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TRACKING THE ORIGIN OF MOISTURE OVER SERBIA USING THE LAGRANGIAN METHOD

Abstract: *In this study, we investigate the sources of moisture over Serbia using a Lagrangian method based on the FLEXPART V9.0 particle dispersion model combined with ERA-Interim reanalysis data, to track changes in atmospheric moisture. This approach computes the budget of evaporation-minus-precipitation by calculating changes in specific humidity along forward and backward trajectories. We considered a period of 34 years, from 1980 to 2014, which allowed the identification of climatological moisture sources and moisture transport towards the country. The results showed that Serbia receive moisture mainly from two sources: the Mediterranean Sea which is the dominant source during the winter (October-March) and the own region which predominate during the summer (April-September).*

Key words: moisture sources, Flexpart, Lagrangian method, Serbia

INTRODUCTION

The study area covers the territory of Serbia, which is located between Central and Southern Europe. It comprises around 18% (88,361 km^2) of the Balkan Peninsula, and almost entire territory (92%) is drained by the Danube River while the rest of the territory belongs to Adriatic and Aegean drainage basin [1]. The northern part of the country is located within the Pannonian Plain and the rest covers the mountainous regions: the Dinaric Alps which stretching through the west and southwestern regions, the Carpathian, Balkan, and Rhodope Mountains occupying the eastern and southeastern areas [2].

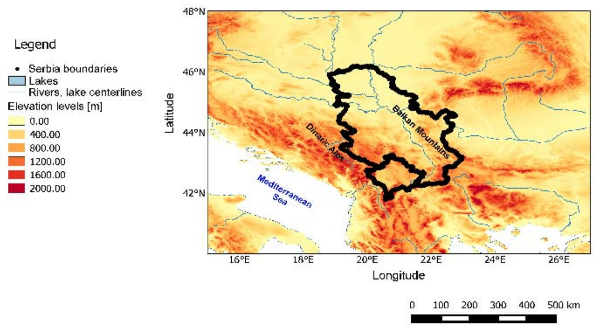

Figure 1. *The black line indicates the boundaries of Serbia. The elevation levels of the region are indicated in colors (meters, m). Data were taken from the HydroSHEDS project available online at https://hydrosheds.cr.usgs.gov*

The average altitude of Serbia is 473 m and varies in elevation from 29 m in eastern parts of the country, near to the borders between Bulgaria and Romania and rises up to 2,656 m on Prokletije Mountain in the south part of the country [3]. The climate of Serbia is very diverse, with the Mediterranean influence in the south and southwestern parts, whereas the north part of the country has characteristics of typical continental climate with air masses predominantly originating from Northern Europe [4].

Precipitation over Serbia varies extensively, and increases with altitude as well as from the north toward the south of the country. Average annual precipitation for the Northern part is estimated below 600 mm while southern regions receive around 1000 mm per year, with except of mountain summits in the southwest which receive over 1000 mm per year. Most of the country has a continental precipitation regime with maximum precipitation occurring during June and May and minimum precipitation occurring during February and October [1].

Many previous studies using the observational data have analyzed the spatial pattern of the temperature and precipitation trends in Serbia and the possible changes in the natural drivers with impacts on water resources, water availability, and extreme hydrological events [2, 4]. The transport of moisture over the region of interest represents the link between the water evaporation from the moisture source regions and the continental precipitation. Knowing that the precipitation is one of the most important elements of the water cycle [5] it is really important to detect and understand the origin of atmospheric moisture over Serbia. Knowledge of the main moisture sources for specific region is crucial to justify physical changes in precipitation both for current

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and future climates [6]. Given the importance of moisture transport, the main objective of this study is to identify main climatological moisture sources for precipitation over Serbia and to analyze their variability comparing the moisture sources variation month by month. Study covers the 34-year time period from 1980 to 2014 and it is performed using the Lagrangian method FLEXPART V9.0 in its backward mode, tracking the air masses that ultimately reach the region of Serbia. Moreover, wet and dry conditions were detected over Serbia during the analysed period using the Standardised Precipitation Evapotranspiration Index (SPEI). Wet and dry conditions represent important elements for the studies connected with climate changes impact, supporting the investigation, monitoring and prediction of extreme hydrological events such as occurrence of drought and floods.

METHODOLOGY

Lagrangian model FLEXPART

The Lagrangian FLEXible PARTicle dispersion model (FLEXPART) developed by Stohl and James [7, 8] was used for the identification of the climatological moisture sources for Serbia during the analyzed period from 1980 to 2014. The model uses global ERA-Interim reanalysis database from the European Centre for Medium-Range Weather Forecasts (ECMWF) which has a horizontal resolution of 1° on 61 vertical levels, ranging from 1000 to 0.1 hPa [9]. FLEXPART model divides the atmosphere into a great number of virtual air particles (approximately 2.0 million) and the mass (m) of each particle is considered to be constant. The particles were transported by a 3-dimensional wind field, and the specific humidity (q), and position of the particles were recorded for each air parcel at each 6 hours' time period (00, 06, 12 and 18 UTC). The transport time of the particle is limited to 10 days, which represent the average water vapor lifetime in the global atmosphere [10].

Recorded changes in the variations of the specific humidity of each air parcel along the time could be calculated and expressed by following equation (1):

$$(e-p) = m\left(\frac{dq}{dt}\right) \qquad (1)$$

where, m represents the mass of a particle and (e − p) represents evaporation minus precipitation, which is the freshwater flux of the particle. Changes in specific humidity permit us to identify where the particles lose moisture through precipitation (p) or gain moisture through evaporation (e). The sum of the freshwater flux (e − p) of all particles presented in the atmospheric column over an area A, represents the total freshwater flux (E – P) expressed by equation (2):

$$(E-P) \approx \frac{\sum_{k=1}^{k}(e-p)}{A} \qquad (2)$$

Where, E represents the total evaporation, P represents the total precipitation, and K represents the number of particles over the area A.

The trajectory of the particles can be followed using backward-in-time analysis with the aim to determinate the main sources of moisture for the target region (E − P > 0) or forward-in-time analysis to investigate the moisture sinks regions after being transported by particles (E − P < 0).

Recently, the Lagrangian method has been used for detection of the main moisture and sinks regions near Serbia, for instance over the Mediterranean Sea [11], the Alps region [12], the Danube River basin [13], etc. Also, the method was successfully applied for investigation of the extreme hydrological events of drought [14] and intense precipitation [15] in the surrounding areas of Serbia.

More detailed information about the functionalities of FLEXPART can be found in the studies of Stohl and James [7, 8] and Gimeno et al. [6].

Detection of wet and dry conditions over the region

To identify dry and wet conditions in Serbia, the Standardised Precipitation Evapotranspiration Index (SPEI) developed by Vicente-Serrano et al. [16] was used. The SPEI follows the same conceptual approach as the Standardised Precipitation Index (SPI), but rather than concentrating on precipitation alone it is based on a climatic water balance (precipitation minus potential evapotranspiration), which is computed on different timescales. The data of precipitation and potential evapotranspiration were obtained from Climate Research Unit (CRU) Time-Series (TS) v.3.24.01 [17]. We identified wet and dry conditions over Serbia during 1980–2014 through the SPEI-1, SPEI-3, SPEI-6, SPEI-12, SPEI-24 time scales. McKee et al. [18] suggested a classification system to define the intensity of dry and wet categories as shown in Table 1.

Table 1. *Dryness/wetness categories based on the SPEI values, according to the categories given by McKee et al. [12], which were applied to the SPI*

Range	Category
$2 \le SPI$	Extremely wet
$1.5 \le SPI < 2.0$	Severely wet
$1.0 \le SPI < 1.5$	Moderate wet
$0 < SPI < 1$	Mild wet
$-1.0 < SPI < 0$	Mild drought
$-1.5 < SPI \le -1.0$	Moderate drought
$-2.0 < SPI \le -1.5$	Severe drought
$SPI \le -2.0$	Extreme drought

RESULTS

The Lagrangian method FLEXPART V9.0 [7, 8] was used to track the air masses over Serbia backward in time with purpose to identify the main moisture source regions. The annual values of 10-day integrated atmospheric moisture budget obtained via backward experiment for Serbia, for the 34-year period 1980-2014, are shown in Figure 2. The areas characterized by the reddish colors (Figure 2) represent regions where (E-P) > 0, meaning that evaporation exceeds precipitation in the net moisture budget, and this is how the main moisture source regions were identified.

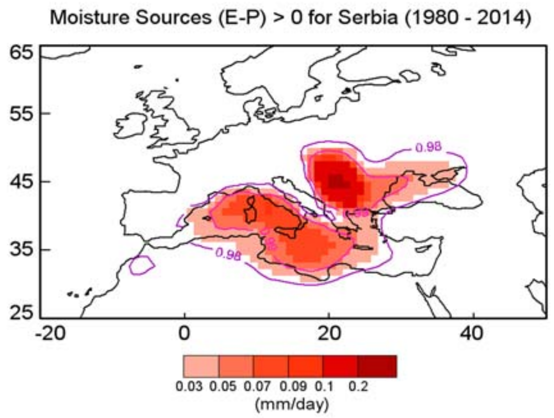

Figure 2. *Climatological annual 10-day integrated (E-P) obtained for the backward experiment for Serbia during the period 1980-2014. The pink contour line delimits the source areas selected using the 98 and 99 percentile of the (E-P)>0 values (i.e., 0.0220 and 0.0525 mm/day, respectively).*

According to the applied thresholds for identification of the water source regions, pink contour line of 0.0220 mm/day corresponds to the 98% percentile of the annual averages of (E-P) > 0 and value of 0.0525 mm/day indicates the 99% percentile obtained by the backward experiment from the methodology described above. Obtained result suggests that Serbia mainly receives moisture from two main source regions: the Mediterranean Sea and from the local evaporative processes as a moisture source for the region throughout the year, indicating the area of Serbia itself as moisture for precipitation. Observing the annual variation, and looking the changes in moisture sources month by month, we obtained plotted maps shown in the Figure 3 revealing that during the winter season (October-March) the dominant source of moisture for Serbia is the Mediterranean Sea while during the summer season (April-September) the main source is its own region (Figure 3). These results are confirmed by findings of other authors [13] that highlighted that the Mediterranean Sea is the predominant moisture source for winter precipitation over the Danube River Basin, taking in consideration that the area of Serbia represents a part of the countries which constitute the catchment of the Danube River Basin.

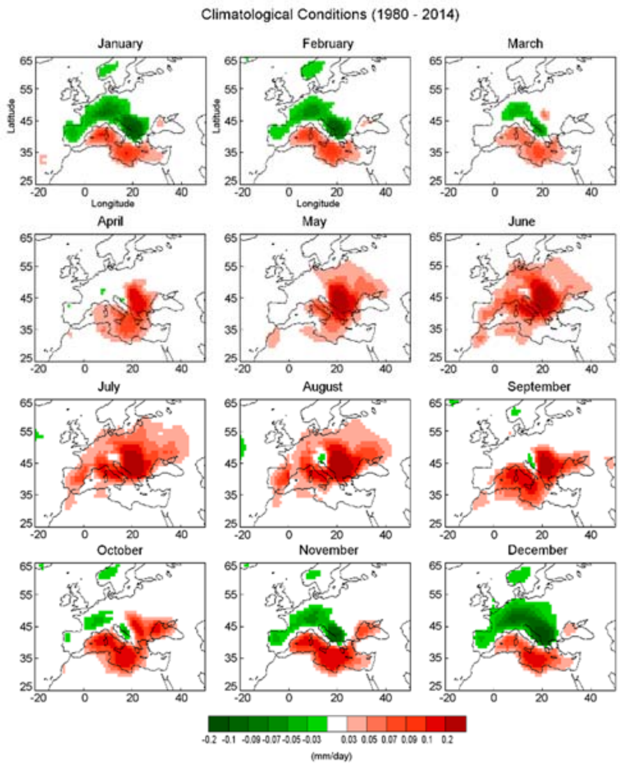

Figure 3. C*limatological monthly 10-day integrated (E − P) values observed for the period January 1980–December 2014, for all the particles bound for Serbia, determined from backward tracking. Red (green) colours represent regions acting as moisture sources (sinks) for the tracked particles.*

As we mentioned above, the identification of wet and dry conditions for a region is important for many aspects linked with climate changes over the region and a detailed study of related hydrological phenomena such as drought and extreme precipitation of floods. Figure 4 shows the SPEI-1,-3,-6,-12,-24 time series for Serbia during the period 1980–2014, in which the negative values (red bars) represent dry conditions and the positive ones (blue bars) represent wet conditions. Looking at the Figure 4, we can see that on the shorter time scale (SPEI-1) the peak value for wet conditions was recorded in 1980, while for the dry conditions the peak value is observed in 2000. For longer time scales, for instance SPEI-24 (which represents the water balance of 24 months), the highest value during the wet period was recorded in 1981, contrary to dry period when the peak value was observed in 2012.

Future analysis and investigation of precipitation and drought events in Serbia based on the identified wet and dry conditions may be useful for prevention, adaptation and protection of natural environment and human lives in the region.

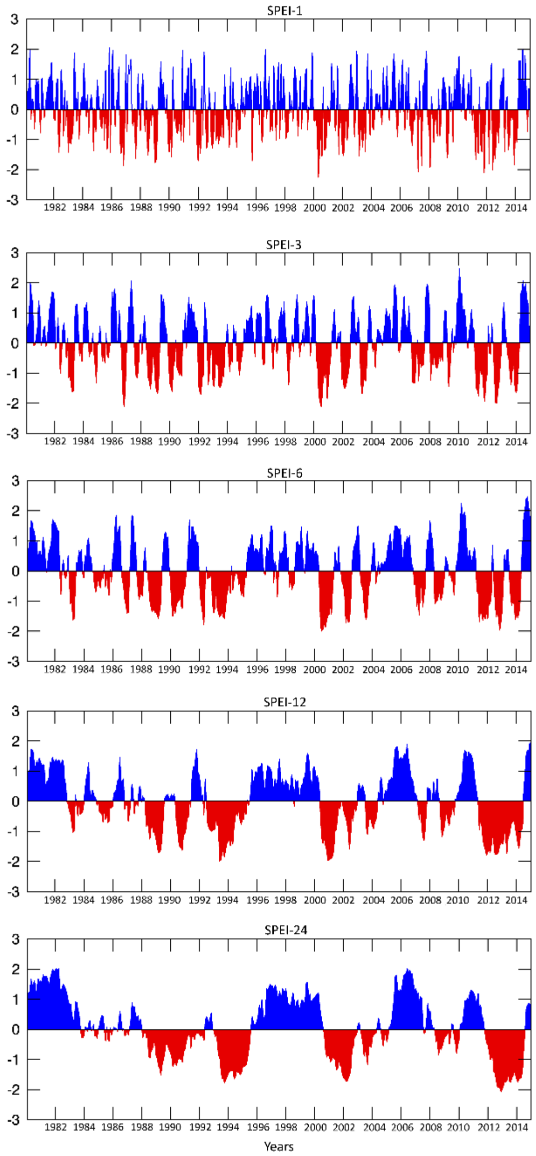

Figure 4. *Time series of Standardized Precipitation Evapotranspiration Index for the region of Serbia during 1980–2014. Red and blue bars represent positive and negative values, respectively.*

CONCLUSION

Obtained result suggests that Serbia mainly receives moisture from two main source regions: the Mediterranean Sea and the local evaporative processes (as a moisture source for the region throughout the year). During the winter season (October-March) the dominant source of moisture for Serbia is the Mediterranean Sea, while during the summer season (April-September) the main source is its own region. Those results have been confirmed by findings of other research revealing that the Mediterranean Sea is the predominant moisture source for winter precipitation over the Danube River Basin.

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Milica Stojanović was born in Leskovac, Serbia, in 1990. She holds a Master's degree in Environmental Engineering, from University of Nis, Faculty of Occupational Safety, Nis, Serbia. The main areas of her research include environmental science, the global water cycle and the impact of climate change on hydrology. Currently, she is a PhD student at University of Vigo, Spain.

PRIMENA LAGRANŽOVOG METODA ZA PRAĆENJE POREKLA ATMOSFERSKE VLAGE ZA SRBIJU

Milica Stojanović, Danica Ćirić, Raquel Nieto, Anita Drumond, Evica Stojiljković, Luis Gimeno

Rezime: *U ovoj studiji istraženi su izvori vlage za Srbiju primenom Lagranžovog disperzionog modela FLEXPART V9.0, koji koristi ERA-Interim podatke za pracenje promena atmosferske vlage. Ovaj model izračunava razliku između isparavanja i precipitacije računajući promene u specifičnoj vlažnosti duž trajektorija čestica nazad (backward) i napred (forward) u vremenu. Za studiju se koristio vremenski period od 34 godine, od 1980 do 2014. Koristeći model trajektorija unazad, moguce je identifikovati klimatološke izvore vlage i pratiti transport te vlage ka Srbiji. Rezultati pokazuju da Srbija dobija vlagu uglavnom iz dva izvora: Sredozemnog mora (koje je dominantni izvor tokom zimskog perioda (oktobar-mart)) i sopstvenog regiona (koji preovladava tokom leta (april-septembar)).*

Ključne reči: izvori vlage, flexpart, lagranžov metod, Srbija.