Summer soil moisture regulated by precipitation frequency in China

Shilong Piao¹,⁵, Lei Yin², Xuhui Wang¹, Philippe Ciais³, Shushi Peng¹, Zehao Shen¹ and Sonia I Seneviratne⁴

¹ Department of Ecology, College of Environmental Science and Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing 100871, People’s Republic of China
² School of Atmospheric Sciences, Nanjing University, Nanjing 210000, People’s Republic of China
³ LSCE, UMR CEA-CNRS, Batiment 709, CE, L’Orme des Merisiers, F-91191 Gif-sur-Yvette, France
⁴ Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland

E-mail: slpiao@pku.edu.cn

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Abstract
Drought is one of the most important but least understood issues in global environmental changes. Decrease in soil moisture is an indicator of drought. Here, we analyze summer (June–August) soil moisture measurement data across 50 sites in China in order to investigate the linkage between climate change and drought. At the country scale, a significant decrease in summer soil moisture in the top 50 cm was observed during 1981–2002, resulting mainly from the decline in soil moisture in North China. Statistical analyses suggest that changes in precipitation frequency have significant consequences for soil moisture dynamics, but our ability to use precipitation frequency changes to explain the variation of soil moisture depends on the discriminating criteria of precipitation events. Among five criteria (0, 5, 10, 15, and 20 mm day⁻¹), the maximum coefficient of correlation between summer soil moisture in the top 50 cm and precipitation frequency occurs when considering the number of days on which the daily precipitation amount is larger than 10 mm (PF10). Spatially, the correlation between soil moisture in the top 50 cm and PF10 is weak for very dry and very wet soils and is much stronger for intermediate values.

Keywords: soil moisture, drought, precipitation change, precipitation frequency

1. Introduction

As one of the major issues in global environmental changes, drought has attracted widespread attention from both scientists and policy-makers. In the past few decades, terrestrial ecosystems have been experiencing frequent extreme drought events, which have already exerted profound impacts on global economy, food security and terrestrial ecosystems [1–3]. An extreme drought in Europe during 2003, for example, not only led to a crop shortfall (more than 20%) in Southern Europe, but also caused about 0.5 Pg of carbon to be lost from terrestrial ecosystems, which corresponds to four years of net ecosystem carbon sequestration [2]. Moreover, it was also associated with severe heat and resulting health impacts [4], as well as damage to building infrastructure induced by soil subsidence [5]. In recent decades, East Asia has experienced more severe drought events, particularly in Northern China where the longest drought events and an increasing drought area were observed [6, 7]. The calculated Palmer Drought Severity Index (PDSI) shows that most of the dry land in China has experienced a significant decrease in PDSI during the last 50 years [8]. Drought in China had been more serious in the 1960s, late 1970s to early 1980s, and late 1990s to the beginning of this century than in other periods at a country scale.
level [9]. In addition, extreme drought events have been expected to become more frequent and more variable in the future as a result of anthropogenic climate change, but large uncertainties also exist in these projections [10–12]. Hence, there is an urgent need to understand the factors that contribute to drought, in order to more accurately assess future drought and its impact.

Decrease in soil moisture is a drought indicator more particularly associated with agricultural droughts [13]. Thus, direct investigations of the linkage between soil moisture and climate factors aid in finding key factors that control drought. Several factors, such as temperature, precipitation, solar radiation, and atmospheric CO₂ concentration, regulate soil moisture [14]. Among these factors, change in precipitation has been hypothesized to impose a first-order control on variation in soil moisture at seasonal and annual scales [15]. However, the relationship between precipitation change and soil moisture has not been adequately quantified, because most previous studies focused mainly on responses of soil moisture to precipitation amount. Change in precipitation frequency is also one of the most important characteristics in current climate change [10, 12, 16], and has been expected to significantly affect hydrological and carbon cycles [17–19], but very few studies have investigated the influence of precipitation frequency on soil moisture [20] due to the lack of long-term observation data. In this study, we use summer soil moisture measurement data to explore the change in summer soil moisture in China from 1981 to 2002 and its relationships with precipitation through considering both precipitation amount and frequency.

2. Data sets and methods

The soil moisture data for five different layers (0–10, 10–20, 20–30, 30–40, 40–50 cm) with a 10 day interval at 169 soil moisture stations were obtained from the National Meteorological Information Center of the China Meteorological Administration. Summer soil moisture is estimated on the basis of the average of soil moisture data for each 10 day interval during the June to August summer period. For each year at each site, if at least one 10 day interval has no data during the summer period, we did not consider the corresponding year at this site as available. Furthermore, in order to reduce the uncertainties caused by a short period of soil moisture measurement, we only consider stations for which at least 15 years of data are available during the 1981–2002 period. Since the primary objective of this paper is to study the effects of climate change on soil moisture, we also excluded stations irrigated during the study period. As a result, a total of 50 stations were used in our study.

The daily precipitation and temperature data for 833 meteorological stations during the 1981 to 2002 period were acquired from the China Meteorological Administration. Summer precipitation frequency is defined as the number of days on which precipitation exceeded a threshold value. Here, five threshold values (0, 5, 10, 15, and 20 mm day⁻¹) are considered to obtain different precipitation frequencies (PF0, PF5, PF10, PF15, and PF15) corresponding to different precipitation events. For the daily climate data at the soil moisture stations where corresponding daily precipitation and temperature measurement data are not available, we used the daily climate data from the site nearest to the station.

In order to illustrate the linkage between interannual variation in summer soil moisture and that in summer climate factors, such as temperature, the magnitude of precipitation and number of precipitation days, we calculate a standardized variable (or z-score) for each factor (equation (1)):

\[ SM_i(i) = \frac{\sum_{1981}^{2002} SM(i) - \sum_{1981}^{2002} SM(i)_{1981}}{\sqrt{\sum_{1981}^{2002} (SM(i) - \sum_{1981}^{2002} SM(i))}} \]

\[ i = 1981, 1982, \ldots, 2002. \] (1)

SM(i) represents summer soil moisture or climate factors in year i.

3. Results

Figure 1(a) shows interannual variations in average summer soil moisture for different layers across 16 stations (figure 2(a)) where soil moisture data are available every year during the 1981–2002 period. Decreasing trends in summer soil moisture are observed for all five layers during the study period, but different layers differ in the magnitude of the trend and its significance. In general, surface soil moisture presents a more serious drying trend than deep soil moisture during the study period. The largest tendency towards a decrease in soil moisture is found at a depth of 10–20 cm with a magnitude of \(-0.0009 \text{ kg kg}^{-1} \text{ yr}^{-1}\) (or with a relative annual decrease rate of 0.5% yr⁻¹) \((P = 0.051)\), followed by 0–10 cm \((-0.0008 \text{ kg kg}^{-1} \text{ yr}^{-1} \text{ or } 0.4% \text{ yr}^{-1}) \((P = 0.007)\), 20–30 cm \((-0.0006 \text{ kg kg}^{-1} \text{ yr}^{-1} \text{ or } 0.3% \text{ yr}^{-1}) \((P = 0.043)\), 40–50 cm \((-0.0006 \text{ kg kg}^{-1} \text{ yr}^{-1} \text{ or } 0.3% \text{ yr}^{-1}) \((P = 0.06)\), and 30–40 cm \((-0.0003 \text{ kg kg}^{-1} \text{ yr}^{-1} \text{ or } 0.2% \text{ yr}^{-1}) \((P = 0.248)\). Overall, summer soil moisture in the top 50 cm is significantly decreased by \(-0.0007 \text{ kg kg}^{-1} \text{ yr}^{-1} \text{ or } 0.3% \text{ yr}^{-1}) \) from 1981 to 2002 \((P = 0.021)\). If we exclude data for 1981 with the highest soil moisture and for 1982 with the lowest soil moisture, the decreasing trend in soil moisture for all layers becomes more significant \((P < 0.02)\).

Figure 1(b) shows the interannual variations in the standardized variable of average summer soil moisture in the top 0.5 m, precipitation amount, precipitation frequency and temperature over 16 stations where soil moisture data are available every year during the period of 1981–2002. PF0 (number of days on which precipitation exceeded 0 mm day⁻¹) is significantly decreased with a magnitude of \(-0.4 \text{ days yr}^{-1} \) \((R = -0.70, P < 0.001)\), while a marginal decreasing trend is observed in PF5 (number of days on which precipitation exceeded 5 mm day⁻¹) and PF10 (number of days on which precipitation exceeded 10 mm day⁻¹; \(R = -0.41, P = 0.06\); \(R = -0.38, P = 0.09\)) as well as precipitation amount \((R = 0.36, P = 0.096)\). There is no statistically significant trend in PF15 (number of days on which precipitation exceeded 15 mm day⁻¹) and PF20 (number of days on which precipitation exceeded 20 mm day⁻¹) from 1981 to 2002 \((P > 0.10)\). It is likely that soil moisture change, the trend in PF0, PF5, PF10, and PF15, becomes more significant \((P < 0.03)\) through excluding data for 1981 and 1982.
5 mm day$^{-1}$; PF10: number of days on which precipitation exceeded 10 mm day$^{-1}$; PF15: number of days on which precipitation exceeded 15 mm day$^{-1}$; PF20: number of days on which precipitation exceeded 20 mm day$^{-1}$. $T_{\text{mean}}$: daily mean air temperature, $T_{\text{max}}$: daily maximum air temperature, $T_{\text{min}}$: daily minimum air temperature.}

| Layer (cm) | PM | PF0 | PF5 | PF10 | PF15 | PF20 | $T_{\text{mean}}$ | $T_{\text{max}}$ | $T_{\text{min}}$ |
|------------|----|-----|-----|------|------|------|----------------|----------------|----------------|
| 0–10       | 0.70 | 0.71 | 0.71 | 0.76 | 0.70 | 0.62 | −0.39 | −0.52 | −0.17 |
| 10–20      | 0.67 | 0.78 | 0.71 | 0.75 | 0.67 | 0.57 | −0.50 | −0.61 | −0.28 |
| 20–30      | 0.71 | 0.76 | 0.74 | 0.80 | 0.74 | 0.63 | −0.46 | −0.61 | −0.18 |
| 30–40      | 0.73 | 0.67 | 0.74 | 0.81 | 0.77 | 0.67 | −0.38 | −0.56 | −0.07 |
| 40–50      | 0.78 | 0.74 | 0.78 | 0.86 | 0.80 | 0.69 | −0.44 | −0.60 | −0.16 |
| 0–50       | 0.75 | 0.78 | 0.76 | 0.82 | 0.75 | 0.64 | −0.47 | −0.61 | −0.22 |

Table 1. Relationship of soil moisture (SM) in different layers with precipitation amount (PM), precipitation frequency (PF), and temperature ($T$). (Note: PF0: number of days on which precipitation exceeded 0 mm day$^{-1}$; PF5: number of days on which precipitation exceeded 5 mm day$^{-1}$; PF10: number of days on which precipitation exceeded 10 mm day$^{-1}$; PF15: number of days on which precipitation exceeded 15 mm day$^{-1}$; PF20: number of days on which precipitation exceeded 20 mm day$^{-1}$. $T_{\text{mean}}$: daily mean air temperature, $T_{\text{max}}$: daily maximum air temperature, $T_{\text{min}}$: daily minimum air temperature.)

Figure 1. Change in average of summer (June–August) soil moisture (kg kg$^{-1}$) and climate over 16 sites where soil moisture data are available in every year during the period of 1981–2002. (a) Change in summer soil moisture for different layers, and (b) interannual variation in the standardized variable of average summer soil moisture in the top 50 cm (SM50); precipitation amount (mm, PM), precipitation frequency (days, PF) and temperature (°C, $T$). PF0, PF5, PF10, PF15, PF20 correspond to the number of days on which precipitation exceeded 0 mm day$^{-1}$, 5 mm day$^{-1}$, 10 mm day$^{-1}$, 15 mm day$^{-1}$, 20 mm day$^{-1}$, respectively. Trends for each variable are shown. The trends are nondimensional and comparable because the variables are standardized. See figure 2(a) for soil moisture sites used in this figure.

Figure 1(b) and table 1 reveal that the interannual variation of summer soil moisture in the top 0.5 m is closely related to precipitation frequency. The correlations between precipitation frequency (especially PF10) and soil moisture for different layers are most significant. Among five different precipitation frequencies, the maximum coefficient of correlation ($R$) between summer soil moisture and precipitation frequency occurs when the daily precipitation threshold is 10 mm day$^{-1}$ ($R = 0.82$), while the correlation of PF20 with soil moisture is lowest ($R = 0.64$), even less than that of precipitation amount ($R = 0.75$) (table 1). Furthermore, the correlation of the number of summer precipitation days with the summer soil moisture changes is higher for a greater soil depth (table 1). When correlated with observed soil moisture, daily maximum temperature displays a more significant link than daily mean and minimum temperature (as can be expected from its impact on evapotranspiration), but which is still less significant than the correlation with precipitation frequency and precipitation amount.

Figure 2 displays the spatial distribution of the linear trends in summer soil moisture in the top 50 cm, precipitation amount and precipitation frequency from 1981 to 2002. Despite its significant decrease as a whole, summer soil moisture in China exhibited a pronounced geographical heterogeneity in its trends (figures 2(a) and (b)), probably due to the different changes in precipitation (figures 2(c)–(f)). There are clear spatial patterns, however. As shown in figures 2(a) and (b), most of the sites in North China show a decreasing trend in soil moisture in the top 50 cm, implying that North China experienced a tendency towards an increase in drought over the last two decades of the 20th century. Such a decrease in soil moisture may be closely related to a downward trend in summer precipitation amount (figure 2(c)) and number of precipitation days (figures 2(d)–(f)) in these regions. Interestingly, dramatic increases of summer precipitation amount and precipitation frequency, however, are observed in South China (figures 2(d)–(f)).

To further understand how the relationship between soil moisture and precipitation frequency varies spatially, we calculate the significance of the correlation between soil moisture in the top 50 cm and PF10 for each site. The results show that, spatially, the correlation is weak for very dry and very wet soils and is much stronger for intermediate values ($P < 0.05$; figure 3). Such change in significance of the correlation between soil moisture in the top 50 cm and PF10 in response to soil moisture in the top 50 cm is still statistically significant even if we exclude two sites with the lowest summer soil moisture. In extremely dry
Figure 2. Spatial distribution of change in summer (June–August) soil moisture in the top 50 cm, precipitation amount, and precipitation frequency. (a) Linear trends in summer soil moisture in the top 50 cm (kg kg\(^{-1}\) decade\(^{-1}\)), where soil moisture observation sites used in figure 1 are indicated with empty black squares, (b) relative change in summer soil moisture in the top 50 cm (% decade\(^{-1}\)), (c) linear trends in summer precipitation amount (mm decade\(^{-1}\)), (d) linear trends in number of days on which precipitation exceeded 0 mm day\(^{-1}\) (days decade\(^{-1}\)), (e) linear trends in number of days on which precipitation exceeded 5 mm day\(^{-1}\) (days decade\(^{-1}\)), (f) linear trends in number of days on which precipitation exceeded 10 mm day\(^{-1}\) (days decade\(^{-1}\)), (g) linear trends in number of days on which precipitation exceeded 15 mm day\(^{-1}\) (days decade\(^{-1}\)), and (h) linear trends in number of days on which precipitation exceeded 20 mm day\(^{-1}\) (days decade\(^{-1}\)).
numerous specialized indices, such as Thornthwaite’s moisture index, can even impact the drinking water supply for local people. On the other hand, in extremely wet areas, strong evaporation processes ensure that slight increases in precipitation frequency have only limited effect on soil moisture. Changes in soil moisture depend on the balance of precipitation, runoff, and evapotranspiration. Our results suggest that our ability to use precipitation frequency changes to explain the variation of soil moisture depends on the discriminating criteria applied to distinguish among precipitation events (table 1). For example, both PF0 and PF5 have lower explanation of variations in soil moisture change than PF10, perhaps indicating the limited effect of too small precipitation events (e.g., less than evaporative demand of atmosphere) on soil moisture.

4. Discussion and summary

Drought is one of the most severe problems in China, and has attracted widespread attention from both scientists and policy-makers. On the basis of inter-decadal change in summer precipitation, previous studies have presumed that South China has experienced more floods, while North China has seen more droughts since the 1980s [21, 22]. However, the temporal trend and spatial pattern of drought in China still remain largely uncertain, since long-term records of a key variable related to drought, soil moisture, are sparse [23]. Results presented in this study suggest that summer soil moisture in most stations of North China experienced an overall decrease during 1981–2002, which supported the conclusion that most of North China has undergone severe drought since the 1980s [21]. This region is mainly the rain-fed agricultural area in China, and such increasing drought may result in decrease in agricultural production, and can even impact the drinking water supply for local people.

In order to monitor and predict changes in drought, numerous specialized indices, such as Thornthwaite’s moisture index (Im) [24] and PDSI [25], have been widely applied in previous studies. It should be noted, however, that these drought indices are generally driven by monthly precipitation amount and temperature, and precipitation frequency is not taken into account. For example, in the current report of the IPCC [12], change in drought over land surface is evaluated on the basis of PDSI and monthly precipitation amount and temperature. The results presented here, however, challenge the results of these previous studies. This is because our correlation analysis suggests that soil moisture is more strongly related to precipitation frequency than precipitation amount, thus implying that the impact of precipitation frequency changes on soil moisture and resulting drought should not be ignored. Previous experimental studies have indicated that for mesic grassland ecosystems of North America, a decline in the number of precipitation days without a modification of the total precipitation amount clearly decreased the soil water content, and thus led to a decrease in vegetation productivity [20, 26]. This is consistent with the results presented in this study. Hence, we find that there is a strong positive correlation between summer soil moisture and precipitation frequency.

Changes in soil moisture depend on the balance of precipitation, runoff, and evapotranspiration. Our results suggest that our ability to use precipitation frequency changes to explain the variation of soil moisture depends on the discriminating criteria applied to distinguish among precipitation events (table 1). For example, both PF0 and PF5 have lower explanation of variations in soil moisture change than PF10, perhaps indicating the limited effect of too small precipitation events (e.g., less than evaporative demand of atmosphere) on soil moisture. On the other hand, if the threshold value used to quantify precipitation frequency is larger than 10 mm day$^{-1}$ (e.g., 15 and 20 mm day$^{-1}$), the explanation of precipitation frequency for soil moisture is likely to decline in value (as suggested by the lower correlation), presumably because the increase in runoff associated with large individual precipitation events partly cancels out the effect of precipitation frequency.

5. Conclusions

We conclude from our statistical analysis of observational soil moisture data that changes in summer precipitation frequency significantly influence summer soil moisture dynamics. Our results do not only suggest that estimations based solely on monthly temperature and precipitation amount might not be able to fully capture climate change induced soil moisture changes, but also imply that the near-future evolution of soil moisture partly depends on the change in precipitation frequency and intensity over time. If precipitation frequency is lower in the future, as characterized by the IPCC [12], the interior of the continents in the northern hemisphere may become more susceptible to droughts in this century.

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