J. Mt. Sci. (2021) 18(11): 3082-3098 e-mail: jms@imde.ac.cn http://jms.imde.ac.cn
https://doi.org/10.1007/s11629-020-6599-9

Original Article

Seasonal freezing-thawing process and hydrothermal characteristics of soil on the Loess Plateau, China

CHOU Ya-ling* https://orcid.org/0000-0002-4629-0213; e-mail: chouyaling@lzb.ac.cn

WANG Li-jie https://orcid.org/0000-0002-0717-3751; e-mail: 577797238@qq.com

**Corresponding author*

Key Laboratory of Disaster Prevention and Mitigation in Civil Engineering of Lanzhou University of Technology, Lanzhou 730050, China

Citation: Chou YL, Wang LJ (2021) Seasonal freezing-thawing process and hydrothermal characteristics of soil on the Loess Plateau, China. Journal of Mountain Science 18(11). https://doi.org/10.1007/s11629-020-6599-9

Abstract: In seasonally frozen soil regions, freezing-thawing action and hydrothermal effect have strong influence on physical and mechanical behavior of shallow soil. A field experiment on the Loess Plateau in Northwest China was carried out to analyze the freezing-thawing process and hydrothermal characteristics of shallow soil considering the climate influence. The results show that the maximum seasonal freezing depth under bare ground surface in this area is from 20 cm to 50 cm. The ground temperature shows a similar changing trend with air temperature, but it has lagged behind the air temperature, and the ground temperature amplitude exponentially decreases with the increase of soil depth. The seasonally frozen soil has experienced four typical stages: unfrozen period, alternate freezing period, freezing period and alternate thawing period. The freezing-thawing process is characterized by unidirectional freezing and bidirectional thawing. The water content of shallow soil is significantly affected by air temperature, evaporation and precipitation, and the soil water content shows a "low-high-low" changing trend with the increase of depth. The soil temperature and water content interact with each other, and are often coupled. The variation trend of soil moisture with time is consistent with the change trend of the ground temperature with time in each soil layer, and the degree of consistency is higher in the near surface soil than that in the lower layer. Also, the spatial-temporal characteristics of soil moisture and temperature is that the volumetric water content and ground temperature of near surface soil have strong variability, and the range value *Ka* and coefficient of variation *Cv* of soil water content and ground temperature in different seasons show a decreasing trend with the increase of depth.

Keywords: Seasonally frozen soil; Freezing-thawing process; Hydrothermal characteristics; Loess Plateau

Received: 30-Nov-2020
1st Revision: 29-Jan-2021
2nd Revision: 29-Apr-2021
Accepted: 19-May-2021

1 Introduction

The spatial and temporal distribution of frozen soils plays an important role in the hydrological cycle, climate change, and the structural integrity of physical infrastructure (Kelleners 2013). Frozen soil accounts for 70% of the global land area, including 14% permafrost and 56% seasonally frozen soil (Xu et al. 2001; Li RP et al. 2007). In seasonal active layer, the freezing-thawing process of soil is always accompanied by complex physical phenomenon such as water transport and heat exchange, and is mainly restricted by local factors such as vegetation, snow cover, water body, topography, water content and salt content (Tyrtikov 1963; Luthin and Guymon 1974;

Zhou et al. 2000). Frozen soil processes delay the winter cooling of the ground surface, and thawed soil processes delay the summer warming of the land surface (Poutou et al. 2004; Luo et al. 2008). The freezing-thawing process also influences rainfall-runoff partitioning, the timing of spring runoff, and the amount of soil moisture that subsequently is available for evapotranspiration in spring and summer (Koren et al. 1999). Soil hydrology and thermal properties are also changed greatly by freezing-thawing process (Luo et al. 2008).

The Loess Plateau in Northwest China is located in seasonally frozen soil region. Considering its unique geographical location and climatic characteristics, the freezing-thawing process of shallow soil is obviously affected by complex terrains and surface conditions. In this seasonally frozen region, roadbeds, slopes, airports and water conservancy projects are mostly in shallow unsaturated soil, and are extensively exposed to the earth surface. Moreover, due to the influence of solar radiation, evaporation, precipitation and other factors (Wang et al. 2004), physical and mechanical behavior of shallow soil has always been in long-term dynamic change under external environments. Some studies have found the physical and mechanical changes due to the moisture-heat exchange during the freezing-thawing processes, such as water migration (Zhang et al. 2017; 2018), heat transfer (Lu et al. 2017; Xu et al. 2016; 2017), and stress redistribution (Lai et al. 2014), may change the bearing capacity of foundations (Lu et al. 2019). Many engineering diseases are closely related to water-heat movement and potential transfer caused by freezing-thawing process. The seasonally frozen soil on the Loess Plateau has a strong response to climate change, and its freezing-thawing process also affects the land-surface hydrothermal model and atmospheric-unsaturated soil interaction model (Chou et al. 2019). Therefore, research on the freezing-thawing process and hydrothermal exchange of soils on the Loess Plateau is very meaningful.

Since the 1930s, scholars began to explore soil water, heat and salt during freezing-thawing period. Philip and De Vries (1957) first proposed the hydrothermal coupling migration model, which pioneered the study of water and heat transfer in the unsaturated soil. Harlan (1973) was generally credited with developing the first numerical model for coupled water flow and heat transport for unsaturated freezing soils. Taylor and Luthin (1978) utilized a modified form of a model presented by Harlan (1973) to present simulation analyses of heat and water flow during soil freezing. Cary et al. (1979) measured soil temperature, salt movement, and water redistribution in unsaturated frozen soil. Singh and Chaudhary (1995) evaluated heat and moisture transfer properties in a frozen-unfrozen water-soil system. Spaans and Baker (1996) presented a new, automated technique to measure a SFC (Soil Freezing Characteristic) in situ, for which there has previously been no method. Shoop and Bigl (1997) studied on water-heat transport of unsaturated soil during freezing-thawing period, and established a mathematical model based on field monitoring data. Sellers and Fremond and Lassoued (2000) presented models for simulating freezing-thawing process and water migration of soil. In recent years, researchers have conducted multi-directional studies on soil water-heat transport in freezing-thawing processes from different research purposes (Kelleners 2013; Kurylyk et al. 2014; Lu et al. 2019).

In China, researches on this issue first began in 1982 (Fang 1982). Numerical simulations of water-heat transfer of soil were developed in freezing-thawing process of soil (Yang et al. 1988; An et al. 1987). Huang et al. (1993) conducted field experiment of water-heat-salt movement of freezing-thawing soil in Yucheng Experimental Station, Shandong Province. The temperature variation and freezing-thawing characteristics of soil under different surface conditions (including membrane, straw and different plants) in Shanxi Province were studied (Zheng et al. 2009; Xing et al. 2012). The dynamic change of soil water and heat during freezing-thawing period in Horqin Sandy Land, Inner Mongolia Province, with sand-meadow land features was analyzed (Li et al. 2012; Liu et al. 2015; Yue et al. 2016). Chang et al. (2014) conducted outdoor experiments on the moisture transport in the aerated zone under freezing-thawing condition in Harbin, Heilongjiang Province. Many other studies conducted field experiment to study freezing-thawing process and hydrothermal effect of soils in different seasonally frozen soil regions, such as Xinjiang Province (Guo et al. 2002), and Jilin Province (Tang et al. 2014).

Although the freezing-thawing process and hydrothermal behaviors of shallow soil are important for the engineering stability in cold regions, such relevant studies have not been carried out to a great extent under the complex climate conditions of the Loess Plateau in China. Therefore, in order to further explore the effect of climate on freezing-thawing process and hydrothermal effect of shallow unsaturated soils, a field experiment for the Loess Hill-Gully Region in the west of Weihe River Valley was performed in the Loess Plateau.

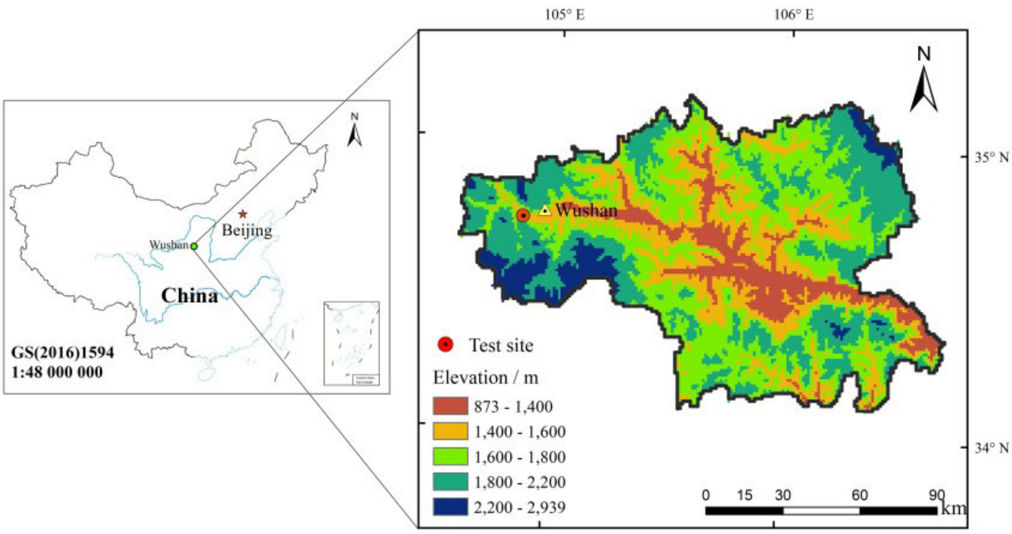
2 Field Location and Observation Method

2.1 Experimental site

The experimental site, established in the second-level terrace near the Northern Bank of the Weihe River in Wushan County, is in the west of Weihe River Valley on the Loess Plateau, in China (Fig. 1). The mean annual air temperature is about 7.8°C-13.5°C, and the precipitation is 400-800 mm. It is cold and arid in winter, hot and rainy in summer. The altitude in the territory is 1365-3120 m. Taken Wei River and Zhang River as the boundary, the topography of Wushan County can be divided into three different landform types: loess gully area in the north, river valley area in the middle, and eroded mountainous area in the south. The field site belongs to continental semi-humid and semi-arid monsoon climate zone, and also is a typical seasonally frozen soil area. The maximum seasonally freezing depth is not more than 1.0 m. In this area, the characteristics of seasonally frozen soil is variable and complex, and the boundary conditions for the water transfer and heat exchange of shallow soils are extremely complex. In this study, the geographical location of experimental site is 104°54′04″E and 34°43′59″N, and with an altitude of 1522 m. The underlying surface of the experimental site is flat, bare, dry and non-saline soil, and the groundwater depth is about 20 m. According to the manually stratified sampling, from ground surface 0-60 cm is cultivated soil, 60-300 cm is mealy sand silty soil, and 300-500 cm is silt soil. There is not drilled below 500 cm.

2.2 Experiment design

During experimental design, the meteorological factors, such as solar radiation, air temperature, air humidity, precipitation, wind speed, wind direction and air pressure, are taken into account. The meteorological data are from the HOBO U30-NRC Weather Station made in Onset HOBO Data Loggers of the United States and set up in the test area (Fig. 2). A circular soil pit with a depth of 500 cm was excavated in the experimental site, and the diameter of the wellhead was about 80 cm. The soil moisture and temperature sensors also made in Onset HOBO Data Loggers of the United States were installed at different depths (Fig.2). The monitoring depth of soil moisture was 20, 50, 90, 140, 200, 270, 350 cm, and the monitoring depth of soil temperature was 5, 20, 50, 90, 140, 200, 270, 350, 480 cm, respectively. The moisture sensor model is S-SMC-M005, and the temperature sensor model is S-TMB-M006. The sensors were embedded by digging holes on the shaft



(a) Full graph (b) Local graph

Fig. 1 Schematic location of the experimental site.

(a) Weather station (b) Exploratory well (c) Sensor layout (d) Sensor connection

Fig. 2 Layout of the study area.

wall, about 30 cm into the wall, and then the exploratory well was backfilled. The sensors were connected to U30-NRC-000 data acquisition instrument, the time interval of sampling is 30 min, and the monitoring period of this research is from June 1, 2017 to June 1, 2018. In this experiment, the soil water content monitored by HOBO is the volumetric water content of soil liquid water. Therefore, the soil water content in summer and autumn is the total soil water content, while the soil water content in the frozen layer in spring and winter is the unfrozen water content.

2.3 Meteorological factors

The movement of water and heat in shallow soil is mainly controlled by climatic conditions. Fig. 3 shows the micro meteorological changes in the study area from June 1, 2017 to June 1, 2018. The solar radiation is small in winter and increases slowly with the coming of spring, and reaches the maximum from June to August. The changing trend of air temperature is roughly the same as that of the solar radiation. The daily maximum air temperature is 38.31°C (July), and the daily minimum air temperature is -13.16°C (January). The air temperature is below 0°C from the end of November to the end of February of the following year. The total precipitation is 414.2 mm, the daily maximum precipitation is 39.2 mm, the monthly maximum precipitation is 98.0 mm (August), and the monthly minimum precipitation is 0 mm (December). The precipitation is mainly concentrated in June-October and March-May of the following year, accounting for 96.0% of the total precipitation. The highest relative humidity is in September, with the highest daily average relative humidity of 97.28%. The lowest relative humidity is in December, with the lowest daily average relative humidity of 27.65%. The maximum wind speed is 0.59 m/s and the maximum gust speed is 3.97 m/s, both of which occur in March. The wind direction is mainly northwest and northwesterly. The atmospheric pressure is between 83.86 kPa and 86.87 kPa, and the maximum atmospheric pressure is in December. There is a certain intrinsic connection between air temperature, solar radiation, relative humidity, precipitation and wind speed.

3 Results and Analysis

3.1 Ground temperature

3.1.1 Annual variation of ground temperature

The variation trend of ground temperature in different soil depths with time is basically consistent with that of solar radiation and air temperature with time, and the ground temperature changes lag behind solar radiation and air temperature. According to the attenuation law of ground temperature wave (Xu et al. 2001), as the ground temperature wave travels down to the underground, the amplitude of ground temperature decays exponentially with the increase of depth in the annual cycle, and the phase of ground temperature wave lags behind with the increase of depth. With the variation of air temperature, the daily average ground temperatures at different depths are shown in Fig. 4. It can be seen that the influence of air temperature on ground temperature of near surface soil is very remarkable. The ground temperature within 200 cm depth under the ground surface fluctuates more obviously, and the fluctuation of ground temperature below 200 cm is relatively gentle.

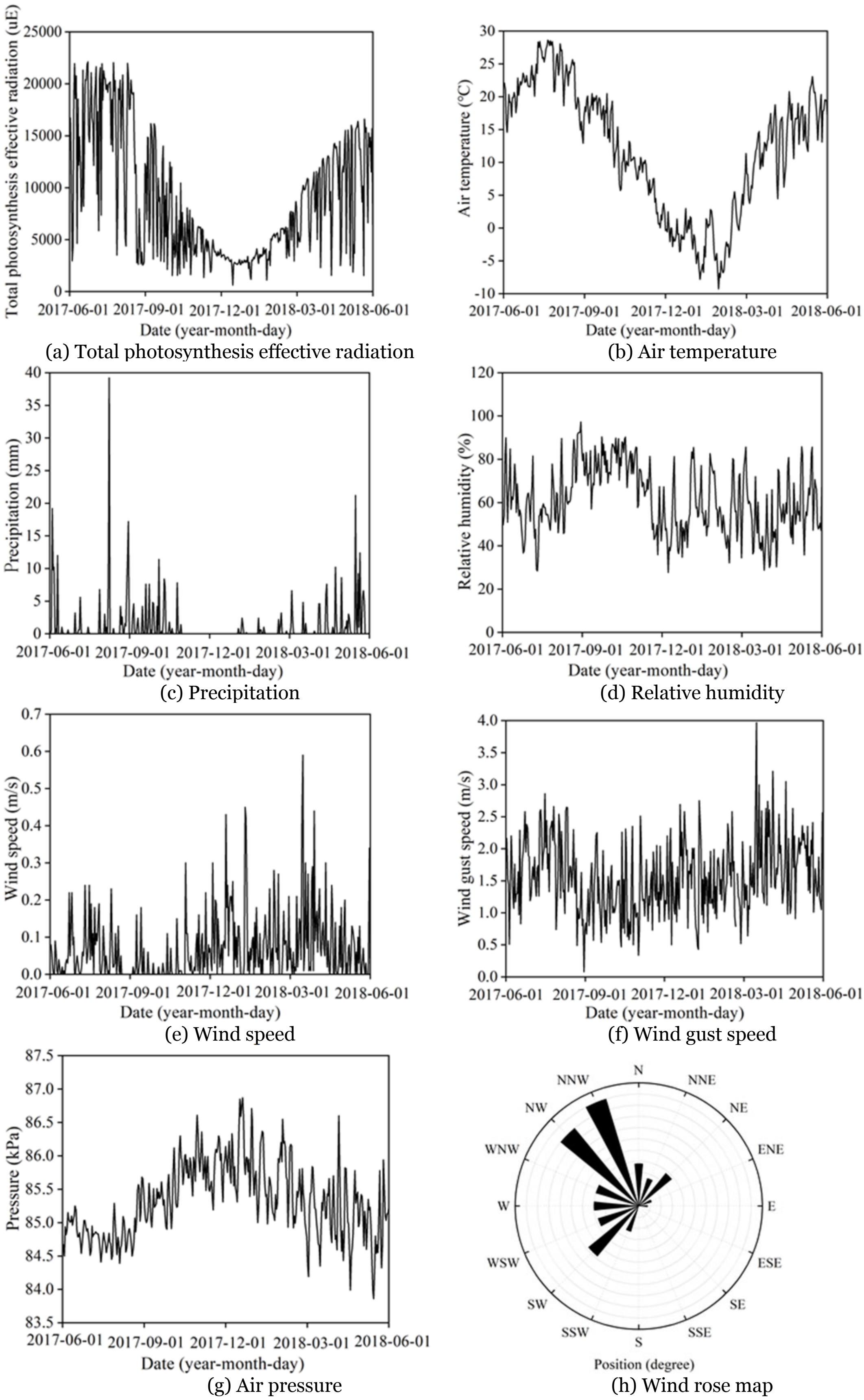


Fig. 3 Micrometeorological Factors in study area.

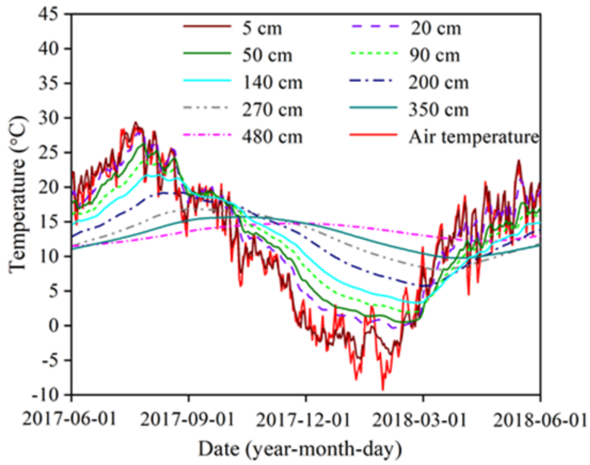


Fig. 4 Variation of air temperature and ground temperature at different soil depths.

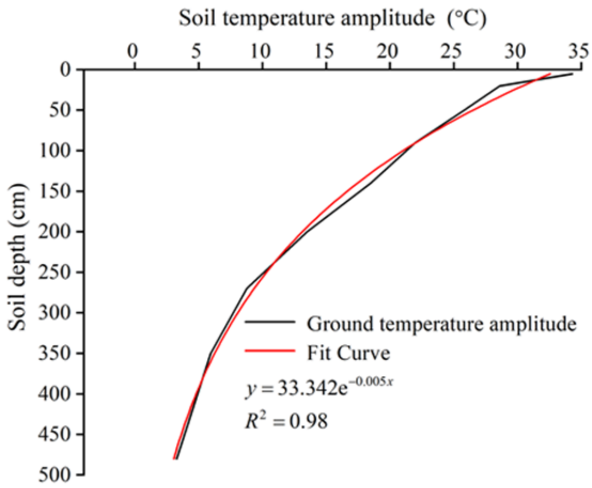


Fig. 5 Changes in ground temperature amplitude at different depths and fit curve during the annual cycle.

With the increase of soil depth, the influence of air temperature on ground temperature is less and less, the appearing time of the ground temperature peak obviously lags behind. In comparison with ground temperature at 5 cm depth under the ground surface, the maximum ground temperature at 200 cm depth lags behind about 34 days, and the lowest ground temperature lags behind about 48 days. The annual variation process of ground temperature can be divided into endothermic stage in spring and summer (March to May and June to August) and exothermic stage in autumn and winter (September to November and December to February).

Throughout the whole year, the annual amplitude variations of ground temperature within 90cm depth under the ground surface are very significant under the influence of air temperature, and the annual amplitudes are more than 20°C. The annual amplitudes of ground temperature at depths of 5 cm, 20 cm, 50 cm and 90 cm under the ground surface are 34.28°C, 28.59°C, 25.81°C and 21.99°C, respectively, while those at depths of 140 cm, 200 cm, 270 cm and 350 cm under the ground surface are 18.46°C, 13.50°C, 8.77°C and 5.94°C, separately. The annual amplitude of ground temperature decreases obviously with the increase of soil depth, and that at the depth of 480 cm under the ground surface is only 3.27°C. As shown in Fig. 5, during the annual cycle, the amplitude of ground temperature decreases exponentially with the increase of depth, and the correlation coefficient reaches 0.98. This conclusion is consistent with the results of literature (Xu et al. 2001).

According to the warming rate expressed by Eq.(1) and cooling rate expressed by Eq. (2) (Hu 2014), the warming rate and cooling rate of the atmospheric temperature and ground temperature at different depths can be obtained more directly.

$$V_s = (T_{max} - T_0) / t_d \quad (1)$$

$$V_d = (T_0 - T_{min}) / t_d \quad (2)$$

In Eq. (1), V_s is the warming rate; T_0 is the initial temperature when the air temperature and ground temperature begin to rise, respectively; T_{max} is the air temperature and ground temperature when the temperature each reaches the maximum value; t_d is the duration from the initial temperature rise to the maximum temperature. In Eq. (2), V_d is the cooling rate; T_0 is initial temperature when the air temperature and ground temperature begin to cool down; T_{min} is the air temperature and ground temperature when the temperature reaches the minimum value; t_d is the duration from the initial temperature cooling down to the minimum temperature. All the parameters in Eq.(1) and Eq.(2) are listed in Table 1.

The warming rate and cooling rate of ground temperature at different depths are shown in Fig.6, respectively. Both the warming rate and cooling rate of ground temperature have tended to reduce gradually with the increase of depth, and the cooling process is generally slower than warming process. The cooling rate and warming rate of air temperature are 0.197°C/d and 0.208°C/d respectively, which are both greater than the cooling rate and warming rate of ground temperature at different depths. The difference between the cooling rate and warming rate of ground temperature within 200 cm is significant, and the cooling rate and warming rate of ground

Table 1 The parameters of temperature rise and fall

Air/soil depth	Temperature rise				Temperature fall			
	T_0 (°C)	Start (m-d)	T_{max} (°C)	End (m-d)	T_0 (°C)	Start (m-d)	T_{min} (°C)	End (m-d)
Air	-6.90	01-30	28.62	07-20	28.43	07-21	-9.27	01-29
5 cm	-3.07	01-13	29.43	07-20	29.11	07-21	-4.84	01-12
20 cm	-0.27	02-07	28.24	07-26	27.4	07-27	-0.35	02-06
50 cm	0.51	02-15	26.3	07-27	25.51	07-28	0.49	02-14
90 cm	1.98	02-22	23.96	07-28	23.95	07-29	1.97	02-21
140 cm	3.33	02-26	21.78	08-08	21.70	08-09	3.32	02-25
200 cm	5.76	03-04	19.24	08-25	19.21	08-26	5.75	03-03
270 cm	8.14	03-19	16.89	09-05	16.87	09-06	8.12	03-18
350 cm	9.80	03-31	15.72	10-15	15.70	10-16	9.78	03-30
480 cm	11.52	06-02	14.77	11-28	14.75	11-29	11.50	06-01

Note: T_0 is the initial temperature; Start is the start date; End is the end date. T_{max} and T_{min} is the air temperature and ground temperature when the temperature each reaches the maximum value and the minimum value.

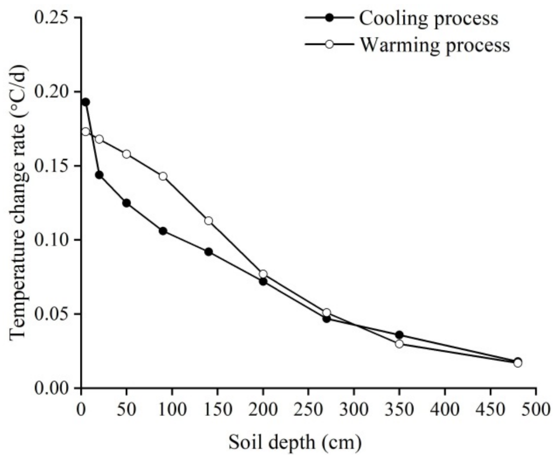


Fig. 6 The change rate of ground temperature at different depths.

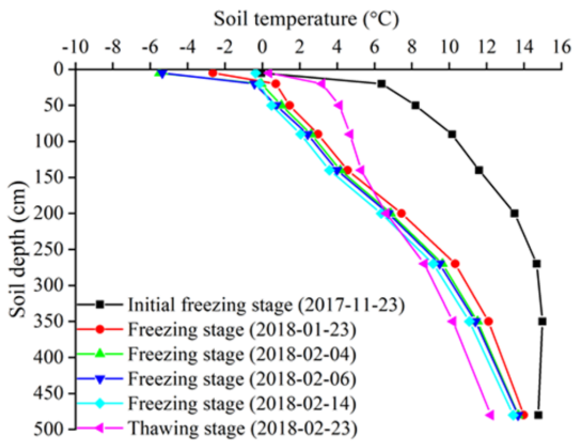


Fig. 7 Freezing and thawing characteristics of soil profile.

temperature are close to each other from 200 cm to 480 cm. In addition, the cooling rate and warming rate of ground temperature at 480 cm are almost the same.

3.1.2 Ground temperature during freezing-thawing

According to the field monitoring data, in terms of the annual cycle, the study area is divided into four typical stages: unfrozen period (or thawing period: Mar.11st-Oct.19th), alternate freezing period (Oct.20th-Nov.22nd), freezing period (Nov.23rd-Feb.23rd) and alternate thawing period (Feb.24th-Mar.10th). With the decrease of air temperature, when the ground temperature is lower than freezing point, the soil begins to freeze. The soil at the study area begins to completely freeze from the ground surface on November 23 and begins to thaw on February 23 of the following year. The whole freezing period has lasted for 90 days and the soil has completely thawed in late February. During the freezing period, the ground temperature shows an increasing trend from the ground surface to the bottom, and the soil shows a large temperature gradient from top to bottom. As the air temperature continues to decrease, the ground temperature tends to decrease and the thickness of the frozen layer increases gradually. It can be seen from Fig. 7(a) that the thickness of frozen soil layer in the initial freezing period (November) is about 5 cm. With the decrease of air temperature, the thickness of frozen soil layer gradually deepens and tends to be stable. It can be seen from Fig. 7(b) that when the air temperature gradually decreases, the frozen layer thickness increases from 5 cm to 20 cm, and the ground temperature continues to decrease. For example, the ground temperature at 20 cm under the ground surface decreased by 0.655°C from January 23rd to

February 4th, and dropped by 0.365°C from February 4th to February 6th, and it was -0.423°C on February 6th. It can be seen from Fig. 4 that the ground temperature at 50 cm below the ground surface is basically above 0°C throughout the whole year, which means that there is no freezing state at 50 cm during the monitoring period. Therefore, the thickness of frozen soil layer in this area is about between 20 cm and 50 cm. The annual average air temperature on the Loess Plateau is higher, so the seasonally frozen layer is thinner. During the thawing period, with the increase of temperature, the surface soil begins to thaw, and the temperature of each soil layer gradually increases (Fig. 7(c)).

The freezing (thawing) index is an important parameter for frozen soil research, which is of great significance to study frozen soil. And it can be useful in evaluating permafrost and seasonally frozen ground distribution, has important engineering applications, and is a useful indicator of high-latitude climate change (Frauenfeld et al. 2007). In general, the freezing (thawing) index is defined as the cumulative negative (positive) temperature of air or soil in a given period of time (Associate Committee on Geotechnical Research 1988). The annual freezing (thawing) index refers to the sum of the product of the duration of the temperature below (above) 0°C and the daily average temperature of air or soil. In seasonally frozen soil regions, the annual freezing index can be used to classify the types of snow cover and assess the depth of seasonal freezing depth. According to the definition of n coefficient (Karunaratne and Burn 2003; Riseborough et al. 2003), the ratio of freezing/thawing index of soil temperature at different depths to the freezing/thawing index of air temperature is defined as the n coefficient of soil temperature at different depths, in which the freezing index and thawing index are the negative accumulated temperature and positive accumulated temperature within one year of each soil layer temperature/air temperature, respectively. According to the monitoring period data, Table 2 shows the soil temperature index and n coefficient, including the freezing coefficient n^- and the thawing coefficient n^+.

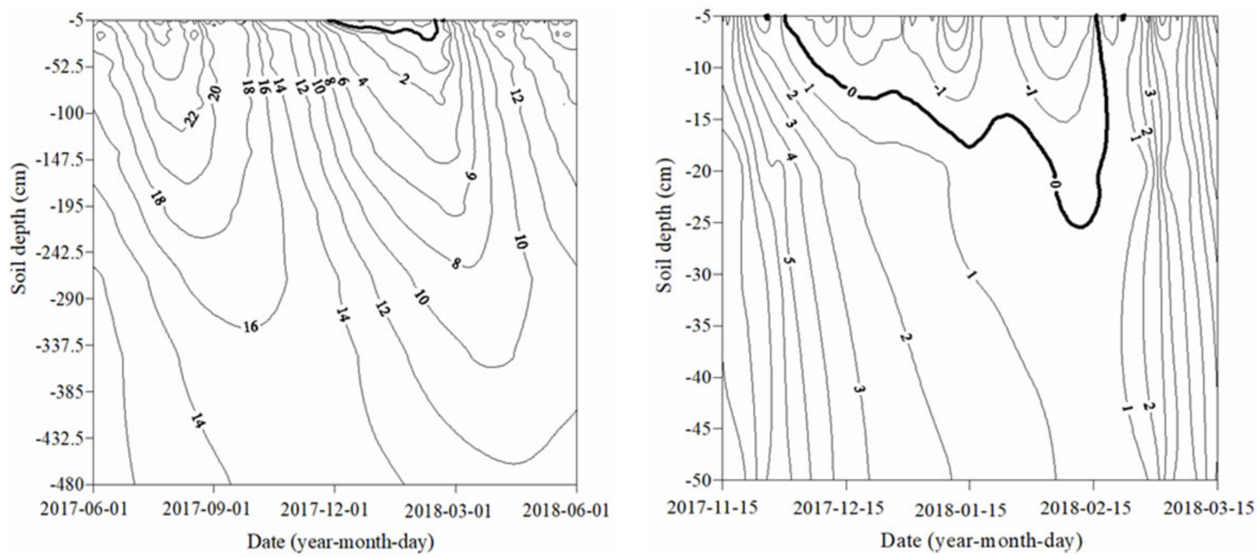
The results show that there is a negative correlation between the freezing coefficient n^- and the thawing coefficient n^+. The larger the freezing coefficient n^- is, the more favorable it is for heat absorption. Otherwise, it is more conducive to heat release (Sheng et al. 2005). It can be seen from Table 2 that with the increase of soil depth, the soil gradually changes from endothermic state to exothermic state, and the freezing coefficient n^- at 5 cm below the ground surface is the largest, which is larger 0.6 than that at 20 cm below the ground surface. It indicates that the endothermic effect within 5 cm below the ground surface is more obvious. With the increase of soil depth, the soil is no longer frozen, and the thawing coefficient n^+ of each soil layer generally tends to increase with increasing depth. It suggests that the exothermic effect of soil increases as the depth increases. The freezing coefficient n^- decreases with the increase of soil depth in principle, while the thawing coefficient n^+ is opposite.

Table 2 The temperature indices within the monitoring period

Soil depth (cm)	Freezing index (°C·h)	Thawing index (°C·h)	Thawing factor n^+	Freezing factor n^-
5	-3786	109248	1.00	0.61
20	-60	113784	1.04	0.01
50		110119	1.00	
90		110846	1.01	
140		110419	1.01	
200		112275	1.02	
270		111761	1.02	
350		113001	1.03	
480		117338	1.07	

3.1.3 Temperature characteristics of soil profile

In order to reflect the dynamic change of ground temperature more intuitively in space and time, Fig. 8 shows the isoline of ground temperature profile in the monitoring period. The density, smoothness, and sinuosity of the contour line can reflect the violent degree of ground temperature change. With the increase of depth, the isoline of ground temperature in each time period changes from dense to sparse, and gradually tends to be gentle, which indicates that the ground temperature gradient gradually decreases with the depth, and the temperature change of lower layer is not as severe as that of the near surface soil. It can be seen from Fig. 8(a) that in terms of the whole year, the ground temperature of each layer has experienced a process of warming, cooling and warming. The near surface soil has obvious seasonal variation characteristics: warming period in summer, cooling period in autumn, freezing period in winter and thawing period in spring. The isoline of soil profile temperature within 50 cm depth during



(a) Full year (b) Part

Fig. 8 Contour chart of soil profile temperature change (unit: °C).

freezing-thawing period is shown in Fig.8(b). The isoline of 0°C twists and turns, and completely shows the freezing-thawing process of soil in bare ground surface. The soil freezing-thawing process is characterized by unidirectional freezing and bidirectional thawing, and the freeze-thaw cycle mainly occurs in the 0-25 cm soil layer below the ground surface.

3.2 Soil water content

3.2.1 Variation characteristics of soil moisture with precipitation

The water content of near surface soil is significantly affected by climate change. Fig. 9 shows the change of precipitation and soil moisture with the seasonal variation at different depths. There is relatively more precipitation in summer and autumn, less in spring and winter, and almost zero in winter. In winter, the main supply way of soil water is snowfall. In spring and summer, the water content of near surface soil is obviously affected by precipitation. With the increase of air temperature in spring, the near surface soil is no longer affected by freezing-thawing process from March. At this time, the precipitation increases, and the soil water content within 50 cm depth under the ground surface presents an obvious increase and fluctuation phenomenon, and the increasing trend of soil moisture is consistent with the change of precipitation. With the increase of depth, the effect of the precipitation on soil water content is obviously weakened and lags behind. In general, precipitation can increase soil water content, but sometimes it is opposite in summer. It can be seen from Fig. 9 that when the precipitation is the largest in summer, the water content of near surface soil is not the highest. Especially, the soil water content at the depth of 20 cm below the ground surface is relatively low, which is mainly due to the high air temperature, sun radiation, surface runoff and surface evaporation in summer. And the annual average evaporation is 1455.8 mm, which is the actually measured value in the experimental site. At the beginning of autumn, the water content of near surface soil increases with the precipitation. In late autumn, the precipitation gradually decreases, and the water content of near

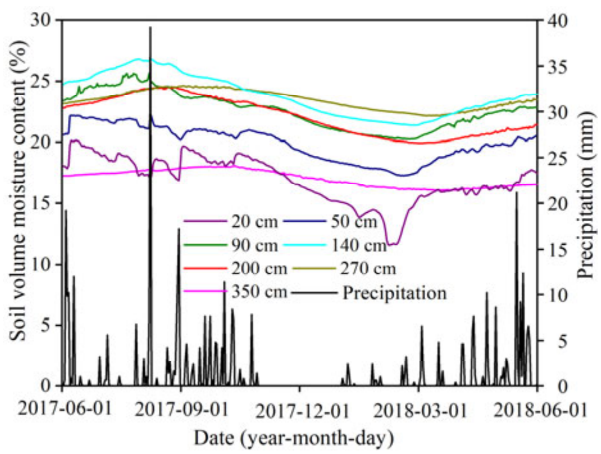


Fig. 9 Variation of soil water content with precipitation at different depths.

surface soil also decreases. The soil water content within 140 cm below the ground surface changes seriously, but the soil water content below 140 cm changes gently. In winter, because of the freezing of near surface soil, the unfrozen water content in soil becomes smaller and smaller due to phase transformation. In terms of the whole year, the significant influence depth of precipitation on soil water content is 140 cm, the soil moisture content from 140 cm to 270 cm is not significantly affected by precipitation, and the soil water content at 350 cm below the ground surface is almost not affected by precipitation. The soil water content shows a "low-high-low" changing trend with the increase of depth, forming a "water-rich area" at the depth of 140 cm. Also, it can be seen that the water content of near surface soil is not only related to precipitation, but

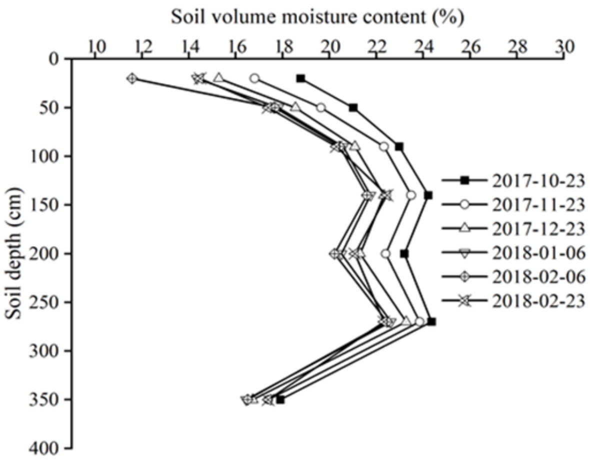


Fig. 10 Vertical distribution of soil water content during freezing and thawing period.

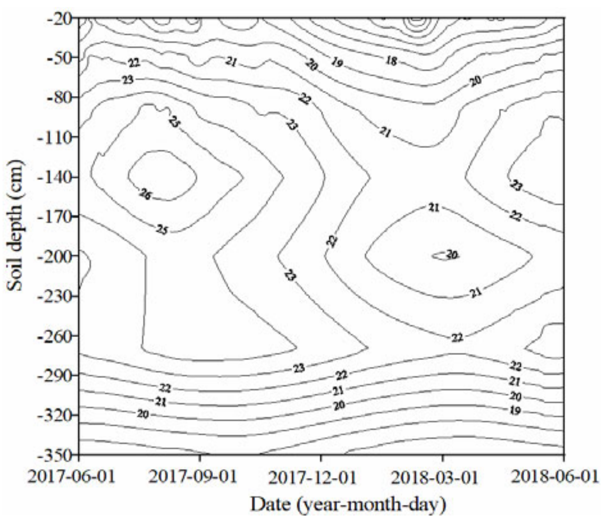


Fig. 11 Contour chart of moisture change in soil profile (unit: %).

also to surface evaporation, infiltration and solar radiation.

3.2.2 Characteristics of soil moisture during freezing-thawing

During the whole freezing-thawing period (November 23 to February 23), water content in the near surface soil changes significantly and redistributes due to the phase change of water. The soil began to freeze on November 23 from the ground surface, and the unfrozen water content of each soil layer began to decrease (Fig. 10). During the whole freezing period, the unfrozen water content of near surface soil gradually decreased. Under the effect of temperature gradient, the unfrozen water of the lower layer gradually moves to the frozen layer, which leads to the decrease of water content in lower soil. Affected by the seasonal active layer (20-50 cm), the unfrozen water content within 20 cm below the ground surface is the lowest. With the increase of freezing thickness, the unfrozen water content decreases more obviously. For example, the water content at 20 cm below the ground surface decreases by 2.76% from November 23 to February 6 of the following year. The soil begins to thaw on February 23 from the surface layer, and the unfrozen water content of soil at each depth increased. It can be seen that the unfrozen water content in seasonal active layer is significantly affected by climate change. During the whole freezing-thawing period, with the increase of depth, the change range of soil water content in each layer becomes smaller and smaller, and the change of water content at 350 cm is very small.

3.2.3 Moisture characteristics of soil profile

Within one year, the temporal and spatial isolines of soil moisture in different soil layers are shown in Fig.11. The variation of soil moisture gradually decreases with the increase of soil depth. The study area belongs to the arid and semi-arid area, and the evaporation is large, so the water content of near surface soil is lower throughout the whole year. Soil water content at 140 cm below the ground surface reaches the highest, forming a "water rich area". Below the depth of 270 cm, the soil moisture content in different seasons changes little. The distribution of water content in different seasons is closely related to the distribution and variation law of soil temperature. Under the condition of no water supply on the ground surface, the soil water movement is mainly affected by the soil temperature change. When the soil temperature is high, the water content of near surface soil accelerates evaporation and enters the atmosphere. In addition, it moves down to the lower soil under the action of potential energy gradient, which results in the soil water content near the ground surface becoming smaller. When the ground temperature is low, the water content of near surface soil changes periodically due to evaporation and the recharge of the water in lower soil layer (Li HX et al. 2007). During freezing process of soil, the unfrozen soil water migrates to the frozen front, which leads to a decline for soil water content across different soil layers, and the soil water content of near surface soil decreases more than that in lower soil. During thawing process of the frozen soil, the unfrozen soil water content increases successively across different soil layers, and the soil water content of near surface soil increases more than that in lower soil.

3.3 Soil water-heat coupling process characteristics

The variation trend of soil moisture and ground temperature in each soil layer is consistent with the seasons (Fig. 12). With the change of ground temperature, the water contents of the all soil layers also change periodically, which reflects that the change of energy gradient caused by the change of ground temperature gradient leads to the soil water movement. The soil moisture content in summer and in autumn is relatively large, and the soil water content within 140 cm depth under the ground surface changes greatly under the influence of air temperature, precipitation, evaporation and other climate factors. The soil water content increases with the increase of soil temperature. Because the heat capacity of water is larger than that of soil, the temperature of high water content soil layer rises slowly, and the peak value of ground temperature lags behind that of soil moisture. In spring and winter, the soil is in the freezing-thawing period, and with the increase of depth, the variation and fluctuation of soil water content is relatively gentle, which is mainly due to the decrease of ground temperature gradient caused by the latent heat of phase change from the water phase change. Soil temperature is an important factor causing the change of soil moisture (Lu and Likos 2012; Fukuda et al. 1980). In fact, short-term rainfall can also affect the temperature and water content of the near surface soil, and will disturb the coupling characteristics of temperature and water content in a local range, making them show a reverse changing trend, while the lower soil will not be affected by rainfall in the short term. In general, the ground temperature and water content affect and interact with each other, and are often coupled. The movement of water and heat in soil is a unified and inseparable system.

3.4 Spatiotemporal statistical analysis of soil water and heat

3.4.1 Statistical characteristic parameters

In order to further reveal the change degree of water content and ground temperature of shallow soil under climate conditions of different seasons, according to mathematical statistics knowledge, the range value *Ka* and coefficient of variation *Cv* can be used to express the variation degree (Chen et al. 2013; Fu et al. 2015). The calculation formula is:

$$Ka = x_{\max} - x_{\min} \tag{3}$$

$$Cv = \frac{\sigma}{\bar{x}} \tag{4}$$

where, $x_{\max}$ is the maximum value of temperature or unfrozen water content; $x_{\min}$ is the minimum value; $\bar{x}$ is the average value; and σ is the mean square error.

Among them, the range value *Ka* reflects the variation range of the test data. The larger the *Ka* value is, the greater the variation range of water content and ground temperature of shallow soil is, and vice versa. The coefficient of variation *Cv* reflects the relative discrete degree of the data. The greater the *Cv* is, the greater the difference of water content and ground temperature of shallow soil is, and vice versa.

3.4.2 Statistical characteristics of spatiotemporal variation of ground temperature

With the increase of soil depth, the influence of the external environment on the ground temperature of each layer is weakened (Chen et al. 2013). It can be seen from Table 3 that with the increase of soil depth, *Ka* and *Cv* in different seasons generally tend to decrease, which indicates that the variation range and variation degree of ground temperature are weakened.

The ground temperature at 5 cm depth changes sharply in spring and autumn, and the peak value of *Ka* appears in spring and reaches 31.896, which

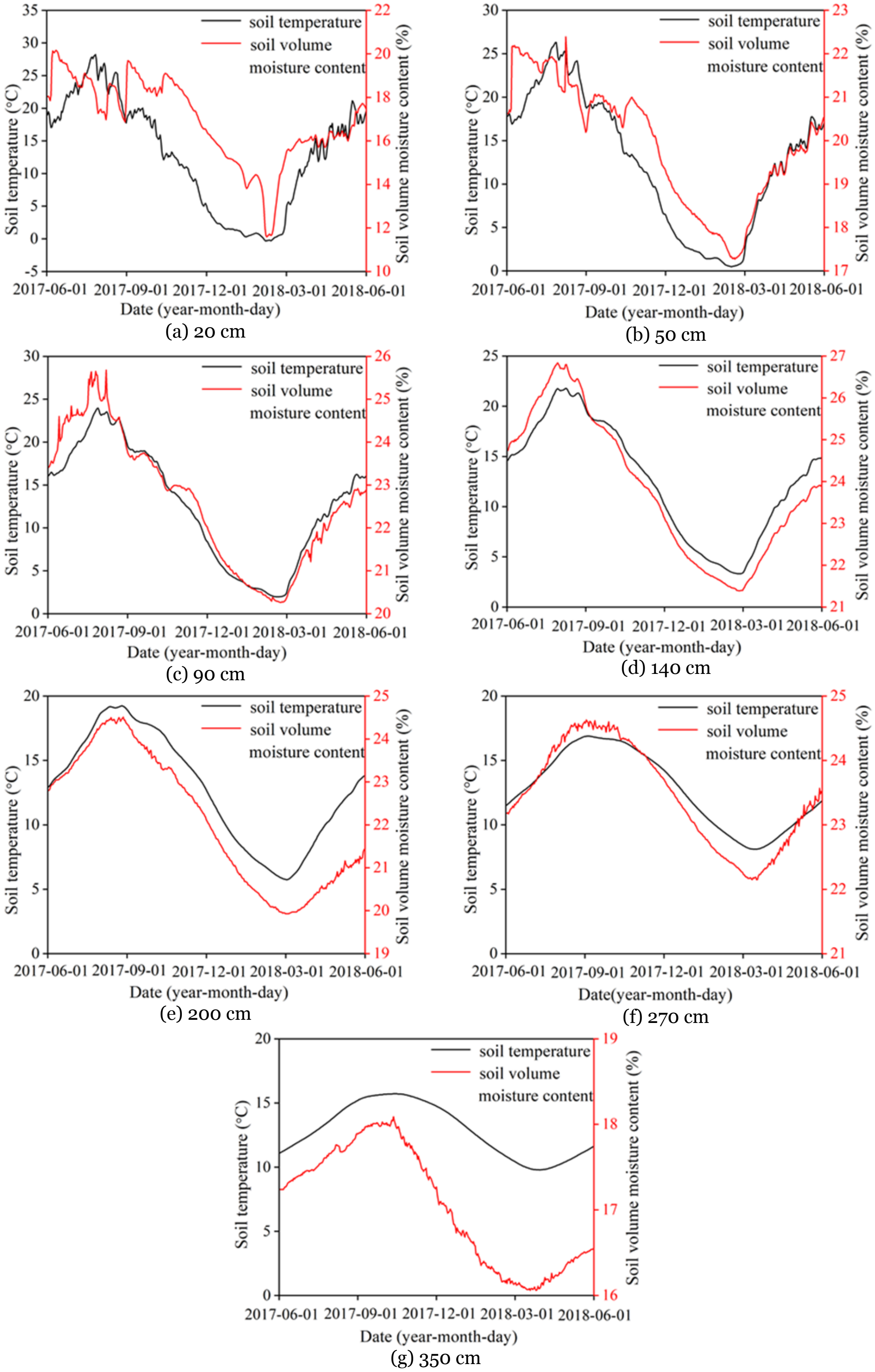


Fig. 12 Variation of ground temperature and soil moisture content at different soil depths.

indicates that the temperature variation within 5 cm depth under the ground surface is more significant in the alternation of cold and warm seasons. Moreover, within the depth of 140 cm below the ground surface, the range value *Ka* in spring and autumn is larger than that in the other two seasons, which indicates that the temperature variation range within this depth range is more severe in spring and autumn. In spring and autumn, the soil is in a more intense period of warming and cooling, so the range value *Ka* is larger.

In terms of a certain depth of soil in different seasons, within the depth of 200 cm, the coefficient of variation *Cv* is generally larger in spring and winter than that in summer and autumn, which indicates that the soil temperature within this depth range shows strong variability in spring and winter, especially in winter. The peak value of *Cv* appears at 20 cm below the ground surface in winter and reaches 0.958, which is 0.820 higher than that in summer. With the increase of soil depth, the variation range of *Cv* between different seasons decreases. The variation range of *Cv* at 50 cm, 90 cm and 140 cm below the ground surface is 0.550, 0.318 and 0.213 respectively, while that at 200 cm, 270 cm, 350 cm and 480 cm below the ground surface is 0.154, 0.105, 0.086, 0.033, respectively, which indicates that the ground temperature changes little in different seasons when the soil depth exceeds 200 cm.

3.4.3 Statistical characteristics of spatiotemporal variation of soil water

The related research showed that with the increase of soil depth, the change range of soil moisture content decreased (He et al. 2003). It can be seen from Table 4 that with the increase of soil depth, *Ka* and *Cv* in different seasons generally show a decreasing trend, which indicates that the variation range and variation degree of soil water content decrease with the increasing depth. Within 50 cm depth below the ground surface, the coefficient of variation *Cv* is larger in spring and winter than that in summer and autumn, which indicates that the soil moisture content within this depth range shows strong variability in spring and winter, and the water migration mechanism during freeze-thaw period in spring and winter is more complicated than that during non-freeze-thaw period in summer and autumn. The variation range of *Cv* between different seasons at 20 cm, 50 cm and 90 cm below the ground surface is 0.059, 0.015 and 0.014, respectively, which shows that the variation degree of soil water content in different seasons at the 20 cm depth is more intense. When the soil depth exceeds 140 cm, in terms of the whole year, in different seasons, the variation range of the coefficient of variation *Cv* of water content in each soil layer decreases, and the variation amplitude of *Cv* at 140 cm depth under the surface is

Table 3 Statistical analysis of temporal and spatial variation of soil temperature under different seasons

Soil depth	Spring		Summer		Autumn		Winter	
(cm)	*Ka*	*Cv*	*Ka*	*Cv*	*Ka*	*Cv*	*Ka*	*Cv*
5	31.896	0.399	22.059	0.199	26.524	0.592	19.592	-1.650
20	18.512	0.310	11.917	0.138	15.449	0.334	5.241	0.958
50	16.231	0.347	9.558	0.127	13.056	0.282	5.985	0.677
90	13.936	0.356	8.039	0.126	10.974	0.221	6.377	0.444
140	11.510	0.339	7.266	0.128	9.409	0.174	6.774	0.341
200	8.065	0.262	6.350	0.129	6.212	0.108	6.860	0.234
270	3.737	0.126	5.374	0.118	2.674	0.050	5.774	0.155
350	1.833	0.051	4.145	0.095	0.979	0.017	4.302	0.103
480	0.821	0.019	2.174	0.052	0.102	0.022	1.681	0.037

Note: *Ka* is the range value and *Cv* is the coefficient of variation.

Table 4 Statistical analysis of temporal and spatial variation of soil moisture under different seasons

Soil depth	Spring		Summer		Autumn		Winter	
(cm)	*Ka*	*Cv*	*Ka*	*Cv*	*Ka*	*Cv*	*Ka*	*Cv*
20	2.540	0.035	3.410	0.048	3.340	0.044	4.940	0.094
50	3.270	0.037	2.900	0.025	1.960	0.022	2.180	0.030
90	2.910	0.034	3.640	0.023	1.010	0.020	1.820	0.023
140	2.690	0.034	2.260	0.025	2.830	0.030	1.890	0.022
200	2.030	0.022	2.400	0.024	2.390	0.025	2.320	0.031
270	3.120	0.020	2.030	0.020	1.131	0.011	1.600	0.018
350	0.580	0.010	0.730	0.011	1.090	0.014	1.310	0.020

Note: *Ka* is the range value and *Cv* is the coefficient of variation.

only 0.012. While the variation amplitude of *Cv* value of each soil layer below the depth of 140 cm under the ground surface is smaller, all of which are less than 0.012, which indicates that the variation degree of soil water content is very little. To sum up, the change of soil water content within 140 cm depth under the ground surface is greatly affected by the external environment, and the soil water content below 140 cm depth under the ground surface is less affected by the external environment change.

4 Discussion

As an indicator of climate change, frozen soil has a significant impact on the evolution of climate and ecological environment. Scholars at home and abroad have conducted a lot of researches on frozen soil and its response to climate change (Yang et al. 2013; Sherstyukov and Sherstyukov 2015; Kalyuzhnyi and Lavrov 2017). Seasonally frozen soil is a common natural phenomenon in the middle and high latitude areas. It is more sensitive to climate change, and has a huge impact on regional climate, water cycle, water balance, etc. Most of the researches on seasonally frozen soil have focused on its temporal and spatial changes and relationship between seasonally frozen soil and climate change (Gao et al. 2003; Du et al. 2012; Fu et al. 2013). At present, the research areas related to the freezing-thawing process and hydrothermal effect of seasonally frozen soil in China are mainly concentrated on the Tibetan Plateau, the Northeastern regions, Shanxi Province, Inner Mongolia Province and Xinjiang Province. Some representative research results are presented here. Based on seasonally frozen soil and hydrothermal monitoring data in Haibei Station, Qinghai, Dai et al. (2020) analyzed the seasonal variation of freezing depth and coupled characteristics of water and heat during freezing-thawing process. In order to study the freezing-thawing process of soil and its response to climate change in the seasonally frozen soil region, Ren et al. (2019) analyzed the daily variation of freezing-thawing process and the relationship between air temperature and soil temperature based on the observation data in Jilin Province. Taking the Harbin high-cold area as the test base, Wang (2010) studied the seasonal freezing-thawing rules and the hydrothermal migration laws in this area. Based on a large number of indoor and outdoor test data, Zheng et al. (2002) systematically studied the seasonal freezing-thawing rules and the characteristics of water migration in frozen and thawed soils in Shanxi Province. Wang (2005) conducted field experiments and simulated the coupling transfer of soil water and heat in dune alternated with wetland area in Horqin Sandy Land, Inner Mongolia Province. Based on the observatory experiment on soil moisture transfer in Changji Plain, Xinjiang Province, Guo et al. (2002) analyzed the distribution of soil moisture potential and the regularity of soil moisture variation during freezing-thawing period. These studies have shown that there are differences in freezing-thawing process and hydrothermal changing trends of seasonally frozen soils in various regions. However, on the whole, the seasonally frozen soil in different regions shows a tendency of frozen soil degeneration, which has led to extremely complex hydrothermal processes.

In recent decades, seasonally frozen soil in China is mainly manifested as decreasing in the maximum freezing depth, the postponement of the freezing date, the advancement of the thawing date, and the shortening of the freezing duration (Chen and Li 2008). Since 1956, the freezing days of near-surface soil in China have dropped at a significant rate of -0.22 $d \cdot a^{-1}$ (Wang and Zhang 2013). The seasonally frozen soil is affected by many factors such as climate change, topography, lithology, vegetation coverage and so forth, which results in the freezing-thawing process and degeneration of frozen soil are extremely complicated. Especially in the background of global warming, the frozen soil layer in the middle and high latitudes has also changed significantly, and the cryosphere where frozen soil is located has become a hotspot of climate change (Dai et al. 2020). Also, the influence of climate warming and humidification on freezing-thawing process is that the seasonally frozen layer will become thinner and the freezing cycle will be shorter. In view of this, this study takes the Loess Plateau of China (located in mid-latitude regions) as the research area. According to field observation data, this paper analyzed the ground temperature and water content, freezing-thawing process and hydrothermal change of soil considering the climate influence. The characteristic of seasonal freezing-thawing process and the response of soil water and ground temperature to climate change are consistent with the research results of other seasonally frozen soil regions. More research results need further continuous monitoring and studying.

5 Conclusions

On the basis of previous studies, this study supplemented the freezing-thawing process and hydrothermal change of shallow soils on the Loess Plateau in Northwest China. The results have provided important parameters and theoretical basis for simultaneously establishing land surface hydrothermal model and getting accurate simulations in Loess Plateau. And according to the measured ground temperature and water content in field, the seasonal freezing-thawing process and hydrothermal change of shallow soil on the Loess Plateau are analyzed. The following conclusions are drawn:

(1) The maximum seasonal freezing depth of bare ground surface in this area is from 20 cm to 50 cm. The seasonally frozen soil has experienced four typical stages: unfrozen period, alternate freezing period, freezing period, alternate thawing period, and the freezing-thawing process is characterized by unidirectional freezing and bidirectional thawing. The change of ground temperature over time is consistent with the change of air temperature over time, but it has lagged behind the air temperature, and the ground temperature amplitude exponentially decreases with the increase of soil depth. At this monitoring point, the significant influence depth of climate on ground temperature is about 200 cm below the ground surface. The soil freezing coefficient decreases with the increase of depth, while the thawing coefficient is opposite. Moreover, the soil warming rate is always greater than the cooling rate at different depths in the interannual range.

(2) The soil water content shows a "low-high-low" changing trend with the increase of depth, forming a "water-rich area" at the depth of 140 cm below the ground surface. The significant influence depth of precipitation on soil water content is about 140 cm, the influence of precipitation on soil water content between 140 cm and 270 cm is not obvious, and the soil water content at 350 cm is almost not affected by precipitation. During the process of soil freezing, the unfrozen water in lower soil gradually migrates to the near surface frozen layer, which results in the gradual decrease of water content in lower soil. The water content of near surface soil, significantly affected by evaporation, precipitation and freezing-thawing process, shows a complex pattern of change.

(3) The movement of ground temperature and water content in soil is a unified and inseparable system. The ground temperature and water content affect and interact with each other, and are often coupled. The variation trend of soil moisture in each soil layer is consistent with the ground temperature, and the degree of consistency is better in the near surface soil than that in the lower layer. The ground temperature and water content of near surface soil are both significantly affected by solar radiation, air temperature, evaporation and precipitation. The variation degree of water content and ground temperature in the near surface soil is extremely severer than that in lower soil, and the range value *Ka* and coefficient of variation *Cv* of soil water content and ground temperature in different seasons both show a decreasing trend with the increase of depth.

Acknowledgement

This study was funded by the National Natural Science Foundation of China (grant number 51769013) and the Basic Research Innovation Group of Gansu Province (20JR5RA478).

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