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ORIGINAL PAPER

Spatial and temporal variabilities of maximum snow depth in the Northern and Central Kazakhstan

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Abstract

This article examined the dynamics of maximum snow cover in the Northern and Central Kazakhstan for the period from 1935 to 2012. Certain number of data from weather stations was collected for both regions (Northern and Central Kazakhstan) of the country in order to observe the spatial and temporal changes in glaciers. Mann-Kendall test along with sequential version of MK test and simple linear regression was used in the analysis. The analysis revealed regularities of the changes in maximum snow depth over spatial and temporal scales. Cumulative sum uncovered a change in trend, which indicated the data of global warming possibly affected the glacier. Periodicities in glacier changes were weakly related to the weather patterns like North Atlantic Oscillation and Atlantic Multidecadal Oscillations. Obtained results, regularities, and inferences can be used in further studies of snow cover and water flow of the rivers, as well as for practical purposes. Recent changes in climate and hydrological flow of the observed catchment became evident for contemporary glaciations evolving hydrological implications of the cryosphere alterations in the study area. Findings of the study are useful in examining the differences in water availability on spatial and temporal scales due to limited availability of the glaciers in the region.

Keywords Snow cover · Snow cover duration (SCD) · Height of the snow cover · Climate change

Introduction

Global warming is being widely discussed and getting attention in different parts of the world including central Asia where agriculture is the core of economy. Water supplies in the region mainly depend on fluvial water originating from mountain areas where glacier significantly contributes into the availability of water (Narama et al. 2010). Therefore, the research on changes of snow cover characteristics in connection with global warming is important for the analysis of river flow and the impact on the atmosphere, as well as analyzing the impact of these changes on the economy and society. This is more significant as reliability of the future water significantly

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depends on the glacier melt more particularly during the summer when water demand for agriculture is very high. In the Tien Shan region, glaciers collect precipitation in the form of snow during the winter and discharge this precipitation as meltwater during the summer season (Hagg et al. 2007). Such sources of water supplies are considered as more resilient to the drought when other sources are depleted. However, with the passage of time, decrease of glacier is expected to lead to decline of river discharge during the dry summer season (Hagg et al. 2007). This is well evident from the recent studies in Tien Shan region including (Narama et al. 2010; Aizen et al. 2006; Li et al. 2006) which have reported a significant shrinkage of the glacier in this region. Such change has significant consequences which are resulting from climate change which may be the result of alteration of regional hydrological cycle and subsequent changes in the streamflow regimes (Chen et al. 2006). A number of studies including (Aizen et al. 2007) reported a decrease in glacier mass from 12.8 to 15.8% in the central and northern Tien Shan Mountains, respectively, whereas (Bolch 2007) reported a significant decrease of glaciated area of up to 32% from 1955 to 1999 in the northern Tien Shan Mountains which mainly resulted due to much significant increase in summer temperature. Such changes in glaciated areas are very significant to the water supplies as water resources in the Tien Shan Mountains like snow and glaciated cover play a crucial role in runoff formation. Such changes make these regions more vulnerable to climate change as changes in temperature affect the ratio of rain versus snowfall, and snow and glacier melt (Duethmann et al. 2015).

According to research by scientists in Kazakhstan by 90 years of the last century, increases in temperature was about 1–1.3 °C (Dolgikh 1999). There is evidence that only during the years 1954–2003, the average annual temperature, according to the data shown in weather station, increased by about 1.5 °C, and for some stations (e.g., Pavlodar, Semipalatinsk) by about 2–2.5 °C (Ministry of Environmental Protection of the Republic of Kazakhstan 2003). Naturally, a significant change in temperature affects on other meteorological parameters, including characteristics of the snow cover. And these changes are especially noticeable in the 70s. Particularly, since the mid-70s, systematic increase in repetition of zonal forms of atmosphere macro-circulation is marked (Salnikov et al. 2011; Kaya et al. 2018). As an example, in mid-latitude, inland areas increase in temperature causes an increase in evaporation and reduces the period of snow accumulation.

Trends in streamflow in the catchments in the mountainous are significantly influenced by the changes in snow and glacier melt than the changes in the precipitation. Some of the recent studies including (Merz et al. 2012) studied the linkage between the trends in streamflow and possible climatic drivers could be investigated by data-based or simulation-based approach. However, this current research only focused on data-based approach which directly relates to changes in runoff due to changes in climate without additional step of applying hydrological model. Such approach can provide explanation to concurrent trends in streamflow and climate and possible causes of detected streamflow trends (Kriegel et al. 2013). To find the influence of glaciation, comparative analysis approach was applied by observing the trends in streamflow of range of glaciated catchments from highly glaciated to low glaciated catchment, to see the influence of glacier melting on streamflow river-flow discharge of two catchments: one which was highly glaciated and another one which was lowest glaciated; their flow was compared during the summer season. Such approach has also been applied in other studies, i.e., (Dahlke et al. 2012) in Sweden.

In order to identify the temporal data of river-flow within a year, long-term decadal mean of daily river discharge was calculated which helped to observe streamflow shift, that could further be related to catchment properties (Kormann et al. 2015). These parameters are catchment elevation, slope, and glaciation. The next step was analysis of precipitation and temperature effects on the river runoff were observed with the simple linear regression. Similar approach has been applied by other authors including (Sorg et al. 2012), for the trends in spring snow water equivalent (Mote 2006) and for the streamflow and mass balance in glacierized catchment (Moore and Demuth 2001). Trends are usually used for the future water security forecast, including influence increasing temperature without changes in precipitation. It is an initial phase expected to cause increased glacier melt discharge due to higher melt rates. However, higher melt rates ultimately exist in glacier area retreat, causing decreasing glacier melt (Baraer et al. 2012; Moore et al. 2009). Other studies like (Stahl and Moore 2006) analyzed trends in residuals of regression model that predicted August streamflow from August temperature and precipitation and July streamflow. As follows, glaciers in their study area have been already passed in the initial phase of increasing discharge. Additionally, negative glacier mass balances over a longer period result in lowering of the glacier surface elevation and reductions of the glacier area. These changes influensed on the glacier mass balance generally: the reduction in glacier area in the ablation zone results in less glacier melt and thus a less negative glacier mass balance, while the lowering of glacier melt reduced snow accumulation (Duethmann et al. 2015).

Although a number of studies observed the changes in Tien Shan river discharge, limited studies focused on long-term changes in daily river discharge in Tien Shan region. This is very significant to the water supplies and more particularly to the food security in the region which mainly rely on fluvial water. The main focus of this study is to observe recent changes in climate and hydrological flow of the observed catchment, to see contemporary glaciation evolving; hydrological implications of the observed cryosphere changes and future work will be to observe the changes in climate and their impact on river discharge and water security of the region.

Study area

The aim of the work is to assess current trends and conditions of formation and descent of sustainable snow cover in Northern Kazakhstan in the conditions of global climate change according to ground and space monitoring.

The importance of snow cover to ensure the sustainability of the natural environment and agriculture of the grain-growing zone of Northern Kazakhstan cannot be overestimated. Data on the length of occurrence, height, and water content of snow cover determine the time of seasonal phase change (Cetin and Sevik 2016a; Cetin and Sevik 2016b). Cycling natural, including hydrological processes, largely determines the timing of the beginning and end of field work in agriculture (Cetin et al. 2018), and as a consequence, the forecast harvest. In this regard, the study of snow cover is of considerable interest.

This study identified a number of weather stations with the availability of the maximum snow depth in snow cover duration in the Northern and Central Kazakhstan. There are study areas in the northern Kazakhstan, which shares border with Russia, within Irtysh (Esil) River Basin. Central Kazakhstan with the Lake Balkhash is key source of water in the region. And this was taken as the second study area with available data.

Materials and methods

This study used snow depth and snow cover data from a number of weather stations including the following: Kostanay, Petropavlovsk, Astana, and Atbasar from the Northern Kazakhstan region and Zhanaarka, Zheskazgan, Karaganda, and Torgai from the Central Kazakhstan region. The spatial and temporal characteristics of annual maximum snow water equivalent (SWEmax) and fall and spring snow cover duration (SCD) were analyzed over the Northern Hemisphere and adjacent area for snow seasons 1948/49–2004/05 using reconstructed daily snow depth, and SWE on a 50-km grid from a simplified snowpack model driven with 6-hourly National Centers for Environmental Prediction (NCEP) reanalyzed air temperature and observed daily precipitation derived from the CANGRID dataset (Brown 2008). A simple linear regression as well as Mann-Kendal test along with Theil-Sen approach has been applied in this study.

To find the seasonal and annual changes in flows, the following statistics were applied:

1. Descriptive statistics, i.e., mean of flow, standard deviation, and coefficient of the variation in flow.
2. Trend analysis in the time series using MK test and sequential MK test.
3. Decadal changes in daily flow using the subsets of the data around 10-year period.
4. Frequency distribution of the flow using the daily data for ~ 20 years to find the shift in flows during different seasons of the year.
5. Wavelet transform to observe key periodicities in flows over seasonal and annual time scales.
6. Regression analysis of the climatic and hydrological data over different time periods.
7. Analysis of residuals, regression with temperature, precipitation, and circulation indices.

Results and discussions

Snow accumulation period is consistently reducing while it is moving from north to south Kazakhstan. So increase of snow cover in the northern regions occurs during all the winter period. In the Northern regions of Kazakhstan, the average of the largest decadal snow is noted in the first and second decades of March, while in the central regions, it is the second and third decades of February. The average of the largest decadal snow cover varies widely. It is consistently decreased from north to south for the considering territory. There is a satisfactory bond between snow cover, the duration and capacity. In 2001–2002, according to the Astana weather station data, the snow cover duration lasted 86 days only, respectively; the snow cover depth is considered to be insignificant—18 cm—while the long-termed mean was about 26 cm. The winter of 1976–1977 was a lot of snow; the maximum snow depth was 39 cm and the duration of snow cover lasted 176 days.

The coefficients of correlation ties between maximum snow depth and duration of its occurrence were calculated, averaged over a period of years (1974–2012). Two dependencies were built for Northern and Central Kazakhstan (Fig. 1). Here, we have used the data of "Kazhydromet" weather station network located in these regions. Note that the correlation coefficients obtained for these dependencies are equal between them. This indicates the same laws of the snow cover regime.

Obtained snow cover characteristics show a strong relation between stations. Strength of dependence links $H_{max} = f(T)$ for

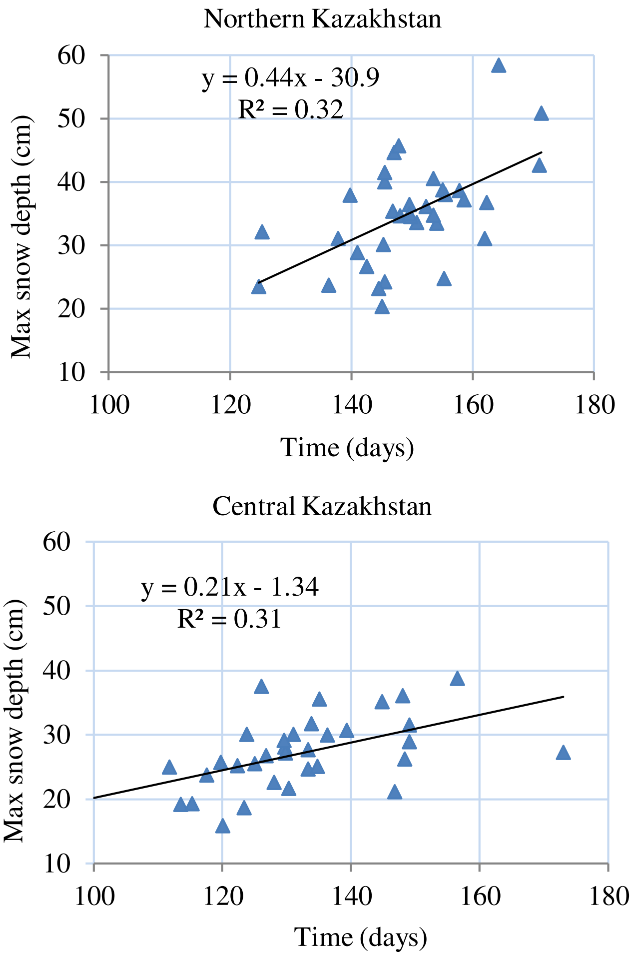

Fig. 1 The graphs of the dependence of the maximum depth of snow on the duration of snow cover in both regions (Northern and Central) Kazakhstan

the Northern Kazakhstan is characterized by a correlation coefficient of $R = 0.56$. The regression equation is of the form $y = 0.44x - 30.9$. The average long-term values of the maximum snow depth were calculated according to annual data. Analysis of the variability of maximum snow depth was carried out by calculating the coefficient of variation, which for the last 38-year period varied to a maximum depth ranging from 0.28 (Astana) to 0.65 (Atbasar). The greatest snow depth before spring snowmelt in open areas on average reaches about 25–35 cm in the northwestern part of the Akmola region and 20–25 cm in the rest of the territory (Table 1).

The highest values of maximum snow depth exceed the average long-termed values approximately 2 times (median value in the territory). The averaged lowest values of maximum snow depth differ from the maximum values for about 6.3 times. Greatest differences between minimum and maximum snow depths observed at Petropavlovsk and Atbasar meteorological stations, respectively, were 12.8 and 8.85 times (according to observations over the period 1974 to 2012). Snow depth varied considerably, in some years, throughout the winter, and also depending on the location of the weather station. Figure 2 shows the spatial variability of this characteristic.

The general pattern of snow cover is traced well. The maximum depth is observed in the north and northwest of the considering territory. Average maximum snow cover depth in the territory during the period from 1974 to 2012 is 32 cm. More detailed characteristics of snow cover depth are shown in Table 1. The oscillation amplitude of snow cover is minimal in the central part of the considering territory; in the area of Zheskazgan and Zhanaarka weather stations, it is 30 cm, and it increases to the northwest and south. The main feature of modern changes of maximum snow cover depth is increasing capacity of the snow cover depth in recent decade. For a number of meteorological stations, it is characteristically the increase of averaged long-term maximum snow depth in comparison with the previous period. All this is well illustrated in the schedule of maximum snow depth (Fig. 3; Table 2).

In low-snow winter, maximum snow depth is only about 15 cm in the northern part of the territory and 10 cm in the south. In snowy winters, the maximum snow depth increases to 50–60 cm in the north of the river basin Yessil and 30–40 cm in the south. In the central part of the considering territory, averaged long-term snow depth was lower by 10–12% than the previous multi-year period.

The calculation of the standard deviation values for snow depth in the last period showed that they vary from 7 cm in Zhanaarka to 28 cm in Atbasar. In the scientific and applied reference (Applied science handbook on climate of the USSR 1989), the observational data for the period 1891–1980 is summarized. Comparative evaluation showed that the average duration of sustained snow cover conditions in northern Kazakhstan for the period 1974 to 2010 in comparison with the previous period, in whole, has not changed significantly. According to the data from the weather stations in Kostanay and Karaganda, the number of days with snow cover remained unchanged. But in Petropavlovsk and Zhanaarka regional weather stations, duration of sustainable snow cover was reduced to 1 day, and in Atbasar and Zhezkazgan regional weather stations, is contrarily increased by 1 day and began to be, respectively, 158 and 115 days. A significant reduction in the duration of snow cover is marked in the regional weather stations of Astana and Torgai. The number of days with snow cover has decreased, respectively, for 9 and 8 days (Moldakhmetov et al. 2013).

Analysis of long-term variability of snow cover in Northern Kazakhstan in recent decades was carried out by plotting the deviation of snow depth from the norm

Table 1 The extreme and average values of the height of the snow cover for the different periods in both regions (Northern and Central) Kazakhstan

Meteorological stations	Time period	Min. depth (cm)	Avg. depth (cm)	Max. depth (cm)
Kostanay	1974–2012	13	31	60
Petropavlovsk	1935–2012	5	37	124
	1935–1973	5	22	62
	1974–2012	14	51	124
Astana	1935–2012	10	26	52
	1935–1973	10	25	52
	1974–2012	15	28	42
Atbasar	1935–2012	8	41	115
	1935–1973	16	39	115
	1974–2012	8	43	102
Yessil	1974–2012	9	26	52
Zhanaarka	1974–2012	10	21	39
Zhezkazgan	1974–2012	7	21	37
Karaganda	1936–2012	7	27	51
	1936–1973	7	25	44
	1974–2012	7	29	51
Torgai	1939–2012	5	29	79
	1939–1973	5	22	79
	1974–2012	14	36	77

for the period 1974 to 2012. Deviations were calculated from the averaged long-term snow cover depth on all nine weather stations. These data were averaged across all the Northern Kazakhstan. Graphics of deviations for snow depth were built according to the results of calculations (Fig. 4).

As seen in Fig. 4, deviations from multi-year averages are both positive and negative. A trend line is described by second-degree polynomial, where x is the time years and y is the snow depth, cm.

Increasing of the quantity values of snow cover was observed until the mid-90s of the last century. Currently, the trend to a decrease in snow cover is prevailing.

Conclusion

The studies lead to the following conclusions:

1. Detected the essential dependence of maximum snow depth on the duration of its occurrence, which allows to determine its value in terms of the Northern and Central Kazakhstan in the absence of these observations on winter precipitation, air temperature fluctuations, and other factors in the formation of maximum snow cover depth.
2. Found that the duration of snow cover in the context of global warming has not changed much. Significant changes are only in the areas of Astana (reduction in the

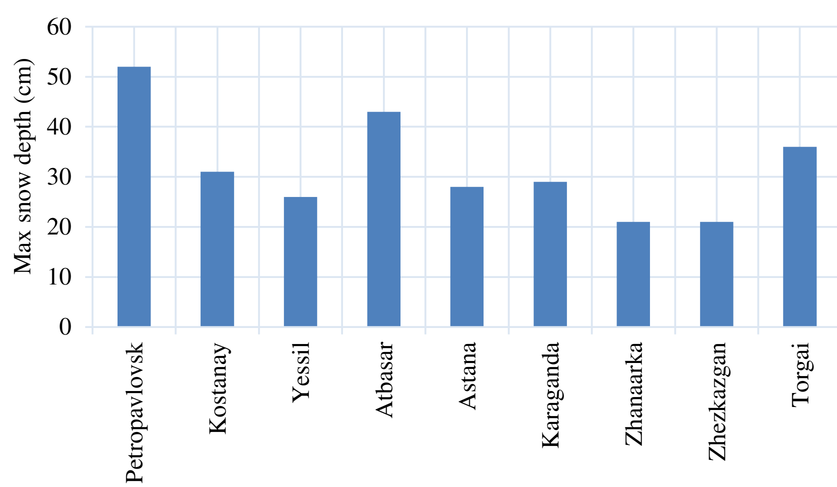

Fig. 2 Spatial variation of maximum snow cover in the Northern and Central Kazakhstan

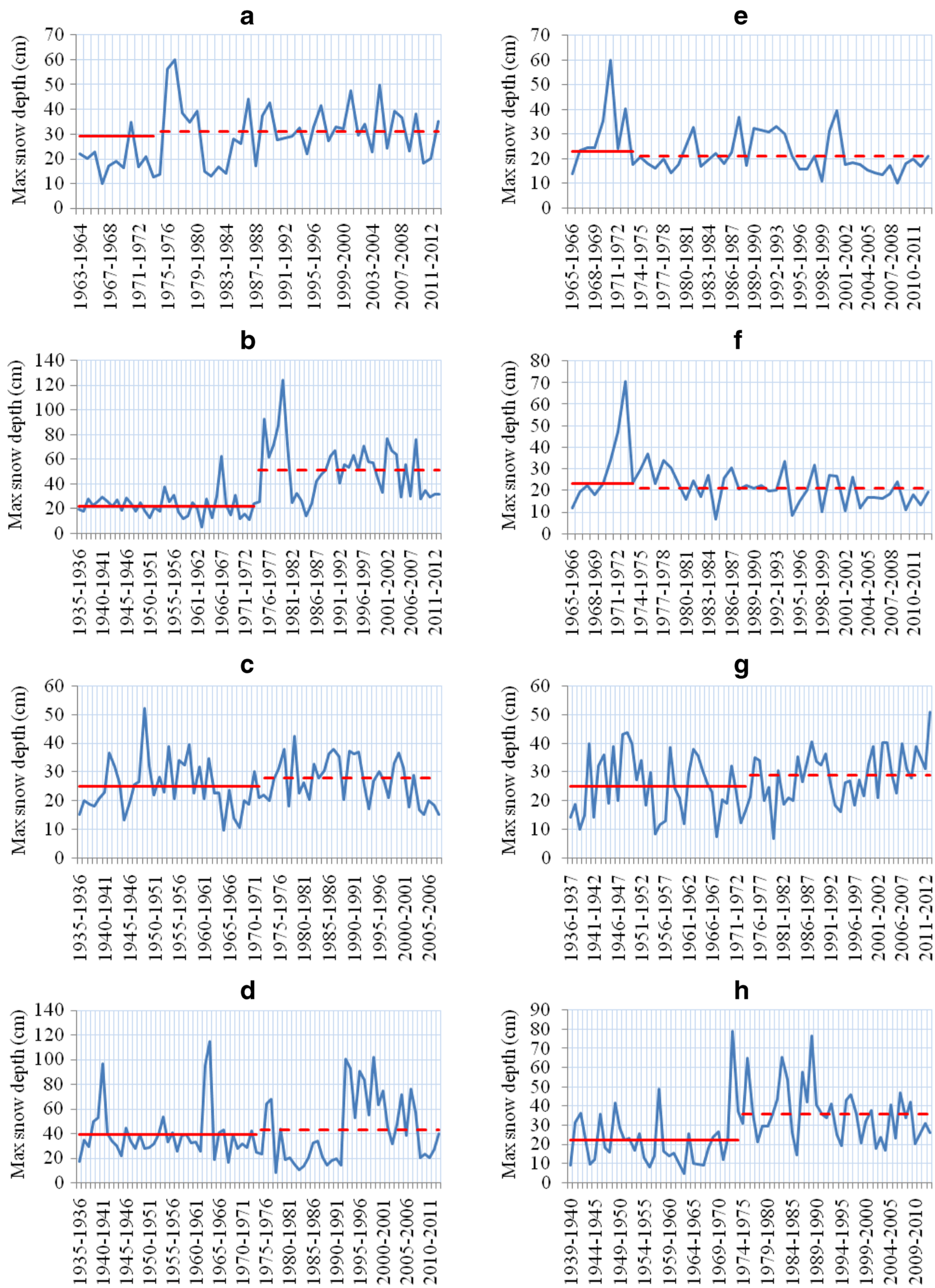

Fig. 3 Dynamics of maximum snow cover depth at the meteorological stations of the Northern and Central Kazakhstan for a long period. **a** Kostanay. **b** Petropavlovsk. **c** Astana. **d** Atbasar. **e** Zhanaarka. **f** Zheskazgan. **g** Karaganda. **h** Torgai

Table 2 Statistical characteristics of the snow cover

Meteorological stations	Time period	Maximum snow cover depth		
		Average maximum snow depth over a multi-year period, cm	σ, cm	Cv
Kostanay	1963–2012	29	12	0.41
	1974–2012	31	12	0.37
Petropavlovsk	1935–2012	37	23	0.62
	1935–1973	22	10	0.43
	1974–2012	51	23	0.45
Astana	1935–2006	26	8	0.32
	1935–1973	25	9	0.35
	1974–2008	28	8	0.28
Atbasar	1935–2012	41	24	0.60
	1935–1973	39	21	0.53
	1974–2012	43	28	0.65
Yessil	1965–2012	24	10	0.42
	1974–2012	26	10	0.40
Zhanaarka	1965–2012	23	9	0.41
	1974–2012	21	7	0.34
Zhezkazgan	1965–2012	23	11	0.47
	1974–2012	21	8	0.36
Karaganda	1936–2012	27	10	0.37
	1936–1973	25	11	0.44
	1974–2012	29	9	0.30
Torgai	1939–2012	29	16	0.55
	1939–1973	22	15	0.67
	1974–2012	36	14	0.40

duration of 9 days) and Torgai regional weather stations (a decrease of 8 days).

3. Analysis of the averaged multi-year maximum snow depth on the considered territory showed that essentially, it is distributed equally; the values fluctuate in the range of 20–30 cm, and only in the area of three weather stations wherein they have a large amount: Petropavlovsk, 57 cm; Atbasar, 43 cm; and Torgai, 36 cm.
4. When analyzing the changes of maximum snow depth in time, first of all, its fluctuations are analyzed in the area of specific weather stations (Fig. 3). At the same time, in a number of regional stations revealed its increase between

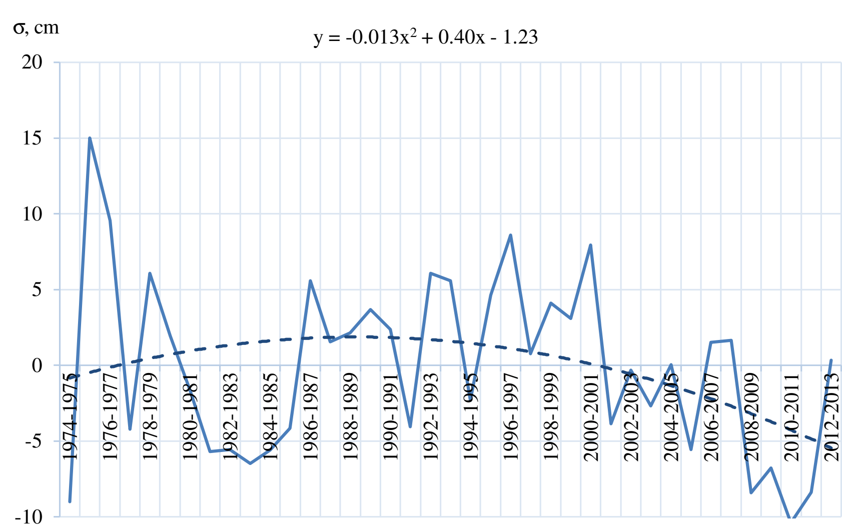

Fig. 4 Deviations from the average maximum snow depth over a multi-year period at the meteorological stations of Northern Kazakhstan

1974 and 2012 in comparison with the period before 1974.

The obtained results, regularities, and inferences can be used in further studies of snow cover and the water flow of the rivers, as well as for practical purposes.

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