Spatial variations in snow cover and seasonally frozen ground over northern China and Mongolia, 1988–2010

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ABSTRACT

This study investigates the spatiotemporal variability of snow cover and seasonally frozen ground in northern China and Mongolia during 1988–2010 with passive microwave remote sensing records. We used the Goodison snow algorithm, adapted by introducing an additional soil freeze/thaw indicator to improve its efficiency in mountainous areas, and soil freeze–thaw algorithm to estimate snow cover onset, duration, ablation and, for the first time, interval between snow cover ablation and thawing of seasonally frozen ground. Snow cover onset, duration, and ablation tended to vary systematically from high to low latitudes, and to trend toward early/long/late in elevated areas. The ablation–thawing interval varied from low to high latitudes/elevations, and from dry to relatively humid areas, being shorter (<2 weeks) in the north and elevated areas but longer in some cold–dry and plain–mountain adjacent regions. During 1988–2010, snow cover showed a later/earlier trend of the onset/ablation on the western Tibetan Plateau and a belt from northeast China to central Mongolia, with trends being stronger in spring than in autumn. The time of snow cover ablation was negatively correlated with maximum temperature in the northern study area, indicating that temperature mainly advanced snow melting in spring. However, no significant relationship between temperature and the interval was observed, suggesting that other unknown factors impact the interval. Furthermore, in the north and on Mt. Changbai the interval changed by <2 weeks, whereas changes were larger in cold–dry and plain–mountain transitional areas, indicating changes of Earth surface systems in those areas.

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1. Introduction

Snow cover and seasonally frozen ground in the springtime are important hydrologic and climatic variables because of their effects on water supplies, energy exchanges, and climate–cryosphere interactions in the atmospheric boundary layer (Brown, 2000; Zhang et al., 2004). Snow cover can directly impact radiative and thermal energy budgets and the thermal condition of soil, and it indirectly impacts atmospheric circulation, hydrological processes, and ecosystem dynamics (McCabe and Wolock, 2010). Many researchers have reported that the area of snow cover has decreased significantly in the Northern Hemisphere and is negatively correlated with winter temperatures (Dye, 2002). Although previous studies have directed less attention to frozen ground than to snow cover effects, Smith et al. (2004) proposed that shifts in the timing of freeze/thaw may have important implications for ecosystem carbon fluxes in high northern latitudes; and Kimball et al.

(2006) found that the timing of the springtime thaw and associated onset of the growing season have a major impact on photosynthetic biomass and vegetation productivity in boreal and arctic biomes.

Understanding the duration and temporal variability of snow cover and of the following period of frozen ground in the springtime may enhance the current understanding of changes in terrestrial ecological systems (Shen et al., 2011). Accurate snow cover and frozen ground information over a large area during long time periods has been done from hemispherical to regional scales (Brown et al., 2007; Brown and Robinson, 2011). Because conventional measurement networks are sparse, remote sensing is widely applied for snow cover and frozen ground detection because such observations can be made quickly, periodically, and extensively (i.e., over a large area) (Zhang et al., 2004; Wulder et al., 2007). The space-borne passive microwave time series from the Special Sensor Microwave/Imager (SSM/I, 1987–present) provides one of the longest continuous microwave remote sensing records, which is suitable for the identification of snow cover and seasonally frozen ground with less consideration of atmospheric conditions (Koenig and Forster, 2004; Han et al., 2010). Sophisticated algorithms for snow cover detection have been applied routinely at various scales (Amlien,

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2008), and a well-adapted soil freeze/thaw algorithm can be applied to SSM/I records (Zhang et al., 2004). However, little research has been carried out to examine the relationship between snow cover ablation and the thawing of seasonally frozen ground in winter–spring transitional period. Previous studies have paid less attention to snow cover and the subsequent springtime seasonally frozen ground at mid-latitudes (Dye, 2002; Han et al., 2011). The objectives of this study were to examine the spatial extent and temporal trend of snow cover, the duration of the interval between snow cover ablation and the thawing of seasonally frozen ground, and the response of these phenomena to temperature changes during the recent two decades (1988–2010). Additionally, because in our previous research we have carefully examined seasonally frozen ground in our study area (Han et al., 2010, 2011), we focused here particularly on the onset, duration, and ablation of snow cover, and on the interval between snow cover ablation and the thawing of seasonally frozen ground.

2. Materials and methods

2.1. Study area

Northern China and Mongolia (Fig. 1) lie between latitudes 31°N and 55°N and longitudes 71°E and 136°E and include humid, semi-humid, semi-arid, and arid zones. We selected this region for our study because these conditions have created complex ecosystems containing components typical of many ecological and physical systems found at mid-latitudes. Previous researches showed that vegetation in the region has been seriously degraded over the past several decades (Tsunekawa et al., 2005), most of the East Asia dust storms originate from the area (Zhang et al., 2008), and the recent degradation of vegetation may have upset the balance of the Earth surface system (Han et al., 2010), especially the near-surface soil dynamics, which is why we selected this area as our study area as well. A study in this area therefore could implicate global change.

2.2. Data collection

We used brightness temperature data from the SSM/I and the Special Sensor Microwave/Imager/Sounder in this research. Those

records are available from the National Snow and Ice Data Center twice daily from both ascending and descending tracks (Armstrong et al., 2011). We used the 19 and 37 GHz vertically polarized brightness temperature (T_{19V} and T_{37V}) data from descending (morning) tracks, which are more suitable for terrestrial snow cover and frozen ground applications (Derksen et al., 2000; Han et al., 2010). Because the daily data cannot cover the whole study area, we used a time series of 7-day minimum values combination (MVC) of brightness temperatures with consideration given to the revisit period. This procedure allowed us to cover the entire study area at least once every 7 days (Han et al., 2010). Finally, we produced a time series of 7-day MVC T_{19V} and T_{37V} from 1988 to 2010 for the study area.

We applied station-based meteorological elements of the Global Summary of the Day product from the National Climate Data Center to our study: the maximum and minimum temperatures (0.1 F) and snow depth (0.1 in.). We used approximately 300 available stations, which are available consistently during 1988–2010, from each year in this study. Snow cover onset, ablation and duration were examined using this record, and served as ground-based measures. And in this research, when station-based records are compared to its nearby certain pixels, we used the nearest 4 pixels' averaged value.

2.3. Data processing

We first detected snow cover and the thawing of seasonally frozen ground by adapting the Goodison snow algorithm and soil freeze–thaw algorithm with SSM/I brightness temperatures. For the analysis we then estimated the interval between snow cover ablation and the thawing of seasonally frozen ground.

2.3.1. Open water and elevated permafrost pixels

Pixels from water-covered areas have a lower brightness temperature that may lead to algorithm failures. Pure pixel mixing analysis revealed that the T_{19V} and T_{37V} of pixels with more than 30% open water decreased by more than 20 K and 15 K, respectively. As a first step we eliminated such pixels by using both the UMD Global Land Cover Classification product and Global Land Cover 2000 product as references. With respect to mid-latitude conditions, elevated permafrost is not relevant to the interval between snow cover ablation and the

Fig. 1. Study area. The red rectangle represents the areas in Fig. 2, and the blue dashed line represents the W–E transect analysis at 47°N in Fig. 7.

thawing of seasonally frozen ground. We therefore eliminated regions with altitudes >3000 m in the interval analysis by using a global digital elevation model (DEM) (available at <http://eros.usgs.gov/products/elevation>).

2.3.2. Snow cover estimation

Many algorithms/products have been proposed/produced since the 1970s with passive microwave remote sensing records. Broad application of the Goodison snow algorithm in North America suggests that the algorithm may be applicable in other similar mid-latitude areas (e.g. northern China and Mongolia). We therefore selected it for identifying areas with or without snow cover in this work, Eq. (1), using its latest update for SSM/I brightness temperatures (e.g. Derksen et al., 2002; Goita et al., 2003; Derksen et al., 2005).

$$\text{SWE} = F_O \text{SWE}_O + F_S \text{SWE}_S + F_C \text{SWE}_C + F_D \text{SWE}_D \quad (1)$$

where

SWE_O	– 20.7–2.59 ($T_{37V} - T_{19V}$) for open area
SWE_S	– 1.95–2.28 ($T_{37V} - T_{19V}$) for sparse forest
SWE_C	– 16.81–1.96 ($T_{37V} - T_{19V}$) for coniferous forest
SWE_D	– 33.50–1.97 ($T_{37V} - T_{19V}$) for deciduous forest.

SWE is snow water equivalent in the original algorithm but it is employed as a snow cover indicator in this work; $\text{SWE} > 0$ indicates snow present on the surface, and $\text{SWE} \leq 0$ indicates no snow on the surface; F_O , F_S , F_C , and F_D represent the fractions of open area, sparse forest, coniferous forest, and deciduous forest in a pixel, respectively; SWE_O , SWE_S , SWE_C , and SWE_D are the snow water equivalents for an open area, sparse forest, coniferous forest, and deciduous forest, respectively. Those four elements are derived from the UMD Global Land Cover Classification product and Global Land Cover 2000 product.

We introduced an additional soil freeze/thaw indicator to avoid Goodison snow algorithm failure in our study area (see details of this improvement in Section 3.1). We assumed snow present on thawed ground to be rare in the study area due to the strong sublimation that occurs in the dryland; we therefore adapted a threshold of T_{37V} based on the findings of a soil freeze–thaw study in the study area (Han et al., 2010). Thus, $T_{37V} > 258.2$ K indicated that no snow was present on the surface, and $T_{37V} < 258.2$ K implied that snow might be present on the surface.

Finally, snow cover was complete when $\text{SWE}_{\text{SSM/I}} > 0$ and $T_{37V} < 258.2$ K over the whole study domain.

2.3.3. Thawing of seasonally frozen ground

Thawing of seasonally frozen ground in the springtime was detected by a soil freeze–thaw algorithm that was adapted for this area with a predefined cutoff for T_{37V} of 258.2 K (Han et al., 2010). The algorithm required two parameters for frozen ground identification: a negative spectral gradient between T_{19V} and T_{37V} ($\partial T_B / \partial f \leq 0$), and a threshold of T_{37V} ($T_{37V} \leq 258.2$ K). Thawing was thus detected when either condition was no longer satisfied.

The interval between snow cover ablation and the thawing of seasonally frozen ground in the spring was then estimated as the difference between the time of thawing and time of ablation.

2.4. Data analysis

We calculated a weight ratio to quantify the snow fraction in the study area during the 23 years.

$$\text{Rw}_i = \frac{1}{23S} \sum_{j=1}^{23} S_{ij} \quad (2)$$

where Rw_i represents the weight ratio in week i , S is the total number of pixels in the study area; and S_{ij} is the snow cover times j during the 23 years for a pixel in the i -th week.

We calculated the trend of snow cover onset, duration, and ablation in each pixel by a least-squares approach (Eq. (3)). The statistical significance of the slopes was assessed at the 95% confidence level.

$$T_X = \frac{n \times \sum_{i=1}^n (i \times X_i) - \left(\sum_{i=1}^n i \right) \left(\sum_{i=1}^n X_i \right)}{n \times \sum_{i=1}^n i^2 - \left(\sum_{i=1}^n i \right)^2} \quad (3)$$

The trend (T_X) of snow cover was equated to the slope of an ordinary least squares regression of year (independent variable) versus the time (dependent variable) of either the onset (T_{On}), duration (T_{Du}), or ablation (T_{Ab}) of snow cover.

We then calculated Pearson's correlation coefficient between anomalies of snow cover and daily maximum temperature in the winter, and between anomalies of the intervals and daily maximum temperature in the winter–spring transitional periods which is the interval of ± 1 week. The statistical significance of these relationships was assessed at the 95% confidence level.

3. Results

3.1. Validation of the algorithm for snow detection

We compared ground-based estimates of snow cover onset, duration, and ablation with the SSM/I-based estimates. The ground-based and SSM/I-based estimates of the week of the year of the onset and ablation and number of weeks of the duration of snow cover were in agreement (total accuracy) for 84.2% (46.4 ± 2.8 for our result, while 46.9 ± 2.6 for ground measurement), 81.1% (11.5 ± 3.8 for our result, while 12.9 ± 3.4 for ground measurement), and 82.1% (17.1 ± 6.1 for our result, while 18.0 ± 6.2 for ground measurement), respectively (Fig. 2). Comparison of results with and without adapting the T_{37V} cutoff showed an effective improvement in the estimation of snow cover duration. We selected an area with largest error without adapting the T_{37V} cutoff, the total accuracy of weeks of the duration of snow cover improving from 36.2% to 83.3% when the cutoff was used. The results were also compared with NOAA snow cover products, obtaining an 81.6% agreement. The use of the T_{37V} cutoff effectively eliminated the overestimation of snow cover duration otherwise associated with the use of the Goodison snow algorithm (Fig. 3).

Fig. 2. Validation of snow cover onset, ablation and duration.

Fig. 3. Results of snow cover duration detected by Goodison snow algorithm (A) without and (B) with introduction of the cutoff of T_{37v} . (C) Is the difference map between (A) and (B).

3.2. The mean patterns of snow cover onset, duration, and ablation

We first examined the time series of weekly snow cover quantified by the weight ratio (R_{wi} ; Fig. 4). The maximum and minimum percentages of snow cover, $55.7 \pm 4.8\%$ and $1.72 \pm 0.02\%$, respectively, occurred on the 5th and 30th weeks of a year, respectively. Snow ablation occurred after the 5th week and before the 30th week, and

snow ablations occurred after the 30th week and before the 5th week of the year.

The mean spatial patterns of the onset, ablation and duration of snow cover (Fig. 5) had great regional differences. Earlier onset/late ablation/longer duration was found in two regions: west of the Tibetan Plateau (around 39°N , 72°E), and in the Mt. Altay area (around 51°N , 84°E) and regions to the north of the Hexi Corridor (around 42°N ,

Fig. 4. The weight ratio (R_{wi}) of snow cover over the course of year. The dots indicate the average R_{wi} , and the vertical bars are the standard deviation of R_{wi} during 1988–2010.

Fig. 5. Mean spatial patterns of the Julian week of snow cover onset (A), ablation (B), and duration (C). '0' indicates no snow cover onset in A, and B, and snow cover duration is less than a week in panel C.

Fig. 6. Trends of snow cover onset (A), ablation (B), and duration (C). Negative–positive values in A, B and C indicate later–earlier, earlier–later, and shorter–longer trends (week/year), respectively. The values of the dots in A and B are the percentages of the variance in the onset of ablation accounted for by the regression between temperature and the onset and ablation. The bars indicate the trends.

95°E). From the Tibetan Plateau, the onset/ablation/duration progressed eastward toward low-elevation areas, where no snow cover was observed. Snow cover onset/ablation/duration normally tended to progress from high to low elevations, and from high- to low-latitude areas except for the Tibetan Plateau. Areas to the south of 40°N were rarely covered with snow except for the Tibetan Plateau. Although snow sometimes fell during the winter, the relatively high winter temperatures caused melting within a short time. Snow likewise seldom accumulated in drylands such as the Taklimakan Desert (around 37–41°N, 75–88°E), and Horqin Sandy Land (around 44°N, 122°E) because of limited snowfall and intense sublimation under the cold and dry conditions.

3.3. Trends of snow cover onset, duration, and ablation

The trends of the onset, duration, and ablation in most of the study area during 1988–2010 were within a relatively small range (e.g. -0.1 to 0.1 weeks per year for onset and ablation; -0.15 to 0.15 weeks per year for duration), and in many cases the trends were not statistically significant ($P > 0.1$). However, there were seasonal differences and some significant ($P < 0.1$) trends, which are described below.

The onset of snow cover in autumn (Fig. 6A) tended to occur later in the year toward the end of the study period on the mid-western portion of the Tibetan Plateau as well as in Mt. Altay (around 44–51°N, 84–95°E) and Qaidam Basin (around 36–39°N, 91–97°E), the latter experiencing the greatest delay of onset. Small delays were also evident in a belt from northeastern China to central Mongolia. Meanwhile, trends toward earlier onsets were occasionally evident in the vicinity of Mt. Tianshan (around 42–44°N, 80–87°E) and to the west and north of the Tibetan Plateau.

The spatial extension of the ablation in spring (Fig. 6B) was similar to the trend of onset in spatial extent, but both the increasing and decreasing trends were stronger. Most of the area on the Tibetan Plateau experienced a trend toward earlier ablation. The trend toward earlier ablation was especially strong on the western Tibetan Plateau, as well as along a belt from northeastern China to central Mongolia. Trends toward later ablation were evident mainly on the northwestern portion of the Tibetan Plateau and in the vicinity of Mt. Tianshan, and there were trends toward slightly later ablation to the west of Mt. Yinshan.

As the result of the opposite temporal trends of onset and ablation, the trend of snow cover duration (Fig. 6C) showed a similar spatial pattern to the trend of ablation. Most of the areas on the Tibetan Plateau showed a trend toward a shorter duration of snow cover. This pattern was especially evident on the western Tibetan Plateau, which experienced the greatest decrease of winter snow cover duration. However, the duration of snow cover increased markedly in regions along the edge of the Tibetan Plateau and in the vicinity of Mt. Tianshan. The belt from the western part of northeastern China to southern Mongolia (around 43–45°N, 109–120°E) was another area of apparent decrease, the duration of snow cover tending to decrease. In contrast, in areas to the south of Mt. Changbai (around 41.5°N, 128°E), to the south of Mt. Yinshan (around 40–42°N, 108–116°E), to the north of northeastern China and Mongolia, and in elevated areas in the western part of the study area snow cover duration showed a slightly increasing trend.

3.4. Relationship between snow cover and temperature

Snow cover onset and ablation were correlated with the maximum temperature during the onset and ablation periods, which are autumn–winter and winter–spring transition periods. The correlations were negative in the northern part of the study area. Temperature had a little impact on the variation of the onset of snow cover (Fig. 6A). We found large negative correlations only in some areas in central and

eastern Mongolia; correlations in the remaining areas were lower ($r < 50\%$).

The times of snow cover ablation and temperature were associated with each other in the spring (Fig. 6B). In areas to the northwest of Mt. Altay and along a belt from regions to the northeast of China to the north of Mongolia, the times of ablation were most strongly associated ($r > 0.60$) with maximum temperature, as was also the case on Mt. Changbai. But such strong relationships were not apparent in the rest of the study area.

3.5. The mean spatial pattern and change of the interval between snow cover ablation and the thawing of seasonally frozen ground

The mean spatial pattern of the interval varied from low to high latitudes and elevations, and from dry to relatively humid areas in the study area (Fig. 7A). The intervals were shorter (in most cases less than 2 weeks) in the north and on some elevated areas (e.g. Mt. Changbai) of the study area. We estimated the intervals to be longer in the areas surrounding the Taklimakan Desert, between Mt. Altay and Mt. Hangayn, from Mt. Gobi Altay through the Desert Basin to the Hulunboir Plateau, to the south of Mt. Yinshan and in the west of the Loess Plateau, and in the adjacent areas between the Northeast Plain and its surrounding mountains. We estimated the intervals to be longest in the Qaidam Basin, to the west of Mt. Tianshan, the Hexi Corridor, the central Desert Basin and Mt. Yinshan, and in some areas between the Northeast Plain and Mt. Changbai–Mt. Xiaohingganling.

The spatial pattern of the standard deviation of the duration of the interval during 1988–2010 (Fig. 7B) was similar to the mean spatial pattern. The interval changed in most of the areas in the north and on Mt. Changbai by less than 2 weeks. In the areas surrounding the Taklimakan Desert, between Mt. Altay and Mt. Hangayn, in the Desert Basin, in the Hulunboir Plateau, in areas to the south of Mt. Yinshan, to the west of the Loess Plateau, and in the adjacent areas between the Northeast Plain and its surrounding mountains, large changes were apparent.

A W–E transect of the standard deviations at 47°N showed how typical intervals varied in regions with different elevations and surface conditions (Figs. 1, 8). The intervals in high-elevation areas (e.g. Mt. Altay, Mt. Hangayn, Mt. Dahingganling, and Mt. Xiaohingganling) were shorter than those in low-elevation areas (e.g. Gurban Tonggut Desert, Northeast Hulunboir Plateau, and the Northeast Plain). Thus, elevations were highly correlated with the standard deviations of the intervals; high/low-elevation areas had small/large standard deviations. In some cases, there is a larger than 10 weeks interval happened in the dry land of northern China and Mongolia, where have very limited snow falling but ground keep freezing until the end of April or later.

4. Discussion

Snow cover can be detected directly by microwave remote sensing records and indirectly by setting a threshold on the estimated snow depth or water equivalent (e.g. Grody and Basist, 1996; Derksen et al., 2002, 2005). The rationale that underlies snow cover detection by microwave remote sensing is the fact that a significant decrease in the brightness temperature at high frequencies (e.g. 37 GHz) is accompanied by an insignificant change at lower frequencies (e.g. 18/19 GHz). The distinct difference in brightness temperatures indicates a universal algorithm for snow cover detection with microwave remote sensing records. However, various land surface conditions (e.g., forests) can change the characteristics of the response function (Goita et al., 2003). In this research, the Goodison snow algorithm performed poorly in some cold-arid regions of our study area. This poor performance was clearly evident in the regions between the Hexi Corridor and Mt. Altay–Mt. Hangayn (Fig. 1). We therefore introduced a cutoff of 258.2 K for T_{37V} in this work to avoid failure of the Goodison snow algorithm (Figs. 2 and 3). Further research will likely be necessary to enable high-

Fig. 7. Mean spatial pattern (A) and standard deviation (B) of the interval between snow cover ablation and the thawing of frozen ground. The gray areas indicate open water, areas with no snow cover, and high-elevation (>3000 m) areas.

Fig. 8. W–E transect at 47°N. The black curve indicates the interval (weeks, scale at left) between snow cover ablation and the thawing of frozen ground. Vertical bars are standard deviations. Blue shading indicates elevation (meters, scale at right).

spatiotemporal resolution of snow cover products, particularly at mid-latitudes, where near-surface regions are expected to undergo severe alterations due to climate change and human activity.

Limited full-covered and continuous daily satellite record at mid-latitudes is currently available, mainly because of limitation of revisit interval for microwave remote sensing programs and atmospheric conditions for visible and near-infrared bands. Han et al. (2010) suggested a 7-day maximum/minimum value combined with SSM/I brightness temperature to be used in seasonally frozen ground studies. This statistics loses detailed information within each 7-day interval but provides an optional metric for producing standard temporal interval datasets at mid-latitudes. However, the 7-day MVC algorithm can introduce an error of ± 1 week, which should be reduced with temporal downscale improvement in future research. Higher spatial resolution satellite records and/or spatial downscale methods are also needed because of the impact of open water on brightness temperatures. In this research, we attributed the longer intervals detected in the areas surrounding Lake Balkhash (Fig. 6B), as well as other lakes (Fig. 7), primarily to the impact of open water on brightness temperatures, an effect that caused algorithm failure even when pixels with more than 30% open water were eliminated. We also considered the time of the first snowfall to be a factor that potentially affects the onset of snow cover, because minimum temperatures at the time of the first snowfall were lower than -10°C , which is sufficient to maintain snow on the ground after a snowfall. In additional, we utilized significance of $P < 0.1$ to analyze the relationship between the snow onset/duration/ablation, which may overdraw the trends in 20 years. Further research to validate this snow trend is highly recommended.

The durations of snow cover and seasonally frozen ground are essential inputs to the examination of climate and Earth near-surface changes during the winter–spring transitional season. Those changes have been particularly significant in the mid-latitudes (McCabe and Wolock, 2010). At mid-latitudes, North America has been a primary focus of snow cover duration studies (Brown et al., 2007; Wulder et al., 2007). Researchers have also paid special attention to western China, especially the Tibetan Plateau, but few similar studies have concerned Mongolia (Qin et al., 2006; Che et al., 2008). Han et al. (2010) reported a relatively severe change of seasonally frozen ground during the spring than during the fall over northern China and Mongolia. Thus, research that focuses on the combination of snow cover ablation and the duration of the interval between snow cover ablation and the thawing of seasonally frozen ground would lead to a better description of seasonal climatic patterns/changes. Future work on snow cover ablation, the interval between snow cover ablation and the thawing of seasonally frozen ground, and the onset of green-up will lead to a better understanding of the surface physical and ecological systems of the Earth in typical mid-latitude areas.

A noteworthy region of special importance in the study area is the Tibetan Plateau, which is mainly covered with permafrost and has a unique effect on the climate of East Asia. Large interannual variations with a small increasing trend of snow cover were evident during 1951–1997 (Qin et al., 2006). However, the change of snow mass was not statistically significant (Che et al., 2008). The time interval of our study was coincident with that of a previous satellite-based snow cover study that reported a reduction of snow cover during 1966–2001 (Rikiishi and Nakasato, 2006). The reason for the difference among those observations remains unclear.

The Earth climate has warmed over the last 100 years during two main periods: (1) 1910–1945; and (2) 1976–present. Warming during the second period has approximately doubled to that of the first period (Walther et al., 2002). Temperature is a popular indicator for assessing the state and change of the climate, and responses of climate change are therefore quantified locally/regionally on the basis of temperature anomalies. Moreover, regional climate changes are very heterogeneous temporally and spatially (Shen et al., 2012; Shen et al., 2014a). Recent warming of Northern Hemisphere land in particular is typically greater

in winter/spring than in other seasons (e.g. Schwartz et al., 2006; Shen et al., 2014b). On average over Northern Hemisphere continents and in relatively cold areas of Eurasia, Brown (2000) reported a significant reduction in April snow cover extension associated with a significant spring warming, an indication that climate changes in mid-latitudes of Eurasia might be great as well. Moreover, East Asian last-freeze dates are getting earlier faster than first-leaf dates, an indication that the impact of climate warming is greater in the winter–spring than in the fall–winter transitional season at mid-latitudes (Schwartz et al., 2006). Results of the present study showed decreasing trends to be larger in the spring, with spatial differences, particularly in the belt from northeast China to central Mongolia, decreasing during the last two decades, which meets the previous results that springtime climatic change is larger than other season at the Northern Hemisphere (IPCC, 2013). Temperature, however, was not the driving force for the trend toward earlier thawing. The decrease could instead be largely attributed to the limited snowfall and intense sublimation under the cold and dry conditions that characterize this area (McKenna-Neuman, 1993). Furthermore, the stronger relationship between snow cover ablation and temperature during the spring in the north also indicated that temperature could potentially advance/delay ablation to a significant extent, the result being a reduction/increase of snow cover duration in the winter and winter–spring transitional season. For the first time we estimated the interval between snow cover ablation and the thawing of seasonally frozen ground, with the interval we supposed to be another important indicator of the winter–spring transitional season. We found, however, no significant relationship of this interval to temperature. Explanations for this result include the possibilities that (1) air temperature was not the driving force behind changes of the interval; and/or (2) the changes were less than one week (e.g. north of the study area) and were therefore undetectable in the weekly combined results.

5. Conclusion

In conclusion, the 7-day MVC SSM/I brightness temperature records provide an optional way to obtain estimates of the time interval associated with snow and seasonal ground conditions in the winter and winter–spring transition periods at mid-latitudes. The Goodison snow algorithm, adjusted with an additional frozen ground indicator to correctly assess snow cover information in some mountain areas, was effective in detecting snow cover on northern China and Mongolia. Snow cover duration and the interval between snow cover ablation and the thawing of seasonally frozen ground are correlated with both latitude and elevation, but the relationships are disturbed in some cold–dry areas. The trend of snow cover is stronger in spring than in autumn, and a major change of the trend of snow cover is evident in the belt from northern China to central Mongolia. In the northern study area temperature plays an important role in snow cover ablation, suggesting that the potential impact of temperature change will occur there first. The interval between snow cover ablation and the thawing of seasonally frozen ground, which this study has been the first to estimate, is clearly correlated with elevation, but its relationship to climatic parameters remains unclear.

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Environment Monitoring Unit of European Commission for the Global Land Cover 2000 product; and the United States Geological Survey for the Digital Elevation Model (DEM) product.

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