Spatial and temporal variations of snow cover in the forest area of middle and high latitude of Northern Hemisphere

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Abstract. Snow cover is an important part of cryosphere and the most seasonally changing land surface cover, which is sensitive to climate change. Previous studies showed that climate warming has already altered the extent and phenology of snow cover, which influences the plant phenology of the forest ecosystem. This research investigates the spatial distribution and temporal trend of snow cover in the forest area of mid and high latitude in the Northern Hemisphere (50°N-90°N,180°W-180°E) based on a satellite-derived snow dataset. Results showed that the spatial distribution of snow cover exhibits a latitudinal gradient in the mid and high latitudes of the Northern Hemisphere. The snow cover onset week (SCOW) and snow cover end week (SCEW) shortened significantly at a rate of 0.23 weeks/10 yr. and 0.48 weeks/10 yr., respectively (P<0.05). Cold season (CS) and snow cover persistence week (SCPW) shortened at a rate of 0.25 weeks/10 yr. and 0.16 weeks/10 yr. 19.62% of the study area showed a trend of a significant advance in SCOW, and 1.36% showed a trend of significant delay (P<0.05). For SCEW, 44.91% of regions showed significant advance and 1.91% of regions showed significant delay (P<0.05). CS was a significantly shorted trend (P<0.05) in 16.95% of the study area and showed a significantly extended trend (P<0.05) in 3.76% of the area. SCPW and CS were similar but different, indicating that transient snowfall exists in parts of the study area.

1. Introduction
Snow cover is an important component of the terrestrial ecosystem and plays an important role in the global water cycle. Snow has the characteristics of high albedo, which directly affects the absorption of the solar radiant energy by the land surface. In addition, snow needs to absorb a lot of heat during the melting process. Snow cover impacts long-wave radiation, short-wave radiation, latent heat, and sensible heat, which makes the change of snow cover alter the surface radiation balance to a large extent. Snow cover is an important part of the energy exchange process in the global climate system and has the potential to alter radiation energy budget distribution and energy regulation on the energy flow between the sub-systems of the ecosystem. Therefore, investigating the temporal and spatial changes of
snow cover is of great significance for understanding the hydrology, regional climate system, and terrestrial ecosystem response to climate change.

According to the report of the IPCC (Intergovernmental Panel on Climate Change), global warming is intensified [1, 2]. From 1880 to 2012, the average surface temperature at the global scale increased by 0.85 °C. Snow cover is a land cover with the widest geographical distribution and the most obvious changes in the cryosphere, which is sensitive to climate change. Snow can be intercepted and redistributed by the forest canopy, and the snow under the forest can keep warm, preventing soil freezing and soil nutrient loss. Snow is a very important form of water storage [4, 5] and an important source of water bodies such as rivers and groundwater [6]. Approximately 75% of freshwater resources on the global land surface are glaciers or snow, and 80% of Eurasia and North America in the cold season are covered with snow. Snow meltwater will cause changes in the underlying surface moisture, which will impact changes in climate and atmospheric circulation. At the beginning of vegetation growth, snow melting provides important water resources for vegetation [7]. The changes in snow cover influence forest phenology and forest ecosystems by affecting the ground radiation balance and water cycle processes under forests. Therefore, it is necessary to study the changes in snow cover in forest areas for a better understanding of the relationship between forest phenology and snow cover changes.

Some researchers showed that the snow melting period in the Northern Hemisphere was advanced at the rate of 5.5 days decade\(^{-1}\) in the full snow season, and the duration of snow date decreased at a rate of 0.8 week decade\(^{-1}\)from 1972 to 2007 [8]. Some studies also showed that the duration of snow cover decreased from 1978 to 2015 [9]. However, the increased duration of snow cover was found in the middle latitude of the Northern Hemisphere, while the duration of snow cover showed a decreasing trend in the high latitude from 2001 to 2014 [10]. At the regional scale, there was a prolonged trend for the duration of snow cover in Northern Eurasia [11] and Russia [12], but a decreasing trend in southern Siberia [11]. Nevertheless, some researchers reported that the end date of snow cover in Eurasia was significantly advanced from 1972 to 2006 according to the EASE-Grid data. The start date of snow cover in autumn changed less, and the duration of snow cover was overall shortening [13]. Meanwhile, some researchers have studied the variation of snow cover at different elevations and mountainous areas [14, 15, 16]. The results showed that the duration of snow cover was shortened at all elevations in the Qinghai-Tibet Plateau from 1966 to 2011 [17] and snow cover duration showed a decreasing trend in about 78% of global mountainous areas [18]. Different research results may be caused by different research regions, time intervals, satellite data sources, topography, and so on. However, there is little research into the change of snow cover across the forest areas. The objectives of the study are to elucidate the spatial pattern and variation of snow cover in the forest area and to quantify the interannual variations of the snow cover onset week (SCOW), the snow cover end week (SCEW), the cold season (CS), and the snow cover persistence week (SCPW). This study lays a foundation for exploring the relationship between snow cover and forest ecosystems.

2. Study area

Climate warming is greatest in the middle and high latitudes of the Northern Hemisphere, twice as fast as in other regions. Patchy snow cover on the surface of vegetation in low latitude areas may be missed in remote sensing images (especially in visible and near-infrared images). In order to ensure seasonal snow cover and obtain stable forest coverage areas, we use Moderate Resolution Imaging Spectroradiometer (MODIS) land cover data (MCD12C1) from 2001 to 2014 to mask areas above 50°N to obtain a stable forest coverage area and use it as our study area.

3. Materials and Methods

3.1. Materials

The EASE Grid 2.0 Weekly Snow Cover V4 dataset is used in this research. Table 1 shows the detailed information of this dataset. The snow cover extents (SCE) for the dataset is based on the "NOAA/NCDC Climate Data Record (CDR) of the Northern Hemisphere (NH) Snow cover extents (SCE)" and
regridded to the EASE-Grid 2.0 [19]. Each grid cell was categorized as snow-covered more than 50% of its area had visible snow cover.

Although the spatial resolution of the EASE Grid 2.0 Weekly Snow Cover V4 dataset is not high, which resulted in the low observation accuracy in the mountainous area. This dataset is the longest available consistent record of continental-scale variations in snow cover [20], and they are considered to be sufficiently accurate for monitoring snow cover variability at a continental scale [21-23]. Therefore, we chose the EASE Grid 2.0 Weekly Snow Cover V4 dataset in the period from 1982 to 2014 to investigate the spatial pattern and variation of snow cover in the forest area of the middle and high latitudes of the Northern Hemisphere.

**Table 1.** Main information of the EASE-Grid 2.0 Weekly Snow Cover V4 dataset

| Parameters             | Value                                      |
|------------------------|--------------------------------------------|
| Spatial Coverage       | N: 90, S: 0, E: 180, W: -180               |
| Spatial Resolution     | 25 km x 25 km                              |
| Temporal Coverage      | 3 October, 1966 to 31 December, 2018        |
| Temporal Resolution    | 7 days                                     |
| Data Format            | Binary                                     |

The land cover data used in this research originate from the Moderate Resolution Imaging Spectroradiometer (MODIS) land cover product (MCD12C1), which provides a suite of global land cover with a spatial resolution of 0.05° in an annual time-step. In this study, we selected available data for each year based on the IGBP classification schemes from 2001 to 2014. Evergreen Needleleaf Forests, Evergreen Broadleaf Forests, Deciduous Needleleaf Forests, Deciduous Broadleaf Forests, Mixed Forests, Closed Shrublands, and Open Shrublands pixels were uniformly merged as forest, which is used in this research.

### 3.2. Methods

In order to estimate the spatial and temporal variations of snow cover in the study area, the snow year was defined as starting from 1 September to 31 August of the following year [24]. The snow cover onset week (SCOW) was defined as the first week when each pixel was initially covered with snow for two consecutive weeks. The snow cover end week (SCEW) was defined as the second week of snow cover for two last weeks in a row. The cold season (CS) was used to measure the timing when snow was likely to fall. The snow cover persistence week (SCPW) was defined as the number of snow cover weeks in the cold season. SCOW, SCEW, CS, and SCPW were calculated based on the EASE Grid 2.0 Weekly Snow Cover V4 dataset. CS was calculated as:

\[
CS = (SCEW - SCOW) + 1
\]  

It is worth noting that snow-free breaks may exist during the cold season, i.e. snow-free periods may be encountered before the last snow-covered week observed in spring or after the first snow-covered week observed in autumn [13]. Otherwise, intermittent snow may occur during the cold season. In order to consider the impact of instantaneous snowfall, SCPW is calculated as:

\[
SCPW = \sum_{i=SCOW}^{SCEW} V_i
\]  

where \( V_i \) is the actual pixel value for one week within the period (0 for snow-free, 1 for snow). The slope calculated by the least square linear fitting method was used to describe the snow cover trend and a t-test was used to evaluate the significance of the change trend [25] through IDL programming.
4. Results and Discussion
In order to represent the overall spatial distribution, we calculated the multi-year average of snow cover parameters in the study area (figure 1). The spatial distribution of snow cover shows differences with latitude gradient. SCOW showed a decreasing trend (figure 1a), while SCEW, CS, and SCPW showed an increasing trend from south to north (figure 1b, figure 1c, figure 1d). However, there are differences in some regions. CS showed a similar spatial pattern with SCPW but not identical, indicating instantaneous snowfall in these areas.

Figure 1. Spatial pattern of multiyear (1982–2014) mean snow cover parameters across the forest area of mid and high latitudes in the Northern Hemisphere (50°-90°N, 180°W-180°E): (a) snow cover onset week (SCOW), (b) snow cover end week (SCEW), (c) cold season (CS, number of weeks), and (d) snow cover persistence week (SCPW, number of weeks).

We used the least-squares linear fitting method to analyze the changes of snow cover in the study area. SCOW and SCEW showed a significant advancement trend from 1982 to 2014 (figure 2). The advancement rates of SCOW and SCEW were 0.23 weeks decade⁻¹ and 0.48 weeks decade⁻¹, respectively (figure 2a, figure 2b). CS and SCPW as a whole showed an insignificant decreasing trend (figure 2c, figure 2d). It is worth mentioning that SCEW, CS, and SCPW showed a significant delay or increase in 1995.

There are significant differences in the climatic conditions among different regions. We further analyzed the change trends of snow cover at a pixel scale (figure 3). From 1982 to 2014, SCOW showed a significant advancement trend (P<0.05) of about 19.62% in the study area, mainly distributed in central Russia, Sweden, Finland and other European countries. SCOW was a significantly delayed trend (P<0.05) of 1.36% in the regions. It is mainly distributed in western Canada (figure 3a, figure 3b).
Figure 2. Snow parameters trends across the forest area of mid and high latitudes in the Northern Hemisphere (50°–90°N, 180°W–180°E) from 1982 to 2014: (a) SCOW, (b) SCEW, (c) CS, and (d) SCPW.

Figure 3. Spatial patterns of snow parameters trend across the forest area of mid and high latitudes in the Northern Hemisphere (50°–90°N, 180°W–180°E), including (a) slope of SCOW, (b) significance of SCOW, (c) slope of SCEW, (d) significance of SCEW, (e) slope of CS, (f) significance of CS, (g) slope of SCPW, (h) significance of SCPW. The legend of (d), (f) and (h) is the same as (b).
SCEW showed a significant advancement trend ($P<0.05$) of 44.91% in the study area, mainly distributed in central Russia and northern Canada. The advancement of SCEW might be potentially related to warming in spring and early snow melting in the study area. However, it also showed spatial heterogeneity. SCEW showed a significantly delayed trend ($P<0.05$) of 1.91% of the regions, with mainly distributed in the north of Khabarovsk Krai in Russia (figure 3c, figure 3d), which may be caused by local climate, terrain and other factors. CS showed a significantly shortened trend ($P<0.05$) of 16.95% in the area. CS was a significantly extended trend ($P<0.05$) of 3.76% in the area (figure 3e, figure 3f). The SCPWin 13.32% of the forest area showed a significantly shorter trend ($P<0.05$), and the SCPWin 4.54% of the area showed a substantially longer trend ($P<0.05$) (figure 3g, figure 3h). Compared with CS, the spatial distribution is consistent, but not identical. This suggested that there might be instant snowfall or the possibility of non-snowfall periods during the cold season period in some regions.

5. Conclusions
There are latitudinal gradient patterns for snow cover, but there are some differences in the local areas, which may be caused by local microclimate, topography, and other factors. From the perspective of time trends, SCOW and SCEW in the middle and high latitudes of the Northern Hemisphere showed a significant advancement trend from 1982 to 2014. CS and SCPW also showed a trend of shortening, but not statistically significant. By analyzing the snow cover changes of each pixel, SCOW and SCEW have shown an advanced trend in most areas, especially in central Russia and other countries and regions. CS and SCPW were shortened in most areas, but a few areas also showed a significant trend of lengthening in southern Norway, northwestern Sweden, and southeastern Russia. The trend and distribution of CS and SCPW were roughly the same, but there were differences in a small number of areas, indicating that there may be instantaneous snowfall in some areas.

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