Received: 15 February 2019 | Revised: 16 November 2019 | Accepted: 23 January 2020
DOI: 10.1002/met.1891

RESEARCH ARTICLE

Meteorological Applications RMetS

Long-term variability and trends of extended winter snowfall in Turkey and the role of teleconnection patterns

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Abstract

In this study, a climatological analysis of daily new snow cover data from 93 meteorological stations (10–2,400 m above sea level) over Turkey during the winter (December–March) period of 1967–2006 is presented. Series of snow cover depth (SCD) (≥1 cm) and number of snowy days (SDs) were analysed to determine the variability and statistically significant trends in the snow climatology. The results showed an inverse relation between SDs and SCD over the central (CAR) and eastern (EAR) Anatolian regions. While positive trends in SDs were observed in the CAR (77% of all stations), the new SCD decreased in time. On the other hand, the intensity of the daily snowfall over the EAR increased due to decreasing (increasing) SD (SCD) trends in the region, especially between the 500 and 1,000 m layer. It was found that higher SCDs occur in the EAR during winter with positive patterns in the east Atlantic/western Russia. The daily mean sea level pressure composite maps of high SCD (>5 cm) show that strong northeasterly flows enable the penetration of cold polar air to the EAR due to the interaction between the Siberian high-pressure centre over Europe and the low-pressure centre over the Caspian Sea. These results help further understanding of the regional variation of the snowfall pattern in Turkey and its response to global climatic change.

KEYWORDS

snow cover depth (SCD), snowfall, synoptic, teleconnection pattern (TP), Turkey

1 | INTRODUCTION

Snow cover at high altitudes is known as the principal resource for water supply, hydroelectricity and tourism (Beniston, 2003; Uhlmann *et al.*, 2009). Contrary to its positive effect on social life, it also causes economic losses in urban and rural settlements due to transportation problems and avalanches (Gürer *et al.*, 1995; Kindap, 2010; Aydın *et al.*, 2014; Vajda *et al.*, 2014).

Several snowfall studies indicating their variations (Dye, 2002) and relationships with local meteorological factors (e.g. temperature, precipitation, geopotential height) and large-scale circulation effects have been done for continental Europe (e.g. Bednorz, 2002; 2004). Vojtek

There are no funders to report for this submission.

et al. (2003) carried out trend analysis and found statistically significant decreasing mean snow depth and number of snowfall days (SDs) below 1800 (2300) m altitude on the northern (southern) slopes over Slovakia. Falarz (2004) showed the existence of an increasing trend in snow cover over mountainous regions of Poland during the last half of the 20th century. The results found by Buisan *et al*. (2015) also showed a statistically significant decrease in the number of snow days over the Spanish Pyrenees for the 1971–2000 period. Because of the long historical snow monitoring data of Switzerland, many researchers have analysed trends of Alpine snow pack and in common they found a decrease in the snowfall amounts at low altitude stations (<1,300 m above sea level) since the mid-1980s due to the increase in local temperature (e.g. Laternser and Schneebeli, 2003; Scherrer *et al*., 2004).

To investigate the possible causes underlying the changes in snowfall characteristics, some authors emphasized local influences such as temperature increase and snowfall/precipitation day ratio (Manley, 1958; Scherrer *et al*., 2004; Serquet *et al*., 2011), while others investigated the role of teleconnection patterns (TPs) such as the North Atlantic Oscillation (NAO), Arctic Oscillation (AO), Scandinavian (SCA) and east Atlantic/western Russia (EA/WR) patterns. Based on TPs, Seager *et al*. (2010) and Kim *et al*. (2013) indicated that snow cover depth (SCD) increases over Europe when the NAO is in a negative phase and vice versa. Ye and Lau (2017) investigated the dynamics behind snow cover changes by taking the NAO into account. Consistent with previous studies, the NAO changes modulate the water vapour transport towards the European continent, and thereby influence the available water vapour there and lead to fluctuations in downward long wave irradiance and cloud cover. From previous studies, while the NAO is shown as the dominant circulation pattern determining the variability of snowfall in Europe, other large-scale circulation mechanisms such as the SCA pattern lead snowstorms in China (e.g. Zhou *et al*., 2009; Zhu and Chen, 2019). Unlike European geographical low-level areas (except from the Alps), almost half of Turkey has high altitude regions exceeding 1,000 m (and a mean altitude of approximately 1,132 m). While the north Anatolian mountains are located on the northern side of the country (reaching highest altitudes at the Kaçkar mountains with 3,932 m, northeast Turkey), the Taurus Mountains, which have a peak point at 4000 m, are positioned parallel to the eastern Mediterranean basin (south of Turkey). The highest mountainous regions are found in the eastern Anatolian region (EAR) and the height of Mount Ararat reaches 5,137 m from sea level. The snowfall in these mountain chains is the main source of water supply for hydropower generation, irrigation, drinking etc. in the EAR. Also, snowmelt during spring months over the EAR increases the flow rate of transboundary waters such as the Euphrates and Tigris, which are controlled by dams, and it enables the transfer of water to Syria and Iraq for irrigation and drinking purposes. On the other hand, water loss through evapotranspiration increases significantly with the areal expansion of irrigation in the ongoing Southeastern Anatolia Project (Yilmaz *et al*., 2019). As a result, demanding water for irrigation purposes in the upper and lower Euphrates–Tigris basin increases the risks in the water–food–energy nexus of the Middle East region.

Besides these positive influences, sudden and intense snowstorms negatively affect the most populated regions of Turkey such as Istanbul (northwest Turkey, most populated city in Europe) (Tayanç *et al*., 1998). Although there are many negative and positive influences of SDs and SCD on social and economic life throughout the whole country, limited snowfall studies exist and are focused on satellite snow cover products (e.g. Akyurek and Şorman, 2002; Tekeli *et al*., 2005). The primary goal of this study was to identify the temporal and spatial variability of the extended winter (December to March) mean SCD and number of SDs over Turkey, and to investigate dominant factors causing snowfall variability by focusing on large- and synoptic-scale, regional and topographical features.

The paper is organized as follows. Section 2 outlines the data sources and analysis methods used in the study. Section 3 shows the results of trend analysis and TPs and spatial differences of the winter SCD and SDs. The results are summarized and further discussed in Section 4.

2 | DATA AND METHODOLOGY

Daily SCD and SDs data for the extended winter period (December–March) from 282 meteorological stations over Turkey were obtained from the Turkish State Meteorological Service for the period 1950–2010. Low-quality snowfall data were detected and eliminated from the raw dataset by applying quality control (QC) methods (Baltacı *et al*., 2018). QC was applied to the observed data using the RCLIMDEX software package provided by the expert team on climate change detection and indices. After QC analysis, a dataset of 93 stations from 1967 to 2006 presented high quality. Because various meteorological stations have migrated from conventional to automatic since 2006 and have had problems during their early years of observation, the series was cut in 2006. Therefore, from 2006 the quality of new snow cover data is questionable.

Snow depth observations at the meteorological stations are taken once a day at 0600 UTC (local time is UTC + 2 hr during winter and UTC + 3 hr during summer). Days with snow depth equal to or larger than 1 cm are considered as days with a snow cover. During the snowfall season, if the daily snow accumulation is less than 1 cm (i.e. not covering the ground) these days are still considered as snowfall in the study. However, these days were separated as −1 to differentiate them from other days.

The station and regional based trends of SCD and SDs were also investigated. For the regional approach, similar to the Erinç (1984) work, the Turkey region was divided into seven sub-regions (Figure 1), namely Marmara region (MR), Aegean (AR), Mediterranean region (MeR), central Anatolia region (CAR), Black Sea region (BSR), EAR and southeastern Anatolia region. The southeastern Anatolia region has the highest average temperature values in Turkey due to its warm climate and low altitude, and thus the limited snowfall data of this region were removed from the analysis. The MeR and AR are the second and third warmest regions of Turkey, respectively, and high altitudes and low temperatures at specific places in these regions enable new snow data to be used daily. The altitudes of the 93 selected stations range from 10 to 2,400 m above sea level. To examine the topographic variability of snowfall, the stations were grouped into three altitude classes (<500 m altitude, 501–1,000 m altitude and >1,000 m altitude) according to Serquet *et al*. (2011). Table 1 shows all stations in each region along with their characteristics. In the MR, the average altitude of the 12 stations (nos. 1–12) is 315 m, with eight stations ranging from 0 to 500 m, three stations between 500 and 1,000 m, and only one greater than 1,000 m. For the AR region, stations located in high mountain regions were used (nos. 13–19). These stations are located in the eastern part (Figure 1) of the AR with an average altitude of 916 m, with most of them between 500 and 1,000 m. In the MeR, snow data from only four stations existed in the dataset due to their high altitude position on Taurus Mountain slopes (nos. 20–23). For the CAR, daily new snow data of 30 stations were used with many of these stations (23 in total) located above 1,000 m height. In the BSR, only three stations are located at the coast, while the others are located on the foothills of the northern Anatolian mountains. Finally, for the EAR, the average altitude of the stations is 1,507 m and the altitude of three stations in this region is over 2000 m.

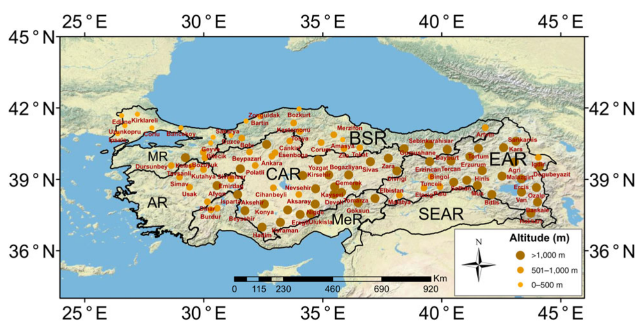

FIGURE 1 Distribution of 93 weather stations in Turkey. The size of each dot is proportional to the altitude of each station. The abbreviations over regions indicate the Marmara (MR), Aegean (AR), central Anatolia (CAR), Black Sea (BSR), Mediterranean (MeR), southeastern Anatolia (SEAR) and eastern Anatolia (EAR) regions

In order to carry out trend analysis and determine the confidence levels of the trends, linear regression and a sequential version of the Mann–Kendall test were used. Regional, topographical and station-based differences were also investigated. The Mann–Kendall is a well-known non-parametric rank-based test widely used in climatological and hydrological studies (e.g. Goossens and Berger, 1986; Karaca *et al*., 1995; Tayanç *et al*., 1997; Ezber *et al*., 2007; Ünal *et al*., 2012). According to the trend results, values above +1.96 and below −1.96 of the normal distribution table represent the 95% significance level.

In order to investigate the influence of TPs on SCD, monthly time series of the indices belonging to five TPs (i.e. NAO, AO, EA/WR, east Atlantic [EA] and SCA) were obtained from the Climate Prediction Center and the National Centers for Environmental Prediction (NCEP) National Oceanic and Atmospheric Administration (NOAA) website (http://www.cpc.noaa.gov/data/). To study the background physical mechanisms that cause snowfall, composite analysis from NCEP/National Center for Atmospheric Research (NCAR) reanalysis data (2.5° × 2.5° spatial resolution) was used for days and winter seasons having extremely high snow accumulation. For this purpose, daily and monthly means from NCEP/NCAR sea level pressure and 500 hPa geopotential height data between 5 ° W and 55 ° E longitude and 30 ° N–60 ° N latitude were extracted for this study.

3 | RESULTS AND DISCUSSION

3.1 | Spatial and temporal variation of mean SDs and SCD in winter over Turkey

Figure 2 shows the spatial variation of extended winter mean SDs and SCD over Turkey for the period 1967–2006. The highest winter mean SDs were detected in the EAR and CAR with mean values of 25 and 17 days, respectively (Figure 2a). In the EAR, daily snowfall events exceed 20 days (17% of all winter days) in many

TABLE 1 Geographic coordinates, altitudes and regional distribution of 93 meteorological stations as well as their long-term (1967–2006) trends from winter (December to March) snowfall days (SDs) and snow cover depth (SCD) in Turkey

Region	No.	Station name	Longitude (° E)	Latitude (° N)	Altitude (m)	SD trend (days/decade)	SCD trend (cm/decade)
Marmara region (MR)	1	Bahcekoy	29.05	41.16	130	1.07	−0.32
	2	Bilecik	29.97	40.14	539	0.58	0.34
	3	Bozuyuk	30.05	39.90	754	0.93	0.2
	4	Corlu	27.81	41.15	183	−0.34	0.25
	5	Dursunbey	28.63	39.57	639	−0.13	0.43
	6	Edirne	26.55	41.67	51	−0.67	0.57
	7	Geyve	30.29	40.52	100	0.65	**−0.61**
	8	Ipsala	26.38	40.91	10	−0.01	0.74
	9	Keles	29.23	39.91	1,063	−0.56	−0.18
	10	Kirklareli	27.21	41.73	232	0.48	**−0.55**
	11	Sakarya	30.39	40.76	31	0.56	−0.28
	12	Uzunkopru	26.68	41.25	52	−0.03	0.2
Aegean region (AR)	13	Afyon	30.56	38.73	1,034	−0.17	**0.71**
	14	Dinar	30.15	38.05	864	0.46	−0.1
	15	Emirdag	31.14	39.00	983	**1.68**	0.06
	16	Kutahya	29.98	39.41	969	0.5	0.27
	17	Simav	28.97	39.09	809	−0.51	0.55
	18	Tavsanli	29.49	39.53	834	0.63	**0.46**
	19	Usak	29.40	38.67	919	−0.24	0.26
Med. region (MeR)	20	Burdur	30.29	37.72	967	0.38	0.1
	21	Elbistan	37.19	38.20	1,137	−0.16	0.01
	22	Goksun	36.48	38.02	1,344	−0.91	0.1
	23	Isparta	30.56	37.78	997	0.32	−0.02
Central Anatolia region (CAR)	24	Aksaray	33.99	38.36	965	0.4	−0.23
	25	Aksehir	31.42	38.36	1,002	1.28	0.15
	26	Ankara	32.86	39.97	891	0.86	−0.04
	27	Beypazari	31.91	40.16	682	0.95	0.06
	28	Beysehir	31.73	37.68	1,141	0.35	−0.07
	29	Bogazliyan	35.25	39.18	1,066	0.81	**−0.38**
	30	Cankiri	33,61	40.60	751	−0.73	0.01
	31	Cihanbeyli	32.92	38.65	969	0.17	**0.67**
	32	Develi	35.47	38.37	1,180	−1.38	0.05
	33	Divrigi	38.11	39.36	1,225	−0.79	0.1
	34	Eregli	34.04	37.52	1,044	0.76	−0.24
	35	Esenboga	32.99	40.12	949	0.46	−0.32
	36	Gemerek	36.08	39.18	1,173	0.03	−0.13
	37	Hadim	32.45	36.98	1,552	−1.57	−0.58
	38	Karaman	33.22	37.19	1,025	−0.18	−0.2
	39	Karapinar	33.52	37.71	1,004	**1.51**	−0.28
	40	Kayseri	35.50	38.68	1,093	1.27	0.02
	41	Kirsehir	34.15	39.16	1,007	0.69	−0.39

(Continues)

TABLE 1 (Continued)

Region	No.	Station name	Longitude (° E)	Latitude (° N)	Altitude (m)	SD trend (days/decade)	SCD trend (cm/decade)
	42	Kizilcahamam	32.64	40.47	1,033	**2.05**	0
	43	Konya	32.55	37.96	1,031	1.15	**−0.62**
	44	Nevsehir	34.70	38.60	1,260	0.37	**−0.37**
	45	Nigde	34.67	37.95	1,211	0.69	0.08
	46	Pinarbasi	36.38	38.72	1,500	0.79	**−0.38**
	47	Polatli	32.16	39.58	885	0.37	0.26
	48	Sivas	37.00	39.74	1,285	0.87	−0.11
	49	Sivrihisar	31.53	39.44	1,070	1.24	−0.09
	50	Tomarza	35.78	38.45	1,347	0.08	−0.17
	51	Ulukisla	34.48	37.54	1,453	−0.56	0.03
	52	Yozgat	34.80	39.82	1,298	1.13	0.06
	53	Zara	37.74	39.89	1,348	**−3.05**	−0.03
Black Sea region (BSR)	54	Amasya	35.83	40.66	412	0.33	−0.11
	55	Artvin	41.81	41.17	628	0.76	0.24
	56	Bartin	32.35	41.62	30	1.03	**−1.36**
	57	Bayburt	40.23	40.25	1,584	−0.09	0.25
	58	Bolu	31.60	40.73	742	1.21	0.18
	59	Bozkurt	34.00	41.95	167	−0.06	0.53
	60	Corum	34.93	40.54	776	0.29	−0.04
	61	Duzce	31.14	40.84	146	1.81	−0.34
	62	Gumushane	39.46	40.45	1,219	0.83	−0.03
	63	Kastamonu	33.77	41.37	800	0.78	−0.08
	64	Merzifon	35.45	40.87	759	0.22	0.05
	65	Sebinkarahisar	38.41	40.28	1,300	−0.51	−0.04
	66	Tokat	36.55	40.33	608	1.27	**−0.32**
	67	Tosya	34.03	41.01	820	0.43	0.25
	68	Zile	35.89	40.29	700	0.79	0.1
	69	Zonguldak	31.77	41.44	137	1.17	−0.33
Eastern Anatolia region (EAR)	70	Agri	43.05	39.72	1,631	**−1.73**	**0.42**
	71	Baskale	44.01	38.04	2,400	**−1.87**	0.49
	72	Bingol	40.50	38.88	1,177	−1.4	0.3
	73	Bitlis	42.10	38.36	1,573	−1.65	0.25
	74	Dogubeyzait	44.08	39.55	1,725	−1.36	0.09
	75	Elazig	39.25	38.63	991	**−3.16**	0.22
	76	Ercis	43.33	39.01	1,678	−1.69	0.06
	77	Erzincan	39.48	39.75	1,218	−0.36	0.02
	78	Erzurum	41.17	39.95	1,757	1.29	−0.15
	79	Hakkari	43.73	37.57	1,728	−1.51	0.04
	80	Hinis	41.69	39.36	1,715	−1.44	0.4
	81	Igdir	44.05	39.92	858	−1.16	−0.03
	82	Kars	43.11	40.60	1,775	**−2.59**	**0.54**

(Continues)

TABLE 1 (Continued)

Region	No.	Station name	Longitude (° E)	Latitude (° N)	Altitude (m)	SD trend (days/decade)	SCD trend (cm/decade)
	83	Malatya	38.21	38.33	898	**−2.73**	**0.7**
	84	Malazgirt	42.53	39.13	1,565	0.43	0.06
	85	Mus	41.50	38.75	1,284	−1.52	0.18
	86	Ozalp	43.97	38.65	2,100	2.22	0.04
	87	Palu	39.92	38.69	1,000	−1.14	0.28
	88	Sarikamis	42.59	40.33	2,103	**−4.1**	**0.35**
	89	Solhan	41.05	38.95	1,365	−0.33	0.14
	90	Tercan	40.38	39.77	1,425	−1.94	0.18
	91	Tortum	41.53	40.30	1,572	0.12	0.1
	92	Tunceli	39.54	39.10	980	−2.27	0.34
	93	Van	43.34	38.46	1,671	0.52	−0.35

The bold values indicate statistically significant trends at the 95% level.

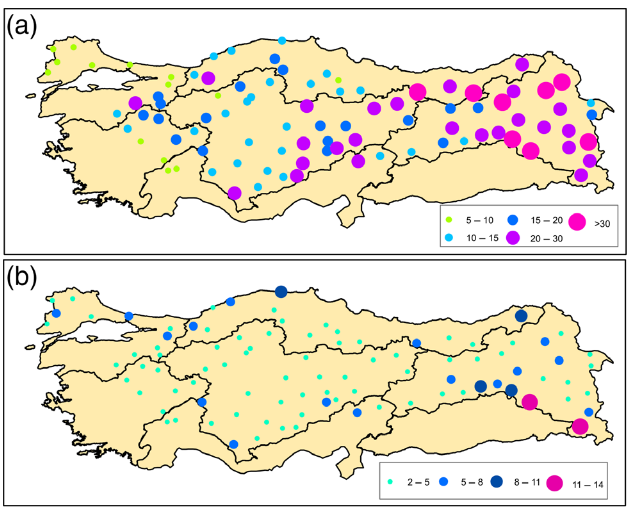

FIGURE 2 Spatial variation of winter (December to March) mean (a) snowy days and (b) snow cover depth (cm) for 93 stations over Turkey for the period 1967–2006

central and eastern stations. In this region, six stations located at Kars, Erzurum, Mus, Ozalp, Sarikamis and Bitlis settlements have the highest mean SD records with values of 31, 31, 31, 34, 37 and 38 days, respectively. The altitudes of these stations vary from 1,284 to 2,103 m. Compared to other stations, the highest winter mean SD records were identified in the Bitlis region. Although the location of this station is not too high (1,543 m), higher frequencies of SDs can be explained by the position of the Bitlis station along with the influence of local meteorological conditions. The topography of the region shows that plains with low altitude exist at the southwest and thus orographic lifting of the southwesterly warm winds can generate cloud formation and precipitation. The situation can be accentuated by the presence of Van lake at the northeast of the region, where northeasterly cold winds can capture moisture from Van lake and generate lake-effect snow. Similar to lake-effect snowfall cases, Kunkel *et al.* (2007) emphasized that snowfall time series do not show similar behaviour in neighbouring stations because of spatial variations on small scales that are highly unlikely to be real.

With regard to daily new snow cover, the highest SCD records exceeding 11 cm were found in Bitlis and Hakkari cities over the EAR (Figure 2b). The winter mean SCD of the EAR was 6 cm. Except from the EAR, the second highest mean SD records are observed in the eastern part of the CAR. Although many days in winter are recorded as snowy in eastern CAR, the depth of this new snow is only between 2 and 5 cm. This result can be explained by the presence of different synoptic circulation conditions, topographical mechanisms such as moisture transport from low levels, and temperature differences between the EAR and CAR. Comparing these two regions, while the CAR has higher temperatures, the EAR is mainly surrounded by high mountains, so that air masses cannot penetrate the inner parts of the region.

In order to evaluate the temporal behaviour of winter mean SDs and SCD for each station and region, their decadal variations, trends and their confidence levels were extracted according to the Mann–Kendall trend test (Table 1). With regard to SDs, generally non-uniform statistically insignificant negative and positive trends are detected at stations over the MR, AR and MeR. Only Emirdag station shows statistically significant positive trends and in total an increase of seven SDs for 40 years is estimated from the beginning of 1967 to the end of 2006. For the CAR and BSR, more uniform weak positive trends in the winter mean SDs are found for the 40 year period. Almost 77% of stations in the CAR have positive SD decadal trends. During the period, while SDs in Karapinar and Kizilcahamam present statistically significant increases with 6 and 8 days, significant negative trends exist in Zara station with 12 days. For BSR, in total, 81% of all stations have weak positive trends. Different from the CAR and BSR, uniform negative trends in SDs are detected for almost 79% of the stations in the EAR. A total of 19 stations in the EAR, Agri, Baskale, Elazig, Kars, Malatya and Sarikamis provinces, show statistically significant negative trends ($p < 0.05$).

To study the temporal variability of the SD numbers, the focus was on Karapinar and Kizilcahamam stations in the CAR for their high positive trends (Figure 3a) and Malatya and Kars stations in the EAR for their high negative trends (Figure 3b). For Kizilcahamam, snowfall events were highly variable, ranging from 7 to 36 days each year. Three winters with the highest SDs were in the years 2000, 2004 and 1987 with 36, 25 and 25 days, respectively. Although Kizilcahamam and Karapinar are located at similar altitudes, the closeness of Karapinar to the Mediterranean basin results in fewer SDs compared to Kizilcahamam. Probably, the Taurus Mountains at the northern part of the MeR generate rainshadow conditions at Karapinar when the wind direction is southerly. The number of SDs for Kizilcahamam was from 3 to 23 days. The highest three snowfall winters were observed during 1992, 1987 and 2003 with 23, 21 and 20 days, respectively. When these two stations were compared, similar peak values of SDs can be found during 1987 for both stations. As previously documented by Tayanç *et al*. (1998), these high records of SDs can be explained by the atmospheric blocking conditions settled over the eastern Mediterranean and Balkan Peninsula. In terms of the eastern Anatolian peninsula, clear decreasing trends in SDs were present in the Malatya and Kars regions (Figure 3b). The three lowest SDs in Kars were found in the 2001, 1989 and 1990 winters with 12, 15 and 16 days, respectively. Sometimes warm years can generate no-snow years in some stations in the EAR, e.g. Malatya station in 1970, 1996 and 2001. Low numbers of SDs during the 2001 winter months can be

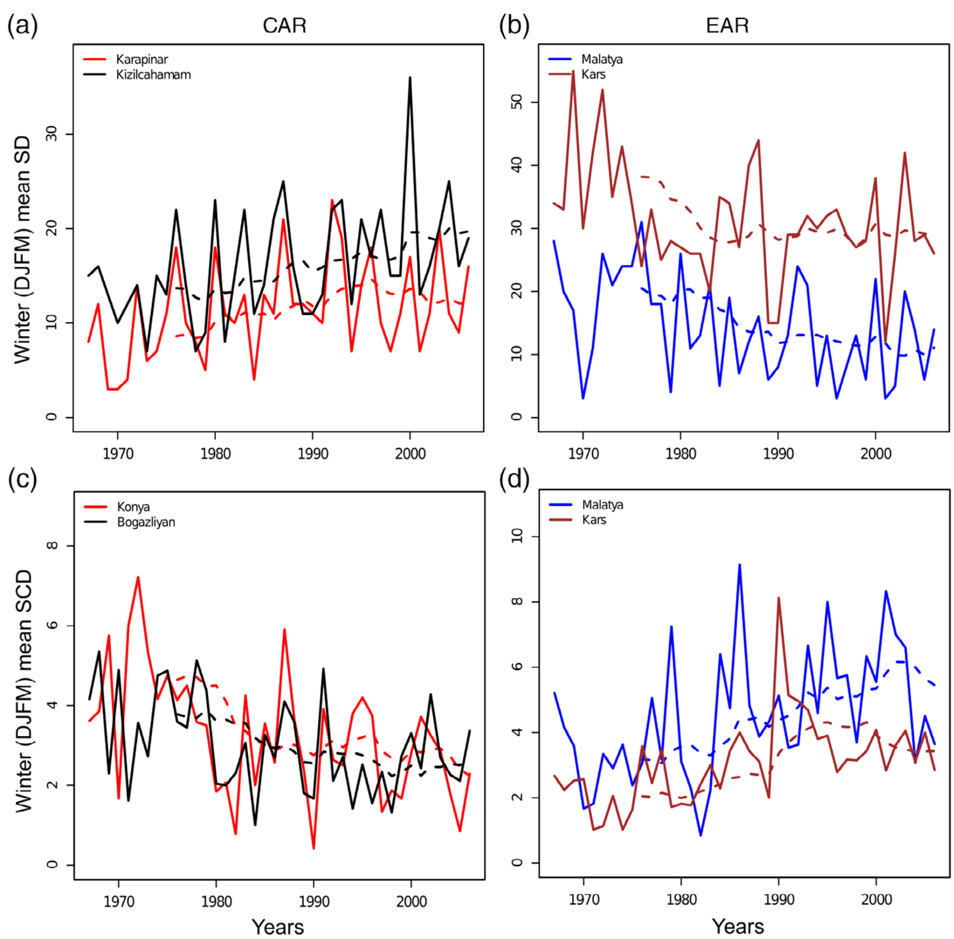

FIGURE 3 Temporal behaviour of winter mean (a), (b) snowy days (SDs) and (c), (d) snow cover depth (SCD). Karapinar, Kizilcahamam, Konya, Bogazliyan (Malatya, Kars) stations in the left (right) panels are used for their high positive (negative) SD trends in the central Anatolia region (CAR) (eastern Anatolia Region [EAR]). The dashed lines indicate the 10 year moving average; DJFM, December–March

explained by the penetration of the summer Asiatic monsoon low pressure system to the EAR, which ended up with above-normal temperature records for many days. In order to evaluate the significant trends in SCD, temporal variations for Konya and Bogazliyan stations located in the CAR (Figure 3c) and Malatya and Kars stations in the EAR (Figure 3d) were analysed. With regard to the CAR, Konya and Bogazliyan stations show similar decreasing trends from 1967 to 2006 (Figure 3c). According to the 10 year moving average, the winter mean SCD decreases from 5 to 2.5 cm. It is obvious that while SDs increase in time over the CAR, the depth of the daily new snow cover decreases. On the other hand, it can easily be seen from Figure 3b and 3d that the intensity of the new snow cover over the EAR increases with time. These results indicate that, although the CAR and EAR are neighbouring territories, different geographical features and atmospheric mechanisms can trigger different snowfall events.

3.2 | Variability of SDs and SCD with respect to height

In order to obtain topographical and regional variations in snowfall, the temporal behaviours of SDs and SCD for the low (0–500 m), mid (501–1000 m) and high (>1,000 m) altitudes of the six regions (Figures 4 and 5) were extracted and studied. In terms of SDs, the numbers of SDs are higher at high altitudes (Figure 4). Although the SDs at stations located above 1,000 m in the MeR and MR decrease with time, the numbers of SDs increase at mid altitude places in these regions. On the other hand, stations in the EAR provide more significant decreasing trends in SDs at both mid and high altitudes. A sharper decrease in winter SDs is detected in the mid altitudes of the EAR. It is clear from Figure 4 that the decrease in the numbers of SDs is more pronounced after 1993. Tayanç *et al.* (2009) showed that Turkey was under the effect of a cool period before 1993 and significant warming has started afterwards. Thus, the result of experiencing a more pronounced decrease in SDs after 1993 at the EAR is associated with the warming up of the region.

When temporal changes of SCD and SDs are considered together, remarkable results are found. While the numbers of SDs at high altitude stations over the CAR increase in time, the new SCD of these stations decreases with time (Figure 5). This negative correlation is due to climate change and warming-up of the region. Recent increases in surface temperature (Tayanç *et al.*, 2009) can contribute to the formation of snow by increasing the convective activity at low levels of the atmosphere (850 hPa). However, increasing temperatures may decrease the accumulation of snow at the surface. Ice crystals occur below 0°C as well as at temperatures just above the freezing point and accumulation of the snow strictly depends on the surface temperature. If the surface temperature is slightly above 0°C, snow will melt in a short time. This idea is supported by the data of the BSR as well, although the winter mean SDs have an increasing trend over the BSR at low altitudes and the SCD at the same altitudes significantly decreases. There are other characteristics of the snow trends in the BSR; the depth of new snow cover is greater than for mid and high altitudes. This condition can be explained by the leading synoptic circulation mechanisms, which influence the region. The movement of cold polar air over the relatively warm Black Sea during the winter months can transfer huge amounts of moisture to the air. When this relatively warm and humid air encounters the steep and cold land mass, it is forced to rise by orography generating large piles of snow formation at low altitudes. Similar to the study of Esteban *et al.* (2005), strong winds in these cases are also important to create an uplift mechanism and support the vertical motions that help generate heavy snow events. On the other hand, places located at higher altitudes in the BSR are exposed to less moisture containing air owing to the condensation and precipitation of the majority of the water content at lower altitudes, leading to smaller accumulations of daily new snow. It is obvious from Figure 5 that significant increasing trends exist in the SCD values of each of the altitudes in the eastern part of the country. As a result of the inverse relation between SDs and SCD over the EAR, it can be said that the intensity of daily snowstorms increases in time, leading to fewer SDs with larger amounts of accumulation. Possible underlying synoptic systems that trigger this atmospheric mechanism are investigated in the next section.

3.3 | The relationship between TPs and SCD

In our earlier study (Baltacı *et al.*, 2018), it was found that the influence of the AO and EA/WR patterns on temperature extremes over Turkey is more significant compared with the other circulation patterns (i.e. NAO, EA, SCA). Thus, the impacts of TPs on the SCD over Turkey were explored. For this reason, similar to Baltacı *et al.* (2018), averages of extended winter (December to March) index values of five TPs for the period 1967–2006 were used. According to the results, the winter mean SCD in many stations located over the central part shows insignificant negative correlations with the NAO pattern. On the other hand, insignificant positive relations between the NAO and SCD were found in the eastern part of Turkey (Figure 6a). The impacts of the AO on SCD show similar behaviour to the NAO. However, the SCD values of six stations in the EAR (i.e. Tercan, Bingol, Palu, Kars, Mus and Igdir) show statistically significant positive correlations with the AO pattern and 58% of all stations (Figure 6b). Compared

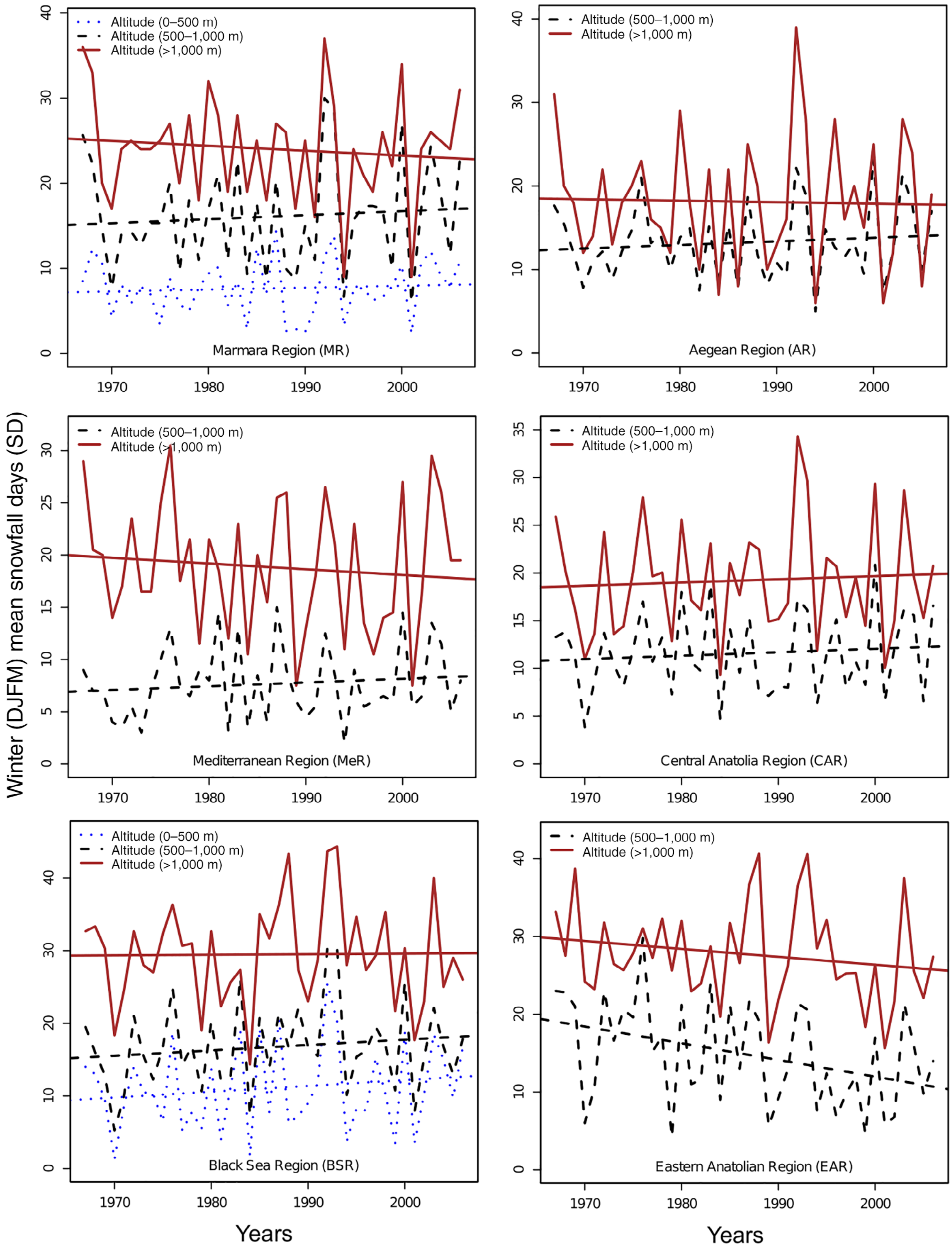

FIGURE 4 Temporal variation of winter mean snowfall days (SDs) for the low (0–500 m), mid (501–1,000 m) and high (>1,001 m) altitudes of each region; DJFM, December–March

with the NAO and AO, insignificant negative correlations in many stations located in the CAR turned to insignificant positive correlations during the EA/WR pattern. The most notable results are found in the EAR. In this region, the winter mean SCD in 96% of all stations shows positive relations with the EA/WR pattern and statistically significant positive correlations were found with SCD in 29% of all stations (i.e. Bingol,

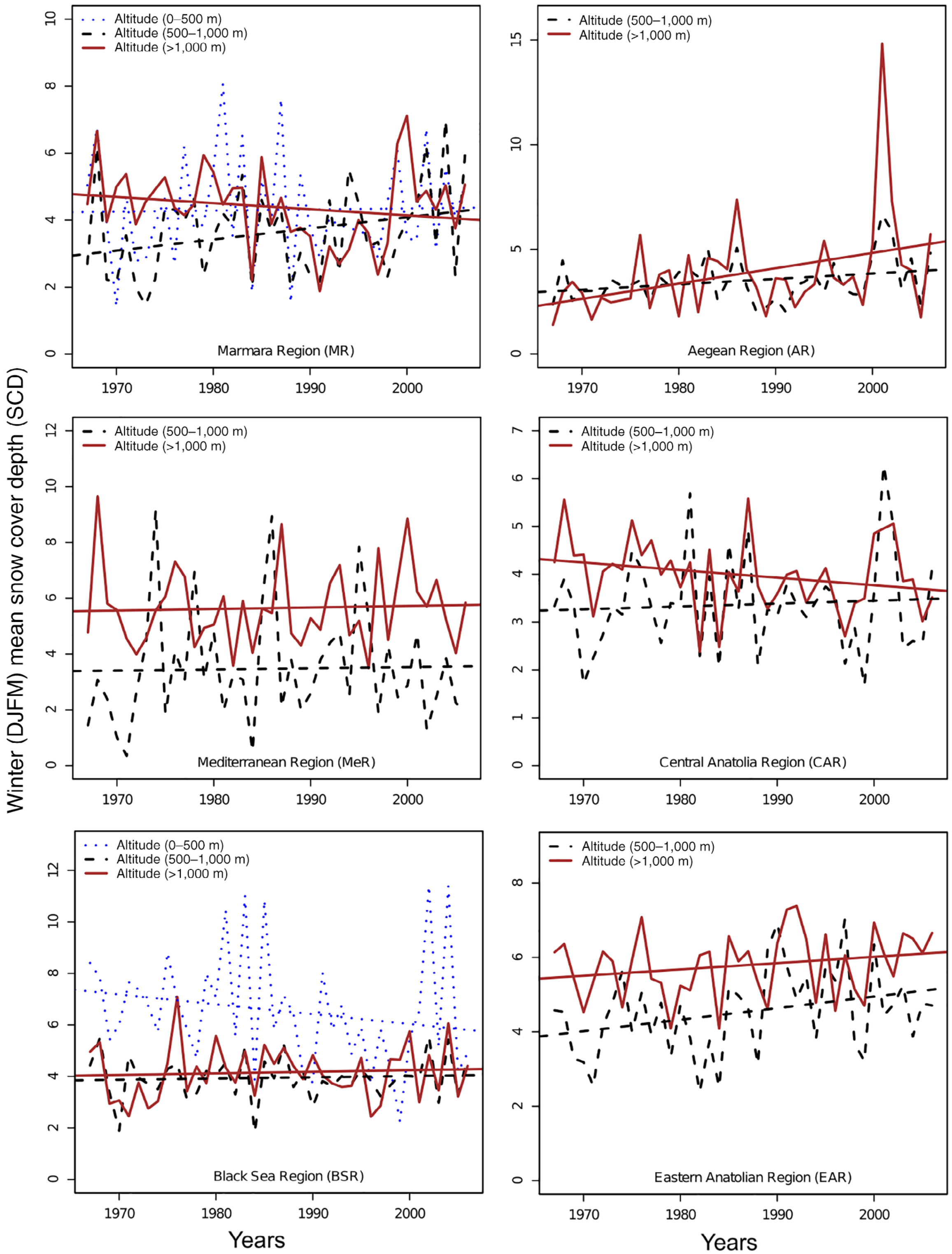

FIGURE 5 The same as Figure 4 but for snow cover depth (SCD)

Solhan, Mus, Bitlis, Van, Malazgirt, Tortum in Figure 6c). This suggests that during positive EA/WR winters, there is generally more SCD in this region. During the EA and SCA patterns, statistically significant relations with SCD were not found in many stations over Turkey (Figure 6d,e).

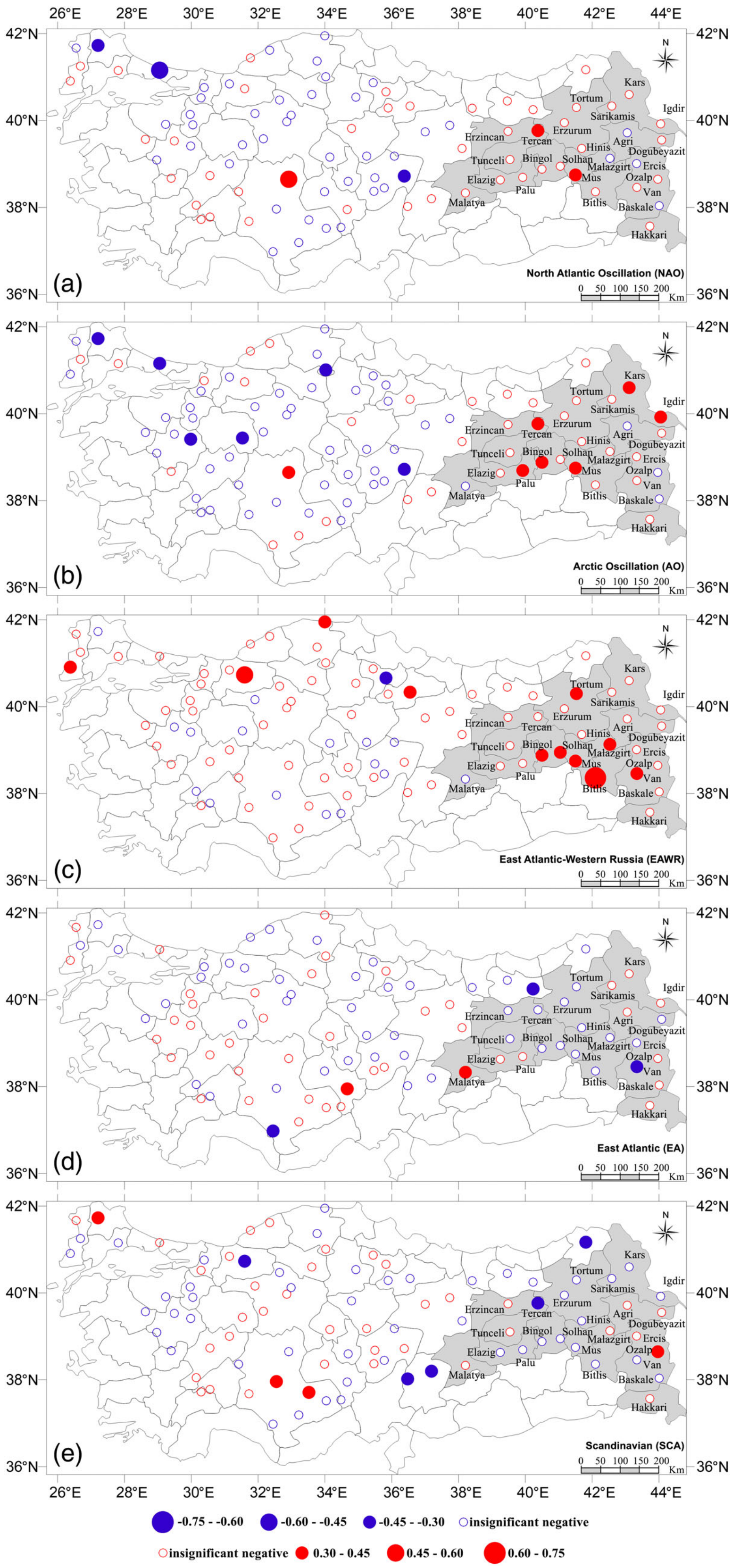

FIGURE 6 Correlation coefficients between extended winter (December to March) mean snow cover depth (SCD) and (a) North Atlantic Oscillation (NAO), (b) Arctic Oscillation (AO), (c) east Atlantic/western Russia (EA/WR), (d) east Atlantic (EA) and (e) Scandinavian (SCA) indices. The grey shaded area indicates the EAR with its station names

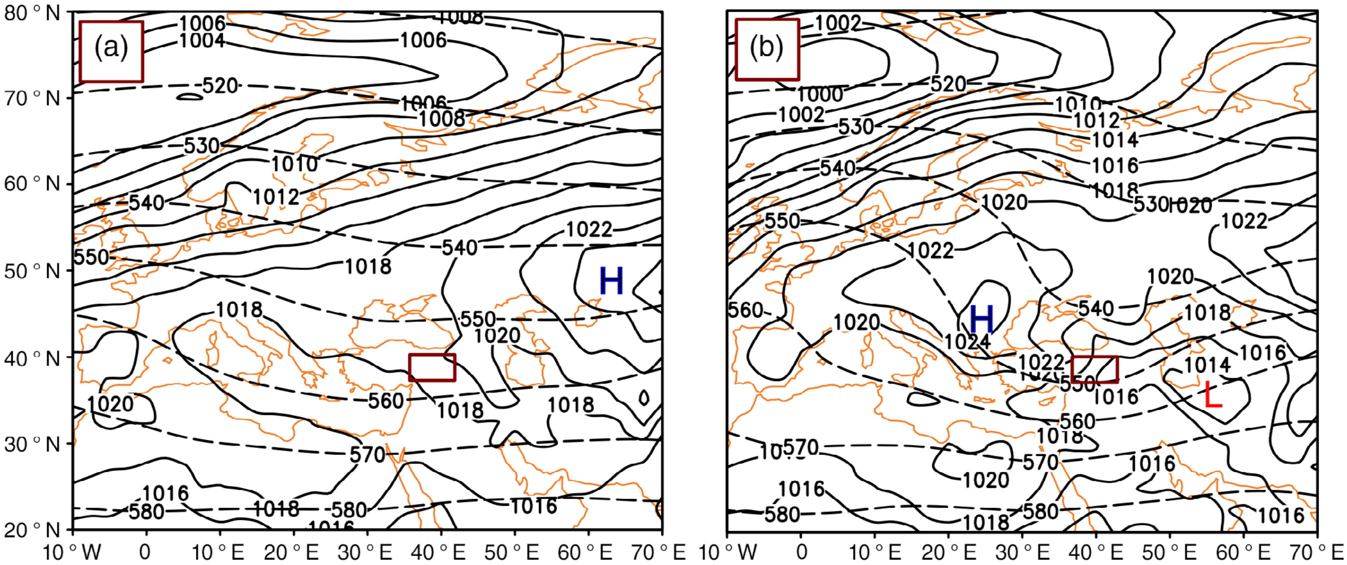

FIGURE 7 The composite maps of sea level pressure (black lines in hPa) and 500 hPa level (dashed lines in dkm) for (a) light snowfall (≤1 cm) and (b) heavy snowstorms (>5 cm) over the eastern Anatolia region (EAR) (brown rectangle) during the period 1967–2006. H and L marks indicate high and low pressure centres, respectively

3.4 | Synoptic evaluation of snowfall data over the EAR

Similar to Bednorz (2008), composite maps of sea level pressure and 500 hPa level for light (≤1 cm) and severe (>5 cm) snowfalls were extracted in order to get an idea about the weather conditions that are dominant during these cases and carry out a synoptic evaluation. During light snowfall events, the high pressure centre (HPC) over the Caspian Sea extends from its origin to the eastern areas of Turkey and prevents the penetration of cold polar air from Russia (Figure 7a). Clockwise (anticyclonic) flow of the HPC brings warm air from the Middle East by southeasterly winds. For the upper level, no cold cell is seen to determine the precipitation type due to the weak westerly flows over 5,550 m. During severe snowstorm events, as a result of the interaction between the HPC over Europe and the low pressure centre over the southern Caspian Sea, northnortheasterly flows at the surface bring cold polar air from Siberia (Figure 7b). In general, during winter months characterized by penetration of the Siberian HPC towards the Black Sea, air masses discharge their significant amount of moisture to the seaside and low altitude areas of the BSR, and consequently dry and cold air is transferred to the inland regions of Turkey. During this atmospheric condition, a strong pressure gradient force generates very strong winds that are responsible for the transfer of cold moist air, mainly originating from northeast Europe (Siberia), to the EAR in a very short time period and facilitates the formation of a low pressure system in the south of the Caspian Sea producing severe snowstorms and blizzards. In addition, the cold cell ahead of the trough axis at upper levels increases the depth of the daily new snow.

4 | CONCLUSION

In this study, linear regression and Mann–Kendall rank tests were used to investigate the long-term variability of the winter mean snowfall days (SDs) and snow cover depth (SCD) based on 93 meteorological stations and six regions. In addition, topographical variations in SDs and SCD and possible atmospheric circulation patterns and synoptic mechanisms causing snowfall events were investigated. The main results are summarized as follows.

Concerning the SDs, the highest winter mean snowfalls are observed in the eastern Anatolian region (EAR) and central Anatolia region (CAR) of Turkey. Temporal behaviours of SDs in these two regions indicate that, while weak positive trends are found in the CAR, statistically significant negative trends are observed in the eastern part of the Anatolian peninsula. On the other hand, the decreasing and increasing trends in SCD are more obvious in the CAR and EAR regions, respectively.

The inverse relationship between low SDs and high daily snow cover increases the intensity of daily new snow over the EAR and this condition is most obvious in the mid altitude stations. In addition to having high winter mean SCDs during positive EA/WR winters, light SDs occur due to the extension of a high pressure centre (HPC) over the Caspian Sea with weak westerly flows at upper levels, which cause inversion. On the other hand, the penetration of cold polar air to the region by strong northerly flows, due to the interaction between a Siberian HPC and a low pressure centre over the Caspian Sea, and the cold cell ahead of the trough axis enable severe snowstorm winter days to be seen (>5 cm).

The results from this study will help towards an understanding of the trends and variations of snowfall and will aid in forecasting seasonal snowfall totals. Enhanced predictions of snow events will allow better preparation for and adaptation to future seasonal snowfall totals.

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REFERENCES

Akyurek, Z. and Şorman, A.Ü. (2002) Monitoring snow-covered areas using NOAA-AVHRR data in the eastern part of Turkey. *Hydrological Sciences Journal*, 47(2), 243–252.

Aydın, A., Bühler, Y., Christen, M. and Gürer, I. (2014) Avalanche situation in Turkey and back calculation of selected events. *Natural Hazards and Earth System Sciences*, 14, 1145–1154.

Baltacı, H., Akkoyunlu, B.O. and Tayanç, M. (2018) Relationships between teleconnection patterns and Turkish climatic extremes. *Theoretical and Applied Climatology*, 134(3–4), 1365–1386.

Bednorz, E. (2002) Snow cover in western Poland and macro-scale circulation conditions. *International Journal of Climatology*, 22, 533–541.

Bednorz, E. (2004) Snow cover in eastern Europe in relation to temperature, precipitation and circulation. *International Journal of Climatology*, 24, 591–601.

Beniston, M. (2003) Climatic change in mountain regions: a review of possible impacts. *Climatic Change*, 59, 5–31.

Buisan, S.T., Saz, M.A. and Lopez-Moreno, J.I. (2015) Spatial and temporal variability of winter snow and precipitation days in the western and central Spanish Pyrenees. *International Journal of Climatology*, 35(2), 259–274.

Dye, D.G. (2002) Variability and trends in the annual snow-cover cycle in Northern Hemisphere land areas, 1972–2000. *Hydrological Processes*, 16, 3065–3077.

Erinç, S. (1984) *Climatology and its Methods*, 3rd edition. Güray Pres Inc.: Istanbul (in Turkish).

Esteban, P., Jones, P.D., Martin-Vide, J. and Mases, M. (2005) Atmospheric circulation patterns related to heavy snowfall days in Andorra, Pyrenees. *International Journal of Climatology*, 25, 319–329.

Ezber, Y., Sen, O.L., Kindap, T. and Karaca, M. (2007) Climatic effects of urbanization in Istanbul: a statistical and modeling analysis. *International Journal of Climatology*, 27, 667–679.

Falarz, M. (2004) Variability and trends in the duration and depth of snow cover in Poland in the 20th century. *International Journal of Climatology*, 24, 1713–1727.

Goossens, C. and Berger, A. (1986) Annual and seasonal climatic variations over the Northern Hemisphere and Europe during the last century. *Annales Geophysicae*, 4, 385–399.

Gürer, I., Tunçel, H., Yavaş, Ö.M., Erenbilge, T. and Sayın, A. (1995) Snow avalanche incidents in north-western Anatolia, Turkey during December 1992. *Natural Hazards*, 11, 1–16.

Karaca, M., Tayanç, M. and Toros, H. (1995) The effects of urbanization on climate of Istanbul and Ankara. *Atmospheric Environment*, 29(23), 3411–3421.

Kim, Y., Kim, K.-Y. and Kim, B.-M. (2013) Physical mechanisms of European winter snow cover variability and its relationship to the NAO. *Climate Dynamics*, 40, 1657–1669.

Kindap, T. (2010) A severe sea-effect snow episode over the city of Istanbul. *Natural Hazards*, 54, 707–723.

Kunkel, K.E., Palecki, M.A., Hubbard, K.G., Robinson, D.A., Redmond, K.T. and Easterling, D.R. (2007) Trend identification in twentieth-century U.S. snowfall: the challenges. *Journal of Atmospheric and Oceanic Technology*, 24, 64–73.

Laternser, M. and Schneebeli, M. (2003) Long-term snow climate trends of the Swiss Alps (1931–99). *International Journal of Climatology*, 23(7), 733–750.

Manley, G. (1958) On the frequency of snowfall in metropolitan England. *Quarterly Journal of the Royal Meteorological Society*, 84, 70–72.

Scherrer, S.C., Appenzeller, C. and Laternser, M. (2004) Trends in Swiss Alpine snow days: the role of local- and large-scale climate variability. *Geophysical Research Letters*, 31, L13215. https://doi.org/10.1029/2004GL020255.

Seager, R., Kushnir, Y., Nakamura, J., Ting, M. and Naik, N. (2010) Northern Hemisphere winter snow anomalies: ENSO, NAO and the winter of 2009/10. *Geophysical Research Letters*, 37, L14703. https://doi.org/10.1029/2010GL043830.

Serquet, G., Marty, C., Dulex, J.-P. and Rebetez, M. (2011) Seasonal trends and temperature dependence of the snowfall/precipitation-day ratio in Switzerland. *Geophysical Research Letters*, 38, L07703. https://doi.org/10.1029/2011GL046976.

Tayanç, M., İm, U., Doğruel, M. and Karaca, M. (2009) Climate change in Turkey for the last half century. *Climatic Change*, 94, 483–502.

Tayanç, M., Karaca, M. and Dalfes, H.N. (1998) March 1987 cyclone (blizzard) over the eastern Mediterranean and Balkan Region associated with blocking. *Monthly Weather Review*, 126, 3036–3047.

Tayanç, M., Karaca, M. and Yenigün, O. (1997) Annual and seasonal air temperature trends patterns of climate change and urbanization effects in relation with air pollutants in Turkey. *Journal of Geophysical Research*, 102(D2), 1909–1919.

Tekeli, E., Akyürek, Z., Şorman, A.A., Şensoy, A. and Şorman, A.Ü. (2005) Using MODIS snow cover maps in modeling snowmelt runoff process in the eastern part of Turkey. *Remote Sensing of Environment*, 97, 216–230.

Uhlmann, B., Goyette, S. and Beniston, M. (2009) Sensitivity analysis of snow patterns in Swiss ski resorts to shifts in temperature precipitation and humidity under condition of climate change. *International Journal of Climatology*, 29, 1048–1055.

Ünal, Y.S., Deniz, A., Toros, H. and Incecik, S. (2012) Temporal and spatial patterns of precipitation variability for annual, wet, and dry seasons in Turkey. *International Journal of Climatology*, 32, 392–405.

Vajda, A., Tuomenvirta, H., Juga, I., Nurmi, P., Jokinen, P. and Rauhala, J. (2014) Severe weather affecting European transport systems: the identification, classification and frequencies of events. *Natural Hazards*, 72, 169–188.

Vojtek, M., Fasko, P. and Stastny, P. (2003) Some selected snow climate trends in Slovakia with respect to altitude. *Acta Meteorologica Universitatis Comenianae*, 32, 17–27.

Ye, K. and Lau, N.-C. (2017) Influences of surface air temperature and atmospheric circulation on winter snow cover variability over Europe. *International Journal of Climatology*, 37, 2606–2619.

Yilmaz, Y., Sen, O.L. and Turuncoglu, U.U. (2019) Modeling the hydroclimatic effects of local land use and land cover changes on the water budget in the upper Euphrates–Tigris basin. *Journal of Hydrology*, 576, 596–609.

Zhou, W., Chan, J.C.L., Chen, W., Ling, J., Pinto, J.G. and Shao, Y. (2009) Synoptic-scale controls of persistent low temperature and icy weather over southern China in January 2008. *Monthly Weather Review*, 137, 3978–3991.

Zhu, L. and Chen, H. (2019) Possible connection between anomalous activity of Scandinavian Atmospheric Teleconnection Pattern and winter snowfall in the Yangtze-Huaihe River Basin of China. *Atmospheric and Oceanic Science Letters*, 12(3), 218–225.

How to cite this article: Baltaci H, Arslan H, Akkoyunlu BO, Gomes HB. Long-term variability and trends of extended winter snowfall in Turkey and the role of teleconnection patterns. *Meteorol Appl*. 2020;27:e1891. https://doi.org/10.1002/met.1891