile ecological environment and is sensitive to climate change. Climate change can therefore affect soil erosion, water resources, and ecosystems on the Loess Plateau. For instance, changes in precipitation, especially in extreme precipitation events, would have an impact on soil erosion because most of the soil loss and environmental damage in this region is caused by infrequent but severe storms (Kang et al., 2001; Zhang and Liu, 2005; Li et al., 2011). In addition, growth of vegetation and crops is sensitive to changes in temperature and precipitation (Zhang and Nearing, 2005; Asseng et al., 2014). Previous studies have revealed that the observed decreases in runoff and sediment loss from the Loess Plateau to the Yellow River are partly due to a decrease in precipitation over the Loess Plateau (Wang et al., 2007; Miao et al., 2011; Kong et al., 2015). The planting boundary of some crops would move northward to higher latitudes and some plants may grow at higher altitudes owing to the climate warming (Li et al., 2013). The risk of crop diseases and pests would increase as a result of climate change (Piao et al., 2010). It is therefore urgent to analyze in detail how the climate on the Loess Plateau has changed in recent decades.

Several existing studies have examined the changes in temperature and precipitation on the Loess Plateau over recent decades. Several studies found that the region-averaged annual mean temperature on the Loess Plateau increased significantly over the last fifty years, whereas the region-averaged annual precipitation showed a non-significant negative trend (Bi et al., 2009; Wang et al., 2012). In terms of climate extremes, trends in the hot-day threshold (maximum temperature 90th percentile — the 10th hottest day per season), the cold-night threshold (minimum temperature 10th percentile — the 10th coldest night per season), and the longest heatwave (maximum number of consecutive days with maximum temperature > long-term 90th percentile for each calendar day) have increased over the period 1961 to 2007, whereas the number of frost days has decreased (Li et al., 2010). Indices for extreme precipitation, such as the heavy rainfall threshold, the number of days with heavy rainfall, and the number of days with erosive rainfall (R12mm), were spatially distributed and decreased from the southeast to the northwest (Li et al., 2010; Wang et al., 2011a).

However, there are several factors that necessitate further analysis. First, these preexisting studies generally focused only on mean temperatures and precipitation or only on few indices for climate extremes. Few studies have examined the changes in climate means and extremes synchronously over the Loess Plateau. Second, the previous studies mainly focused on changes in precipitation amount or frequency but ignored other features, such as intensity, duration, and type of precipitation. Moreover, questions remain as to whether changes in frequency or changes in intensity of rainfall contribute most to changes in the total precipitation amount. Third, owing to the distinctive climate on the Loess Plateau, with a well-defined rainy season and dry winters, the distribution of precipitation across the year tends to be very uneven. This temporal inequality in precipitation plays a significant role in the soil erosion, flow of water, and overall ecosystem on the Loess Plateau, but few studies have quantified it. Fourth, most previous studies focused only on the whole trends in precipitation and temperature, and dismissed the comparisons of dissimilar trends over the different periods. Taking more climate variables into consideration will be useful for determining the areas that are most sensitive to climate change. Furthermore, in previous studies, relatively few stations were used to study the climate on the Loess Plateau. Considering the complex topography and climate on the Loess Plateau, a dataset with dense meteorological data is needed to provide more accurate information about climate changes in this region.

Therefore, the objectives of this study are as follows: (1) to present an overview of the changes in mean and extreme climate over the Loess Plateau using gridded datasets with high-density data from meteorological stations; (2) to investigate the spatial patterns and temporal inequality in precipitation over the course of a year; and (3) to determine the dissimilarities in climate between past and recent decades.

2. Data and methods

2.1. Data

The observed daily precipitation (PR) datasets were taken from a gauge-based daily precipitation analysis on a 0.5° × 0.5° grid (Shen et al., 2010). The daily mean temperatures (TM), maximum temperatures (TX), and minimum temperatures (TN) were obtained from a surface temperature 0.5° × 0.5° gridded dataset (v2.0) developed by the National Meteorological Information Center of the China Meteorological Administration (National Meteorological Information Center, 2012). The datasets for precipitation and temperature were constructed from approximately 2400 station observations across China, including