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Spatiotemporal variability of snow cover timing and duration over the Eurasian continent during 1966–2012

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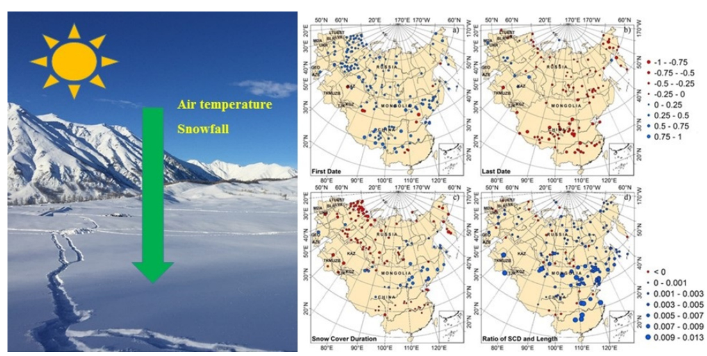
HIGHLIGHTS

- Snow cover timing and duration were investigated across Eurasia based on in-situ observations.
- Snow cover features represented latitude gradient across Eurasia.
- Elevation gradient of snow cover phenology was found on the Tibetan Plateau.
- Changes in snow cover duration depended on air temperature and snowfall.

GRAPHICAL ABSTRACT

1103 stations with long-term (1966–2012) ground-based snow measurements were used to investigate spatial and temporal variability in snow cover timing and duration and the major environmental controls on the observed changes across the Eurasian continent. Delayed FD, advanced LD, and decreasing SCD were represented in most areas across Eurasia. Changes in snow phenology were closely related to the changes in air temperature and snowfall.



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ABSTRACT

The timing and duration of snow cover critically affect surface albedo, surface energy budgets, and hydrological processes. Previous studies using in-situ or satellite remote sensing data have mostly been site-specific (Siberia and the Tibetan Plateau), and remote sensing and/or modeling data include large uncertainties. Here, we used 1103 stations with long-term (1966–2012) ground-based snow measurements to investigate spatial and temporal variability in snow cover timing and duration and factors impacting those changes across the Eurasian continent. We found the earliest annual onset and latest disappearance of snow cover occurred along the Arctic coast, where the long-term (1971–2000) mean annual snow cover duration (SCD) was more than nine months which was the longest in this study. The shortest SCD, ≤10 days, was found in southern China. The first and last dates of snow cover (FD and LD, respectively), SCD, and the ratio of SCD to snow season length (RDL) were generally latitude dependent over the Eurasian Continent, while were elevation dependent on the Tibetan Plateau. During the period from 1966 through 2012, FD delayed and LD advanced by ~1 day/decade, and RDL increased by about 0.01/decade. The LD, SCD, and RDL anomalies (relative to the period 1971–2000) were also significantly correlated with latitude. Advances in LD and positive RDL were more significant in low-latitude regions, decreases in SCD were more significant in high-latitude regions. Changes in SCD were related to air temperature and snowfall in autumn and warming in spring. SCD specifically increased in the northern Xinjiang and northeastern China

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due to increased snowfall. The significant reduction in SCD in southwestern Russia, the Tibetan Plateau and along the Yangtze River was mainly affected by climate warming.

1. Introduction

Snow cover is crucial to the cryosphere and the global climate system as a whole. The timing (i.e., the annual onset and termination) and duration of snow cover affect snow extent, surface albedo, the annual energy balance (Bulygina et al., 2009), soil thermal regime (Zhang, 2005), ecosystem carbon exchange (IGOS, 2007), and atmospheric carbon accumulation (Callaghan and Hohansson, 2011). Recently, however, changes in snow cover timing and duration have been influenced by changes to weather patterns and climate (Bulygina et al., 2009), impacting hydrology, terrestrial ecosystems, and socioeconomic systems in high mountain areas (Hock et al., 2019; Kang et al., 2020), increasing winter runoff over the 21st century (Hock et al., 2019), and advancing the growing season for vegetation (Wang et al., 2018; Xie et al., 2018). Furthermore, shorter snow cover durations impact mountain tourism and recreation (e.g., downhill skiing, climbing, mountaineering, etc.), and the closing of many ski resorts because of unfavorable snow conditions have caused large economic losses (Beaudin and Huang, 2014). It is therefore necessary to investigate recent changes in snow cover timing and duration and the factors influencing them.

Each winter, the average maximum terrestrial snow extent covers nearly 50% of land surfaces in the Northern Hemisphere (Robinson et al., 1993; IGOS, 2007). A large fraction of the Eurasian continent is covered by snow in winter, with some areas covered by snow for more than half a year. Based on weather station data, snow cover termination has advanced by 2.6 ± 5.6 days/decade over the Eurasian continent during 1980–2006, and this change is correlated with spring air temperature (Peng et al., 2013). In northern Eurasia, the number of winter snow cover days has increased by 1.2 days per decade during 1936–2000, whereas ground-based data show a significant decrease since 1975 (Kitaev et al., 2005). Weather station data show that the number of snow cover days has decreased significantly in western and southern regions of European Russia since 1951 (Razuvaev and Bulygina, 2007; Bulygina et al., 2009) but increased in central and western Siberia and on the coast of the Sea of Okhotsk during 1966–2010 (Bulygina et al., 2009, 2011). Based on MODIS snow cover products spanning 2001 to 2014, the number of snow cover days has increased significantly in northeastern China and decreased in northwestern China (Huang et al., 2016).

Observed changes in timing and duration of snow cover vary greatly depending on the data set used, especially on the Tibetan Plateau (TP; Brown and Mote, 2009). An important reason for this variation might be the lack of long-duration time series data from ground-based observations over Eurasia as a whole. Although ground-based measurements are relatively reliable and provide long time-series data sets crucial to investigate the climatology and variability in snow cover timing and duration, previous studies have focused only on certain regions or countries. In addition, because studies in different areas span different periods, it is impossible to directly compare snow cover changes in different areas. Although snow cover data obtained from satellite remote sensing and modeling could mitigate regional deficiencies of in-situ snow measurements, they are of relatively low spatial resolution (25×25 km for passive microwave satellite remote sensing), limited availability (optical remote sensing is limited by cloud cover), and their accuracy depends on the algorithms used to process the data, leading to great uncertainty and bias, particularly in areas of complex terrain.

Previous studies have highlighted inconsistent regional variabilities in snow cover duration, likely due to the complex climate and terrain conditions over the Eurasian continent. Ye et al. (2015) analyzed interdecadal changes in snow cover, surface temperature, and atmospheric circulation over Eurasia and concluded that snow cover change was mainly affected by the atmospheric change. Wu and Chen (2016) reported that atmospheric circulation has an important effect on snow water equivalent via wind-induced changes to the surface sensible heat flux in Siberia and the Russian Far East. Although it is known that snow cover change is affected by air temperature and rainfall (Yim et al., 2010; Zuo et al., 2012; Wu et al., 2014), relatively few studies have investigated the influence of climatic factors on snow cover timing and duration. Therefore, the relationship between snow cover and climate requires further analysis to better determine the factors influencing snow cover timing and duration.

The motivations of this study are to (I) investigate the spatiotemporal variability of snow cover timing and duration across Eurasia during the period 1966–2012, (II) identify the major environmental controls on the observed changes, and (III) quantify the effects of climatic factors on the variations in snow cover timing and duration.

2. Data and methodology

We collected a pool of daily snow depth observations at meteorological stations from 17 countries across Eurasia during the period 1881–2013 from the Russian Research Institute for Hydrometeorological Information-World Data Center (RIHMI-WDC; Bulygina et al., 2009), the National Snow and Ice Data Center (NSIDC, University of Colorado at Boulder; Armstrong, 2001), and the National Meteorological Information Center (NMIC, China Meteorological Administration; Ma and Qin, 2012). Snow depths are measured following WMO (2018) methods across Eurasia with a sturdy ruler, stake or extendible graduated rod.

To minimize random and systematic errors in our snow data set, we implemented a consistent quality control according to the assessment criteria. First, as the World Meteorological Organization's approach to calculate anomalies is based on 30-yr climate normal periods (IPCC, 2013), we used the period 1971–2000 as our normal period. To ensure data continuity, stations with fewer than 20 years of data during 1971–2000 were excluded. Second, data exceeding two standard deviations compared to the long-term (1971–2000) average annual values were also omitted. Finally, after implementing these quality control measures, the data set we used comprised 1103 stations across Eurasia (Fig. 1, Table 1).

There are many different methods to define snow cover timing and duration (Bulygina et al., 2009). We defined a snow year as the period from 1 July to 30 June of the following year, and a snow cover day as any day with snow depth ≥ 1 cm. Snow cover days were used to estimate the onset and termination of snow cover and snow cover duration. There may exist some inhomogeneities in snow depth records predating 1965 because procedures for making snow observations had changed across the former USSR (Bulygina et al., 2009). Therefore, we selected the period 1966–2012 for our analysis.

We defined the variables for each station:

(1) Snow cover day: any day with snow on the ground reaching ≥1 cm deep;
(2) FD: the first snow cover day of each snow year;
(3) LD: the last snow cover day of each snow year;
(4) SSL: snow season length, the number of days from FD to LD each snow year;
(5) SCD: snow cover duration, the number of snow cover days each snow year;

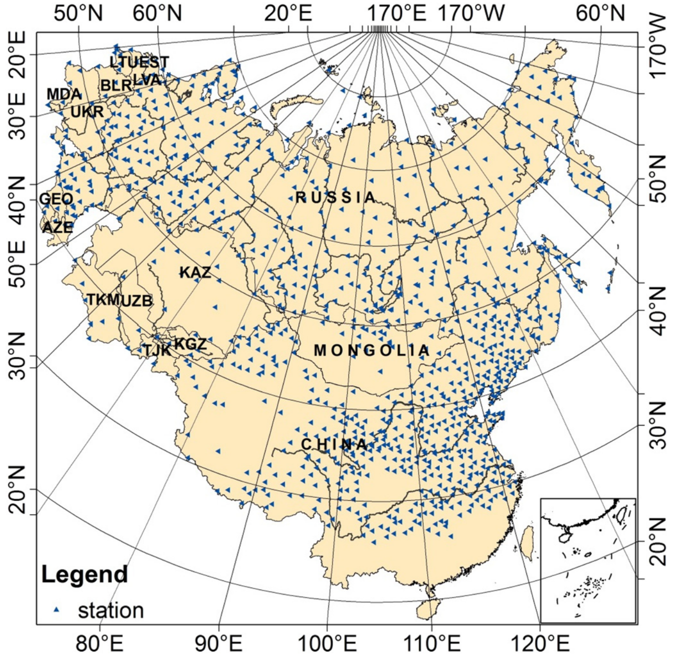

Fig. 1. Meteorological stations across the Eurasian continent used in this study.

(6) RDL: the ratio of SCD to SSL, reflecting the stability of snow cover; and
(7) Long-term mean annual FD, LD, SCD, and RDL: averaged annual values over the climate normal period 1971–2000.

We used daily air temperature and precipitation records compiled by RIHMI-WDC and NMIC for 1031 stations across the former USSR and China to analyze the relationship between snow cover timing and climatic factors. Daily precipitation data were divided into solid and liquid fractions (represented by the solid fraction S) according to the daily mean air temperature ($\bar{T}$, °C) as (Brown, 2000):

$$S = \begin{cases} 1.0 & \text{for } \bar{T} \le -2.0\ ^\circ\text{C}, \\ 0.0 & \text{for } \bar{T} \ge +2.0\ ^\circ\text{C}, \\ 1.0 - 0.25 \times (\bar{T} + 2.0) & \text{for} -2.0\ ^\circ\text{C} < \bar{T} < +2.0\ ^\circ\text{C}. \end{cases} \quad (1)$$

Daily snowfall was calculated as the product of daily precipitation and the daily S value.

We used the anomaly method to partly overcome problems arising from different data availability periods and absolute background conditions (e.g., elevation). We calculated anomalies of the annual FD, LD, SCD, and RDL values relative to the climate normal period (1971–2000) for each station, then averaged the station-level anomalies into anomalies for the entire Eurasian continent. The Student t-test was used to evaluate the statistical significance of the changes in FD, LD, SCD and RDL, and the correlation coefficients of snow cover timing, terrain factors and climatic factors. We set the significance level of this study at $\alpha = 0.05$.

3. Results

3.1. Climatology of FD, LD, SCD, and RDL

Long-term (1971–2000) mean FD, LD, and SCD values varied with latitude over the Eurasian continent (Fig. 2). The earliest long-term mean annual FD was in July in the Severnaya Zemlya (high Arctic), whereas the latest was in February in southern regions around 30° N (Fig. 2a). The earliest and latest long-term mean annual LDs were in January in southern China and in June along the Arctic coast, respectively (Fig. 2b). Long-term mean annual SCDs increased with latitude, the longest being more than 270 days along the Arctic coast and the shortest generally less than 10 days in most areas of southern China (Fig. 2c).

Long-term mean annual RDLs >0.5 were observed in most regions across the former USSR, the northern Xinjiang, and northeast China (Fig. 2d), which are stable snow cover regions (Zhang and Zhong, 2014) with annual mean SCD >60 days. It is worth noting that long-term mean annual RDLs above 0.5 were also observed in some areas of southern China, where FDs and LDs of snow cover were regularly in January and February, respectively; in those areas, SCDs and SSLs were stable and snow cover was continuous. Despite shallow mean annual snow depths (<1 cm) in these areas (Zhong et al., 2018), occasional extreme snow events (e.g., blizzards) have had important impacts on local ecological and social systems. Therefore, once the extreme snow event occurs, it can be prevented in advance.

Long-term mean annual RDLs were significantly different on the TP, with values less than 0.1 in some areas. Although snow accumulated early and disappeared late (long SSL), shallow snow depths (<3 cm) made it difficult to maintain snow cover (Zhong et al., 2018), possibly due to climatic conditions, complex topography, and/or the blowing of snow by strong winds on the TP. Solar radiation on the TP is also stronger than in many other regions at similar latitudes (Xiao et al., 2018) and can heat through shallow snow. Therefore, it is difficult to forecast extreme snow events in areas with low RDL values.

3.2. Changes in FD, LD, SCD and RDL

Across Eurasia, we observed statistically significant long-term trends of delayed onset (later FD) and advanced disappearance (earlier LD) of snow cover from 1966 through 2012 (Fig. 3). The long-term FD anomaly trend was positive, with the onset of snow cover being delayed by approximately 1 day/decade (Fig. 3a). From the mid-1960s through the mid-1980s, FD anomalies were generally negative but not statistically significant relative to the long-term mean. Subsequent FD anomalies were mostly positive and the onset of snow cover was significantly delayed by a maximum of about 7 days during the 2000s. Thereafter, decreasing FD anomalies indicate earlier snow cover. The long-term LD anomaly decreased by approximately −1 day/decade (Fig. 3b); in detail, it fluctuated from the mid-1960s through the late 1980s before significantly advancing by approximately 3 days/decade.

Despite significant FD and LD anomalies, we did not observe a significant long-term SCD trend during the study period (Fig. 3c), possibly due to synchronous changes to LD and FD during several sub-periods. For example, SCD fluctuated from the mid-1960s to the 1980s, then

Table 1
Data sources used in this study.

Dataset	Spatial distribution	Number of stations	Source
Daily snow depth	Former USSR	586	Russian Research Institute for Hydrometeorological Information-World Data Center (RIHMI-WDC)
			National Snow and Ice Data Center (NSIDC), University of Colorado at Boulder
	Mongolia	25	National Snow and Ice Data Center (NSIDC), University of Colorado at Boulder
	China	492	National Meteorological Information Center (NMIC) of the China Meteorological Administration
Daily air temperature and precipitation	Former USSR	579	Russian Research Institute for Hydrometeorological Information-World Data Center (RIHMI-WDC)
	China	452	National Meteorological Information Center (NMIC) of the China Meteorological Administration

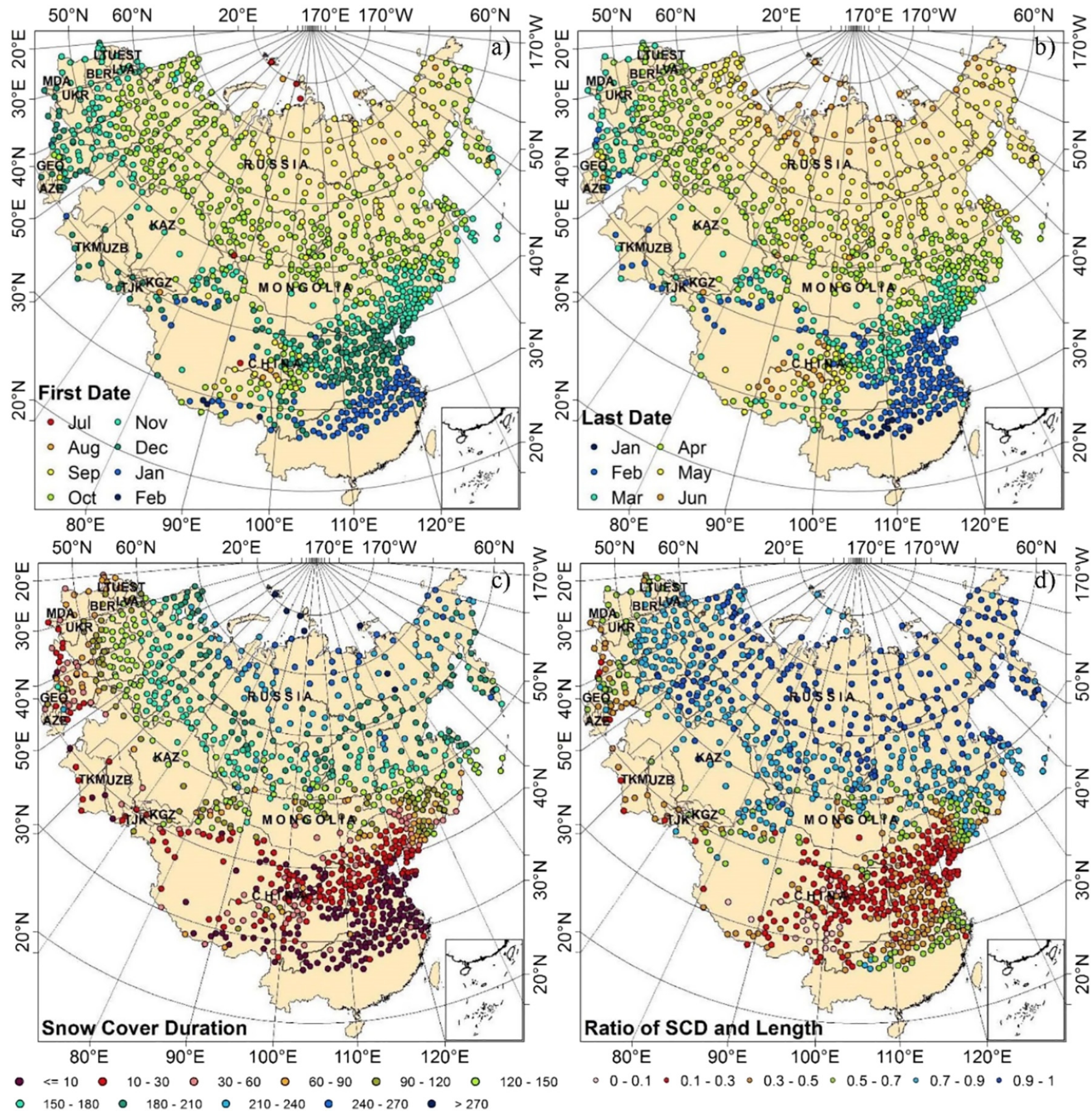

Fig. 2. Long-term (1971–2000) mean annual (a) FD, (b) LD, (c) SCD, and (d) RDL across the Eurasian continent.

decreased by approximately 5 days until the late 2000s, followed by a return to the long-term mean value. This recent increase in SCD might be attributed to rapidly advancing snow cover onset dates despite continuously advancing snow disappearance dates. The RDL anomaly significantly increased by 0.01/decade from 1966 through 2012 (Fig. 3d), changing from a negative to a positive anomaly around the mid-1980s, and fluctuated over a ~5-yr cycle. This increasing RDL anomaly indicates that the snow accumulation time is becoming increasingly stable, consistent with the observed changes in SCD and SSL during the study period over Eurasia.

The long-term FD, LD, SCD, and RDL anomalies also varied spatially during the study period (Fig. 4). Delayed FDs were observed in most areas of European Russia, the Siberian Plain, the western regions of the central Siberian Plateau, northeast China, and the TP, accounting for 12% of the 1103 stations (Fig. 4a). Advanced LDs were statistically significant in most areas of the central Siberian Plateau, the Russian Far East, the TP, and south of the Yangtze River (10% of all stations; Fig. 4b). Decreasing SCD anomalies were statistically significant in western Russia, northeastern regions of the Russian Far East, the TP, and eastern China, accounting for 17% of all stations (Fig. 4c). These decreases in SCD may be mainly due to delayed FDs in western Russia, advanced LDs in the Russian Far East, and changes to both FD and LD in the TP and south of the Yangtze River. In contrast, increasing SCD anomalies were statistically significant in Sakhalin, northern regions of Xinjiang, northeastern China, and the Inner-Mongolia Autonomous Region. We observed statistically significant RDL anomalies across most of Eurasia, especially in eastern areas (>80° E, Fig. 4d), and decreasing RDL anomalies were sporadically distributed in Siberia and the TP.

4. Discussion

4.1. Comparison with the previous results

There are some differences when compared with the previous studies (Table 2). There are four possible reasons to explain these differences:

(1) Variable definitions. Peng et al. (2013) defined the onset and termination of snow cover as the first and last continuous five days with snow observed on the ground, respectively, and the snow year as the period from 1 August to 31 July of the following year. Definition differences might cause differences in the

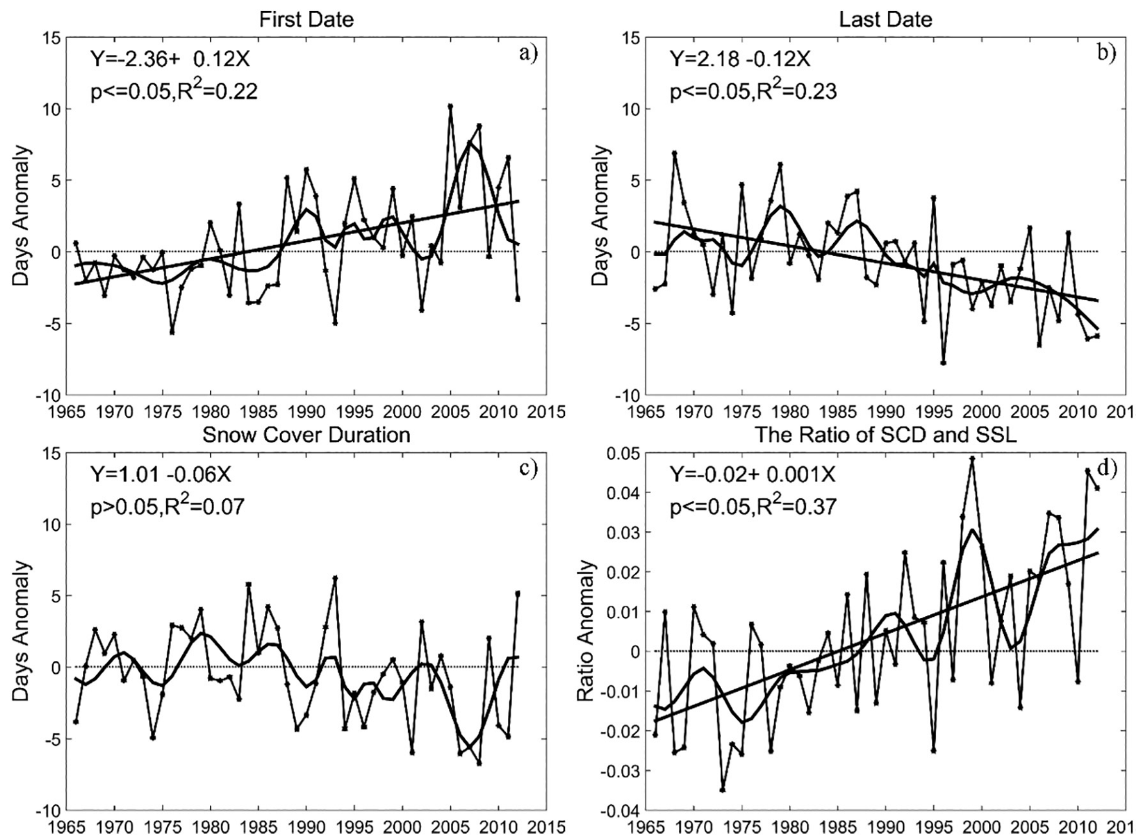

Fig. 3. Interannual variations of (a) FD, (b) LD, (c) SCD, (d) and RDL from 1966 through 2012 with respect to the long-term (1971–2000) mean across the Eurasian continent. Thin lines and points show the annual FD, LD, SCD, and RDL anomalies, thick curves represent the smoothed trends using wavelet analysis, and thick lines present the linear regression trend.

statistical results, especially on LD. Indeed, we observed onset dates in July in the high Arctic, which might have inadvertently been classified as termination dates based on the snow year definition of Peng et al. (2013).

(2) Study periods. The snow depth data used by Peng et al. (2013) and Bulygina et al. (2009) spanned the periods 1979–2006 and 1966–2007, respectively. Our expanded study period may therefore have resulted in different LD and SCD trends.

(3) The numbers of stations used. Peng et al. (2013) used data from only 305 stations across Eurasia, which cannot fully represent changes of snow cover timing over the whole area. Bulygina et al. (2009), on the other hand, used daily snow depth data from 820 Russian stations; over a similar coverage area, the 586 stations of the former USSR we used include a broader, more complete coverage area that more comprehensively captures spatial changes in snow cover phenology. Furthermore, the sensitivity of snow cover to air temperature and precipitation is regionally variable (Fallot et al., 1997; Park et al., 2013), and differences in site-selections between these and our studies may also be responsible for the observed differences.

(4) Interpolation methods. Bulygina et al. (2009) interpolated their data to obtain the spatial variation of SCD whereas we did not, which may have expanded their spatial distribution and may explain the differences between the two studies.

4.2. Correlations between terrain factors and the timing and duration of snow cover

The distributions of FD, LD, SCD, and RDL generally display a latitudinal dependence (Fig. 5). In general and with increasing latitude, FD advances and LD is delayed by about 2 days per degree latitude (Fig. 5a and b, respectively), and SCD increases by about 6 days per degree latitude (Fig. 5c). However, RDL varies non-linearly with latitude, decreasing from 25 to 30° N, increasing from 30 to 60° N, and then stabilizing before again decreasing above 70° N.

Although FD, LD, SCD, and RDL vary significantly with latitude across Eurasia, the timing and duration of snow cover on the TP does not obviously show such a dependency (triangles in Fig. 5). Instead, snow cover timing and duration on the TP depends on elevation: with increasing elevation, FD advances by ~2 days/100 m (Fig. 6a), LD is delayed by ~3 days/100 m (Fig. 6b), SCD increases by ~1 day/100 m (Fig. 6c), and RDL decreases by about 0.005/100 m (Fig. 6d), indicating more ephemeral snow cover at higher elevations.

The LD, SCD, and RDL anomalies are also significantly correlated with latitude (Fig. 7b–d), although this is not the case for FD anomalies (Fig. 7a), indicating that FD was delayed equally over the study period at all studied latitudes. Advances in LD over the study period were generally more extreme in low-latitude regions (Fig. 7b) and primarily on the TP (Fig. 4b). Compared to low-latitude regions, decreases in SCD over the study period were more significant in high-latitude regions (Fig. 7c), mainly due to significant decreases across northern European Russia (Fig. 4c). However, significant increases in SCD were observed in mid-latitude regions, especially in northeastern China. Positive RDL anomalies decreased with increasing latitude (Fig. 7d). This result implies that snow cover became more continuous and stable at low latitudes during the study period (Fig. 4d).

4.3. Response to air temperature and precipitation

Snow cover variability is closely related to climate change (Hock et al., 2019). To examine the relationship between snow cover phenology and climatic factors, we calculated correlation coefficients between

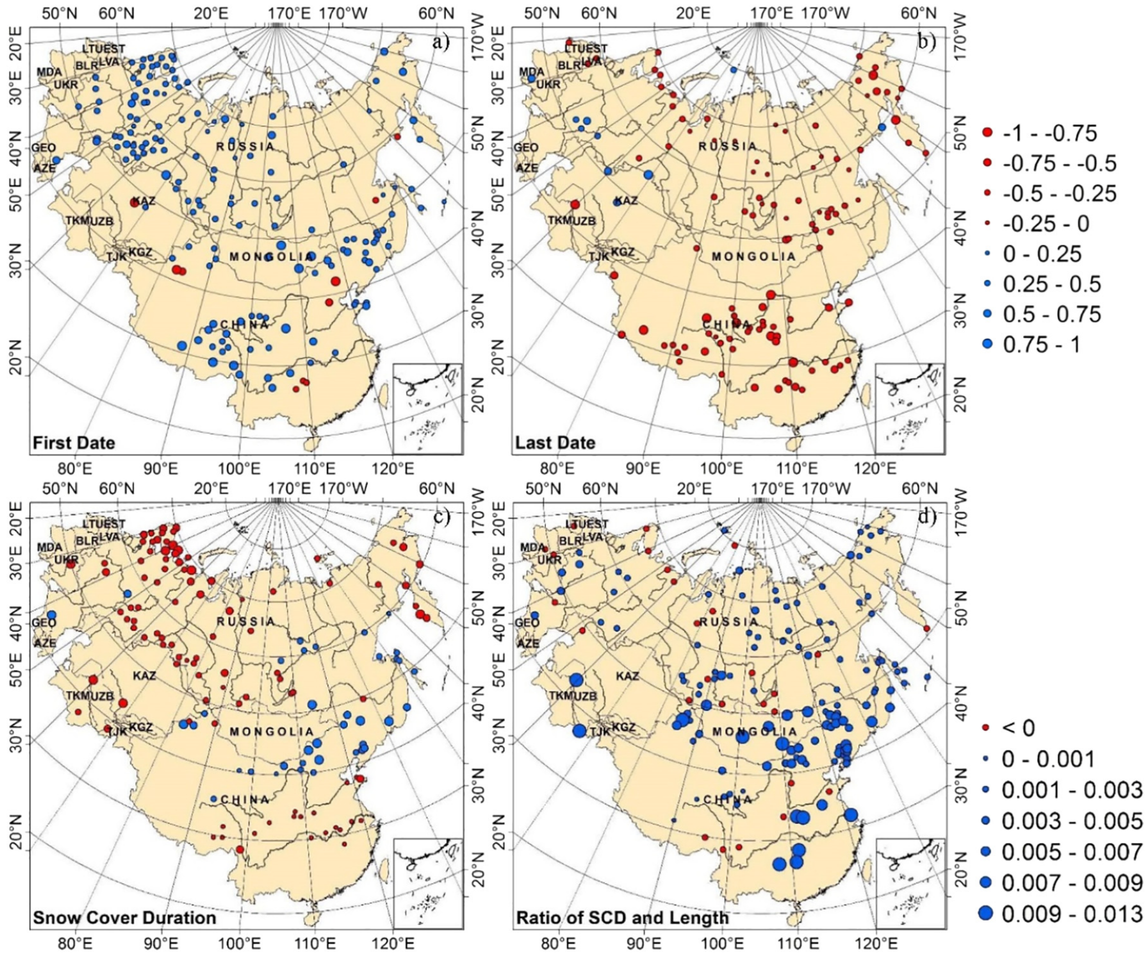

Fig. 4. The spatial distribution of linear trend coefficients (d/yr, see Fig. 3) of the (a) FD, (b) LD, (c) SCD, and (d) RDL anomalies for each station from 1966 through 2012. Sites with $p > 0.05$ are not shown. Red circles represent advancing (a, b) or decreasing trends (c, d), and blue circles represent delayed (a, b) or increasing trends (c, d). (a–c) use the upper scale, and only (d) uses the lower scale.

SCD, daily air temperature, and accumulated snowfall during November to March for 1031 stations over the period 1966–2012 across the Eurasian continent. Significant negative correlations between SCD and air temperature are observed in western regions of European Russia, southern regions of Russia and central Asia, the northern Xinjiang, northeast China, the TP, and south of the Yangtze River (Fig. 8a). The increased sensitivity of SCD to air temperature in these regions may indicate decreased SCDs in areas experiencing higher temperatures.

Compared with the former USSR, closer positive relationships between SCD and snowfall are observed across China, especially in the northern Xinjiang, northeast China, and the TP (Fig. 8b). In these areas, the number of snow cover days correlated with the amount of snowfall, with areas receiving more solid precipitation showing longer SCDs. Indeed, the spatial distribution of snowfall change showed a similar variability to that in SCD (Fig. 8c). Snowfall decreased in some areas of northern European Russia, southwestern Siberia, and the northeastern Russian Far East, which may be a major factor in the observed SCD decreases over the study period in those areas (Fig. 4c). Both SCD and snowfall increased in the northern Xinjiang and northeastern China. Although SCD is highly correlated with air temperature in those locations, mean air temperatures were below 0 °C during the cold season, and increasing temperature could not have directly resulted in the observed SCD change (Fallot et al., 1997). Therefore, the strong correlation between SCD and snowfall implies that increased snowfall led to the observed increase in SCD. SCD changes were more affected by air temperature on the TP and along the Yangtze River, possibly due to high air temperatures during the cold season making ephemeral snow easy to melt. Winds blowing ephemeral snow on the TP also contributed to the short observed SCD there. It was worth noting that SCD and snow depth were negatively correlated in southwestern Russia, with SCD

Table 2
Comparison of the changes in snow cover timing and SCD in different study areas.

Region	Time	Onset	Termination	Change in SCD	Number of stations	Reference
Eurasia	1966–2012	1.2 d/10 yr	−1.2 d/10 yr		1103	This study
	1979–2006	1.3 ± 4.9 d/10 yr	−2.6 ± 5.6 d/10 yr		305	Peng et al. (2013)
European Russia and Sakhalin	1966–2012			No significant change	586 in the former USSR	This study
	1966–2007			Significantly decrease	820 in Russia	Bulygina et al. (2009)
Central Siberia Plateau and Russian Far East	1966–2012			No significant change	586 in the former USSR	This study
	1966–2007			Significantly increase	820 in Russia	Bulygina et al. (2009)

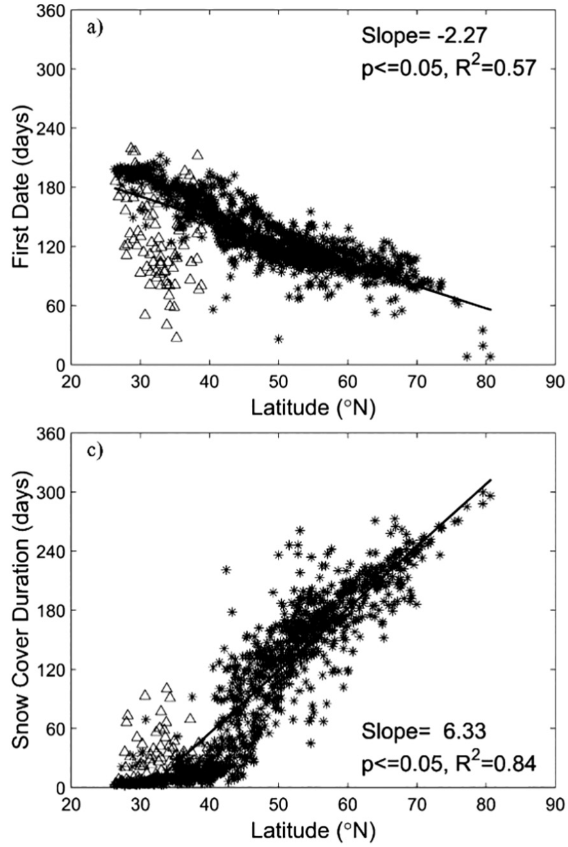

Fig. 5. Changes of (a) FD, (b) LD, (c) SCD, and (d) RDL with latitude for all stations from 1971 to 2000. Asterisks show the mean value for each station across the Eurasian continent, excluding the Tibetan Plateau, and triangles represent the mean for each station on the Tibetan Plateau. Thick lines are the linear (non-linear in (d)) regression trends. Slope units are d/° N in (a–c).

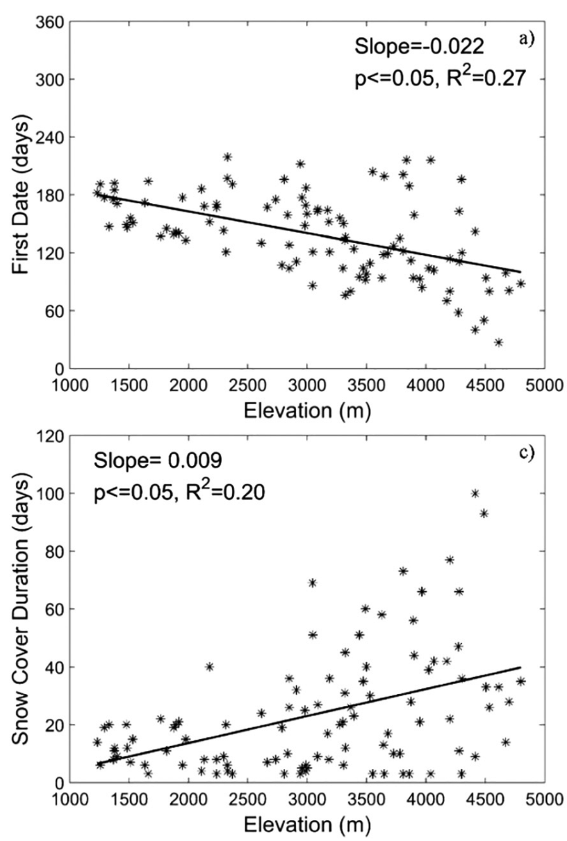

Fig. 6. Changes of the mean (a) FD, (b) LD, (c) SCD, and (d) RDL with elevation for each station on the Tibetan Plateau from 1971 to 2000. Thick lines are linear regression trends; slope units are d/m in (a–c).

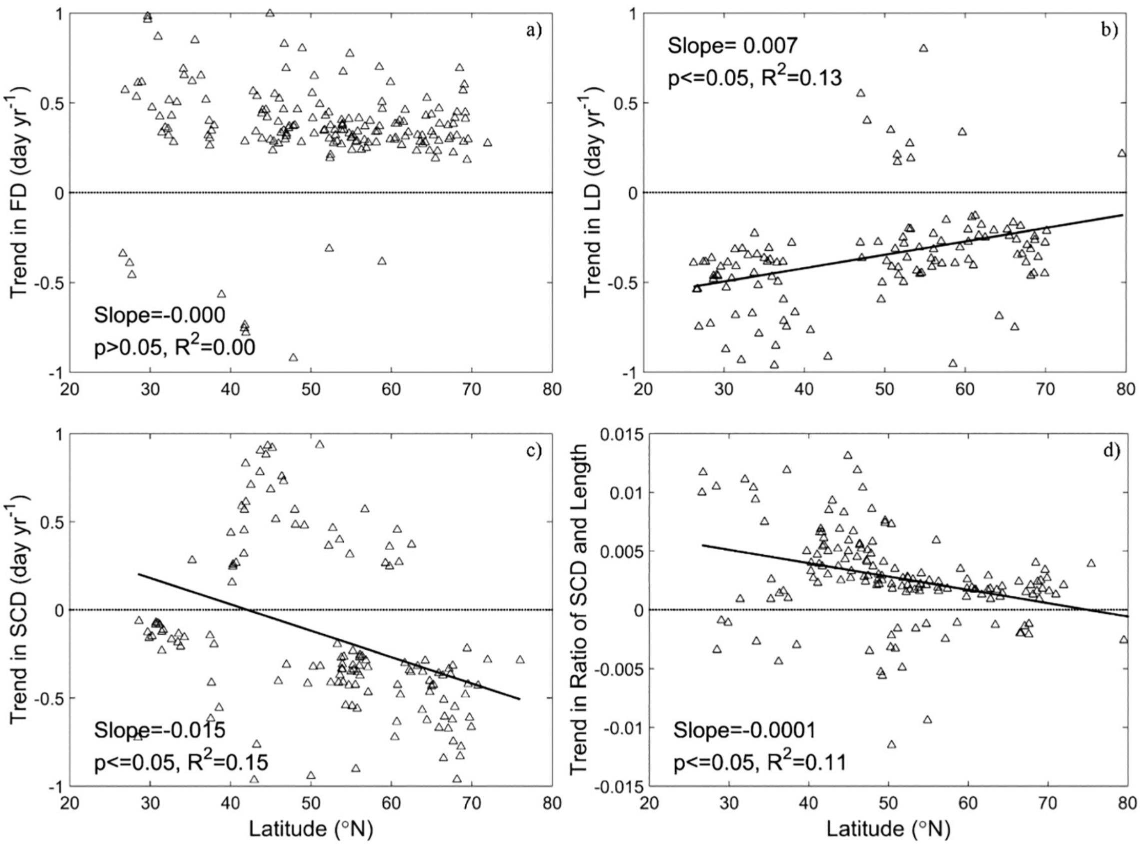

Fig. 7. Linear trend coefficients of the (a) FD, (b) LD, (c) SCD, and (d) RDL anomalies as a function of latitude for each station over the Eurasian continent. Thick lines are linear regression trends; slope units are (d/yr)/° N in (a–c).

decreasing but snow depth increasing (Fig. 6 in Zhong et al., 2018): the increasing snow depth there was affected by extreme snowfall during a shorter accumulation period.

To investigate the impact of seasonal climatic factors on SCD, we calculated correlation coefficients between seasonal SCD, snowfall, and air temperature in autumn, winter, and spring from 1966 through 2012 (Table 3). Changes in SCD were significantly affected by both snowfall and air temperature in autumn. The effects of snowfall and air temperature variations on SCD were not significant in winter. However, changes in SCD were determined by air temperature in spring, with increasing air temperature resulting in decreased SCD, implying positive feedback between warming of the air and snow cover change.

Based on the impact of air temperature on SCD, we analyzed relationships between changes in air temperature and observed anomalies in snow cover timing and duration. The results show that FD was delayed by approximately 4 days/°C increase in mean September–November air temperature (Fig. 9a), implying that the overall delay

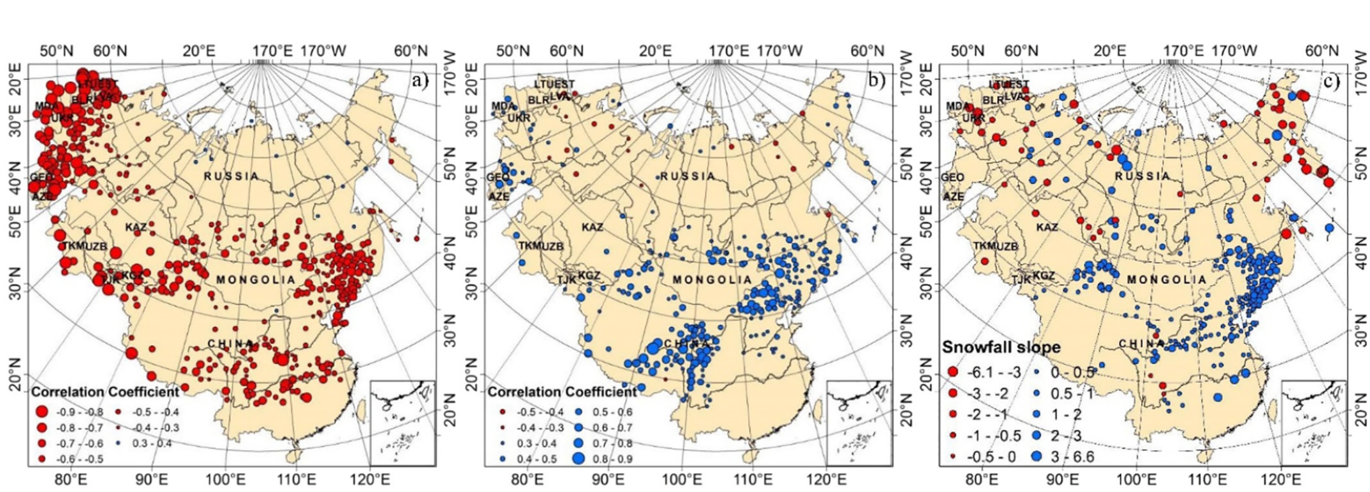

Fig. 8. The spatial distribution of (a) correlation coefficients between SCD and air temperature, (b) correlation coefficients between SCD and snowfall, and (c) linear trend coefficients (mm/yr) of snowfall from 1966 to 2012 over the Eurasian Continent. Sites with $p > 0.05$ are not shown. Red circles represent negative relationships (decreasing trends), and blue circles positive relationships (increasing trends).

Table 3
Correlation coefficients between SCD, snowfall, and air temperature in autumn (September–November), winter (December–February), and spring (March–may) over the Eurasian continent from 1966 through 2012. Two asterisks indicate a 99% confidence level, other values are not statistically significant ($p > 0.05$).

	Snowfall	Air temperature	Snowfall	Air temperature	Snowfall	Air temperature
	Autumn		Winter		Spring	
SCD	0.58**	−0.51**	0.2	−0.27	0.18	−0.8**

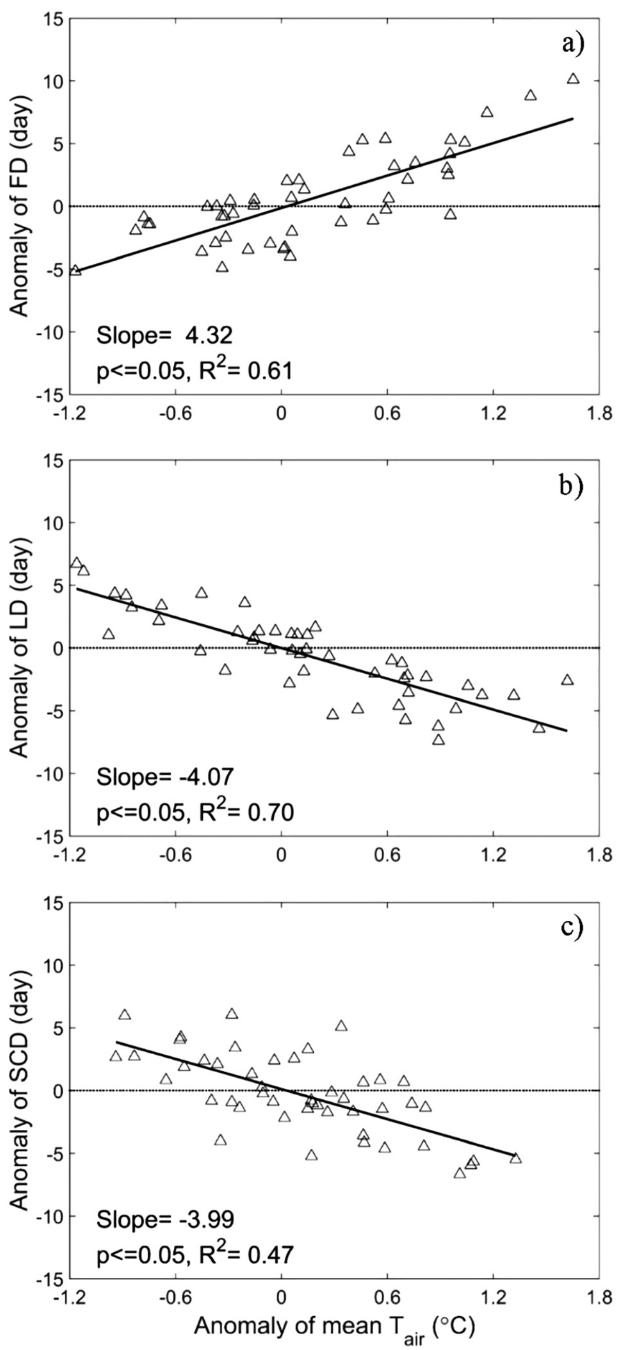

Fig. 9. Relationships between snow cover anomalies and thermal anomalies from 1966 through 2012 across the Eurasian continent: (a) autumn (September–November) mean air temperature and FD anomalies, (b) spring (March–May) mean air temperature and LD anomalies, and (c) annual (July to June of the following year) mean air temperature and SCD anomalies. Thick lines are linear regression trends. Slope units are d/°C.

in FD was caused by autumn warming in recent decades across Eurasia. Similarly, LD advanced by approximately 4 days/°C increase in mean March–May air temperature (Fig. 9b), implying that earlier snow cover termination is closely related to increasing air temperature during snowmelt months in the past several decades across Eurasia. These results are consistent with the correlation coefficients reported in Table 3. On this basis, the SCD trend decreases with increasing air temperature by about 4 days/°C (Fig. 9c). Those indicated that the important effect of changes in air temperature on the snow phenology variation.

Besides, reduced snow surface albedo and increased solar radiation (3–6 times larger than that in autumn; Zhang, 2005) during spring melting periods may also contribute to reduced SCDs. Furthermore, light-absorbing impurities in snow can also reduce snow cover surface albedo, inducing warming of the snow cover, causing snowmelt and SCD reduction (Bond and Bergstrom, 2006; Ménégoz et al., 2014; Qu et al., 2014; Zhang et al., 2017, 2018; Zhong et al., 2019).

5. Summary and conclusions

We used daily snow depth measurements from 1103 stations across Eurasia to investigate the spatial and temporal variability in snow cover timing and duration from 1966 through 2012. Our main findings are as follows.

The earliest snow accumulation and latest snow cover termination occurred on the Arctic coast from 1971 through 2000. The longest and shortest long-term mean annual snow cover duration (SCD) were more than 270 days on the Arctic coast and fewer than 10 days in southern China, respectively. Generally, the first and last dates of snow cover (FD and LD, respectively), SCD, and the ratio of SCD to snow season length (RDL) were latitudinally dependent over the Eurasian continent: per 1° increase in latitude, FD was advanced by 2 days, LD delayed by 2 days, and SCD increased by 6 days. On the TP, however, these variables were instead dependent on elevation: per 100 m increase in elevation, FD was advanced by 2 days, LD delayed by 3 days, SCD increased by 1 day, and RDL decreased by 0.005.

Compared to the 1971–2000 climate normal period, the FD, LD, and RDL anomalies showed statistically significant long-term variations from 1966 through 2012 over the Eurasian continent: FD was delayed by approximately 1 day/decade, LD advanced by about 1 day/decade, and RDL increased by about 0.01/decade.

The spatial distributions of the LD, SCD, and RDL anomalies were significantly correlated with latitude, whereas FD, LD, SCD, and RDL were correlated with elevation on the TP. Importantly, decreased RDL with increasing elevation indicates increasingly ephemeral snow cover at higher altitudes on the TP. Therefore, increased snowfall and SCD in these areas might significantly affect human livelihoods and livestock.

Increasing SCDs resulted from increased snowfall in the northern Xinjiang and northeastern China. In contrast, decreasing SCDs were more strongly affected by increased air temperature in southwestern Russia, the TP, and along the Yangtze River. Changes in SCD were closely related to changes in air temperature and snowfall in autumn and increasing air temperature in spring.

CRediT authorship contribution statement

Xinyue Zhong: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Tingjun Zhang:** Conceptualization, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Shichang Kang:** Formal analysis, Methodology, Visualization, Writing - review & editing. **Jian Wang:** Formal analysis, Writing - review & editing.

Declaration of competing interest

The authors declare that there are no conflicts of interest.

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