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Interannual summer streamflow variability over Romania and its connection to large-scale atmospheric circulation

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Abstract

In this study the spatial and temporal variability of summer (June – July – August (JJA)) streamflow over Romania, as recorded at 46 hydrological stations over the period 1935 -2010 is analyzed. An empirical orthogonal function analysis (EOFs) and Canonical Correlation Analysis (CCA) were used to characterize the spatial and temporal variability of summer streamflow and the relationship with large-scale atmospheric factors. It is shown that the dominant summer mode captures in-phase variability of river flow anomalies over the entire country, while the second mode of variability is characterized by a northwest - southeast dipole, emphasizing the influence of topography over the streamflow variability. Based on a CCA analysis it is shown that more than 50% of the summer streamflow variability is influenced by cloud cover and summer temperatures, via the modulation of precipitation and potential evapotranspiration. In general, positive (negative) streamflow anomalies, at country level, are associated with cyclonic (anticyclonic) circulation, the advection of moist (warm and dry) air, enhanced (reduced) precipitation and positive (negative) cloud cover anomalies.

KEY WORDS: Romania, atmospheric circulation, streamflow variability, empirical orthogonal functions, canonical correlation analysis

1. Introduction

Over the past decades Europe has experienced heavy floods with major consequences for thousands of people and millions of Euros worth of damage (Kundzewicz et al*.,* 2007). One of the best examples is the summer 2013 flood in Central Europe which showed how vulnerable modern society is to hydrological extremes and emphasizes once again the need for improved forecast methods of such extreme climatic events. In this respect, streamflow forecasting is of great importance to water resources management and flood defense. On the other hand, to be able to improve the skill of the streamflow forecast, one needs to get a better understanding of the streamflow processes and the influence of large scale atmospheric circulation on the streamflow variability. Characterization of hydrological variability on climatic time scale and connections to climatic forcings provide potential improvement for hydrological forecasts, especially if the forcings are predictable or slowly evolving (Souza and Lall, 2003; Croley, 2003). Evidence from long hydrological records shows that periods with anomalous hydrological behavior (Arnell et al., 1993) are associated with persistent climate anomalies.

The interaction between river streamflow and low-frequency climate patterns has been studied for various hydrological systems all over the world (Dettinger and Diaz, 2000; Barlow et al., 2001; Barros et al., 2004; Ward et al., 2010). In addition, the analysis of the meteorological-hydrological connections resulting from synoptic climatic patterns has been suggested to be essential for understanding and predicting the behavior of river streamflow (Stahl and Demuth, 1999; Bierkens and Van Beek, 2009). Two of the most important phenomena that influence streamflow variability are the North Atlantic Oscillation (NAO) and El Niño-Southern Oscillation (ENSO) (Dettinger and Diaz, 2000; Cullen et al., 2002; Lorenzon-Lacruz et al., 2011, Gamiz-Fortis et al., 2011; Ionita et al., 2008, 2011, 2012). The indices of these two large-scale climatic patterns have been used as predictors for the seasonal streamflow anomalies over Europe (Trigo et al., 2002; Rimbu et al.; 2004; Ionita et al., 2008). Correlations with hydrological data have shown that when NAO index is high river flow is above average in the northern part of Europe and below average in the southern part of Europe (Shorthouse and Arnell, 1997; Dettinger and Diaz, 2000). Another atmospheric pattern that strongly influences the precipitation and streamflow over Europe, especially on the southern part, is the East Atlantic/ Western Russia pattern (EA/WR) (e.g. Ziv et al., 2007, Ionita et al., 2014a).

Streamflow is an integrated response to climate, water transfer, evapotranspiration and the effect of human activities on the natural water flows. The response time of the streamflow to climate conditions depends strongly on the catchment area characteristics (e.g. geology, topography, soils and vegetation) and among different climatic regions (Post and Jackeman; 1996; Fleig et al., 2011). In the same time, the hydrological response to climate is also season dependent because the water resources, the climatic conditions and the hydrological processes vary throughout the year (Tallaksen, 1995; Garcia-Ruiz et al., 2008).

Romania is situated in the southeastern-central part of Europe, north of the Balkan Peninsula and the western shore of the Black Sea. The climatic conditions are dependent on the country's varied topography. The Carpathians serve as a barrier for the Atlantic air masses, limiting their oceanic influences to the west and center of the country, which experience milder winters and heavier rainfalls as a result. The mountains also block the continental influences of the vast plain to the north in the Ukraine, which results in frosty winters and less rain to the south and southeast. Various studies, focused over Romania, have shown certain changes in surface air temperature and precipitation (Bojariu and Paliu, 2001; Tomozeiu et al., 2002; 2005; Ionita et al., 2013, Busuioc et al., 2014). The streamflow variability over this region has been studied only for particular regions (Stefan et al., 2004, Rimbu et al., 2004). A first step towards a more comprehensive study, at country level, was made in a recent paper by Ionita et al., (2014b), which showed that the Arctic (AO)/North Atlantic Oscillation (NAO), East Atlantic (EA), East Atlantic/Western Russia (EAWR) and Scandinavian (SCA) patterns control a significant part of the interannual winter streamflow variability over Romania.

Since the influence of well-known teleconnection patterns, like NAO or El Niño-Southern Oscillation (ENSO), is strongest in winter, most studies which have examined the influence of the atmospheric circulation on the river streamflow are confined to the winter season (Rimbu et al., 2004; Déry and Wood, 2004; Bower et al., 2006; Araneo and Compagnucci, 2008, Ionita et al., 2014b). Only a few studies have examined the variability of river streamflow outside the winter months (Kingston et al., 2006a, b; Ionita et al., 2008, 2011, 2012) over the European region. It has been suggested (Kingston et al., 2006a) that the studies of winter relationship, between streamflow variability and climate related patterns, should not be extrapolated to other seasons, due to the fact that streamflows show a monthly variability both in magnitude and direction (Lawler et al., 2003). As such, the aim of this study is to analyze the spatio-temporal variability of summer streamflow variability over Romania and its relationship with large scale atmospheric circulation based on a country wide data network. The paper is organized as follows: in Section 2 a short description of the data sets and the methods used in this study is given. In Section 3 the main results are presented. The discussion and the main conclusions follow in section 4.

2. Data and Methods

The streamflow data series used in this study have been provided by the National Institute of Hydrology and Water Management (INHGA). The time series consist of monthly streamflow values recorded at 46 stations located over the whole Romanian territory (Figure 1) and cover the period 1935–2010. The streamflow time series have continuous record and are quality controlled. Due to the fact that Romania is under the influence of a temperate-continental climate, the streamflow variability is influenced mainly by the climatic conditions and to a lesser degree by the topography and regional factors (e.g. geology, vegetation). The streamflow seasonal variability is determined by the climatic factors, their intensity and frequency (Zavoianu, 2002). During summer, the streamflow contribution to the annual mean streamflow varies between 15% in the north-west part of the country up to 30% in the southern and eastern part of the country (Figure 1b). The high contribution to the annual mean streamflow recorded at the station situated in the south and eastern part of the country can be the direct results of summer heavy precipitation events, which are very common for this part of the country (Chelcea and Ionita, 2013).

To investigate the relationship of summer streamflow variability with global sea surface temperature we use the Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST, Rayner et al., 2003). This data has a 2ºx2º spatial resolution and covers the period 1871–2012. In the present study we use SST data for the period 1935-2010. For the Northern Hemisphere atmospheric circulation we used the summer geopotential height at 850mb (Z850), the summer zonal wind at 850mb (u850) and the summer meridional wind at 850mb (V850) on a 2º x 2º grid, from the Twentieth Century Reanalysis (V2) data (Whitaker et al., 2004; Compo et al., 2006; Compo et al., 2011), for the period 1935-2010. The temperature at 850 hPa level (TEMP) has been extracted from the same data set (Whitaker et al., 2004; Compo et al., 2006; Compo et al., 2011).

The precipitation (PP), cloud cover (CLD) and Potential Evapotranspiration (PET) data sets were extracted from the gridded data set CRU TS3.1 from the Climatic Research Unit (CRU) of the University of East Anglia (Harris et al., 2013). This data set provides monthly values for various parameters for the global land areas and the temporal coverage is 1901–2012 on a 0.5° x 0.5° grid.

The dominant patterns of summer streamflow variability are based on Empirical Orthogonal Function (EOF) analysis (e.g. von Storch and Zwiers, 1999). The EOF technique aims at finding a new set of variables that captures most of the observed variance from the data through a linear combination of the original variables. The EOF analysis represents an efficient method to investigate the spatial and temporal variability of time series which cover large areas. This method splits the temporal variance of the data into orthogonal spatial patterns called empirical eigenvectors.

To identify the coupled summer streamflow and TEMP, CLD and PET patterns we used a Canonical Correlation Analysis (CCA). CCA it is a way of measuring the linear relationship between two multidimensional variables (Preisendorfer, 1988). It identifies two bases, one for each variable, that are optimal with respect to correlations and it finds, at the same time, the corresponding correlations. The same methodology has been applied to study the connection between the summer drought variability over Europe and global SST (Ionita et al., 2012a), the spatial and temporal variability of climate extremes over Romania and their associated large-scale mechanism (Busuioc et al., 2014) and the interannual summer air temperature variability over Greece and its connection to large scale atmospheric circulation (Busuioc et al., 2014). The

CCA uses as input the output of the EOF analysis (von Storch and Zwiers, 1999) applied to combined standardized anomalies of the predictand (e.g. summer streamflow)/predictors (e.g. TEMP, CLD and PET).

3. Results

3.1 Spatio-temporal variability of summer streamflow variability

The EOFs resulted from the standardized summer streamflow data set (anomaly divided by standard deviation) allows us to recognize the regions with different streamflow climatology. For this study just the first two EOFs patterns, which together explain more than 71% of the total variance, have been retained. The leading EOF accounts for 60.07% of total variance, while the second EOF accounts for 11.59% of the total variance. These EOF's are well separated according to the North rule (North et al., 1982). The sum of all remaining EOFs adds to ~29% of the total variance.

The first EOF (Figure 2a) has a monopolar structure showing the same sign for all the analyzed stations, with the highest loadings over the central and northern part of the country. This monopolar structure emphasizes that the streamflow variability over Romania is influenced by the same factors (e.g. the large scale circulation). The corresponding principal component (PC1) presents pronounced interannual and decadal variability (Figure 2b). Positive streamflow anomalies have persisted from the beginning of 1960's up to 1985 and negative streamflow anomalies have persisted from 1985 up to 2010 (Figure 2b). The driest summers (negative streamflow anomalies), in terms of summer PC1, were recorded for the years 1946, 1950, 1999, 2003, while the wettest (positive streamflow anomalies) were recorded during the years 1940, 1969/1970, 1974/1975, 1980 and 2005, respectively.

The second EOF pattern (Figure 2c) describes 11.59% of the total variance of the summer streamflow and has a dipole-like structure. This dipole-like structure emphasizes the influence of the Carpathian Mountains on the streamflow variability. This pattern is associated with negative loadings in the north-western part of the country and positive loadings over the south-eastern part of the country. Summer PC2 (Figure 2d) is characterized by enhanced interannual variability with driest summers (negative streamflow anomalies), in terms of summer PC2, recorded for the years 1945, 1974, 1980, 1998, while the wettest summer (positive streamflow anomalies) were recorded during the years 1975, 1991 and 2005, respectively.

3.2 Coupled modes of variability

Before applying a CCA, the dimensionality of the summer streamflow and TEMP, CLD and PET datasets is reduced by an EOF analysis. The first 10 EOF modes of the summer streamflow and the first 11 modes of summer TEMP, CLD and PET are retained as an input into the CCA. The first 10 EOFs capture approximately 92% of the total variance for summer streamflow and more than 87% of the summer TEMP, CLD and PET variability. The optimum number of retained EOFs was chosen so that using one more EOF would not change significantly the canonical correlation (Werner and Von Storch, 1993; Von Storch, 1995). Among other statistical methods, CCA has the advantage to select pairs of optimally correlated spatial patterns, which may lead to a physical interpretation of the mechanism controlling the climate variability (Barnett and Preisendorfer, 1987; Von Storch et al., 1993; Von Storch, 1995). This multivariate approach is increasingly being used in the atmospheric sciences as well, investigating climate data, geophysical fields, and ocean-atmosphere relationships (e.g., Barnston and Ropelewski 1992; Bretherton et al. 1992; Ionita et al., 2012; Busuioc et al. 2014).

Figure 3 shows the first CCA mode associated with summer streamflow variability over Romania. The first CCA pattern, referred from now on as CCA1, which explains 52.31% of the total variance of summer streamflow variability and 13.226% of the three predictors' fields, has a monopolar structure with high positive loadings at all the analyzed stations (Figure 3a). The first canonical mode associates simultaneously positive streamflow anomalies all over the country, negative PET (Figure 3c) and TEMP (Figure 3d) anomalies and positive CLD (Figure 3e) anomalies over the whole central and southern part of Europe, with the highest values of coefficients over Hungary and the northwestern part of Romania. From Figure 3 is obvious that positive streamflow anomalies, at country level, are very sensitive to the thermodynamic contributions coming from TEMP, PET and CLD. Similar results have been found by Busuioc et al. (2014) which showed that the extreme summer precipitation over Romania is mostly sensitive to thermodynamic factors (e.g. TEMP and specific humidity at 700mb) compared to the dynamics factors (e.g. sea level pressure). The spatial structure of CCA1 for summer streamflow resembles the structure of summer EOF1 (Figure 2a). The year to year variations of the normalized temporal components of the first CCA pairs are presented in Figure 3b. The two time series (TS1 streamflow and TS1 predictors) are significantly correlated (r = 0.80) and have a temporal behavior similar to summer PC1 (Figure 2b). The two canonical time series present strong variability both on interannual as well as on decadal time scale.

The second CCA pair, referred from now on as CCA2, exhibits a correlation between the time series corresponding to the summer streamflow (TS2) and the predictors of r = 0.57. The explained variance of CCA2 corresponding to the summer streamflow is 9.31%, while for the three predictors is 11.15%, respectively. The second CCA pattern (Figure 4a) has a more regional distribution compared to CCA1. For the summer streamflow, the highest positive loadings are found over the central and eastern part of Romania (the extra-Carpathian region), while the north-western part of the country (the intra-Carpathian region) is characterized by negative, but smaller loadings (Figure 4a). Positive streamflow anomalies over the central and eastern part of the country are associated with weak positive PET (Figure 4c) and TEMP (Figure 4d) anomalies and negative CLD (Figure 4e) anomalies over these regions. Compared to CCA1, the loadings of PET, TEMP and CLD are much smaller, implying the fact that other factors might play a more important role in the variability of the second CCA streamflow mode. The second pair of canonical temporal series (Figure 4b) presents mostly interannual variability and a shift towards more positive values at the beginning of the 1970's.

3.3 Relationship with large scale atmospheric circulation and sea surface temperature

To identify the physical mechanism responsible for the connection between the summer streamflow variability as identified by the CCA and large-scale atmospheric circulation we constructed the composite maps between the first two principal components corresponding to the first two canonical modes (TS1 and TS2) of the summer streamflow and Z850 and wind vectors at 850mb for the years of **High** (TS > 0.75 std. dev.), respectively **Low** (TS < -0.75 std. dev.) values of the normalized times series of the TSs. This threshold was chosen as a compromise between the strength of the climate anomalies associated to flow anomalies and the number of maps which satisfy this criteria. Further analysis has shown that the results are not sensitive to the exact threshold value used for our composite analysis (not shown). Moreover, in this sub-section the relationship between the summer streamflow variability and precipitation (PP) and the North Atlantic Ocean SST is analyzed in terms of correlation maps between the first two TSs and summer PP and summer SST. The results of the correlation analysis are shown in Figure 5 (c and d) and Figure 6 (c and d), in which the correlations that are exceeding the 95% significance level are hatched.

The composite map of Z850 anomalies and the wind vectors at 850mb for the years characterized by high values of TS1 (TS1> 0.75 std. dev.) shows a dipole-like structure, with positive Z850 anomalies over the British Isle, North Sea and Scandinavian Peninsula and a deep center of negative Z850 anomalies centered over the eastern part of Europe (Figure 5a). The negative Z850 anomalies centered over the eastern part Europe are consistent with enhanced precipitation (Figure 5c) over this region and the advection of moist air from the Mediterranean region (Figure 5d) towards Romania (see the wind vectors in Figure 5a) and as a consequence high streamflow anomalies all over the Romanian territory. For the years characterized by negative values of TS1 (TS1 < -0.75std) the composite maps of Z850 anomalies and the wind vectors at 850mb is characterized by a wave train with positive Z850 anomalies over the eastern coast of U.S. and western North Atlantic, negative Z850 anomalies over the eastern Atlantic Ocean, positive Z850 anomalies over the eastern part of Europe and negative Z850 anomalies over Russia (Figure 5b). This kind of pattern favors the advection of dry and warm air from the south-eastern part of Europe towards Romania and reduced precipitation and hence low streamflow anomalies. The Z850 and wind anomalies patterns identified for TS1 are in full agreement with the results found in the previous section. In general, positive (negative) streamflow anomalies, at country level, are associated with cyclonic (anticyclonic) circulation, the advection of cold and moist (warm and dry) air, enhanced (reduced) precipitation and positive (negative) CLD. Positive streamflow anomalies over the entire country (positive TS1 values) are also associated with enhanced precipitation at the country level (Figure 5c) and an

282 SST pattern characterized by positive SST anomalies over the tropical Atlantic Ocean and the central part and negative SST anomalies over the Mediterranean Sea (Figure 5d).

284 The composite map of Z850 anomalies for the years characterized by high TS2 values (> 0.75 std. dev.) shows a different structure compared to the case of summer TS1 (Figure 6a). Positive streamflow anomalies over the central and eastern part of Romania and negative streamflow anomalies over the western part of Romania are associated with a wave-train in the Z850 field characterized by positive Z850 anomalies over the western coast of North Atlantic Ocean, negative Z850 anomalies over Greenland, positive Z8500 anomalies over the British Isle, North Sea and the Scandinavian Peninsula and negative Z850 anomalies over the southern part of Europe. In this case the south-eastern part of Romania is under the action of cyclonic activity, most probably coming from the Mediterranean region, which is known to be a region of intense cyclonic development. This Z850 pattern is associated with strong advection of warm and dry air from the north-eastern part of the continent towards the western part of Romania (low streamflow) and warm and humid air from the Black Sea towards the southern and eastern part of the country and enhanced precipitation (Figure 6c). The composite map of Z850 anomalies for the years characterized by low (<-0.75 std. dev.) TS2 values (Figure 6b) features also a wave-train like structure, with negative Z850 anomalies over the western coast of the Atlantic Ocean extending up to the northern part of Europe and the Scandinavian Peninsula flanked on the north side by positive Z850 anomalies all over Greenland and on the southern part by positive Z850 anomalies over the northern part of Africa and southern part of Europe. The anticyclonic activity over the southern part of Europe causes reduced precipitation and low streamflow over the southern and central part of Romania, while the cyclonic activity over the central Atlantic and the northern part of European enhances precipitation over the western part of Romania. High

streamflow over the southern and central part of Romania and low streamflow over the western part (positive values of TS2) are associated with an SST pattern characterized by negative SST anomalies over the tropical Atlantic and south of Greenland and positive SST anomalies over the European coast and the Mediterranean Sea (Figure 6d). The SST from the Mediterranean Sea has a strong influence on the development of the cyclonic activity over this area (Quereda et al., 2011), which in turns affects the streamflow variability especially over the southern and central part of Romania. Warm SSTs in summer, especially over the western part of the Mediterranean Sea (where the positive correlations between TS2 and summer SST are) are associated with explosive cyclogenesis (Quereda et al., 2011) due to the fact that positive SST anomalies over this area stand as highly convective surfaces with respect to the overlying air. In agreement with our findings, in a recent study Vespreamu-Stroe et al (2012) have shown that the wind regime over the Romanian territory, especially over the south-eastern part, is strongly influenced by the cyclogenesis in the Mediterranean region. They showed that enhanced cyclogenesis over the Mediterranean region induces positive winds anomalies and storm occurrences especially over the south-eastern part of Romania (where the highest loadings of CCA2 are found).

5. Discussion and conclusions

In summary, in this study we have investigated the spatio-temporal variability of the summer streamflow over Romania and its relationship with large-scale atmospheric circulation and global SST. There is a lack of studies that assess this relationship, especially over Romania, and the existing ones are either restricted to different parts of the country (Stefan et al., 2005) or just over a single catchment area (Rimbu et al., 2004). The only study made at country level, has been recently published by Ionita et al. (2014b). In this study it is shown that different climate modes of variability (e.g. AO/NAO, EA, EAWR and SCA) control a significant part of the interannual winter streamflow variability over Romania. The aim of the current study was to analyze the variability of summer streamflow and identify the main triggers of this variability. The results obtained here differ significantly from the ones obtained for the winter season. This is not so surprisingly, if one takes into account that the influence of well-known teleconnection patterns is strongest in winter and less visible in summer (Kingston et al., 2006a). In this study it is shown that the variability of summer streamflow is influenced by atmospheric circulation patterns that do not project onto any well-know teleconnection patterns and most of this variability is strongly influenced by variations in summer temperature, cloud cover and potential evapotranspiration.

A large part of the summer streamflow variability is explained by a monopolar structure, both for the EOF analysis as well as for the CCA analysis, suggesting that more than 60% (explained variance of summer EOF1) of the summer streamflow is driven by the same mechanism via the large-scale atmospheric circulation. The summer streamflow variability over Romania is characterized by dry summers (negative streamflow anomalies) for the period 1940 up to 1965 and 1985 up to 2009 and wet summers (positive streamflow anomalies) for the period 1965 up to 1984. The second mode of summer variability (EOF2) is characterized by a dipole-like structure and emphasizes the influence of the Carpathian Mountains, being more sensitive to regional/local factors, like topography.

The CCA experiments with the combined large-scale predictors and summer streamflow served to investigate the co-variability between PET, TEMP, CLD and the Romanian streamflow for a network of 46 stations, at country level. The first coupled mode (CCA1) emphasizes that more than 52% of the total summer streamflow variability can be explained by a linear combination of PET, TEMP and CLD. Positive streamflow anomalies, at country level, are associated with negative PET and TEMP anomalies and positive CLD anomalies. Our results are in full agreement with previous studies which showed that for the spring and summer seasons, an increase in air temperature is associated with reduced precipitation, which can be the result of reductions of cloudiness (Tang et al., 2010). The increase in temperature could be further enhanced by soil moisture reduction, which in turn reduces the evaporation and evaporative cooling on the surface. Based on the aforementioned results we can argue that cloud and temperature forcings are determinant for more than 50% of the summer streamflow variability, throughout the modulation of summer precipitation and evapotranspiration. Similar results have been found recently by Busuioc et al. (2014) which showed that the variability of summer temperature and precipitation extremes is controlled by the thermodynamic factors, via TEMP and specific humidity at 700hPa level. In general, positive (negative) streamflow anomalies, at country level, are associated with cyclonic (anticyclonic) circulation, the advection of cold and moist (warm and dry) air, enhanced (reduced) precipitation and positive (negative) CLD.

Global warming is expected to result in substantial changes in streamflow and thus affect the water supplies management (IPCC, 2013). Since more than 50% of the summer streamflow variability was found to be influenced by the thermodynamic factors and taking into account the projected increase in the mean temperature, especially over the southern part of Europe (IPCC, 2013) one could expect an increase in the water resources scarcity in the future over these regions. In agreement with these findings, Barsan et al. (2014) have shown that the summer streamflow over the extra-Carpathian region shows a decreasing trend in the last 35 years and they speculated that this decreasing trend is related to the increase in the mean air temperature at country level.

The second CCA mode of summer streamflow variability presents strong interannual variability and more local characteristics. The relationship with PET, TEMP and CLD persists, but the amplitudes of the canonical modes are much smaller compared to the first mode. For the second canonical mode the Carpathian Mountains have a strong influence on the summer streamflow variability. CCA2 shows an opposite relationship between the summer streamflow and PET, TEMP and CLD when compared to CCA1, especially over the extra-Carpathian regions. Positive summer streamflow anomalies over the extra-Carpathian regions are associated with weak positive TEMP and PET anomalies over the southern part of Romania. This contrasting relationship can be explained via the *Clausius-Clapeyron* relation. Due to increased temperature, model projections show that rainfall will become more intense, mostly due to the presence of more moisture in the atmosphere (IPCC, 2014). The projections show an increase in the intensity of precipitation, but a decrease in the frequency of precipitation events. As such, an increase in the temperature could lead to more intense precipitation and hence floods, yet to longer dry periods between two rain events and hence droughts (IPCC, 2013). This could explain the contrasting relationship between the summer streamflow and TEMP and PET for CCA1 and CCA2, especially over the south-eastern part of Romania which is very sensitive to changes in temperature and evapotranspiration. Busuioc at el. (2014) have shown also that positive TEMP and specific humidity anomalies, with the highest magnitude over the southern part of Romania, are associated with negative anomalies of extreme dry periods, which is in agreement with the results identified for CCA2.

In general, negative (positive) streamflow anomalies on the northwestern (south and south-eastern) part of the country are associated with reduced (enhanced) precipitation over the northwestern (south and south-eastern) part of Romania as a response to the influence of large-scale atmospheric circulation and Atlantic Ocean and the Mediterranean SST. Negative (positive) summer streamflow anomalies over the northwestern (south and south-eastern) part of the country are associated with anticyclonic (cyclonic) circulation which in turn favors the advection of warm and dry (humid and warm air) from the eastern part of the continent (Mediterranean Sea).

The results shown here help to understand the variability of the summer streamflow conditions over Romania and identify possible mechanism behind this variability. In conclusion, we have shown that the streamflow variability over Romania is strongly related to large-scale atmospheric patterns and this kind of analysis can be useful to connect long-term hydrological variability to climate forcings. In agreement with previous studies (e.g. Tang et al., 2010; Tang and Leng, 2012, Busuioc et al., 2014) we show that a large part of the summer streamflow variability is very sensitive to cloud and temperature forcings. Such an analysis provides a useful tool to find meaningful physical mechanism which can explain the changes in the regime of streamflow variability. Moreover, the characterization of the climate influence on the streamflow variability could provide a useful basis for the construction of statistical or dynamical prediction models for the evolution of streamflow, which in turn could lead to a better water resources management, at country level.

References

Araneo DC, Compagnucci RH. 2008. Atmospheric circulation features associated to Argentinean Andean rivers discharge variability, *Geophys. Res. Lett*. **35**: L01805, doi:10.1029/2007GL032427.

Arnell NW, Krasovskaia I, Gottschalk L. 1993. River flow regimes in Europe. In Flow Regimes from International Experimental and Network Data (FRIEND), vol. 1. *Hydrological Studies, Gustard A (ed.). Institute of Hydrology: Wallingford, Oxfordshire, UK : 112-121.*

Barlow M, Nigam S, Berbery EH. 2001. ENSO, Pacific Decadal Variability, and U.S. Summertime Precipitation, Drought, and Stream Flow. *J. Climate*. **14**: 2105–2128.

Barnett TP, Preisendorfer R. 1987. Origin and levels of monthly and seasonal forecast skill for United States surface air temperatures determined by canonical correlation analysis. *Mon. Wea. Rev.* **115**: 1825–1850.

Barnston AG, Ropelewski CF. 1992. Prediction of ENSO episodes using canonical correlation analysis. *J. Climate*. **5**: 1316-1345.

Barros V, Chamorro L, Coronel G, Baez J. 2004. The Major Discharge Events in the Paraguay River: Magnitudes, Source Regions, and Climate Forcings. *J. Hydrometeorol*. **5**: 1161–1170.

Birsan MV, Zaharia L, Chendes V, Branescu E. 2014. Seasonal trends in Romanian streamflow. *Hydrol. Process*. **28**: 4496–4505. doi: 10.1002/hyp.9961

Bojariu R, Paliu D. 2001. North Atlantic Oscillation projection on Romanian climate fluctuations in the cold season, Detecting and Modelling Regional Climate Change and Associated Impacts, M. Brunet and D. Lopez eds., Springer-Verlag , 345-356.

Bouwer LM, Vermaat JE, Aerts JCJH. 2006. Winter atmospheric circulation and river discharge in northwest Europe, *Geophys. Res. Lett*. **33**: L06403, 10.1029/2005GL025548.

Bretherton C, Smith C, Wallace JM. 1992. An intercomparison of methods for finding coupled patterns in climate data. *J. Climate*. **5**: 541-560.

Busuioc A, Dobrinescu A, Birsan MV, Dumitrescu A, Orzan A. 2014. Spatial and temporal variability of climate extremes in Romania and associated large-scale mechanisms. *Int. J. Climatol*., doi: 10.1002/joc.4054.

Chelcea S, Ionita M. 2013. Extreme value analysis of the Barlad river time series, "OVIDIUS" University annals – Constanta, year XIV– issue 15 (2013), series: Civil Engineering, Section VII. Hydrology and Hydrogeology. Environment Protection, pp. 273 – 280, ISSN 1584-5990, Ovidius University Press, Constanţa, Romania.

Compo GP, Whitaker JS, Sardeshmukh PD, Matsui N, Allan RJ, Yin X, Gleason BE, Vose RS, Rutledge G, Bessemoulin P, Brönnimann S, Brunet M, Crouthamel RI, Grant AN, Groisman PY, Jones PD, Kruk M, Kruger AC, Marshall GJ, Maugeri M, Mok HY, Nordll Ø, Ross TF, Trigo RM, Wang XL, Woodruff SD, Worley SJ. 2011. The Twentieth Century Reanalysis Project. *QJR Meteorol. Soc.* **137**: 1-28. DOI: 10.1002/qj.776.

Compo GP, Whitaker JS, Sardeshmukh PD. 2006. Feasibility of a 100 year reanalysis using only surface pressure data. *Bull. Amer. Met. Soc*. **87**: 175-190.

Croley TE II, Luukkonen CL. 2003. Potential Effects of Climate Change on Ground Water in Lansing, Michigan. *Journal of the American Water Resources Association* **39**: 149-163.

Cullen HM, Kaplan A, Arkin P, DeMenocal PB. 2002. Impact of the North Atlantic Oscillation on Middle Eastern climate and streamflow. *Clim. Change* **55**: 315– 338.

Déry SJ, Wood EF. 2004. Teleconnection between the Arctic Oscillation and Hudson Bay river discharge. *Geophys. Res. Lett*. **31**, L18205, doi:10.1029/2004GL020729.

Dettinger MD, Diaz HF. 2000. Global characteristics of streamflow seasonality. *Journal of Hydrometeorology*. **1**: 289– 310.

Fleig AK, Tallaksen LM, Hisdal H, Hannah DM. 2011. Regional hydrological drought in north-western Europe: linking a new regional drought area index with weather types. *Hydrol. Process*. **25**: 1163–1179.

Gámiz-Fortis SR, Hidalgo-Muñoz JM., Argüeso D, Esteban-Parra MJ, aCastro-Díez Y. 2011. Spatio-temporal variability in Ebro river basin (NE Spain): global SST as potential source of predictability on decadal time scales, *J. Hydrol*. **409**: 759–775.

García-Ruiz JM, Regüés D, Alvera B, Lana-Renault N, Serrano-Muela P, Nadal-Romero E, Navas A, Latron J, Martí-Bono C, Arnáez J. 2008. Flood generation and sediment transport in experimental catchments affected by land use changes in the central Pyrenees. *J. Hydrol*. **356 (1–2)**: 245–260.

Harris I, Jones PD, Osborn TJ, Lister DH. 2013. Updated high-resolution grids of monthly climatic observations. *Int. J. Climatol*. **34**: 623–642. doi: 10.1002/joc.3711

Ionita M., Lohmann G., Rimbu N. 2008. Prediction of Elbe discharge based on stable teleconnections with winter global temperature and precipitation, *J Climate* **21**: 6215 - 6226. DOI:10.1175/2008JCLI2248.1

Ionita M, Rimbu N, Lohmann G. 2011. Decadal variability of the Elbe river streamflow. *International Journal of Climatology* **31 (1):** 22–30. DOI: 10.1002/joc.2054.

Ionita M, Lohmann G, Rimbu N, Chelcea S, Dima M. 2012a. Interannual to decadal summer drought variability over Europe and its relationship to global sea surface temperature. *Clim. Dyn.* **38(1–2)**:363–377.

Ionita M, Lohmann G, Rimbu N, Chelcea S. 2012b. Interannual Variability of Rhine River Streamflow and Its Relationship with Large-Scale Anomaly Patterns in Spring and Autumn. *J. Hydrometeor*. **13**: 172–188.

Ionita M, Rimbu N, Chelcea S, Patrut S. 2013. Multidecadal variability of summer temperature over Romania and its relation with Atlantic Multidecadal Oscillation, *Theor. Appl. Climatol*. **113**: 305 – 315. doi: 10.1007/s00704-012-0786-8.

Ionita M. 2014a. The impact of the East Atlantic/Western Russia pattern on the hydroclimatology of Europe from mid-winter to late spring, *Climate* 4: 296-309.

Ionita M, Chelcea S, Rimbu N, Adler MJ. 2014b. Spatial and temporal variability of winter streamflow over Romania and its relationship to large-scale atmospheric circulation. *Journal of Hydrology*. DOI: 10.1016/j.jhydrol.2014.09.024

IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi:10.1017/CBO9781107415324

Kingston DG, Lawler DM, McGregor GR. 2006a. Linkages between atmospheric circulation, climate and streamflow in the northern North Atlantic: research prospects. *Progress in Physical Geography* **30(2):** 143–174.

Kingston DG, McGregor GR, Hannah DM, Lawler DM. 2006b. River flow teleconnections across the northern North Atlantic margin. *Geophysical Research Letters* **33:** L14705. DOI:10·10292006/GL026574.

Kundzewicz ZW, Mata LJ, Arnell N, Döll P, Kabat P, Jiménez B, Miller K, Oki T, Şen Z, Shiklomanov I. 2007. Freshwater resources and their management. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (ed. by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson), 173–210. Cambridge University Press, UK http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter3.pdf.

Lawler DM, McGregor GR, Phillips ID. 2003. Influence of atmospheric circulation changes and regional climate variability on river flow and suspended sediment fluxes in southern Iceland. *Hydrol. Process* **17(16)**: 3195–3223.

Lorenzo-Lacruz J, Vicente-Serrano SM, López-Moreno JI, González-Hidalgo JC, Morán-Tejeda E. 2011. The response of Iberian rivers to the North Atlantic Oscillation, *Hydrol. Earth Syst. Sci.* **15**: 2581-2597, doi:10.5194/hess-15-2581-2011.

North GR, Bell TL, Cahalan RF, Moeng FJ. 1982. Sampling errors in the estimation of empirical orthogonal functions, *Mon. Wea. Rew*. **110(7)**: 699-706.

Post DA, Jakeman AJ. 1996. Relationships between catchment attributes and hydrological response characteristics in small Australian mountain ash catchments. *Hydrol. Process*. **10**: 877–892

Preisendorfer RW. 1988. Principal Component Analysis in Meteorology and Oceanography. Amsterdam: Elsevier, 425 pp.

Quereda J, Monton E, Escrig J. 2011. Teleconnections between the North Atlantic SST and Mediterranean rainfall. *Tethys* **8**: 31–42, DOI:10.3369/tethys.2011.8.04

Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A. 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res*. **108**: No. D14, 4407 10.1029/2002JD002670

Rimbu N, Dima M, Lohmann G, Stefan S. 2004. Impacts on the North Atlantic Oscillation and the El Niño-Southern Oscillation on Danube river flow variability. *Geophysical Research Letters* **31**: L23203, doi:10.1029/2004GL020559.

Shorthouse CA, Arnell NW. 1997. Spatial and temporal variability in European river flows and the North Atlantic oscillation, in: *Regional Hydrology – Concepts and models for sustainable water management, IAHS.*

Souza Filho FA, Lall U. 2003. Seasonal to interannual ensemble streamflow forecasts for Ceara, Brazil: Applications of a multivariate, semiparametric algorithm, *Water Resources Research* **39**: 1307. DOI:10.1029/2002WR001373.

Stefan S, Ghioca M, Rimbu N, Boroneant C. 2004. Study of meteorological and hydrological drought in southern Romania from observational data. *Int. J. Climatol.* 24: 871–881. doi: 10.1002/joc.1039

Tallaksen LM. 1995. A review of baseflow recession analysis. *J. Hydrol.* **165**: 349–370.

Tang Q, Leng G, Groisman PY, 2012. European Hot Summers Associated with a Reduction of Cloudiness. *J Climate* **25**: 3637–3644

Tang Q, Guoyong L. 2012. Damped summer warming accompanied with cloud cover increase over Eurasia from 1982 to 2009, *Environ. Res. Lett.* **7** 014004

Tomozeiu R, Busuioc A, Stefan S. 2002. Changes in seasonal mean of maximum air temperature in Romania and their connection with large-scale circulation. *Int J Climatol.* **22**:1181-1196.

Tomozeiu R, Stefan S, Busuioc A. 2005. Winter precipitation variability and large-scale circulation patterns in Romania. *Theor Appl Climatol*. doi:10.1007/s00704-004-0082-3.

Trigo RM, Osborn TJ, Corte-Real JM. 2002. The North Atlantic Oscillation influence on Europe: climate impacts and associated physical mechanisms, *Clim. Res*. **20**: 9 – 17.

Verpreamu-Stroe A, Cheval S, Tatui F. 2012. The wind regime of Romania – Characteristics, trends and North Atlantic Influences. *Forum Geografic* 12/2012; XI (2):118-126. DOI: 10.5775/fg.2067-4635.2012.003.d

Von Storch H. 1995. Spatial Patterns: EOFs and CCA. In: Analysis of climate variability: application of statistical techniques (eds. H. Von Storch and A. Navarra). Springer Verlag, 227–258.

Von Storch H, Zwiers FW. 1999. Statistical Analysis in Climate Research. Cambridge University Press, 494 pp.

Ward PJ, Beets W, Bouwer LM, Aerts JCJH., Renssen H. 2010. Sensitivity of river discharge to ENSO, *Geophys. Res. Lett*. **37**: L12402, doi:10.1029/2010GL043215 .

Werner P, Von Storch H. 1993. Interannual variability of Central European mean temperature in January–February and its relation to large–scale circulation, *Clim. Res*.**3**: 195–207.

Whitaker JS, Compo GP, Wei X, Hamill TM. 2004. Reanalysis without radiosondes using ensemble data assimilation. *Mon. Wea. Rev*. **132**: 1190-1200.

Xoplaki E, González-Rouco JF, Gyalistras D, Luterbacher J, Rickli R, Wanner H. 2003. Interannual summer air temperature variability over Greece and its connection to the large-scale atmospheric circulation and Mediterranean SSTs 1950-1999. *Clim. Dyn*. **20**: 537-554.

Zavoianu I. 2002. Hidrologie, editia a II-a, Ed. Fundatiei Romania de Maine, 2002, ISBN 973-582-456-6

Ziv B, Dayan U, Kushnir Y, Roth C, Enzel Y. 2006. Regional and global atmospheric patterns governing rainfall in the southern Levant. *Int. J. Climatol*. **26**: 55–73.

Figure captions

Figure 1. a) The topographic map of Romania and the location of the stations used in this study; b) The contribution (%) of summer streamflow to the mean annual streamflow for the 46 streamflow over Romania for the 1935-2010 period.

Figure 2. a) First EOF (EOF1) of summer (June/July/August - JJA) streamflow; b) the corresponding time series (PC1) and the 7years running mean (black line); c) The second EOF (EOF2) of summer (June/July/August - JJA) streamflow; d) The corresponding time series (PC2) the 7years running mean (black line). For PC1 and PC2 time series the units are standardized anomalies.

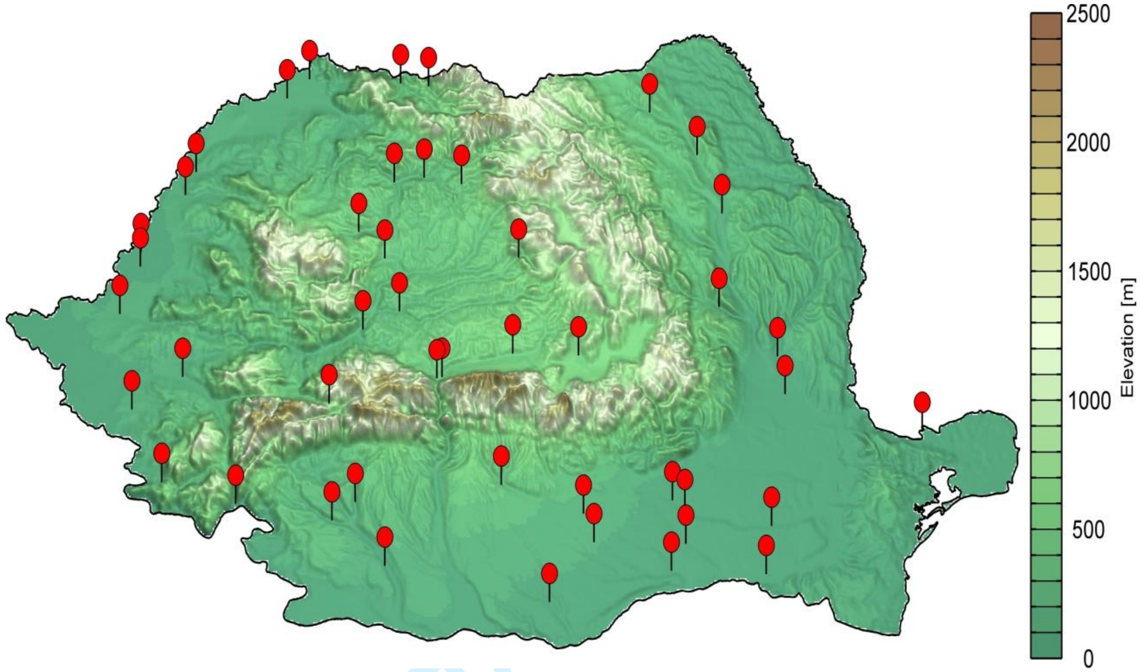
Figure 3. a) The spatial pattern of the first CCA (CCA1) of the summer streamflow; b) The normalized time components of CCA1: TS1 streamflow (black line) and TS1 predictors (red line); c) The spatial pattern of the first CCA (CCA1) of the summer PET; d) The spatial pattern of the first CCA (CCA1) of the summer TEMP and e) The spatial pattern of the first CCA (CCA1) of the summer CLD.

Figure 4. a) The spatial pattern of the second CCA (CCA2) of the summer streamflow; b) The normalized time components of CCA1: TS1 streamflow (green line) and TS1 predictors (magenta line); c) The spatial pattern of the second CCA (CCA2) of the summer PET; d) The spatial pattern of the second CCA (CCA2) of the summer TEMP and e) The spatial pattern of the second CCA (CCA2) of the summer CLD.

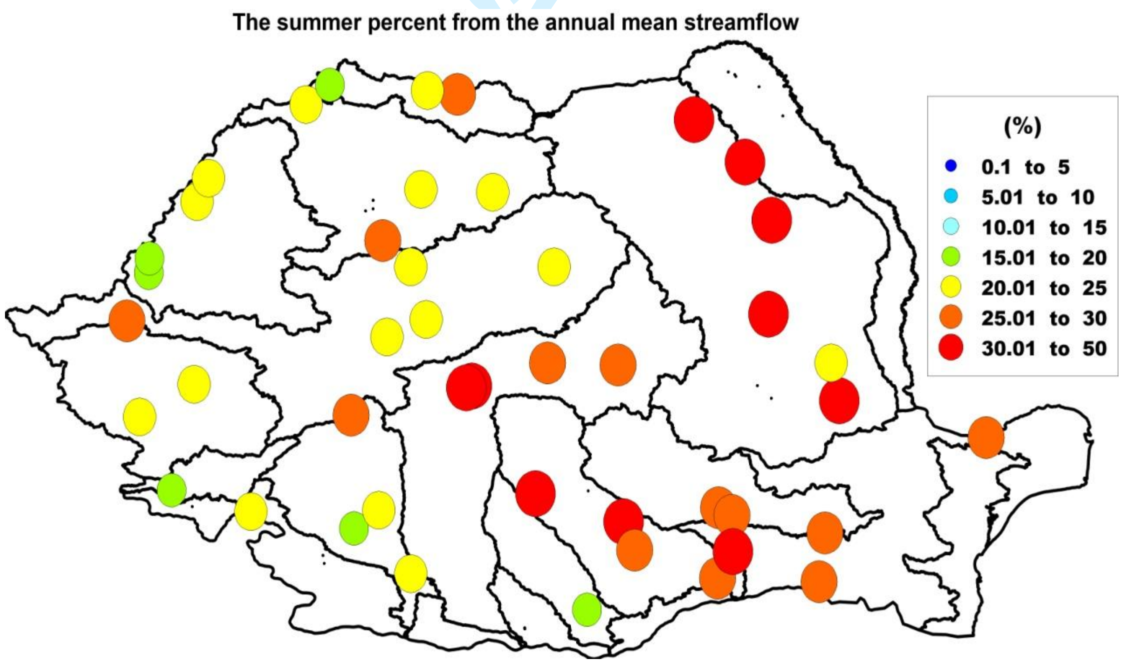
Figure 5. a) The **High** (TS1 > 0.75 std. dev.) composite map between summer streamflow TS1 and summer Geopotential Height at 850 mb (Z850 – shaded areas) and summer 850mb Wind vectors (arrows); b) The **Low** (TS1 < -0.75 std. dev.) composite map between summer streamflow TS1 and summer Geopotential Height at 850 mb (Z850 – shaded areas) and summer 850mb Wind vectors (arrows); c) The correlation map between summer streamflow TS1 and summer PP; d) The correlation map between summer streamflow TS1 and summer SST. The dotted areas indicate regions where the correlations are exceeding the 95% significance level.

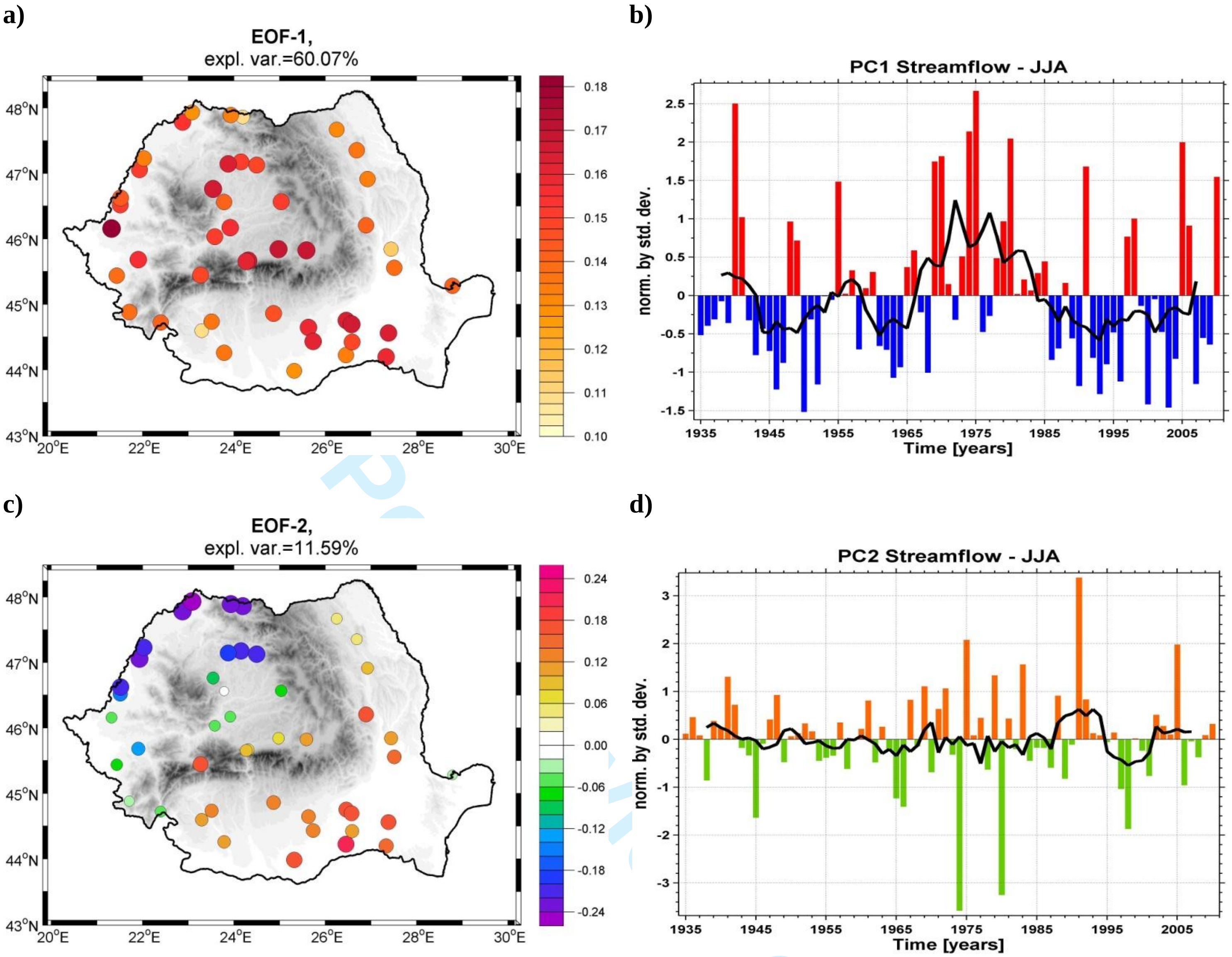
Figure 6. a) The **High** (TS2 > 0.75 std. dev.) composite map between summer streamflow TS2 and summer Geopotential Height at 850 mb (Z850 – shaded areas) and summer 850mb Wind vectors (arrows); b) The **Low** (TS2 < -0.75 std. dev.) composite map between summer streamflow TS2 and summer Geopotential Height at 850 mb (Z850 – shaded areas) and summer 850mb Wind vectors (arrows); c) The correlation map between summer streamflow TS2 and summer PP; d) The correlation map between summer streamflow TS2 and summer SST. The dotted areas indicate regions where the correlations are exceeding the 95% significance level.

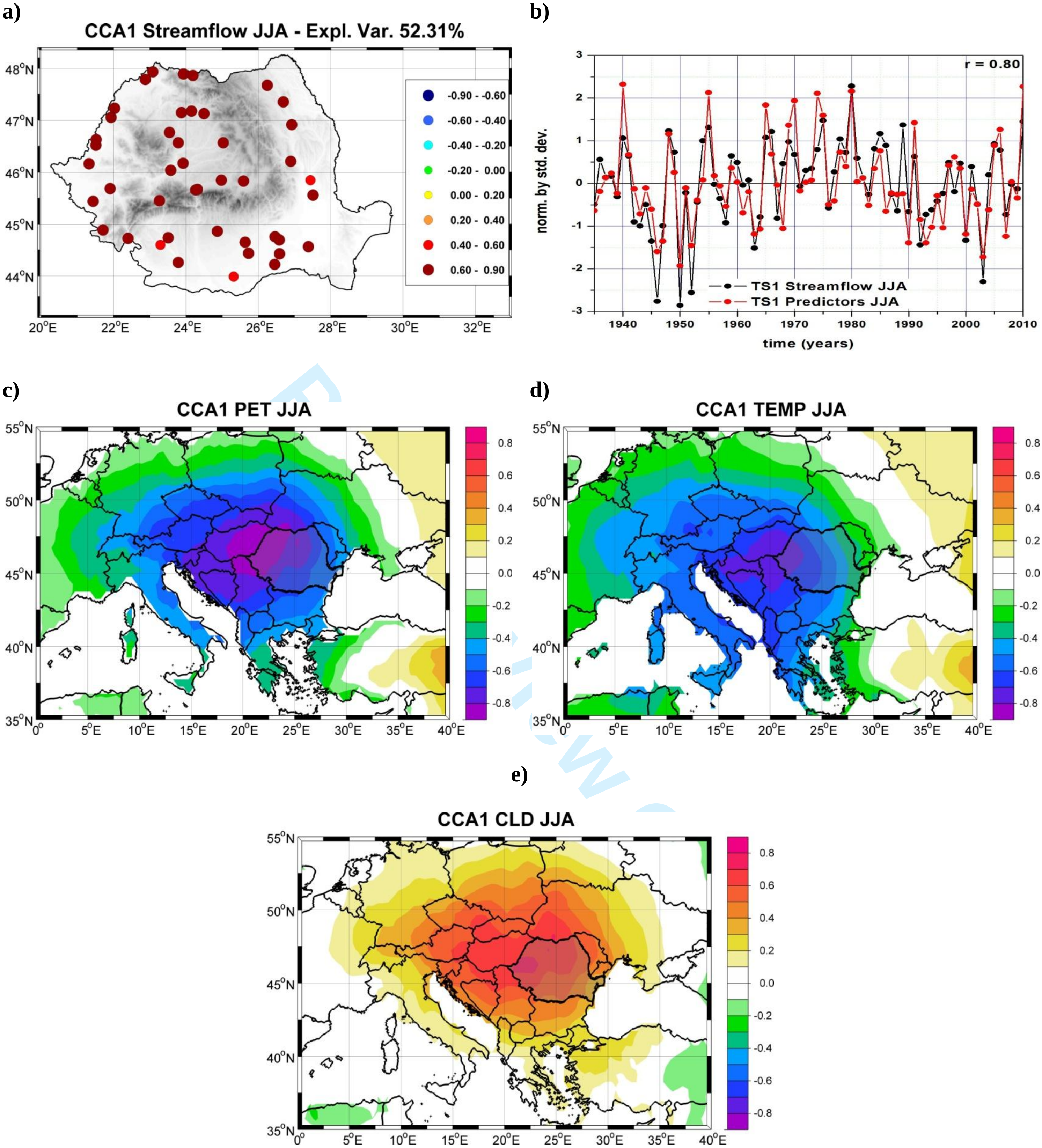
a)

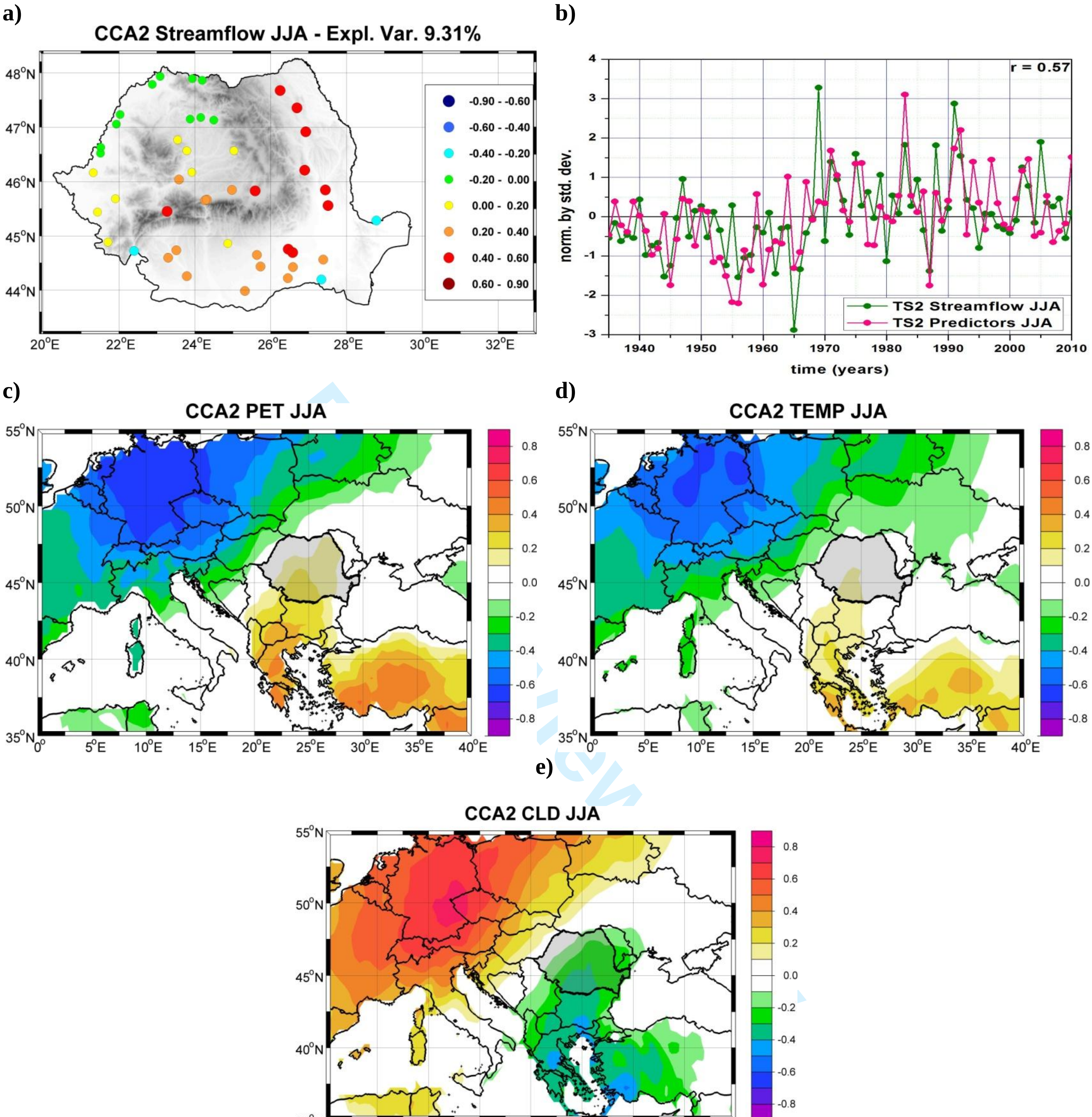

2500
2000
1500
1000
500
0
Elevation [m]

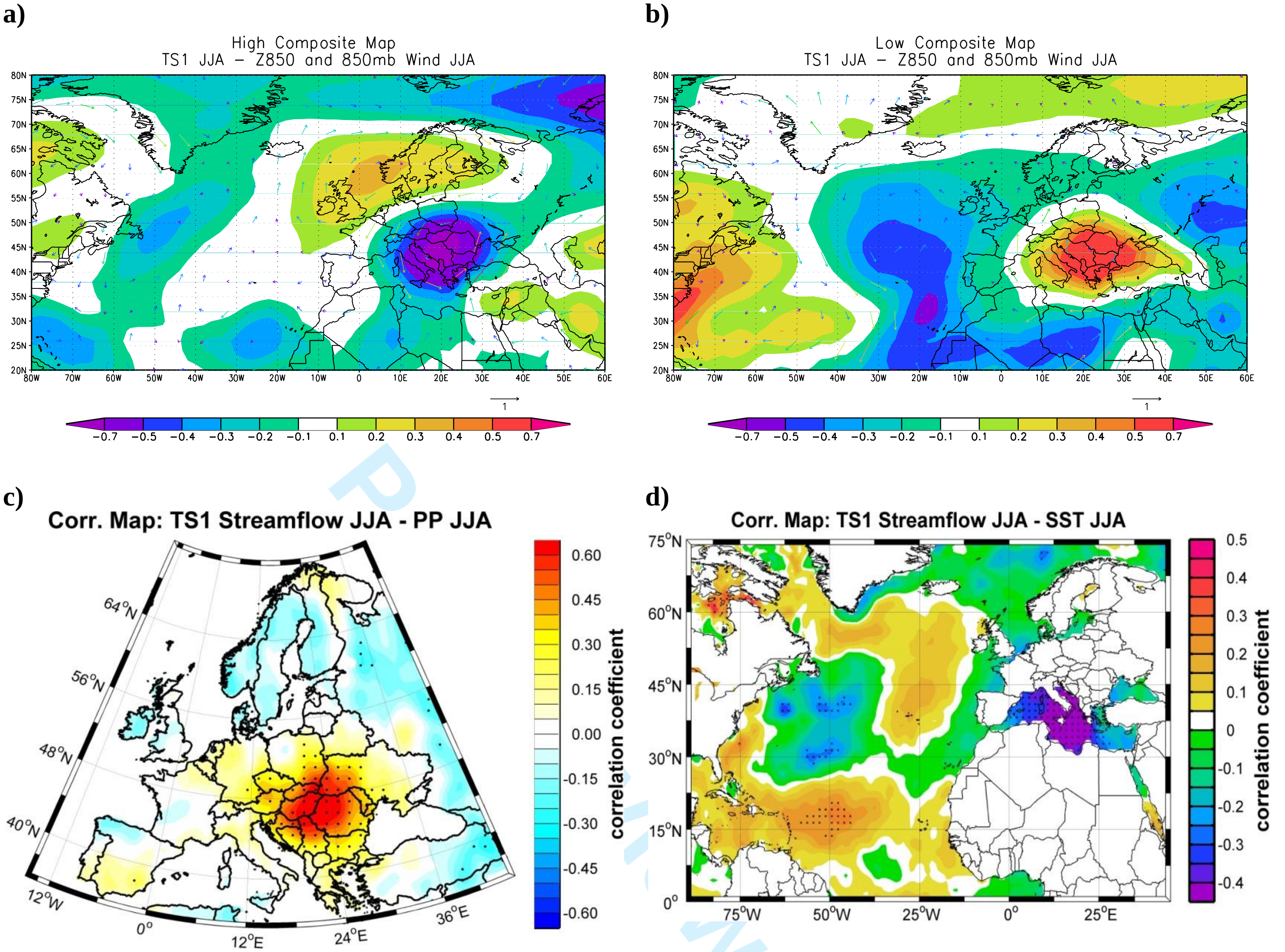
b)

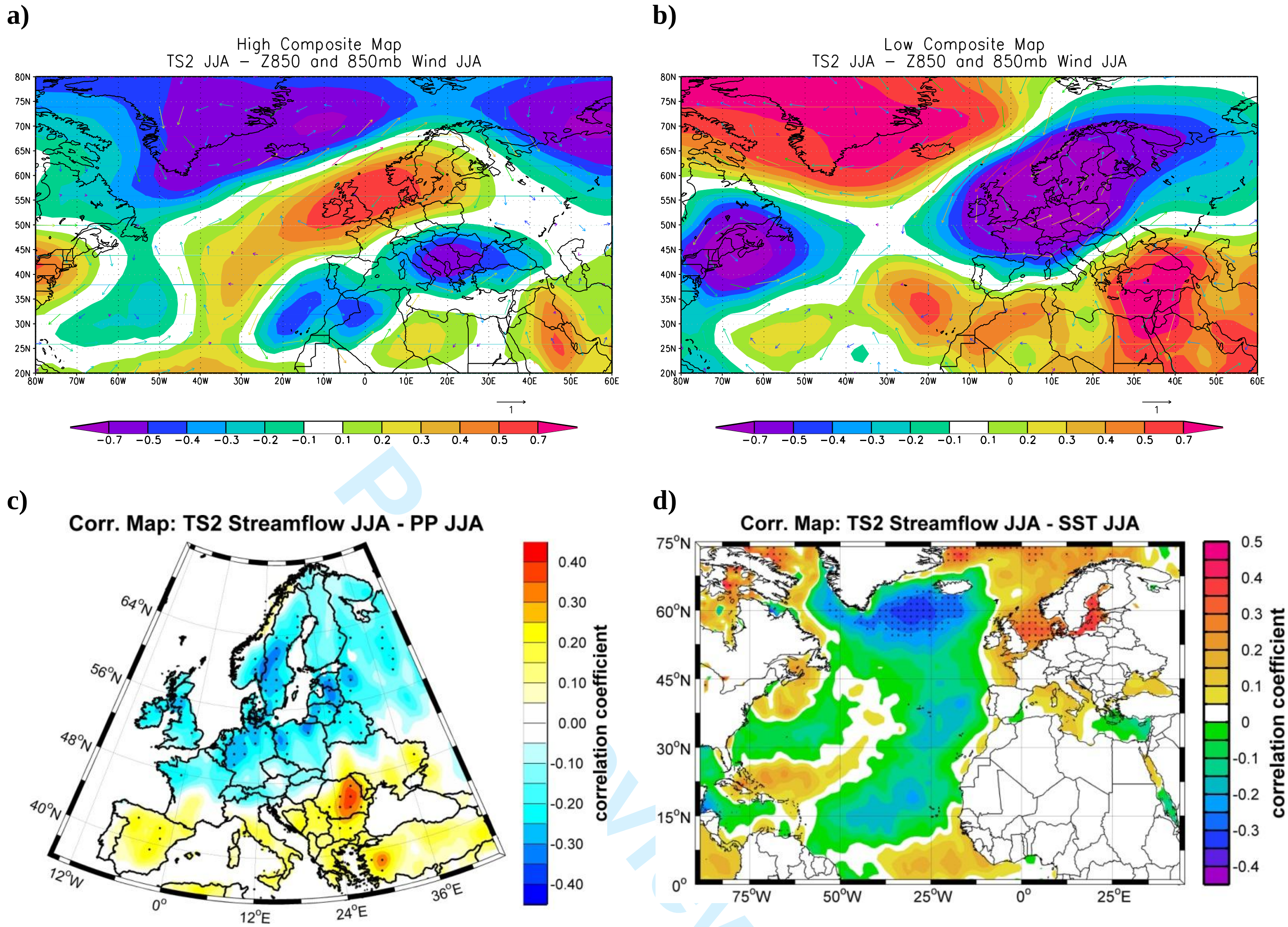

The summer percent from the annual mean streamflow
(%)
0.1 to 5
5.01 to 10
10.01 to 15
15.01 to 20
20.01 to 25
25.01 to 30
30.01 to 50


a)
EOF-1,
expl. var.=60.07%
b)
PC1 Streamflow - JJA
norm. by std. dev.
Time [years]
c)
EOF-2,
expl. var.=11.59%
d)
PC2 Streamflow - JJA
norm. by std. dev.
Time [years]


a)
CCA1 Streamflow JJA - Expl. Var. 52.31%
-0.90 - -0.60
-0.60 - -0.40
-0.40 - -0.20
-0.20 - 0.00
0.00 - 0.20
0.20 - 0.40
0.40 - 0.60
0.60 - 0.90
b)
r = 0.80
norm. by std. dev.
TS1 Streamflow JJA
TS1 Predictors JJA
time (years)
c)
CCA1 PET JJA
d)
CCA1 TEMP JJA
e)
CCA1 CLD JJA


a)
CCA2 Streamflow JJA - Expl. Var. 9.31%
-0.90 - -0.60
-0.60 - -0.40
-0.40 - -0.20
-0.20 - 0.00
0.00 - 0.20
0.20 - 0.40
0.40 - 0.60
0.60 - 0.90
48°N
47°N
46°N
45°N
44°N
20°E 22°E 24°E 26°E 28°E 30°E 32°E
b)
r = 0.57
norm. by std. dev.
time (years)
TS2 Streamflow JJA
TS2 Predictors JJA
1940 1950 1960 1970 1980 1990 2000 2010
c)
CCA2 PET JJA
d)
CCA2 TEMP JJA
e)
CCA2 CLD JJA
55°N 50°N 45°N 40°N 35°N
0° 5°E 10°E 15°E 20°E 25°E 30°E 35°E 40°E
0.8 0.6 0.4 0.2 0.0 -0.2 -0.4 -0.6 -0.8


a)
High Composite Map
TS1 JJA – Z850 and 850mb Wind JJA
b)
Low Composite Map
TS1 JJA – Z850 and 850mb Wind JJA
c)
Corr. Map: TS1 Streamflow JJA - PP JJA
correlation coefficient
d)
Corr. Map: TS1 Streamflow JJA - SST JJA
correlation coefficient


a)
High Composite Map
TS2 JJA – Z850 and 850mb Wind JJA
b)
Low Composite Map
TS2 JJA – Z850 and 850mb Wind JJA
−0.7 −0.5 −0.4 −0.3 −0.2 −0.1 0.1 0.2 0.3 0.4 0.5 0.7
c)
Corr. Map: TS2 Streamflow JJA - PP JJA
correlation coefficient
d)
Corr. Map: TS2 Streamflow JJA - SST JJA
correlation coefficient