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Temporal and spatial patterns of precipitation variability for annual, wet, and dry seasons in Turkey

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ABSTRACT: In the present study, annual, wet and dry seasons precipitation records for the period 1961–2008 from 271 stations in Turkey were analysed using the rotated empirical orthogonal function (REOF), the Mann-Kendall trend test and the continuous wavelet transform (WT) method. Additionally, relationships between time variability of the significant spatial patterns and North Atlantic Oscillation (NAO), Arctic Oscillation (AO), and North-Sea Caspian Pattern (NCP) are examined. The REOF method was used to analyse the annual, dry, and wet season variability of precipitation patterns over Turkey. The Mann-Kendall method was used to detect the temporal trend of the rotated principal components (RPCs) time series, and the continuous wavelet method was used to explore the periodicity of precipitation changes. Continuous WT results indicate that the significant 3–4 year, 6–10 year, and 12–16 year bands are the major period components. Precipitation in Turkey is uneven in space and time, and its complex temporal structure and spatial variations are different in each dry and wet season. The Mann-Kendall test results show that decreasing annual precipitation is the dominating trend throughout Anatolia, including west, and southwest sections. Increasing annual precipitation can be observed in only northeast Black Sea region of Turkey. Decreasing wet/dry season precipitation that we observe throughout the country, except northeast coasts and eastern parts of Turkey, is expected to have a strong impact on the economic livelihood of the region, especially on agricultural production, drinking water supply, and hydroelectricity production. Copyright © 2010 Royal Meteorological Society

KEY WORDS REOF; Mann-Kendall test; wavelet transform; teleconnections; precipitation variability; Turkey

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1. Introduction

According to the recent IPCC Assessment Report (AR4), climate change is expected to magnify regional differences in Europe's natural resources, and it is projected to worsen vulnerability of the countries due to high temperatures and decreasing annual precipitation in the Southern Europe and the Mediterranean region (Intergovernmental Panel on Climate Change, IPCC, 2007). This global trend should be quantified at the regional scale where both increasing and decreasing trends are identified. Furthermore, the First National Communication (FNC, 2007) Report of Turkey on Climate Change (FNCC) was released in 2007. This report includes the preliminary results of Önol (2007) and Önol and Semazzi (2009) about the climate change projections over Eastern Mediterranean, including Turkey, using a regional climate model for the present conditions (RF) and Special Report on Emission Scenarios (SRES) A2 scenario. Their model simulations show significant increase in temperature and decrease in precipitation in most parts of Eastern Mediterranean. Önol and Unal (2010) examine the regional and interannul variability of the climate projection based on SRES A2 scenario on the climate regions of Turkey.

Increased precipitation variability, combined with predicted higher temperatures and increasing evapotranspiration amounts, may have greater impact on economic and social characteristics of the regions. Precipitation variability influences both water resources and occurrence of extreme events such as droughts and floods, and consequently, it has a significant impact on agriculture, economy, and energy production. In the last two decades, a number of studies were performed on precipitation variability of the Mediterranean basin and the surrounding countries, where most of them concentrate on its relation to dynamical and physical processes (e.g. Xoplaki *et al*., 2004; Kostopoulou and Jones, 2005; Krichak and Alpert, 2005; Tolika and Mahares, 2005, Livada *et al*., 2008).

Turkey, located in the southeastern part of Europe within the latitude–longitude zones of 36°–42 °N and 26°–45 °E, is one of the largest countries in the region with an area coverage of around 780 000 km^2. Although it is situated in the temperate zone, Turkey experiences various climate types due to highly variable topography. Since Turkey is in the Mediterranean climatic region of the subtropical zone, it has a sensitive climate.

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In recent years, it is evident that severity of long period of dry conditions in Southern Europe and Eastern Mediterranean countries has increased. Precipitation variability dominates both water resource supply and the occurrence of droughts and floods. Therefore, its variability can have strong impact on the life especially in regions strongly dependent upon water resources, agriculture, and hydroelectricity production such as Turkey. Therefore, it is critical to have a firm understanding of precipitation.

In the past two decades, droughts have struck, especially in the west, center and southeast parts of Turkey. For example, the 1989–1990 and 2007–2008 droughts were the worst in the last 50 years, and dramatic water shortages result in a crisis, especially in the major cities of Turkey such as Istanbul, Ankara, and Izmir. In recent decades, the precipitation variability in Turkey for different periods, and stations focusing on seasonality, trend, and periodic behaviour has been investigated by several studies (e.g. Turkes, 1996; Kadıodlu, 2000; Karaca *et al*., 2000; Komuscu, 2001; Kutiel *et al*., 2001; Kalaycı and Kahya, 2006; Tatlı, 2006; Sensoy, 2008; Türkeş *et al*., 2009). Kadıodlu (2000) examines PCs of the parametric spatial Pearson and non-parametric Spearman rank correlation matrices to depict the seasonal characteristics of precipitation in Turkey. Türkeş *et al*. (2009) analyse long-term changes and trends of precipitation totals by using Mann-Kendall rank correlation test in Turkey. They also investigate the spatial variability of precipitation records of 97 stations by using un-rotated principal component analysis. Kalaycı and Kahya (2006) examine the impact of precipitation variability on water resources. Basing on these studies we infer that in order to better understand the characteristics of the precipitation variability in both spatial and temporal scales in Turkey, it is essential to use several statistical methods to check the stability and consistency of the findings.

The main objective of this study is to analyse the inter-annual and inter-decadal precipitation variability and their year-to-year modulation, classifying years into wet and dry seasons, and to determine the relationship between the precipitation and teleconnection indices in the Atlantic Ocean and Mediterranean. We first determine significant spatial patterns of precipitation for annual and wet/dry seasons by using the Rotated Empirical Orthogonal Function (REOF) method. Then, temporal variability of time series corresponding to the significant patterns is explored in terms of long-term trend and periodic behaviour by using methods of Mann-Kendal and Wavelet Transform (WT). Additionally, we investigate the relationship between time variability of the significant spatial patterns and the teleconnection indices such as NAO (North Atlantic Oscillation), Arctic Oscillation (AO), and North-Sea Caspian Pattern (NCP).

2. Data

The precipitation data we use are provided by the Turkish State Meteorological Service (TSMS) in Ankara. In this study, we analyse the characteristics of spatio-temporal variation in Turkey based on the monthly precipitation data from the rain gauge stations for a 48-year period from 1961 to 2008. Initially, the dataset comprises 271 meteorological stations. However, the total of 165 stations is found suitable for the analysis. These stations are chosen to obtain the best possible spatial coverage with relatively continuous monthly records. Hence, stations with three or more consecutive missing values are eliminated from the final set. Records with missing values over less than three months are completed by using the average of the values of the previous and successive years. If missing value is at the first or the last year of the dataset, we fill the gap by long-term climatological monthly mean. Furthermore, Wald-Wolfowitz (W-W) run test is used to verify the homogeneity of precipitation series. The W-W run test is a non-parametric test used in determining the randomness or homogeneity of a dataset used in climate applications (Oliver, 1981; Vining and Griffiths, 1985). More precisely, it can be used to test the hypothesis that the elements of the sequence are mutually independent. A map of the selected meteorological stations used in this study is shown in Figure 1.

Year-to-year fluctuations in dry-period rainfall over Turkey have a vital influence on agriculture, crop yields, hydrology, and related industries. For this purpose, we have also analysed the wet and dry seasons separately

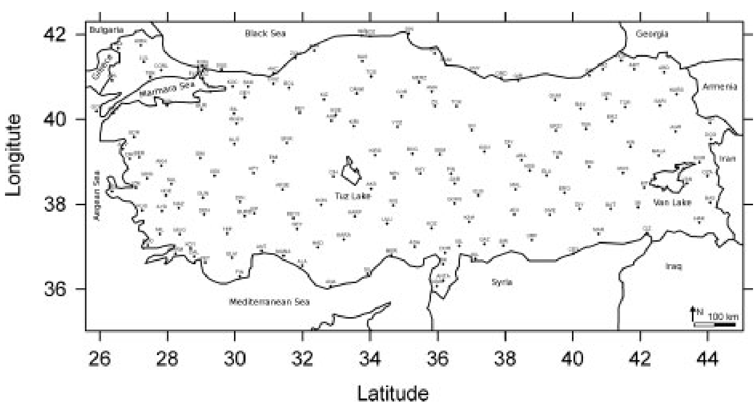

Figure 1. Rain gauge station distributions used in this study.

Table I. The annual variation of the monthly mean precipitation and corresponding SPI values.

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Avg
Precip.(mm)	83.05	71.84	66.33	58.96	47.96	31.31	17.79	18.16	27.96	57.11	75.76	97.29	54.47
SPI	0.45	0.27	0.26	0.24	0.07	−0.35	−0.74	−0.77	−0.57	0.05	0.36	0.45	0.27

in addition to analysing the annual totals of precipitation. To accomplish this, we use the Standardized Precipitation Index (SPI) values, which are the number of standard deviations that the observed value would deviate from the long-term mean so that the standardised precipitation can be compared over a region (Mc Kee *et al.*, 1993).

In order to determine the dry and wet (rainy) seasons, first, SPI values for each station are calculated, then distribution of SPI values for each month is examined, and finally country averages of all SPI values for each month are obtained. Table I presents the average of monthly precipitation and SPI values of all stations. To determine the dry and wet seasons of Turkey, we compared the maps of SPI values for transition months, such as September and October. We found that a majority of the areas correspond to low SPI values in September, while there is a mixture of negative and positive SPI values which are close to zero and localised moderate SPI values around the eastern Black Sea coast only in October. On the other hand, November SPI values for all stations clearly indicate that November is within the wet season of Turkey with consistent positive SPI values. By inspecting the monthly averages of precipitation, their regional distribution and SPI values, the annual precipitation distribution in the country is divided into the wet season between the months of November and April, and dry season between June and September. May and October, with SPI values close to zero, cannot be classified as wet or dry.

3. Methodology

Owing to the complexity of climate change at all timescales, it is necessary to use a series of refined statistical methods to infer the most important dynamical processes affecting the regional climate variability from the observations. This investigation into precipitation variability in Turkey has a number of components. First, in order to understand and define the spatial precipitation variability and year-to-year fluctuations for annual wet and dry periods over Turkey, we analysed the precipitation data by using REOF and identified the most dominant spatial and temporal patterns of Turkish precipitation. Additionally, the Mann-Kendal test is used to reveal the trends of precipitation. Periodical behaviours of the precipitation are also investigated by WT.

3.1. The empirical orthogonal function (EOF) method

EOF analysis attempts to find a relatively small number of independent variables which convey as much of the original information as possible without redundancy. This analysis can be used to explain the structure of the variability within a dataset in an objective way, and to analyse relationships within a set of variables (Montroy, 1997). In this analysis, a set of orthogonal functions to represent a time series is used as follows:

$$z(x, y, t) = \sum PC(t) \times EOF(x, y) \quad (1)$$

Where, $z(x, y, t)$ is the original time series as a function of time (t) and space (x, y) and probably correlated to each other. It is desirable to predict a smaller set of new variables, which are a linear combination of the original variables and explain most of the variability of the original data. Even though EOF analysis gives the most efficient compression of the data, eigenvectors do not necessarily correspond to true dynamic structures of the physical system. A single physical process may be shared by more than one EOF. When meteorological and climatological investigations are made in a square or rectangular domain, the first unrotated eigenvector has always a positive/negative anomaly over the entire domain, whereas the second one has a positive/negative anomaly in the west and a negative/positive anomaly in the east (Richman, 1986). However, the rotated solutions are less affected by domain shape that is chosen. In order to overcome the effects of domain shape dependence, sub-domain instability, the rotated EOF analysis is employed in this study. VARIMAX rotation method is chosen because it maximises the variance of squared correlations between each rotated principal component (RPCs) and each variable, so that the simplest pattern is described while explaining the maximum amount of variance.

3.2. The Mann-Kendall test

The non-parametric rank-based Mann-Kendall statistical test has been used to detect trends (Mann, 1945; Kendall, 1975). It is based on the null hypothesis that a sample of data is serially independent and identically distributed. The test does not assume any particular distribution of the data and compares each value with all the values measured in subsequent periods.

In this study, we used the Mann-Kendall test to assess the significance of trends of the PCAs, which can be detected by the Kendall coefficient-t (Mann test). When a time series shows a significant trend, the period from which the trend is demonstrated can be obtained effectively by this test. In a time series, for each element $\boldsymbol{y}_i$, the number n_i of elements $\boldsymbol{y}_j$ preceding it ($i > j$) is calculated such that $y_i > y_j$, the test statistic t is then given by

$$t = \sum n_i \quad (2)$$

and it is distributed very nearly as a Gaussian normal distribution with an expected value of $E(t) = n(n-1)/4$ and a variance of

$$var\ t = n(n-1)(2n+5)/72. \tag{3}$$

A trend can be seen for high values of $u(t)$, where

$$u(t) = [t - E(t)]/\sqrt{vat\ t}. \tag{4}$$

This principle can be usefully extended to the backward series, and $u_i{}' = -u(t_i{}')$ can be obtained. The intersection of the $u(t)$ and $u'(t)$ curves denotes approximately the beginning of the trend. This is called the sequential version of the Mann-Kendall test (Goossens and Berger, 1986).

3.3. Wavelet transform (WT)

Wavelet analysis is a powerful tool for analysing the temporal frequency change or changes in variance. Wavelets have been first introduced by Grossman and Morlet (1984). The basic objective of the WT is to achieve a complete time-frequency representation of the signal and hence, it allows the detection of localised and transient phenomena at different time scales, such as discontinuities, frequency changes of oscillations or abrupt changes. WT gives a connection between time and frequency of the signal. One-dimensional continuous WT was first introduced by Grossman and Morlet (1984). Lau and Weng (1995) used WTs to detect climate signal. Then, several applications of the wavelet transfer have been employed in atmospheric sciences (Torrence and Compo, 1998).

WT of a function $f(t)$ is defined as the integral transfer of $Wf(\lambda,t)$ (Kumar and Foufoula-Georgiou, 1997).

$$Wf(\lambda, t) = \int_{-\infty}^{\infty} f(u)\overline{\psi}_{\lambda,t}(u)du$$

$$\lambda > 0$$

$$\psi_{\lambda,t}(u) \equiv \frac{1}{\sqrt{\lambda}}\psi\left(\frac{u-t}{\lambda}\right)$$

where, λ is a scale parameter; t is a location parameter; $\psi_{\lambda,t}$ (u) is the complex conjugate of $\psi_{\lambda,t}$ (u).

4. Precipitation climatology

Turkey is situated on the Anatolian and Asia Peninsula. Turkey lies within the subtropical climate zone where climatic conditions are quite temperate, predominantly Mediterranean prevailing to the west and south regions and largely continental in the inland regions with a 653.6 mm annual average precipitation. Most of the annual precipitation occurs in the winter months when the depression and frontal activity are frequent and intense over the country. July and August are normally the driest months. This variability is a result of the interactions between geographic locations and the movements of seasonal systems. In winter, because the region is under the influence of the polar front, cold air masses from Balkan Peninsula and the lowest pressure area centred in the Mediterranean with frontal passages toward east. However, in summer, the polar front shifts to the northern latitudes and, consequently, weak frontal passages and maritime effects become dominant. Furthermore, anticyclonic pressure patterns are also important for Turkey's climate such as Azores high in summer and Siberian anticyclone during winters.

The topographical map of Turkey is shown in Figure 2. Figure 3a shows the computed climatological annual precipitation based on the 1961–2008 period. On the annual mean basis precipitation is characterised by strong spatial variability due to the strong relief by topography and sea–land contrast. As seen from the map, Turkey is surrounded by the Black Sea in the north, Aegean Sea and Mediterranean Sea in the west and south, respectively. The Aegean region in the west has a typical Mediterranean climate. The coastal areas of the Mediterranean region in the south are separated from central Anatolia by the South Anatolian Mountains (Taurus Mountains) which reach up to 3000 m. Generally, there is strong gradient of topography from west to east along the coastline. The topographic effects, associated with the mountainous terrain, in particular, greatly complicate the climate variability. The Taurus Mountains lie parallel to the coasts preventing Mediterranean influences to pass the inland areas in the central Anatolia plateau. Similarly, the North Anatolian Mountains in the north are parallel to the Black Sea coasts, in the west tending to be low, but in the east

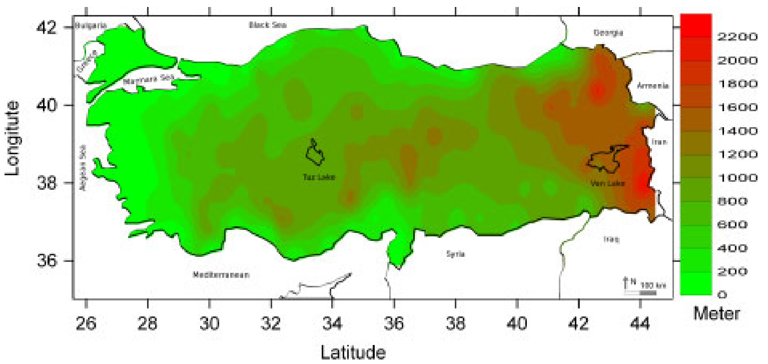

Figure 2. A topographic map of Turkey. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

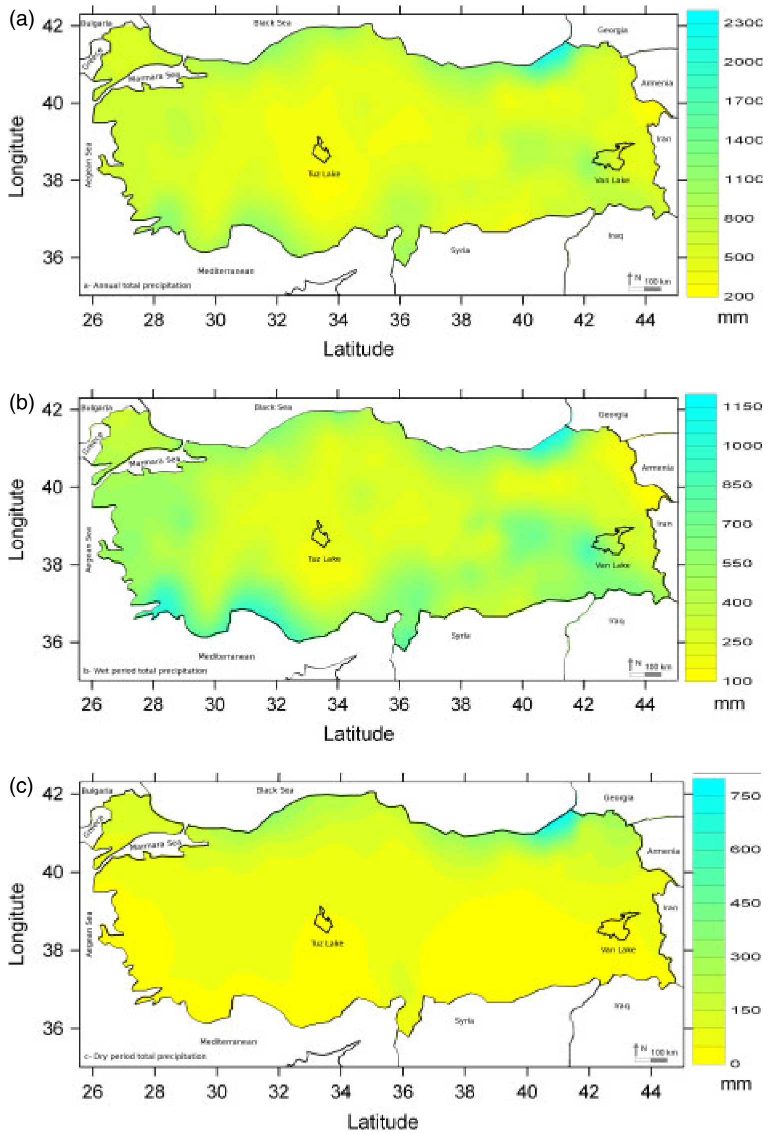

Figure 3. Precipitation distribution over Turkey for the period 1961–2008: a) for annual precipitation; b) for wet season (Nov–Apr); and c) for dry season (Jun–Sep). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

reach to 3942 meters in elevation. Consequently, spatial and temporal variation of climatic parameters such as precipitation in Turkey presents complex interrelationship between the topography, synoptic patterns, elevation and local orographic features (Deniz *et al.*, 2010).

The wet and dry season precipitation variability is also shown in Figure 3b and c. The precipitation patterns for wet and dry seasons are significantly different. During the wet period, the highest monthly values are measured along the northeast Black Sea coast and southwest of the Mediterranean region. This coastal area in the northeast receives the highest amount of rainfall exceeding 2500 mm in a year due to the interaction between the orography and weather systems. As the air system travels above the Black Sea and reaches the Black Sea mountains, the orographic uplift results in precipitation. Therefore, the eastern Black sea coast receives precipitation all year around as seen in Figure 3c which shows high precipitation values even during dry period. For example, precipitation values in Hopa station in this region for annual wet and dry periods are 2227, 1095, and 736 mm, respectively. On the other hand, Marmaris in the southwest Mediterranean coast of Turkey illustrates 1218 mm annual, 1072 mm wet and 30 mm dry-period's precipitation. It is striking that dry- to wet-period precipitation ratios are 67% for Hopa and 3% for Marmaris.The Central Anatolia Plateau is located between the two folded mountains and receives a small amount of rainfall, which is less than 300 mm in a year. On the east, eastern Anatolia region having a strong relief has a highest point with 5137 m (Agri Mountain) and the largest Lake in Turkey (Van Lake). Southeastern Anatolia is in the south of Eastern Anatolia having with a plateau extending to the Syria and Iraqi. This region is characterised by lower precipitation amounts (around 331 mm).

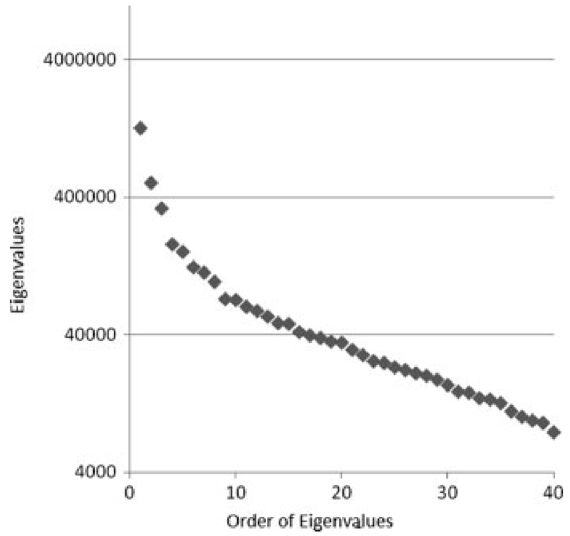

Figure 4. Scree plot of annual eigenvalues *versus* eigenvector numbers.

5. Teleconnections *versus* precipitation variability

5.1. Spatio-temporal variability of precipitation

The EOF analysis with VARIMAX rotation is carried out on the annual and wet/dry season precipitation to define significant precipitation patterns. In order to determine the number of significant orthogonal functions which identify the spatial and temporal characteristics of possible physical significance, we applied scree test. The plot of annual eigenvalues *versus* eigenvector numbers is shown in Figure 4 for annual precipitation only. The first five eigenvalues are well separated from the rest and explain 64.8% of the total variance.

Table II. The percentage of variance captured by each REOF for precipitation data.

Rotated components	Rotated Variance (%)		
	Annual	Wet period	Dry period
First	19.6	21.4	21.7
Second	16.5	17.5	11.5
Third	11.1	13.4	10.6
Fourth	9.2	12.7	7.8
Fifth	8.4	6.4	7.6
Total	64.8	71.4	59.2

The same approach is used to determine a significant number of new variables for wet/dry seasons. Then, these five components are rotated according to VARIMAX approach which distributed the variances relatively evenly over the components. Therefore, for example, variances of first-rotated EOFs for annual and wet/dry seasons are reduced to approximately 20%. Table II presents the percentage of variance captured by each REOF for precipitation data in a decreasing order. The mean annual precipitation cycle in Turkey can be described by the composition of the first five rotated EOFs which take into account 64.8% of the total variance. The wet season has a higher spatial coherence than the dry period since they capture 71.4% of variability with only five components.

For annual precipitation, Figure 5a–e illustrates first five dominant patterns. The first REOF pattern has highest loadings and accounts for 19.6% of the total precipitation variance. As seen in Figure 5a, almost all

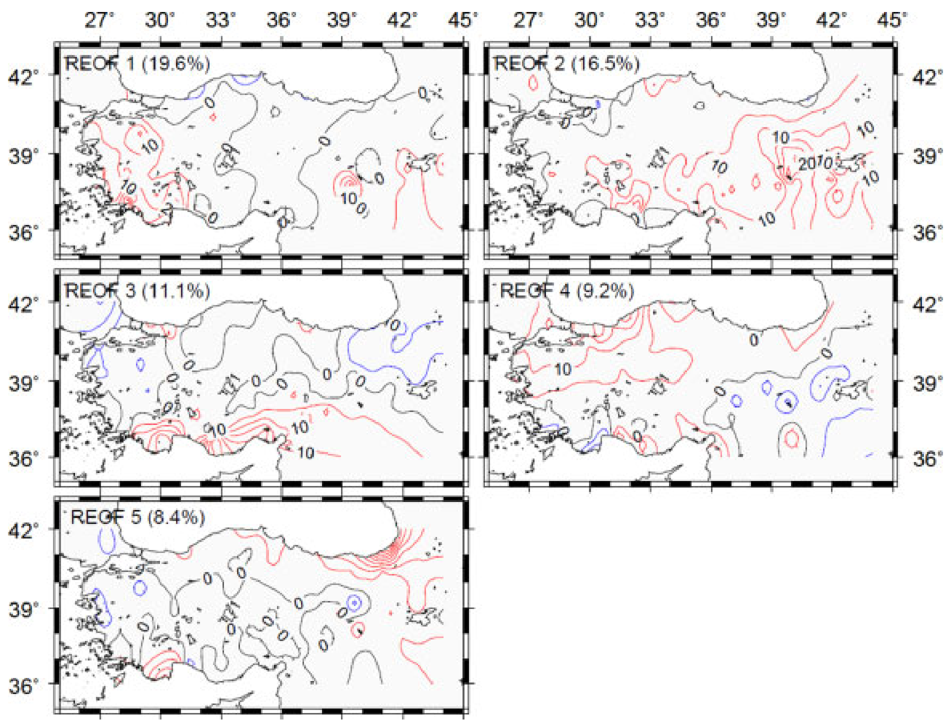

Figure 5. Annual rotated REOF precipitation patterns for the period 1960–2008 for a: 1st REOF; b: 2nd REOF; c: 3rd REOF; d: 4th REOF; e: 5th REOF. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

loadings are positive throughout the country, and the pattern is characterised by an area of large positive variation between west and east, and south and north extending through southeast of Anatolia. However, the first REOF pattern is centred mainly on the west of Turkey. Hence, corresponding principal component represents mainly variability in the western part of Turkey. REOF2 (Figure 5b) indicates high loadings in the eastern part of Turkey with 16.5% captured variance. The largest coefficients are located around highest topography regions of eastern Anatolia and the coefficients decrease towards the southwestern part of the region following the topography (Figure 2). REOF3 indicates the Mediterranean coastal regions with 11.1% of the total variability. The coefficients have approximately zonal distribution with the highest and positive values along the Mediterranean coast. There are slightly negative coefficients on the northwest and northeast of the country. REOF4 pattern represents mainly northwest of Turkey (Marmara region) with 9.2% explained variance. There are also scattered centres on the Antalya and Iskenderun Bays on the Eastern Mediterranean coast of Turkey. The last REOF indicates the eastern Black Sea coasts with 8.4% variability. The high coefficients correspond to the region of largest annual precipitation areas as seen in Figure 3a.

Figure 5a–e presents the RPCs of the annual precipitation and their associated linear trends. RPCs 1–4 show the existence of negative trends, meanwhile RPC5 characterising precipitation in the eastern Black Sea coast tends to increase.

Wet/dry season REOFs are shown in Figures 6 and 7, respectively. Comparisons of Figures 5–7 show that annual precipitation of Turkey is controlled by wet season since annual patterns largely follow the wet patterns. Especially the first two rotated EOFs of wet season are mainly characterised by loadings similar to the annual EOFs which represent approximately 35% of variability. On the other hand, as seen in Figure 3, most of the variability associated with REOFs 1–5 for dry season are along the Black Sea coast.

5.2. Trends in RPCs

Trends of the RPCs for annual wet and dry phases are analysed using the Mann-Kendall method, which is also capable of detecting the starting year of possible climatic discontinuities or changes. Here, the MK trend test of only RPC1 of the annual and wet/dry seasons are shown in Figure 8 a)–c), respectively. Time series of RPC 1–4 indicate a clear decreasing trend on all regions except northeast Black Sea. The time series of RPC5 which characterises precipitation variability on the eastern Black Sea region presents a significant increasing precipitation trend.

MK trend analysis of wet period RPC series is shown in Figure 8b). The first two PCs indicate decreasing trend, the third PC changes approximately constant rate in time, the fourth one indicates decreasing and the fifth one shows increasing trend which correspond to the northeast Black Sea region. Dry period trends of the RPC series are given in Figure 8c). Dry period trends present small increases for the first two RPCs, which centres mainly on the western parts and eastern parts of Anatolia, respectively. However, the third, fourth, and fifth PCs in the dry periods, which address the whole of Anatolia, the Mediterranean coasts and northeast Black Sea

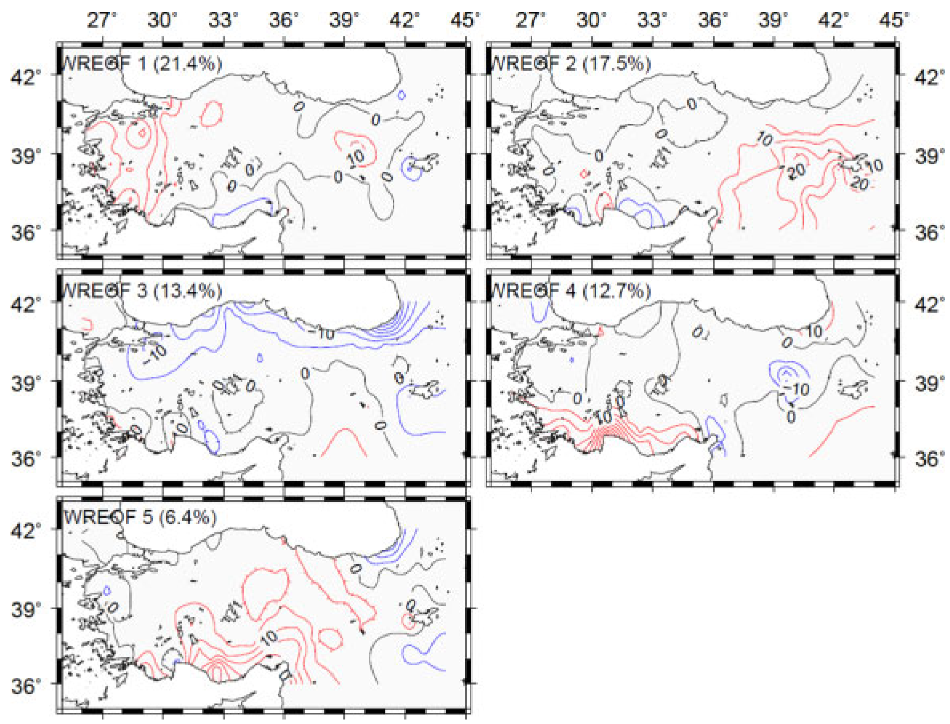

Figure 6. Wet season REOF precipitation patterns for the period 1960–2008 for a: REOF 1; b: REOF 2; c: REOF 3; d: REOF 4; REOF 5. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

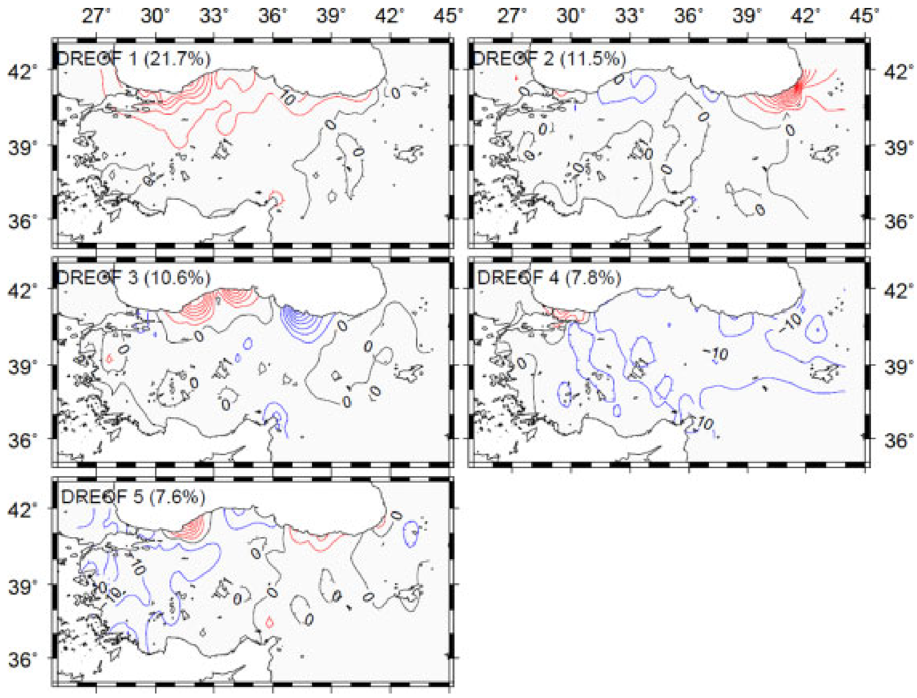

Figure 7. Dry season REOF precipitation patterns for the period 1960–2008 for a: REOF 1; b: REOF 2; c: REOF 3; d: REOF 4; e: REOF 5. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

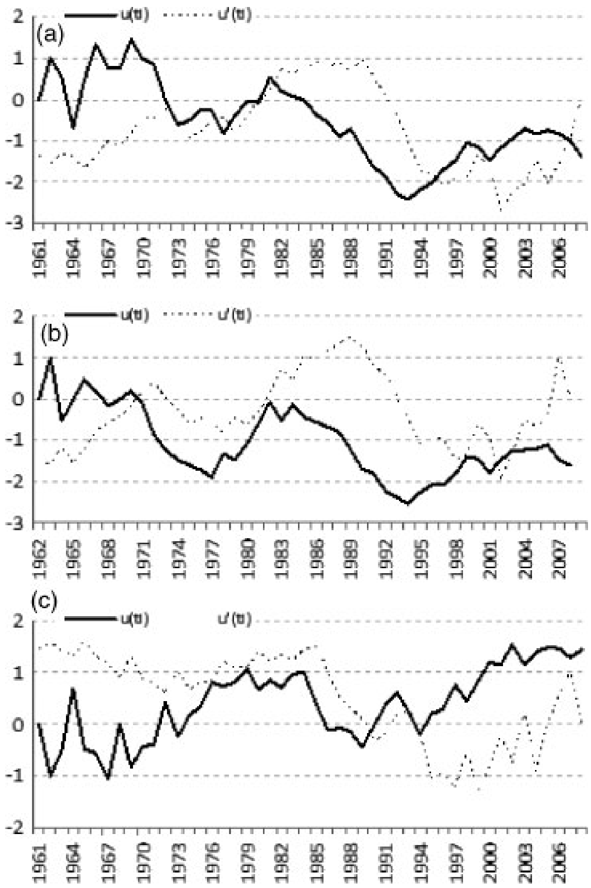

Figure 8a)–c). MK trend test of the RPCs of the annual and wet/dry season.

coasts, respectively, do not significantly change in time. MK trends analysis of the RPC series show that, in general, annual precipitation decreases in the west, south, and southeastern parts of Turkey. The only increasing trend of the annual precipitations is found in the eastern Black Sea coasts. It is consistent with the projected climate change trends. However, the Mann-Kendall test estimates that only the trend of the fifth REOF is significant with 95% confidence level. Since the other RPCs are dominated by inter-decadal oscillations, time series of the RPCs show increasing and decreasing trends in different years of the study period. Therefore, they are not found significant with 95% confidence level due to decadal variability, even though general trend is positive. Moreover, except for the Black Sea coast, all calculated trends are negative/positive for wet/dry seasons. For the Black Sea region, both wet and dry season precipitations increase between 1961 and 2006. Dry season precipitation trends are larger than the wet season.

5.3. Periodic behaviour of precipitation and wavelets

In this study, the Morlet wavelet analysis is employed to detect the precipitation variations with time in Turkey. Basing on the precipitation data of 1961–2008 from 165 stations, we have analysed multi-time-scale characteristics such as periodic behaviours, time localisation of wet and dry periods, and annual precipitation in Turkey using continuous Morlet Wavelet tools. The confidence level of 95% is chosen as a threshold value to determine the significant wavelet powers. Then, the wavelet spectrums are interpreted accordingly. In this study, we used MATLAB wavelet functions to complete the analysis. The wavelet spectrum of RPCs for annual and wet/dry seasons' precipitation performed by using the Morlet window is shown in Figure 9a)–c). In this figure, large and small

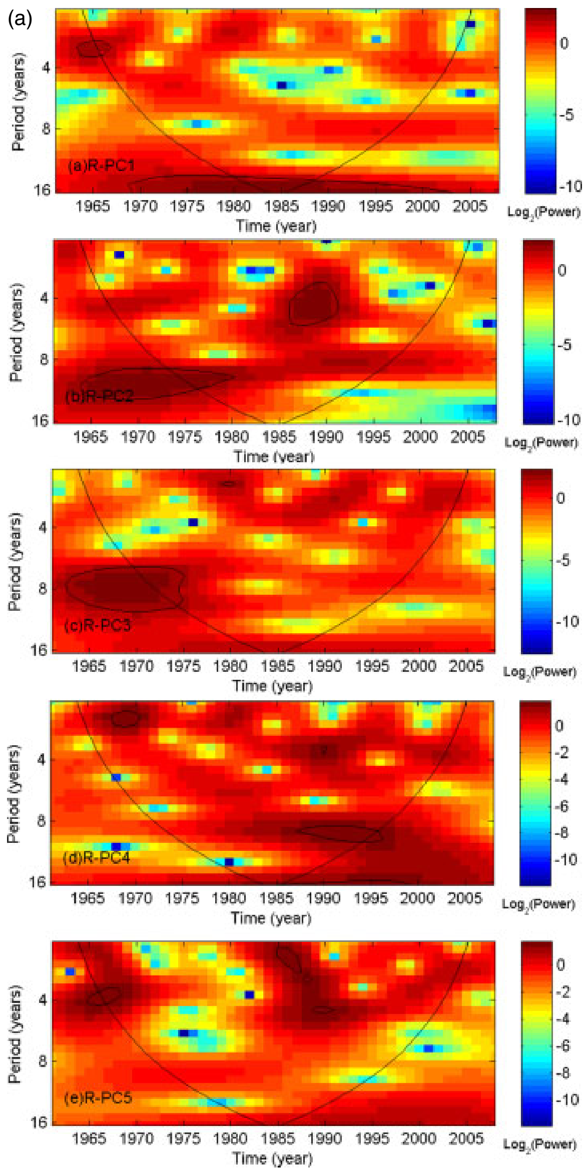

Figure 9a)–c). The wavelet spectrum of RPCs for annual and wet/dry season's precipitation. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

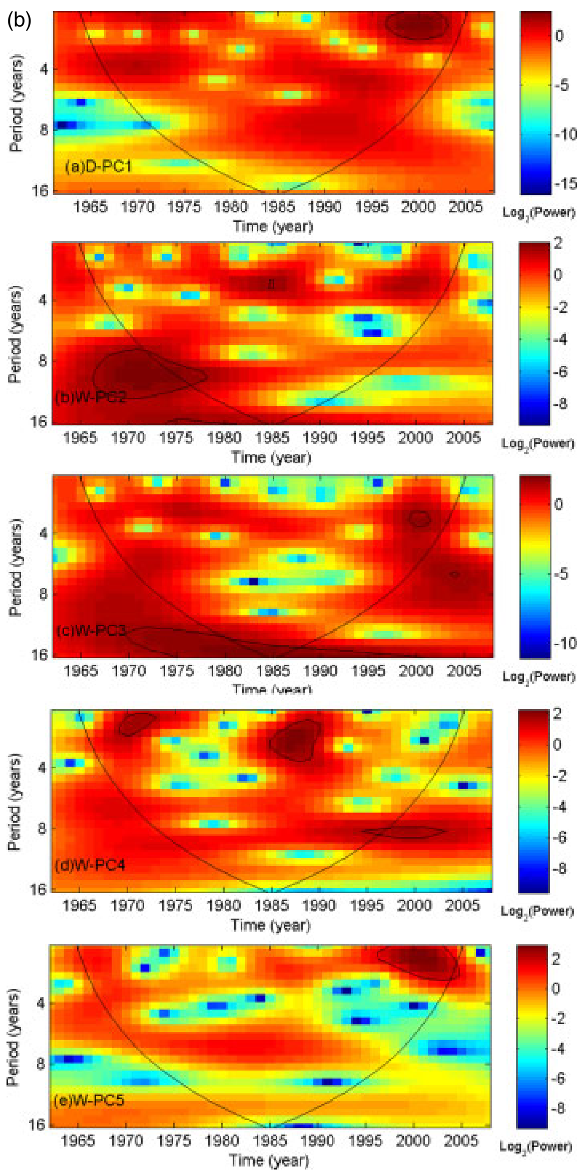

Figure 9a)–c). (*Continued*).

wavelet coefficients represent strong and weak absolute coherences between the time series and the wavelet, respectively. The contour levels in the wavelet spectrum delineate specified wavelet powers, and dark black contours in the wavelet spectrum marks areas where the power is significant at 95% confidence level of a red-noise process. At any given period, changes in the strength of coherence are represented by the density of the wavelet spectrum. A dominant period is reflected by the horizontal pattern spanning that time period. The region below the solid black line in the wavelet spectrum represents the cone of influence (COI), which is defined as the e-folding time for the auto-correlation of wavelet power at each scale. In the COI region, variance or power is reduced due to edge effects and is not considered as significant. Large powers illustrate relatively strong variability at the corresponding time scale. Results of the analyses of the temporal organisation of decadal and bi-decadal fluctuations and their connections with the teleconnection indices are presented in Table III.

The first REOF pattern (Figure 5a) is centred mainly on the western part of Anatolia. The MK trend test of the RPC time series of this region (Figure 8a)) indicates that precipitation has decreased after 1981. The wavelet power spectra for the RPCs are shown in Figure 9a). The 95% confidence regions demonstrate that 1964–1966 and 1979–1981 include intervals of higher precipitation variance. Significant inter-annual (3–4 year) oscillations are identified in precipitation series for the periods of 1964–1966 and 1979–81. While inter-decadal (8–10 year) oscillations were rather weak before 1980, following 1982, it is strengthening and has a maximum value in 1995.

The analysis presents mainly that the spatial pattern of the precipitation field might have changed since 1980, and the dominant period is about 8–10 years for

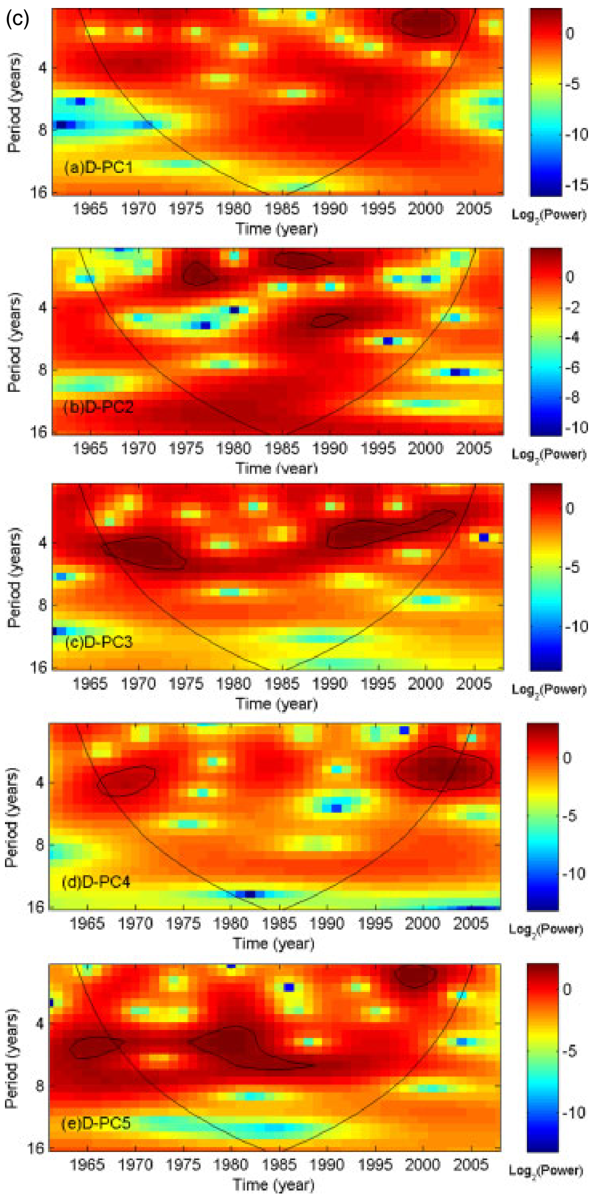

Figure 9a)–c). (*Continued*).

1961–1984 and approximately 5 years for 1994–2006. Figure 9a), b, and c shows the wavelet power spectra for the principal components of annual and wet/dry period precipitation and their periods in years. The contour lines enclose regions of statistically significant wavelet power in the time-frequency domain at the 95% confidence level of a red-noise process. In Figure 9a), the wavelet power spectra for the RPCs are presented with 95% confidence regions and demonstrate approximately periods of 1961–1985 and 1994–2006 with higher precipitation variances. There is a significant inter-annual (3–4 year) oscillation standing out in the 1980s, while inter-decadal (around 9–10 year) oscillation from 1960 to1985. The first RPC loadings are centred on the Aegean region in the west; hence, this regional precipitation can be characterised by high-frequency oscillations with the periods of 3 years, which is stronger in 1980s. The wavelet

Table III. The wavelet spectrum of RPCs for annual precipitation and their connections with indices.

		RPC1	RPC1 IA2[b]	RPC1 ID[c]	RPC2 IA2[b]	RPC2 ID[c]	RPC3	RPC3 IA1[a]	RPC3 IA2[b]	RPC3 ID[c]	RPC4	RPC4 IA2[b]	RPC4 ID[c]	IA2[b]	ID[c]
Annual	**NAO**	−0.44	−0.69	−0.58	−0.62			−0.55	−0.46	**−0.75**	−0.55	−0.63	0.64	−0.65	−0.51
	AO	−0.57	**−0.82**	**−0.84**	**−0.75**		−0.40			−0.61	−0.38	−0.70		−0.53	**−0.73**
	NCP	−0.45	−0.62	−0.67	−0.56	−0.39			−0.54	**−0.87**		−0.60		−0.52	**−0.74**
Wet	**NAO**	−0.41		−0.58											−0.55
	AO	−0.49	−0.59	**−0.89**	**−0.73**							−0.64	−0.62	**−0.70**	−0.66
	NCP		−0.42	**−0.84**	−0.63							−0.58	−0.58	**−0.86**	**−0.77**
Dry	**NAO**				−0.61								0.57		0.54
	AO		0.41		**−0.72**					**−0.84**					
	NCP			−0.60	−0.46	−0.53				−0.65					

Only 99% significant correlations are listed. Correlations which are larger than 0.7, are marked with bold numbers.
[a] 2–7 yr.
[b] 8–9.5 yr.
[c] 10–15 yr.

spectrum of the second RPC, with the loadings centred on the eastern Anatolia region, indicates approximately 4 years oscillation dominating the late 1980s. Following the 1990s, an 8-year oscillation appears. The third RPC wavelet, with the pattern centering on the Mediterranean coasts, indicates approximately 3 years oscillation, where the peak within these periods is recognisable in the 1980s and 1990s. Wavelet spectrum corresponding to the Marmara region indicates approximately 3 years oscillation, which is stronger in the beginning of 1980s and 1990s. The last RPC wavelet, which is centred on Eastern Black Sea, presents approximately 3-5 years oscillation with large variance in the late 1960s and 1990s.

5.4. Teleconnections

Simultaneous physical variations in climate over different parts of the world are teleconnections. In this study, we investigated the relationship between Turkish precipitation variability and teleconnection patterns in inter-annual and inter-decadal time scales. To accomplish this, a frequency-time decomposition of teleconnection indices of: (i) North Atlantic Oscillation; (ii)Arctic Oscillation, and (iii) North-Sea Caspian Pattern, are obtained by using wavelet analysis (the figures are not shown here). Owing to the local affects on precipitation, teleconnection influences on precipitation series may not be detected by simple correlation coefficient (as seen in Table III). Therefore, the correlation coefficients are calculated between the filtered teleconnection indices and filtered significant RPCs of the annual and wet/dry seasonal precipitation.

5.4.1. NAO index

The NAO Index is identified by Wallace and Gutzler (1981). NAO is the widely used teleconnection index and a measure of meridional oscillation of atmospheric mass between the sub-tropical anticyclone near the Azores and the sub-polar low-pressure system near Iceland. It determines westerly wind strength over the North Atlantic in winter. NAO strongly influences the European and Mediterranean climate. It has been shown that positive phase of NAO is associated with a northward shift in the Atlantic storm activity, and it leads to wetter condition in northern Europe and drier conditions over the Mediterranean during winter months (Ghioca, 2009). Our analysis reveals that NAO index has negative correlations with almost all principal components of annual precipitation, except decadal RPC4 and RPC5 for dry season (Table III). RPC4 and RPC5 loadings are negative almost everywhere on the domain, with the center of high variations located on the central Anatolia and northeastern part of Turkey, and on the western (Aegean) regions. Therefore, the dry precipitation change in these regions is still associated with the inverse NAO index. However, only the first and the fourth RPCs of unfiltered annual precipitation, representing the western and central parts of Turkey, show significant correlations. The filtered RPCs are generally in good agreement with the AO variability. In addition, significant inter-annual changes (2–7 years) of AO induce precipitation anomaly only on the Mediterranean region. Moreover, an anti-correlation between NAO index and precipitation is also obtained along Aegean region (RPC1) during the wet season. This result is consistent with the findings of Türkeş and Erlat (2008), which is based on the relationship of the precipitation time series at 61 stations with the winter NAO index. In addition, negative correlations, although statistically not significant, are identified during spring and autumn. Similarly, Tan and Unal (2003) also found that dry/wet conditions over Turkey are dominant during positive/negative NAO index in the winter season. Krichak and Alpert (2005) found similar signatures of the NAO in the atmospheric circulation during wet winter months over the Mediterranean region. Our results also highlight the role of large-scale circulation patterns for the region's precipitation and its changes. All filtered annual RPCs with the periods of 8–15 years are associated with the NAO. However, wet RPC1 and RPC5 are significantly correlated with the NAO. In general, our results suggest that the NAO influence on the region is not nearly as significant as the AO in the low frequencies in winter.

Decreasing wet/dry seasonal precipitation in the west part of the country will have strong impact on life, agriculture, drinking water, and hydro-electricity production. The same suggestion is valid for the east and southeastern Anatolia. This result will have an impact on the southeast Anatolia development project (GAP, in Turkish) and the headwater regions for the Tigris and Euphrates rivers whose waters are shared primarily between Turkey, Syria, and Iraq, which was explained by Cullen and deMenocal (2000) based on NAO indices.

5.4.2. AO index

The AO teleconnection pattern is characterised by a see-saw of atmospheric pressure between the Arctic and northern middle latitudes between 37° and 45°. AO represents the state of atmospheric circulation over the Arctic. Its positive phase brings lower-than-normal pressure over the polar region, and higher pressure in the mid-latitudes, steering extra tropical storms northward, bringing wetter weather conditions to northern Europe, and drier conditions to the eastern Mediterranean and the Middle East. Over Europe, wetter conditions prevail over the eastern Mediterranean.

Our results also support the previous findings. The AO index is the most correlated index with the precipitation field over Turkey among all the indices examined here (Table III, the first column of each RPC). Especially, precipitation variability for annual totals and wet periods in the western part of Turkey and Mediterranean coast are connected to the variability of the AO index. However, the relationship of the AO index and Turkish precipitation field is increasing towards the low frequencies. For instance, RPCs for annual, wet/dry periods are closely coupled with AO in the time scales of 8–15 years. Correlations between filtered times series of RPCs and AO index are significant at 99% significance level

(Table III). Specifically, all RPCs of annual precipitation reveal very high correlations with AOI in the time scales around 8–9.5 years, except the RPC3 signifying the Mediterranean region. However, only RPC1, 3 and 5 are related to the AOI in decadal time scales (10–15 years) in the western part of Turkey, Mediterranean and eastern Black Sea. All correlations are found to be negative, that is, positive phase of the AO index results in lower-than-normal precipitation amounts in Turkey. During wet period, precipitation variability in the western part of Turkey, extending towards Marmara and north of central Anatolia, is linearly congruent with the inverse AO index in decadal time scales, and the correlation coefficient (−0.89) is the highest among all the regional correlations for all time scales under study.

Similar to the annual precipitation, Turkey, excluding Mediterranean coast, is under the influence of around 8-year and decadal fluctuations in the AO during wet season. However, RPC 1 and 2 show noteworthy connection with the AO in an 8-year time scale for dry season. Since the first dry RPC is centred mainly on northwestern Turkey and the second dry RPC is on the eastern Black Sea area, opposite signs of correlations between the RPCs and the AO index state that eastern Black sea area becomes wetter, while the western part of Turkey becomes drier in around 8 years time scales during dry period. This result suggests that, lower-than-normal pressure over the polar region and higher pressure in the mid-latitudes (for AO negative phase) cause positive precipitation anomaly on the west and negative precipitation anomaly on the east of the Black Sea coast.

5.4.3. NCP index

NCP index is identified by using the differences of 500 hPa geopotential heights over the regions near the North Sea and northern Caspian Sea, normalised by the standard deviation of the specific month. The NCP is evident at the 500 hPa level and more pronounced during winter and the transitional seasons. A negative NCP implies an increased cyclonic anomaly circulation around the western pole of the NCP and an increased anticyclonic anomaly circulation around the eastern pole of the NCP. This results in an increased southwesterly anomaly circulation towards the Balkans and western Turkey. Similarly, during the positive NCP, the circulation suggests an increased northwesterly circulation towards Eastern Europe, and an increased northeasterly circulation towards the Black Sea. This leads to an increased northeasterly anomaly circulation towards the western Turkey (Kutiel *et al*., 2001). Kutiel and Benorach (2002) found no significant correlation between NCP and NAO indices and above-normal precipitation over the Balkans and Middle East during positive NCP index years. On the other hand, Kutiel *et al*. (2002) state that Greece and Turkey receive more rainfall during negative NCP years, while the Black Sea region of Turkey receives more rainfall during positive phase of NCP. Relationship of the NCP index with the surface variables are also investigated in the Eastern Mediterranean domain by other studies (Tatlı, 2007; Ghasemi and Khalili, 2008). Gunduz and Ozsoy (2005) report that the heat fluxes over the Aegean and southern Black Sea from October through March are considerably affected by the NCP for frequencies lower than 5 years. They also show that NCP index has a higher correlation with the AO index than with the NAO index.

In this study, we have analysed the correlation between RPCs and the NCP index for annual total precipitation and wet/dry period precipitation. We obtained a significant negative correlation coefficient (−0.45) only between the RPC1 and the NCP index for annual precipitation (Table III). However, filtered RPCs are linked to the variations of NCP index in time scales of 8–15 years. For annual precipitation of Turkey, RPC 1, 3, and 5 (corresponding regions: western Turkey, Mediterranean, and eastern Black Sea, respectively) are very well connected to the decadal fluctuations of the NCP index. Since all correlations calculated are above 0.5 and significant, we can conclude that NCP controls the precipitation on all regions in the period of 8 years. For the dry period, the strength of the connection between Turkish precipitation and the NCP index weakens except at the northern latitudes (RPC 1–4). Therefore, the decadal fluctuations of the NCP trigger the June–September precipitation anomalies at this zone and contribute to the annual variability.

6. Conclusions

Precipitation is one of the most important climatological variables in Turkey, due to its importance in water supply, agriculture, energy generation, and economic activities. Precipitation in Turkey presents a complicated spatial and temporal structure. Given the complexity of the precipitation variability on various spatial and temporal scales, systematic methods are needed to examine the spatio-temporal variability of precipitation and to explore possible causes of the shift of its variability from the series of the annual, wet (Nov–Apr) and dry period (June–Sept) precipitation data.

In this study, precipitation data for 1961–2008 from 165 stations in Turkey have been analysed using the REOF method, the Mann-Kendall method, and Morlet WT method. Total of five principal components are found, and they are rotated by VARIMAX rotation to overcome domain dependencies related to un-rotated principal component analysis. The precipitation time series from annual basis are analysed to detect the spatial patterns for annual periods using the REOF analysis technique, and to demonstrate the trends of precipitation by Mann-Kendal method and to detect the rainfall periodicities using continuous Morlet WT of annual RPC series.

The major conclusions of this study can be summarised as follows:

1. The REOF analysis results for annual precipitation illustrate that there are five coherent precipitation

regions in Turkey. They are mainly centred around West of Turkey in the first REOF, eastern parts of Mediterranean, eastern and southeastern Anatolia in the second REOF, the Mediterranean coast in the third REOF, the northwestern part of Turkey in the fourth REOF and finally, the eastern Black Sea coast in the fifth REOF. The REOF analysis of wet/dry period precipitation reveals that the annual precipitation variability is controlled mainly by the wet season, since most of the significant REOFs for the annual and wet periods are represented by the similar spatial patterns.
2. The MK trends analysis of the RPC series show that, in general, annual precipitation decreases in the west, south, and southeastern parts of Turkey. The only increasing trend of the annual precipitations is found in the eastern Black Sea coasts. However, the Mann-Kendall test estimates that only the trend of the fifth REOF is significant with 95% confidence level. Since the other RPCs are dominated by inter-decadal oscillations, the time series of the RPCs show increasing and decreasing trends in different years of the study period. Therefore, they are not found significant even though general trend is positive.
3. Similar to the above explanation, wet and dry period trends are not found significant with 95% confidence level. Moreover, except Black Sea coast, all calculated trends are negative/positive for wet/dry seasons. For the Black Sea region, both wet and dry season precipitations increase between 1961 and 2006. Dry season precipitation trends are larger than the wet season. Therefore, annual precipitation positive trend of the Black Sea region are dominated by dry period.
4. Results of precipitation periodicities from wavelet analysis reveal that there are obvious periodic oscillations of 3–4 years and 8–10 years for the annual precipitation variation. There is a significant inter-annual (3–4 years) oscillation standing out in the 1980s in most of the regions, while almost decadal (around 10 year) oscillation dominates years between 1960 and 1985.
5. Relationship between precipitation variability and teleconnection patterns in inter-annual and inter-decadal time scales are examined to accomplish a frequency-time decomposition of teleconnection indices of: NAO, AO, and NCP.
6. The NAO influence on the region is not nearly as significant as the AO in the low frequencies in the wet season. Decreasing wet/dry season precipitation in the west part of the country, the east and southeastern Anatolia will have strong impact on agriculture, drinking water, and hydro-electricity production. This result will have an impact on the southeast Anatolia development project and the headwater regions for the Tigris and Euphrates Rivers, which is explained by Cullen and deMenocal (2000).
7. The AO index is the most correlated index with the precipitation field over Turkey. All RPCs of annual precipitation reveal very high correlations with AO index in the time scales around 8–9.5 years, except the RPC3 signifying the Mediterranean region.
8. The decadal fluctuations of the NCP index are well correlated with the annual precipitation RPCs corresponding to the regions of western Turkey, Mediterranean and eastern Black sea. Therefore, the NCP controls the precipitation on all regions in the period of 8 years.

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