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Regional impacts of global change: seasonal trends in extreme rainfall, run-off and temperature in two contrasting regions of Morocco

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Abstract. In Morocco, socio-economic activities are highly vulnerable to extreme weather events. This study investigates trends in mean and extreme rainfall, run-off and temperature, as well as their relationship with large-scale atmospheric circulation. It focuses on two Moroccan watersheds: the subhumid climate region of Bouregreg in the north and the semi-arid region of Tensift in the south, using data from 1977 to 2003. The study is based on a set of daily temperature, precipitation and run-off time series retrieved from weather stations in the two regions. Results do not show a homogeneous behaviour in the two catchments; the influence of the large-scale atmospheric circulation is different and a clear spatial dependence of the trend analysis linked to the distance from the coast and the mountains can be observed. Overall, temperature trends are mostly positive in the studied area, while weak statistically significant trends can be identified in seasonal rainfall, extreme rainfall events, average run-off and extreme run-off events.

1 Introduction

In Morocco, during the last decade many devastating rain events caused severe damage in several regions. The deadly flood of 22 November 2014 in the south of Morocco caused the fatalities of at least 36 persons (Atlasinfo, 2014). The flood of 29 and 30 November 2010 caused enormous human and material losses in Casablanca (Yabiladi, 2015). In the province of Settat, the flood of 23 and 24 December 2001 caused the deaths of eight people and flooded several industrial units and villages in the region (Aujourd'hui le Maroc, 2014). Also in the Ourika valley, the flood of 17 August 1995 caused more than 230 deaths, 500 missing persons, 200 damaged cars and further property damages (Saidi et al., 2003). Most studies on climate variability in Morocco have focused on the interannual variability of recorded and forecasted climatic variables as well as their connections with large-scale atmospheric circulation and have shown trends toward hotter and drier conditions (Knippertz et al., 2003; Driouech et al., 2009, 2010; Sinan et al., 2009; Singla, 2009; Sebbar et al., 2011; Tramblay et al., 2012; Schilling et al., 2012; Khomsi et al., 2013; Khomsi, 2014). Some studies of extreme rainfall events, using climatic indices, have also been performed, including studies by Driouech (2010), Tramblay et al. (2012, 2013), Donat et al. (2014) and Falahi et al. (2015) while studies that concerned run-off extremes and their trends are rare. Also, most studies on extreme events in Morocco have been performed at the national scale; studies done at small scales e.g. on watersheds, where the regional trends can be studied at the subscale of the climatically integrative subcatchments, are rare.

In watersheds, the analysis of the hydrological cycle is best approached through the analysis of the different components of the water balance. This expresses the fact that over any time period, water input to an area must be equal to output and changes in storage. Input is rainfall, while out-

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put includes evaporation (mostly enhanced with temperature, particularly in semi-arid regions; Er-Raki et al., 2010) and run-off. Therefore the water balance analysis must take into consideration three important parameters: rainfall, temperature and run-off.

The objectives of this work are to analyse long-term trends in extreme and total rainfall, and average temperature and run-off, in addition to their relationship with large-scale atmospheric circulation over 27 years between 1977 and 2003, in two contrasting areas in Morocco: (i) the Bouregreg River basin in the north, where many agricultural activities have developed and where most river run-off is stored in a large dam for portable water consumption for the most heavily populated basin in the country (with about 7 million people between Casablanca and Kenitra, including the capital city of Rabat), and (ii) the Tensift River basin in the south, which is the most touristic area in Morocco with more than one million inhabitants and a growing need of water for tourism and irrigation. The paper is organised as follows: the study area, the data sets and the methods used are described in Sect. 2, the results are given in Sect. 3 and eventually, these results are summarised and discussed in Sect. 4 and main conclusions are drawn.

2 Study area, data sets and methodology

2.1 Study area

Morocco is the most north-western country in Africa (Fig. 1). It is located in the southern part of the Mediterranean region and it is considered among the most vulnerable countries with respect to climate variability, especially with a possible increased frequency of extreme events (Agoumi, 2003; Sinan et al., 2009; Schilling et al., 2012). The Bouregreg River basin (located between 5.4 and −6.8° W and 32.8 to −34° N), occupies a large area of the Moroccan central plateau (Fig. 1). It is a combination of monotonous plateaus, deep gorges and basins partitioned by steep ridges over an area of 9656 km^2 (Marghich, 2004) on the western humid side of the country. The elevation rises up to 1627 m and 50 % of the area is located between 500 and 1000 m (SIGMED[1] project; Mahe et al., 2013). The climate is subhumid to semi-arid (Mahé et al., 2012) and average annual rainfall ranges from about 400 mm in coastal regions to 760 mm in the western part of the basin (Fig. 2). The number of rainy days per year is between 75 and 100 in the mountainous regions and between 60 and 75 elsewhere. The Tensift River basin (7.2 to −9.4° W and 30.8 to −32.2° N) covers an area of 19 400 km^2 in the south of the humid side of the Atlas mountain (Fig. 1). The topography of the High Atlas mountains influences the rainfall distribution and the climate is semi-arid (Chehbouni et al., 2008; Mahé et al., 2012). Rainfall is low in the plains where the annual total does not exceeds 350 mm, whereas in the mountains it can reach more than 600 mm (Fig. 2). The number of rainy days is between 25 and 50 per year for coastal areas and the Haouz central plain, and 45 to 70 in the mountains (CID, 2004).

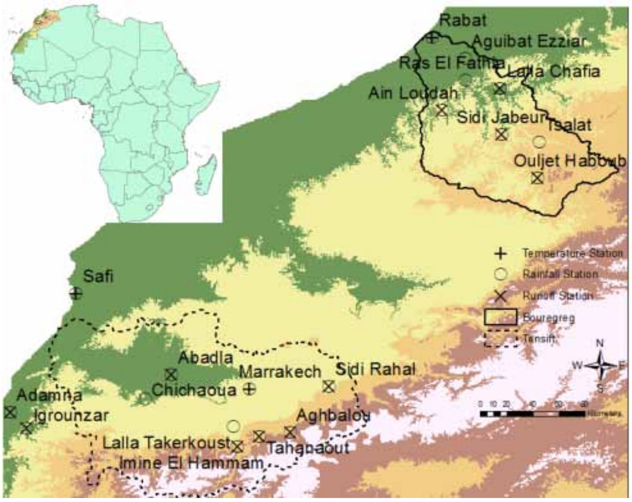

Figure 1. Location of Morocco in Africa (up left map) and daily rainfall, run-off and temperature stations in the Bouregreg and the Tensift watersheds.

2.2 Rainfall, run-off and temperature data

Daily rainfall data for the Bouregreg and the Tensift watersheds were collected from 8 and 11 stations respectively (Fig. 1). Three of these stations (Rabat from the Bouregreg and Marrakech and Safi from the Tensift) belong to the synoptic network of the Moroccan Meteorological Office (Direction de la Météorologie Nationale – DMN) while the other ones belong to the Hydraulic Basin Agency of Bouregreg and Chaouia (Agence du Bassin Hydraulique du Bouregreg et de la Chaouia – ABHBC) and the Hydraulic Basin Agency of Tensift (Agence du Bassin Hydraulique du Tensift – ABHT), in Morocco. These agencies also provided the daily run-off data for 4 stations in the Bouregreg Basin and 9 stations in the Tensift Basin (Fig. 1). Daily maximum and minimum temperature data were collected from the Moroccan Meteorological Office and concern the stations of Rabat, Marrakech and Safi. All of the collected rainfall, run-off and temperature data underwent quality control before being publicly available; this control is performed according to the recommendations of the World Meteorological Organization (WMO, 1993, 1996 and references therein; Zahumensky, 2004).

This study was performed on a seasonal basis from 1977 to 2003, after applying the criteria suggested by Kuglitsch (2010) for reducing the influence of missing data in a collected time series:

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[1] The SIGMED project stands for "spatial approach of the impact of agricultural activities in the Maghreb on sediment transport and water resources in large river basins" – http://armspark.msem.univ-montp2.fr/sigmed/

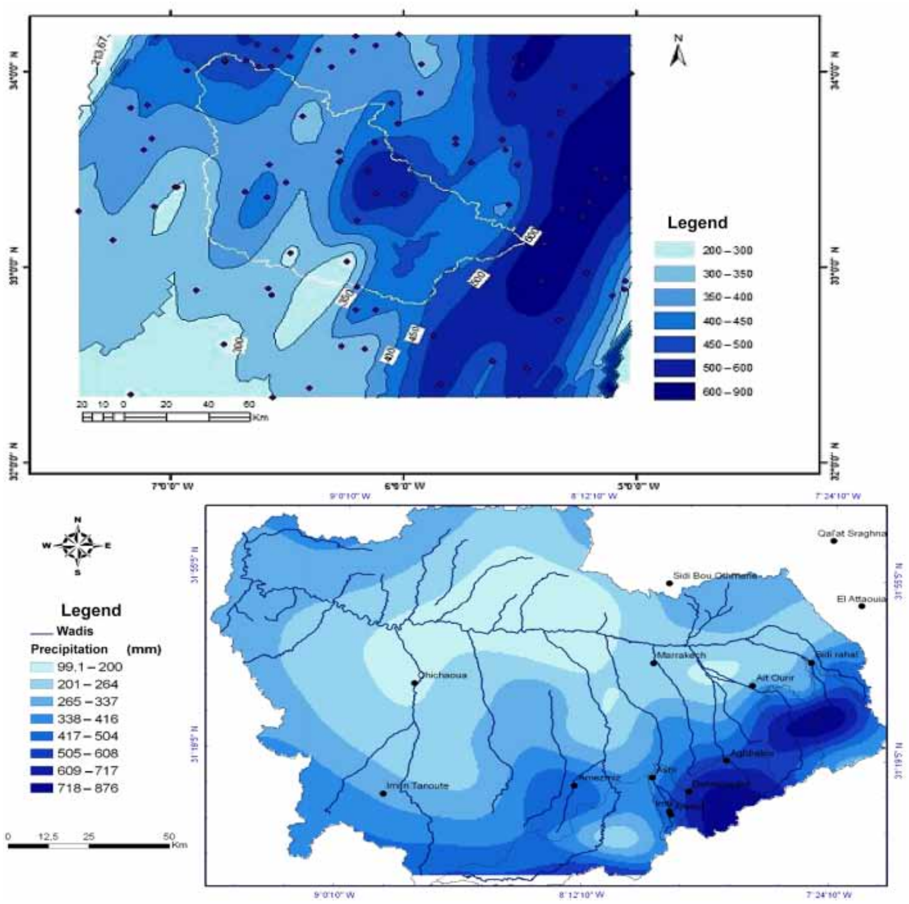

Figure 2. Annual rainfall distribution in the catchments of Bouregreg (upper panel) between 1972 and 2000 (adapted from Boudhar, 2009) and Tensift (lower panel) between 1980 and 1999 (adapted from Trabi, 2013).

1. a month is considered complete when it contains no more than three missing days
2. a season is considered as available when all months are complete in respect to criterion 1
3. a station data set is considered as complete when no more than three consecutive seasons are missing.

The homogeneity of the collected data was checked by identifying change points affecting the series of seasonal rainfall amounts, seasonal temperature averages and seasonal run-off averages.

2.3 Atmospheric circulation indices

The annual data of the North Atlantic Oscillation (NAO, Van Loon et Rogers, 1978; CPC, 2014) and the Mediterranean Oscillation (MO, Conte et al., 1989; Dunkeloh and Jacobeit, 2003) indexes available on the website of the Climatic Research Unit (CRU, http://www.cru.uea.ac.uk/cru/data) were used in order to study the relationship between these two atmospheric modes and the evolution of seasonal amount and extreme events of rainfall, seasonal average and extreme events of run-off and temperature between 1977 and 2003.

2.4 Methods

Four seasons are investigated here: autumn (September–November), winter (December–February), spring (March–May) and summer (June–August). In order to study the homogeneity of data, change points in the data sets of seasonal total rainfall, seasonal average run-off and seasonal average maximum and minimum temperatures, were analysed using the non-parametric test of Pettitt at 5 % significance level (Pettitt, 1979). Although it is recommended to apply homogeneity tests relatively, i.e. testing with respect to a neighbouring station that is supposedly homogeneous, it is difficult to apply them in a data sparse network (Wijngaard et al., 2003). The rationale behind the use of the Pettitt test in this work is to check whether a homogeneity break (i.e. a change in the mean) is observed in the data, which could impact the results of the trend analysis (Beaulieu et al., 2012).

To study extreme events, the 5th, 10th, 90th and 95th percentiles computed across the whole time period are used as thresholds, as they are widely employed and recommended by the STARDEX (STAtistical and Regional dynamical Downscaling of EXtremes for European regions; http://www.cru.uea.ac.uk/projects/stardex/) and the ETCCDI (Expert Team on Climate Change Detection and Indices; http://cccma.seos.uvic.ca/ETCCDI/) projects. In addition, exceptional events were selected using the 1st and 99th percentiles as thresholds. This approach was applied to the rainfall, run-off and maximum and minimum temperature seasonal data, between 1977 and 2003. The following definitions have been used:

- a heavy precipitation (run-off) event is a day that recorded precipitation (run-off) greater than or equal to the 90th percentile
- an intense precipitation (run-off) event is a day that recorded precipitation (run-off) greater than or equal to the 95th percentile
- an exceptional precipitation (run-off) event is a day that recorded precipitation (run-off) greater than or equal to the 99th percentile
- a hot (cold) event is a day that recorded maximum (minimum) temperature greater (lower) than or equal to the 90th (10th) percentile
- a very hot (cold) event is a day that recorded maximum (minimum) temperature greater (lower) than or equal to the 95th (5th) percentile
- an extremely hot (cold) event is a day that recorded maximum (minimum) temperature greater (lower) than or equal to the 99th (1st) percentile.

The magnitudes of trends in seasonal time series of total rainfall, average run-off and temperature and the number of extreme events have been analysed using the non-parametric method proposed by Theil (1950) and Sen (1986) for univariate time series. This approach involves computing slopes for all the pairs of ordinal time points and then using the median of these slopes as an estimate of the overall slope. Since Sen's slope is robust against outliers, it is widely used for the estimation of trending magnitudes of climate series (Deo et al., 2007; Guentchev and Winkler, 2010; Hidalgo-Muñoz et al., 2011; Tramblay et al., 2013). The statistical significance of the obtained trends is tested using the modified Mann–Kendall test proposed by Hamed and Rao (1998) for autocorrelated time series. The test is performed at significance level of 5 %.

Correlations between large-scale indices and total rainfall, average run-off and temperature time series and their extreme events were estimated using the Mann–Kendall test (Kendall, 1938, 1975). The later measures the strength of the monotonic relationship between two time series X and Y. It is a rank-based procedure and is therefore resistant to the effect of unusual values.

3 Results

3.1 Trends in total precipitation and number of extreme rainfall events

3.1.1 Total rainfall

All seasonal rainfall series were found to be homogeneous, according to the Pettitt test at the 5 % significance level, indicating no change points in the time series. Table 1 shows the trends in seasonal rainfall estimated for the selected stations. For all seasons and in both watersheds, all the magnitude trends are very weak and hardly exceed 3 mm yr^{-1}. None of the seasonal trends are significant. In autumn, increasing rainfall is found in the major parts of the Bouregreg basin, and only for the station of Ouljet Haboub in the south a decreasing rainfall tendency is observed. In the Tensift basin, decreasing rainfall trends are observed in the centre of the watershed and at the south-west stations, while increasing tendencies of very small amplitudes are found near the mountains and at the coastal station of Safi. In winter, the rainiest season, decreasing trends are found in both watersheds, but some increasing trends are noticed in the south of the Bouregreg catchment. In spring, a decrease in rainfall is noticed in the Bouregreg watershed, while increasing tendencies are found in several locations within the Tensift basin. In summer, very weak amplitudes are shown in the rainfall tendencies of the two basins. For this season, results must be considered with caution due to the very high number of dry days, in particular in the south. When aggregated at the annual scale, some significant trends towards a decrease have been found by Tramblay et al. (2013) in the same region.

3.1.2 Extreme rainfall events

The magnitude trends in extreme rainfall events of the studied stations, during the four seasons were estimated. Almost all of the observed magnitude trends are negligible and not significant. Some weak trends, hardly exceeding 1 day decade^{-1}, appear in the heavy autumn events of Ain Loudah (0.59 day decade^{-1}) and Ouljet Haboub (-0.56 day decade^{-1}), the winter heavy events of Sidi Jabeur (-0.43 day decade^{-1}), the heavy spring events of Ras El Fathia (-0.48 day decade^{-1}) and the intense events of Safi (0.45 day decade^{-1}) from the Tensift basin. All these observed trends are statistically non-significant. This shows that for both catchments there are no noticeable trends in extreme precipitation; similar results were found in Morocco by Filah et al. (2015).

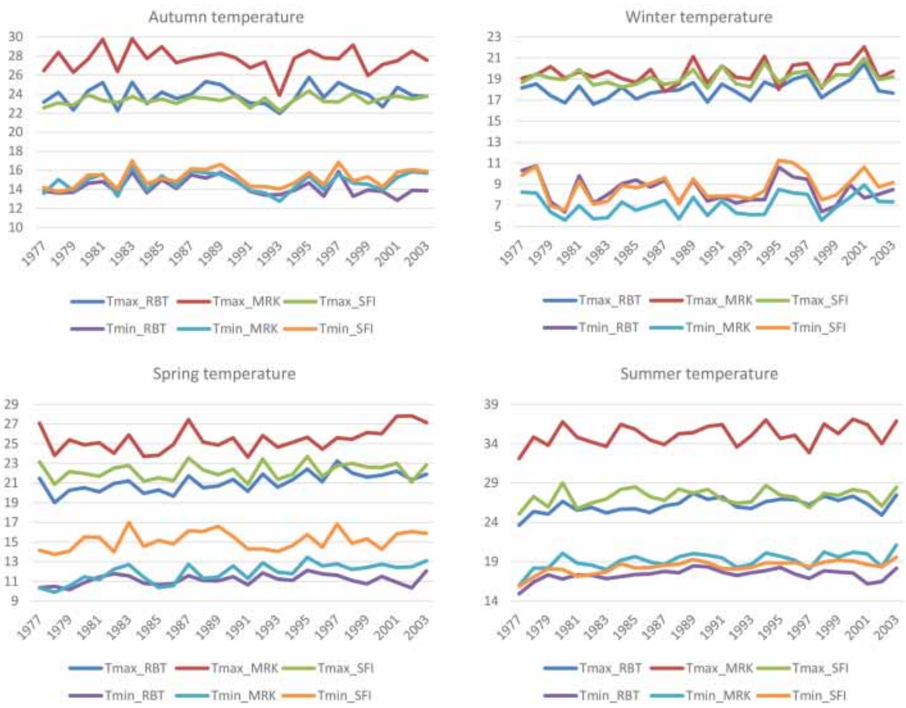

Figure 3. Seasonal tendencies in average maximum and minimum temperatures in the catchments of Bouregreg and Tensift.

3.2 Trends in average run-off and extreme run-off events

3.2.1 Average run-off

For all the studied discharge stations, apart from the station of Tahanaout where a shift is detected in the spring of 1996, no significant change points have been detected with the Pettitt test. Table 1 shows the trends in seasonal run-off recorded at the different stations. During the four seasons in both watersheds, most of the observed trends in run-off are weak. None of the seasonal trends are statistically significant. In winter, some upward trends are observed in the watershed of Bouregreg, while decreasing trends appear in the watershed of Tensift. In spring, average run-off exhibits a slight downward trend for the two stations located in the centre of the Bouregerg basin. For the Tensift basin, decreasing trends are observed at the stations located near to the mountains. This downward trend in run-off in the Tensift basin has been attributed to reduced snow amounts in high-elevation areas by Simmoneaux et al. (2008).

3.2.2 Extreme run-off events

Table 2 shows the trend magnitudes for extreme run-off events at the studied stations, during the four seasons. Overall, there is no clear pattern towards a general increase or decrease of extreme run-off events. In autumn, heavy run-off events show an increasing trend in Ain Loudah while decreasing trends in heavy and intense events are observed in Ouljet Haboub, near to the mountains. In the Tensift watershed, heavy run-off events tends to increase in Sidi Rahal and decrease in Tahanaout and Adamna. In winter, all the stations of the Bouregreg watershed witnessed an increase in heavy run-off events, while intense events increase in Ain Loudah and Lalla Chafia. At most of the stations in the Tensift watershed, a decrease in heavy run-off events is observed. In spring, heavy events show a decrease in Lalla Chafia and an increase in Ouljet Haboub from the Bouregreg basin. Increasing trends are also found in Abadla and Adamna from the Tensift basin. In summer, intense run-off events increased in three of the four stations in the Bouregreg basin and heavy events increased in Ouljet Haboub and Sidi Jaber. In the Tensift watershed, upward trends were noticed in the heavy run-off events in Imine El Hammam, while downward trends were observed in heavy events and intense events in Tahanaout. During all seasons and in all stations, exceptional events indicating extreme floods did not record any tendencies.

3.3 Trends in average extreme temperatures and number of temperature extreme events

3.3.1 Observed average maximum and minimum temperature

The Pettitt test did not detect significant change points in the different time series of temperature. Figure 3 shows seasonal

Table 1. Tendencies in seasonal total rainfall (mm yr^{-1}) and average run-off ($\mathrm{m}^3\,\mathrm{s}^{-1}\,\mathrm{yr}^{-1}$); significance level = 0.05, uncertainties are ±1 the standard error of the slope.

Station	Region	Autumn		Winter		Spring		Summer	
		Rainfall	Run-off	Rainfall	Run-off	Rainfall	Run-off	Rainfall	Run-off
Aguibat Ezziar	Bouregreg	1.11 ± 1.7	–	−0.3 ± 3.54	–	−2.59 ± 2.17	–	−0.03 ± 0.03	–
Ain Loudah	Bouregreg	1.84 ± 1.64	0.01 ± 0.01	0.34 ± 1.54	0.11 ± 0.06	−0.63 ± 1.24			
Lalla Chafia	Bouregreg	2.35 ± 1.98	0.01 ± 0.05	−0.85 ± 3.44	0.11 ± 0.30	−0.71 ± 1.28	−0.09 ± 0.12		
Ouljet Haboub	Bouregreg	−3.14 ± 1.71	−0.01 ± 0.02	2.05 ± 4.28	−0.02 ± 0.09	−0.73 ± 0.92	0.02 ± 0.06	−0.37 ± 0.29	
Ras El Fathia	Bouregreg	0.81 ± 1.27	–	−0.48 ± 4.66	–	−1.7 ± 1.39	–		–
Sidi Jabeur	Bouregreg	0.23 ± 0.85	0.01 ± 0.10	0.30 ± 0.45	0.02 ± 0.09	−0.92 ± 1.27	−0.03 ± 0.07	−0.02 ± 0.04	0.01 ± 0.00
Tsalat	Bouregreg	0.32 ± 15.19	–	−0.95 ± 2.68	–	−0.41 ± 1.50	–	0.15 ± 0.35	–
Rabat	Bouregreg	2.19 ± 1.84	–	−0.34 ± 5.52	–	−1.29 ± 1.17	–	−0.02 ± 0.03	–
Abadla	Tensift	−1.01 ± 0.9	0.01 ± 0.03	−1.01 ± 1.23	−0.11 ± 0.09	0.82 ± 0.83	0.03 ± 0.12		
Aghbalou	Tensift	1.25 ± 1.77	−0.01 ± 0.02	−2.88 ± 2.00	−0.05 ± 0.05	0.74 ± 2.11	−0.04 ± 0.13	0.31 ± 0.29	
Lalla Takerkoust	Tensift	0.07 ± 0.36	–	−0.61 ± 1.09	–	1.40 ± 1.43	–	0.11 ± 0.11	–
Chichaoua	Tensift	−1.23 ± 0.97	–	−0.77 ± 1.12	–	0.85 ± 0.67	–		–
Imine El Hammam	Tensift	−0.03 ± 1.51	−0.01 ± 0.03	−2.15 ± 1.94	0.04 ± 0.09	0.83 ± 1.48	0.02 ± 0.11	−0.08 ± 0.36	0.02 ± 0.03
Marrakech	Tensift	−0.11 ± 0.91	–	−0.32 ± 1.70	–	1.34 ± 1.34	–		–
Safi	Tensift	0.14 ± 0.77	–	−0.84 ± 1.93	–	1.32 ± 0.98	–	−0.01 ± 0.01	–
Sidi Rahal	Tensift	0.08 ± 0.29	0.02 ± 0.02	−1.32 ± 1.80	−0.07 ± 0.06	1.00 ± 3.69	−0.02 ± 0.05	−0.16 ± 0.36	
Tahanaout	Tensift	−0.60 ± 1.61	0.01 ± 0.01	−0.95 ± 1.47	−0.02 ± 0.01	0.92 ± 1.19	−0.04 ± 0.03	0.08 ± 0.49	−0.01 ± 0.01
Adamna	Tensift	−0.83 ± 1.45	−0.01 ± 0.01	−0.53 ± 2.18	−0.02 ± 0.04	0.84 ± 1.16	0.01 ± 0.01		
Igrounzar	Tensift	−0.12 ± 0.31		−2.73 ± 2.25		0.53 ± 1.42			

Table 2. Tendencies in heavy (90), intense (95) and exceptional (99) run-off events (day decade^{-1}); significance level = 0.05.

Weather station	Region	Autumn 90	Autumn 95	Autumn 99	Winter 90	Winter 95	Winter 99	Spring 90	Spring 95	Spring 99	Summer 90	Summer 95	Summer 99
Ain Loudah	Bouregreg	0.59 ± 0.32			1.56 ± 0.89	0.56 ± 0.26							
Lalla Chafia	Bouregreg				2.14 ± 1.31	0. 10 ± 0.54		−0.11 ± 0.21				0.56 ± 0.67	
Ouljet Haboub	Bouregreg	−0.91 ± 0.12	−0.67 ± 0. 80		1.25 ± 1.05			0.43 ± 0.12			0.56 ± 0.45	0.43 ± 0.32	
Sidi Jabeur	Bouregreg				0.67 ± 0.98						0.95 ± 0.55	0.62 ± 0.33	
Abadla	Tensift				−1.25 ± 0.95			1 ± 1.2					
Aghbalou	Tensift												
Imine El Hammam	Tensift										0.62 ± 0.58		
Sidi Rahal	Tensift	0.87 ± 1.07			−1.33 ± 1.08								
Tahanaout	Tensift	−0.59 ± 0.39			−1.11 ± 0.63						−2.50 ± 1.64	−0.56 ± 0.29	
Adamna	Tensift	−0.43 ± 0.39			−1.43 ± 1.25	−0.71 ± 0.44		0.91 ± 0.87					
Igrounzar	Tensift				−0.59 ± 0.59								

average maximum and minimum temperatures recorded at the different stations. For all seasons and stations, all the trends found in average maximum and minimum temperatures are not significant at the 5 % confidence level, according to the Mann–Kendall test. Most of the trends observed are positive and hardly exceeding 0.07 °C yr^{-1}. Tendencies in average minimum temperatures are greater than those in average maximum temperatures.

3.3.2 Number of extreme temperature events

Tables 3 and 4 show the trend magnitudes for extreme hot and cold events observed at the different stations during the four seasons. In autumn, decreasing trends are noticed in hot and very hot events in Rabat and Marrakech while increasing trends are found for Safi. Cold events are decreasing in most cases, but increasing trends are noticed in cold events of Rabat. In winter, very hot events increase in Safi, while cold and very cold events tend to increase in the northern stations and decrease in the southern stations. In spring, upward trends prevail in extreme hot events while downward trends prevail in extreme cold events. Many statistically significant tendencies are found, mainly in hot events in Rabat, cold and very cold events in Safi and Marrakech. In summer, hot events show an increase in Rabat while negative trends are found for very hot events in Safi and hot events in Marrakech. Statistically significant decreasing trends are observed for hot and very hot events in Safi and Marrakech.

3.4 Relationship with atmospheric circulation indexes

In an attempt to explain the observed trends by large-scale atmospheric influences, we investigated the relationship between seasonal total and extreme rainfall, seasonal average and extreme run-off and temperature with the large-scale atmospheric circulation indices describing the NAO and the MO. Generally, we observe that most of significant correlations are negative, indicating that the extreme values in the hydroclimatic parameters investigated in this study (precipitation, temperature and discharge) may be linked to negative phases of the NAO and MO indexes. However the relationships with the NAO and MO remains limited, since the correlation coefficients do not exceed 0.6. NAO appears slightly correlated with autumn total rainfall in Ain Loudah from the Bouregreg (−0.459) and with average minimum temperature and cold events in Safi from the Tensift (−0.403 and 0.425). Intense rainfall events in spring at Imine Hammam and exceptional events in Tahanaout are correlated to the NAO index (−0.45 and −0.455), these two stations are close to the High Atlas mountains in the Tensift basin. The other seasonal correlations with the NAO remain weak. Significant correlations exist between the MO in autumn and the total precipitation and extreme rainfall in many stations from the Bouregreg catchment (Table 5). In autumn, the MO is also correlated with the intense rainfall events of Safi and Igrounzar

Table 4. Trends in cold (90), very cold (95) and extremely cold (99) events (day decade^{-1}); bold text means that the trend is statistically significant; significance level = 0.05.

Weather	Region	Autumn			Winter			Spring			Summer		
station		90	95	99	90	95	99	90	95	99	90	95	99
Rabat	Bouregreg	1.00 ± 1.26			2.17 ± 1.68	1.43 ± 0.94		−0.91 ± 0.81					
Safi	Tensift	−0.91 ± 1.56	−0.50 ± 0.65		−1.87 ± 1.27	−0.91 ± 0.70		**−4.29 ± 1.22**	**−2.50 ± 0.82**		**−5.00 ± 1.17**	**−2.31 ± 0.61**	
Marrakech	Tensift	−1.67 ± 1.40	−0.83 ± 1.14		−1.58 ± 1.58	−0.91 ± 0.70		**−3.68 ± 1.61**	**−2.50 ± 1.08**		**−5.00 ± 1.65**	**−2.22 ± 0.87**	

Table 3. Trends in hot (90), very hot (95) and extremely hot (99) events (day decade^{-1}); bold text means that the trend is statistically significant; significance level = 0.05.

Weather	Region	Autumn			Winter			Spring			Summer		
station		90	95	99	90	95	99	90	95	99	90	95	99
Rabat	Bouregreg	−0.71 ± 1.56	−0.62 ± 0.86					**2.73 ± 1.01**	0.95 ± 0.64		1 ± 1.33		
Safi	Tensift	0.77 ± 1.08	1.18 ± 1.04			0.77 ± 0.78		2.10 ± 1.20	1 ± 0.74		−0.87 ± 0.89		
Marrakech	Tensift	−2.50 ± 1.44	−0.56 ± 0.59					2.00 ± 1.39	1.43 ± 0.84		−0.95 ± 1.17	*N*	

Table 5. Autumn correlations between NAO and MO indexes and total rainfall, heavy rainfall events, average run-off and heavy run-off events in the Bouregreg and Tensift catchments; bold text shows a significant coefficient; significance level = 0.05.

Station	Region	NAO				MO			
		Rainfall		Run-off		Rainfall		Run-off	
		Total	Heavy events	Total	Heavy events	Total	Heavy events	Average	Heavy events
Aguibat Ezziar	Bouregreg	−0.287	−0.126	–	–	**–0.505**	**–0.447**	–	–
Ain Loudah	Bouregreg	**–0.459**	**–0.397**	**–0.289**	**–0.305**	**–0.524**	**–0.435**	−0.339	**–0.360**
Lalla Chafia	Bouregreg	−0.240	−0.225	−0.209	−0.253	**–0.383**	**–0.419**	−0.339	**–0.342**
Ouljet Haboub	Bouregreg	−0.172	0.204	**–0.323**	−0.173	−0.314	0.031	−0.140	−0.137
Ras El Fathia	Bouregreg	−0.287	−0.120	–	–	**–0.467**	**–0.320**	–	–
Sidi Jabeur	Bouregreg	−0.134	−0.097	−0.157	−0.139	−0.238	−0.119	−0.299	**–0.334**
Tsalat	Bouregreg	−0.268	−0.239	–	–	**–0.448**	−0.105	–	–
Rabat	Bouregreg	−0.172	0.029	–	–	**–0.429**	**–0.356**	–	–
Abadla	Tensift	−0.099	−0.155	−0.080	−0.104	−0.296	−0.239	−0.074	−0.174
Aghbalou	Tensift	−0.163	−0.124	−0.182	**–0.309**	−0.375	**–0.291**	−0.212	**–0.314**
Lalla Takerkoust	Tensift	−0.131	0.039	–	–	−0.162	0.016	–	–
Chichaoua	Tensift	−0.060	0.155	–	–	−0.289	−0.049	– –	
Imine El Hammam	Tensift	−0.044	−0.030	−0.182	−0.063	−0.130	−0.128	−0.218	−0.113
Marrakech	Tensift	−0.155	−0.003	–	–	−0.312	−0.136	–	–
Safi	Tensift	−0.226	−0.138	–	–	−0.431	**–0.359**	–	–
Sidi Rahal	Tensift	−0.266	−0.096	−0.145	−0.245	−0.162	−0.099	−0.145	−0.256
Tahanaout	Tensift	−0.044	0.013	−0.120	−0.097	−0.273	−0.209	−0.151	−0.153
Adamna	Tensift	−0.175	−0.187	−0.084	−0.059	−0.261	−0.204	−0.096	−0.206
Igrounzar	Tensift	−0.179	**–0.399**	−0.065	−0.131	−0.233	**–0.335**	−0.138	−0.257

near to the Atlantic coast of Tensift and intense run-off events in Ain Loudah from the Bouregreg. In winter, intense run-off events in the station of Adamna from the Tensift catchment and extreme cold events in Rabat and Safi are linked to the MO. The summer average maximum temperature is affected by the MO at the station in Marrakech (0.504).

4 Discussion

The results obtained above show that the climatic features and variability can be very different according to the areas studied in Morocco; they depend on the seasons and the geographical location relative to the coasts and mountains, thus different results of the trend analysis were found inside each watershed.

Over 27 years between 1977 and 2003, temperature trends are mostly positive in the studied area, while no statistically significant trends could be identified in extreme temperature events, seasonal cumulative rainfall, extreme rainfall events, average run-off and extreme run-off events. These findings at the seasonal timescale are in agreement with the results found on precipitation and temperature by Filah et al. (2015), but cannot be compared directly with the general tendency towards drier conditions and decreasing amounts of precipitation already found at the annual scale by different authors in other regions of Morocco (Driouech, 2010; Singla et al., 2010). In fact, the analysis at the small-scale of individual watersheds and the seasonal approach chosen for this study makes this comparison difficult.

The positive trends in seasonal mean maximum and minimum temperatures found in this study are in agreement with the results of Donat et al. (2014) and those obtained for other countries in Europe (Jones, 1995; Brunetti et al., 2004). From these studies and Filah et al. (2015), the rise in minimum temperature in Morocco is large compared to the detected trends in maximum temperature. Some trends found in extreme temperatures and seasonal cold events are caused by changes in atmospheric circulation mainly in autumn and winter as shown by the link with atmospheric indexes NAO and MO. According to Khomsi et al. (2012), the north-east disturbed weather is linked to most of the cold temperature events in Morocco. This weather type appears during the cold season, when the country is subject to air circulation from the north-east which crosses the Mediterranean. During the warm season, hot events appear when the axis of the zonal ridge is located in the north of Morocco; the country is under an eastern or north-eastern regime called Chergui that brings dry and warm air.

In autumn and winter, the geographical location of the station of Rabat, in the north-west of Morocco, on the Atlantic coasts and on the trajectory of almost all the depressions from the north, makes its climate vulnerable to cold events. Upward trends in cold events may also be explained with the observed decrease in minimum temperature. In the south of Morocco, the increase in autumn average temperature and the decrease in the frequency of cold events are related to the large-scale patterns in the Atlantic and the Mediterranean. Decreasing trends in the autumn hot events in Marrakech may also be explained with the microclimate of the city caused by its geographical location near the foothills of the High Atlas mountains.

In autumn, the increase in rainfall in the north and centre of the Bouregreg basin is related to the Mediterranean large-scale atmospheric pattern which also affects the extreme rainfall regime. Decreasing trends that appear in the rainfall at the station in Ouljet Haboub near to the mountains is linked to the decline in surface run-off at the same station. The signs of trends in extreme rainfall and run-off events follow those observed in total rainfall and average run-off. In winter, the general decrease in rainfall for both watersheds enhances the decrease in run-off average and extremes mainly in the south. In the south of the Tensift basin, extreme run-off trends are the result of the Mediterranean influence. Some increases in average run-off are linked to increases in run-off extremes.

In spring and summer, averages of minimum and maximum temperature recorded important increasing trends that can explain the significant tendencies found in spring hot events and seasonal cold events, which are confirmed by the study of Filah et al. (2015). Increasing seasonal hot events mainly in Rabat may be also due to an increase in the frequencies of Chergui large-scale atmospheric patterns that reach the country from the north or the north-east. The stations of Safi and Marrakech in the south are not impacted by this large-scale pattern and the station in Marrakech is rather under the influence of Mediterranean large-scale atmospheric patterns in summer. The amount of rainfall that decreases notably in the northern basin and increases in the southern, mainly in spring, confirms the topographic influence on rain in Morocco: the Tensift basin in the south include the High Atlas mountains that can induce weather instabilities, giving rise to important quantities of rainfall mainly in transitional seasons.

5 Conclusions

This study has focused on the analysis of the trends in total rainfall, average run-off and temperature, as well as their extremes and their relationship with two atmospheric circulation indexes in two contrasting Moroccan regions: the Bouregreg watershed and the Tensift watershed, between 1977 and 2003. It was carried out at the seasonal scale using 19 stations for rainfall, 11 for run-off and 3 for temperature.

The results show that during the studied period, no statistically significant generalized trends could be identified in total and extreme rainfall events or in average or extreme run-off. Some correlations are found with large-scale atmospheric circulation especially in the Mediterranean, however these correlations remain limited. On the contrary, temperature trends are mostly positive in both regions.

The findings of this study highlight the fact that the northern and southern regions are impacted differently by large-scale atmospheric circulation and may respond in different ways to recent global warming. This response depends on the season studied and the considered region characteristics, and it emphasises the need for more local to regional studies. It would be worthwhile making such a study of other areas in Morocco if more data becomes available. Obtained results could then be compared with those of the present study.

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