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Anomaly feature of seasonal frozen soil variations on the Qinghai-Tibet Plateau

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The seasonal frozen soil on the Qinghai-Tibet Plateau has strong response to climate change, and its freezing-thawing process also affects East Asia climate. In this paper, the freezing soil maximum depth of 46 stations covering 1961-1999 on the plateau is analyzed by rotated experience orthogonal function (REOF). The results show that there are four main frozen anomaly regions on the plateau, i.e., the northeastern, southeastern and southern parts of the plateau and Qaidam Basin. The freezing soil depths of the annual anomaly regions in the above representative stations show that there are different changing trends. The main trend, except for the Qaidam Basin, has been decreasing since the 1980s, a sign of the climate warming. Compared with the 1980s, on the average, the maximum soil depth decreased by about 0.02 m, 0.05 m and 0.14 m in the northeastern, southeastern and southern parts of the plateau, but increased by about 0.57 m in the Qaidam Basin during the 1990s. It means there are different responses to climate system in the above areas. The spectrum analysis reveals different change cycles: in higher frequency there is an about 2-year long cycle in Qaidam Basin and southern part of the plateau in the four representative areas whereas in lower frequency there is an about 14-year long cycle in all the four representative areas due to the combined influence of different soil textures and solutes in four areas.?

Anomaly feature of seasonal frozen soil variations on the Qinghai-Tibet Plateau WANG Cheng-hai1,2, DONG Wen-jie3, WEI Zhi-gang2 (1. College of Resource and Environmental Science, Lanzhou University, Lanzhou 730000, China; 2. Cold and Arid Regions Environmental and Engineering Research Institute, CAS, Lanzhou 730000, China; 3. Institute of Atmospheric Physics, CAS, Beijing 100029, China) 1 Introduction Soil freezing-thawing process in cryosphere plays an important role in regional climate and environmental change. Permafrost is a sensitive indicator (Pavlov, 1994). Because the seasonal freeze-thaw layer (activity layer) occurs in the upper part of the annual temperature change layer which is much nearer to the surface, it is much more sensitive and much quicker responsive to climate warming. If the net daily heat flux out of the ground is positive, the freezing front advances; if it is negative, the freezing front retreats, and a thawing front may form at the surface and advance into the soil (Keith et al., 1999). For example, Betts et al. (1996) have shown that it was possible to improve forecasts of northern hemisphere weather by better representation of the effects of soil temperature on latent and sensible heat flux in the boreal forest (Betts et al., 1996). Recent studies show that there is close correlation between freezing-thawing process and climate and environmental change. The thermal dynamic action plays an important role in general circulation model design and climate prediction of the Qinghai-Tibet Plateau. For instance, snow depth change on the plateau can affect flood and drought in summer of China. However, there are less research results on the relationship between frozen soil seasonal change on the plateau and regional climate change. The Qinghai-Tibet Plateau is a region in which there is the largest permafrost area with maximum thichness and lower temperature in middle and low latitude. The vastness of permafrost area on the plateau is related to its peculiar terrain and the frozen soil has especial seasonal changes. Persistent low temperature can reduce and restrain soil temperature increase, so soil freezing and thawing also represents the energy and water exchange between land and atmosphere. The existing studies showed that annual mean temperature on the plateau generally increases by about 0.2-0.4℃ in comparison with that of the 1970s. And especially in winter, temperature increases rapidly and annual temperature range decreases year by year, resulting in extensive degradation of permafrost area. It appears that seasonal freezing depth decreases and thawing depth increases (Li, 1996; Wang, 1996; Zhou et al., 1996).

Up to now, however, studies about frozen soil have only focused on the permafrost (Cheng, 1990; Jin et al., 2000; Zhou et al., 1982). As seasonal change of soil freezing and thawing associates with heat regimes near the plateau surface directly, the exchange of heat and moisture near surface affects regional and East Asia climate and circulation. Understanding entirely mechanism and degree between climate change and soil freezing and thawing is useful to design climate model and improve our ability of predicting climate and environmental change, and also useful to take countermeasures for climate and environmental malignant change. It is very important to study annual anomaly features of seasonal frozen soil in spatial and temporal aspects. 2 Data and method 2.1 Data In order to analyze the spatial and temporal anomaly features of seasonal frozen soil on the Qinghai-Tibet Plateau, we selected the maximum freezing soil depth at 46 meteorological stations (Figure 1) covering 1961-1999 on the plateau. All the stations lie in the east of the plateau because the interior of the plateau is an untouched continuous permafrost area. Selected stations spread widely and their altitudes vary greatly, such as the lowest Minghe station is in Qinghai province with an altitude of about 1814.8 m, mean annual precipitation of 346.9 mm, mean annual temperature of 7.8 oC. In cold month (January) the temperature is about -6.4 oC, the maximum freezing soil depth occurs in February, the minimum surface temperature is about -29.3 oC. The highest station of all is in Nagqu of Tibet with altitude being about 4508.0 m, mean annual precipitation, about 406.9 mm, mean annual temperature, about -1.9 oC, and the minimum surface temperature about -43.7 oC. Climate background of these stations are different, the northern part of the plateau is controlled by cold high under westerly trough and it is cold and dry. The minimum precipitation is found at Lenghu station locating in Qaidam Basin, where the altitude is about 2733.0 m, annual precipitation is about 16.7 mm, mean annual temperature is about 2.7 oC and mean monthly temperature is -12.7 oC in cold month (January). The southern part of the plateau is mainly affected by southern trough, it is especially easy to be affected by warm and humid air current from Bay of Bengal, resulting in high humidity and high temperature with annual precipitation of over 500 mm. The central part of the plateau is mostly affected by plateau altitude, both of humidity and temperature are lower and annual precipitation is under 300 mm (Dai, 1990). Because annual variation of the maximum freezing soil depth is not only affected by latitude and altitude, but also affected by climate background, soil texture, vegetation and solute. It is appropriate to analyze its spatial and temporal features by using principal component method. 2.2 method Using Empirical Orthogonal Function (EOF) first and then rotated empirical orthogonal function (REOF), we analyzed spatial and temporal features of the maximum freezing soil depth. According to EOF theory, a standard data matrix （Z hereafter）can always be expressed as: where mVk is m x k dimensions spatial eigenvector matrix (V hereafter) and kTn is k x n dimensions temporal coefficient matrix (T hereafter). Orthogonal transformation for (1) is given below: where L is spatial eigenvector, named as spatial loading vector (LV). Because Z has been standardized, apparently, L is the same as V in spatial pattern. Quantitatively, Ljk is one of the elements of L and is the correlation coefficient between the kth component and the jth station´s time serial of freezing soil depth. F and T have the same features, named as principal component (PC). In order to stand out regional features of LV, according to Horle, Ngarcheung Lau (1982) (Horel D 1981), based on EOF, eigenvector is orthogonally rotated, such as for whatever two factors, the loading vector matrix and orthogonal transform matrix is as follows respectively: Extensively, the loading vector of every 2 factors of L is rotated step by step. In general, if n factors need to be rotated, times of rotation are needed. After rotation, the total variance of rotation each time is given as: Clearly, at the ith rotation, the variance is G (i), at i+1th, it is G (i+1), when G (i) increases to G (i+1) the rotation stops, as no apparent changes occur to total variance. In general application, a threshold value |G（i+1）-G（i）|<α can be set as termination of the adjusted factor loading matrix. The resulting rotated LV and PC then changed into rotated loading vector (RLV) and rotated principal component (RPC) respectively. LV is the main anomaly features to express equivalent scale of the analyzed field and RLV denotes regional features of the analyzed field. For details, please refer to Horel, 1981. We select the first 10 components for rotating based on EOF results. The square main tendency function is where the constants a0, a1 and a2 can be determined by least square estimate (LS). 3 The anomaly features of maximum freezing soil depth on the Qinghai-Tibet Plateau The data sets of maximum soil depth on the Qinghai-Tibet Plateau was analyzed by using EOF and REOF. LV and PC represent loading vector and temporal principal component before rotating, while RLV and RPC are rotated loading vector and rotated principal component respectively. Quantity variance represents strong or weak regional features of the analyzed fields. According to the theories of REOF and EOF, the values of LV and RLV in the figure are correlation coefficients, the square value is correlation coefficient between original time serial and PC or RPC, because the variance of original time serial is equal to 1, so is the ratio of represent variance to original variance. Thereby the higher value in the figure has significance. An absolute value of LV or RLV represents sensitivity of interannual variation of original time serial variance. Table 1 indicates the contribution percentage of every PC and RPC to total variance of sea sonal freezing soil depth. As the first two loading vectors have already occupied 60% of the total variance with relative little difference of the rest of PC (Table 1), we only analyzed the 1st and 2nd loading vector. After rotating, PC1 and PC2 decrease, i.e., parts of the variance of PC1 and PC2 transfer to other PC. Similarly, because approximately 69.8% of the total variance explained by the first four loading vectors with relative little difference of the rest of RPC, we only analyzed these vectors. The first two loading vectors of the seasonal frozen soil that used to indicate the intact features of seasonal frozen soil are showed in Figure 2. The first loading vectors (LV1) are positive values almost throughout the Qinghai-Tibet Plateau except the weak negative values in southeast of the plateau. The central (maximum) value of the loading vector is 0.6. In this area, the seasonal change of plateau frozen soil is most sensitive and the rate of change is largest. The altitude of the entire plateau is high, but the terrain of it is more complicated and the altitudinal differences of various stations are greater, so the rate of change is great although the frozen period is long. Because of controlled by the same climate system, the continual and large scale frozen soil still constitutes the first feature of seasonal change of plateau frozen soil. Figure 2b shows the second spatial pattern of seasonal frozen soil. It indicates the opponent changing tendency between northwest and southwest of the plateau. Northwest of the plateau is easy to be influenced by the cold air coming from north, especially the block of the cold air to south, these make the cold air change their character in the Qaidam Basin and at the same time make the freezing soil depth change since the surface of the plateau is heated by the variety of cold air. Because the southward cold air is inaccessible to get to southwest of the plateau, both altitude seasonal climate influence the freezing soil depth. We have discussed the intact spatial anomaly features of the seasonal changes of the plateau frozen soil. The main one is the difference between northwest and southwest of the plateau. For standing out the distributive character of the seasonal changes of the plateau frozen soil in different areas of the plateau, we rotated the main 10 components and loading vectors mentioned previously. We got four main spatial anomaly distributive areas of seasonal change of the plateau frozen soil on the basis of the first four rotated loading vectors (Figure 3). The isoline that RLV1 values (Figure 3a) is greater than 0.6 contains an anomaly spatial area that indicates a direction of northeast-southwest. That is to say, this expresses that this type can explain the variance up to 60% for this area´s maximum freezing soil depth. The maximum centers are located in Nagqu and Zadoi. The central value of the loading vector is 0.90, and it is 0.91 in areas northeast of the plateau, such as Zadoi and Caka where the main frozen soil is in patch distribution. As mentioned before, soil humidity is relatively low in these areas and these areas are the most sensitive areas to seasonal change of the plateau frozen soil. Comparing the principal component PC and the rotated principal component RPC, we can find the RPC1 is lower than PC1 in rate of the total variance, but RLV1 is higher than LV1. This illustrates the principle of REOF, that is, the rotated loading vector becomes larger and stands out the local character of interannual change of seasonal frozen soil in northeast of the plateau after being rotated, this is the first anomaly pattern--the plateau northeast pattern. Figure 3b shows the second loading vector RLV2 of seasonal change of the plateau frozen soil. The isoline (α=0.5) contains an anomaly spatial area. The highest center is located in Golmud and Lenghu on the plateau with its value up to 0.88. In other words, LV2 occupies 50% of the annual variance of seasonal change of the maximum freezing soil depth in this area. This area is located in Qaidam Basin, where it is dry with deficient water, salinization-alkalization is quite obvious; the cold air coming from northwest is easy to get to this area which is mainly controlled by the cold high pressure ahead of westerly trough in winter. This area belongs to river valley seasonal frozen soil area, which is another sensitive anomaly area of interannual change of frozen soil--the Qaidam Basin type. Figure 3c shows the third loading vector RLV3 of seasonal soil interannual change of the plateau seasonal frozen soil. The areas with absolute values greater than -0.35 contain this anomaly spatial area, that is to say, the higher value areas are located between south of the Bayan Har Mountains and north of the Nyainqentanglha Mountains. The highest value is located in Yushu of Qinghai Province and Lhorong of Tibet, and the central value (in Lhorong) is 0.88. These areas belong to alpine gorge island frozen soil area and relate closely to southwest summer monsoon in China and are the areas that receive the maximum amount of precipitation over the plateau. These areas are the other sensitive areas of annual change of the Qinghai-Tibet Plateau frozen soil--the plateau southeast type. Figure 3d shows the fourth loading vector RLV4 of seasonal change of the plateau frozen soil. The areas with absolute values greater than 0.4 are around Zetang-Cona in southern part of the plateau. The maximum value center is located in Zetang where the value is 0.84. Because this area is located in the Yarlung Zangbo river gorge on northern slope of the Himalayan Mountains, and belongs to the intermediate zone between alpine island permafrost and Yarlung Zangbo river gorge seasonal frozen soil, this type is similar to the southeast pattern of the plateau. But this area is not easily influenced by southwest monsoon, so this area is another sensitive area of the interannual change of plateau seasonal frozen soil--the plateau south pattern. In summary, the interannual anomaly patterns of the plateau seasonal frozen soil mainly include the plateau northeast pattern, the Qaidam Basin pattern, the plateau southeast pattern and the plateau south pattern. They are the most sensitive areas of interannual change of the plateau seasonal frozen soil. 4 The temporal tendency and features of interannual anomaly of the plateau seasonal frozen soil 4.1 The annual change and tendency of freezing soil depth at representative stations RPC resulting from REOF analysis for the plateau seasonal frozen soil indicates the temporal change corresponding to the RLV spatial abnormal types. Because the larger values of RLV indicate the relativity among RPC and original frozen soil serial, we use the representative stations in which the center value is the highest of each anomaly area to analyze the temporal tendency. Figure 4 gives the annual change and tendency of maximum freezing soil depth for four representative stations. It shows that the interannual change tendency of the plateau freezing soil depth changes with time in two types. The first type is parabola with maximum value, such as Caka (36o47´N, 99o05´E) which represents the northeast pattern, Cona (27o59´N, 91o57´E), the south pattern, Qamdo (31o09´N, 97o10´E), the southeast pattern. In these areas, the freezing depth increased prior to the 1970s, maintained a higher value from the 1970s to the 1990s and decreased since the 1990s. Compared with the 1980s, in the 1990s the freezing depth decreased by 0.05 m, 0.02 m and 0.14 m in Caka, Cona and Qamdo respectively. The second type is parabola with the minimum value, such as Lenghu (38o50´N, 93o23´E) which represents the Qaidam Basin pattern. The freezing depth was higher prior to the 1970s, lower from the 1970s to the 1990s and increased since the 1990s. Compared with the 1980s, in the 1990s the maximum freezing depth increased by 0.57 m; in other words, the changing tendency of the maximum freezing depth is opposite in the Qaidam Basin to the northeastern part of the plateau. This tendency shows changes of different freezing soil depths corresponding to climate system vary, that is to say, the climate system influencing different places of the plateau varies. 4.2 The change period of soil seasonal freezing depth on the Qinghai-Tibet Plateau Figure 5 shows the spectral analysis of seasonal freezing depth of the four representative stations. We can find that except Coka, an about 14-year period at four stations in lower frequency portion, another is a two-year period in high frequency portion occurs except Lenghu and Cona. This not only indicates the variations in the climate system controlling the four areas, but also the differences in soil textures and solutes in four sensitive areas is different to a certain degree. Different soil textures and solutes have different sensitivities to climate, this is reflected in great differences in time needed to completely freeze and thaw soils with different textures under same moisture and negative temperature conditions. But for the longer time scale, the change period is similar, indicating the effect to the continuous temperature changes. 5 Conclusions and discussion There are many evidences to show the significant dynamic effects of the Qinghai-Tibet Plateau to atmosphere. But heat effects and heat distribution over the Qinghai-Tibet Plateau has been a point of argument for a long period of time. Heat regimes and distribution are influenced by underlying surface of the physical properties and vegetation types. The areas of the plateau belong to permafrost; whether soil is frozen or unfrozen directly affect the heat-moisture exchange between land and atmosphere. So understanding the status of frozen soil is useful for us to study the plateau´s response to climate and its impact on atmospheric circulation. There are 4 anomaly areas distributed based on interannual variations of soil freezing depth. There are 4 types of anomaly areas responsive to climate change, i.e., northeastern, southern and central parts of the plateau, that are all controlled by the same climate system, and Qaidam Basin is a unique area which is different from the other three areas. Variations of freezing soil depth has experienced a high-low-high change process during the 1960s to the 1990s, representing a response to climate change. It is particularly worthnoting that significant maximum freezing depth decrease has occurred since the 1990s on the plateau except for Qaidam Basin. If it is only considered as a result of responding to climate system, this implies that climate has entered a warming period in China since the 1990s, the same as global warming. Variations of freezing soil depth has a slow change character. Results of spectral analysis suggest that compared with snow, soil freezing-thawing responsive to solar radiation is slow, so its release and absorption of soil heat capacity. Therefore, it may have continued effects on atmospheric circulation. References Figure 1 The distribution map of meteorological stations on the Qinghai-Tibet Plateau Figure 2 The first two loading vectors of the maximum freezing soil depth on the Tibetan Plateau (the interval of line is (a) 0.04, (b).0.1) Figure 3 The first four rotating loading vectors of the maximum freezing soil depth on the Tibetan Plateau (the interval of line is 0.2) Figure 4 Annual change (solid line) and tendency (dash line) of normalized variables of maximum soil freezing depth for Caka (a), Lenghu (b), Yushu (c) and Cona (d) Figure 5 The power spectral curve of maximum soil freezing depth (solid line) and red noise (dash line) for Caka (a), Lenghui (b), Qamdo (c) and Cona (d) Table 1 Contribution percentage of the first ten PC and RPC to square variance (%)

关键词： Qinghai-Tibet Plateau; seasonal frozen soil; rotated empirical orthogonal function analysis; anomaly areas