Long term spatio-temporal analyses of snow cover in Central Asia using ERA-Interim and MODIS products

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Abstract. In this study, an approach for generating a long term series of snow-cover products from 1979 to 2015 was proposed by integrating the data of ERA-Interim snow-depth and 8-day cloud-free MODIS snow-cover derived by removing cloud from MOD10A2/MYD10A2 product. On the basis of the spatio-temporal analyses and evaluation of snow-cover duration (SCD) during the hydrological year from 1979/1980 to 2014/2015 over Central Asia, the average start and melt date of snow-cover (SCS and SCM, respectively) were estimated using the long term snow-cover product. The results suggested that the snow-cover product derived by this approach is fairly satisfactory with the mean bias error (MBE) of -0.55%±5.03%. The SCD, SCS and SCM all presented an apparent north-south towards gradient as long as mountainous regions and waterbodies were avoided. The mean SCD over the high-latitude and high-mountainous regions were all beyond 122 days, however, it gradually became shorter with a significant level of α < 0.05 or even α < 0.001 from 1979/1980 to 2014/2015. In contrast, the SCD over low-latitude and low-altitude regions, like Turkmenistan and Uzbekistan, were evidently shorter than the former, but it became significantly longer with a significant level of α < 0.05 or even α < 0.001 in the southwestern, northern Turkmenistan and most of Uzbekistan in the same duration. Notably, most of Turkmenistan and Uzbekistan, where snow-cover usually appeared late and melting out early, even always stay snow-free throughout the year.

1. Introduction
Snow is one of essential factors in cryosphere and is very sensitive to global climate change, especially in the arid and semi-arid Central Asia [1]. ERA-Interim is the latest global atmospheric reanalysis dataset produced by European Centre for Medium-Range Weather Forecast (ECMWF) [2] under the project following ERA-15 and ERA-40. The goal of this project is to resolve several difficult problems mainly related to representation of hydrological cycle, the consistency of the reanalyzed geophysical fields on time and optimization of various reanalysis techniques, such as data selection, quality control, bias correction and performance monitoring, which seriously affected the quality of the reanalysis production of ERA-40 in data assimilations [2]. Previous study shows that ERA-Interim has made substantial progress in producing global estimates of the basic dynamical fields [3]. Temperature variations from 1979 to 2011 were studied in Central Asia, the result suggested that temperature variations revealed from the ERA-Interim reanalysis matched well with the local
climate records [4]. The reanalysis dataset of ERA-Interim ozone was verified by the ERA-Interim TCO (total column ozone) only about 2% lower than the ozone monitoring instrument measured between 50°S and 50°N [5]. Nevertheless, to our best knowledge, long term analysis on spatio-temporal variability of snow-cover by using ERA-Interim reanalysis dataset of snow-depth (m of water equivalent) was not found in literatures, which is essential to understand dynamics of long-term snow-cover variations in Central Asia from 1979 to 2015.

Aiming to generate long term snow-cover product in Central Asia by using ERA-Interim snow-depth reanalysis and cloud-free MODIS 8-day snow-cover datasets, this study proposed an approach by integrating ERA-Interim snow-depth reanalysis and cloud-free MODIS 8-day snow-cover datasets to investigate spatial distribution of mean SCD (snow-cover duration) in each hydrological year in the period from 1979/1980 to 2014/2015 over Central Asia. In order to examine and evaluate the spatio-temporal variability of SCD, Mann-Kendall rank statistical test was used, and the average beginning (SCS) and melting out (SCM) date of snow-cover for each hydrological year were estimated by the produced long time series of snow-cover product to investigate the variations of SCD in the same duration in Central Asia.

2. Materials and methods

2.1. Study region
Located at mid-latitudes of the north-western hemisphere (35–55°N, 46–85°E), Central Asia, as the target area of this study, consists of five Central Asian countries without the Caspian Sea: Kazakhstan, Kyrgyzstan, Tajikistan, Uzbekistan and Turkmenistan, covering an area of nearly 4x10^6 km^2 [6, 7] as illustrated in Figure 1. Mountains and plateau (i.e. Tianshan, Pamir plateau), vast deserts (i.e. Kara Kum, kyzyl Kum and Taklamakan) with less forest (1%), lots of grasslands and shrubs (48%) [8] characterize its diverse and complex underlying surface with elevation ranging from -227 m a.s.l. to 7441 m a.s.l. of decreasing trend in topography from southeast to northwest of this region. The temperate continental climate predominates in Central Asia with characterization of warm and arid summer months and cold winter seasons [9], which is primarily caused by the rain-shadow effect of the Tianshan Mountains and Pamir plateau situated in the southeast of this region, isolating almost entire Central Asia from warm and humid air masses originating from the Indian Ocean [10]. Global climate changes pose heavy effects on eco-environment condition of the region, especially on glaciers and snow covers in this climate change sensitive region [11].

![Figure 1. Overview of Central Asia including topographic feature and major water body.](image)

2.2. Data utilized

2.2.1. 8-day cloud-free MODIS snow-cover dataset. The 8-day snow products MOD10A2 (Terra, V005) and MYD10A2 (Aqua, V005) obtained from the National Snow and Ice Data Centre (NSIDC)
were utilized to calculate the threshold of snow-depth for generating cloud-free and accurate time series of snow-cover dataset. For covering the entire Central Asia, eight MODIS tiles (h21v03, h22v03, h23v03, h21v04, h22v04, h23v04, h22v05 and h23v05) were selected for the period from the 1st of September, 2000 to the 31st of August, 2015, spanning totally fifteen complete hydrological years during 2000/2001 and 2014/2015. Spatial resolutions of MOD10A2/MYD10A2 are both 500m with projection of Sinusoidal (SIN). The cloud removal approach in five steps ensured the satisfied quality of cloud-free images being generated with accuracy ranging from 90% to 94%, the overall accuracy of post-processed snow-cover dataset between 2000/2001 and 2014/2015 was between 92.79% and 93.34% over Central Asia [8, 12].

2.2.2. ERA-Interim snow-depth data. The ERA-Interim, covering the period from January 1979 to present, was initiated in the year of 2006 by the ECMWF, which was derived based on a 12-hourly four-dimensional variational analysis (4D-Var) including the adaptive estimation of biases in satellite radiance data [13]. Two analyses per day were implemented at 00:00 and 12:00 UTC (universal time coordinated) in ERA-Interim, serving as initial data fields for the subsequent forecasts [14]. Snow-depth (m of water equivalent) product with the highest spatial resolution of 0.125° derived from the ERA-Interim reanalysis with WGS-84 geodetic coordinate provided by ECMWF (http://apps.ecmwf.int/) was selected in this study. In order to match the MODIS 8-day snow-cover product in time, snow-depth at 12:00 UTC was adopted. According to [13], some locations of coastal sea and lake area were falsely identified as snow-free due to some pronounced errors were introduced in the pre-processing of ice mapping system (IMS) snow-cover derived from NOAA/NESDIS at ECMWF, a possible solution was to remove all the major water body from the original daily snow-depth reanalysis. In present study, we just adopt this suggestion as shown in Figure 1.

2.3. Methods

2.3.1. The algorithm for generating long-term snow-cover product. In order to accurately generate a long time series of snow-cover product, it is necessary to determine the threshold of SD derived from ERA-Interim to determine the dates when the snow-cover started to accumulate as well as the snow-cover began to vanish. The algorithm for generating long-term snow-cover product involves four steps. The first step is to generate 8-day maximum SD product through compositing 8 days of SDs derived from ERA-Interim. Note duration of 8 days of SDs should be in the same time duration of 8 days for MOD10A2 datasets from 2000/2001 to 2014/2015. The second step is to determine the threshold of each 8-day maximum SD according to the snow coverage rate of MOD10A2 for the same period with the method of iteration. The third step is calculating the mean value of each 8-day thresholds from 2000 to 2015. The fourth step is to apply the mean 8-day threshold to the corresponding 8 days of daily SD data derived from ERA-Interim for the period from 1979 to 2015.

2.3.2. Calculation of snow-cover start and melt Date. The produced daily snow-cover data were then aggregated to generate full time series of hydrological years (1 September through 31 August) for all years from 1979/1980 to 2014/2015 according to Equation (1):

\[ SCD = \sum_{i=1}^{n} s_i \]  

where SCD represents snow-cover duration; n stands for the number of observations, which is beginning with 1st September and ending with 31st August of the next year; and the \( s_i \) is the value of pixel, recoded as 0 or 1, derived from produced daily produced snow-cover data sets.

The snow-cover start (SCS) and snow-cover melt (SCM) date were considered as important indicators of trends and lasting changes [8]. The algorithms described in [15] for computing SCS and SCM were adopted in this study to calculate the SCS and SCM during the period from 1979/1980 to 2014/2015 in Central Asia with some parameters being modified as shown in Equation (2) and (3), respectively.

\[ SCS = Fd - SCD_{8Fd} \]
SCM = Fd + SCD_{aFd}

where SCD_{aFd} and SCD_{bFd} stand for after and before Fd referring to SCD, respectively. The Fd was determined to consist with the maximum snow-cover extent throughout all the study period, which is on the date of 26 January. Notably, snow-cover was conceived to remain throughout a year once it appears when the Equation (2) and (3) are applied, which means that we ignore any transient snow events during a hydrological year. This assumption may not directly reflect the actual conditions, however, it can present the quantitative variation of SCS and SCM, which was also the best way to display SCS and SCM in only single chart, respectively.

3. Results and discussions

3.1. Accuracy of the algorithm for generating snow-cover data

As shown in Figure 2, each mean 8-day threshold of SD throughout the year was derived for snow-depth of ERA-Interim between each individual in successive during hydrological years from 2000/2001 to 2014/2015. After applying these thresholds to 8-day ERA-Interim snow-depth products from 2000/2001 to 2014/2015, mean bias error (MBE) of the estimated results derived by this algorithm was only -0.55%±5.03% (MBE ± Standard Deviation), which was much better than that (16.42% ±13.98%) derived by original algorithms from ERA-Interim data. Finally, these mean 8-day thresholds of SD were applied to daily snow-depth data of ERA-Interim correspondingly, which can generate a long time series of daily and high-spatial-resolution (0.125 degree) snow-cover products from 1979 to 2015 over the Central Asia.

3.2. The spatial distribution of mean snow-cover days

Spatial distribution of snow-cover is essential for better understanding the snow-runoff processes. Using the produced daily snow-cover data sets, SCD map are generated during the period from 1979/1980 to 2014/2015. The mean SCD derived from the entire time series is better suited for a general overview of snow-cover conditions. The annual mean SCD between 1979/1980 and 2014/2015 were illustrated in Figure 3. From Figure 3, we can find that SCD tended to decrease from north to south with decreasing latitude, except these alpine regions of southeastern Pamirs and Tianshan Mountains and northeastern Altai Mountains over Central Asia. SCD below 50°N was less than 122 days in this north-south gradient. And furthermore, it has been snow-cover free for many years in the southern Turkmenistan. SCD in the Tianshan Mountains and northern Kazakhstan above 50°N are all beyond 122 days. Specially, in the alpine regions of southeastern Pamirs and northeastern Altai Mountains, some locations were snow covered longer than 244 days. Generally, the SCD
presented an increase trend from south to north over Central Asia during the period in hydrological year from 1979/1980 to 2014/2015, besides that the altitude of terrain is also an important factor affecting the spatial distribution of SCD.

**Figure 3.** Annual mean snow-cover days from 1979/1980 to 2014/2015 in the Central Asia.

3.3. **Detection of the spatio-temporal variations of snow-cover days**

The method of Mann-Kendall test was applied in this study to detect the spatial and temporal variation trend of SCD during the period from 1979/1980 to 2014/2015 in Central Asia. As illustrated in Figure 4, Mann-Kendall test for spatial variation of SCD between 1979/1980 and 2014/2015 in Central Asia suggested that SCD decreased in most part of Central Asia, i.e. Kazakhstan, Pamirs, Tianshan Mountains and Altai Mountains, significant decrease appeared in the central and northwestern Kazakhstan, eastern Pamirs and southern Tianshan. In the meanwhile, the first EOF mode (EOF-1) of temperature experienced a drastic increase trend in these regions from 1979 to 2011 (Hu et al., 2014). However, the SCD became significantly longer with a significant level of a < 0.05 in the southwestern Kazakhstan, northern Turkmenistan and most of Uzbekistan. In the most of Turkmenistan, especially in the southeast, SCD almost kept no change during the period from 1979/1980 to 2014/2015. As the snow-cover in Central Asia is affected by a variety of climatic factors, such as temperature, precipitation, sea-level pressure and so on, unfortunately, a few studies on the correlation between climatic factors and snow-cover in Central Asia was conducted. The following the sensibility of snow-cover in Central Asia to climatic factor will be analysed.
3.4. The spatial distribution of mean SCS and SCM

The start and melt of snow-cover duration (SCS and SCM) are considered the most important parameters except SCD. Mean SCS and SCM, derived from single-year SCS and SCM during the period from the hydrological year of 1979/1980 to 2014/2015, were illustrated in Figure 5 and 6.

From Figure 5 we can find that mean conditions of SCS conform to the mean SCD shown in Figure 4 with earliest snow-cover in the alpine regions of southeastern Pamirs and northeastern Altai Mountains. Conversely, the latest snow-cover is located in the Turkmenistan and parts of Uzbekistan in the southwest, where usually stay snow-free. Like the spatial distribution of SCD, an apparent north-south gradient of SCS emerged in Central Asia except the alpine regions and waterbodies. In these alpine regions the topography predominated the main influential factor on snow-cover but not latitude. Figure 6 illustrated the mean SCM for all hydrological years from 1979/1980 to 2014/2015, which coheres with mean SCD (Figure 3) and mean SCS (Figure 5). The mean SCM was also characterized by north-south gradient as long as mountains and water bodies were avoided. In these alpine regions the key factor affected the SCM is topography but not latitude.

4. Conclusions
In this study, an approach for generating a long time series of snow-cover product from 1979 to 2015 was proposed by integrating the data of ERA-Interim snow-depth and 8-day cloud-free MODIS snow-cover derived by removing cloud from MOD10A2/MYD10A2 product. Based on the spatio-temporal variations and evaluation of snow-cover duration (SCD) during the hydrological year from 1979/1980 to 2014/2015 over Central Asia, the average start and melt date of snow-cover (SCS and SCM, respectively) were estimated using the long time series of snow-cover product. The results suggested that:

1. The mean bias error of the proposed algorithm is only -0.55% ± 5.03%, which is much better than the one unprocessed procedure (16.42% ± 13.98%). It suggests that the algorithm combined with ERA-Interim snow-depth and cloud-free MODIS snow-cover is significantly effective and the snow-cover results have high accuracy.

2. The spatial distribution of mean SCD presented obviously north-south gradient as long as alpine regions and waterbodies were avoided. The mean SCD in high-latitude regions were all beyond 222 days, however, it became significantly shorter with significant levels of a < 0.05 or even a < 0.001 from 1979/1980 to 2014/2015. In contrast, the SCD in low-latitude and low-elevation regions, like Turkmenistan and Uzbekistan, were relatively very shorter than other regions. Furthermore, the trends of their SCD became notably longer with a significant level of a < 0.05 or even a < 0.001 in the southwestern, northern Turkmenistan and most of Uzbekistan.

3. The spatial distribution of both mean SCS and SCM conforms to mean SCD, presenting an obvious north-south gradient except the alpine regions and waterbodies. In the high-latitude or high-mountains regions, including Pamirs, Tianshan Mountains, Altai Mountains and the Kazakhstan northward 50°N, where the snow-cover appeared early and melting late. However, in the other regions, such as Turkmenistan and Uzbekistan, snow-cover appeared late and melting early, even stayed snow-free throughout the year.

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