Trends in Orographic Rainfall over the Fertile Crescent

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Abstract

The author presents a precipitation climatology and its trend over the mountainous areas of the Middle East using the dense network rain-gauge observation data gathered by the APHRODITE project. Coastal and orographically induced precipitation zones are found in semi-arid regions, and those patterns are consistent with those observed by the Precipitation Radar of the Tropical Rainfall Measuring Mission.

The author then uses 34-year monthly precipitation data over Turkey, Israel and Iran to show seasonal precipitation trends. There is a strong and significant decreasing trend over Turkey and Israel in winter, especially in January. Trends over Turkey differ from month to month, while general trends over Iran differ little from season to season. On the other hand, Iran has orographically characterized trends. Trends are affected by the mountain ridges and slopes of the Taurus, Anatolian, Zagros, Erboz and other ranges.

Then she compares the trends at thirteen high stations paired with low stations under the same synoptic conditions for the winter season. Most station pairs showed decreasing trends in the ratio of precipitation at the high stations to that at the low stations. Exceptional cases, which showed increasing trends in the ratio, were observed in the easternmost part of the Taurus Mountains (north of Syria) and in the northwestern part of Turkey.

Key words: Middle East, mountain climate, orographic precipitation, paleo-climate, precipitation trend

1. Introduction

Quantitative measurement of precipitation is important in water management as well as climate study. Hence, tremendous efforts have been made to develop grid precipitation data for the last two or three decades. Satellite observations can be used to estimate precipitation. However, accurate measurements of precipitation over land from satellite observations are particularly difficult. Hence, the collection and analysis of precipitation data using rain gauges have been urged (Xie *et al*., 2007; Yatagai *et al.*, 2009). Moreover, rain-gauge data have an advantage of long-term data archives created for use in discussing climatic trends.

However, in the process of making a rain-gauge based product, characteristic features of rainfall distribution such as small-scale orographic patterns are sometimes smoothed out. As is described below, long-term trends in precipitation in mountainous regions are very important to ascertain, especially in arid/semi-arid regions.

Mountain water resources are important in arid/semi-arid regions, and quantitative estimations of orographic precipitation are critically important to climate change studies, including model simulation studies, in relation to the global warming issue. Recently, the amounts of precipitation and water resources and their trends over the East Mediterranean and part of the Middle East have become a concern since most climate models simulate a decreasing trend in future precipitation under global warming scenarios (IPCC, 2007; Milly *et al*., 2005; Nohara *et al*., 2006; Kitoh *et al*., 2008) and evidence has been reported showing a trend of decreasing precipitation over the Middle East (Alpert *et al*., 2002, 2006; Bolle 2003, Zhang *et al*., 2005; Yatagai, 2005).

However, no detailed trend has yet been clarified over the Middle East, especially for the mountainous regions, because of a lack of assembled data (Adam *et al*., 2006). National data for the Middle East are neither well assembled nor available to the international research community (Zhang *et al*., 2005); hence, the global dataset and global analysis have yet to clarify the distribution pattern of precipitation in the region and its seasonal changes and trends.

A recent rain-gauge collection (Yatagai *et al*., 2008) indicated a crescent-shaped rainfall area over the Middle East, which corresponded to the ancient Fertile Crescent. Roughly speaking, the crescent-type distribution of precipitation is due to mountains (Zagros, Anatolian Plateau) and coastal hills along Israel and Syria. This orographic rainfall is a water source for rivers such as the Tigris, Euphrates and Jordan River, so orographic rainfall of the Fertile Crescent was critical in ancient times as well as at present and in the future. Issar and Zohar (2004) described paleo-climate studies over the Middle East. In spite of much archaeological evidence, there are few descriptions of climate zones and those that exist are based on limited data. To investigate historical trends in the orographic rainfall over such a region seems to be a worthy endeavour for interpreting various kinds of proxy data in the future. Hence, I show the seasonal patterns of precipitation distribution and their trends over the crescent-shaped orographically-induced rainfall area with long-term ground-observation precipitation data collected in Turkey, Israel and Iran.

The object of this study is to display seasonal precipitation over the Middle East and to study the trends in orographically induced precipitation regions. Since winter is a main precipitation season in this area, I concentrate on winter precipitation in this paper.

2. Data and Precipitation Climatology

2.1 Data

The precipitation dataset used in this study is similar to that used by Yatagai *et al*. (2008). Although we collected daily precipitation data throughout the APHRODITE project <http://www.chikyu.ac.jp/precip/>, here I only use monthly precipitation data. Since trend analysis is the main purpose of this study, I used only quality-controlled long-term data series.

As complementary data, I also use rainfall patterns determined from Tropical Rainfall Measuring Mission (TRMM) satellite observations and water vapour transport computed using the European Centre for Medium-range Weather Forecasts (ECMWF) 15-year reanalysis (Gibson *et al*., 1997) from a previous study (Yatagai, 2003).

2.2 Climatology

Figure 1 shows a gauge-based annual precipitation climatology over the Middle East (Yatagai *et al*., 2008). A clear crescent-shaped pattern is observed through Israel, part of Syria, southeastern Turkey, northernmost Iraq and western Iran. As shown in the orography map (Figure 1, bottom), the orographic precipitation is due to moisture transported mainly from the west. The moisture pattern of winter is presented in Fig. 2. There are strong precipitation zones to the south of the Caspian Sea (northern Iran), around the Black Sea and in western Turkey. These wet zones are mainly due to adjacent inland sea water.

The middle panel of Fig. 1 is a composite chart of the 10-year average of the annual mean precipitation rate as determined by the precipitation radar (PR) on board the TRMM. Radar can depict the character of orographic rainfall. (north of 36°N is not shown since the coverage of the TRMM/PR does not extend that far). There is clear orographic precipitation along the Zagros Mountains (western Iran) and precipitation maxima occur along the eastern Mediterranean coast. The TRMM/PR pattern shows a weak maximum at the centre of Saudi Arabia that confirms a similar maximum on the precipitation map based on rain gauges (upper panel).

Figure 2 (upper) shows the winter (December-February) pattern of precipitation. It resembles the annual one (Fig.1), and the crescent shape of the precipitation distribution is clear in winter. To illustrate the general air flow and hydrological conditions, the water vapour flux pattern for winter is also shown in Fig. 2 (lower). In the Middle East domain, generally speaking, moisture comes from the west, and the Mediterranean Sea and Arabian Sea show divergence. In winter, relatively strong moisture convergence is observed around Iraq and the eastern Black Sea. The orographic rainfall discussed above is due to western or southwestern moisture converging in and around the mountainous terrain. Since a moisture flow pattern based on precipitation does not always correspond to the mean moisture flow pattern, especially over arid/semi-arid regions (Yatagai & Yasunari, 1998), further investigation using daily precipitation/and circulation fields is expected in the future.

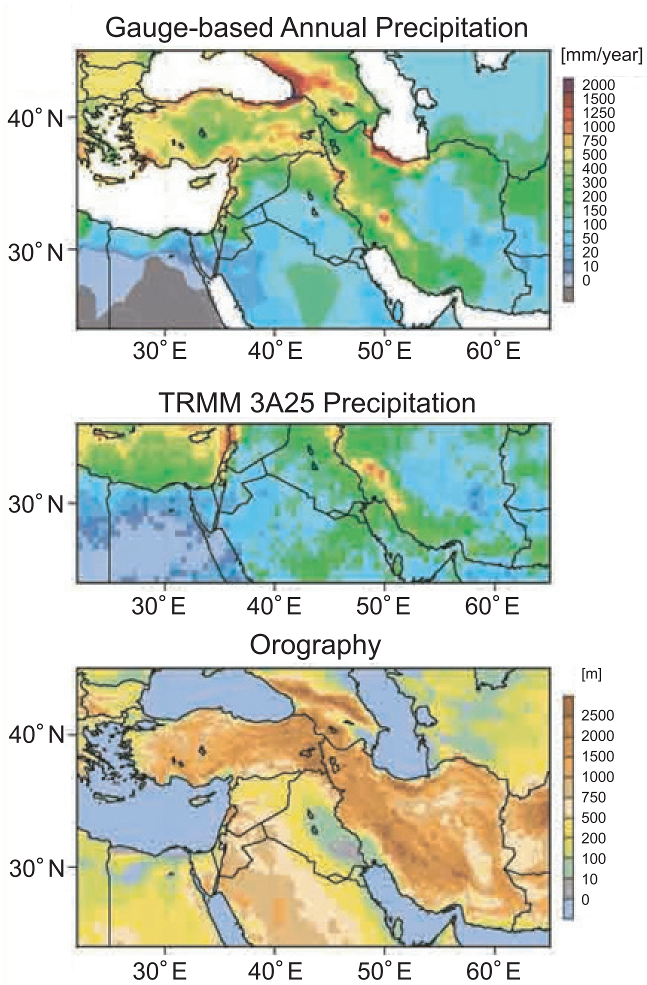

Fig. 1 Top: Annual precipitation climatology (mm/year) derived using a rain-gauge network (Yatagai *et al*., 2008). Middle: Annual precipitation pattern derived from ten years of observations (1998-2007) by the Precipitation Radar on board the TRMM (3A25 monthly product). Bottom: Orography (m).

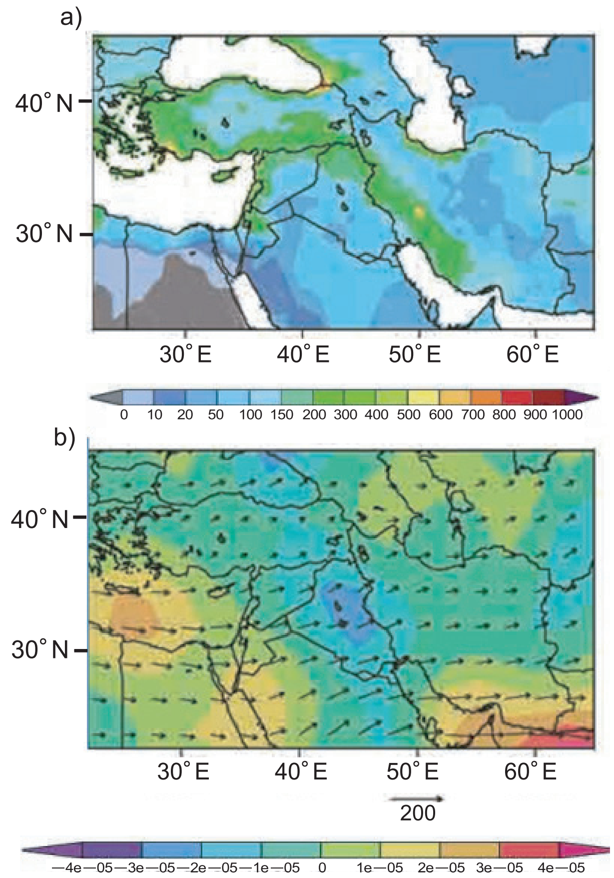

Fig. 2 a) Winter (December-February) precipitation climatology (mm/3months) defined by Yatagai *et al*. (2008).
b) Vertically integrated winter-mean water vapour flux (mm·m/s) and its divergence (kg/m^2·s).
Unit vectors of the water vapour flux are shown on the maps. Red to light green indicates divergence and violet to blue to green indicates convergence.

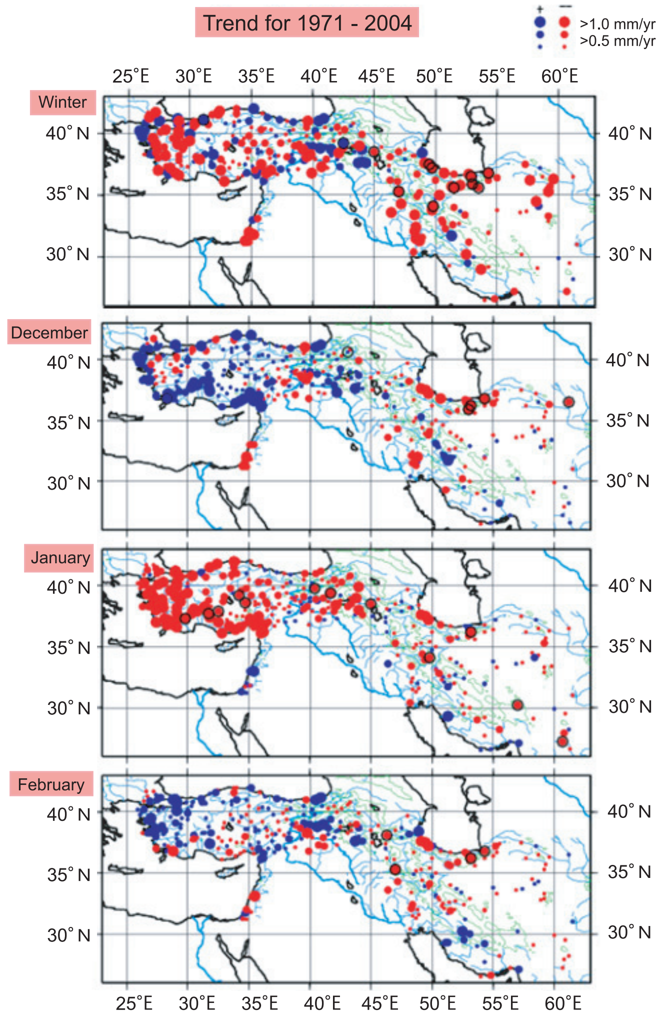

Fig. 3 Linear trends of winter and monthly (December, January and February) precipitation for the period of 1971–2004. Blue dots indicate increasing trends while red dots indicate decreasing trends. Black open circles indicate the time series to be beyond the 5% significant level according to the t-test.

3. Precipitation Trends

Here I discuss mainly winter precipitation trend patterns. Figure 3 shows seasonal precipitation and winter month trends during 1971-2004 over Turkey, Israel and Iran. Since the periods of data coverage differ with the dataset and stations, I only used stations at which more than 30 years of data were available for the period of 1971-2004. For winter precipitation, I added December precipitation of the previous year to the summation of that of January and February. I applied the t-test to detect trends.

There are general decreasing trends in winter throughout Turkey, Israel and most of Iran. Significant decreasing trends can be seen in the northern part of Iran. In the Middle East domain, generally speaking, moisture comes from the west. Interestingly, trends for the three winter months over Turkey and Israel vary, whereas there is more uniformity over Iran. There are strong increasing trends in the south of Turkey in December and in the west in February. In Iran, there are decreasing trends in the west and along the Caspian Sea throughout the winter. Interestingly, the trends differ along the Zagros mountain chain. There is an increasing trend along the western foothills, decreasing trend along the western slopes of the Zagros, and increasing trend in central Iran (east of the Zagros).

From a macroscopic view, one can see that the trend patterns are not sporadic but they show the same signals in some regions of 300 - 1,000 km horizontal scale of orographically characterized region. For example, batches of the same trend signals are found in the following regions: west of the Taurus Mountains (January), Anatolia (January), along the Caspian Sea (winter), the western part of Turkey (winter), and upper reaches of the Tigris and Euphrates (winter).

As mentioned before, it is important to investigate the trends and dominant factors of interannual variation in precipitation in elevated places, especially for places where there is an influx of precipitation into an arid region. Dominant factors of international variability have been investigated in the arid region of China and adjacent mountains, and interannual variation modes which are related to both highlands and lowlands have been found to show larger amplitude than that of a mode which shows independent variabilities between highlands and the lowlands (Yatagai, 2007). The trend results shown here are consistent with those of previous studies. Namely, in general, the trend signals are the same in high and low places where the same large-scale moisture flow or synoptic systems affect their precipitation amounts.

3.1 Regional analysis of trends in orographic precipitation

It is important to clarify whether trends at relatively high stations, which are considered to be more important as water resources, are increasing or not. Hence, here I will examine the trends in pairs of high and low places which show similar international variation signals which eliminate such large-scale variability.

I selected some regions where batches of the same trend signals appeared with respect to the orography. Figure 4 shows four regions (A-D) I will discuss in the next few figures (Figs. 5-8).

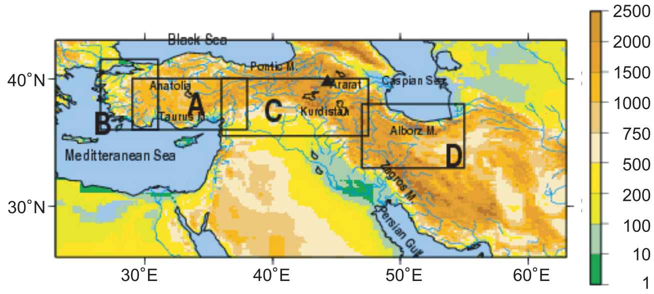

Fig. 4 Map of major mountains and close-up areas to be shown in subsequent figures. Color represents altitude (m).

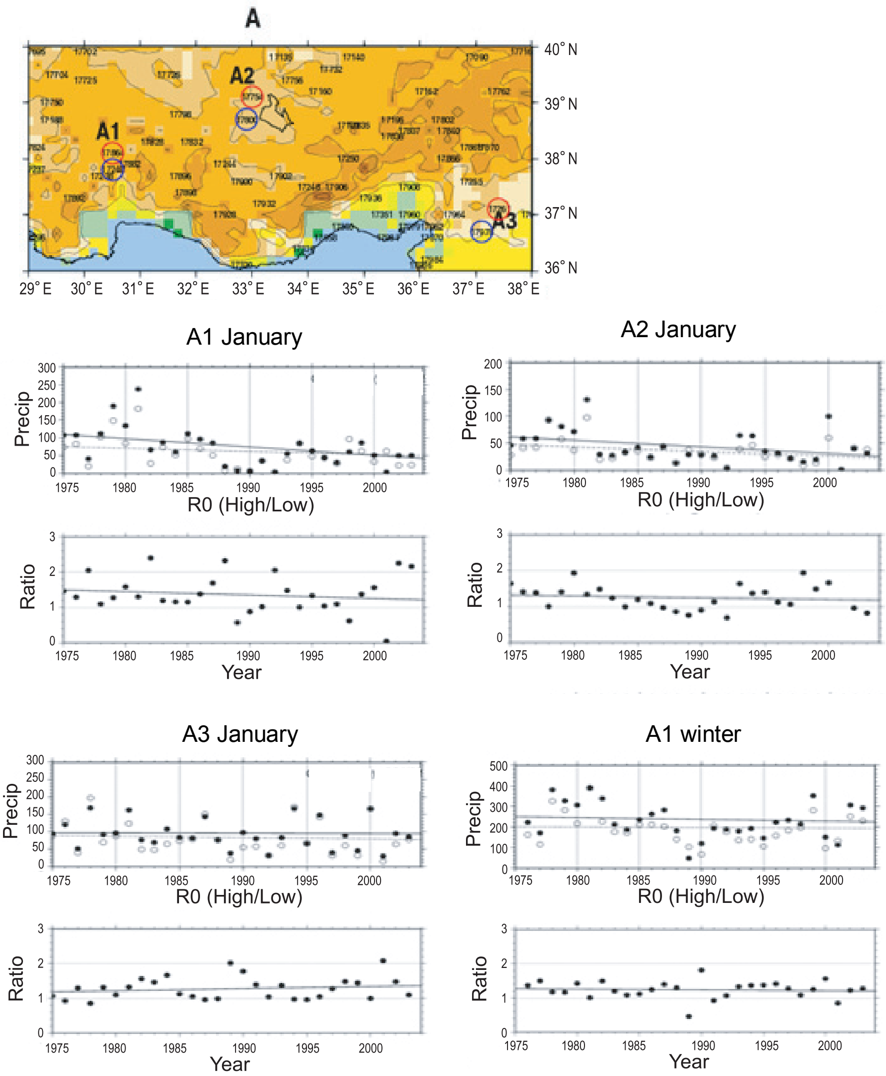

Fig. 5 Map of Region A (Taurus Mountains) shown in Fig. 4. Colours showing elevation are the same as in Fig. 6. Contours are drawn every 1,000 m. Numbers in the map are stations used in this study. A1, A2 and A3 are the station pairs along the mountains. Red circles show higher stations and blue circles show lower stations.

The upper graphs of A1, A2 and A3 show January precipitation of each year, in which closed (open) circles show precipitation data of higher (lower) stations and straight (dashed) lines show linear trends of higher (lower) stations. "Ratio" means the precipitation ratio of high station vs. low station, and the straight line shows the trend of this ratio.

3.1.1 Taurus Mountains (Region A)

It is expected that more stable results may be available if we treat seasonal trends rather than monthly trends. However, monthly trend patterns in the winter season differed very much from one to the next (Fig. 3). Hence, I show the January trend pattern along the Taurus Mountains, where I found significant decreasing trends in January. Figure 5 (upper map) shows stations in Region A for which there are 30 years of data from the period 1975-2004.

I selected station pairs within each orographically characterized region where stations showed similar trend signals with the following criteria: 1) The distance between the pair of stations was less than approximately 100 km (1 degree). 2) The lower elevation station was located in the (dominant) windward direction from the higher elevation station. (I used Fig. 1 and other climatological figures.) Here I refer to the two stations in a pair as the high station and the low station. 3) The correlation coefficients between the high station and low station were very high (around 0.9 or higher).

In Figure 5 I show only three pairs (A1, A2 and A3) but actually I investigated more stations by taking the correlation coefficients at each pair of stations for 1975-2004. Table 1 shows a summary of the location information (longitude, latitude and altitude) and correlation coefficients and trends in January. I calculated the ratio (Ro) of precipitation at the high station to that of the low station, and the linear trend of Ro. Graphs included in Fig. 5 show trends of station pairs (A1, A2 and A3) for January and the trend of A1 for the winter season (December, January and February (DJF)). Each upper graph shows the precipitation amount and trend and each lower graph shows Ro=(precipitation at high station)/(precipitation at low station) and its trend.

As we saw previously, all six stations shown in Fig. 5 showed a decreasing trend for January. However, Ro showed a decreasing trend in A1 and A2 but an increasing trend in A3. That means decreasing trends at high stations relative to low stations were observed at A1 and A2.

Next I show the results for the winter season (DJF). A summary is given in Table 2. Plots of precipitation and Ro at the A1 pair in winter are given in the right-bottom corner of Fig. 5.

Ro in winter at A1 showed a weak decreasing trend, although the amplitude in Ro was smaller than in January. Ro in winter at A2 showed a decreasing trend and that of A3 showed an increasing trend as summarized in Table 2, which was consistent with the results of January itself. Comparing the correlation coefficients between Table 1 (January) and Table 2 (winter), the correlation of the winter season always showed a higher value than that of January. Hence, I will mainly argue for the winter season.

3.1.2 Western Turkey (Region B)

Figure 6 shows the pattern of Region B, shown in Fig. 4, enlarged. To select the station pairs, I took into account the distance between the two stations, wind direction (moisture transport) and elevation. I selected station pairs that showed very high correlation coefficients (larger than 0.9) in winter. I did not write about

Table 1 Station pairs and their locations. Correlation coefficients, trends at each station, trends of Ro (precipitation at high station/precipitation at low station) for January. Red numbers in the Ro trend indicate a decreasing trend in Ro. C1 is not shown since it is the same as A4.

Pair	Station ID	Longitude (deg.)	Latitude (deg.)	Altitude (m)	R	Trend	Trend of Ro
A1 (high)	17864	38.08	30.45	1160	0.905	-2.338	-9.71E-03
A1 (low)	17240	37.77	30.55	997		-0.895	
A2 (high)	17754	39.10	33.00	1010	0.924	-1.233	-4.65E-03
A2 (low)	17800	38.65	32.93	969		-0.864	
A3 (high)	17261	37.38	37.07	855	0.945	-9.631	6.11E-03
A3 (low)	17978	37.12	36.72	638		-0.353	
B1(high)	17292	28.37	37.22	646	0.901	-3.993	-2.02E-03
B1(low)	17924	28.68	36.97	24		-1.807	
B2(high)	17742	27.18	39.12	53	0.935	-2.082	-9.85E-03
B2(low)	17180	26.88	39.07	3		-1.276	
B3(high)	17676	29.08	40.13	1878	0.676		
B3(low)	17116	29.07	40.18	100			
B4(high)	17704	29.50	39.55	834	0.854	-0.716	1.32E-02
B4(low)	17700	28.63	39.58	639		-1.923	
B5(high)	17725	29.97	39.42	969	0.817	-1.852	-2.96E-03
B5(low)	17704	29.50	39.55	834		-0.716	
C2(high)	17768	38.92	39.07	953	0.818	-0.421	-1.90E-03
C2(low)	17804	38.75	38.80	808		-0.326	
C3(high)	17847	38.28	39.77	1000	0.931	-0.842	-2.97E-02
C3(low)	17874	39.45	38.13	700		-1.385	
C4(high)	17740	41.70	39.37	1715	0.599		
C4(low)	17776	41.07	38.97	1365			
C5(high)	17880	44.02	38.05	2400	0.547		
C5(low)	17285	43.73	37.58	1728			
D1(high)	990159	50.73	36.86	79	0.786	-0.999	-2.20E-02
D1(low)	40732	50.67	36.90	-20		0.646	

the results for B3 of January, since the correlation coefficient was low (Table 1).

Decreasing trends in Ro are found the for the coastal station pairs, B1 and B2. At both station pairs, some recent years show more precipitation at the low station, and the Ro of B2 fell below 1 after the late 1980s.

A clear increasing trend in Ro is found at B3, where differences in altitude as well as differences in precipitation amounts are large between the high station and the low station. I chose this pair, which are aligned in a north-south direction, since the wind from the Sea of Marmara and from the Black Sea come to this mountain. However, I may consider the local wind direction in the future.

The high station of B4 (17704) is the same as low station of B5. Both correlation coefficients at B4 and B5 are very high (larger than .95). However, for pair B4, precipitation at the high station is less than at the low station. Therefore, we need to be careful about interpreting the increasing trend of Ro in B4. On the other hand, at station pair B5, the high station (17725) shows more precipitation than the low station (17704), and the Ro of B5 shows the largest decreasing trend among the station pairs shown in Table 2.

There are more complicated moisture flow patterns among the Region B pairs, namely, it might not be simply westerly at B5 but the southerly mountain makes a complicated moisture flow and convergence system there. I won't argue about the cause of increasing Ro at B3 and B4, since I cannot clarify the moisture transport and orographic precipitation system there.

3.1.3 Upper reaches of the Tigris and Euphrates (Region C)

Then we move on to the northern part of the Fertile Crescent, the upper reaches of the Tigris and Euphrates (Region C). In the map of Fig. 7, the station pair C1 is actually the same as pair A3. I showed the results of A3 January in Fig. 7 but not for the winter pattern. As shown in Table 2, an increasing trend in Ro is also found in this season.

A clear decreasing trend in Ro is observed at C2 in winter. It is remarkable that the C1 (=A3) pair shows a different Ro trend signal from the surrounding station pairs. C3 shows a very small decreasing trend in Ro, however Ro exceeds 1 for the years 1986-1993 but falls below 1 during the other years. We must consider the local circulation, especially for the southerly mountain ridge.

At station pairs C4 and C5, the high station has less precipitation than the low station. It is unclear from this analysis why the high station has less precipitation, as the high station might be located above the maximum precipitation zone or there may be higher altitudes than the high station itself, and the high station observes rainfall from the airflow over such higher places. In any case, we may distinguish the meaning of the decreasing trend of Ro at C4 and C5 from that of C2.

I checked the station pairs to the east of C5, but I could not find a good pair in the Iranian region included in Region C.

Table 2 Same as Table 1 but for winter (DJF). Results for all Regions A, B and C are shown.

Pair	Station ID	Long. (deg.)	Lat. (deg.)	Alt. (m)	R	Trend	Trend of Ro
A1 (high)	17864	38.08	30.45	1160	0.972	-0.878	-2.20E-03
A1 (low)	17240	37.77	30.55	997		-0.289	
A2 (high)	17754	39.10	33.00	1010	0.967	-0.947	-5.98E-03
A2 (low)	17800	38.65	32.93	969		-0.354	
A3 (high)	17261	37.38	37.07	855	0.980	0.736	4.26E-03
A3 (low)	17978	37.12	36.72	638		-0.327	
B1(high)	17292	28.37	37.22	646	0.972	-1.013	-1.20E-03
B1(low)	17924	28.68	36.97	24		-0.402	
B2(high)	17742	27.18	39.12	53	0.945	-1.656	-5.23E-03
B2(low)	17180	26.88	39.07	3		-5.19E-04	
B3(high)	17676	29.08	40.13	1878	0.935	-1.126	4.49E-03
B3(low)	17116	29.07	40.18	100		-1.100	
B4(high)	17704	29.50	39.55	834	0.959	-0.298	1.79E-03
B4(low)	17700	28.63	39.58	639		-0.963	
B5(high)	17725	29.97	39.42	969	0.962	-1.238	-9.21E-03
B5(low)	17704	29.50	39.55	834		-0.298	
C2(high)	17768	38.92	39.07	953	0.977	-0.529	-6.54E-03
C2(low)	17804	38.75	38.80	808		-3.68E-02	
C3(high)	17847	38.28	39.77	1000	0.949	-1.920	-1.15E-03
C3(low)	17874	39.45	38.13	700		-1.650	
C4(high)	17740	41.70	39.37	1715	0.965	-0.276	-2.08E-03
C4(low)	17776	41.07	38.97	1365		0.233	
C5(high)	17880	44.02	38.05	2400	0.923	0.316	-2.41E-04
C5(low)	17285	43.73	37.58	1728		3.173	
D1(high)	990159	50.73	36.86	79	0.882	-2.654	-7.92E-03
D1(low)	40732	50.67	36.90	-20		-0.571	

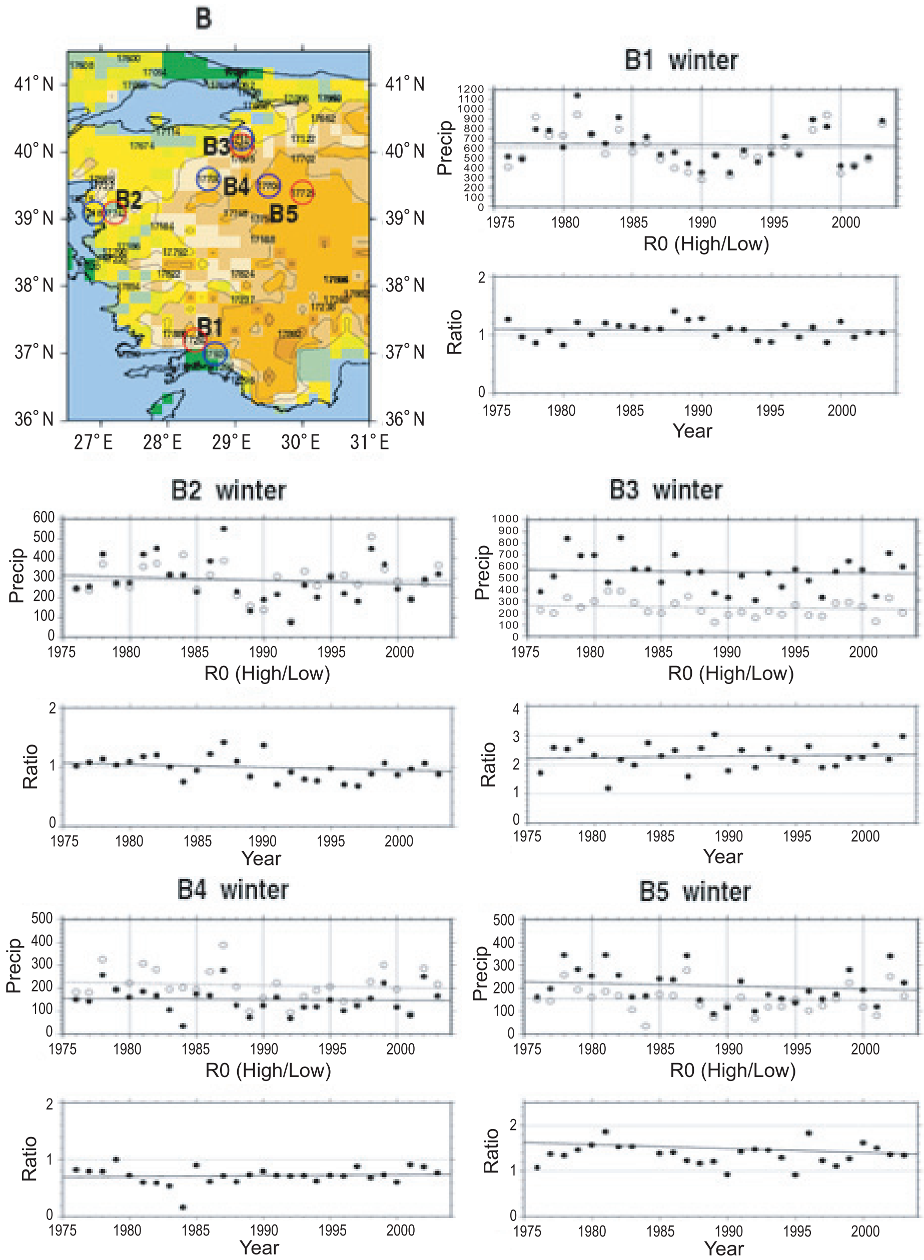

Fig. 6 Same as Fig. 5 but for Region B (west Turkey) in the winter season.

3.1.4 Along the Caspian Sea (Region D)

There are significant decreasing trends along the Caspian Sea, to the north of the Erboz Mountains. It is a very interesting place in terms of prominent orographic precipitation, but no idealized station pairs are found between the mountains and foothills. However, I chose D1, where there was a difference in altitude (high station = 70m, low station = –20m). The correlation coefficient of this pair is relatively lower than the others I have shown (=0.882), as seen in the results of this station pair in Fig. 8. A clear decreasing trend of Ro is found at this station pair.

I have checked station pairs north of the Persian Sea and Zagros Mountains, since they show a regional trend structure. However, it is difficult to find a good station pair according to my criteria described above, so I do not show the results for other parts of the Iranian domain.

3.1.5 Discussion

In this study, to select the station pairs, I considered differences in altitude and avoided choosing pairs that straddled big mountain chains. I considered regions characterized by similar trend patterns and selected pairs with very high correlation coefficients. Hence, it should be pointed out that most station pairs show decreasing trends in Ro except for some regions.

If we view the locations more locally, sometimes both high stations and low stations may exist in small valleys and/or on small mountains forming a pair. Hence, this analysis is too rough to discuss the micro-physical effect that should be examined with regard to the same cloud system. We should carefully consider it, but there may a need for more station networks with long-term observations and idealized station pairs or for other methods together with this type Ro analysis.

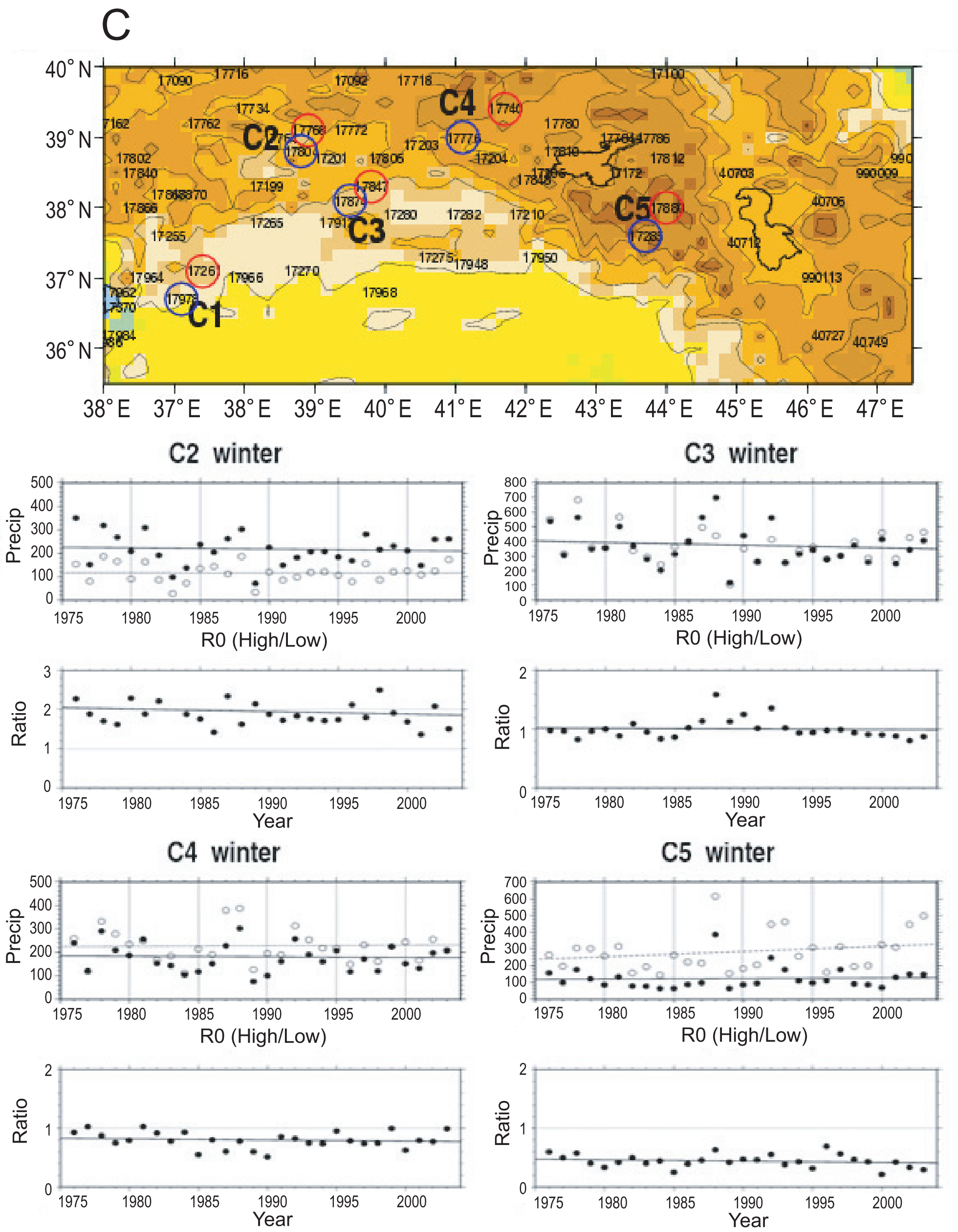

Fig. 7 Same as Fig. 4 but for Region C (southeast Turkey). C1 is not shown, since it is the same as A4.

The “Fertile Crescent,” famous in archaeology, runs from the Jordan Valley northwards through inland Syria, into southeastern Turkey, then eastwards through northern Iraq, and finally southeastward along the Zagros foothills of western Iran (Bellwood, 2005). It is a zone of gentle gradients with comparatively moist and fertile alluvial soil, thus it is also called the cradle of civilization. The Fertile Crescent is flanked to its south by desert and to its north and east by high mountains, hence, precipitation there is extremely important as a feed source for rivers and groundwater in the desert area, including Mesopotamia, the land in and around the Tigris and Euphrates Rivers.

In spite of its importance, as we saw in Fig. 3, winter precipitation has shown decreasing trends over most parts of the Fertile Crescent. In the station-pair analysis, stations A3, C1, C2, C3, C4 and C5 belonged to the Fertile Crescent region. Interestingly A3 and C1, exceptionally showing decreasing trends in Ro, belong to the northwest part of the Fertile Crescent.

The horizontal resolution of climate models has become finer and finer, and it could simulate a crescent shape of precipitation (Kitoh *et al.*, 2008, Kitoh & Arakawa, 2011). However, representation of the orographic precipitation around the Fertile Crescent is still a challenging issue (Kitoh & Arakawa 2011). Climate models are expected to be used for paleo-climate interpretation, but observational facts and precise analyses of precipitation are primarily important to the interpretation of archaeological proxy records. The beginning and the transition of agriculture and civilization must have been regulated by temperature and precipitation. In

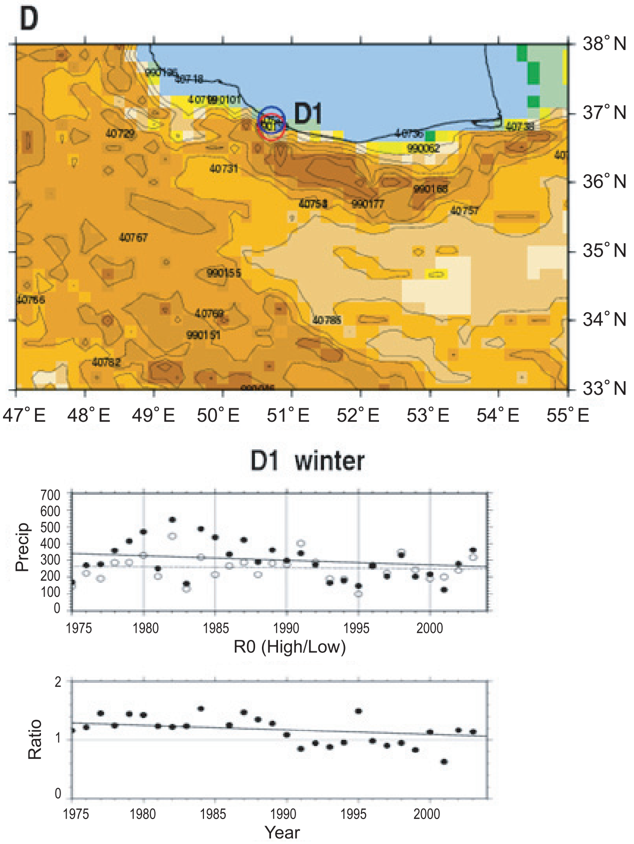

Fig. 8 Same as Figure 4 but for Region D (along the Caspian Sea).

this arid/semi-arid region, changes in the location of the precipitation zone, including in altitudinal zones, according to global climate change are often a critical issue affecting agriculture.

4. Summary

I have presented winter precipitation trends for Turkey, Israel and Iran using 34-year monthly precipitation data. There was a strong and significant decreasing trend in winter over Turkey and Israel, especially in January. Trends over Turkey differed greatly from month to month, while those over Iran did not differ so much from season to season. On the other hand, Iran has orographically characterized trends. I showed winter trend patterns, and found orographically characterized trend patterns (groups) on the 300 - 1,000 km scale.

Then I compared the trends at 13 station pairs of high stations and low stations under the same synoptic conditions for winter in western and southern Turkey and along the Caspian Sea. Most station pairs showed decreasing trends in Ro, which is the ratio of the precipitation at the high station to that at the low station. The exceptional cases, which showed increasing trends in Ro were observed in the easternmost part of the Taurus range (north of Syria) and in the northwest part of Turkey, which is a part of the Fertile Crescent. In order to understand the archaeologically important era and to predict future hydro/agricultural conditions of the Crescent region, it is primarily important to understand the quantitative precipitation distribution and its local changes associated with global change. Further investigations are needed, considering detailed orography and wind/rainfall systems of that region.

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