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Long-Term Variability and Trends in Snow Depth and Cover Days Throughout Iranian Mountain Ranges

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Key Points:

- Declines in annual snow depth and cover days in Iranian mountains in 1982–2018
- Identifying climate factors controlling snow resource declines in Iranian mountains
- Discussing the role of such snow resource declines in the water crisis in Iran

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Abstract In Iran, the mountain snow cover generally feeds major rivers and thereby largely provides water resources required for improving human lives and protecting nature. Hence, understanding historical variability and trends in mountainous snowpack water resources in Iran in response to global warming and climate change can play a critical role in the sustainable development of this country. Accordingly, this study investigated long-term (1982–2018) snowpack climatology at 13 hydrometeorological measurement stations scattered throughout the Iranian mountain ranges, with a focus on Elburz, Azerbaijan, Zagros, and Khorasan mountainous regions. The non-parametric Mann-Kendall test was used to detect statistically significant ($p < 0.05$) trends, the Pettitt test to identify possible abrupt shift years, the Pearson's correlation coefficient to measure relationships among different time series, and the partial correlation to determine the most important climate factor influencing snowpack dynamics. The annual snow depth (maximum snow depth) significantly declined throughout Iranian mountain ranges during 1982–2018, with an average rate of 1.0 (3.4) cm decade⁻¹. The annual snow cover days (SCDs) also showed significant decreasing trends, ranging from 3 to 15 days decade⁻¹ during 1982–2018, in 69% of the stations studied. Such considerable reductions in snow depth and cover days were mainly related to the compound effects of substantial increases in temperature, sunshine, and wind speed as well as decreases in precipitation and cloudiness during the SCDs across the Iranian mountain ranges. However, precipitation was the most influential climate factor controlling snow resources throughout both the Elburz and Zagros mountains in Iran.

1. Introduction

Snow storage is one of the most important freshwater resources and an essential element of the hydrological cycle around the world. It is considerably declining along with global warming and climate change resulting primarily from the significant increases in atmospheric greenhouse gas concentrations (IPCC, 2022). During 1970–2010, the snow cover area shrank by 8×10^5 (km² decade⁻¹) in the Northern Hemisphere (Brown & Robinson, 2011), and snow melting was 60 times faster than before the Industrial Revolution (Winski et al., 2018). If the anthropogenic emission of greenhouse gases into the Earth's atmosphere is not mitigated, the declines in both snow cover area and duration will considerably be accelerated (Hock et al., 2019; Katsuyama et al., 2017; Shrestha et al., 2021; Zhang et al., 2015).

From a hydrological point of view, snowpack stores water during cold months and then releases it gradually as snowmelt into rivers in the late spring and early summer (e.g., Mote et al., 2005). The snow cover duration also affects the growing season throughout the cold climate environments on Earth (Irannezhad & Kløve, 2015; Keller et al., 2005). Based on Irannezhad et al. (2022a, 2022b, 2022c, 2022d), hence, improving our knowledge about snow resource changes in response to global warming and climate change plays a critical role not only in attaining water security but also in achieving the 2030 United Nations (UN) Agenda for Sustainable Development (United Nations, 2015); particularly in developing countries due to their high density of human population, susceptible infrastructures, and poor land use development and management (Liu et al., 2017; Yin et al., 2011).

Previous studies have already reported the impacts of anthropogenic global warming on snow depth and cover in different cold climate regions on Earth, including the Tibetan Plateau (Zhang et al., 2015), Finland (Irannezhad et al., 2016), Japan (Katsuyama et al., 2017), the US (Fassnacht et al., 2016), Australia (McGowan et al., 2018),

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the Alps (Spandre et al., 2019), Canada (Shrestha et al., 2021), the Northern Hemisphere (Wang et al., 2018), and both Arctic (Sobota et al., 2020) and Antarctic regions (Irannezhad et al., 2022a, 2022b, 2022c, 2022d). The conversion of precipitation type from snowfall to rainfall is also one of the other most important anthropogenic global warming impacts on cold environments around the world (Dolant et al., 2018; Irannezhad et al., 2017; Łupikasza et al., 2019). Despite all this, there are a few reports about statistically ($p < 0.05$) significant increases in local/regional snow cover during recent decades. For example, Yi et al. (2021) concluded that in the high-altitude areas throughout the northwest of the Tibetan Plateau, the extent of snow cover increased between 2002 and 2018 in response to considerable increases in snowfall to precipitation ratio. Similarly, Mackintosh et al. (2017) found that regional cooling due to climate change has led to the advance of glaciers in the South Pacific during 1983–2008. On our planet, hence, snow resource alterations in response to the ongoing climate warming and change are primarily dependent upon the balance between both temperature and precipitation patterns (Irannezhad et al., 2016), which substantially control different snowpack hydrological processes (Irannezhad et al., 2015).

Iran has become drier over the last 60 years (Lashkari et al., 2021; Rahimi et al., 2019; Sadeqi & Kahya, 2021), and suffered from excessive increases in irrigated cultivable lands (Irannezhad et al., 2018; Maghrebi et al., 2020; Mirzaei et al., 2019). These changes in climatic conditions and land use patterns have already raised serious freshwater challenges in this country (Ashraf et al., 2019; Karimi Alavijeh et al., 2021; Noori et al., 2021). Many permanent rivers have become seasonal (Minaei & Irannezhad, 2018), groundwater tables have plummeted to unprecedented levels (Ashraf et al., 2021; Noori et al., 2021), and lakes (e.g., Lake Urmia, the largest enclosed lake in Iran) are in danger of drying up completely (Pouladi et al., 2021). Although Iran is located in the arid and semi-arid regions (Tabari et al., 2014), its major rivers (e.g., Karun, Karkheh, Zayandeh-rud, and Ghezel Ozan) are principally fed by snowmelt water originating from the mountains throughout the country (Ghorbani, 2012; Sabzevari et al., 2015). Despite such great hydrological importance, however, spatio-temporal changes in snow cover patterns in Iran have been investigated only by a few previous studies (e.g., Ghadimi et al., 2019; Ghasemifar et al., 2019), and mostly limited to the major river or lake basins throughout the country (e.g., Choubin et al., 2019; Keikhosravi, 2021; Seyediilmabad & Moradi, 2016). To our knowledge, hence, a comprehensive analysis of historical variability and changes in snow resources throughout different mountainous regions in Iran is still lacking and well-motivated.

The overall aim of this study was to investigate spatio-temporal variability and trends in snowpack dynamics throughout Iranian mountain ranges during 1982–2018 in response to indisputable global warming and climate change. The specific objectives were to (a) analyze historical changes in snow depth and cover days across the mountainous regions of Iran; (b) detect statistically significant trends in hydrometeorological factors controlling snowpack accumulation and melt processes, including surface air temperature, precipitation, cloudiness, sunshine hours, and wind speed; and (c) assess the impact of such factors on snow depth variability in Iranian mountainous regions.

2. Materials and Methods

2.1. Study Area and Data Description

Iran is located in the Middle East region (Figure 1), boasts a diverse topography, with elevations ranging from -28 m near the Caspian Sea to a towering 5,670 m at the Damavand Peak, above mean sea level. The country is geographically enclosed by two mountain ranges in the northwest-west and north-northeast, exerting significant influence on both the spatial and temporal patterns of surface air temperature and precipitation (Ganji, 1968). This complex topography plays a pivotal role in shaping Iran's climate, which ranges from hyper-arid conditions in central areas to super-humid climates along the Caspian Sea shores in the north (Sadeqi & Kahya, 2021). In Iran, precipitation gradually decreases from northwest to southeast, while surface air temperature follows an opposite pattern (Hadi Pour et al., 2020). Such patterns are naturally associated with (a) the Siberian high-pressure system affecting the southern widths within the northern band of Iran, (b) the Mediterranean rain-bearing system entering from the west, and (c) a low-pressure southern system (Khalili et al., 2016).

This study used daily precipitation, minimum and maximum surface air temperatures, snow depth, sunshine hours, cloud cover, and wind speed (Table 1) time series at 13 hydrometeorological measurement stations (Figure 1) scattered throughout Iranian mountain ranges. These stations were selected because of (a) covering long-term (1982–2018) historical records, (b) having less than 10% of missing data, (c) including an average of

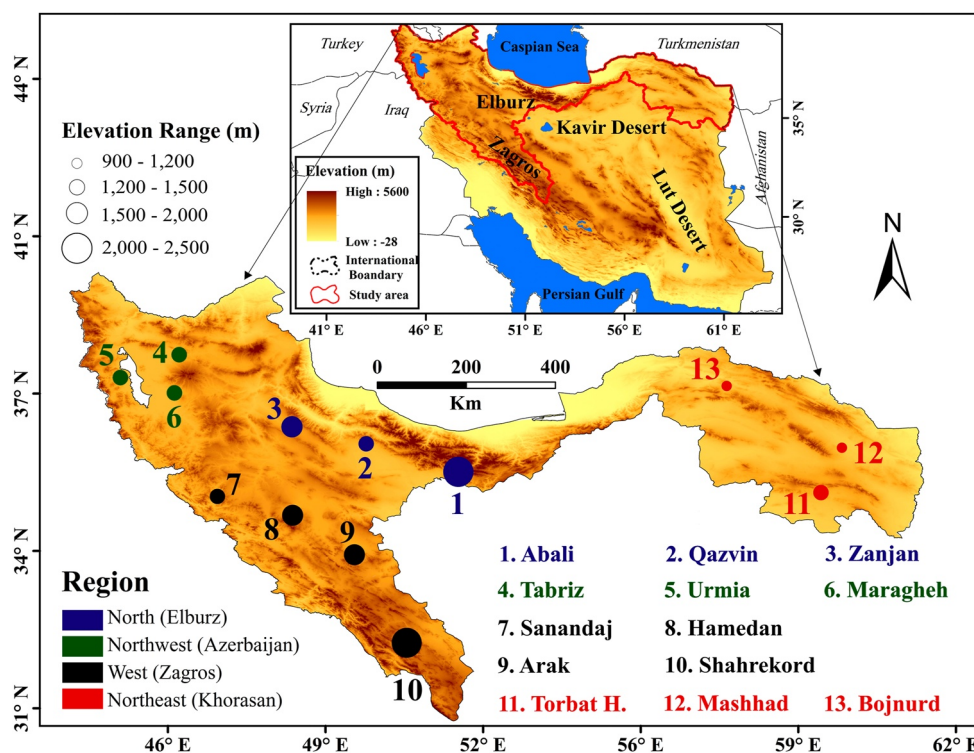


Figure 1. Study area and location of all selected hydrometeorological measurement stations throughout Iranian mountain ranges.

more than 25 days with snow cover (snow depth >0.00 cm) in the first ten years of records, and (d) representing four different mountainous regions in Iran defined by this study: north or Elburz, northwest or Azerbaijan, west or Zagros, and northeast or Khorasan (Figure 1). Besides, all the stations are of the synoptic type, continuously monitored by the World Meteorological Organization (WMO) and adhering to its standards: strategically situated outside open areas without population, away from obstructions and heat sources, and at a distance from different water bodies. Such positioning minimizes the potential impact of urban environments, ensuring the reliability of the collected weather data. Based on available records (Table 1), we derived six other indicators (Table 2), primarily focusing on snow depth and cover days. To determine the first and last snow cover days, we used the Julian days through the water year: from the 1st of September to the following 31st of August, ranging from 1 to 365/366 on normal/leap years.

The long-term average values from 1982 to 2018 for annual snow depth during snow cover days (SCDs) exhibited variation. Bojnurd (Maragheh) recorded the lowest at 2.9 cm, while Abali registered the highest at 27.7 cm (Table 3). The number of SCDs varied, ranging from a minimum of 19 days at the Torbat H. station to a maximum of 125 days at Abali (Table 3). Notably, Abali also experienced the earliest first (FSCD) and latest last (LSCD) snow cover days, occurring on the 15th of November and the 10th of April, respectively (Table 3). When considering spatial distribution, the highest long-term average values for all Tmean (4.1°C) during the SCDs were observed at the Mashhad station, while the lowest average (approximately -0.6°C) was documented at Hamedan and Abali (Table 3). Annual precipitation during the SCDs across Iran's mountainous areas ranged from 79 to 335 mm on average, with the Maragheh and Abali stations recording the minimum and maximum values, respectively (Table 3).

2.2. Statistical Methods

The Mann-Kendall (M-K) non-parametric trend test (Kendall, 1975; Mann, 1945) is applied for detecting statistically significant ($p < 0.05$)

Table 1
Primary Hydrometeorological Variables Selected for This Study

Variable	Definition	Unit
T_{min}	Daily minimum near-surface air temperature	°C
T_{max}	Daily maximum near-surface air temperature	°C
Snow Depth	Daily snow depth	cm
Precipitation	Daily precipitation	mm
Sunshine	Daily sunshine hours	hour
Cloud Cover	Daily cloud cover	Okta
Wind Speed	Average daily wind speed at the height of 2 m	m/s

Table 2
Indicators Derived From the Primary Variables Given in Table 1

Indicator	Definition	Unit
T_{mean}	The average value of daily maximum and minimum near-surface air temperatures	°C
Diurnal Temperature Range (DTR)	Difference between daily maximum and minimum near-surface air temperatures	°C
Snow Depth Maximum (SDM)	The maximum snow depth	cm
Snow Cover Days (SCD)	The number of days with snow cover (daily snow depth >0 mm) in the water year ^a	Day(s)
First Snow Cover Day (FSCD)	The first day with snow cover (daily snow depth >0 mm) in the water year ^a	Julian day
Last Snow Cover Day (LSCD)	The last day with snow cover (daily snow depth >0 mm) in the water year ^a	Julian day

^aWater year: from the 1st of September to the following 31st of August.

trends in time series of all hydrometeorological variables (Table 1) and indicators (Table 2) selected by this study. The modified version of the M-K test (Hamed & Rao, 1998) is also performed to eliminate the effect of serial correlation. To estimate the magnitude of such significant trends, the Sen's slope method (Sen, 1968) is primarily used. The non-parametric Pettitt test (Pettitt, 1979) is also employed for determining abrupt shift points in different time series. Numerous studies have already applied these methods for investigating the effects of climate variability and change on snow resources around the world (e.g., Irannezhad et al., 2017; Kazemzadeh & Malekian, 2018; Li et al., 2019; Thakur et al., 2020). All these statistical methods are comprehensively described in Sadeqi et al. (2021).

The Pearson's correlation coefficient (Helsel & Hirsch, 1992) was used to measure the relationships between snow depth and climatic conditions throughout Iranian mountain ranges. Furthermore, the partial correlation (Helsel & Hirsch, 1992) was performed to determine the most important climate factor contributing to snowpack dynamics. This statistical technique is commonly used to investigate the relationship between two variables while controlling the influence of one or more additional variables.

3. Results

3.1. Snow Depth

Across the entire Iranian mountain ranges, the long-term average values for annual snow depth and its maximum (SDM) during snow cover days (SCDs) in 1982–2018 were 6.9 and 21.8 cm, respectively (Table 4). The annual snow depth ranged from 2.7 cm in 2018 to 17.3 cm in 1992 (Table 4). Similarly, the lowest (8.4 cm) and highest (46.7 cm) annual SDMs were recorded in 2018 and 1992 (Table 4). Such declines in both annual snow depth and SDM over time were in turn shown by their statistically significant ($p < 0.05$) decreasing trends of -1.13 and -3.60 (cm decade⁻¹) (Table 4) in Figures 2a and 2b.

Across four different Iranian mountainous regions, the long-term average values for annual snow depth (SDM) during the SCDs for the period 1982–2018 ranged from 3.8 cm (12.7 cm) in Khorasan to 13.1 cm (42.0 cm) in Elburz (Table 4). During the SCDs in 1982–2018, the lowest annual snow depth (1.3 cm) and SDM (2.5 cm) were measured in 2018 across the Khorasan region (Table 4). However, the highest annual snow depth (47.2 cm) and SDM (118.0 cm) had been recorded in 1992 over Elburz (Table 4). In this region (Elburz), there was a substantial decrease in annual snow depth during SCDs from 1982 to 2018, with a rate of 2.45 cm decade⁻¹ (Table 4). The West (Zagros) and the Northeast (Khorasan) were the only regions that experienced significant declines in both snow depth and SDM during 1982–2018 (Table 4). Such decreases were at the rate of 0.62 and 1.15 (cm decade⁻¹) for snow depth, while 1.98 and 3.77 (cm decade⁻¹) for SDM, in the West and the Northeast regions, respectively (Table 4). The Northwest (Azerbaijan) was the region with a significant decreasing trend (-1.90 cm decade⁻¹) only in annual SDM during the SCDs over the period 1982–2018 (Table 4).

The annual snow depth decreased throughout Iranian mountain ranges during 1982–2018 (Figure 3a), with an average rate of 1.0 cm decade⁻¹. The annual snow depth maximum (SDM) also declined at all stations studied, with an average rate of 3.4 cm decade⁻¹ (Figure 3a). Such decreases in snow depth and SDM, however, were

Table 3
The Long-Term (1982–2018) Average Values for Different Hydrometeorological Variables (Table 1) and Indicators (Table 2) During the Snow Cover Days (SCDs) at the Selected Measurement Stations (Figure 1) Throughout Different Mountainous Regions in Iran

Region	Station name	Station no.	Latitude (E)	Longitude (N)	Altitude (m)	Snow depth (cm)	SDM (cm)	SCD (days)	FSCD (Julian day)	LSCS (Julian day)	T _{mean} (°C)	T _{min} (°C)	T _{max} (°C)	DTR (°C)	Precipitation (mm)	Cloudiness (Okta)	Daily sunshine (hour)	Wind speed (m/s)	Average missing data (%)
North (Elburz)	Abali	1	35.75	51.88	2465	27.7	91.0	125	74	222	-0.5	-4.5	3.4	7.9	353	3.6	5.7	1.7	2.09
	Qazvin	2	36.32	50.02	1279	5.6	17.1	28	107	178	1.7	-3.6	6.9	10.6	108	3.9	5.1	1.2	1.00
	Zanjan	3	36.66	48.52	1659	6.1	18.0	51	91	199	0.3	-5.0	5.6	10.7	111	3.9	5.0	2.3	1.10
Northwest (Azerbaijan)	Tabriz	4	38.12	46.24	1361	3.9	13.7	36	91	196	1.1	-3.4	5.5	8.9	80	4.3	4.9	2.4	1.34
	Urmia	5	37.66	45.06	1328	6.7	21.6	48	98	193	0.0	-4.9	5.0	9.9	96	4.0	4.9	1.6	1.33
West (Zagros)	Maragheh	6	37.35	46.15	1344	3.0	10.0	30	102	185	0.9	-3.2	4.9	8.1	79	4.4	4.6	1.8	3.93
	Sanandaj	7	35.25	47.01	1373	4.3	14.1	22	115	178	1.2	-4.6	7.0	11.5	115	3.9	4.9	1.6	1.59
	Hamedan	8	34.87	48.53	1741	8.0	21.6	37	105	190	-0.6	-6.4	5.3	11.7	105	3.6	5.3	1.5	1.80
	Arak	9	34.07	49.78	1703	6.6	18.8	29	107	186	1.2	-4.1	6.5	10.6	112	3.6	5.4	1.2	1.99
Northeast (Khorasan)	Shahrekord	10	32.29	50.84	2049	6.4	19.2	30	106	184	0.2	-6.5	7.0	13.7	147	2.8	6.6	1.5	0.98
	Torbat H.	11	35.33	59.21	1451	4.0	11.8	19	113	181	2.3	-3.1	7.7	10.8	98	3.2	5.9	1.4	0.96
	Mashhad	12	36.24	59.63	999	4.5	15.2	21	105	190	4.1	-1.2	9.4	10.7	110	6.4	4.9	1.9	1.25
	Bojnurd	13	37.49	57.30	1065	2.9	10.9	35	98	199	2.9	-2.4	8.3	10.7	90	6.2	5.1	1.7	1.65

Table 4
Summary Statistics and Trends in Different Hydrometeorological Variables (Table 1) and Indicators (Table 2) During the Snow Cover Days (SCDs) Throughout Iranian Mountain Ranges and Different Mountainous Regions During in 1982–2018

Area	Mountain	Snow depth (cm)	SDM (cm)	SCD (days)	FSCD (Julian day)	LSCS (Julian day)	T _{mean} (°C)	T _{min} (°C)	T _{max} (°C)	DTR (°C)	Precipitation (mm)	Cloudiness (Okta)	Sunshine (hour)	Wind speed (m/s)	
Iran	Entire Iranian Mountain Ranges	Long-term Average	6.9	21.8	39	101	1.1	-4.1	6.4	10.5	123	4.1	5.3	1.7	
		Minimum	2.7	8.4	14	84	167	-3.4	-8.7	2.0	8.9	67.9	3.2	4.4	1.0
	Year of Minimum	2018	2018	2018	2012	2018	2008	2008	2008	1988	2018	2018	1988	1983	
	Maximum	17.3	46.7	75	121	212	3.9	-1.7	9.7	11.7	185.9	5.0	6.6	2.3	
	Year of Maximum	1992	1992	1992	1999	1997	2015	2015	2015	2018	1992	1988	1997	2013	
Mountainous Regions	North (Elburz)	Long-term Average	13.1	42.0	68	90	200	0.5	-4.4	5.3	9.7	190	3.8	5.3	1.7
		Minimum	3.1	10.0	28	62	179	-4.1	-9.3	0.9	8.1	108.8	3.0	4.5	1.0
	Year of Minimum	1999	1995	2009	1994	2006	1989	1989	1989	1988	1997	2018	1988	1983	
	Maximum	47.2	118.0	107	114	229	3.6	-1.9	9.0	10.9	294.1	4.7	6.6	2.5	
	Year of Maximum	1992	1992	1992	2009	1992	2018	2018	2018	1997	1996	1988	1999	2010	
Northwest (Azerbaijan)	Long-term Average	Interannual Trend	-0.24	-0.60	-1.0	0.1	-0.6	0.07	0.05	0.07	0.02	-0.02	0.02	0.01	
		Long-term Average	4.6	15.3	39	97	191	0.6	-3.9	5.1	9.0	85	4.2	4.8	1.9
	Minimum	1.9	5.0	6	69	157	-4.3	-8.3	-0.4	6.9	11.3	3.2	3.0	1.1	
	Year of Minimum	2009	2009	2010	1995	2009	1983	1983	1983	1988	2009	2018	1983	1991	
	Maximum	11.3	34.5	95	138	218	3.5	-1.4	8.5	10.8	158.4	5.6	6.2	2.9	
West (Zagros)	Long-term Average	Interannual Trend	-0.03	-0.19	-0.8	0.2	-0.6	0.05	0.02	0.08	-1.11	-0.02	0.04	0.05	
		Long-term Average	6.3	18.4	29	108	184	0.5	-5.4	6.5	11.9	119	3.5	5.6	1.5
	Minimum	1.8	4.5	7	82	154	-5.1	-11.3	1.2	9.3	17.5	2.2	4.1	0.9	
	Year of Minimum	2013	2018	2018	1983	2018	2008	2008	2008	2006	2018	2018	2006	1995	
	Maximum	18.5	45.8	81	138	213	4.0	-2.3	10.8	14.3	232.0	4.5	7.3	2.4	

Table 4
Continued

Area	Mountain	Parameters	Snow depth (cm)	SDM (cm)	SCD (days)	FSCD (Julian day)	LSCS (Julian day)	T _{mean} (°C)	T _{min} (°C)	T _{max} (°C)	DTR (°C)	Precipitation (mm)	Cloudiness (Okta)	Sunshine (hour)	Wind speed (m/s)
		Year of Maximum	1989	1989	1992	1999	1997	2013	2015	2015	2018	1992	2006	1997	2012
		Interannual Trend	-0.11	-0.38	-0.7	0.3	-0.6	0.06	0.04	0.08	0.04	-2.30	-0.02	0.03	0.03
	Northeast (Khorasan)	Long-term Average	3.8	12.7	2.5	105	190	3.1	-2.2	8.5	10.8	99	5.3	5.3	1.7
		Minimum	1.3	2.5	2	74	144	-2.1	-7.4	3.3	8.8	38.7	4.5	4.1	0.7
		Year of Minimum	2018	2018	2018	1984	2010	2008	2008	2008	1990	2010	2016	1991	1984
		Maximum	8.6	20.0	60	151	212	5.5	0.2	11.0	12.6	175.6	6.8	7.0	2.8
		Year of Maximum	2008	1992	1989	2018	1996	2010	2010	2013	2014	1993	2010	2018	2018
		Interannual Trend	-0.06	-0.20	-0.5	0.2	-0.2	0.06	0.06	0.06	0.02	-0.62	0.00	0.02	0.03

Note. Statistically significant ($p < 0.05$) trends are given in both bold and italic.

statistically significant ($p < 0.05$) in about 46% and 62% of stations studied through Iranian mountain ranges, respectively (Figures 3a and 3b). With the highest altitude in the study area, the Abali station experienced the maximum but statistically insignificant ($p > 0.05$) decreasing trends in both annual snow depth (4.6 cm decade⁻¹) (Figure 3a) and SDM (8.8 cm decade⁻¹) (Figure 3b). At this station (Abali), besides, the significant abrupt shift year was 1996 for annual snow depth (Figure 3c).

3.2. Snow Cover Days (SCDs)

On average, the Iranian mountain ranges experienced 39 snow cover days (SCDs) during each water year during 1982–2018 (Table 4). The first (FSCD) and last (LSCD) snow cover days were generally the 101st and 191st Julian days or the 11th of December and 11th of March, respectively (Table 4). The annual SCDs significantly decreased by 7 (days decade⁻¹) in the Iranian mountain ranges during 1982–2018 (Figure 2c) in response to substantially earlier LSCDs (−6 days decade⁻¹) (Figure 2d). Similarly, statistically significant decreases in both annual SCDs and LSCDs were found in the three mountainous regions of North (Elburz), Northwest (Azerbaijan), and West (Zagros) (Table 4). The Northeast (Khorasan) region experienced the lowest substantial decline rate (5 days decade⁻¹) in annual SCDs, but no clear changes in annual FSCDs and LSCDs (Table 4). In this region, the long-term (1982–2018) average value for annual SCDs (25 days) was also less than all other three West (29 days), Northwest (39 days), and North (68 days) (Table 4).

During 1982–2018, decreasing trends detected in the SCDs were statistically significant ($p < 0.05$) in about 69% of the stations studied (Figure 4a). The highest range (12–15 days decade⁻¹) of such significant declining trends was seen in the northwest of Iran (Figure 4a). At the Sanandaj station, the less frequent SCDs (3–6 days decade⁻¹, $p < 0.05$) (Figure 4a) were mainly attributable to both later FSCDs (6–9 days decade⁻¹, $p < 0.05$) (Figure 4b) and earlier LSCDs (6–9 days decade⁻¹, $p < 0.05$) (Figure 4c). However, the significantly earlier LSCDs (Figure 4c) were the only contributor to the lower number of SCDs at the Shahrekord, Qazvin, Zanjan, and Maragheh stations (Figure 4a). At two of these stations (Qazvin and Maragheh), the Pettitt test revealed downward shift years in both SCD (1993 and 1998) (Figure 4d) and LSCD (1998 and 1999) time series (Figure 4f).

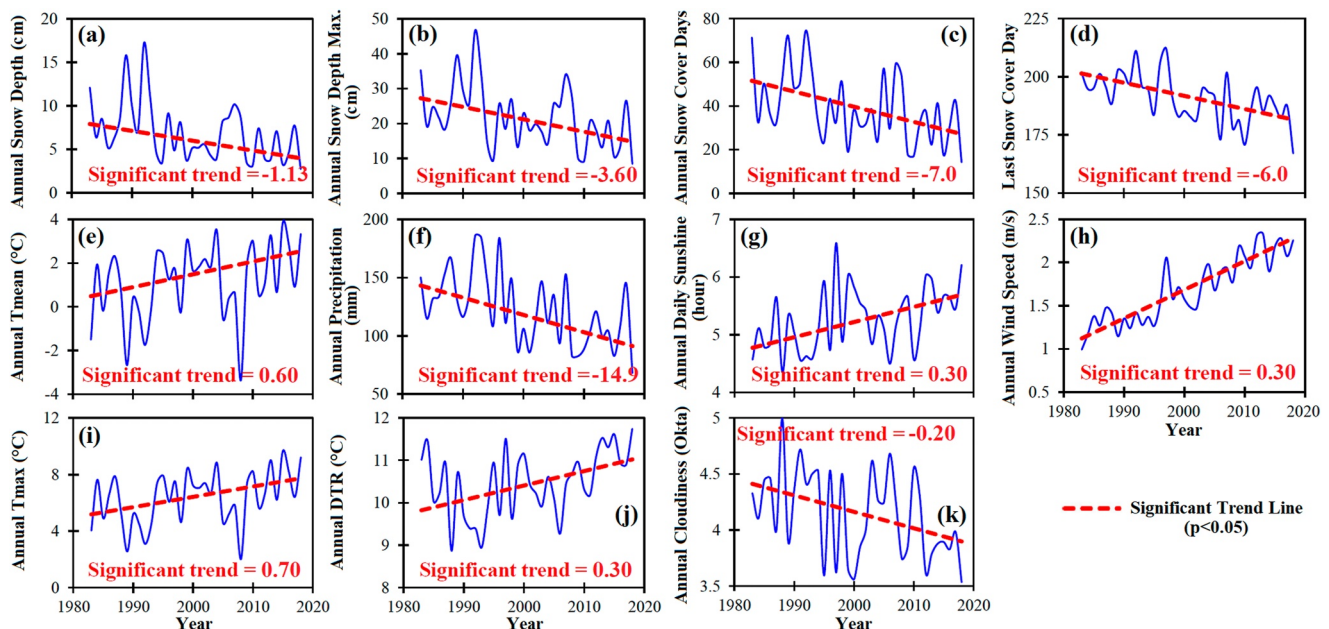


Figure 2. Long-term (1982–2018) variability and trends (decade⁻¹) in annual values of different hydrometeorological variables (Table 1) and indicators (Table 2) during the snow cover days (SCDs) across the entire Iranian mountain ranges.

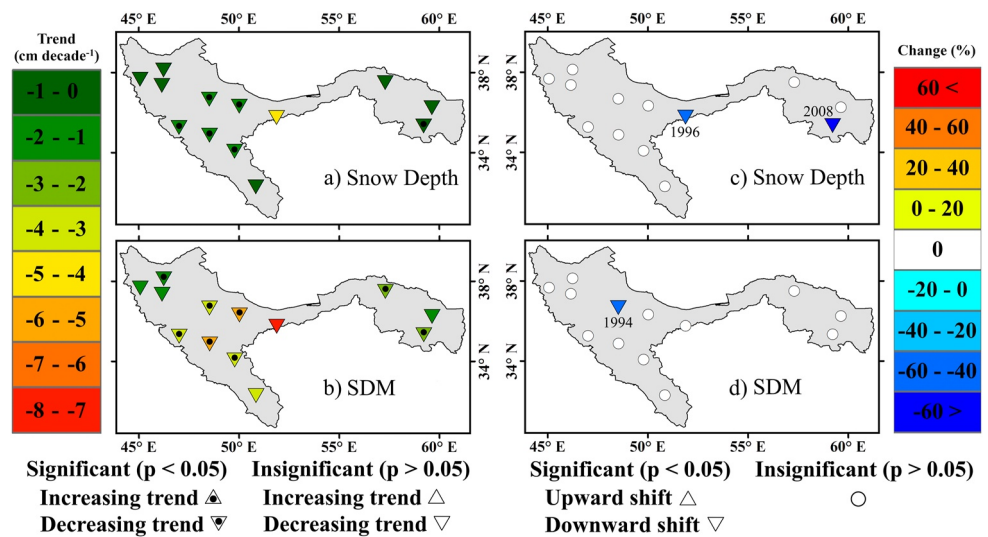


Figure 3. Trends and abrupt shift years in annual snow depth (a) and (c) as well as in annual SDM (b) and (d), respectively, during the snow cover days (SCDs) at the hydrometeorological measurement stations studied throughout Iranian mountain ranges over the period 1982–2018. The changes (%) in (c) and (d) represent the difference of long-term average values for annual snow depth and SDM, respectively, during the SCDs between after and before the abrupt shift year detected at the 5% significance level.

3.3. Climatic Conditions During the SCDs

3.3.1. Surface Air Temperature

The entire Iranian mountain ranges experienced the coldest (warmest) year in 2008 (2015), with an annual T_{mean} of -3.4°C (3.9°C), T_{min} of -8.7°C (-1.7°C), and T_{max} of 2.0°C (9.7°C) during the SCDs over the period 1982–2018 (Table 4). Across such ranges, both annual T_{mean} (Figure 2e) and T_{max} (Figure 2i) during the SCDs showed statistically significant warming trends of 0.6 and 0.7 ($^{\circ}\text{C decade}^{-1}$) in 1982–2018 (Table 4). The annual T_{max} during the SCDs was also increased over all four mountainous regions at the rate of 0.6–0.8 ($^{\circ}\text{C decade}^{-1}$, $p < 0.05$), but significant increases in T_{mean} were only found in both Elburz and Khorasan (Table 4). Among all the regions, the warmest climate was found in Khorasan with the long-term average values of annual T_{mean} , T_{min} , and T_{max} during the SCDs of 3.1, -2.2 , and 8.5°C , respectively (Table 4).

The increasing trends in annual T_{mean} and T_{min} (T_{max}) during the SCDs were statistically significant ($p < 0.05$) in about 31% (46%) of stations (Figures 5a–5c). The significant warming trends in annual T_{mean} during the SCDs at the Mashhad, Arak, and Zanjan stations were attributable to the substantial increases in both annual T_{min} and T_{max} during the SCDs (Figures 5a–5c). The Arak station showed the highest range of significant warming trends in annual T_{mean} during the SCDs (1.2 – $1.5^{\circ}\text{C decade}^{-1}$) associated with the highest increasing rate in annual T_{min} (0.9 – $1.2^{\circ}\text{C decade}^{-1}$) and T_{max} (1.2 – $1.5^{\circ}\text{C decade}^{-1}$) during the SCDs (Figures 5a–5c). During the SCDs, T_{max} warmed at a higher rate than T_{min} over time. Hence, during the SCDs, significant rising trends in DTR were mainly seen at the stations with substantial increases in T_{max} , particularly in the northwest of Iran (Figure 5d).

Figure 6 shows the Pettitt test for different surface air temperature variables and indicators (T_{min} , T_{max} , T_{mean} , and DTR) during the SCDs throughout the Iranian mountain range over the period 1982–2018. An abrupt increase shift in annual T_{mean} , T_{max} , and T_{min} during the SCDs was seen in about 31%, 23%, and 15% of stations studied, respectively (Figures 6a–6c). At the Shahrekord (Mashhad) station, all these surface air temperature variables experienced an abrupt warming shift in the SCDs during 2008 (1998) (Figures 6a–6c). Statistically significant ($p < 0.05$) abrupt shifts in annual DTR during the SCDs were all upward occurred in about 38% of stations (Figure 6d). Such increased shifts in annual DTR during the SCDs were mainly seen in the western part of Iranian mountain ranges through the water years 2002–2005.

3.3.2. Precipitation, Cloudiness, Sunshine Hours, and Wind Speed

In general, the long-term (1982–2018) average value for annual precipitation during the SCDs over the entire Iranian mountain ranges was about 123 mm (Table 4). Across different mountainous regions, it ranged from 85 mm in Azerbaijan to 190 mm in Elburz (Table 4). Statistically significant decreasing trend ($-14.9 \text{ mm decade}^{-1}$) in annual precipitation during the SCDs over the entire Iranian mountain ranges (Figure 2f) was mainly attributable to significant declines in annual precipitation over both Azerbaijan ($-11.1 \text{ mm decade}^{-1}$) and Zagros ($-23.0 \text{ mm decade}^{-1}$) mountainous regions (Table 4). It decreased at all stations studied, except Torbat H., during 1982–2018 (Figure 7a). Such decreases were, however, statistically significant in about 46% of stations mainly located in the western parts of Iranian mountain ranges (Figure 7a). The highest rate of these significant decreasing trends was $37 \text{ (mm decade}^{-1}\text{)}$ found at the Sanandaj station (Figure 7a). The Pettitt test also showed abrupt downward shifts around 1997–1998 in annual precipitation during the SCDs at stations throughout the northwestern parts of our study area (Figure 7e).

The annual cloudiness during the SCDs over the entire Iranian mountain ranges during 1982–2018 was between 3.2 Okta in 2018 and 5.0 Okta in 1988, with a long-term average value of 4.1 Okta (Table 4). It significantly decreased at the rate of $0.2 \text{ (Okta decade}^{-1}\text{)}$ in 1982–2018 (Table 4). The same rate ($0.2 \text{ Okta decade}^{-1}$) of the decreasing trend was also found in the annual cloudiness during the SCDs across the Elburz, Azerbaijan, and Zagros mountainous regions (Table 4). Spatially, the long-term average value of cloudiness during the SCD ranged from 2.8 Okta at the Shahrekord station to 6.4 Okta at the Mashhad station (Figure 7b). All statistically significant ($p < 0.05$) trends in the cloudiness during the SCD were downward and seen in about 62% of stations mainly scattered in the western parts of Iranian mountain ranges (Figure 7b). The highest range of such trends was between -0.4 and $-0.3 \text{ Okta decade}^{-1}$ found at the Arak, Qazvin, and Zanjan stations. Similarly, the cloudiness during the SCD experienced an abrupt decreasing shift around 2007, 2006, and 1988 at these three stations of Arak, Qazvin, and Zanjan, respectively (Figure 6f).

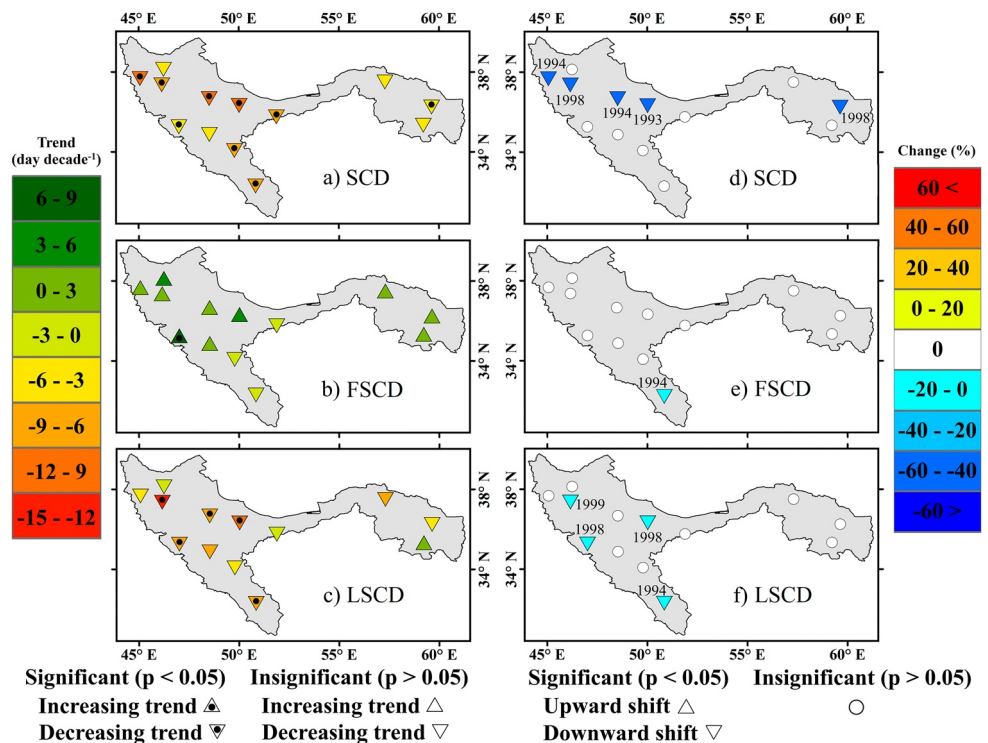


Figure 4. Trends and abrupt shift years in annual SCD (a) and (d), FSCD (b) and (e), and LSCD (c) and (f), respectively, at the hydrometeorological measurement stations studied throughout Iranian mountain ranges during 1982–2018. The changes (%) in (d), (e), and (f) represent the difference of long-term average values for annual SCD, FSCD, and LSCD, respectively, between after and before the abrupt shift year detected at the 5% significance level.

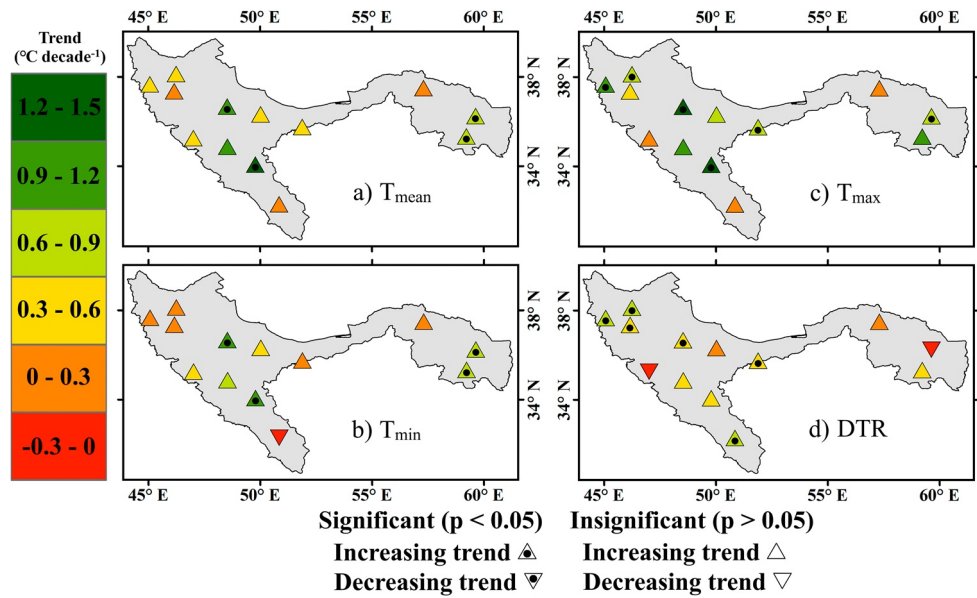


Figure 5. Trends in annual T_{mean} (a), T_{min} (b), T_{max} (c), and DTR (d) during the SCDs at the hydrometeorological measurement stations studied throughout Iranian mountain ranges over the period 1982–2018.

The daily sunshine during the SCDs was generally about 5.3 hr across the entire Iranian mountain ranges during the period 1982–2018 (Table 4). It significantly increased over the entire Iranian mountain ranges ($0.3 \text{ hr decade}^{-1}$) (Figure 2g) as well as over the West ($0.3 \text{ hr decade}^{-1}$) and the Northwest ($0.4 \text{ hr decade}^{-1}$) mountainous regions (Table 4). However, the daily sunshine during the SCDs generally varied between 4.6 and 6.6 hr observed at the Maragheh and Shahrekord stations (Figure 7c). It showed significant increasing trends at the Arak, Hamedan, Sanandaj, Urmia, and Tabriz (Mashhad) stations located in the west (most east) of Iranian mountain ranges (Figure 7c). The highest rate of such increasing trends was $0.4 \text{ hr decade}^{-1}$ found at the Urmia station (Figure 7c).

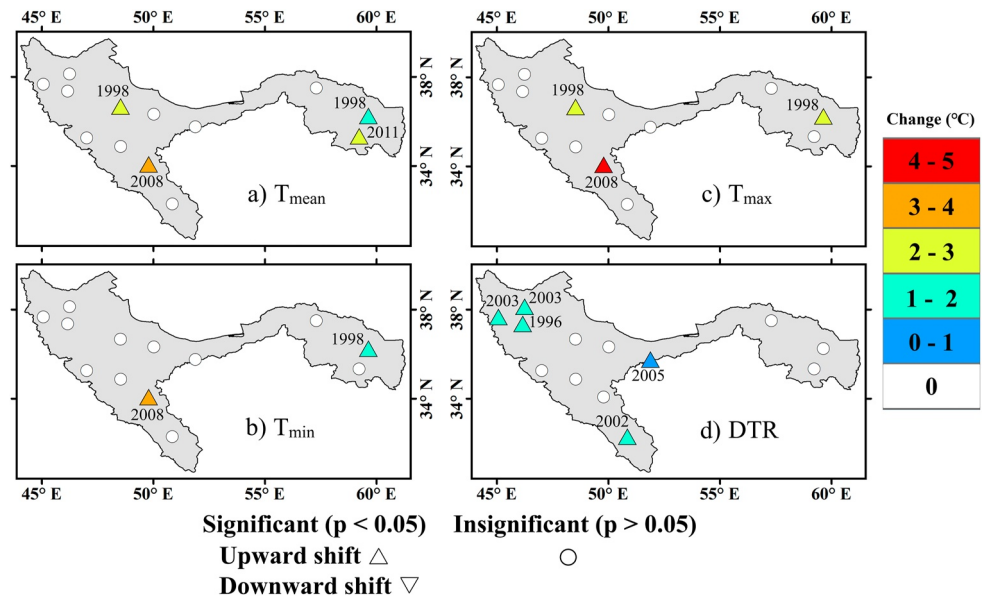


Figure 6. Abrupt shift years in T_{mean} (a), T_{min} (b), T_{max} (c), and DTR (d) during the SCDs at the hydrometeorological measurement stations studied throughout Iranian mountain ranges over the period 1982–2018. The changes (C°) represent the difference of long-term average values for T_{mean} , T_{min} , T_{max} , and DTR during the SCDs between after and before the abrupt shift year detected at the 5% significance level.

The Pettitt test also determined an abrupt upward shift around 1993 (1996) in daily sunshine during the SCDs at the Hamedan (Urmia and Tabriz) stations (Figure 7g).

The wind speed during the SCDs was about 1.7 (m s⁻¹) over the Iranian mountain ranges (Table 4) during 1982–2018. It showed statistically significant increasing trends across the entire Iranian mountain ranges (Figure 2h) and all four different mountainous regions of Iran, at the rate between 0.1 and 0.5 (m s⁻¹ decade⁻¹) (Table 4). On average, the wind speed during the SCDs was spatially from 1.2 ms⁻¹ at both the Arak and Qazvin stations to 2.4 ms⁻¹ at the Tabriz station. It significantly increased at about 62% of stations, with an average rate of 0.3 ms⁻¹ decade⁻¹ (Figure 7d). The highest rate of such increasing trends was 0.65 ms⁻¹ decade⁻¹ seen at the Urmia station (Figure 7d). Statistically significant abrupt upward in the wind speed during the SCDs was observed at all stations, except Bojnurd (Figure 7d). The shifts in wind speed during the SCDs mainly occurred in the 1990s (2000s) throughout the northwestern (eastern) parts of Iranian mountain ranges (Figure 7h).

3.4. Climate Factors Influencing Snowpack Dynamics

In general, snow depth showed statistically significant negative correlations with all T_{mean}, T_{min}, and T_{max} during the SCDs throughout Iranian mountain ranges over the period 1982–2018 (Table 5). Such negative relationships were stronger in the Zagros and Azerbaijan than in the Elburz and Khorasan mountainous regions (Table 5). Similar spatial distribution of such relationships between the snow depth and all T_{mean}, T_{min}, and T_{max} during

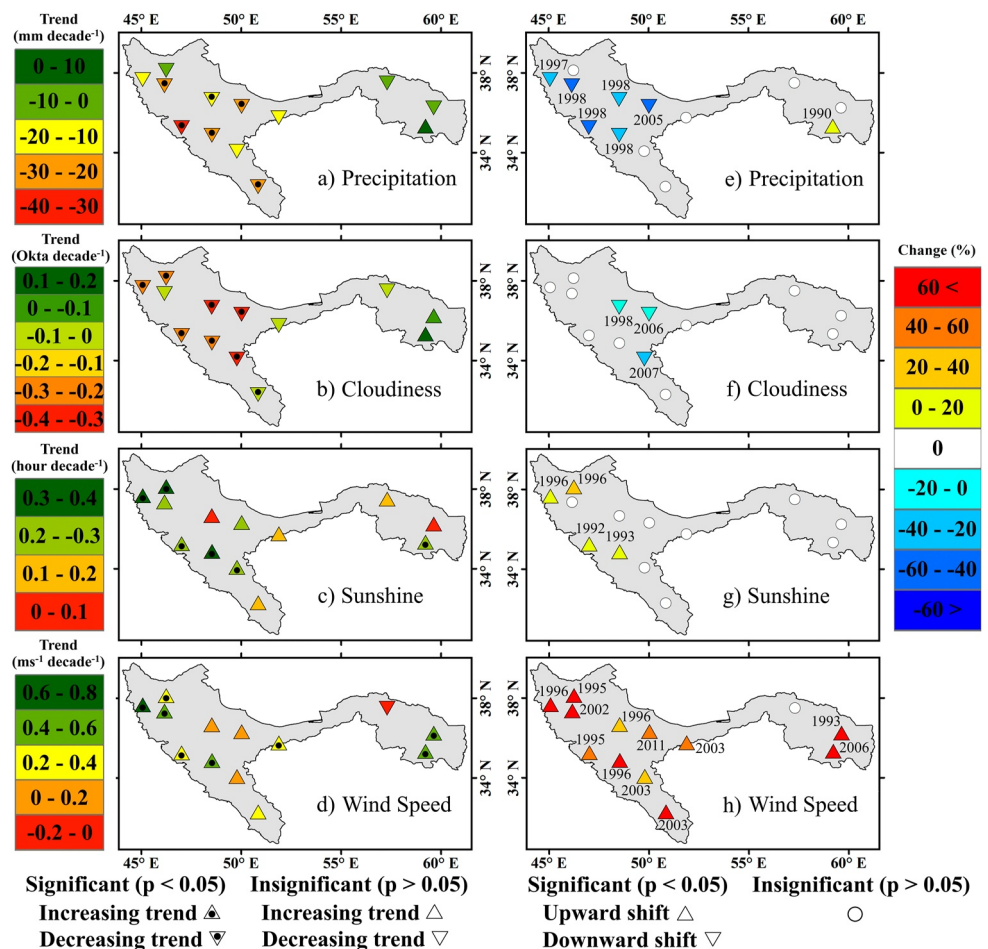


Figure 7. Trends and abrupt shift years in annual precipitation (a) and (e), cloudiness (b) and (f), sunshine (c) and (g), and wind speed (d) and (h) during the SCDs, respectively, at the hydrometeorological measurement stations studied Iranian mountain ranges over the period 1982–2018. The changes (%) in (e), (f), (g), and (h) represent the difference in long-term average values for annual precipitation, cloudiness, sunshine, and wind speed during the SCDs, respectively, between after and before the abrupt shift year detected at the 5% significance level.

the SCDs were also shown in Figures 8a–8c. The correlations of snow depth with both DTR (Figure 8d) and cloudiness (Figure 8f) during the SCDs were not clear at any of the hydrometeorological stations studied, but statistically significant across the entire Iranian mountain ranges, with the Pearson's correlations of -0.47 and 0.36 , respectively (Table 5). Along with the surface air temperature, all precipitation, sunshine, and wind speed during the SCDs substantially influenced historical variations in the snow depth throughout the entire Iranian mountain ranges as well as both Zagros and Elburz mountain regions (Table 5) and their selected measurement stations (Figures 8e–8g, and 8h).

There were generally significant relationships among different climatic factors influencing historical variations in snow depth during the SCDs throughout Iranian mountain ranges. Statistically significant positive correlations were obviously measured between T_{mean} , T_{min} , and T_{max} across all Elburz, Azerbaijan, Zagros, and Khorasan mountains (not shown). The sunshine was principally in significant negative (positive) associations with the cloudiness (T_{max}) at all hydrometeorological stations (except Bojnurd) studied (Table 6). In about 54% (46%) of these stations, the wind speed showed substantially positive (negative) correlations with the T_{max} and the sunshine (precipitation) during the SCDs (Table 6). Besides, we basically found positive and negative relationships of precipitation with cloudiness and sunshine in about 46% and 69% of stations, respectively (Table 6).

Figure 9 illustrates the correlations of snow depth with each of the different climatic factors while controlling the relationships among them. Accordingly, the snow depth was in significant positive (negative) relationships with the T_{mean} (T_{min}) only at the Hamedan station (Figures 9a and 9b) (Table 5). In particular, there were significant positive associations between the snow depth and the precipitation during the SCDs at the Abali, Qazvin, Arak, and Shahrekord stations over the period 1982–2018 (Figure 9e). Accordingly, such relationships were also found for the entire Iranian mountain ranges as well as for both Elburz and Zagros mountainous regions (Table 5). All cloudiness, sunshine, and wind speed played a key role in the snow depth variability at the Bojnurd station (Figures 9f–9h). Both sunshine and wind speed showed statistically significant positive and negative correlations, respectively, with the snow depth at the Torbat H. station (Figures 9g and 9h). However, the sunshine was in a negative relationship with the snow depth at the Sanandaj station (Figure 9g).

4. Discussion

4.1. Snow Resource Decline in Iran

Previous studies on historical snow resource patterns in Iran have primarily focused on spatiotemporal changes in snow cover area and duration estimated by remote sensing data sets (e.g., Ghasemifar et al., 2019; Keikhosravi

Table 5

Correlations and Partial Correlations of Snow Depth With All the Other Hydrometeorological Variables (Table 1) and Indicators (Table 2) During the Snow Cover Days (SCDs) Throughout Iranian Mountain Ranges and Different Mountainous Regions During in 1982–2018

	Area	Mountain	Snow Depth versus T_{mean}	Snow Depth versus T_{min}	Snow Depth versus T_{max}	Snow Depth v.s. DTR	Snow Depth versus Precipitation	Snow Depth versus Cloudiness	Snow Depth versus Sunshine	Snow Depth versus Wind Speed
Correlation	Iran	Iranian Mountain Ranges	<i>-0.83</i>	<i>-0.78</i>	<i>-0.85</i>	<i>-0.47</i>	<i>0.61</i>	<i>0.36</i>	<i>-0.53</i>	<i>-0.53</i>
	Mountainous Regions	Elburz	<i>-0.67</i>	<i>-0.63</i>	<i>-0.70</i>	<i>-0.34</i>	<i>0.53</i>	0.30	<i>-0.48</i>	<i>-0.53</i>
		Azerbaijan	<i>-0.70</i>	<i>-0.68</i>	<i>-0.71</i>	-0.30	0.19	<i>0.36</i>	<i>-0.42</i>	<i>-0.34</i>
		Zagros	<i>-0.88</i>	<i>-0.90</i>	<i>-0.82</i>	-0.16	<i>0.51</i>	0.31	<i>-0.50</i>	<i>-0.46</i>
		Khorasan	<i>-0.69</i>	<i>-0.65</i>	<i>-0.66</i>	-0.27	0.32	-0.07	-0.18	<i>-0.35</i>
Partial Correlation	Iran	Iranian Mountain Ranges	0.05	-0.10	0.03	-0.10	<i>0.53</i>	-0.28	-0.30	0.03
	Mountainous Regions	Elburz	0.04	0.04	-0.12	0.19	<i>0.40</i>	-0.10	-0.32	-0.17
		Azerbaijan	0.06	0.11	-0.35	0.32	0.19	-0.09	-0.17	-0.21
		Zagros	0.08	-0.14	-0.02	0.00	<i>0.48</i>	0.28	0.08	-0.04
		Khorasan	-0.09	-0.09	0.17	-0.16	0.24	-0.05	0.04	-0.15

Note. Statistically significant ($p < 0.05$) correlations and partial correlations are given in both bold and italic.

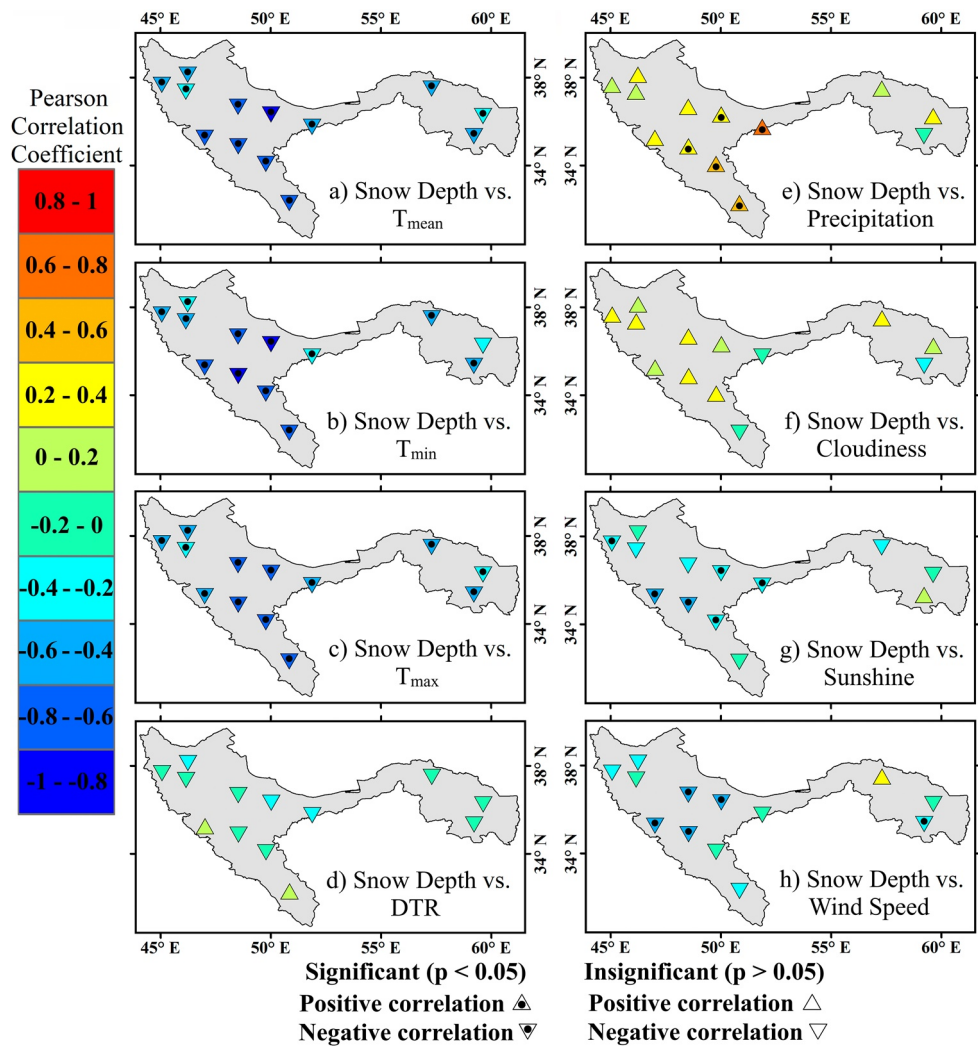


Figure 8. The Pearson's correlation coefficients of snow depth with T_{mean} (a), T_{min} (b), T_{max} (c), DTR (d), precipitation (e), cloudiness (f), sunshine (g), and wind speed (h) during the SCDs at the hydrometeorological measurement stations studied Iranian mountain ranges over the period 1982–2018.

Kiany et al., 2017; Safarianzengir et al., 2020). However, to the best of our knowledge, the present study is the primary research that applied daily snow depth measurements to investigate long-term (1982–2019) variability and trends in snowpack dynamics across Iranian mountain ranges. Similar to previous studies (e.g., Choubin et al., 2019; Ghadimi et al., 2019; Keikhosravi Kiany et al., 2017), we found statistically significant decreasing trends in snow depth throughout the western parts of the Elburz and Zagros mountainous regions in Iran during 1982–2019. In these two mountains (Elburz and Zagros), such considerable declines in snow depth were associated with fewer SCDs resulting primarily from earlier LSCDs over time. Substantial decreases in both SCDs and LSCDs were also detected over the Khorasan mountainous region in the northeast of Iran.

The increase in surface air temperature in Iran over the last 60 years has been higher than the global average (Sadeqi & Kahya, 2021). It has been reported that the rise in air temperature is expected to be severe in the highlands of the west of the country, which would fundamentally alter the hydrological regime in snow-dominated basins (Darand, 2020; Irannezhad et al., 2016). Additionally, our study found that T_{mean} , T_{min} , and T_{max} warmed during 1982–2018 in Iran. Recent findings suggest that the increase in air temperature is likely to continue in the future decades in Iran, which could contribute to snow melting and more evaporation, negatively impacting water resources in the country, which is already facing a water crisis (Karimi Alavijeh et al., 2021). Regarding changes in surface air temperature based on 13 in situ stations, however, DTR generally provides more information on

Table 6

Selected Relationships Between Climatic Factors Influencing Snow Depth at All Hydrometeorological Measurement Stations Studied Throughout Iranian Mountain Ranges Over the Period 1982–2018, Based on the Pearson's Correlation Coefficients

Mountain region	Station name	Station no.	Sunshine versus Cloudiness	Sunshine versus T_{max}	Wind speed versus T_{max}	Wind speed versus Sunshine	Wind speed versus Precipitation	Precipitation versus Cloudiness	Precipitation versus Sunshine
North (Elburz)	Abali	1	<i>-0.76</i>	<i>0.39</i>	0.07	0.05	-0.20	0.12	<i>-0.43</i>
	Qazvin	2	<i>-0.81</i>	<i>0.56</i>	<i>0.62</i>	<i>0.39</i>	-0.01	<i>0.56</i>	<i>-0.38</i>
	Zanjan	3	<i>-0.70</i>	<i>0.39</i>	<i>0.36</i>	<i>0.34</i>	-0.08	<i>0.61</i>	<i>-0.34</i>
Northwest (Azerbaijan)	Tabriz	4	<i>-0.85</i>	<i>0.52</i>	<i>0.45</i>	<i>0.53</i>	-0.16	<i>0.49</i>	<i>-0.42</i>
	Urmia	5	<i>-0.82</i>	<i>0.44</i>	<i>0.33</i>	<i>0.66</i>	<i>-0.45</i>	<i>0.65</i>	<i>-0.37</i>
	Maragheh	6	<i>-0.84</i>	<i>0.60</i>	0.18	0.20	<i>-0.48</i>	0.25	-0.20
West (Zagros)	Sanandaj	7	<i>-0.74</i>	<i>0.59</i>	<i>0.40</i>	<i>0.40</i>	-0.13	0.09	-0.09
	Hamedan	8	<i>-0.75</i>	<i>0.73</i>	<i>0.54</i>	<i>0.57</i>	<i>-0.41</i>	0.27	<i>-0.75</i>
	Arak	9	<i>-0.83</i>	<i>0.64</i>	<i>0.39</i>	0.23	-0.02	0.28	<i>-0.35</i>
	Shahreکرد	10	<i>-0.71</i>	<i>0.48</i>	0.26	<i>0.39</i>	<i>-0.38</i>	0.33	<i>-0.71</i>
Northeast (Khorasan)	Torbat H.	11	<i>-0.83</i>	<i>0.42</i>	<i>0.43</i>	0.25	0.11	<i>0.40</i>	-0.31
	Mashhad	12	<i>-0.79</i>	<i>0.46</i>	<i>0.55</i>	<i>0.37</i>	-0.11	0.21	-0.28
	Bojnurd	13	<i>-0.63</i>	0.17	-0.29	-0.12	<i>0.35</i>	<i>0.40</i>	<i>-0.48</i>

Note. Statistically significant ($p < 0.05$) correlations are given in both bold and italic.

climate change than T_{mean} because it is related to T_{max} and T_{min} as well as it is more sensitive to radiation energy balance change (Braganza et al., 2004; Zhang et al., 2021). Changes in DTR can also influence the start of the growing season (Huang et al., 2020), mortality and morbidity (Davis et al., 2020), and cloud cover (Libanda et al., 2019).

Previous studies concluded that DTR decreased in most parts of the world (Braganza et al., 2004; Zhang et al., 2021), although increased in some areas (Libanda et al., 2019). In several cases, a combination of both positive and negative trends has been observed (Liu et al., 2021; Nawaz et al., 2019; Sun et al., 2019). Based on a combination of results from the present study and Sadeqi and Kahya (2021), it can be concluded that T_{min} increased faster than T_{max} before 1990 in the Iranian mountain ranges, while T_{max} increased more rapidly than T_{min} afterward. Thus, the DTR experienced a negative trend prior to 1990 and then a positive trend thereafter. Some studies have also addressed this issue. For example, Vose et al. (2005) acknowledged that DTR declined widely in the world during the period 1950–1980, but increased afterward in Europe, West USA, Australia, and India. Moreover, similar to Nawaz et al. (2019) study focusing on Pakistan, we found that the DTR trend was generally positive across the high-altitude areas throughout Iran (Figure 10).

In general, the reduction of annual precipitation during the SCDs contributed to the statistically significant decline in snow depth and cover days in the Iranian mountain ranges. Karimi et al. (2015) reported that the main reason for glaciers shrinking in Elburz is the decrease in wintertime precipitation. Glaciers have experienced remarkable retreats in Iran (Farajzadeh & Karimi, 2014; Motiee et al., 2020), and over half of the glaciers are expected to disappear by the end of this century (Karimi et al., 2021). In other words, the mountain glaciers and snowline of Iran are highly vulnerable to climate change (Ghadimi et al., 2019), similar to many other regions around the world (Irannezhad et al., 2022a, 2022b, 2022c, 2022d). The findings suggest that precipitation should be closely monitored and considered in water resource management strategies, particularly in the Iranian mountain range where snowpack dynamics play a critical role in the water supply.

A decrease in cloud cover in Iran during the snow season has led to an increase in sunshine hours by approximately $0.25 \text{ hr decade}^{-1}$ ($\sim 15 \text{ min decade}^{-1}$), which was statistically significant at about half of the stations studied. Rahimzadeh et al. (2014) also reported an increasing trend in sunshine hours at many stations in Iran, particularly in the western parts. Moreover, Eastman and Warren (2013) showed a slight declining trend in cloud cover around the world. By increasing sunshine hours, the sun provides more radiant energy and melts snow more

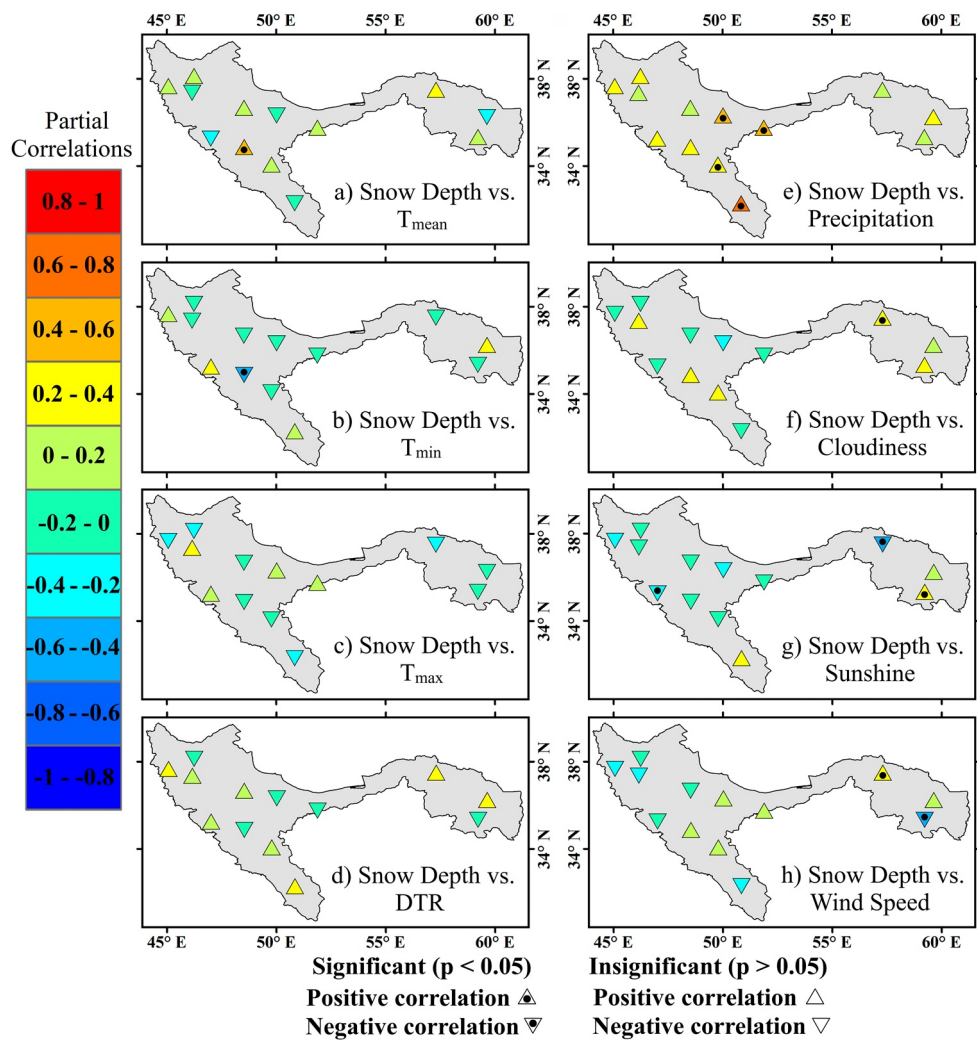


Figure 9. The partial correlations of snow depth with T_{mean} (a), T_{min} (b), T_{max} (c), DTR (d), precipitation (e), cloudiness (f), sunshine (g), and wind speed (h) during the SCDs at the hydrometeorological measurement stations studied Iranian mountain ranges over the period 1982–2018.

quickly (Chen et al., 2006), with serious implications for water resources and ecosystems on Earth, including in Iran.

Wind can generally lead to sublimation and evaporation from snow surfaces, resulting in reduced snow depth (Stigter et al., 2018). Therefore, in this study, we investigated long-term (1982–2018) changes in wind speed and their impacts on snow resources in Iran. Our results indicated a considerable increasing trend in average near-surface wind speed across all four mountainous regions of Iran. Although numerous studies (Guo et al., 2017; Zhang et al., 2019) have already concluded a declining trend in wind speed across the Northern Hemisphere, recent reports have shown an increasing trend in wind speed throughout high-altitude areas, particularly in winter (Ding et al., 2021; Li et al., 2018; Zhang et al., 2019). Similarly, we found significant increasing trends in wind speed across the high-altitude (mountainous) areas in Iran (Figure 10), with the highest rate at the Urmia station in Azerbaijan.

4.2. Effect of Less Snow on Water Crisis in Iran

Iran is facing a severe water crisis due to mismanagement, overuse of water resources, and anthropogenic development, resulting in a water scarcity condition exacerbated by climate change impacts (Moridi, 2017). With less than $1,700 \text{ m}^3 \text{ year}^{-1}$ of renewable water per capita, Iran has already entered a water stress state (Moridi, 2017).

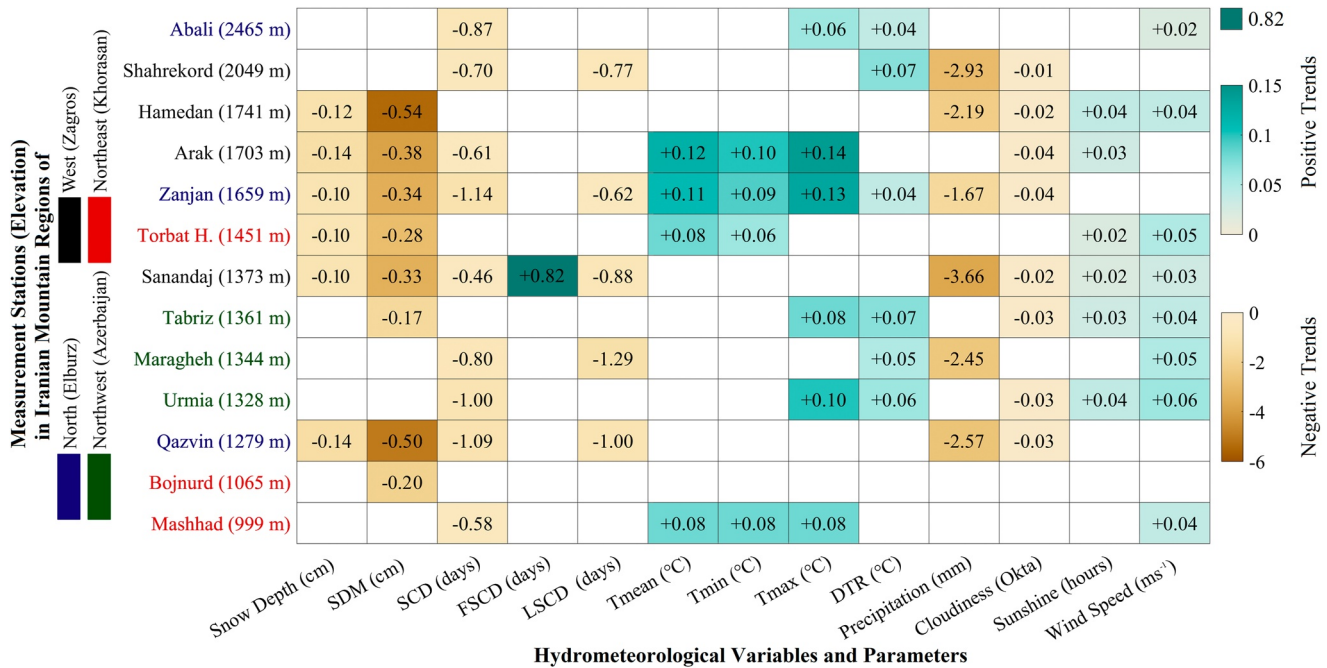


Figure 10. Long-term (1982–2018) interannual significant ($p < 0.05$) trends in different hydrometeorological variables (Table 1) and indicators (Table 2) during the snow cover days (SCDs) at the studied measurement stations (Figure 1) based on their elevations.

The reduction of snow as one of the most important freshwater resources in Iran could further exacerbate such a water crisis in this country. Less snowmelt water poses serious challenges to agricultural activities in Iran during the growing season when rainfall is minimal and most irrigation water is supplied through surface or groundwater resources. As a significant contributor to Iran's economy, agriculture consumes around 90% of available water resources throughout the country (Ashraf et al., 2019; Mirzaei et al., 2019).

Declines in snow resources principally alter flow regimes in different water bodies (e.g., Irannezhad et al., 2022a, 2022b, 2022c, 2022d) throughout snow-dominant environments, resulting in significant depletion of springtime groundwater level (Okkonen & Kløve, 2010) as well as a substantial increase in the risk of summertime droughts. Besides, anthropogenic activities such as overexploiting of groundwater and uncontrolled pollution of freshwater resources have already deteriorated the quality of water resources in Iran (Sharifi et al., 2021; Torabi Haghighi et al., 2020). In Iran, for example, Lake Urmia—one of the largest saltwater lakes on Earth—began to dramatically shrink in the late 1990s due to anthropogenic development, mismanagement, and water overuse (Alizade Govarchin Ghale et al., 2018; Pouladi et al., 2021). Similarly, many other natural lakes (e.g., Lake Bakhtegan) and rivers (e.g., Karun and Zayandeh-Rud Rivers) in Iran are in critical condition, causing some clashes over water between residents or with the government in some parts of the country. Hence, it is crucially important today for Iran to develop sustainable water resources management strategies for adaptation and mitigation of declining snow resources in response to climate change (a decrease in precipitation and an increase in surface air temperature) and human activities in the future (Hosseini Baghanam et al., 2020; Kalbali et al., 2021; Mirdashtvan et al., 2018; Zareian, 2021).

5. Conclusions

This study conducted a comprehensive analysis of long-term (1982–2018) snow depth and snow cover days (SCDs) variability and trends in Iranian mountain ranges. The research also examined historical variations in key climate factors affecting snowpack dynamics (surface air temperature, precipitation, cloudiness, sunshine, and wind speed), while assessing their relationships with snow resources across the diverse mountainous regions in Iran. The major conclusions were:

- Snow depth significantly declined in Iranian mountain ranges during 1982–2018, particularly throughout the western parts of the Elburz and Zagros mountains regions. Substantial decreases in the annual number of snow cover days (SCDs) were also seen throughout all Elburz, Zagros, and Azerbaijan mountain regions, primarily in association with the earlier LSCDs. The abrupt shift years of such downward trends in both SCD and LSCD were mostly seen between 1993 and 1999.
- All historical trends in annual T_{\min} , T_{\max} , and T_{mean} during the SCDs were positive (warming) over Iranian mountain ranges, but sequentially significant in about 31%, 46%, and 31% of hydrometeorological measurement stations. Both annual precipitation and cloudiness during the SCDs substantially decreased in the most of stations throughout all three mountain regions of Elburz, Azerbaijan, and Zagros in 1982–2018. Long-term increases in annual sunshine (wind speed) during the SCDs were also statistically significant in 67% (100%) and 75% (50%) of stations throughout Azerbaijan and Zagros mountains, respectively. Across the Khorasan mountainous region, however, sunshine (wind speed) considerably increased only in one (two) out of three stations selected by this study. Besides, most of the significant abrupt downward or upward shift years detected in all of surface air temperature, precipitation, cloudiness, sunshine, and wind speed were detected through the 1990s.
- Throughout Iranian mountain ranges, annual snow depth variability principally showed significant negative associations with all annual T_{\min} , T_{\max} , and T_{mean} during the SCDs over the period 1982–2018. Along with the surface air temperature, precipitation (sunshine and wind speed) during the SCDs also played a considerable positive (negative) role in historical snowpack dynamics throughout both Elburz and Zagros mountain regions in Iran. There were also significant relationships among these climate factors influencing snowpack variability in different Iranian mountainous regions.
- Substantial snow resource declines detected in both Elburz and Zagros mountain regions in Iran were generally related to the significant correlations among T_{\max} , precipitation, cloudiness, sunshine, and wind speed during the SCDs. Adjusting the effects of such correlations, this study determined that none of these climate factors, except precipitation, could alone cause considerable changes in snow depth throughout Iranian mountain ranges. In particular, hence, substantial reductions in annual precipitation during the SCDs played the most influential role in statistically significant decreases in snow depth and cover days throughout both mountainous regions of Elburz and Zagros in Iran over the water years between 1982 and 2018.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The data utilized in this study is available online through the Iran Meteorological Organization (IRIMO) website at <https://data.irimo.ir> (might be accessible only in Iran). The data is provided at no cost for researchers affiliated with Iranian universities. For researchers outside of Iranian universities, the data may be available for a fee. Please note that data access conditions may apply.

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