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Climate change impacts on snowmelt runoff for mountainous transboundary basins in eastern Turkey

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ABSTRACT: This study investigates whether snowmelt runoff for the selected 15 streamflow stations located in the Euphrates, Tigris, Aras, and Çoruh basins in eastern Anatolia, Turkey, has shown a consistent hydrologic response to global climatic changes over the past several decades. It also investigates the future runoff changes in these basins. The analysis utilizes streamflow and meteorological data from 1970 to 2010 available within the study area to identify spatial and temporal patterns of trends in the seasonality of streamflow, temperature, and precipitation. Results indicate significant temperature increases (average 1.3 °C across the stations) over the time period. They also indicate increases in annual precipitation (average 7.5% across the stations) but the increases are not significant, in general. The streamflow timings in the mountainous basins are found to have already shifted to earlier days in the year (9 days on average), and this is a clear indication of earlier spring melting of snowpack due to increasing temperatures in recent years. Eight among fifteen stream gauging stations in the basins show significant time shifts in snowmelt runoff according to statistical trend tests (based on 90% confidence level). A regional climate change simulation based on a high emissions scenario suggests 10–30% declines in the annual surface runoffs of Aras, Euphrates, and Tigris basins and a slight increase (about 4%) in the annual surface runoff of Coruh basin by the end of the present century. It further indicates that the timing of the peak flows will continue to shift earlier (by about 4 weeks over the century) in response to further warming, increasing the fraction of winter runoff while decreasing the fraction of spring runoff in the year in all these basins.

KEY WORDS Climate change; snowmelt runoff; warming; temporal shift; trend; climate projection; model; temperature

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1. Introduction

The mountainous region of eastern Anatolia, Turkey, occupies the basins supporting potentially the 31% of the total surface runoff of the country that is equivalent to water amount of 193 billion m^3 year^{-1} (DSI, 2009). This volume of water is largely reached by surface runoff from the Euphrates and Tigris Rivers originating from this region. Snowmelt runoff during spring and early summer usually constitutes 60–70% of the total annual runoff in these two snowmelt-dominated river basins (Sorman, 2004). Projected hydrologic variables are critically important in operation and management of water resources especially in the downstream water stressed semi-arid regions. The natural release of water from snowpack in conjunction with wise management of several man-made reservoirs in these regions therefore plays a critical role in handling sustainable water resource projects under the influence of climate change and variability.

As the climate is the main factor affecting all elements of hydrological cycle, but particularly with precipitation and streamflow, the changes and variability in climate directly affect the quantity of water resources. Observed global warming over several decades has been linked to changes in the large-scale hydrological cycle such as, increasing atmospheric water vapour content; changing precipitation patterns, intensity and extremes; reduced snow cover and widespread melting of ice; and changes in soil moisture and runoff, according to the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2007). Observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems. According to the fourth report of IPCC (IPCC, 2007) many studies have shown significant trends in streamflow, which demonstrates statistically significant links with trends in precipitation or temperature. In various regions of the world, the interannual variations in streamflow have been found to be more strongly related to precipitation changes than to temperature changes. On the other hand, in most parts of eastern Europe, a major shift in streamflow from spring to winter has been associated not only with a change in precipitation totals but more particularly with a rise in temperatures; in other words, precipitation has fallen as rain, rather than snow, and therefore has reached rivers more rapidly than before (e.g. Arnell, 1999).

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There are a number of other studies available in the literature (e.g. Bou-Zeid and El Fadel, 2002; Chen *et al.*, 2007; Loukas *et al.*, 2007) dealing with the effects of climate change on hydrologic variables across various geographical locations of the world. These studies highlighted the significant increase in temperature and an upward trend in precipitation shortage during the past several decades and pointed out the potential of further exacerbation of existing water shortages in various basins. Mizyed (2009) evaluated the impacts of climate change scenarios on agricultural water demand in the West Bank in the eastern Mediterranean region. This study reports that the future increases in temperatures could potentially augment agricultural water demand by up to 17% and lead to reductions in annual groundwater recharge by up to 21%. Among the studies that focused on climate change impact on water resources in Turkey, Fujihara *et al.* (2007) indicated a considerable decrease in future streamflow with occurrence of the peak monthly flow earlier than that at present as a result of estimated decreases in precipitation in the Seyhan river basin located in southern Turkey, while Sen *et al.* (2011) showed significant shifts in snowmelt runoff times to earlier times with the analysis of seven streamflow stations from Euphrates and Tigris basins. The latter concluded that the increases in temperature, whether they are due to climate change and/or changes in North Sea – Caspian Pattern (NCP), cause the shifts in the timing of springtime snowmelt towards earlier times.

Changes in snowmelt-derived streamflow timing are of considerable concern in semi-arid regions of Mediterranean basins where water supplies are under stress. Because the mountain snowpack serves as a natural reservoir for cold-season precipitation storage and releasing its water during the spring months to the rivers, understanding the processes of snowmelt timing and streamflow is key to managing water resources, and questions about the hydrologic impacts of climate variability and change are of particularly great importance in the regional mountain water supply systems (Stewart, 2009). As documented by Stewart *et al.* (2004), in the western United States, a region with very high urban and agricultural water demands, spring/early summer snowmelt runoff accounts for 50–80% of the total annual runoff for snowmelt-dominated basins. Similarly, runoff from snowmelt-dominated basins in the mountainous and semi-arid regions of eastern Turkey accounts for 60–70% of the total annual runoff for the region (DSI, 2009). For this reason, understanding the factors and estimating the timing and the quantity of stream flow due to snowmelt in Euphrates and Tigris basins, where large reservoirs are located, is crucial for effective management of water resources.

In this study, the aim is to explore regional climate change in the eastern Anatolia, to demonstrate the relation between climate change and variability of hydrological process response via changes in mass and timing of snowmelt runoff, and to understand the current and projected values of climate change impacts on the hydrological processes. The present study could be considered as a continuation study of Sen *et al.* (2011). It includes more data coverage (both spatially and temporally), different methodology in analysing the historical changes in regional hydroclimatic parameters, and an analysis of future runoff projections for the region. In the analyses, 15 stream gauging stations from General Directorate of State Hydraulic Works (GDSHW) located in the Euphrates, Tigris, Aras, and Çoruh basins are considered for daily streamflow for the period of 1970–2010, while 10 meteorological stations from General Directorate of Meteorology (GDM) are used for temperature (daily maximum, minimum, and average) and daily precipitation data for the same time period. The long-term trends of the temperature, streamflow, and precipitation data are identified by nonparametric trend analysis methods, and the interrelation between these variables is analysed. It is envisaged that the results of this study can offer decisional references for the water resource managers of the Euphrates, Tigris, Çoruh, and Aras river basins.

2. Study area and data

The study region is characterized by a high and mountainous topography (Figure 1). Elevation usually exceeds 2000 m. The North Anatolia and Caucasus Mountains in the north and Taurus Mountains in the south hold the rain clouds, and therefore the study area is under the influence of the continental climate with long and very cold winter, and frequent heavy snowfall which remains on the ground from November until the end of April (the average temperature is −13 °C for winter and 17 °C for summer). Because of its high elevation, ratio of precipitation falling as snow *versus* rain is higher than that in the other regions of Turkey.

The study area hosts some hydropower development projects including the Southeastern Anatolia Project, aiming to produce energy and to irrigate large semi-arid plains to the south of the region through a number of hydropower systems and dams. Streamflow measurements located downstream of large dams are all excluded in this study so that the selected streamflow gauging stations are not regulated by large storage reservoirs. Watersheds with small reservoirs whose effect is less than 10% on the downstream streamflow are assumed to be unregulated (Kahya and Karabörk, 2001). In the selection of streamflow stations in the region, the length of the records and the continuous nature of the data are also considered. After filtering the data for study area, length and quality, 15 streamflow stations from Euphrates, Tigris, Çoruh, and Aras basins remain for the analysis. All these stations have almost 40-year continuous daily measurements between 1970 and 2010, which enable us to detect possible trends in streamflow data. Table 1 provides information about the identification number, name, record length, and elevation of the selected streamflow stations. These 15 stations are distributed as 8, 3, 2, and 2 to the Euphrates, Tigris, Çoruh, and Aras basins, respectively. In addition, daily air temperature and precipitation data

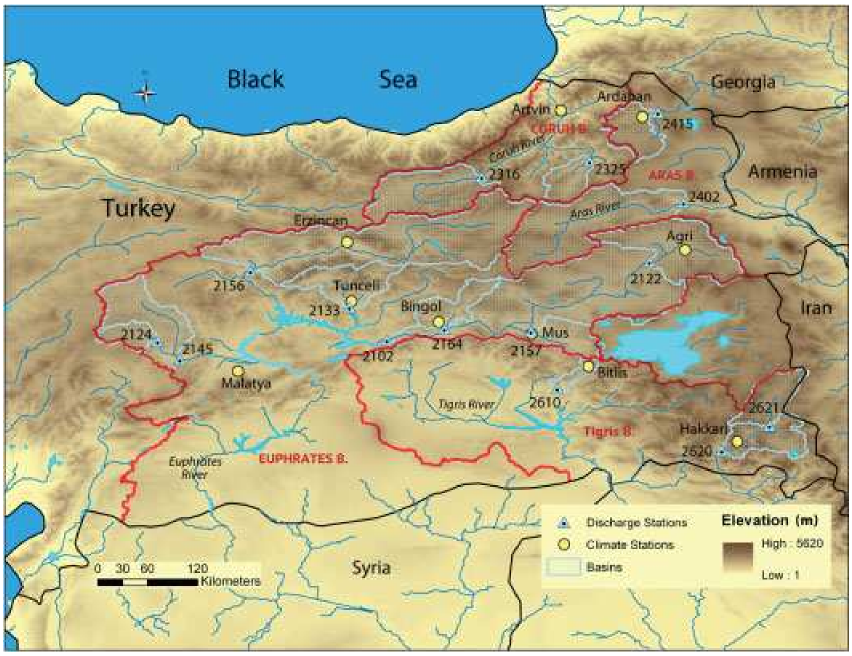

Figure 1. Map of eastern Anatolia of Turkey showing the locations of 15 streamflow stations (triangles with a dot) with their sub-basins (dotted areas) and river network and ten meteorological stations (circles). Thick lines denote the four large basins in the region. Background shows the topography of the region.

Table 1. Selected streamflow stations and their relevant information.

Number	Station name	Data period	Elevation (m)
Euphrates Basin			
2102	Palu	1936–2010	852
2122	Tutak	1953–2010	1552
2124	Yazıköy	1954–2010	1193
2133	Melekbahçe	1953–2009	875
2145	Hisarcık	1962–2010	933
2156	Bağıştaş	1968–2010	865
2157	Karaköprü	1968–2007	1250
2164	Çayağzı	1968–2010	990
Tigris Basin			
2610	Baykan	1954–2010	698
2620	Üzümcü	1968–2010	1072
2621	Musahan	1968–2010	1725
Çoruh Basin			
2316	İspir Köp.	1964–2010	1170
2325	Aşağı Kumlu	1973–2010	1129
Aras Basin			
2402	Kağızman	1953–2010	1140
2415	Ur Köp.	1969–2010	1750

Table 2. Selected meteorological stations and their relevant information.

Number	Station name	Data period	Elevation (m)
1	MALATYA	1970–2010	947
2	BİNGÖL	1970–2010	1177
3	TUNCELİ	1970–2010	981
4	MUŞ	1970–2010	1322
5	AĞRI	1970–2010	1632
6	ERZİNCAN	1970–2010	1218
7	BİTLİS	1970–2010	1573
8	HAKKARİ	1970–2010	1727
9	ARDAHAN	1970–2010	1829
10	ARTVİN	1970–2010	628

are obtained from GDM for ten sites in (or near) these basins. Details of these stations such as the identification number, name, record length, and elevation are provided in Table 2. Meteorological stations are usually located in or nearby urban areas owing to the energy requirements or maintenance accessibility. The locations of these stations as well as streamflow measurement sites, sub-basins, and stream network are shown in Figure 1.

GDSHW and GDM follow the basic principles of the data quality control introduced by the World Meteorological Organization (WMO). Information about such quality control methods applied to data can be found in Sönmez (2013) and Gokturk *et al.* (2008). The additional data quality analysis performed in the present study revealed that the streamflow values for the year 1989 amounted to an outlier for all stations, with a relatively warm winter and dry water year (Cullen and deMenocal, 2000; Sen *et al.*, 2011). For this reason, for each station the outlier is replaced with the average value of the whole period (i.e. 1970–2010).

3. Methodology

In order to detect the changes in the streamflow timing, researchers have used different measures, such as 'spring pulse onset' that defines the date when snowmelt-derived streamflow begins to make the major 'climb up' in spring or early summer (Cayan *et al.*, 2001), and 'centre time' (CT) that defines the date that marks the timing of the centre of mass of annual flow (Stewart *et al.*, 2005), or the date when half of the flow for each water year has occurred (Sen *et al.*, 2011). In CT estimation for a station, first the half of the total streamflow for the water year is calculated, and then, the date when the cumulative flow (starting from the beginning of the water year, i.e. 1st of October) exceeds this quantity is identified as CT. In this study, we adopted CT as the measure to detect any shifts in streamflow timing. CT was estimated from daily streamflow measurements for every year from 1970 to 2010 for all measurement sites. In addition to CT methodology, we provide the number of days having daily average temperature below freezing point and the number of wet days below freezing point from 1 October to CT of the corresponding year for each streamflow gauging station in order to support the finding that the shifts in CTs are related primarily to the changes in the timing of snowmelt. Streamflow stations are paired with meteorological stations that are near or within the basin of interested stream gauging station to prepare these analyses. Precipitating days (days with more than 0.1 mm of precipitation) from paired meteorological station are counted from 1 October to CT of the corresponding year to find number of wet days for each streamflow station.

Meteorological variables (daily mean, maximum, minimum temperature, and precipitation), streamflow and CT values for the study period are investigated by nonparametric trend tests of Mann–Kendall (Hirsch and Slack, 1984) and Spearman's rho (Caruso and Cliff, 1997) to determine if their values are changing over the time and to calculate the amount or rate of that change. Missing data years for stream gauging stations (2010 at 2133 and 1970, 1971, and 1972 at 2325) are filled with the fitted linear trend lines. Nonparametric tests or distribution free tests for trends are considered to be appropriate because streamflow and precipitation data are usually not normally distributed (Gebert and Krug, 1996). These tests are used successfully in many studies (e.g. Gebert and Krug, 1996; Yue *et al.*, 2002; Kahya and Kalayci, 2004) to identify the trends in the streamflow and precipitation data. In this study, 90% confidence level, a measure of confidence in rejecting the null hypothesis, is used. The corresponding (Z-critical) standard deviation for 90% confidence level is 1.65.

The future changes in the climate of Turkey have been addressed in a few studies (e.g. Önol and Semazzi, 2009; Önol *et al.*, 2013). These studies suggest substantial future precipitation reductions in the southern basins of Turkey, including Euphrates and Tigris, which could result in significant reductions in the surface runoff. Indeed, a study by Bozkurt and Sen (2013) indicates that not only the surface runoff in the headwaters of the Euphrates basin will decrease but also its peak flows will shift to earlier days. The magnitude of the changes depends on the emissions scenarios used in the modelling. Here we would like to include an analysis of the future temporal changes in the surface runoff of the four main basins considered in this study using one of the high emissions scenario (A2) simulations in Önol *et al.* (2013) that is expected to give the upper bounds of the possible changes in these basins. The emission scenario was simulated by the general circulation model (GCM), ECHAM5, which is developed and maintained by Max Planck Institute, Germany. The outputs of ECHAM5 were downscaled using the regional climate model, RegCM3, of International Centre for Theoretical Physics, Italy. The final resolution of the surface outputs is 27 km. The reference period is the 30 years between 1961 and 1990, and the future period covers the 30 years between 2070 and 2099. Further information about the performance of the reference term simulation could be found in Bozkurt *et al.* (2012), and the detailed information about the future simulation could be found in Önol *et al.* (2013).

RegCM3 includes the Biosphere-Atmosphere Transfer Scheme (BATS; Dickinson *et al.*, 1993) to simulate surface processes involving energy and water balance. Therefore, a simulation with RegCM3 provides many surface parameters such as shortwave and longwave components of radiation, fluxes (latent and sensible), soil, foliage and air temperatures, evapotranspiration, soil moisture, runoff, etc. The present study uses basin averages of the grid-based runoff (not routed to basin outlet) as the model outputs. Because it aims to explore the changes in runoff amount and timing in the present century, a subsequent routing experiment with a hydrological model is deemed unnecessary, as it would not affect the bulk results.

4. Results

4.1. Analyses

4.1.1. Temperature

Reductions in snow cover and temporal shifts in snowmelt timing could be attributable to rises in temperature. Therefore, annual averaged daily time series of temperature are first analysed to assess whether a regional warming at study basins in the eastern Anatolia is observable. Figure 2(a) and (b) shows box plots for annual means of daily maximum and minimum temperatures from ten meteorological stations, and Figure 2(c) illustrates the annual values of daily mean temperatures (from the same stations) averaged for the snow accumulation period from November to February. All three temperature parameters show some degree of inter-station variability. Minimum temperature exhibits the lowest variability (smaller boxes) for the ten meteorological stations, and this behaviour is more obvious after the year 1990. The average temperature values for the snow accumulation period (Figure 2(c)) demonstrate more pronounced year-to-year variability than the annual mean minimum and maximum temperatures. The box plots do not show clear monotonous warming trends for none of the parameters. Nevertheless, they indicate that the second half of the period is usually warmer than the first half for these parameters. This is particularly more observable in minimum air temperature, which is primarily a function of large-scale atmospheric

Table 3. Results of statistical trend analyses applied to daily average temperature of meteorological stations.

Station	Mann–Kendall	Trend	Spearman's rho	Trend
AGRI	2.75	(+)	2.62	(+)
ARDAHAN	2.64	(+)	2.66	(+)
ARTVIN	2.48	(+)	2.53	(+)
BINGOL	0.17		0.17	
BITLIS	2.26	(+)	2.14	(+)
ERZINCAN	3.79	(+)	3.64	(+)
HAKKARI	2.41	(+)	2.5	(+)
MALATYA	3.63	(+)	3.46	(+)
MUS	2.75	(+)	2.72	(+)
TUNCELI	2.19	(+)	2.12	(+)

The confidence level is 90%.

circulation (Figure 2(b); median values stay mostly above 5 °C constant line after the year 1989).

The behaviour of each individual temperature record is also investigated with their fitted linear trend lines from 1970 to 2010. It should be noted, however, that the observed changes in temperature (and other variables) might be understated, as they were calculated from linear trends. Figure 3 shows the results of changes in maximum, minimum, and daily average temperatures as well as changes in daily average temperature during accumulation (November to February) and melting (March to June) periods according to fitted linear trend lines. Temperatures of all stations increase in various magnitudes during the 40-year period. Amongst the network means, the highest increase occurs in the accumulation period temperature (1.69 °C). In addition, the increase in minimum temperature (1.45 °C) is higher than the increases in the average and maximum temperatures (1.30 and 1.37 °C, respectively). It could be argued that these increases, especially the warming in the accumulation period, might have affected the form of precipitation, changing it from snow to rain, which could reduce the snowpack amount.

Significance of trends in temperature increases is determined using Mann–Kendall and Spearman's rho tests. Each station dataset is taken into account separately. Table 3 summarizes the results of trend analyses of these two methods applied to daily average temperatures considering a 90% confidence level corresponding to 1.65 threshold value. Both tests consistently show statistically significant positive trends in temperature for all stations except Bingol, the highest values being obtained for Erzincan and Malatya stations. These results, which are based on two different testing methodologies, provide a strong evidence of regional warming in the eastern Anatolia.

4.1.2. Precipitation

Increase in air temperature can affect precipitation and water cycle because it leads to increases in atmospheric water vapour that may result in more intense precipitation events even when the total annual precipitation does not change. As reported by Trenberth *et al.* (2007) and IPCC (2007), the percentage contribution of very wet days to total annual precipitation has increased during last 50 years, even in places where mean precipitation amounts are not increasing. Using observations from ten meteorological stations changes in precipitation are also investigated for the study area. Figure 4 shows box plots of annual precipitation of the stations for each year from 1970 to 2010. Precipitation variability among stations through years and within a year is quite high as the precipitation amount is sensitive to topography (orographic precipitation) and weather systems (frontal precipitation through extra-tropical cyclones) in this region. However, there is no discernible trend in total annual precipitation in the region during the 40-year period.

Figure 5 shows the percentage changes in total precipitation during accumulation and melting periods, and in annual daily averaged precipitation. The network mean of annual daily average precipitation increases slightly (7.5%) from 1970 to 2010. However, the rate of increase in winter precipitation (14.3%) is almost twice as much as that of annual daily mean precipitation. Unlike winter and annual changes, spring precipitation shows a slight decreasing trend (−5.2%). Stations 1, 5, and 7 indicate some negative trends for annual daily mean precipitation, while other stations show either no trend or slight positive trend. Decreasing trends in stations 5 (Agri) and 7 (Bitlis) are likely caused by precipitation decreases in winter period (−28.2 and −7.4%, respectively), while the decreasing trend in Station 1 (Malatya) could be attributed to precipitation decrease in melting period (−46.3%). It is the winter period that has the highest increase both in temperature (+1.69 °C) and in precipitation (14.3%). Evidence suggests that milder winters have yielded higher annual precipitation totals in the region. In addition, precipitation does not show a coherent signal of change in the region but it does show intra-annual changes.

Both trend tests applied to total precipitation of accumulation period do not yield any significant trend for the stations except for Agri with a meaningful negative trend and Ardahan with a very strong positive trend (Table 4). Because annual total precipitation does not show noticeable changes (see Figure 5), statistical trend testing methods are not applied to this parameter. However, annual precipitation change at Ardahan is also statistically significant because this station shows a very high increasing rate both in accumulation (+63.3%) and in melting (+43.4%) periods. It is noted that, in general, precipitation changes are not significant in the region while temperature increases are meaningful. This situation may cause changes in the type of precipitation, i.e. from snow to rain, which may have important hydrologic implications for the region.

4.1.3. Streamflow

The impact of global warming on streamflow is commonly assessed via changes in snowmelt amount and timing for snowmelt-dominated basins. Sen *et al.* (2011) suggests that the recent warming period in Turkey starts after the year 1990. Thus, they compared a period after 1990

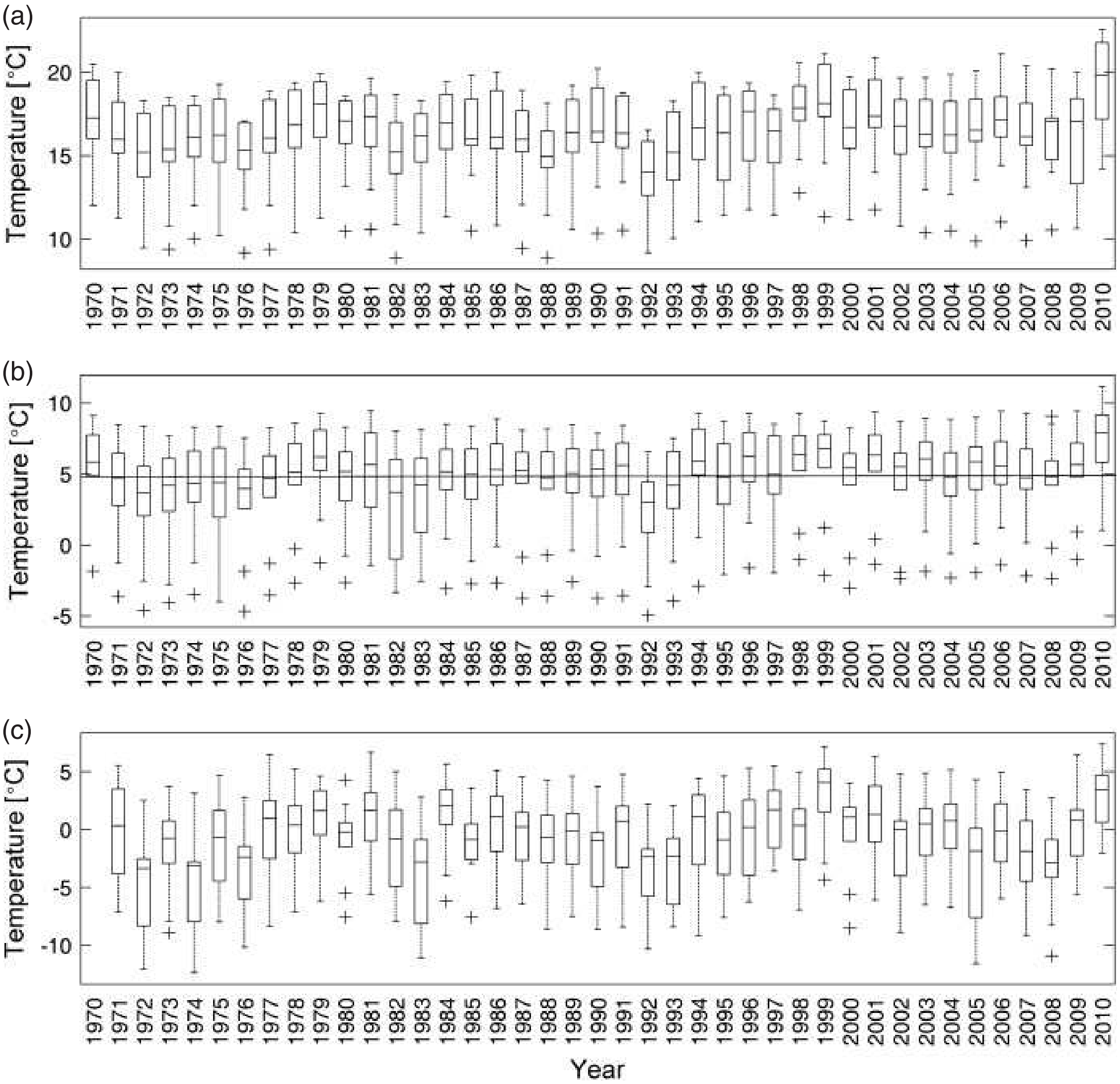

Figure 2. Box plots of ten meteorological stations for each year from 1970 to 2010 for annual averaged daily maximum temperature (a), daily minimum temperature (b), and daily averaged temperature for accumulation period (c). On each box, the central mark is the median; the lower and upper edges of the box are the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and outliers are shown as plus signs. The whisker length is 1.5 as default value.

Table 4. Results of statistical trend analyses applied to the total precipitation of accumulation period at meteorological stations.

Station	Mann–Kendall	Trend	Spearman's rho	Trend
AGRI	−1.85	(−)	−2.23	(−)
ARDAHAN	3.16	(+)	3.25	(+)
ARTVIN	0.99		0.87	
BINGOL	0.90		0.93	
BITLIS	−0.15		−0.14	
ERZINCAN	1.32		1.40	
HAKKARI	0.71		0.80	
MALATYA	0.34		0.40	
MUS	1.46		1.49	
TUNCELI	1.60		1.44	

The confidence level is 90%.

with a period before 1990 to determine the changes in the discharges. The comparison produced higher discharges for March (beginning of melting period) and lower discharges for May (ending of melting period), which clearly indicated a shift in the timing of the peak discharges. However, this method does not provide actual changes in the discharges from beginning to end of the whole period. In the present study, instead of dividing the whole period into two parts to detect the changes in streamflow, as in Sen *et al.* (2011), we adopted the same analysis as in temperature and precipitation given above. Figure 6 shows box plots of annual averaged daily streamflow of 15 gauging stations for each year from 1970 to 2010. Spatial variability of discharge values within a year is generally small, and the boxes usually exhibit similar size throughout the study period. The least spatial variability is observed in the years 2000 and 2001. Drought conditions may exist throughout the region as total annual precipitation of 2001 indicates the lowest median value during 1970–2010 period (Figure 4). Overall, the average daily streamflows

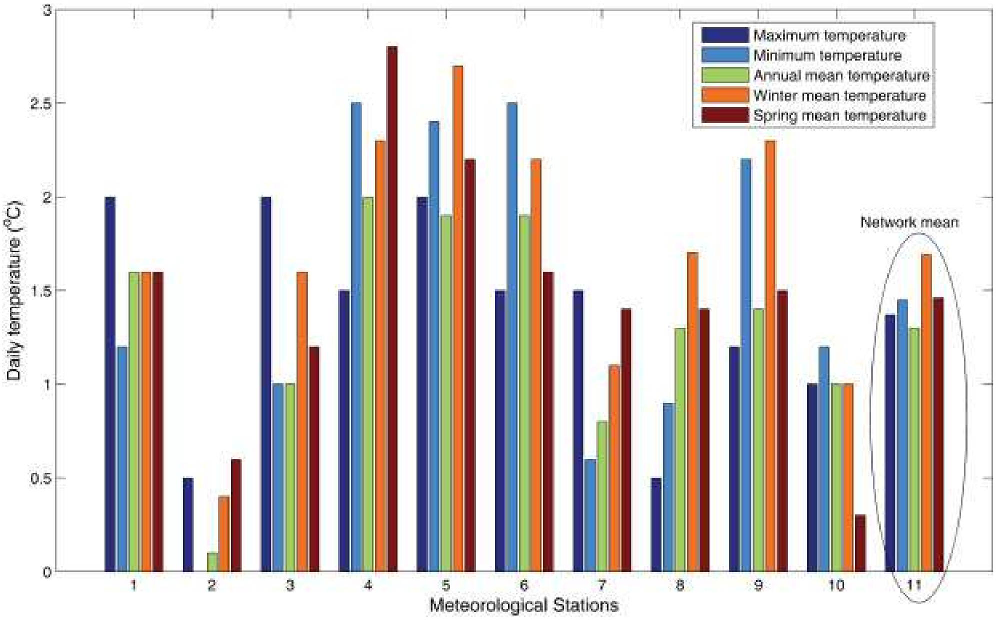

Figure 3. Changes in temperatures of meteorological stations according to fitted linear trend lines between 1970 and 2010. Changes are considered for daily maximum, minimum, and average temperatures during annual cycle as well as daily average temperatures during accumulation and melting periods.

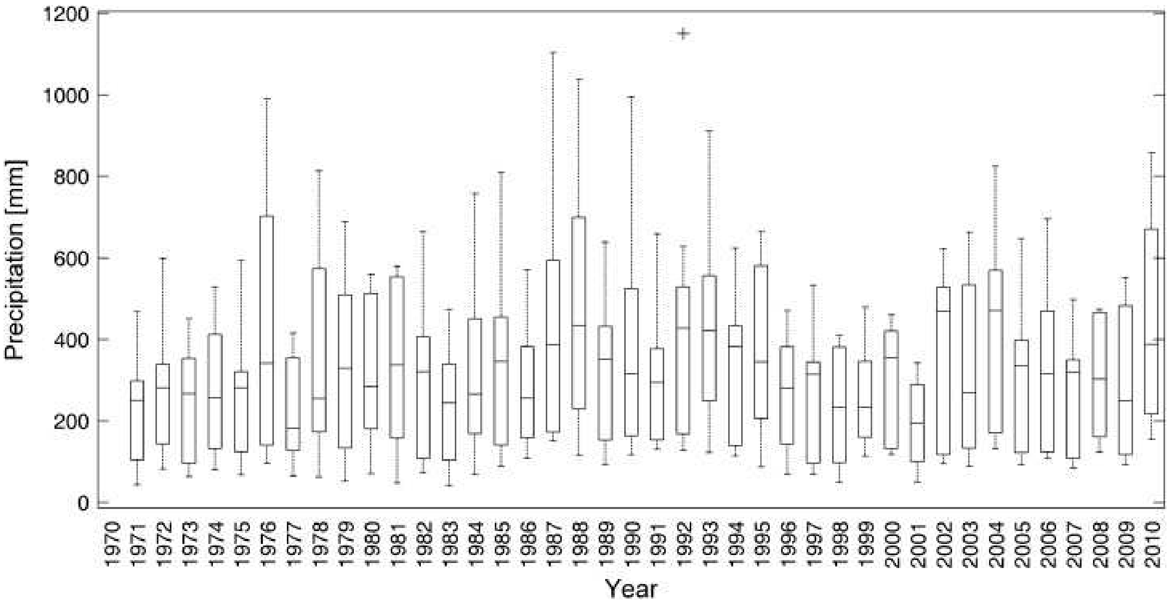

Figure 4. Box plots of total annual precipitation of ten stations for each year from 1970 to 2010.

of the sub-basins in the Euphrates basin together show 3.3% increase, in the Tigris basin 8.5% decrease, in the Çoruh basin 22.9% increase, and in the Aras basin 23.7% increase. Trend analysis tests are applied to annual discharge values, and their results are given in Table 5. Among 15 stations both testing methodology yields significant trends for only three stream gauging stations (2124, 2145, and 2316). Meaningful trends are also obtained for these stations when both trend tests are applied to discharge values for melting period. Stations 2124 and 2145 give a highly amplified decreasing trend (−3.74), while Station 2316 reveals an important increasing trend (+2.17) at 90% confidence level. As mentioned earlier, the observations in Malatya meteorological station, which is close to the basin of the former two gauging stations (2124 and 2145), show substantial decrease in spring precipitation (−46.3%), and this change is probably the reason for the strong decreasing trend in their discharges. On the other hand, significant positive trend at 2316 stream gauging station could be attributed to increasing winter and spring precipitation rates in the basin as indicated by Artvin meteorological station.

In order to better interpret the impact of existing global warming on snowmelt runoff, the CT analysis that helps

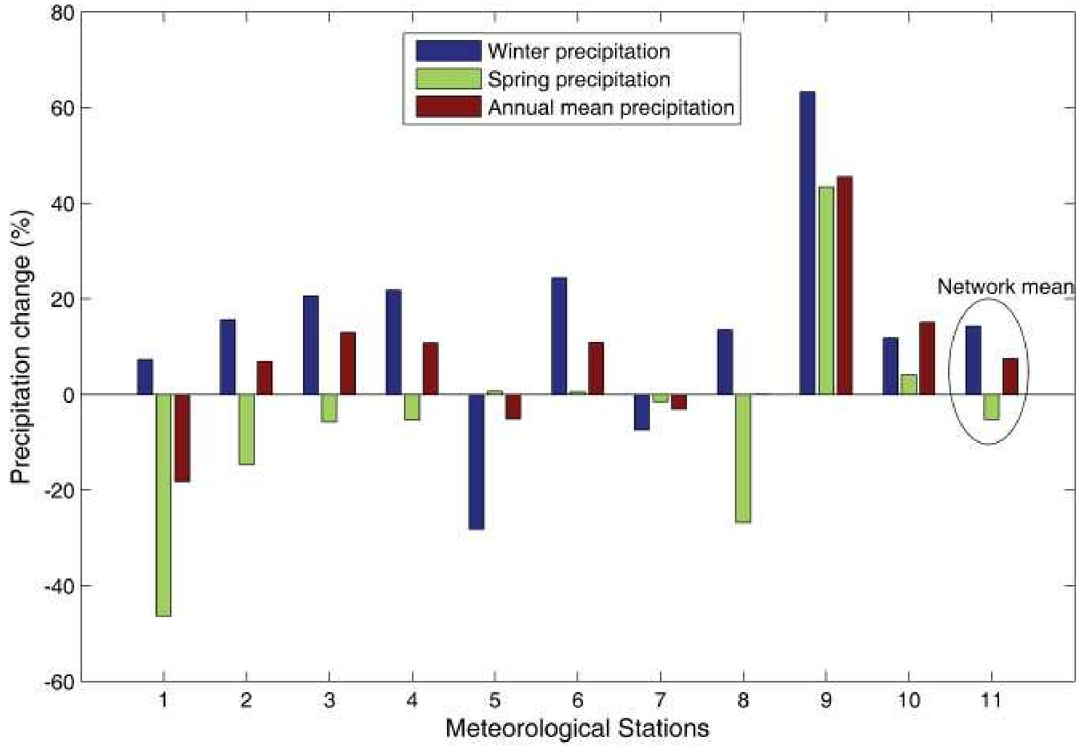

Figure 5. The percent precipitation changes of meteorological stations according to the fitted linear trend lines between 1970 and 2010 are shown for the accumulation, melting, and annual periods.

identify possible temporal shifts in snowmelt timing is performed. Box plots of calculated CT of 15 stream gauging stations for each year from 1970 to 2010 are shown in Figure 7. They indicate a decreasing tendency, especially during the second half of the period. For example, the median CT values are mostly below the constant line of 200 (corresponding to April 18) for that period, while they are consistently above the line for the years prior to 1989. Decreasing tendency in CT values is examined according to the fitted linear trend lines for each station, and the results are given in Table 6. Regardless of any changes in discharges – overall, the discharge changes are not significant in the region – CT values decrease with time at all stations. The range of decrease over the

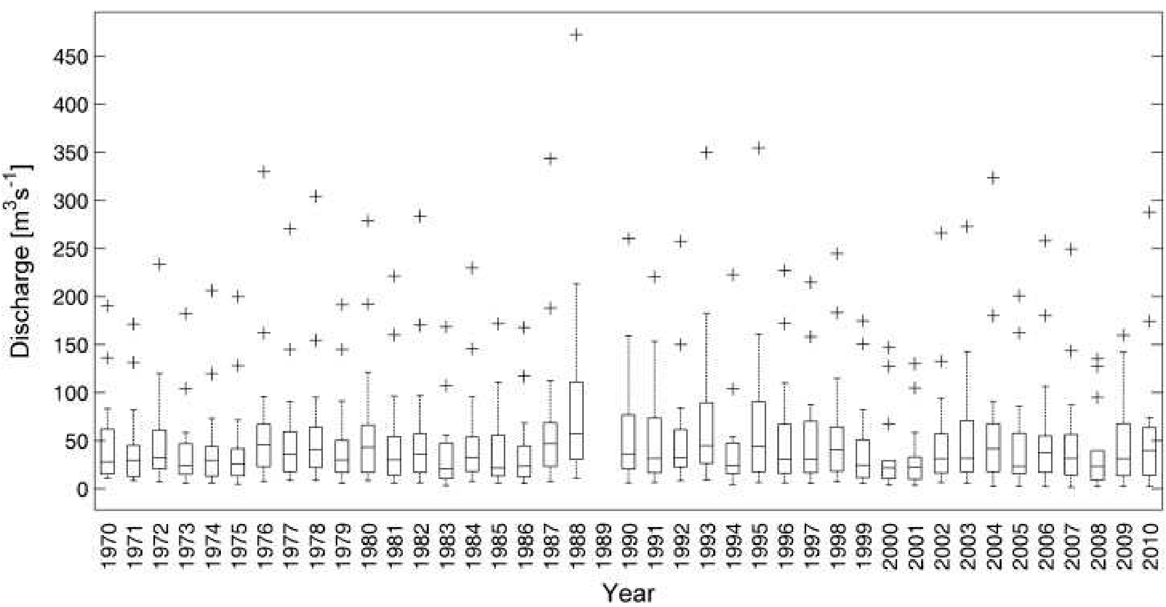

Figure 6. Box plots of annual averaged daily streamflow of 15 gauging stations for each year from 1970 to 2010.

Table 5. Results of statistical trend analyses applied to the annual average streamflow data.

Station	Mann–Kendall	Trend	Spearman's rho	Trend
2102	0.1		0.11	
2122	0.78		0.97	
2124	−3.74	(−)	−3.61	(−)
2133	1.41		1.33	
2145	−3.74	(−)	−3.59	(−)
2156	1.58		1.65	(+)
2157	0.80		0.65	
2164	0.62		0.65	
2610	0.33		0.39	
2620	−1.70	(−)	−1.25	
2621	0.64		0.03	
2316	2.17	(+)	1.98	(+)
2325	0.80		0.96	
2402	1.70	(+)	0.82	
2415	0.10		1.03	

The confidence level is 90%.

whole period varies from 2 to 19 days in the region, and if the stations with significant discharge changes (2124, 2145, and 2316) are excluded, then the average shift for the region is about 7 days. If all stations are considered, the average shift amounts to 9 days. These numbers are consistent with those reported in other studies (e.g. Stewart, 2009).

The results of significance test of the CT shifts are given in Table 6, and regardless of significance level, almost all stations show negative trend, which means shifts to earlier times. Furthermore, at least one of the two applied statistical methods produces significant CT shifts for 8 of the 15 stations. As stated by Stewart (2009), detecting statistically significant changes in snowmelt-derived streamflow timing is a complicated problem because of the complexities of the response and of both temperature and precipitation changes and high variability on different timescales. Such complexities might have resulted in not having statistically significant CT shifts at more stations in the present study.

4.1.4. *Combined analysis of streamflow, temperature, and precipitation*

There is some indication that the combined effects of temperature and precipitation changes could increase the monthly maximum flows and thus increase the frequency and severity of flooding events (Falloon and Betts, 2006). Trenberth *et al.* (2007) report that the rainfall decrease is often attributable to a reduction in the number of rainy days rather than the intensity of rain when it occurs. Meteorological stations that are near the basin of stream gauging stations are paired with corresponding streamflow stations to analyse the combined effects of hydroclimatic variables. Table 7 lists the station pairs, in which each stream gauging station is paired with a meteorological station (see the locations of paired stations in Figure 1). Using daily average temperatures of meteorological stations, the days with average temperature smaller than 0 °C are counted from 1 October to CT of each year for paired stations. Furthermore, precipitation data are introduced to this analysis to determine the number of wet days, which implicitly describes the number of snowy days at the same station pairs. These calculated area-averaged analyses, namely 'number of days below freezing' and 'number of wet days below freezing', are shown from 1970 to 2010 in Figure 8. In this figure, the variable is shown with deviation from the mean of entire time series.

Both the number of days below freezing and the number of snowy days clearly show a decreasing trend during the study period. Concurrent warming with the amplification of temperature in the region is responsible for the decrease in the number of days with daily average temperature below freezing, which implies more snowmelt before CT causing temporal shifts in snowmelt runoff to earlier

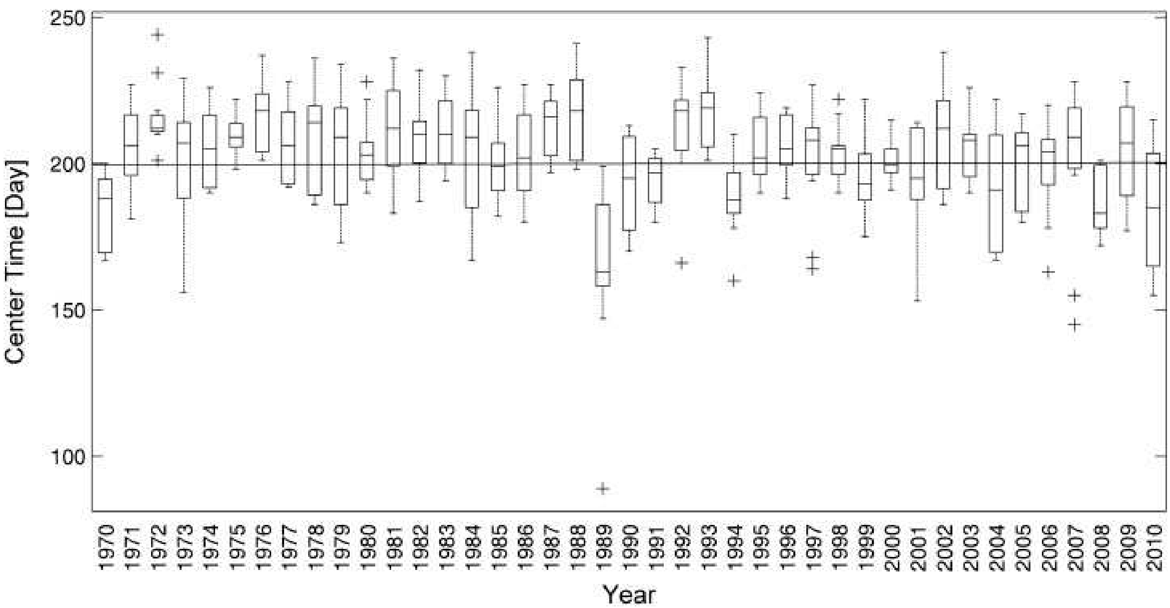

Figure 7. Box plots of calculated CT of 15 stream gauging stations for each year from 1970 to 2010 are shown.

Table 6. Results of statistical trend analyses applied to the CT data of stream gauging stations and their corresponding CT shifts to earlier time.

Station	CT shifts to earlier time (days)	Mann–Kendall	Trend	Spearman's rho	Trend
2102	7	−0.64		−0.9	
2122	2	0.6		−0.3	
2124	19	−1.85	(−)	−1.94	(−)
2133	2	−0.1		−0.69	
2145	16	−1.94	(−)	−1.10	
2156	6	−1.38		−1.65	(−)
2157	6	−0.63		−0.88	
2164	12	−1.61		−1.88	(−)
2610	8	−1.90	(−)	−1.26	
2620	11	−2.99	(−)	−3.50	(−)
2621	14	−3.12	(−)	−3.10	(−)
2316	4	−0.71		−0.85	
2325	3	−0.25		−0.39	
2402	7	−1.35		−2.06	(−)
2415	10	−0.95		−1.03	

Changes (in days) are obtained according to the fitted linear trend line between 1970 and 2010. The confidence level is 90%.

Table 7. Stream flow stations paired with the meteorological stations located within or near the basin of stream gauging station.

Meteorological station name	Streamflow station number
ARTVIN	2325
ARTVIN	2316
ARDAHAN	2415
ERZINCAN	2156
AGRI	2122
AGRI	2402
TUNCELI	2133
MALATYA	2124
MALATYA	2145
BINGOL	2164
BINGOL	2102
MUS	2157
BITLIS	2610
HAKKARI	2620
HAKKARI	2621

times as shown above. As reported by Stewart (2009), response of snowmelt runoff to such climatic changes has been greatly dependent on elevation, with the greatest impact at lower- and mid-elevations around or below 1300 m. The decrease in low- and mid-elevation snowpack is accompanied by a significant decline in the amount of precipitation falling as snow and a significant decrease in the number of snow days (Beniston *et al.*, 2003; Laternser and Schneebeli, 2003; Scherrer *et al.*, 2004). Furthermore, in consistent with this study, Sönmez *et al.* (2013) showed decreasing amount in the extent of snow cover and a shifting trend in snow amount towards earlier times in winter in the eastern Anatolia. As most of stream gauging stations are located at mid-elevations in this study, decreasing trend in the number of snowy days also provides evidence corroborating these findings. It should be noted, however, that meteorological stations may not adequately represent the basins and the type and amount of precipitation may greatly vary with altitude in short distances. In addition, meteorological stations are usually located within urban areas (albeit they do not cover large areas in the eastern Anatolia, a region with low population), and the urban climate could differ from the general climate of the basin. On the other hand, changes in streamflow, which, in a sense, samples large mid- to high-elevation areas with relatively less human interference, should provide more robust signals for the human-induced climate change, as they are related to precipitation type changes (from snow to rain) in cold season and shifts in snowmelt timing, both of which are primarily caused by temperature increases.

As a summary of the analysis of the historical records, it could be said that the CT and trend analysis of streamflow observations indicate shifts in the timing of streamflow for snowmelt-dominated basins in the study region over the 40-year period between 1970 and 2010. As a consequence of regional warming, the number of days below freezing and number of snowy days (between 1 October and the CT of the stations) both decrease. Results of significance of CT shifts as well as significant test results of temperature, precipitation, and streamflow are all summarized on a map of eastern Anatolia in Figure 9.

4.2. Analysis of future changes

Climate change projections for the eastern Mediterranean – Black Sea region indicate up to about 6 °C warming at the eastern Anatolian basins by the end of 21st century (e.g. Önol and Semazzi, 2009; Önol *et al.*, 2013). The future warming, due to its impact on snowmelt and precipitation, is expected to cause a decline in the winter snowpack of the eastern Anatolia. This would increase winter runoff and reduce spring runoff, thus shifting CTs to earlier days. Figure 10 illustrates the runoff fractions (total monthly runoffs over total annual runoff) of the Euphrates, Tigris, Aras, and Coruh basins for two periods, 1961–1990 and 2070–2099. The future simulation is based on a high emissions scenario. In a sense, the future values could be considered as the upper boundary of the possible changes in these basins. Spatial averaging is performed for only the parts of the basins that fall in the territory of Turkey (Figure 1). The annual runoff of three basins decreases as 11.6% for Aras, 23.5% for Euphrates, and 28.5% for Tigris based on future simulations. However, it is projected to increase in the Coruh basin by about 4%. It seems from Figure 10 that the runoff fractions of December, January, and February (i.e. winter) of all rivers will substantially increase in the future (from 9 to 38% for Aras, from 8 to 34% for Coruh, from 25 to 49% for Euphrates and from 28 to 50% for Tigris) while the runoff fractions of April and May will substantially decrease (from 49 to 15% for Aras, from 50 to 17% for Coruh, from 35 to 9% for Euphrates, and from 35 to 11% for Tigris). The changes in March runoff fractions are comparatively small. Overall, these changes mean further shifts (on

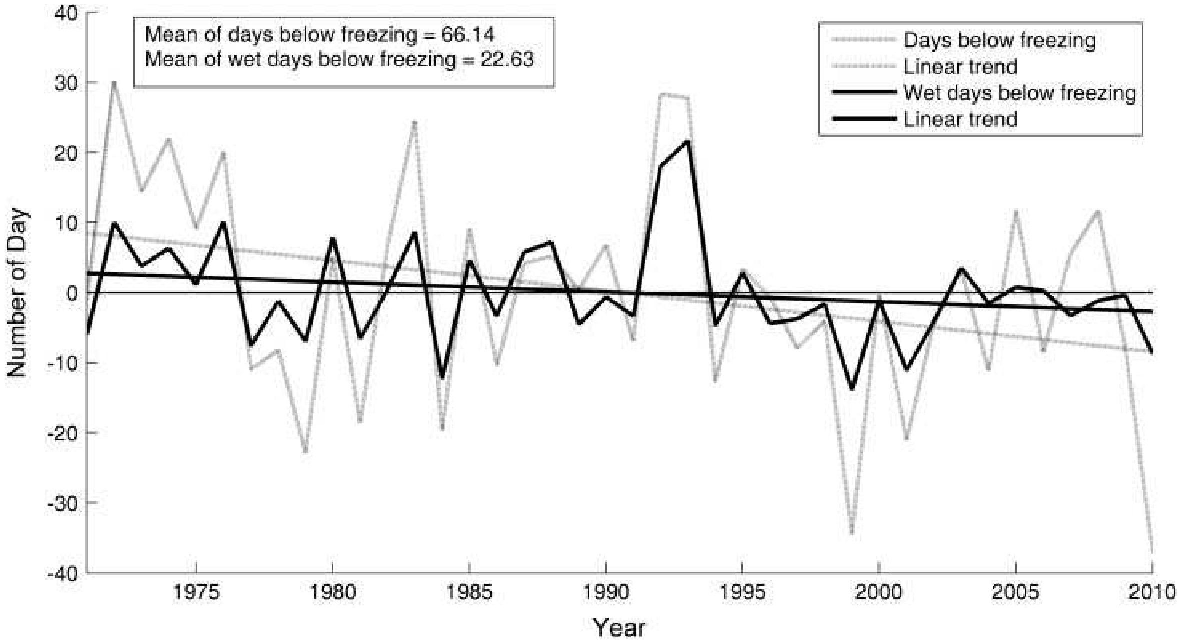

Figure 8. Area-averaged analyses of the number of days below freezing and the number of wet days below freezing are shown from 1970 to 2010. Deviations from their mean values are shown.

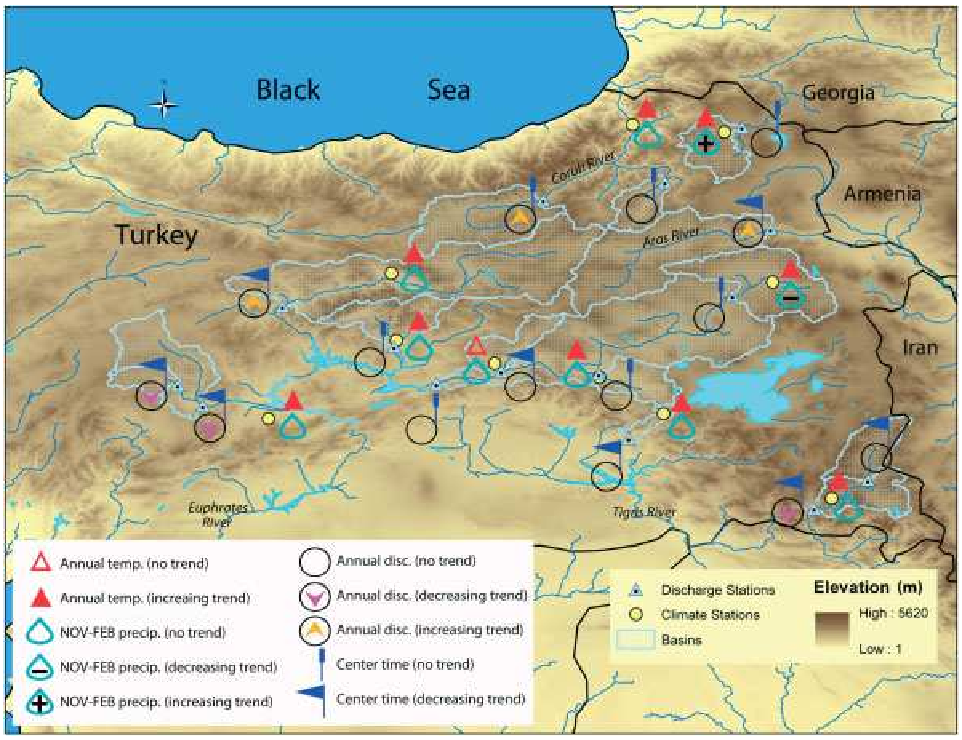

Figure 9. Trend test results obtained through this study for annual discharge, CT, winter precipitation, and annual temperature at stream gauging and meteorological stations are summarized on the map of Eastern Anatolia of Turkey. Different flags are used to describe whether a trend exists or not.

the order of 4 weeks) to earlier times in the streamflow timings of these rivers in the future.

5. Summary

The seasonal snowmelt runoff in the mountainous basins of eastern Turkey has experienced changes over the past several decades (Sen *et al.*, 2011; Sönmez *et al.*, 2013). This study investigates the regional trends in hydroclimatic variables in the eastern Anatolia, Turkey, for the 40-year period between 1970 and 2010 to explore and evaluate the evidence for the impact of climate change. Analysis of temperature time series in the eastern Anatolia yields statistically significant increasing trends in the

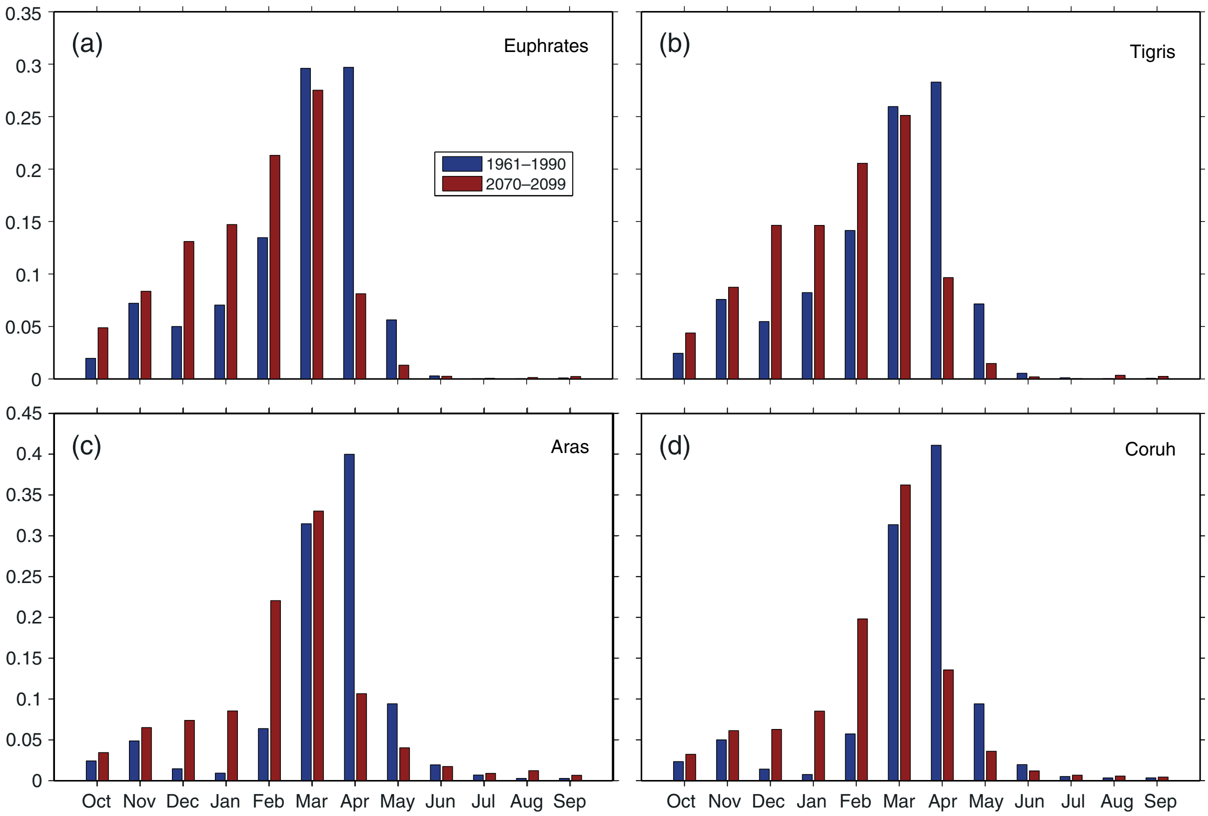

Figure 10. Present time (1961–1990) and future (2070–2099) monthly surface runoff fractions (monthly totals over annual totals) for the basins (a) Euphrates, (b) Tigris, (c) Aras, and (d) Coruh. The future projections are based on a high emissions scenario, A2.

region over the study period. Annual precipitation tends to increase too. The analysis indicates that much of this increase occurs in winter. However, the winter increases in precipitation are found to be mostly insignificant at 90% confidence level. It is suggested that regional warming in the study area has greater effect on precipitation characteristics through its type. Observed winter warming causes an increased fraction of the precipitation to fall as rain, resulting in a reduced snowpack, as also reported by other studies for this region (e.g. Sönmez *et al.*, 2013). Despite no significant trend in streamflow changes, Tigris and Aras basins as well as the middle parts of Euphrates basin show statistically meaningful CT shifts to earlier times. Such shifts are most likely caused by the temperature increases in the region, which start to melt the snow earlier in recent years. For the basins in the lower mountainous parts of the Euphrates basin, the CT shifts to earlier times are more pronounced than those in the upper parts of the basin, probably because of combined effect of the temperature increases and significant decreases in the streamflow of the lower sub-basins. According to climate projections for the four main basins, the timing of the peak flows will continue to shift to earlier days (by about 4 weeks over the present century) in response to projected further warming. The findings of the present study are in general consistent with the results of similar studies that investigate the impact of global warming on the hydroclimatic variables for the mountainous basins with snow-fed rivers (e.g. Mote *et al.*, 2005; Stewart *et al.*, 2005; Stewart, 2009).

As suggested in general and supported by the findings of this study, the mountainous areas are reacting to temperature and precipitation shifts and therefore yielding strong evidence for the response of warming trend in mountain snowpack and snowmelt runoff. Seasonal climate variability and change are naturally linked to snowmelt runoff in a way that warmer cold-season temperatures reduce snow accumulation, as a greater fraction of the precipitation comes as rain, while warmer spring temperatures hasten snowmelt, thereby shifting the timing of runoff to earlier times in the season and reducing the amount of spring flows.

6. Conclusions

The following main conclusions can be drawn from the present study:

- According to linear trend lines fitted to temperature time series between 1970 and 2010, daily average temperature in the eastern Anatolia was increased by 1.3 °C. This increase in temperature advances the timing of snowmelt and subsequently causing a temporal shift in the CT of the streamflow.
- Meteorological stations generally do not show statistically meaningful trends in annual total precipitation over the same period.

- There has been little concurrent change in the total annual discharge, and only two of the streamflow stations (both trend tests yield significant decrease) show evidence for decreasing volumes of melting period streamflow.
- During the study period, the timing of spring streamflow has shifted earlier in the year. The major spring snowmelt runoff peak now arrives up to 9 days earlier across the region, which results in declines in the fractions of spring and early summer river discharge.
- Rising temperatures in snowmelt-dominated region yield discernable decreases in the area-averaged number of cold days below freezing and number of snowy days towards the end of the period.
- The peak timing of snowmelt runoffs is shifted to earlier times significantly in the Euphrates, Tigris, and Aras basins in the study area. On the other hand, for the Çoruh basin, the shifts exist but these are not statistically significant at 90% confidence level.
- A regional climate change simulation based on a high emissions scenario produces 11.6, 23.5, and 28.5% declines in the annual surface runoffs of Aras, Euphrates, and Tigris basins respectively and about 4% increase in the annual surface runoff of Çoruh basin by the end of the century. It further indicates that the timing of the peak flows will continue to shift to earlier days, increasing the fraction of winter runoff while decreasing the fraction of spring runoff in the year in all four basins.

These results are important in hydrologic regimes of river systems available in mountainous region of eastern Turkey. The effects of shifts in melting of snow should be considered in planning of dam reservoirs in order to sustain the effective storage and effective use of water. These results should be used in Turkey's water management policies to be followed in the future and could provide support for research and decision making in the science and policy-making arenas.

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