1 Seasonal snow cover regime and historical 2 change in central Asia from 1986 to 2008

3 **Hang ZHOU¹, Elena AIZEN¹, Vladimir AIZEN¹**

4 ¹Geography Department, College of Science, University of Idaho, Moscow ID 83844, U.S.A.

5 E-mail: hzhou@uidaho.edu

6 Phone: 1-208-392-2829

7

7

8 **Abstract**

9 A series of statistics describing seasonal snow cover extent and timing in Central Asia (CA) have
10 been derived from AVHRR satellite images for the time period from 1986 to 2008. Analysis of
11 long term mean snow cover statistics shows that the area weighted mean of long term snow
12 covering days (SCD) for the whole CA is 95.2 ± 65.7 days. High elevation mountainous areas
13 above 3000 m in Altai, Tien Shan and Pamir, which account for about 2.8% of total area in CA,
14 have SCD greater than 240 days. Deserts (Karakorum Desert, Taklamakan Desert, Kumtag
15 Desert) and rain shadow areas of major mountains, accounting for 27.0% of total area in CA,
16 have SCD in the range of 0 - 30 days.

17 Factors affecting snow cover distribution have been analyzed using simple linear regression and
18 segmented regression. For plain regions and windward regions, the SCD rate is +5.9 days / 100
19 m, while for leeward regions, the rate jumps from +0.7 days / 100 m to +10.0 days / 100 m at
20 about 2335 m. Latitude affects the SCD, especially in plain regions with insignificant change of
21 elevation, with rates of 9 - 10 days / degree from south to north.

22 The Mann-Kendal test and the Theil-Sen regression methods have been applied to analyze the
23 spatial heterogeneous trends of change of SCD, snow cover onset date (SCOD), and snow cover
24 melt date (SCMD). Area weighed mean SCD in the whole CA does not exhibit significant trend
25 of change from 1986 to 2008. Increase of SCD was observed in the northeastern Kazakh Steppe.
26 Low elevation areas below 2000 m in Central Tien Shan and Eastern Tien Shan, as well as mid-
27 elevation areas from 1000 m to 3000 m in Western Tien Shan, Pamiro-Alai and Western Pamir,
28 also experienced increase of SCD, associated with both earlier SCOD and later SCMD. Decrease

29 of SCD was observed in mountainous areas of Altai, Tien Shan and Pamir, and vast areas in
30 plains surrounding the Aral Sea.

1 Introduction

Seasonal snow cover is an important component of the hydrological cycle, affecting glacier mass balance (Jansson et al., 2003), soil moisture content (Edwards et al., 2007) and river runoff (Dozier, 1987; Singh, 2010). In many arid or semi-arid regions, seasonal snow cover is the major water resource for both natural ecosystems and human society (Barnett et al., 2005). In central Asia (CA¹), melt water from seasonal snow cover is the dominant component of river runoff, as pointed out by various researches of selected river basins (Aizen et al., 1995; 1996; Chevallier et al., 2014; Pohl et al., 2014) or general estimation for the large regions (Barnett et al., 2005).

Seasonal snow cover has also been considered as an essential climate variable, as its varying extent, depth, and surface properties have impacts on the surface energy balance and atmosphere circulation (Li et al., 2014; Handorf et al., 2015), via its modification of surface albedo (Robinson et al., 1986; Chapin et al. 2005) and the energy consumption during the snow melting phase (Aizen et al., 2000). Seasonal snow cover is sensitive to the changing climate, as numerous studies report a decrease of seasonal snow cover in northern hemisphere since the 1970s due to increasing air temperature (Groisman et al., 1994; Dye, 2002; Choi et al., 2010; Peng et al., 2013). CA has experienced a general increase of temperature in the 20th century (Aizen et al., 1997; Lioubimtseva et al., 2005; Aizen et al., in preparation), while climate models predicted a further warming up to 7 °C until the end of the 21st century (Mannig et al., 2013; IPCC, 2014). Possible decrease of seasonal snow cover extent in the high mountains of Tien Shan and Pamir, and the associated decrease of river

¹ List of abbreviations

CA: Central Asia; CARs: Central Asian Republics; KS: Kazakh Steppe; AD: Aral-Caspian Desert; TR: Tarim; SA: Siberian Altai-Sayan; MA: Mongolian Altai; WT: Western Tien Shan; NT: Northern Tien Shan; IK: Issyk Kul; IT: Inner Tien Shan; ET: Eastern Tien Shan; CT: Central Tien Shan; WP: Western Pamir; PA: Pamiro-Alai; CP: Central Pamir; EP: Eastern Pamir; SCE: Snow Cover Extent; CDR: Climate Data Record; SCAP: Snow Cover Area Percentage; PSCAP: Perennial Snow Cover Area Percentage; SCD: Snow Covering Days; SCOD: Snow Cover Onset Date; SCMD: Snow Cover Melt Date; SCmax: Maximum Snow Cover Area Percentage; DSCmax: Date of Maximum Snow Cover Area Percentage

runoff are the major consequences of climate change in CA (Ososkova et al., 2000; Siegfried et al., 2012).

Various efforts have been spent on studying seasonal snow cover in CA, dating back to the time of the former Soviet Union (FSU). From a current perspective, those studies are outdated by using only data before the 1990s (Kotlyakov et al., 1997; Aizen et al., 1997), or working on the whole northern hemisphere using coarse resolution satellite images or in-situ observations (Groisman et al., 1994; Brown, 2000; Dye, 2002; Brown & Robinson, 2011), or focusing on sub-regions within CA using recent satellite images or station observations (Liang et al., 2008; Wang et al., 2008; Zhou et al., 2013; Wang et al., 2013; Dietz et al., 2014). Our previous work (Zhou et al., 2013) constructed a long term historical archive of snow cover extent data using AVHRR satellite images from 1986 to 2008 for the whole CA, and analyzed the patterns of snow cover change in the Amu Dar'ya Basin. The results showed a significant decrease of Snow Covering Days (SCD) in mountainous regions above 3000 m in the basin, mainly accompanied by earlier Snow Cover Melting Date (SCMD), while Snow Cover Onset Date (SCOD) shifted earlier in mid-elevation zone (2000 – 3000 m) of Western Pamir. Dietz et al. (2014) analyzed snow cover changes from 1986 to 2014 using AVHRR data within the country boundaries of Central Asian Republics (CARs), Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan, showing that SCMD shifted earlier significantly in elevation zone between 2100 m and 3500 m, while SCOD moved earlier over the CARs and no significant change of SCD was detected in any elevation zone. There exists a knowledge gap after Kotlyakov et al. (1997) about the seasonal snow cover regime for the whole CA based on recent comprehensive remote sensing dataset. The slight difference between the two recent studies about snow cover changes in CA also suggest that the analysis of the seasonal snow cover change in a finer spatial resolution than before is needed to better understand the spatial heterogeneous changes of seasonal snow cover after the late 1980s.

In this study we analyzed a series of snow cover statistics derived from the AVHRR snow cover extent data archive for the whole CA geographical region to quantify: 1) the spatial distribution and timing characteristics of seasonal snow cover duration, 2) the determining factors for seasonal snow cover distribution, including elevation, relative location to major mountain systems, and latitude, 3) the changing patterns of seasonal snow cover for the research period from 1986 to 2008 and, 4) the relationship between changes of seasonal snow cover and climate.

2 Research Area

In this study CA is defined as the geographical region in the center of the Eurasian continent, spanning from 51 °E to 113 °E, and from 32 °N to 56 °N (**Figure 1**). The Mongolian Steppe and the Gobbi Desert are located in its east, while the Caspian Sea and the Aral Sea are situated in the west. Western Siberia and the Altai-Sayan Mountains are located in the north, while the Taklamakan Desert and the Karakum Desert are situated in the south. The CA region, as considered in this study, covers an area of $\sim 6.3 \times 10^6 \text{ km}^2$, including the entire territory of CARs, as well as Xinjiang Autonomous Region in China and southwestern Siberia in Russia.

Though the major terrain type within CA is plains (**Figure 1**), the major mountain ranges of CA extend for more than 5000 km, from the Altai Mountains in the north (**Figure 1-A**) to the Pamir Mountains in the south (**Figure 1-C**), with the Tien Shan Mountains situated between these two mountain systems (**Figure 1-B**). High mountains in CA modulate the air mass movement and control moisture distribution and atmospheric pressure in low to mid latitude of Asia. Various studies have pointed out that the westerlies is the dominant wind in CA, bringing moisture to this region from the Atlantic Ocean (Aizen et al., 2004; Aizen et al., 2005; Aizen et al., 2009; Mölg et al., 2013). The high mountains also serve as ‘water towers’ (Barnet et al., 2005; Immerzeel et al., 2010).

To estimate the spatial variability of seasonal snow cover and its changing patterns, we further subdivide CA into 15 climatic regions (**Figure 1**), according to certain climatic considerations and topographical features (**Aizen et al., in preparation**).

3 Data and methods

3.1 Snow cover statistics

Snow cover extent data derived from Advanced Very High Resolution Radiometer (AVHRR) were used as the basis for calculating snow cover statistics in this research. All AVHRR level-1b data available for CA (**NOAA, 1998; NOAA, 2007**) were collected and processed with Special AVHRR Processing Software (SAPS) (**Khlopenkov et al., 2007**) for calibration and georectification. An aggregated rating based snow identification scheme was used to generate daily AVHRR snow cover extent, which was further composited into 8-day maximum-snow-extent data. The 8-day maximum-snow-extent data went through a set of spatial and temporal filters for filling cloudy pixels or gaps (**Zhou et al., 2013**). A series of snow cover statistics were calculated from the 1 km resolution 8-day AVHRR Cloud/Gap Free Maximum Snow Extent data.

We performed extensive validations of the AVHRR snow cover products at different processing levels and different temporal resolutions to ensure the trustworthiness of the data. To ensure temporal stability of the snow cover identification scheme, snow cover data derived from AVHRR image segments obtained by different satellites at the same day were compared. The results show that the general accuracy between different AVHRR sensors is always higher than 90%. Daily AVHRR snow cover data were compared with in-situ ground snow survey (**Figure 1**) in 1987 – 1996 (**Krenke, 1998**). Due to the recoding constraint of the snow survey data, we only analyzed the Probability of Detection (POD) of snow identification. Annual average POD is within the range of 80% - 93%, with a mean of 88.18%. Furthermore, daily AVHRR snow cover products were

compared with daily MODIS snow cover products in 2003 – 2008. Both snow cover products perform similarly with a general accuracy of 98.51% and a kappa coefficient of 0.89. More details about the accuracy of the snow cover products utilized in this study can be found in (Zhou et al., 2013).

3.1.1 Snow Cover Area Percentage (SCAP) and Perennial Snow Cover Area Percentage (PSCAP)

The 8-day Cloud/Gap Free Maximum Snow Extent data at 1 km resolution was synthesized into 5 km resolution SCAP (%) data by calculating the percentage of snow covered area within the 5 km grid, for representing the variation of snow cover in CA. Then PSCAP (%) was computed as the minimum value of SCAP at each 5 km grid point in all 8-day periods from 1986 to 2008 to represent the spatial distribution of perennial snow and glaciers.

3.1.2 Snow Covering Days (SCD)

SCD (days) is defined as the number of days covered by snow in a hydrological year for a grid point. The start of a hydrological year in CA is defined as August 29th, which is the start of 31st 8-day period, based on analysis of long-term meteorological and hydrological data in the research region. SCD was first calculated at 1 km resolution then synthesized to 5 km resolution with the mean function.

3.1.3 Snow Cover Onset Date (SCOD) and Snow Cover Melt Date (SCMD)

SCOD (Julian day) and SCMD (Julian day) were calculated as the start and end dates of stable snow duration in a hydrological year at each 1 km grid point for describing the timing of seasonal snow cover using an approximation algorithm (Wang et al., 2009; Zhou et al., 2013). Both SCOD and SCMD for each hydrological year calculated at 1 km resolution were then synthesized to 5 km resolution by the mean function.

143 SCOD is calculated by the following equation:

$$144 \quad \text{SCOD} = D' - \text{SCD}', \quad \text{Eq. 1}$$

145 where SCD' is the number of days with snow cover within the period of snow starting season, which
 146 was determined by the climate regime of our research region, while D' is the Julian day of the end of
 147 the defined snow starting season.

148 Similarly, SCMD is calculated as:

$$149 \quad \text{SCMD} = D'' + \text{SCD}'', \quad \text{Eq. 2}$$

150 where SCD'' is the number of days covered by snow within the period of snow melting season, and
 151 D'' is the Julian day of the start of the defined snow melting season.

152 Based on analysis of long term meteorological and hydrological data in the research region, the
 153 snow starting season is defined as from the start of a hydrological year, which is August 29th (the
 154 start of the 31st 8-day period in a year) to December 27th (the start of the 46th 8-day period in a year).
 155 The snow-melting season is defined as the period from January 17th (the start of the 3rd 8-day period
 156 in a year) to the May 1st (the start of the 16th 8-day period in a year) for our study region (ZHOU, et
 157 al., 2013).

158 **3.1.4 Maximum Snow Cover Area Percentage (SCmax) and Date of Maximum Snow Cover** 159 **Area Percentage (DSCmax)**

160 SCmax (%) and DSCmax (Julian day) were derived from SCAP data at 5 km resolution, with
 161 SCmax defined as the maximum SCAP at each grid point in a hydrological year, and DSCmax as
 162 the corresponding date when SCmax was observed.

3.1.5 Long term mean snow cover statistics

Long term mean values, as well as standard deviations of SCAP, SCD, SCOD, SCMD, SCmax and DSCmax were calculated to represent the general distribution of seasonal snow cover in CA from 1986 to 2008.

Simple linear regression and segmented regression (**Muggeo et al., 2008**) with five different types of model formulations (**Table 2-1**) were conducted in the R software (**R Core Team, 2015**) to analyze the dependence of long-term mean SCD (*SCD*) on elevation and latitude in different climatic regions. Comparisons of the performance of these models for each climatic region were conducted based on adjusted R^2 , AIC and ANOVA test with significance level at 0.05. Comparisons among the ‘Only latitude’, ‘Only elevation’ and ‘Elevation and latitude’ models show relative importance of elevation and latitude on *SCD* in different climatic regions. Comparison between ‘Only elevation’ and ‘Breaking elevation’, and comparison between ‘Elevation and latitude’ and ‘Breaking elevation and latitude’ examine and analyze the existence of segmented linear relationship between *SCD* and elevation.

3.2 Trend of change analysis

Both linear trend test and Mann-Kendall test (**Mann, 1945; Kendal, 1975**) were performed on time series of SCD, SCOD, SCMD, SCmax and DSCmax with a significance level of 0.05 for detecting possible trend of change of snow cover statistics. The slopes calculated by the Theil-Sen regression (**Theil, 1950; Sen, 1968; Fernandes et al., 2005**) were reported as indicators of the general direction and magnitude of change, for grid points where both tests show a same sign of change and have p-values less than 0.05.

Hierarchical Clustering (**Lattin et al., 2003**) analysis was applied at each climatic region for each trend slope calculated to group clustering points with same direction and similar magnitude of change together. Location (standardized projected x and y coordinates in meters) and magnitudes of significant trend of change were used as input variables. For each cluster, the mean and standard deviation of magnitudes of change were reported.

3.3 Auxiliary data

The Digital Elevation Model (DEM) obtained from the Consultative Group on International Agricultural Research (CGIAR) (**Reuter et al., 2007**) was used to describe topography in CA. The DEM at 90 m resolution has been re-projected to the same coordinate system (**Zhou et al., 2013**) as the snow cover statistics data, and resampled to 5 km resolution.

Gridded monthly air temperature and precipitation dataset derived from an archive of 457 stations in CA was used in this study to provide a general overview of climate change during the research period in CA (**Aizen et al., in preparation**). Regional averaged values of air temperature and precipitation were calculated in defined latitudinal and longitudinal ranges, corresponding to groups of regions (**Table 1**) in Aral Sea, Altai, northeastern Kazakh Steppe, Pamir and different parts of Tien Shan.

4 Results

4.1 Spatial distribution of seasonal snow cover

Long-term mean snow covering days (*SCD*) (**Figure 2-b**) was used as the main seasonal snow cover characteristic, since the long-term mean snow cover onset date (*SCOD*) (**Figure 2-c**) and the long-term mean snow cover melt date (*SCMD*) (**Figure 2-d**) have similar spatial distribution

patterns as *SCD*. The whole CA has an area weighted mean of 95.2 days for *SCD* with a standard deviation of 65.7 days, while the area weighted mean values of *SCOD* and *SCMD* are Nov 23rd $\pm$ 26 days and Mar 7th $\pm$ 36 days, respectively. Analysis of these snow cover characteristics (**Figure 1**, **Figure 2-b, 2-c and 2-d**) shows that mountainous areas of Altai (> 2000 m), Tien Shan (> 3000 m) and Pamir (> 3000 m), accounting for 2.8% of total area in CA, experience the highest *SCD*, which is greater than 240 days. Those mountainous areas also have the highest perennial snow cover area percentage (PSCAP) (**Figure 2-a**). Vast areas in northern CA, spanning from the Kazakh Steppe to the low elevation areas (< 2000 m) in Siberian Altai, have *SCD* in the range of 90 – 240 days; while southern CA with elevation lower than 3000 m, spanning from Aral-Caspian to Tarim, have *SCD* in the range of 0 – 90 days. Areas with low values of *SCD* (0 - 30 days), accounting for 27.0% of total area in CA, mainly distribute in deserts, including the Karakorum Desert spanning from Aral-Caspian to southeastern part of Western Pamir, the Taklamakan Desert in Tarim, and the Kumtag Desert at the southeastern part of Eastern Tien Shan. Low values of *SCD* below 30 days can also be observed in rain shadows of great mountains, such as the western coast of Lake Issyk Kul and the southeastern part of Inner Tien Shan (**Figure 2-b**).

More than 73% of the areas in CA have long-term mean maximum snow cover (*SCmax*) higher than 95%. Two main areas with *SCmax* less than 95% are the Karakorum Desert and the Taklamakan-Kumtag deserts spanning from Tarim to southeastern part of Eastern Tien Shan (**Figure 2-e**). The long-term mean date of maximum snow cover (*DSCmax*) is observed after Jan 1st in most areas in CA. High mountains in Pamir, Tien Shan and Altai have earlier *DSCmax* before

225 Jan 5th, compared with vast areas with low elevation (< 3000 m), which have DSC_{max} between Jan
 226 5th and Jan 26th (**Figure 2-f**).

227 **4.2.1 Plains**

228 Kazakh Steppe (KS) has an average SCD of 124.5 ± 32.6 days. The SCD increases with latitude,
 229 from about 91.6 ± 24.9 days in the south to 139.8 ± 16.1 days in the north. At maximum, 83.6% of
 230 KS area is covered by snow on the 1st day of year (**Figure 3-1**). The snow coverage stays above
 231 80% until approximately the 50th day of year (Feb 19), drops down quickly to below 1% on the 110th
 232 day of year (Apr 20), then starts building up on approximately the 270th day of year (Sept 27).

233 Aral-Caspian Desert (AD) has a short area weighted mean of SCD (36.2 ± 27.5 days). The
 234 shortest SCD (0 - 5 days) can be observed in its southwestern part along the seashore of the Caspian
 235 Sea, and in its southeastern part in the Karakum Desert. Longer SCD (108.1 ± 29.7 days) is
 236 observed along the Kopet Dag Mountains at the southern border of AD with the Iranian Plateau.
 237 Except for those local cases, the SCD shows an increasing trend along latitude, from about $10.6 \pm$
 238 7.0 days at its southern part to about 54.0 ± 18.4 days in its northern part. The maximum snow area
 239 coverage of 45.3% is observed on the 1st day of year (**Figure 3-2**). The snow cover shrinks quickly
 240 to below 0.01% on the 100th day of year (Apr 10), leaving only the Kopet Dag Mountains hosting
 241 remaining snow cover. After about the 300th day of year (Oct 27), snow cover starts building up.

242 **4.2.2 Altai and surrounding areas**

243 Siberian Altai-Sayan (SA) has a longer area weighted mean of SCD (172.1 ± 47.5 days) than its
 244 southeastern neighbor Mongolian Altai (MA) (101.3 ± 53.2 days), because SA receives more
 245 moisture from the westerlies due to its northwest location to the Altai Mountains. High mountains ($>$

3000 m) facing north or west in SA have a long *SCD* (294.0 ± 31.8 days). Low elevation areas, when surrounded by high mountains, have a mean *SCD* of 123.1 ± 24.8 days, in contrast with the longer mean *SCD* of 166.3 ± 19.0 days when in open environment. The maximum snow cover is observed at the end of a calendar year at about 75.0% (**Figure 3-4**). The snow coverage stays above 60% to around the 100th day of year (Apr 10), then goes down to below 1% on about the 170th day of year (Jun 19), while the snow cover expansion starts around the 220th day of year (Aug 8).

MA also has long *SCD* in mountains with a mean value of 225.6 ± 45.7 days, though shorter than in the mountains of SA. The western Mongolia part of this climatic region experiences even shorter *SCD* (63.6 ± 21.8 days) compared with the southern part of this climatic region (103 ± 18.7 days), since it is surrounded by the Eastern Sayan Mountains in the north, the Mongolian Altai Mountains in the south, the Siberian Altai Mountains in the west and the Mongolian Plateau in the east. The snow coverage in MA reaches its maximum of 69.9% at the beginning of a calendar year (**Figure 3-5**), shrinks down to around 2% on the 160th day of year (Jun 9), and then starts expanding on around the 250th day of year (Sep 7).

4.2.3 Tien Shan and surrounding areas

Western Tien Shan (WT) has a short mean *SCD* (80.2 ± 67.8 days) mainly because of the existence of a large area of warm and dry plains in its western part with low values of *SCD* (37.6 ± 18.1 days), including the Fergana Valley. The mountainous areas in the northeastern part of WT have longer *SCD* (227.6 ± 63.8 days). In WT, the maximum snow cover of 58.8% of the total area is observed on the 9th day of year (Jan 9), and decreases to the minimum of 2.2% on the 209th day of year (Jul 28) (**Figure 3-6**).

267 The mean *SCD* in Inner Tien Shan (IT) is 162.5 ± 79.5 days, while vast areas of high mountains
 268 greater than 3000 m in IT, including the At-Bashi and the Kokshaltoo ranges, experience *SCD*
 269 around 204.1 ± 71.0 days. The low plains to the western slope of those mountains have relative low
 270 *SCD*, with a mean of 91.7 ± 2.1 days; while areas located in rain shadow of those mountains at the
 271 eastern slope have mean *SCD* of 11.8 ± 3.9 days. The maximum snow cover of 86.1% happens on
 272 the 41st day of year (Feb 10) and goes down to the minimum of 16.5% on the 209th day of year (Jul
 273 28) (**Figure 3-9**).

274 Northern Tien Shan (NT) has a mean *SCD* of 136.3 ± 70.3 days, and the high mountains have
 275 mean *SCD* of 259.5 ± 45.0 days, while its low elevation plains have a mean *SCD* of 81.4 ± 25.6
 276 days. The valley in the southwestern part of NT between the Kirgiz Alatau and the Moldo Too
 277 ranges, as well as the valley in the southeastern part of NT between the Ketmen and the Kokshaltoo
 278 ranges, have a mean *SCD* of 23.7 ± 13.7 days, which are the lowest in NT, due to their location in
 279 the rain shadow of mountains surrounding them. In general the snow cover in NT shrinks from the
 280 peak of 80.7% on the 25th day of year (Jan 25) to the minimum of 5.0% on the 209th day of year (Jul
 281 28) (**Figure 3-7**).

282 The climatic region of Issyk Kul Lake basin (IK) has a mean *SCD* of 108.6 ± 97.2 days. The
 283 high elevation mountains in the northern and southern part of IK have long *SCD* (207.4 ± 78.6
 284 days), while the low plains, surrounding the warm Issyk Kul Lake experience shorter *SCD* than the
 285 regional average, from 3.0 ± 9.8 days at the western lake shore to 81.0 ± 23.4 days at the eastern

lake shore. The snow cover in IK reaches its maximum of 51.3% on the 41st day of year (Feb 10) and goes down to the minimum of 9.0% on the 209th day of year (Jul 28) (**Figure 3-8**).

Central Tien Shan (CT) has a mean *SCD* of 111.5 ± 95.4 days, where the high mountains have high values of 206.4 ± 83.2 days, while the low elevation areas along foot of mountain ranges having low values of 32.8 ± 13.8 day. The lowest *SCD* (0 - 5 days) can be observed at the southeastern part of CT bordering Tarim, as this part of CT is situated in the rain shadow of the Samin Ula Mountains. Its maximum snow cover of 60.2% happens on the 9th day of year (Jan 9) while the minimum coverage of 9.6% occurs on the 209th day of year (Jul 28) (**Figure 3-11**).

Eastern Tien Shan (ET) has a shorter mean *SCD* (75.8 ± 59.7 days) than other climatic regions in Tien Shan. Similar to other climatic regions, its high elevation mountain ranges experience long time of snow cover (212.6 ± 72.6 days). The ET can be further separated into a northern and a southern part by the mountain ranges extending from west to east in the middle of the region. The southern part (the Turfan basin) has much shorter *SCD* (13.8 ± 8.2 days) compared with the northern (the Jungar basin) one (90.6 ± 24.0 days). The snow cover in ET reaches its maximum status of 59.4% at the beginning of a year, and then shrinks down to about 2% on the 110th day of year (Apr 20). The snow cover starts accumulating on about the 270th day of year (Sept 27) (**Figure 3-10**).

Tarim (TR) is the climatic region with the shortest area weighted mean *SCD* (20.2 ± 27.2 days).

It also has the highest coefficient of variation (1.35) of *SCD* among all climatic regions in CA, which suggests that snow only appears occasionally in most places in Tarim. The minimum value of *SCD* of 0.0 shows that there are places in TR where snow had not been observed by AVHRR

sensors during the 23-years research period. Areas with the shortest *SCD* (0 - 5 days) are mostly located at the eastern part of TR in the Kumtag Desert, while relatively longer *SCD* (104.7 ± 65.5 days) can be observed at high mountain ranges, e.g., the Kunlun Mountains in the southern part of TR bordering the Tibetan Plateau. TR has much lower maximum snow coverage at about 27.9% compared with other climatic regions, happening on around the 9th day of year (Jan 9) (**Figure 3-3**). The snow cover goes down quickly to below 1% of the total area of TR on about the 50th day of year (Feb 19) and stay at similar values until about the 300th day of year (Oct 27), with snow cover only exists in high mountains during this time.

4.2.4 Pamir and surrounding areas

Western Pamir (WP) has an area weighted mean *SCD* of 83.7 ± 87.5 days, with large variation within the region. The high mountains in the eastern part of WP have a mean *SCD* of 238.0 ± 47.4 days, while the plains along the Amu Dar'ya River and its tributaries have a mean *SCD* of 10.9 ± 7.9 days. Valleys surrounded by mountains in WP also experience low *SCD* at a similar level. Its snow cover reaches the peak value of 56.4% on the 9th day of year (Jan 9), and shrinks down to the minimum of 3.1% on the 249th day of year (Sept 6) (**Figure 3-12**).

Pamiro-Alai ranges (PA), at the northern Pamir, have a mean *SCD* of 162.6 ± 86.0 days, with 47.8% of its area higher than 3000 m have a mean *SCD* of 237.5 ± 52.6 days. The relatively lower mountain valleys in PA, for example, the Zaravshan Valley in the west, have lower *SCD* at 53.6 ± 22.9 days. Similar to WP, snow coverage in PA also reaches the maximum value on the 9th day of year (Jan 9) with a value of 80.6%, and the minimum snow coverage on the 249th day of year (Sept 6) with a value of 13.5% (**Figure 3-13**).

Central Pamir (CP), with most of its areas higher than 3000 m, has the longest mean *SCD* (256.7 ± 78.3 days) in all climatic regions. At maximum, 97.9% of CP is covered by snow on the 49th day of year (Feb 18), while the lowest amount of snow cover (40.4%) happens on the 257th day of year (Sept 14) (**Figure 3-14**).

Eastern Pamir (EP) has a shorter mean *SCD* (171.0 ± 94.9 days) compared with CP, although it is in the similar elevation range. Obstruction of moisture bearing westerly to EP by the high mountains in nearby WP and CP causes the lower *SCD* in EP. Though high values of *SCD* (228.3 ± 80.5 days) can still be observed at high mountain regions (> 3500 m) in EP, the lower elevation valleys (1800 m – 3500 m) surrounded by mountains usually has quite short *SCD* (38.5 ± 42.2 days), with the smallest values (0 – 5 days) found in most of the eastern part, between the Sarikol ranges and the Taxkorgan ranges, or to the east of the Taxkorgan range. EP has the maximum snow coverage of 83.5% on the 57th day of year (Feb 26) and the snow coverage shrinks down to the minimum of 32.2% on the 257th day of year (Sept 14) (**Figure 3-15**).

4.2 Factors affecting seasonal snow cover duration

It is well known that elevation, relative location to major mountains and latitude are the main factors determining the spatial distribution of seasonal snow cover (**Kotlyakov, 1997; Severskiy & Severskiy, 2003; Parajka et al., 2010**). We revisit this topic with more comprehensive and advanced data for CA, using *SCD* as the representation of snow cover duration.

4.2.1 Snow cover duration and elevation

Examination of the relationship between *SCD* with elevation (**Figure 4 and 5**) for the whole CA shows the positive correlation between them with a mean increasing rate of 2.3 days / 100 m

(Pearson's $r = 0.34$, $p\text{-value} = 0.0$). The magnitude of the correlation varies across different elevation zones and climatic regions.

Below ~2000 m, *SCD* is not strictly increasing with elevation, especially for the elevation zone below 1000 m (**Figure 4**). Climatic regions with substantial portions of flat areas below 1000 m, including KS, AD, SA and ET, have weakened positive relationships (KS and SA) or even negative relationships (AD and ET) between *SCD* and elevation in low elevation zone. TR and MA, as climatic regions with large portion of flat areas, also have similar weakened positive relationships between *SCD* and elevation, for areas below 3000 m and below 2000 m, respectively (**Figure 5**). This could be caused by other factors, e.g. latitude, having a strong influence on *SCD* distribution for low elevated areas with small elevation changes, which will be discussed in following part of this section.

Between 2000 m and 5000 m, the positive relationship between *SCD* and elevation is relatively stable compared with areas under 2000 m (**Figure 4**). The mean increasing rate at this elevation range is 5.8 days / 100 m, which is much higher than the mean increasing rate for the whole CA, and accounts for most of the correlation between *SCD* and elevation.

Above 5000 m, the values of *SCD* in mountainous regions tend to stabilize at about 320 days (e.g., EP and PA) (**Figure 5-15, 5-13**) to 350 days (e.g., CT and CP) (**Figure 5-11, 5-14**) without any increase with elevation. The stabilizing phenomenon is related to the fact that under 5 km spatial resolution, most of the high elevation grid points with elevation greater than 5000 m are mainly filled with perennial snow or glaciers (**Figure 2-a**).

4.2.2 Snow cover duration and latitude

Examination of the relationship between *SCD* with latitude in condition of elevation (**Figure 7-a**) shows a positive relationship between *SCD* and latitude. Increasing rates of *SCD* by latitude for each 1000 m elevation zone were calculated, showing increasing rates of about 9 days / degree for elevation zones below 3000 m. In higher elevation the increasing rates tend to be higher, with the strongest increasing rate of 15.3 days / degree exists in the elevation zone above 4000 m (**Figure 7-b**).

4.2.3 Classification of climatic regions

Five different types of linear statistical models (**Table 2-1**) were fitted to *SCD*, elevation and latitude data in each climatic region. Climatic regions were classified into three groups based on comparisons of the performance of those models.

4.2.3.1 Plain climatic regions

KS (**Figure 5-1**) and AD (**Figure 5-2**) are two regions with the ‘Only latitude’ model performing significantly better than the ‘Only elevation’ model. The adjusted- R^2 values for the ‘Only latitude’ model are 0.52 and 0.49 for KS and AD, respectively, while the adjusted R^2 values for the ‘Only elevation’ model are 0.02 and 0.01.

Segmented regression with the ‘Breaking elevation’ model shows a critical elevation at ~1750 m for both KS and AD, separating the relationship between *SCD* and elevation to two parts. In the lower elevation part, *SCD* has large variations at the same elevation and smaller increasing rate of *SCD* by elevation, while in the higher elevation part *SC* increases with elevation consistently and more quickly than in the lower elevation part. Both climatic regions have similar increasing rates at the

higher elevation zone, which are 12.1 days / 100 m and 11.3 days / 100 m, respectively.

Comparisons among the ‘Elevation and latitude’, ‘Breaking elevation’ and ‘Breaking elevation and latitude’ (**Table 2-1**) models for these two climatic regions show that the performance of the first one is at a similar level as the latter two, despite the latter two’s more complex structure. Such a lack of improvement of performance for complex models indicates that most of the variation of *SCD* in the lower elevation part in these two climatic regions can be accounted for by the effect of latitude.

4.2.3.2 Windward climatic regions

Climatic regions other than KS and AD can be classified to two groups based on the criteria whether a significant break of the relationship between *SCD* and elevation exists in the elevation range from 1000 m to 3000 m (see section 3.1.5). For SA (**Figure 5-4**), WT (**Figure 5-6**), NT (**Figure 5-7**), WP (**Figure 5-12**), PA (**Figure 5-13**) and CP (**Figure 5-14**), the segmented regression with ‘Breaking elevation’ and ‘Breaking elevation and latitude’ either cannot find a significant breaking point under significance level $\alpha=0.05$, or the resulting linear model does not perform better than the corresponding simple linear model as shown by comparison of AICc, adjusted- R^2 and ANOVA test under significance level of 0.05. This group was named as windward group since climatic regions in this group are in general located to the windward side of nearby major mountain systems. In this group, there are positive relationships between *SCD* and elevation. The positive increasing rates are not constant but increase with elevation until elevation reaches ~5000 m, and the changes in these rates occur slowly and continuously.

4.2.3.3 Leeward climatic regions

For MA (**Figure 5-5**), IK (**Figure 5-8**), IT (**Figure 5-9**), CT (**Figure 5-11**), ET (**Figure 5-10**), and EP (**Figure 5-15**), segmented linear models perform better than corresponding simple linear models. This group was named as leeward group since these climatic regions are in general located to the

leeward side of nearby major mountain systems. In this group, the increasing rates of *SCD* with elevation are insignificant at low elevation zone, speed up at a certain critical elevation, and then stabilize when the elevation reaches approximately 5000 m.

The increasing rates of *SCD* with elevation for MA are 1.2 days / 100 m and 15.9 days / 100 m, for areas below and above 2215 m, respectively. In areas surrounding the Tien Shan Mountains, the critical elevation separating the relationship between *SCD* and elevation can be observed in the range from 2700 – 2900 m for different climatic regions. The increasing rates for the lower part vary from 1.6 days / 100 m in CT to 5.5 days / 100 m in IK; while for higher part the increasing rates vary from 11.5 days / 100 m in IT to 16.3 days / 100m in IK (**Figure 6**). EP, as in the leeward side of Pamir Plateau, has the smallest increasing rate of *SCD* for low elevation (< 2750 m) at 0.4 days / 100 m, while the increasing rate for high elevation part is 13.2 days / 100 m, only 2 – 3 days smaller than in MA, ET and CT.

TR has shorter *SCD* at all elevation zones compared with any other climatic region in CA (**Figure 5-3**). The increasing rate of *SCD* is also smaller than in other climatic regions, and shows a break at around 3000 m. The increasing rates are 1.4 days / 100 m and 8.8 days / 100 m for areas below and above 3000 m, respectively. Since several nearby mountains of the head water for Tarim River are also included, the elevation range for TR goes up to higher than 5000 m. TR has an exceptional low *SCD* (< 250 days) for areas above 5000 m because most of such high elevation areas are located at its far southeastern border with Tibetan Plateau with relatively low amount of precipitation (Kotlyakov, 1997; Aizen et al., in preparation).

4.2.3.4 Comparison of snow cover duration between windward and leeward climatic regions

Leeward climatic regions tend to have shorter *SCD* at the same elevation compared with corresponding windward climatic regions. MA has shorter mean values of *SCD* at all elevation zones than SA (**Figure 8-a**), and the differences are most distinct (up to 100 days) in 1000 m - 3000 m. EP also has shorter *SCD* than other climatic regions in Pamir, with the highest difference of about 145 days observed in the elevational range from 3000 m – 4000 m (**Figure 8-c**). In Tien Shan (**Figure 8-b**) mean *SCD* in windward regions are about 70 days longer than in leeward regions at the elevations from 1000 m to 3000 m, and about 20 days longer in the elevational range 3000 m - 4000m. For areas above 4000 m or below 1000 m, the leeward side has slightly longer mean *SCD* than the windward side, with differences less than 20 days.

4.2.4 Linear modeling of snow covering days

To synthesize the relationship between *SCD* with elevation and latitude, linear regression models for *SCD* using elevation and latitude as independent variables were fitted separately for plains, windward and leeward climatic regions (**Table 2-2**). For plains and windward climatic regions, the ‘Elevation and latitude’ model was used, while for leeward climatic regions the ‘Breaking elevation and latitude’ model was used. Latitude has a similar effect on *SCD* for all three types of regions. Elevation has similar effect for plains and windward climatic regions. In leeward climatic regions, the general critical elevation separating zones with different types of relationships is 2335 m detected by segmented regression. At lower elevation, the increasing rate for *SCD* with elevation is smaller (0.7 days / 100 m) compared with the other two types of regions, though in higher elevation the *SCD* increases at a much faster rate (10.7 days / 100 m).

It should be noticed that the distribution of elevation gradient of snow cover duration ($SCD/Elev$) is not homogeneous within each climatic region. For example, the mid-elevation (2000 m – 3000 m) zone in WT and WP with orthogonal direction to the westerlies tend to have more prolonged SCD and larger SCD/Elevation than at other altitudes. In CT and EP, areas landlocked by nearby mountains tend to have longer SCD and smaller $SCD/Elev$ than other areas in open environment. The effect of “relative location” to major nearby mountains have been taken into account at a regional scale by classification of climatic regions as windward or leeward, while the local scale effect of “relative location” has not been considered. To further analyze the influence of the “relative location” the estimation of appropriate indices for the local scale effect might be required. A combination of elevation, latitude and relative location might be the basis for a geographical distributed statistical model for long term snow cover distribution.

4.3 Trend of seasonal snow cover change

The dynamics of area weighted mean monthly SCAP for the whole CA (**Figure 9**) during the past 23 years show no significant trend of change. The area weighted mean annual SCAP for the whole CA dropped down to its minimum in 1988, increased to its maximum in 1993, then stayed relatively stable around the long term mean value of 25%. The Theil-Sen regression and the Mann-Kendal test analysis of gridded SCD, SCOD, SCMD, SCmax and DSCmax were conducted, showing no significant trend of change for SCmax and DScmax almost everywhere in the research area during the period from 1986 to 2008. For the whole CA, SCD, SCOD and SCMD have area weighted mean change rates of -0.02 days / year, -0.06 days / year and -0.01 days / year, respectively. Spatial patterns of the SCD, SCOD and SCMD changes are heterogeneous, with large portions of the research area experience no significant change, while strong significant change with different directions happened in different regions in CA (**Figure 10**).

Below 2000 m, the mean trend of change (αSCD) for areas with significant change is slightly less than 0 days / year, with a large standard deviation of αSCD of ~ 1 days / year. The αSCD decreases with increasing elevation, with the lowest value of -1.57 days / year observed in areas with elevation above 4000 m (**Figure 11-a**). The values of αSCD for most climatic regions are either around or below 0 days / year, except KS, ET and CT, which have αSCD at 0.13, 0.13 and 0.85 days / year, respectively (**Figure 11-b**).

4.3.1 Areas with decreasing seasonal snow duration

Vast areas of southern KS, northern AD, SA and MA experienced decreases of SCD. There are two main clusters with significant decreases of SCD: 1) the Aral Sea region, where SCD decreased at a rate of -1.43 days / year while SCMD shifted earlier with greater extent to the east and southwest, at a rate of -1.00 days / year; 2) upper reach of the Orb River in the southwestern part of SA, where SCD decreased at a mean rate of -1.56 days / year, with later SCOD (0.99 days / year) and earlier SCMD (-0.89 days / year).

Significant decrease in SCD is observed in Tien Shan. From ET and CT in the eastern branch of Tien Shan, to IT, IK, NT and WT in the western branch of Tien Shan, SCD decreased in areas above 2000 m (**Figure 11-c-6 to Figure 11-c-11**). A cluster of significant SCD decreases is observed in the mountains between ET and CT, with a mean rate of decreasing SCD at -1.16 days / year, associated with later SCOD (0.68 days / year) and earlier SCMD (-0.73 days / year). In contrast, SCD increased in the lower elevation areas (< 3000 m) in ET and CT (**Figure 11-c-10 and Figure 11-c-11**).

Another cluster of significant decreasing SCD is located in the mountains among southwestern NT, eastern WT and IT, with a mean rate of -1.18 days / year. In eastern WT mountains (> 3000 m),

significant decrease of SCD occurred with an average rate of -1.22 days / year, associated with postponed SCOD (0.60 days / year) and earlier SCMD (-0.94 days / year). In southwestern NT mountains (2000 – 4000 m), SCD decreased with a rate of -1.05 days / year, in companion with both later SCOD (0.63 days / year) and earlier SCMD (-0.75 days / year). SCD decreased nearly everywhere in IT, especially at its western and southern high mountains at elevation range from 2500 m to 4500 m, with an average rate of -1.28 days / year. Decreases of SCD in those areas are mainly associated with earlier SCMD with a mean rate of -0.92 days / year. SCOD also turned later, but in a smaller area mainly at its southern high mountains with elevation greater than 3000 m, and with a smaller magnitude of 0.72 days / year.

Mountainous areas with elevation above 3000 m in Pamir, as well as in PA, which is the transition zone between Pamir and Tien Shan, experienced significant decreasing SCD (**Figure 11-c-12 to Figure 11-c-15**) with a mean rate of -1.59 days / year. In PA, SCD decreased significantly with an average rate of -1.28 days / year associated with earlier SCMD (-0.77 days / year) in the eastern end of the valley with high elevation (> 2500 m). In WP, the eastern high mountains bordering CP and EP at elevation higher than 3000 m experienced decreasing SCD with a mean speed of -1.78 days / year. SCOD also shifted later with a mean rate of 0.75 days / year in those areas while SCMD moved earlier with a rate of -0.80 days / year. Most parts of CP, especially its southern part with elevation higher than 4000 m, experienced significant decrease of SCD at a mean rate of -0.80 days / year. The dominating feature of snow cover change in EP is the widespread significant trend of decreasing SCD at a mean rate of -1.46 days / year, associated with delayed SCOD across different elevation zone from 2000 m to higher than 5000 m. The mean magnitude of change for the trend of SCOD is 0.84 days / year, with stronger magnitude at higher elevation, especially at the elevation range 4000 - 5000 m. There is less number of grid points with significant trend of change for SCMD, which mostly clustered in the center of EP with a mean change rate of -0.85 days / year.

The decreasing SCD in high mountains in Altai, Tien Shan and Pamir in the research period from 1986 to 2008, can result in a change of hydrological regime in CA, as less water is available stored in seasonal snow cover in the cold season. The earlier SCMD, associated with a significant increase of spring air temperature in those mountain regions might lead to a change of the timing and seasonal distribution of stream flow.

4.3.2 Areas with increasing seasonal snow duration

Increasing SCD can be observed in the northeastern part of KS and the northwestern part of SA, where the center of Siberian High (north of 48 °N, east of 65 °E) in winter is situated (**Jeong et al., 2011; Hasanean et al., 2013**). Those areas experienced an increase of SCD at a rate of 0.96 days / year, associated mainly with later SCMD (0.71 days / year).

Increased SCD is also observed at low elevational regions below 2000 m in CT and ET, while decreased SCD is observed in their high mountain areas above 2000 m (**Figure 11-c-10 and Figure 11-c-11**). In the southeastern part of CT along its border with Tarim at the elevation zone of 1000 - 2000 m, the SCD increased with a mean rate of 1.52 days / year, in companion with earlier SCOD (-0.64 days / year) and later SCMD (0.85 days / year). In the northern and northeastern part of ET, significant increase of SCD is observed across different elevations with an average rate of 1.58 days / year. The increasing trend of SCD is associated with earlier SCOD (-1.01 days / year) and later SCMD (0.92 days / year).

In addition, significant increases of SCD occurred at mid-elevation areas in the western parts of the climatic regions WT, PA and WP. In WT, areas to the west of the Ugamskiy Range and the Chatkalskiy Range in the elevation range of 1000 – 2000 m (**Figure 11-c-6**) experienced increases of SCD with an average rate of 1.15 days / year, associated with earlier SCOD at an average rate of -0.82 days / year; while SCMD did not have significant trend. In PA, there exist patches of places

with increasing SCD (1.24 days / year) associated with earlier SCOD (-0.72 days / year) in the western opening of the valley at the elevation range 1000 m – 2000 m (**Figure 11-c-13**). In the northwestern part of WP bordering PA, areas to the west of mountain ranges at elevation range 1000 m - 3000 m (**Figure 11-c-12**) experienced an increase of SCD at an average rate of 0.83 days / year, as well as SCOD shifting earlier with a mean rate of -0.72 days / year.

4.4 Seasonal snow cover change and climate change

To validate the evaluated snow cover changes for the period of 23 years, we analyzed the climatic changes in different sub-regions of CA in association with statistically significant snow cover changes. Areas surrounding the Aral Sea have experienced significant decrease of SCD, mainly associated with earlier SCMD. The spring temperature in this region increased with a rate of 0.09 °C / year, while the winter precipitation decreased with a rate of -0.55 mm / year (**Figure 12-a**). In the Altai climatic regions, especially SA, SCD decreased significantly, associated with later SCOD and earlier SCMD. Such changes can be attributed to the increase of air temperature, especially the spring air temperature with a significant increasing rate of 0.07 °C / year (**Figure 12-b**).

In high mountains of Tien Shan and Pamir, SCD decreased significantly mainly associated with earlier SCMD, though Central Pamir was also affected by widespread delayed SCOD. Linear trend analysis suggests that both Pamir and Tien Shan have experienced significant increases of spring temperature at rates of 0.06 °C / year and 0.05 °C / year, respectively (**Figure 12-c and 12-d**), while the autumn and winter air temperature and seasonal precipitation (autumn, winter and spring) do not have significant changes.

Comparisons of the seasonal temperature and precipitation trends for regions with significant decreasing SCD suggests that the increasing spring air temperature is closely associated with the decreasing SCD. A positive feedback loop might lead to such association, as warming air

temperature can lead to increasing melt while decreasing snow cover extent can result in higher surface albedo and increasing air temperature. This also explains the more widespread and stronger trend of decreasing SCMD (earlier snow melt) compared with the trend of increasing SCOD (later beginning of snow accumulation) (**Figure 10-c and 10-b**).

Significant increase of SCD can be observed in the northeastern Kazakh Steppe, accompanied by delayed SCMD. Several studies have reported an increase of Eurasian snow cover after the mid-1990s (**Jeong et al., 2011**), especially in Siberia which is close to the northeastern KS. The Siberian High (SH) has seen a resurgence in recent years since the mid-1990s (**Jeong et al., 2011**) after a long term decline from the late 1960s to the early 1990s (**Panagiotopoulos et al., 2005; Hasananean et al., 2013**). Cohen and Entekhabi (**1999**) linked changes in Eurasian snow cover with variability in the extent of the SH, as extensive Eurasian snow cover lead to expanded extent of SH. Thus, the increased snow cover in southern Siberia might be the cause for a bouncing back of the SH (**Cohen et al., 2010 and Jeong et al., 2011**). The precipitation in March increased significantly with a rate of 0.59 mm / year while air temperature experienced a non-significant weak increase and stayed below freezing in general (**Figure 12-e**). Such an increase of precipitation in early spring can lead to an extension of the snow season and delayed SCMD. SCD also increased significantly in the low elevation areas between Tarim and Central Tien Shan and in the low elevation areas in Eastern Tien Shan. The winter temperature at this region decreased at a rate of -0.06°C / year, while winter precipitation increased at a rate of 0.17 mm / year (**Figure 12-f**), which is in favor of increasing SCD during the research period.

5 Discussion

5.1 Comparison with historical snow cover regime studies based on in-situ observations

Kotlyakov et al. (1997) described the snow cover regime all over the world based on regular ground observation data from the 1960s to the 1980s. Spatial distribution of the number of snow covered days (N_{sn} , similar as SCD in this study) is found to be related with altitude, exposition of macro-slope relative to trajectories of major moisture flow, and latitude. The latitudinal gradient for N_{sn} is 5 to 9.5 days / degree with a mean of 8 days / degree for the Northern Hemisphere, comparable with the latitudinal gradient of SCD (~ 9 days / degree for areas below 3000 m) reported for CA in this study. Leeward slopes tend to have lower N_{sn} compared with windward slopes, with one example showing that the mean N_{sn} in the western part of Pamir is 250 - 300 days on 3500 m, in contrast with 40 - 50 days on the same elevation in the eastern part of Pamir. The values reported in this example (Kotlyakov et al., 1997) is comparable with what we found in presented study (Figure 8-c). Average altitudinal gradient of N_{sn} varies across different slopes, with higher values in leeward slopes than in windward slopes. In general, this study provides an update of the description about the snow cover regime in CA based on recent remote sensing data.

5.2 Comparison with snow cover regime studies based on satellite observations

A series of studies analyzed historical snow cover change in the 20th century for the Northern Hemisphere mainly based on NOAA weekly snow cover extent (SCE) climate data record (CDR) (Robinson et al., 1993; Brown & Robinson, 2011), as well as in-situ measurements (Groisman et al., 1994; Brown, 2000; Dye 2002; Brown & Robinson, 2011). A common finding of these studies is that the SCE decreased systematically in the Eurasia continent since the 1970s, especially in March and April. Such decrease is mainly driven by the warming of air temperature, and the

feedback loop among snow cover, radiative balance and spring air temperature (**Groisman et al., 1994**). Though the results of those studies cannot be directly compared with presented study, due to different spatial and temporal coverage, different spatial resolution and different summary statistics for snow cover, the general decrease of spring snow cover in companion with increasing spring air temperature aligns with our findings of decreasing SCD in CA mountainous areas well.

There also exists several publications about snow cover change in sub-regions of CA. Aizen et al. (**1997**) analyzed the snow cover change from 1940 to 1991 using in-situ observations in 110 stations in the Tien Shan region, suggesting a general decrease of snow resources nearly everywhere in the research region, with snow duration down by 9 days. Such decrease of snow resource is in companion with increasing air temperature, despite a slight increase of precipitation. Khan and Holko (**2009**) analyzed snow cover changes in the Aral Sea Basin based on NOAA weekly SCE CDR, re-analysis data and station observations, suggesting decreasing trend of SCE from 1971 to 2006. Our previous study about snow cover changes in Amu Dar'ya Basin from 1986 to 2008 (**ZHOU et al., 2013**) reported significant decreasing trends of SCD in mountainous regions, mainly accompanied with earlier SCMD, while SCOD has shifted earlier in WP and delayed in CP. Results about snow cover changes presented in this study confirm with previous findings of decreasing snow cover, especially in spring, while providing an extended spatial coverage over the whole CA, as well as finer spatial resolution. Even though the results reported in this paper might not be directly compared with previous findings due to differences in underlying data, research area, and research period, the general decreases of seasonal now cover in mountains presented in this paper correspond to previous findings well.

An independent analysis of snow cover change in the Central Asian Republics (CARs) from 1986 to 2014 were conducted by Dietz et al. (**2014**) based on AVHRR imageries (referred as **D2014** in later

634 texts). Summary statistics for snow cover extent and timing characteristics, including SCD, *SCDES*
 635 and *SCDLS* (same as SCD, SCOD and SCMD in this study) were calculated at each 100 m
 636 elevation zone within the CARs, and within different catchment groups. Trends of the summary
 637 statistics were analyzed using Mann-Kendal test. The results show that SCMD shifted earlier
 638 significantly in upstream catchments of Amu Dar'ya and Syr Dar'ya, as well as in the elevation
 639 range between 2500 and 3200 m, which is in agreement with our previous work and the results of
 640 this study in general. It is reported that SCOD moved earlier significantly all over CARs, and no
 641 significant trend of SCD change can be detected in any catchment group or elevation zone, which
 642 differs from our findings. In this study, within the boundary of CARs, significantly decreased SCD
 643 was observed in mountainous areas of Tien Shan and Pamir, while only patches in WP and WT
 644 experienced SCOD shifted earlier. The disagreement might come from the slightly different
 645 temporal coverage of the two studies (1986 to 2008 in the presented study vs. 1986 to 2014 in
 646 **D2014**). Another possible cause of the difference is the different calculation unit used when
 647 conducting trend tests. In **D2014**, trend calculation was conducted at each 100 m elevation zone
 648 across the whole CARs and different catchment groups within the CARs. As shown in our results,
 649 the trend of change for snow cover statistics exhibits large spatial variability across/within different
 650 climatic regions and altitudinal ranges. Calculation conducted at the grid level as in the presented
 651 study can preserve and quantify such spatial variability, enabling further analysis of the dependence
 652 of trends on climatic and topographic factors, while calculation conducted at catchment groups and
 653 100 m elevation zones within the political boundaries might lump areas with different directions of
 654 change together, resulting in diluted or altered signals of changes.

6 Conclusion

Analysis of the long term mean snow cover statistics shows that the whole CA has area weighted mean values of *SCD*, *SCOD*, *SCMD* of 95.2 ± 65.7 days, Nov 23rd ± 26 days and Mar 7th ± 36 days. More than 73% of the areas in CA have *SCmax* greater than 95% before Jan 26th. High mountainous regions of Altai, Tien Shan and Pamir, accounting for ~2.8% of total area in CA, have *SCD* longer than 240 days and *DSCmax* before Jan 5th. The northern part of CA, from Kazakh Steppe to Siberian Altai and Mongolian Altai, have *SCD* in the range of 90 - 240 days, while the southern part of CA have *SCD* in the range of 0 – 90 days. Deserts and rain shadows of major mountains, which also accounts for about 27.0% of total area in CA, have *SCD* in the range of 0 - 30 days.

Simple linear regression and segmented linear regression analysis show that elevation is the most significant factor determining the distribution of *SCD* among elevation, latitude and relative location to major mountains. The relationship between *SCD* and elevation varies according to the relative location to nearby major mountain systems. Latitude has a strong influence in *SCD* in plain climatic regions (Kazakh Steppe and Aral-Caspian Desert). Climatic regions other than KS and AD were classified as windward and leeward regions, based on the different types of relationship between *SCD* and elevation. A positive relationship with a magnitude of 5.9 days / 100 m can be found for plains and windward side mountainous regions, while the magnitude changes from 0.7 days / 100 m to 10.0 days / 100 m at ~2335 m for leeward side mountainous regions. Latitude affects the distribution of *SCD* with a magnitude of 9 – 10 days / degree.

Analysis of the snow cover change for the period from 1986 to 2008 reveals several areas with different types of snow cover change. Analysis of climate changes in areas with different types of snow cover change show that the climate changes are in accordance with the snow cover changes. Increase of SCD can be observed in the northeastern Kazakh Steppe with a rate of 0.96 days / year, mainly associated with later SCMD and a decrease of air temperature in March. SCD also increased in lower elevation area below 2000 m in Central Tien Shan and Eastern Tien Shan with a rate of about 1.5 days / year, as well as in mid-elevation areas (1000 m – 3000 m) in Western Tien Shan (1.15 days / year), Pamiro-Alai (1.24 days / year) and Western Pamir (0.83 days / year), associated with both earlier SCOD and later SCMD. Decreased SCD can be observed at areas surrounding the Aral Sea with a rate of -1.43 days / year while SCMD shifted earlier in the same place though with greater geographical extent. Mountains in Altai, Tien Shan and Pamir also experienced significant decreases of SCD, with rates of -1.56 days / year, -1.16 days / year and -1.59 days / year, respectively. Such decreases of SCD mainly associated with earlier SCMD, with rates of -0.89 days / year, -0.73 days / year and -0.81 days / year for mountainous areas in Altai, Tien Shan and Pamir, respectively. The decreases of SCD and the SCMD shifting earlier can be attributed mainly to the significant increase of spring air temperatures in the research period between 1986 and 2008.

Acknowledgement

This research was supported by grants from the National Science Foundation AGS-1304898 and the National Aeronautics and Space Administration NNX08AL686.

694

695 **Tables**

696 Table 1 Region definitions as longitudinal and latitudinal ranges

Region	description	latitudinal range	longitudinal range
Aral Sea	Places surrounding Aral Sea	52.5°N – 67.5 °N	42.5°E – 47.5 °E
Northeastern KS	Northeastern part of Kazakh Steppe	50 °N – 55 °N	70 °E – 82.5 °E
Altai	Siberian Altai-Sayan and Mongolian Altai	47.5 °N - 52.5 °N	80 °E - 95 °E
Pamir	Central Pamir and Eastern Pamir	37.5 °N - 40 °N	72.5 °E - 75 °E
Western mountains of Tien Shan	junction of major mountains among Tien Shan climatic regions	40 °N – 42.5 °N	70 °E - 80 °E
Boundary zone among Central Tien Shan, Tarim and Eastern Tien Shan	Lower plains spanning from Central Tien Shan to Tarim and Eastern Tien Shan	40 °N – 42.5 °N	80 °E - 90 °E

697

Table 2-1 Linear models for *SCD* with elevation and latitude

ID	short name	formula in R style	description
1	Only latitude (OL)	$SCD \sim Lat$	<i>SCD</i> depends on latitude only
2	Only elevation (OE)	$SCD \sim Elev$	<i>SCD</i> depends on elevation only
3	Elevation and latitude (EL)	$SCD \sim Elev + Lat$	<i>SCD</i> depends on both elevation and latitude
4	Breaking elevation (BE)	$SCD \sim Elev : I(Elev > critical_elevation)$	<i>SCD</i> depends on elevation only, with the relationship breaks at a certain critical elevation
5	Breaking elevation and latitude (BEL)	$SCD \sim Elev : I(Elev > critical_elevation) + Lat$	<i>SCD</i> depends on elevation and latitude, with the relationship breaks at a certain critical elevation

Table 2-2 Regression result for *SCD* with elevation and latitude for different types of climatic regions

Region name	Regression model	R^2
Plains	$SCD = 0.0585 \text{ elev} + 9.6778 \text{ lat} - 380.0674$	0.8927
Leeward side mountainous regions	$SCD = 0.0068 \text{ elev} + 10.0256 \text{ lat} - 388.9821 \text{ (elev} < 2335)$	0.7181
Windward side mountainous regions	$SCD = 0.1004 \text{ elev} + 10.0256 \text{ lat} - 388.9821 \text{ (elev} \geq 2335)$	
	$SCD = 0.0611 \text{ elev} + 9.1655 \text{ lat} - 366.9686$	0.8234

SCD (days), elev (m), lat (degree)

706

707 **Figures**708 **Figure 1 Topography and climatic regions in central Asia (CA)**

709 Main map shows the digital elevation model derived from GGIAR SRTM data and division of
 710 climatic regions in CA:

711 1: Kazakh Steppe (KS), 2: Aral-Caspian Desert (AD), 3: Tarim (TR); 4: Siberian Altai-Sayan (SA),
 712 5: Mongolian Altai (MA); 6. Western Tien Shan (WT), 7: Northern Tien Shan (NT), 8: Issyk Kul
 713 (IK), 9: Inner Tien Shan (IT), 10: Eastern Tien Shan (ET), 11: Central Tien Shan (CT); 12: Western
 714 Pamir (WP), 13: Pamiro-Alai (PA), 14: Central Pamir (CP), 15: Eastern Pamir (EP)

715 Grey triangles show location of ground snow survey data

716 Inset maps A), B) and C) show major mountain systems in Altai, Tien Shan and Pamir.

717 **Figure 2-a Perennial Snow Cover Area Percentage (PSCAP) from 1986 to 2008 in CA**718 **Figure 2-b Long-term mean Snow Covering Days (SCD) from 1986 to 2008 in CA**719 **Figure 2-c Long-term mean Snow Cover Onset Date (SCOD) from 1986 to 2008 in CA**720 **Figure 2-d Long-term mean Snow Cover Melt Date (SCMD) from 1986 to 2008 in CA**

721 **Figure 2-e Long-term mean Maximum Snow Cover Area Percentage (SCmax) from 1986 to**
 722 **2008 in CA**

723 **Figure 2-f Long-term mean Day of Maximum Snow Cover (DSCmax) from 1986 to 2008 in CA**724 **Figure 3 Long-term mean 8-day SCAP and maximum SCAP for each climatic region**

725 The star shows the date for maximum SCAP, while light blue span indicates 2 std of SCAP

726 **Figure 4 Scatterplots of long-term mean SCD against elevation in CA**

727 red solid line showing the moving mean, dash lines showing the extent of 2 moving std

728 upper panel depicting the histogram and density of SCD distribution

729 right panel depicting the histogram and density of elevation distribution

730 **Figure 5 Scatterplots of long-term mean SCD against elevation in each climatic region**

731 red solid line showing the moving mean, dash lines showing the extent of 2 moving std

732 **Figure 6 Increasing rates of *SCD* by elevation in leeward climatic regions**

733 **Figure 7-a Relationship between long-term mean SCD and latitude in condition of elevation**

734 **Figure 7-b Increasing rate of *SCD* by latitude in different elevation zones**

735 **Figure 8-a SCD distribution between windward side and leeward side climatic regions in Altai**

736 Windward side: Siberian Altai-Sayan (SA); Leeward side: Mongolian Altai (MA)

737 **Figure 8-b SCD distribution between windward and leeward climatic regions in Tien Shan**

738 Windward side: Western Tien Shan (WT), Northern Tien Shan (NT); Leeward side: Issyk Kul (IK),

739 Central Tien Shan (CT), Eastern Tien Shan (ET) Inner Tien Shan (IT)

740 **Figure 8-c SCD distribution between windward side and leeward side climatic regions in**

741 **Pamir**

742 Windward side: Western Pamir (WP), Pamiro-Alai (PA), Central Pamir (CP); Leeward side: Eastern
 743 Pamir (EP)

744 **Figure 9 Monthly SCAP in CA from 1986 to 2008**

745 **Figure 10-a Trend of SCD change detected by Theil-Sen regression**

746 Only grids showing significant changes under Mann-Kendal test with significant level of 0.05 were
 747 shown.

748 **Figure 10-b Trend of SCOD change detected by Theil-Sen regression**

749 Only grids showing significant changes under Mann-Kendal test with significant level of 0.05 were
 750 shown.

751 **Figure 10-c Trend of SCMD change detected by Theil-Sen regression**

752 Only grids showing significant changes under Mann-Kendal test with significant level of 0.05 were
 753 shown.

754 **Figure 11-a Box plots of trend of SCD in different elevation ranges**

755 **Figure 11-b Box plots of trend of SCD in different climatic regions**

756 **Figure 11-c Box plots of trend of SCD in different elevation ranges within each climatic region**

757 **Figure 12-a Air temperature and precipitation change in areas surrounding Aral Sea**

758 **Figure 12-b Air temperature and precipitation change in Altai**

759 **Figure 12-c Air temperature and precipitation change in western mountains of Tien Shan**

760 **Figure 12-d Air temperature and precipitation change in Pamir**

761 **Figure 12-e Air temperature and precipitation change in Northeastern Kazakh Steppe**

762 **Figure 12-f Air temperature and precipitation change in in boundary zone among Central**
763 **Tien Shan, Tarim and Eastern Tien Shan**
764

764

765 **References**

- 766 Aizen, V. B., Aizen, E. M., & Melack, J. M. (1995). Climate, snow cover, glaciers, and runoff in the
767 Tien Shan, Central Asia. *Water Resources Bulletin*, 31(6), 1113–1129.
- 768 Aizen, V. B., Aizen, E. M., & Melack, J. M. (1996). Precipitation, melt and runoff in the northern
769 Tien Shan. *Journal of Hydrology*, 186(1-4), 229–251.
- 770 Aizen, V. B., Aizen, E. M., Melack, J. M., & Dozier, J. (1997). Climatic and hydrologic changes in
771 the Tien Shan, central Asia. *Journal of Climate*, 10(6), 1393–1404.
772 [http://doi.org/10.1175/1520-0442\(1997\)010<1393:CAHCIT>2.0.CO;2](http://doi.org/10.1175/1520-0442(1997)010<1393:CAHCIT>2.0.CO;2)
- 773 Aizen, E. M. E., Aizen, V. B. V., Melack, J. M., & Krenke, A. N. (2000). Heat exchange during
774 snow ablation in plains and mountains of Eurasia. *Journal of Geophysical Research*, 105(D22),
775 013–027. Retrieved from <http://onlinelibrary.wiley.com/doi/10.1029/2000JD900279/full>
- 776 Aizen, V. B. (2004). Association between atmospheric circulation patterns and firn-ice core records
777 from the Inilchek glacierized area, central Tien Shan, Asia. *Journal of Geophysical Research*,
778 109(D8). <http://doi.org/10.1029/2003JD003894>
- 779 Aizen, V. B., Aizen, E., Fujita, K., Nikitin, S. A., Kreutz, K. J., & Takeuchi, L. N. (2005). Stable-
780 isotope time series and precipitation origin from firn-core and snow samples, Altai glaciers,
781 Siberia. *Journal of Glaciology*, 51(175), 637–654.
782 <http://doi.org/doi:10.3189/172756505781829034>
- 783 Aizen, V. B., Mayewski, P. a., Aizen, E. M., Joswiak, D. R., Surazakov, A. B., Kaspari, S., ...
784 Finaev, A. (2009). Stable-isotope and trace element time series from Fedchenko glacier (Pamirs)
785 snow/firn cores. *Journal of Glaciology*, 55(190), 275–291.
786 <http://doi.org/10.3189/002214309788608787>
- 787 Aizen, V. B., Aizen, E. M., ZHOU, H., in preparation, Climate changes in central Asia in the 20th
788 century
- 789 Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on
790 water availability in snow-dominated regions. *Nature*, 438(7066), 303–9.
791 [doi:10.1038/nature04141](http://doi.org/10.1038/nature04141)
- 792 Böhner, J., & Böhner, J. (2006). General climatic controls and topoclimatic variations in Central and
793 High Asia. *Boreas*, 35(2), 279–295. <http://doi.org/10.1080/03009480500456073>
- 794 Brown, R. D. (2000). Northern Hemisphere Snow Cover Variability and Change, 1915–97. *Journal*
795 *of Climate*, 13(13), 2339–2355. [doi:10.1175/1520-0442\(2000\)013<2339:NHSCVA>2.0.CO;2](http://doi.org/10.1175/1520-0442(2000)013<2339:NHSCVA>2.0.CO;2)

- 796 Brown, R. D., & Robinson, D. a. (2011). Northern Hemisphere spring snow cover variability and
797 change over 1922–2010 including an assessment of uncertainty. *The Cryosphere*, 5(1), 219–
798 229. <http://doi.org/10.5194/tc-5-219-2011>
- 799 Bryson, R. (1986). Airstream Climatology of Asia. In Y. Xu (Ed.), *Proceedings of International*
800 *Symposium on the Qinghai-Xizang Plateau and Mountain Meteorology SE - 36* (pp. 604–619).
801 American Meteorological Society. http://doi.org/10.1007/978-1-935704-19-5_36
- 802 Chapin, F. S., Sturm, M., Serreze, M. C., McFadden, J. P., Key, J. R., Lloyd, a H., ... Welker, J. M.
803 (2005). Role of land-surface changes in arctic summer warming. *Science (New York, N.Y.)*, 310,
804 657–660. <http://doi.org/10.1126/science.1117368>
- 805 Chevallier, P., Pouyaud, B., Mojaïsky, M., Bolgov, M., Olsson, O., Bauer, M., & Froebrich, J.
806 (2014). River flow regime and snow cover of the Pamir Alay (Central Asia) in a changing
807 climate. *Hydrological Sciences Journal*, (July), 1–16.
808 <http://doi.org/10.1080/02626667.2013.838004>
- 809 Choi, G., Robinson, D. a., & Kang, S. (2010). Changing Northern Hemisphere Snow Seasons.
810 *Journal of Climate*, 23(19), 5305–5310. doi:10.1175/2010JCLI3644.1
- 811 Cohen, J., & Entekhabi, D. (1999). Eurasian snow cover variability and Northern Hemishpere
812 climate predictability. *Geophysical Research Letters*, 26(3), 345–348.
813 <http://doi.org/10.1029/1999GL900200>
- 814 Cohen, J., Foster, J., Barlow, M., Saito, K., & Jones, J. (2010). Winter 2009-2010: A case study of
815 an extreme Arctic Oscillation event. *Geophysical Research Letters*, 37(July), 1–6.
816 doi:10.1029/2010GL044256
- 817 Dietz, A., Conrad, C., Kuenzer, C., Gesell, G., & Dech, S. (2014). Identifying Changing Snow
818 Cover Characteristics in Central Asia between 1986 and 2014 from Remote Sensing Data.
819 *Remote Sensing*, 12752–12775. doi:10.3390/rs61212752
- 820 Dozier, J. (1987). Recent research in snow hydrology. *Review of Geophysics*, 25(2), 153–161.
821 doi:10.1029/RG025i002p00153
- 822 Dye, D. G. (2002). Variability and trends in the annual snow-cover cycle in Northern Hemisphere
823 land areas, 1972-2000. *Hydrological Processes*, 16(15), 3065–3077.
824 <http://doi.org/10.1002/hyp.1089>
- 825 Edwards, A. C., Scalenghe, R., & Freppaz, M. (2007). Changes in the seasonal snow cover of alpine
826 regions and its effect on soil processes: A review. *Quaternary International*, 162-163, 172–181.
827 doi:10.1016/j.quaint.2006.10.027
- 828 Fernandes, R., & G. Leblanc, S. (2005). Parametric (modified least squares) and non-parametric
829 (Theil–Sen) linear regressions for predicting biophysical parameters in the presence of
830 measurement errors. *Remote Sensing of Environment*, 95(3), 303–316.
831 doi:10.1016/j.rse.2005.01.005

- 832 Groisman, P. Y., Karl, T. R., Knight, R. W., & Stenchikov, G. L. (1994). Changes of Snow Cover,
833 Temperature, and Radiative Heat Balance over the Northern Hemisphere. *Journal of Climate*,
834 7(11), 1633–1656. doi:10.1175/1520-0442(1994)007<1633:COCTA>2.0.CO;2
- 835 Handorf, D., Jaiser, R., Dethloff, K., Rinke, A., & Cohen, J. (2015). Impacts of Arctic sea ice and
836 continental snow cover changes on atmospheric winter teleconnections. *Geophysical Research*
837 *Letters*, 42(7), 2367–2377. <http://doi.org/10.1002/2015GL063203>.
- 838 Hasanean, H. M., Almazroui, M., Jones, P. D., & Alamoudi, a. a. (2013). Siberian high variability
839 and its teleconnections with tropical circulations and surface air temperature over Saudi Arabia.
840 *Climate Dynamics*, 41, 2003–2018. doi:10.1007/s00382-012-1657-9
- 841 Immerzeel, W. W., van Beek, L. P. H., & Bierkens, M. F. P. (2010). Climate change will affect the
842 Asian water towers. *Science (New York, N.Y.)*, 328(5984), 1382–5.
843 <http://doi.org/10.1126/science.1183188>
- 844 IPCC. (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional*
845 *Aspects. Contribution of Working Group II to the Fifth Assessment Report of the*
846 *Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D.*
847 *Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B.*
848 *Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)].*
849 Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.
- 850 Jansson, P., Hock, R., & Schneider, T. (2003). The concept of glacier storage: a review. *Journal of*
851 *Hydrology*, 282(1-4), 116–129. doi:10.1016/S0022-1694(03)00258-0
- 852 Jeong, J.-H., Ou, T., Linderholm, H. W., Kim, B.-M., Kim, S.-J., Kug, J.-S., & Chen, D. (2011).
853 Recent recovery of the Siberian High intensity. *Journal of Geophysical Research: Atmospheres*,
854 116(D23), n/a–n/a. doi:10.1029/2011JD015904
- 855 Khan, V. M., & Holko, L. (2009). Snow cover characteristics in the Aral Sea Basin from different
856 data sources and their relation with river runoff. *Journal of Marine Systems*, 76(3), 254–262.
857 <http://doi.org/10.1016/j.jmarsys.2008.03.012>
- 858 Khlopenkov, K. V., & Trishchenko, A. P. (2007). SPARC: New Cloud, Snow, and Cloud Shadow
859 Detection Scheme for Historical 1-km AVHRR Data over Canada. *Journal of Atmospheric and*
860 *Oceanic Technology*, 24(3), 322–343. doi:10.1175/JTECH1987.1
- 861 Kotlyakov, V. M. (Ed.). (1997). *World Atlas of Snow and Ice Resources*. Moscow.
- 862 Krenke, A. (1998). Former Soviet Union hydrological snow surveys, 1966-1996 Version 1, Edited
863 by NSIDC. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. Retrieved
864 September 1, 2009, from <http://nsidc.org/data/g01170.html>. doi:
865 <http://dx.doi.org/10.7265/N58C9T60>
- 866 Lattin, J., Carroll, D., & Green, P. (2002). *Analyzing Multivariate Data*. Duxbury Press; 1 edition.
867 Retrieved from [http://www.amazon.com/Analyzing-Multivariate-CD-ROM-Duxbury-](http://www.amazon.com/Analyzing-Multivariate-CD-ROM-Duxbury-Applied/dp/0534349749/ref=sr_1_1?s=books&ie=UTF8&qid=1323192580&sr=1-1)
868 [Applied/dp/0534349749/ref=sr_1_1?s=books&ie=UTF8&qid=1323192580&sr=1-1](http://www.amazon.com/Analyzing-Multivariate-CD-ROM-Duxbury-Applied/dp/0534349749/ref=sr_1_1?s=books&ie=UTF8&qid=1323192580&sr=1-1)

- 869 Li, F., & Wang, H. (2014). Autumn Eurasian snow depth, autumn Arctic sea ice cover and East
870 Asian winter monsoon. *International Journal of Climatology*, 34(13), 3616–3625.
871 <http://doi.org/10.1002/joc.3936>
- 872 Liang, T., Huang, X., Wu, C., Liu, X., Li, W., Guo, Z., & Ren, J. (2008). An application of MODIS
873 data to snow cover monitoring in a pastoral area: A case study in Northern Xinjiang, China.
874 *Remote Sensing of Environment*, 112(4), 1514–1526. doi:10.1016/j.rse.2007.06.001
- 875 Lioubimtseva, E., & Henebry, G. M. (2009). Climate and environmental change in arid Central Asia:
876 Impacts, vulnerability, and adaptations. *Journal of Arid Environments*, 73(11), 963–977.
877 doi:10.1016/j.jaridenv.2009.04.022
- 878 Lydolph, P. E. (1977). *Climates of the Soviet Union*. Amsterdam [etc.]: Elsevier.
- 879 Mannig, B., Müller, M., Starke, E., Merckenschlager, C., Mao, W., Zhi, X., ... Paeth, H. (2013).
880 Dynamical downscaling of climate change in Central Asia. *Global and Planetary Change*, 110,
881 26–39. doi:10.1016/j.gloplacha.2013.05.008
- 882 Mölg, T., Maussion, F., & Scherer, D. (2013). Mid-latitude westerlies as a driver of glacier
883 variability in monsoonal High Asia. *Nature Climate Change*, 4(1), 68–73.
884 doi:10.1038/nclimate2055
- 885 Muggeo, V. M. R. (2008). segmented: An R package to Fit Regression Models with Broken-Line
886 Relationships. *R News*, 8(May), 20–25. doi:10.1159/000323281
- 887 NOAA. (1998). NOAA Polar Orbiter Data User's Guide. Retrieved September 1, 2009, from
888 <http://www2.ncdc.noaa.gov/docs/podug/index.htm>
- 889 NOAA. (2007). NOAA KLM USER'S GUIDE. Retrieved September 1, 2009, from
890 <http://www.ncdc.noaa.gov/oa/pod-guide/ncdc/docs/klm/index.htm>
- 891 Ososkova, T., Gorelkin, N., & Chub, V. (2000). Water resources of central Asia and adaptation
892 measures for climate change. *Environmental Monitoring and Assessment*, Retrieved from
893 <http://link.springer.com/article/10.1023/A:1006394808699>
- 894 Panagiotopoulos, F., Shahgedanova, M., Hannachi, A., & Stephenson, D. B. (2005). Observed
895 trends and teleconnections of the Siberian high: A recently declining center of action. *Journal*
896 *of Climate*, 18(9), 1411–1422. <http://doi.org/10.1175/JCLI3352.1>
- 897 Parajka, J., Pepe, M., Rampini, A., Rossi, S., & Blöschl, G. (2010). A regional snow-line method for
898 estimating snow cover from MODIS during cloud cover. *Journal of Hydrology*, 381(3-4), 203–
899 212. <http://doi.org/10.1016/j.jhydrol.2009.11.042>
- 900 Peng, S., Piao, S., Ciais, P., Friedlingstein, P., Zhou, L., & Wang, T. (2013). Change in snow
901 phenology and its potential feedback to temperature in the Northern Hemisphere over the last
902 three decades. *Environmental Research Letters*, 8(1), 014008. doi:10.1088/1748-
903 9326/8/1/014008

- 904 Pohl, E., Knoche, M., Gloaguen, R., Andermann, C., & Krause, P. (2014). The hydrological cycle in
 905 the high Pamir Mountains: how temperature and seasonal precipitation distribution influence
 906 stream flow in the Gunt catchment, Tajikistan. *Earth Surface Dynamics Discussions*, 2(2),
 907 1155–1215. <http://doi.org/10.5194/esurfd-2-1155-2014>
- 908 R Core Team (2015). R: A language and environment for statistical computing. R Foundation for
 909 Statistical Computing, Vienna, Austria. URL <http://www.R-project.org/>.
- 910 Reuter, H. I., Nelson, A., & Jarvis, A. (2007). An evaluation of void-filling interpolation methods
 911 for SRTM data. *International Journal of Geographical Information Science*, 21(9), 983–1008.
 912 <http://doi.org/10.1080/13658810601169899>
- 913 Robinson, D. A., Scharfen, G., Serreze, M. C. M., Kukla, G., & Barry, R. G. (1986). Snow melt and
 914 surface albedo in the arctic basin. *Geophysical Research Letters*, 13(9), 945–948.
 915 <http://doi.org/10.1029/GL013i009p00945>
- 916 Robinson, D. a., Dewey, K. F., & Heim, R. R. (1993). Global Snow Cover Monitoring: An Update.
 917 *Bulletin of the American Meteorological Society*. [http://doi.org/10.1175/1520-](http://doi.org/10.1175/1520-0477(1993)074<1689:GSCMAU>2.0.CO;2)
 918 [0477\(1993\)074<1689:GSCMAU>2.0.CO;2](http://doi.org/10.1175/1520-0477(1993)074<1689:GSCMAU>2.0.CO;2)
- 919 Rototaeva, O.V. 1983. Glaciologicheskoe raionirovanie Pamira (The Pamir glaciological zoning).
 920 *Data of Glaciological Studies*, V. 46, M., pp. 39-51(in Russ.)
- 921 Schiemann, R., Glazirina, M. G., & Schär, C. (2007). On the relationship between the Indian
 922 summer monsoon and river flow in the Aral Sea basin. *Geophysical Research Letters*, 34(5),
 923 L05706. <http://doi.org/10.1029/2006GL028926>
- 924 Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. *Journal of the*
 925 *American Statistical Association*, 63, 1379 – 1389.
- 926 Severskiy, I. V., & Severskiy, E. V. (2003). The influence of local factors on snow cover and
 927 seasonal ground freezing in the Tien Shan. In Phillips, Springman, & Arenson (Eds.),
 928 *Permafrost* (pp. 1023 – 1028).
- 929 Siegfried, T., Bernauer, T., Guennet, R., Sellars, S., Robertson, A. W., Mankin, J., ... Yakovlev, A.
 930 (2012). Will climate change exacerbate water stress in Central Asia? *Climatic Change*, 112,
 931 881–899. doi:10.1007/s10584-011-0253-z
- 932 Singh, V. P. (2010). *Snow and Glacier Hydrology* (p. 756). Springer; Softcover reprint of hardcover
 933 1st ed. 2001 edition. Retrieved from [http://www.amazon.com/Glacier-Hydrology-Science-](http://www.amazon.com/Glacier-Hydrology-Science-Technology-Library/dp/9048156351/ref=sr_1_1?s=books&ie=UTF8&qid=1323193452&sr=1-1)
 934 [Technology-Library/dp/9048156351/ref=sr_1_1?s=books&ie=UTF8&qid=1323193452&sr=1-](http://www.amazon.com/Glacier-Hydrology-Science-Technology-Library/dp/9048156351/ref=sr_1_1?s=books&ie=UTF8&qid=1323193452&sr=1-1)
 935 [1](http://www.amazon.com/Glacier-Hydrology-Science-Technology-Library/dp/9048156351/ref=sr_1_1?s=books&ie=UTF8&qid=1323193452&sr=1-1)
- 936 Sorg, A., Bolch, T., Stoffel, M., Solomina, O., & Beniston, M. (2012). Climate change impacts on
 937 glaciers and runoff in Tien Shan (Central Asia). *Nature Climate Change*, 2(10), 725–731.
 938 <http://doi.org/10.1038/nclimate1592>

- 939 Surazakov, a B., Aizen, V. B., Aizen, E. M., & Nikitin, S. a. (2007). Glacier changes in the Siberian
 940 Altai Mountains, Ob river basin, (1952–2006) estimated with high resolution imagery.
 941 *Environmental Research Letters*, 2(4), 045017. <http://doi.org/10.1088/1748-9326/2/4/045017>
- 942 Theil, H. (1950). A rank-invariant method of linear and polynomial regression analysis, I.
 943 *Nederlands Akad. Wetensch. Proc.*, 53, 386 – 392.
- 944 Wang, X., & Xie, H. (2009). New methods for studying the spatiotemporal variation of snow cover
 945 based on combination products of MODIS Terra and Aqua. *Journal of Hydrology*, 371(1-4),
 946 192–200. doi:10.1016/j.jhydrol.2009.03.028
- 947 Wang, X., Xie, H., & Liang, T. (2009). Comparison and validation of MODIS standard and new
 948 combination of Terra and Aqua snow cover products in northern Xinjiang, China. *Hydrological*
 949 *Processes*, 429(October 2008), 419– 429. doi:10.1002/hyp
- 950 You, Q., Fraedrich, K., Ren, G., Ye, B., Meng, X., & Kang, S. (2012). Inconsistencies of
 951 precipitation in the eastern and central Tibetan Plateau between surface adjusted data and
 952 reanalysis. *Theoretical and Applied Climatology*, 109(3-4), 485–496.
 953 <http://doi.org/10.1007/s00704-012-0594-1>
- 954 Zhou, H., Aizen, E., & Aizen, V. (2013). Deriving long term snow cover extent dataset from
 955 AVHRR and MODIS data: Central Asia case study. *Remote Sensing of Environment*, 136, 146–
 956 162. doi:10.1016/j.rse.2013.04.015

Air Temperature (°C)

Precipitation (mm)

Air Temperature (°C)

Precipitation (mm)

Air Temperature (°C)

Precipitation (mm)

Air Temperature (°C)

Precipitation (mm)

Air Temperature (°C)

Precipitation (mm)

Unit: days

water

Unit: %