Changes in the near-surface soil freeze–thaw cycle on the Qinghai-Tibetan Plateau

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A B S T R A C T
Changes in the near-surface soil freeze–thaw cycle on the Qinghai-Tibetan Plateau (QTP) were detected using daily soil freeze/thaw states derived from Special Sensor Microwave/Imager data from 1988 to 2007. Linear trends in freeze and thaw dates, the number of total frozen days of each pixel, and the numbers of monthly and yearly frozen days averaged over the whole QTP were analyzed. Principal component analysis was used to investigate the spatial variation in the freeze–thaw cycle. The results show that on the QTP there was a trend toward earlier onset date of soil thaw by approximately 14 days, and later onset date of soil freeze by approximately 10 days over the period 1988–2007. The number of frozen days has decreased over the QTP by 16.8 days per decade. This decrease in the number of frozen days has occurred mainly from April to September, with a more pronounced trend in warmer months. The most significant changes were in the northeastern and southwestern QTP, where discontinuous permafrost, island permafrost, and seasonally frozen ground are presented. The northwestern QTP had almost no change, where permafrost is cold and stable. The trend in the near-surface soil freeze–thaw cycle is positively related with climate warming on the QTP. Much warmer winters may account for significantly earlier thawing, later freezing, and a substantial reduction in the number of frozen days on the QTP. These changes in the near-surface soil freeze–thaw cycle can be used both as an effective indicator of the permafrost change and for mapping of permafrost stability. Changes in near-surface soil freeze–thaw cycle and consequently permafrost conditions would have dramatic influence on hydrologic processes, ecosystem, and engineering operations over the QTP.

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1. Introduction

The Qinghai-Tibetan Plateau (QTP) is the world’s highest region and is often called as the third pole (Qiu, 2008), and it is sensitive to climate change (Cheng, 1996; Liu et al., 2006; IPCC, 2007). Much evidence indicates that the mountain cryosphere of the QTP has been changing rapidly (Li et al., 2008; Kang et al., 2010; Qin and Ding, 2010), but most evidence relies on sporadic observations. A broad understanding of regional-scale changes in cryosphere has not yet been established. The near-surface soil freeze–thaw cycle is sensitive to climate change and is closely related to changes in permafrost, seasonally frozen ground, hydrological processes, and ecosystems. However, because of the scarcity of in situ observations, changes in the near-surface soil freeze–thaw cycle have only been observed in limited areas, such as along the Qinghai-Tibetan Railway or Highway (Cheng and Wu, 2007; Wu and Zhang, 2008, 2010; Zhao et al., 2010) and in other relatively accessible areas (Jin et al., 2000; Wang et al., 2000; Zhao et al., 2004). The objective of this paper is to provide a reliable and up-to-date analysis of changes in the near-surface soil freeze–thaw annual cycle on the QTP by taking advantage of long-term, continuous observations from passive microwave remote sensing.

Over the past two decades, investigators have developed a variety of methods to detect the freeze/thaw state of the surface soil using passive microwave remote sensing. These methods can generally be classified into three different types. The first type of classification method can be called the dual-indices method. This method uses a “negative spectral gradient” between higher (36/37 GHz) and lower (18/19 GHz) channels and a low brightness temperature at 36/37 GHz (Zuendorfer and England, 1992). The mechanism underlying this effect is that (1) the temperature of the frozen soil is low and (2) when the soil freezes, the scattering-darkening caused by volume scattering tends to be more significant

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at higher frequencies, which reduces the effective emissivity at high frequencies. When this method is used, two empirical thresholds of the dual indices are determined depending on ground observations. The thresholds for negative spectral gradient and brightness temperature at 36/37 GHz vary from −0.3 K/GHz to 0.0 K/GHz and from about 220 K to 258 K in different regions (Zuenderorfer and England, 1992; Cao and Chang, 1997; Zhang and Armstrong, 2001; Zhang et al., 2004). The second type of method uses a time series analysis (Smith et al., 2004). The mechanism underlying this method is that when soil freezes, (1) the brightness difference between higher and lower frequencies diminishes, and (2) the emissivity significantly increases. These phenomena can be captured by high temporal frequency microwave remote sensing. The third type of method is the classification tree method, which combines the above mechanisms with a scattering index and other existing classification rules to sort out other factors related to land status, such as precipitation and snow (Jin et al., 2009). In addition to these methods, the detection of the soil and vegetation freeze/thaw state using active microwave sensors, such as radar and scatterometer, has also been performed by many investigators (Way et al., 1997; Froeling et al., 1999; Kimball et al., 2001). It is also worth emphasizing that a major objective of the next-generation microwave satellite SMAP (Soil Moisture Active Passive) (Entekhabi et al., 2004, 2010) is to measure the freeze/thaw state with simultaneous L-band backscattering observations. Therefore, more active research in microwave remote sensing of soil freeze–thaw cycle can be expected.

Most of the results to date indicate that the surface soil has been thawing and that the growing season has been significantly prolonged in the Arctic, North American boreal area, Siberia, and other regions (Froeling et al., 1999; Wismann, 2000; Zhang et al., 2003; Kimball et al., 2004; Smith et al., 2004; Jin et al., submitted for publication; Kim et al., 2011). However, as the third pole of the world and one of the world’s largest mountain cryosphere areas, the near-surface soil freeze–thaw cycle on the QTP has not been systematically investigated. Therefore, in this study, a modified dual–indices classification algorithm was applied to detect the changes in the near-surface soil freeze–thaw cycle on the QTP based on the daily soil freeze/thaw states derived from Special Sensor Microwave/Imager (SSM/I) data from 1988 to 2007. The aim of this study is to provide an overall picture of the changes in the near-surface soil freeze–thaw cycle on the QTP, which is very important for understanding cryospheric change in this area.

2. Data and methods

2.1. Study area

The QTP is the largest plateau in China, and it is the world’s highest plateau (Qiu, 2008) with an average height of 4500 m above sea level. It is located between 74–105° E and 25–40° N and covers an area of approximately 2,545,000 km² (Fig. 1).

2.2. Data

The passive microwave remote sensing data used were the daily SSM/I data from 1988 to 2007. The SSM/I data are archived at the National Snow and Ice Data Center (http://nsidc.org/) and were re-sampled into the unified Equal Area Scalable Earth Grid (EASE-Grid) format with a resolution of 25 km (Armstrong and Brodzik, 1995). The vertical polarization brightness temperatures at 19.35 and 37.0 GHz for the SSM/I data were selected for use with the dual-indices algorithm. The overpass time occurs around 06:00 and 18:00 local time for the SSM/I data. Because the near-surface soil freeze/thaw states change quickly with the soil temperature, we used the cold-overpass data in the early morning to capture the daily soil freeze–thaw cycles, specifically including the F8-SSM/I ascending data (6:00), F11-SSM/I descending data (6:00) and F13-SSM/I descending data (6:00). An improved cross-sensor calibration has been done for the SSM/I version 6 product (Brodzik and Knowles, 2002), which was used in this study.

A land cover map of China (Liu et al., 2005) was used in the calibration of the dual-indices classification algorithm. The land cover map was resampled to a resolution of 25 km, consistent with SSM/I EASE-Grid data sets. Table 1 shows the dominant land cover types of China, including grasslands (covering 33.31% of the land surface), forests (24.77%), cropland (20.22%), unusable land (13.93%), deserts (5.70%), and water bodies (2.07%).

The daily minimum ground surface temperature data from meteorological stations of the Chinese Meteorological Administration (CMA), located in regions of permafrost and seasonally frozen
ground across China, were used to calibrate and validate the classification algorithm. The daily minimum ground surface temperature was measured at the soil surface with a minimum thermometer.

An air temperature distribution map of the QTP in January (Li et al., 2005) was used to analyze the relationship between the number of frozen days and the winter air temperature.

### 3. Classification method

A dual-indices classification algorithm that uses the spectral gradient between the 37 GHz ($T_{37v}$) and 18/19 GHz ($T_{18/19v}$) brightness temperatures (SD) and the 37 GHz vertical-polarization brightness temperature (Zuerndorfer and England, 1992; Zhang and Armstrong, 2001) was applied to detect the freeze/thaw state of the surface soil. The algorithm can be expressed as

\[ T_{37v} < T_{\text{cutoff}} \]

\[ SD = T_{37v} - T_{18/19v} < SD_{\text{cutoff}} \]

where $T_{\text{cutoff}}$ and $SD_{\text{cutoff}}$ are, respectively, the brightness temperature and spectral gradient thresholds for determining the surface soil freeze/thaw state. It was found that these two thresholds vary greatly in different regions and for different land cover types (Zuerndorfer and England, 1992; Cao and Chang, 1997; Zhang and Armstrong, 2001). Therefore, in this study, the thresholds are recalibrated for different land cover types.

In total, 77 CMA stations with a relatively homogeneous land cover type across a 3 × 3 pixel area were selected to calibrate the thresholds in Eqs. (1) and (2). The calibration included the following steps. (1) A linear relationship between the daily minimum ground surface temperature and the ground surface temperature at SSM/I overpass time was established by a least-squares linear regression, with a $R^2$ of 0.95 and a standard deviation of 1.2 ◦C. (2) According to the above regression equation, the daily minimum ground surface temperature corresponding to the soil freezing point (0 ◦C) at the hour of SSM/I overpass were determined as −1.07 ◦C, which were adopted to separate the frozen and thawed training samples from the matchup SSM/I time series. (3) The mean values and the standard deviations of the $T_{37v}$ and the SD were calculated for the frozen and thawed training samples for each land cover type. The thresholds of $T_{37v}$ and SD were determined as the above mean values. The calibration results for different land cover types are presented in Table 1. (4) A pixel was classified as being in a frozen state if both the $T_{37v}$ and the SD were less than the thresholds; otherwise, the pixel was classified as being in a thawed state. (5) The pixels with the land cover type of a water body or a desert were masked out of the analysis.

Validation was performed using the daily minimum surface temperatures from another 273 CMA stations between

**Table 1**

<table>
<thead>
<tr>
<th>Land surface type</th>
<th>Calibration results: thresholds of $T_{37v}$ and SD</th>
<th>Validation results: accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_{37v}$</td>
<td>SD</td>
</tr>
<tr>
<td>Irrigated cropland</td>
<td>261.26</td>
<td>−2.00</td>
</tr>
<tr>
<td>Nonirrigated cropland</td>
<td>262.28</td>
<td>−1.75</td>
</tr>
<tr>
<td>Dense forest</td>
<td>264.21</td>
<td>−2.31</td>
</tr>
<tr>
<td>Shrubland</td>
<td>262.47</td>
<td>−2.80</td>
</tr>
<tr>
<td>Sparse forest</td>
<td>263.38</td>
<td>−1.90</td>
</tr>
<tr>
<td>Higher coverage grassland</td>
<td>260.62</td>
<td>−2.73</td>
</tr>
<tr>
<td>Moderate coverage grassland</td>
<td>261.84</td>
<td>−2.78</td>
</tr>
<tr>
<td>Lower coverage grassland</td>
<td>262.32</td>
<td>−2.99</td>
</tr>
<tr>
<td>Unusable land</td>
<td>256.00</td>
<td>−4.00</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 2.** The mean number of frozen days between 1988 and 2007 on the Qinghai-Tibetan Plateau.
January 1, 1988 and December 31, 2006. Overall, the classification accuracy of the surface soil freeze/thaw state was approximately 88.7%, and the accuracy varied by land cover type (Table 1). These results indicate that the re-calibrated algorithm can detect the surface soil freeze/thaw state with sufficient accuracy.

Based on the re-calibrated dual-indices classification algorithm, the daily surface soil freeze/thaw state classification results were obtained for the period from 1988 to 2007. Because there are data gaps between the neighboring swatches of SSM/I, especially at lower latitude, a 7-day moving average was then calculated to fill the data gap. After the above data processing, a daily dataset for the surface soil freeze/thaw state across China was obtained (more details can be found in Jin et al., submitted for publication). We used this dataset for further analysis.

4. **Trend analysis**

The following criteria were used to detect changing trends in the near-surface soil freeze–thaw cycle:

1. The freeze date and thaw date of each pixel. The onset date of soil freeze is defined as the first day after August 1 when a pixel is classified as being in the state of freeze for three successive days. The onset date of soil thaw is defined as the first day after January 1 and before August 1 when a pixel is classified as being in the state of thaw for three successive days. The trends in freeze and thaw dates show changes in the timing of the land surface freeze–thaw cycle.
(2) The total number of frozen days for each pixel. The total number of frozen days is defined as the actual number of days of surface soil freeze.

(3) The numbers of area-averaged monthly and yearly frozen days from 1988 to 2007.

A trend analysis of the above changing criteria was performed using linear regression. P-values were calculated to test the statistical significance of trends in the area-averaged monthly and yearly frozen days. Only trends with a P-value less than or equal to 0.01 were considered statistically significant and accepted for further analysis.

4.1. Principal component analysis

To determine the spatiotemporal variation in the near-surface soil freeze–thaw cycle, principal component analysis (PCA) was used to analyze the seasonal and inter-annual variations in the near-surface soil freeze/thaw state of each pixel. The standardized PCA proposed by Eastman and Fulk (1993) was used. Because the image data set is a time series of an environmental variable, the first principal component represents the variable’s characteristic feature, and the second and other principal components represent gradually decreased change elements in sequence (Eastman and Fulk, 1993). PCA helps to identify the place with greatest change in the near-surface soil freeze–thaw cycle and its relationship with other environmental variables. In this paper, the PCA analysis was performed using IDRISI Andes software. We used monthly images of surface soil frozen days from 1988 to 2007 as the input. In total, there are 240 images in our time series.

5. Results

5.1. Spatial distribution of the near-surface soil freeze/thaw state

Fig. 2 shows the spatial patterns in the number of frozen days averaged over the last 20 years from 1988 to 2007. The number of frozen days on the QTP is very large: over 350 days in the northwestern QTP (Qiangtang Highland); over 300 days in the Qilian Mountains, the Himalayas, and other high mountains; and 250–300 days for other parts of the northern and western QTP. The above areas are all located in regions of permafrost as shown in Fig. 3 of Li et al. (2008). For regions with seasonally frozen ground, the frozen period lasted about 200–250 days. Only marginal areas in the eastern and very southern QTP with relatively low elevations have a soil freeze time of fewer than 200 days. The area-averaged frozen days for the whole QTP are 269 days. A correlation analysis shows that the spatial pattern of the number of frozen days is negatively correlated with the distribution of January air temperatures, with a correlation coefficient of −0.76. This correlation is significant at the 0.01 level.

5.2. Trend of near-surface soil thaw and freeze dates

Fig. 3a and b shows changes in the onset dates of surface soil thaw and freeze on the QTP from 1988 to 2007. During this period, the onset date of soil thaw went ahead by 14.3 ± 13.0 days.

![Relationship between the change in the number of frozen days and the elevation.](image-url)
almost (mean value ± 1 standard deviation) days, indicating a much earlier thawing. The most significant advances happened in the northeastern and southwestern QTP, particularly in the transitional zone between regions of permafrost and seasonally frozen ground. Shorter advances occurred in the northwestern QTP, where the most stable permafrost exists, and changes in surface soil freeze are almost undetectable, which means the trend approaches zero, because the area is frozen all year (Fig. 3a). The onset dates of soil freeze lagged by 10.1 ± 11.2 days on the QTP. Significant changes also occurred in discontinuous permafrost and island permafrost areas, which most likely represents unstable permafrost and regions with seasonally frozen ground (Li et al., 2008, Fig. 3), whereas lesser changes occurred in the northwestern QTP (Fig. 3b).

5.3. Changes in the total number of frozen days

The total number of frozen days decreased by approximately 10–50 days over the past two decades, but the changes were spatially variable (Fig. 4). Our results show the following: (1) Across almost the entire QTP, the number of frozen days decreased, except for in a small area in the very southern QTP and in the northwestern QTP. (2) The number of frozen days decreased more significantly in the northeastern and southwestern QTP, where the change had a magnitude of approximately 40–50 days. The decrease in the number of frozen days in the central QTP was moderate, i.e., approximately 20–30 days. The number of frozen days in the northwestern QTP did not change considerably. (3) Most of the changes happened at elevations between 2500 and 5000 m (Fig. 5) in zones containing discontinuous permafrost, island permafrost, and seasonally frozen ground.

PCA was used to analyze the number of surface soil frozen days from 1988 to 2007. The PCA results indicate that the first three components represent spatial patterns of the number of frozen days on the QTP and the greatest changes to these patterns (Fig. 6). The variances of the first three components comprise 80.29%, 12.72%, and 2.24% of the total variance, respectively. Loading charts show the correlation coefficients between the monthly images and the first to third principal components (Fig. 7). If a sequential image in the time series is positively correlated with a component, it means that this image has a similar spatial pattern to the component. In contrast,
if a sequential image is negatively correlated with a component, it tends to be the inverse of the spatial pattern in the component image (Eastman and Fulk, 1993).

Fig. 6 indicates that the first component clearly represents the spatial structure of the surface soil freeze state. A higher integrated value in the component 1 indicates a higher number of frozen days. The area with the highest number of frozen days is located in the northwestern QTP, the Himalayas, and other high mountains, which is consistent with Fig. 2. With respect to the loadings (Fig. 7), all of the sequential images are positively correlated with Component 1. The correlations are much higher (>0.9) in autumn and winter (September–March of the next year) but lower in spring and summer (April–August). These correlations indicate that the distribution of surface soil freeze in autumn and winter contains a latent spatial pattern that is more similar to that of Component 1. The spatial pattern in spring and summer is also comparable with that of Component 1 but with less similarity. All of these findings suggest that the soil freeze is a very dominant phenomenon on the QTP.

Component 2 (Fig. 6) shows the spatial pattern of the annual near-surface soil freeze–thaw cycle, which is positively correlated with the images from April to August (Fig. 7), whereas images in other months have negative correlations. The area with negative correlations in the eastern QTP corresponds spatially to the seasonally frozen ground area, which has a longer thawing season than freezing season. The area with positive correlations in the northwestern QTP corresponds to the stable permafrost area, which has a much longer freezing season than thawing season. The very northwestern part with the highest positive correlation even experienced no annual freeze–thaw cycle. The central QTP shows an intermediate annual soil freeze–thaw cycle, where is the transitional zone between regions of permafrost and seasonally frozen ground. The discontinuous permafrost and island permafrost are distributed in this area. Component 2 clearly illustrates the seasonality of the annual cycle of near-surface soil freeze–thaw.

Component 3 (Fig. 6) has two areas of positive correlation, and the loading chart also displays two annual cycles (Fig. 7). The peak values in winter may correspond to the areas of positive correlation in the northwestern QTP, where the soil is permanently frozen. The peak values in summer may correspond to the areas of positive correlation in the eastern QTP, where the soil remains thawed for most of the year. The change in the number of frozen days in these two areas is weak. The area of negative correlation corresponds to the area where the number of frozen days decreased much more significantly. Therefore, component 3 also represents the change in the number of frozen days. The spatial pattern in component 3 is in consistency with the results in Fig. 4.

5.4. Trends in the numbers of area-averaged frozen days

Table 2 shows the trends in the numbers of area-averaged monthly and yearly frozen days from 1988 to 2007 on the QTP. We consider that a trend is statistically significant only if the P-value is less than or equal to 0.01. Therefore, the hypothesis that there are linear trends in most winter months, i.e., January, February, October, November, and December, was rejected. The trend in March could be considered significant, but the slope of the regression equation (normalized to a decadal rate) was low enough (Table 2) that the trend could be neglected. Therefore, only trends from April to September were analyzed. These findings are consistent with climatology on the QTP (Dai, 1990; Tang et al., 2003). The freeze/thaw shifting is most likely to happen in April–September on the QTP.

In each month from April to September, there was a decreasing trend in the number of frozen days (Fig. 8). In the warmer months, especially in July and August, the decreases were more significant. In total, there was a decrease of approximately 33.7 days from 1988 to 2007, with a decadal rate of 16.8 days.

6. Discussion

What is the forcing factor for the change in the near-surface soil freeze–thaw cycle on the QTP? Is the change significant and comparable with that found in other related studies? We will answer these questions by comparing the results obtained in this paper with the results from previous investigations.

The near-surface soil freeze–thaw cycle is clearly and positively related to climate warming on the QTP. Liu and Chen (2000) and Liu et al. (2006) reported that the air temperature on the QTP had an increasing trend. In particular, the increases in winter and at night were among the highest and most significant when compared with other regions (Liu et al., 2009; Qin et al., 2009). Wu and Zhang (2008) also reported that the air temperatures in the winter along the Qinghai-Tibetan Highway and Railway increased on average by 2.9–4.2 °C from 1995 to 2005. Warming winters and warming nights mean less freezing. Many evidences have shown that the duration of seasonal ground freezing has shortened in response to a warming climate, especially the increase in winter air temperature (Zhao et al., 2004; Yang et al., 2010). It was also found in this paper that the number of frozen days has a strong positive
Table 2
Summary of the statistics of the changes in the numbers of area-averaged frozen days in different months from 1988 to 2007 on the Qinghai-Tibetan Plateau.

<table>
<thead>
<tr>
<th></th>
<th>Correlation coefficient</th>
<th>Statistical significance (P-value)</th>
<th>Decadal rate (days/10 years)</th>
<th>Decreased days from 1988 to 2007 (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.21</td>
<td>0.38</td>
<td>0.03</td>
<td>0.07</td>
</tr>
<tr>
<td>February</td>
<td>−0.22</td>
<td>0.36</td>
<td>−0.17</td>
<td>−0.34</td>
</tr>
<tr>
<td>March</td>
<td>−0.56</td>
<td>0.01</td>
<td>−0.39</td>
<td>−0.78</td>
</tr>
<tr>
<td>April</td>
<td>−0.72</td>
<td>0.00</td>
<td>−1.26</td>
<td>−2.53</td>
</tr>
<tr>
<td>May</td>
<td>−0.71</td>
<td>0.00</td>
<td>−2.08</td>
<td>−4.15</td>
</tr>
<tr>
<td>June</td>
<td>−0.80</td>
<td>0.00</td>
<td>−2.54</td>
<td>−5.07</td>
</tr>
<tr>
<td>July</td>
<td>−0.86</td>
<td>0.00</td>
<td>−3.87</td>
<td>−7.73</td>
</tr>
<tr>
<td>August</td>
<td>−0.93</td>
<td>0.00</td>
<td>−3.81</td>
<td>−7.62</td>
</tr>
<tr>
<td>September</td>
<td>−0.78</td>
<td>0.00</td>
<td>−1.78</td>
<td>−3.56</td>
</tr>
<tr>
<td>October</td>
<td>−0.35</td>
<td>0.13</td>
<td>−0.76</td>
<td>−1.51</td>
</tr>
<tr>
<td>November</td>
<td>−0.46</td>
<td>0.04</td>
<td>0.32</td>
<td>0.64</td>
</tr>
<tr>
<td>December</td>
<td>0.19</td>
<td>0.41</td>
<td>0.09</td>
<td>0.18</td>
</tr>
<tr>
<td>May–September</td>
<td>−0.93</td>
<td>0.00</td>
<td>−14.07</td>
<td>−28.14</td>
</tr>
<tr>
<td>Year</td>
<td>−0.89</td>
<td>0.00</td>
<td>−16.84</td>
<td>−33.69</td>
</tr>
</tbody>
</table>

Fig. 8. Changes in the numbers of area averaged frozen days in different months from 1988 to 2007 on the Qinghai-Tibetan Plateau.
correlation with the winter air temperature distribution on the QTP (Section 3.1), so that we conclude that the increasing air temperatures, particularly in winter, may account for an earlier thaw, later freeze, and substantial decrease in the number of frozen days on the QTP.

A longer thaw period (growing season) is also comparable with other studies. Gao et al. (2005) reported that earlier thawing occurred in the eastern part of QTP from 1980 to 1999 based on in situ observations from 50 weather stations. Liu et al. (2006) found that the length of the growing season increased at a decadal rate of approximately 4 days (17 days during 43 years from 1961 to 2003) over the eastern and central QTP. These results are consistent with the results obtained in the present study. However, the warming trends found in this study are larger than previously found warming trends because of the following: (1) The warming has been accelerating over the past two decades. (2) Our results are for the whole QTP, whereas previous results were only for the eastern QTP. (3) As stated before, the QTP warming is more significant at night. Because the overpass time of the SSM/I is at night at 6:00 am local time, it can capture the larger warming trend at night. Compared with similar results from other parts of the world (Zhang et al., 2003; Smith et al., 2004; Bartsch et al., 2007; Han et al., 2010), our observed decrease in the number of frozen days and increase in the growing season on the QTP are the largest.

The results suggest that the changes in the near-surface soil freeze–thaw cycle can be used as a strong indicator of permafrost change. China’s permafrost, especially the altitudinal permafrost that is mainly located on the QTP, is very sensitive to climatic warming. Significant permafrost degradation has occurred and continues to occur on the QTP (Jin et al., 2006; Cheng and Wu, 2007; Li et al., 2008; Wu and Zhang, 2008; Wu et al., 2010; Yang et al., 2010). However, mapping permafrost using remote sensing is very difficult because the current spaceborne remote sensing is still not able to penetrate the surface layer. Is it possible to use the near-surface soil freeze/thaw state, which can be much more easily detected from remote sensing, to indicate changes in the permafrost and seasonally frozen ground?

The results from this study suggest an affirmative answer to the above question. The decrease in the number of frozen days was closely related to the type of permafrost or seasonally frozen ground. The most significant changes in the number of frozen days and onset dates of soil thaw and freeze all occurred in regions of discontinuous permafrost, island permafrost, and the transitional zone between permafrost and seasonally frozen ground. According to Cheng (1984), the above areas can be classified into sub-stable, transitional, unstable, and extremely unstable types of permafrost. The permafrost in these areas has higher temperatures and more ice (Cheng and Wu, 2007) so it is more sensitive to climate warming. Therefore, the results obtained in this paper clearly indicate that the instability of permafrost can be detected based on a change in the near-surface soil freeze–thaw cycle. A greater change in the number of frozen days and onset dates of soil thaw and freeze indicates greater instability of the permafrost or seasonally frozen ground.

What is the potential impact of changes in the near-surface soil freeze–thaw cycle on hydrology and ecosystems? Soil freezing and thawing processes will greatly increase the heat exchange between the atmosphere and the ground surface (Cheng and Wu, 2007). Therefore, changes in the near-surface soil freeze–thaw cycle, such as changes in its duration, timing, seasonality, and amplitude, will greatly impact water and energy cycles. Such changes tend to generate a drier land surface because water infiltration and evapotranspiration are both enhanced. The changes in soil moisture will further influence large-scale precipitation. The pattern in the response of the precipitation to the near-surface soil freeze–thaw cycle tends to be very complex; for example, Gao et al. (2005) concluded that if the spring thaw starts earlier, the summer precipitation in southern China may increase, but the summer precipitation in the middle and lower reaches of the Yangtze River may decrease. Because the headwater areas of the Yangtze River and the Yellow River are experiencing significant changes in freeze–thaw cycles, as shown in this study, the hydrological regimes of these large rivers will definitely change accordingly.

Changes in the near-surface soil freeze–thaw cycle will also greatly impact ecosystems. The QTP has a particularly fragile ecosystem. A decrease in the number of frozen days will lead to an expanding growing season. However, thawing surface soil will also result in increased carbon and greenhouse gas emissions from the soil. Additionally, subsidence of the ground and changes to the micro-landscape can be expected and could potentially result in unstable conditions for engineering. Because the Qinghai-Tibetan Railway runs through an area that has strong changes in the near-surface soil freeze–thaw cycle, the impact of the freeze–thaw cycle on the engineering stability of the railway is also of great concern.

7. Conclusions

Changes in the near-surface soil freeze–thaw cycle on the QTP were detected using daily soil freeze/thaw states derived from SSM/I data from 1988 to 2007. The near-surface soil freeze–thaw cycle is changing rapidly on the QTP. The number of frozen days has decreased by approximately 10–50 days, with a mean value of 33.7 days from 1988 to 2007. This decrease in the number of frozen days had a more pronounced trend in warmer months, i.e., from April to September. The onset dates of soil thaw and freeze have also changed significantly. The results show that on the QTP there was a trend toward earlier onset date of soil thaw by 14.3 ± 13.0 days and later onset date of soil freeze by 10.1 ± 11.2 days over the period 1988–2007. The most significant changes were in the north-eastern and southwestern QTP, where discontinuous permafrost, island permafrost, and seasonally frozen ground are distributed. The northwestern QTP had small changes, where stable permafrost exists.

The near-surface soil freeze–thaw cycle is a sensitive indicator to climate warming on the QTP. The results in this paper suggest that the increasing air temperatures, particularly in winter, may account for an earlier thaw, later freeze, and substantial decrease in the number of frozen days on the QTP. The change in the near-surface soil freeze–thaw cycle is also an effective and reliable indicator of permafrost change on the QTP. This study indicates that a greater change in the number of frozen days and onset dates of soil thaw and freeze indicates greater instability of the permafrost. The change in the near-surface soil freeze–thaw cycle detected through a time series of passive microwave remote sensing over the long term can potentially be used to indicate changes in permafrost and seasonally frozen ground.

The hydrology on the QTP and in nearby areas, and even Asian monsoons, will respond to changes in the near-surface soil freeze–thaw cycle accordingly. Greenhouse gas emissions from frozen soil will tend to increase. However, the impacts on hydrology and ecology need further investigation. The influence on the “Asian water tower” (Xu et al., 2008) should be quantified. The relationship to changes in other cryospheric components, such as snow cover, also needs to be investigated in future studies.

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