Research on Influencing Factors of Freezing and Thawing Process in the regions over 5000 m a.s.l

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Abstract—The freezing and thawing process is a unique feature of the alpine permafrost ecosystem, which controls the growth of microorganisms and alpine meadows, and plays a vital role in animal husbandry development, ecosystem functions and services. Meanwhile, the freezing and thawing process is also affected by external environmental factors, and its spatial differences are very significant, especially in the regions over 5000 m a.s.l. In this study, the freezing and thawing process periods of the Cuoma Township (CM), Xiangmao Township (XM) and Xiaotanggula Mountain (XTGL) sites in the Nagqu River Basin are divided, the effects of altitude, vegetation coverage, air temperature, and organic matter content on the freezing and thawing process are analyzed, the main influencing factors are discussed. The results show that in the regions over 5000 m a.s.l, the thaw initiation period (TIP) starts in early April, the entirely thawed period (ETP) starts in end of May, the freeze initiation period (FIP) starts in end of October, and the entirely frozen period (EFP) starts in early November. Compared with the regions below 5000 m a.s.l, FIP and EFP in the regions over 5000 m a.s.l start earlier, the TIP starts later and the freezing rate is faster. Organic matter content is the main influencing factor during FIP and EFP, and air temperature is the main influencing factor during TIP and ETP. This study is helpful to clarify the changes of freezing and thawing process in the regions over 5000 m a.s.l, and also provides theoretical support for ecological protection and restoration.

1. Introduction

In the low and middle latitudes, the Qinghai-Tibet Plateau is the frozen soil area with the highest altitude and the largest area, it is also rich in frozen soil resources [1]. The soil moisture freezes in the cold season, melts in the warm season, the freezing and thawing process (FTP) is a significant physical feature of the surface in seasonal frozen soil regions [2,3]. In the process of water freezing, heat is released and the volume becomes larger, and in the process of melting, heat is absorbed and the volume becomes smaller. The FTP not only affects the surface energy balance, hydrological cycle process, soil properties and greenhouse gas emissions [4-12], but also controls the growth and survival of alpine vegetation and soil microorganisms [13].

With the global climate warms, the active layer thickens, and the carbohydrates stored in the permafrost are gradually released into the atmosphere, thereby further aggravating the local and even global warming process [2]. Previously, a large number of studies have shown that permafrost is gradually degrading from the edge to the inside [14-17]. Due to the high fragility and sensitivity of the permafrost ecosystem in the Qinghai-Tibet Plateau [18,19], the impact of climate change on FTP is more significant [13]. Changes in FTP can disrupt the balance of the original frozen soil ecosystem, and even lead to the evolution of some organisms in the frozen soil ecosystem. At the same time, the FTP is affected earlier and the impact is greater in the regions over 5000 m a.s.l, but it is rarely paid attention to. Therefore, understanding the FTP in the regions over 5000 m a.s.l, comparing it with the regions below 5000 m a.s.l, and analyzing the reasons for the differences are very important for clarifying the dynamic change process of soil water and heat in the regions over 5000 m a.s.l. When climate warming affects the FTP, different environmental factors may cause different results. Therefore, it is also necessary to analyze the influence of different influencing factors on the FTP. Of course, in order to better protect the frozen soil ecosystem in the alpine region, the main influencing factors in different periods need to be analyzed, which can provide theoretical support for ecological protection and restoration in the regions over 5000 m a.s.l, and also provide more information for ecological construction in alpine region.

The study area of this paper is the Nagqu River Basin (NRB) of the Qinghai-Tibet Plateau. The research objects are concentrated in the surface soil where the ground and the atmospheric material and energy exchange frequently [2,3,20,21]. The phase change, change time and change rate of soil moisture are the basis for the division. The freezing and thawing process

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period (FTPP) of the regions over 5000 m a.s.l in the NRB is divided, and the main influencing factors in different periods are analyzed. The main purpose of this article is threefold: (1) To understand the FTP in the regions over 5000 m a.s.l at NRB; (2) To understand the difference between the FTP in the regions over 5000 m a.s.l and those below 5000 m a.s.l; (3) To understand the main influencing factors in different FTPPs.

2. Materials and Methods

2.1. Study area

The NRB (Figure 1.) is located at the northern part of the Tibet Autonomous Region, surrounding with the Tanggula Mountains, the Nyainqentanglha Mountains and the Gangdisi Mountains. The NRB has an area of 16,328 km2, a length of 460 km and a total fall head of 920 m. The bedrock of the basin is fragmented, with a deep marine sediment cover. The average elevation is above 4500 m, decreasing from the northwest to the southeast. There is snow throughout the year. There are many lakes and rivers in the basin, and the riverbed is a quaternary holocene modern riverbed [22].

The NRB is located in the plateau sub-cold zone with the monsoon semi-humid weather, which experiences low temperature, thin air, dry atmosphere and strong solar radiation. There is mainly alpine frozen soil above the snow line and in the periglacial area, shallow meadow soil and thin grass felt soil in the surrounding water system, while swamp soil, new soil and other soils in other areas.

The Nagqu River is the source of the Nujiang River. Its main streams contain the Mugequ, the Chengqu, the Gongqu and the Luoqu. The total length of the tributaries is 318 km [23].

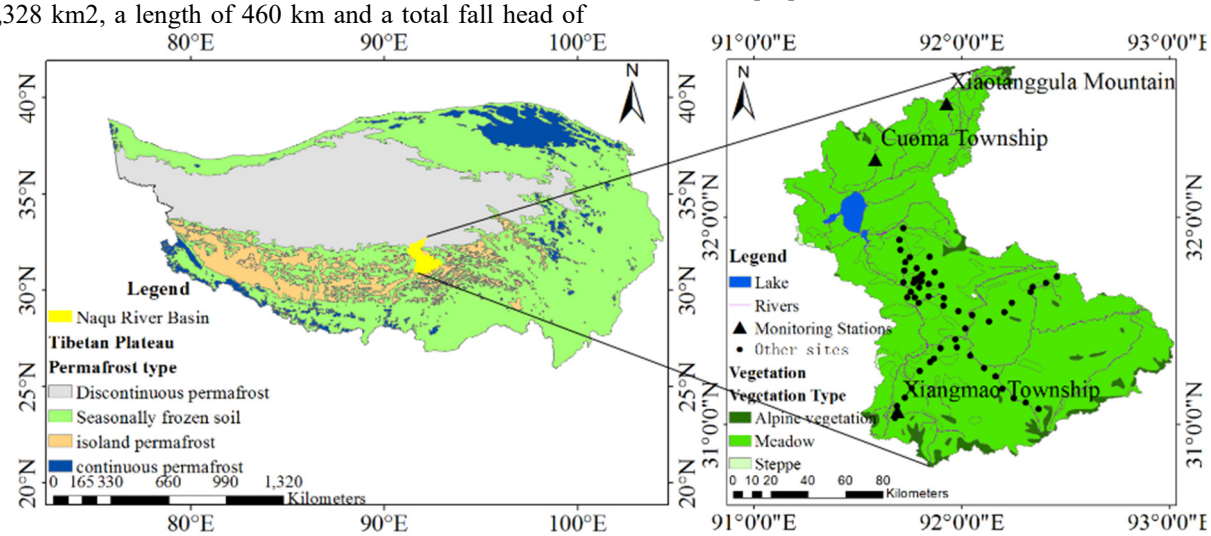

Fig.1 The location of the NRB, different colors are different permafrost types on the left, different colors are different vegetation types on the right

2.2. Data collecting and processing

With the support of the National Natural Science Foundation of China, three meteorological stations had been set up in Cuoma Township (CM), Xiangmao Township (XM), Xiaotanggula Mountain (XTGL) since October 2016. These meteorological stations can monitor air temperature, top soil temperature (TST) and top soil moisture (TSM). TST and TSM are measured through sensors, three sensors are installed at different locations on each station. The sensor of TST and TSM is buried in the soil to a depth of 10 cm. Our instrument for measuring the TST and TSM is the SM300 soil moisture sensor from Delta, UK, which has an accuracy of ±0.1 °C and ±0.1% TSM. The instrument for measuring air temperature is the SM300 sensor from Wotai, which has an accuracy of ±0.2 °C.

Some data of TST and TSM is used for us from Yang Kun et al. [24-26], and the instruments used by Yang Kun et al. are the EC-TM and 5TM from the USA; which has an accuracy of ±1 °C and ±2% VWC.

This study applies two types of data. One type of data is a large number of continuous monitoring data from meteorological stations (our site built in the NRB). We chose the observed data of air temperature, TST and TSM (recorded every 30 minutes) from April 2017 to March 2018 in CM, XM and XTGL. Moreover, we selected TST and TSM data from 50 other sites in the NRB from January 1, 2011 to December 31, 2014. The analysis in this paper used the daily average data. The other type of data such as altitude, vegetation coverage, and organic matter content is derived from manual measurement in July 2017. Vegetation coverage is measured by the field spectrometer (ZWGD-01, ChinaNet Power, Beijing), the organic matter content is measured by redox reagent titration [27,28], and the altitude data is from the GPS coordinate system. Table 1 presents the altitude, vegetation type, vegetation coverage and organic matter content of the meteorological stations in the CM, XM and XTGL.

Table 1. The characteristics of the monitoring point

Monitoring stations	CM	XM	XTGL
Latitude	32°16′	31°3′	32°33′
Longitude	91°35′	91°41′	91°49′
Altitude (m)	4760	4730	5050
Vegetation type	Alpine meadow	Alpine meadow	Alpine meadow

Vegetation coverage (%)	70	60	10
organic matter content (g/kg)	14.9	11.7	31.4

2.3. The division method of freezing-thawing process

Based on the change of TST and TSM, the FTP in the regions over 5000 m a.s.l. is divided into freeze initiation period (FIP), entirely frozen period (EFP), thaw initiation period (TIP) and entirely thawed period (ETP) [29-31]. As shown in Figure 2, when the TST becomes lower than 0 °C (the red circle), the ETP ends, and the FIP begins. When the TSM continues reducing to the minimum (the yellow circle), the inflection point is the end of FIP and the start of EFP. When the TST becomes higher than 0 °C (the blue circle), the EFP ends, and the TIP begins. When the TSM increases to the maximum (the green circle), the inflection point is the end date of TIP and the start date of ETP.

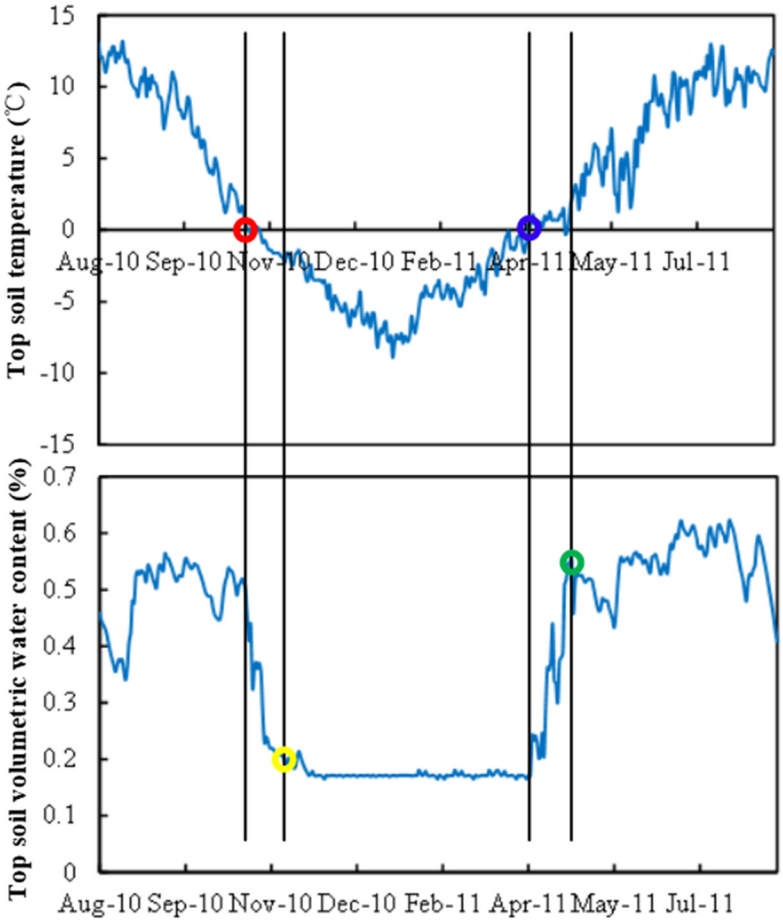

Fig.2 The division method of freezing-thawing process

3. Test Results and Discussions

3.1. Characteristics of soil temperature change

TST change at XTGL can be seen from Figure 2, and the trend is sinusoidal during the year [32,33]. The temperature begins to increase in early April 2017 until reaching the highest level in late July 2017, then reduce to the minimum in early January 2018. The reduction rate of TST occurr in three stages during the cooling process: top soil slowly cool from late July 2017 to middle October 2017, quickly cool from middle October 2017 to middle November 2017 and slowly cool from middle November 2017 to early January 2018.

The average minimum TST is -8°C. Compared with the regions below 5000 m a.s.l., the maximum TST of Xiaotangula is relatively small, and the minimum TST is lower, but the difference between the two is similar. When TST reaches 0 °C, the water in the top soil is frozen. The time to reach 0 °C and the duration of subzero status have an apparent influence on the freezing-thawing process of the active layer [34-36]. The top soil in the regions below 5000 m a.s.l. reaches 0°C later, and the subzero temperature state lasts for a short time. The top soil of XTGL begin to fall below 0°C in early November, and it is subzero temperature state for 151 days in a year. It indicates that the soil in the regions over 5000 m a.s.l. starts to freeze earlier and lasts longer.

3.2. Characteristics of soil moisture change

Regardless of the regions over 5000 m a.s.l. or the regions below 5000 m a.s.l., the maximum TSM appears almost in the same time, but the minimum TSM in the regions over 5000 m a.s.l. appears earlier.

TSM starts the increasing period in the regions over 5000 m a.s.l. 33 days earlier than that in the regions below 5000 m a.s.l. When the top soil enters the entirely thawed period, TSM is going to exceed 14%, and when the TSM exceed 14%, the regions over 5000 m a.s.l. is 2 times as much as the regions below 5000 m a.s.l. It can be seen from the above analysis, and the value of the TSM is stable from the beginning of November to the beginning of April in the regions over 5000 m a.s.l., because the soil has frozen. The regions below 5000 m a.s.l. also has the same phenomenon, but the time duration is shorter. And the variation rate of TSM in the regions over 5000 m a.s.l. is larger than that in the regions below 5000 m a.s.l.

3.3. The division of freezing-thawing process

From the method in Section 2.3, we divide the FTPP at XTGL (the regions over 5000 m a.s.l.) as follows:

(1) FIP is from end of October to early November. In this period, the shortwave radiation received by the soil is less than the radiation of long wave radiation, TST begins to fall below 0 °C, TSM begins to decrease, and the top soil is freezing.

(2) EFP is from early November to early April. In this period, TSM is stable between 10% and 11%, the top soil enters sub-zero temperature, and the top soil is frozen.

(3) TIP is from early April to the end of May. In this period, the water in the top soil layer increases with thawing, the ability to absorb solar radiation increases, and the surface albedo is smaller, thus the solar shortwave radiation absorbed by the surface is larger than the radiation of long wave radiation, the top soil is thawing.

(4) ETP is from the end of May to the middle of October. In this period, the top soil is thawed, and the TSM fluctuates in a fixed range, which is greatly affected by water such as rainfall.

Comparatively, FIP and EFP in the regions over 5000 m a.s.l. start earlier than that in the regions below 5000 m a.s.l., and TIP begins later. In the regions over 5000 m a.s.l., the duration of subzero status is longer and the freezing rate is faster. The difference of external environmental factors affects the FTP [37-39], which indirectly affects TST and TSM.

3.4. Relationship between soil temperature and moisture

The change of TST affects the process of TSM transport. At the same time, the thermal properties of TSM also have an important influence on the change of TST. TSM and TST are interactive [32,33,40]. As shown in Figure 3, TSM increase with the increase of TST in most cases, but it is special in a few cases. When TSM reaches a minimum, the effect of TST reduction on TSM can be ignored. When TSM reaches a maximum, the effect of TST on TSM still exists, but the correlation between the two changes. (Figure 3). The change of TSM is a complicated process. When the TSM is completely frozen (lower limit), the increase of TST causes the ice in the soil to thaw, and the TSM increases; when the ice in the soil is completely thawed (upper limit), the increase of TST accelerates the evaporation of TSM, and the TSM reduces.

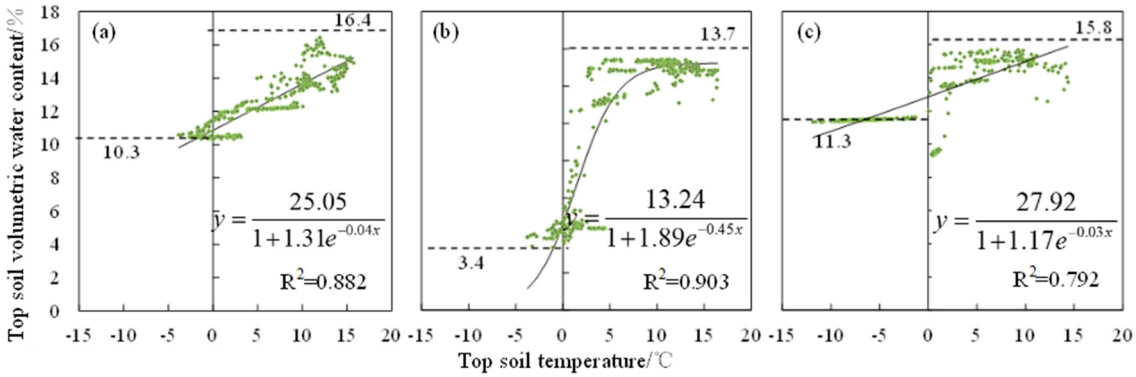

Fig.3 The relationship between TST and TSM, y is the TSM, x is the TST.

Considering the phenomenon of "upper and lower limit", a variety of models were used to fit it. The results show that the logistic model has the best comprehensive fitting effect [41,42], but the fitting effect in the regions below 5000 m a.s.l. is better than that in the regions over 5000 m a.s.l., and the results are shown in Figure 3. However, the TSM and TST changes is affected by rainfall, snowfall, etc. When rainfall occurs, the TSM increases, rainfall can weaken solar radiation and reduce heat absorbed by the soil, and the evaporation of surface water absorbs heat, which may affect the fitting effect [37,43]. These are the effects of external factors (i.e. altitude, air temperature, vegetation coverage, organic matter content), which also affect the fitting effect.

3.5. Indirect effect of altitude on freezing and thawing process

Altitude is one of the local factors affecting FTP. Moreover, altitude also affects air temperature, vegetation coverage, and soil organic matter content, thus altitude is the basis for analyzing other influencing factors. We use our monitoring site data and the data of other sites to divide the FTPP at different altitudes (Figure 4).

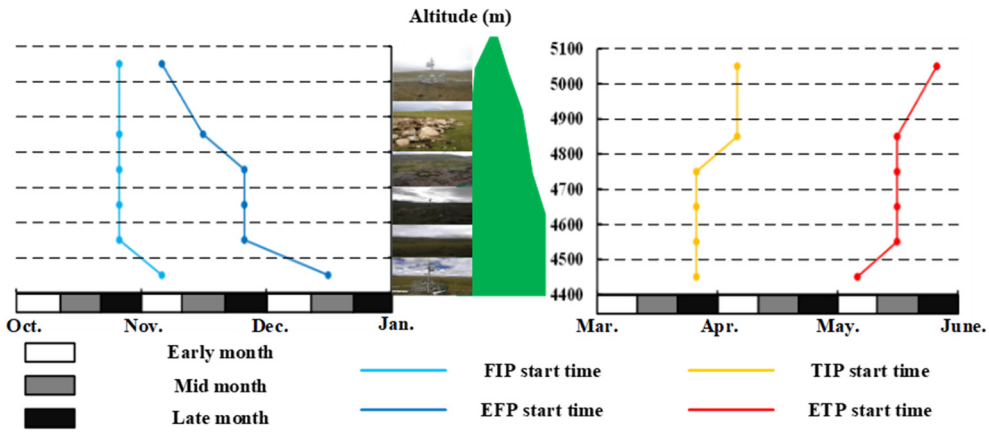

Fig.4 Division of the freezing-thawing process period at different altitudes in the NRB

With the altitude increases, the air thermal storage capacity gradually decreases, and the ground's reverse radiation ability decreases, resulting in a gradual decrease in air temperature. Lower TST lead to longer EFP, while the freezing of water in the soil requires less energy to be released, the start time of EFP (the end of FIP) is advanced, shortening the duration of the freezing process. Moreover, the higher altitude also causes the soil to enter the subzero temperature state in advance, and the time to leave the subzero temperature state is delayed, the start time of FIP is advanced and the end time of EFP is delayed. And the freezing-thawing process of the Fenghuo Experimental Site (below 5000 m a.s.l.) was divided by Wang [39] and Liu [38]. Compared with the Fenghuo Mountain, the EFP at XTGL is one month earlier, the duration of the continuous freezing lasts one more month, and the ETP moves forward by one month. Therefore, compared with the regions below 5000 m a.s.l, in the regions over 5000 m a.s.l., the lower TST, the earlier TSM reaches the minimum, ETP and TIP start later, EFP starts earlier, and EFP lasts longer.

3.6. Indirect effect of air temperature on TST and TSM

The process of water and heat exchange takes place between the top soil and atmosphere, and the change of air temperature plays a key role in FTP. Figure 5 reveals that TST increases with the increase of air temperature, but the effect of air temperature on TSM is more complicated. It can be inferred that the TSM affected by air temperature also appear the similar "upper and lower limit" phenomenon. TSM is mainly affected by TST, and air temperature indirectly affects TSM. A large number of experiments have been carried out, and the result shows that the logistic model has the best fitting effect on the relationship between air temperature and TSM, and the fitting effect in the regions below 5000 m a.s.l. is better than the regions over 5000 m a.s.l. When the air temperature is considered to be linear with TST, the fitting effect is best, as shown in the Figure 5.

In summary, the effects of air temperature on TSM vary in different periods. During the FIP and TIP, air temperature is positively correlated with TSM, while air temperature is negatively correlated with TSM during the ETP. The effect of air temperature on TSM can be ignored during the EFP.

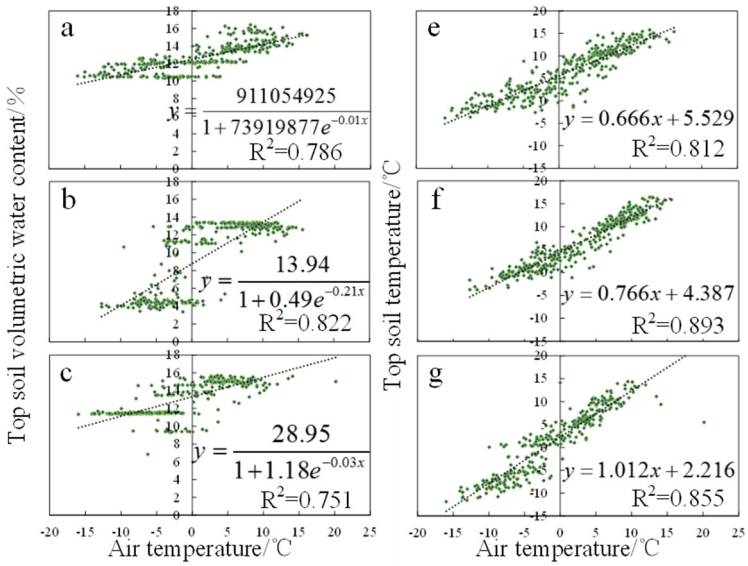

Fig.5 Effect of air temperature on TST and TSM, a/b/c is the effect of air temperature on TSM in CM/XM/XTGL, d/e/f is the effect of air temperature on TST in CM/XM/XTGL

3.7. Indirect effect of vegetation coverage on freezing and thawing process

The FIP and TIP of top soil in XTGL are earlier than those in the other two places, and the change of TSM is more rapidly. The reason may be that the vegetation coverage of CM and XM is higher than that of XTGL (Table 2), then more solar radiation is blocked by vegetation, which buffers the process of water and heat exchange between the ground and atmosphere, and the rapid change of temperature in the top soil is weakened. This result is the same with that of Li [37] and Liu [38]. However, the vegetation coverage in the regions over 5000 m a.s.l. is always smaller than that in the regions below 5000 m a.s.l. [44,45]. Compared with the Fenghuo Experimental Site [38,39], the vegetation coverage of the XTGL is lower, and the solar radiation that the vegetation can block is smaller, which makes the top soil absorb more energy, in this way, the TIP is relatively advanced. The maximum temperature difference of top soil in the regions over 5000 m a.s.l. is higher than that in the regions below 5000 m a.s.l. of about 6 °C (Table 3), which indicates that the lower vegetation coverage leads to greater annual variation of top soil temperature.

The role of vegetation coverage is to weaken the influence of the external environment. It cannot directly change TSM and TST, but its indirect impact on TSM and TST cannot be ignored. The vegetation coverage in the regions over 5000 m a.s.l. is always less than the regions below 5000 m a.s.l., thus the change rate of TSM is faster in the regions over 5000 m a.s.l., and the FIP is shorter.

3.8. Indirect effect of organic matter content on freezing and thawing process

As an important index of soil properties, organic matter content plays an essential role in the thermal conductivity and thermal capacity of soil. The organic matter content of top soil in XTGL is higher than that of the other two stations (Table 1), but the TIP and FIP of the XTGL is shorter and faster than the other two stations, which is contrary to the study of Zhang et al [46,47]. Their results show that the organic matter content is higher, the soil thermal conductivity is lower and the thermal capacity is higher, and the influence of solar radiation and air temperature on the soil reduced. That is to say, the heat that the soil diffuses into the atmosphere is reduced in the winter, and the heat absorbed by the soil from the atmosphere is reduced in the summer. But there are some differences in the regions over 5000 m a.s.l.

The main reason for the above situation is that FTP is affected at the same time by a series of factors such as altitude, air temperature, vegetation coverage and organic matter content, etc. The effect of organic matter content on FTPs may be less than other factors.

3.9. The main influence factor

The effect of organic matter content is misunderstood in Section 4.5, indicating that the influence of different environmental factors is different. Therefore, we analyze the influencing factors of TST and TSM during the FTP, which play different roles in different periods. Many researchers used CANOCO [48-51] for redundancy analysis (RDA), RDA is a constrained principal component analysis, which can analyze the relationship between samples and environmental factors, and the environmental factor that has the greatest effect on the sample is obtained. In this study, TST and TSM are selected as samples; altitude, air temperature, vegetation coverage, and organic matter content are considered as environmental factors, which are sorted by RDA (Figure 6).

In Figure 6, altitude, organic matter content, air temperature, vegetation coverage are environmental factors, and they are red arrow lines. TST and TSM are samples, and they are blue arrow lines. The longer the line of environmental factors, the greater the influence. We can find out that the influence of organic matter content is greater than that of the other three factors during FIP and EFP, and the influence of air temperature is greater during TIP and ETP. Therefore, in the analysis of satellite remote sensing and construction of model, the influence of different environmental factors in different periods should be considered, the weight of the most impact factors should be increased at different periods.

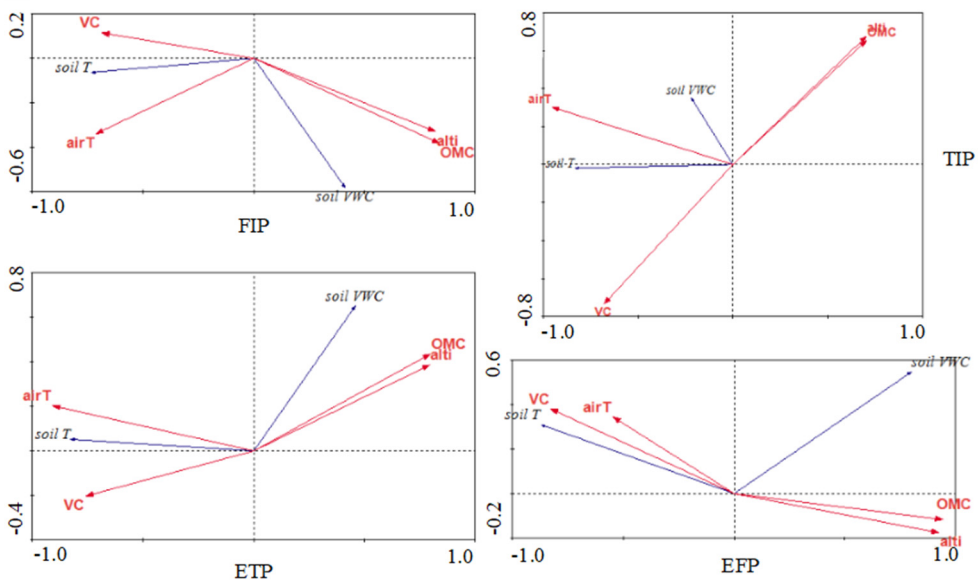

Fig.6 Analysis of the main influence factors in different periods

4. Conclusion

Based on the results and discussions presented above, the conclusions are obtained as below:

In the NRB of Qinghai-Tibet Plateau, the FTP of top soil in XTGL(the regions over 5000 m a.s.l) can be divided into four periods: freeze initiation period (FIP), entirely frozen period (EFP), thaw initiation period (TIP) and entirely thawed period (ETP). The TIP starts in early April, the ETP starts at the end of May, the FIP starts at the end of October, and the EFP starts at the beginning of November. Compared with the regions below 5000 m a.s.l, the FTP of the regions over 5000 m a.s.l is different. The FIP and EFP of XTGL start earlier, the TIP starts later and the freezing rate is faster. And the FTP of the regions over 5000 m a.s.l is more affected by altitude, vegetation coverage, and organic matter. The main influencing factor is organic matter content during FIP and EFP, the main influencing factor is air temperature during TIP and ETP.

With the warming of the climate, the FTP in alpine regions must change. The EFP may be shortened, the ETP may be extended, the FIP and TIP may be advanced, and the change process in the regions over 5000 m a.s.l may be more obvious. The growth of a series of organisms such as microorganisms and alpine vegetation is controlled by the FTP, and their growth progress may also be changed. Therefore, in future research, more attention should be paid to the monitoring of the FTP, and the difference between environmental factors above 5000 m a.s.l and below 5000 m a.s.l should be continuously studied, and more valuable information should be provided for the alpine regions to deal with climate change.

Acknowledgments

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