Conference Proceedings Paper

Tracking the Origin of Moisture (and Moisture for Precipitation) over the Danube River Basin through a Lagrangian Approach

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Abstract: In this study we investigate the sources of moisture (and moisture for precipitation) over the Danube River Basin (DRB) through a Lagrangian approach which uses the FLEXPART V9.0 Lagrangian particle dispersion model together with ERA-Interim reanalysis data to track changes in atmospheric moisture along 10-day trajectories. This approach computes the budget of evaporation minus precipitation by calculating changes in specific humidity along forward and backward trajectories. We considered a temporal period of 34 years, from 1980 to 2014 which allowed identifying climatological sources and moisture transport towards the basin at interannual scale. Results showed that the DRB receives moisture mainly from seven different oceanic, maritime and terrestrial moisture source regions: North Atlantic Ocean, North Africa, Mediterranean Sea, Black Sea, Caspian Sea, Danube River Basin and Central and Eastern Europe. The contribution of these sources differs with the season. During the Wet season (October–March) the main moisture source for the DRB is the Mediterranean Sea, while during the Dry season (April–September) the dominant source of moisture in the DRB itself. Moisture coming from each source has a different contribution for the precipitation in the DRB. Between the studied sources results show that the moisture coming from the Mediterranean Sea provides the highest values for precipitation in the basin during both seasons, extending to the whereas the whole basin for the Wet season and more confined to the western side during the Dry one. Moisture coming from the Caspian Sea and the Black Sea was that less contribute to precipitation.

Keywords: moisture sources and sinks; Lagrangian approach; precipitation; FLEXPART; Danube River Basin

1. Introduction

The global hydrological cycle is both an important element of the climate system and a decisive driver of water resources, that is why there is a huge interest in hydrology and meteorology for understanding the origin of moisture for precipitation over a region of interest [1–3]. Europe is not the exception, so many studies have been done showing a decreasing trend in precipitation over Central and Southern Europe and increasing over Northern Europe [4].

Rivers present a important part in the global hydrological cycle, returning about 35% of continental precipitation to the oceans. Rivers have also a significant socio-economic role in the industry activity, transportation, agriculture and domestic fresh water supplies [5]. Derived from a changing climate the hydrological cycle of river basins is varying and this affects their physical conditions on a regional scale [6]. The Danube river with their length of 2870 km and a catchment area about 817,000 km² (as shown in Figure 1) is the second longest river in Europe. 19 countries (Germany, Austria, Slovakia, Hungary, Croatia, Serbia, Montenegro, Romania, Bulgaria, Moldova, Ukraine, Poland, Czech Republic, Switzerland, Italy, Slovenia, Bosnia-Herzegovina, Albania, Macedonia) constitute the Danube River Basin (DRB), which makes it the world's most international river basin [7]. Connected with 27 large and over 300 small tributaries (DRB district), the river plays an important role in the ecological balance of the region and many socio-economic implications as waterway, natural resource and source of energy [8].

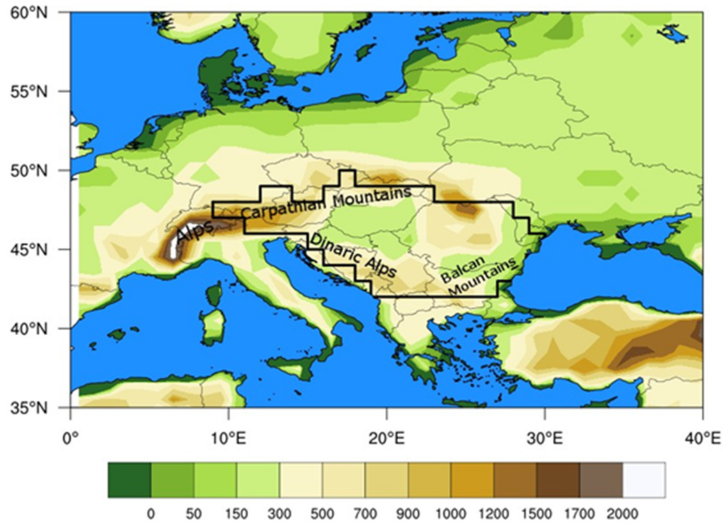


Figure 1. The black contour line indicates the Danube river basin area. In colours is indicated the elevation of the region (units in meters).

The climate of the DRB is very diverse with Atlantic influences in the Western part of the upper basin and Mediterranean one in the southern part of central and lower basin. The nearest to the Mediterranean Sea does that it receives high precipitation during the whole year [9].

The Danube river flow is determined mostly by the precipitation and evaporation processes from the Danube catchment basin. The mean quantity of rainfall that falls in the area of the Danube River catchment basin strongly dependent on the orography, being one-third of the basin constituted by mountains and rest consists of hills and plains. The amount of total annual precipitation is estimated about 2000 mm per year in the high regions (the Alps in the West, the Dinaric-Balkan mountain chains in the South and the Carpathian Mountains in the northern part), about 500 mm per year in the plains and lower than 600 mm in the Danube delta. The annual mean evaporation is estimated between 450 and 650 mm per year [8].

Many previous studies, using observational data in the DRB, have been written to explain the effects of precipitation and temperature changes on the Danube flow regime on the possible changes in natural drivers with impacts on water resources, water availability, extreme hydrological event, the water quality of water resources and the ecosystem in the DRB [10].

Given the importance of the DRB in the moisture budget, the main objective of this paper is tracking the origin of moisture for precipitation over the DRB through the use of the Lagrangian method developed by Stohl and James [11,12]. This approach has been extensively and successfully used in many regions over the World, including the Orinoco River basin [13], the Sahel [14], China [15], Iceland [16], Central America [17], or the Mediterranean region [18].

Specific objectives are: (i) the identification of the climatological major source of moisture over DRB during the period of 34 years from 1980 to 2014 by backward tracking the air masses that ultimately reach the DRB; (ii) to analyse the seasonal variability of these sources comparing the wet season (April–September) with the dry one (October–March); and (iii) to study the influences on the different moisture sources for the precipitation at subregional scale in the basin by forward tracking the air masses departing each source region and reaching the DRB.

2. Data and Methodology

This study is based on the method developed by Stohl and James [11,12], which uses the Lagrangian particle dispersion model FLEXPART V9.0 [12] together with ERA-interim reanalysis data [19] available every 6 h at a 1° horizontal resolution on 61 vertical levels from 0.1 to 1000 hPa. The analysis covers a 34-year period from October 1980 to September 2014. Through this Lagrangian approach, we want to determine the major moisture source for the DRB and their contributions in precipitation over it.

The method consists in dividing the atmosphere into a large number of air particles approximately 2.0 million with constant mass and which must take into account the density and volume of the air. They are after transported using 3-dimensional wind field. The transport time of the particles is limited to 10 days because it is the averaged period of residence of the water vapour in the atmosphere [20]. Changes in specific humidity (q) with time, help us to identify those particles that lose moisture through precipitation (p) or receive it through evaporation (e). The Lagrangian method allows us to track the air particles along their backward and forward trajectories. Recently, Drumond et al. [21] explained the use of backward and forward analysis and tracking the moisture over the Amazon Basin.

Using the Lagrangian model FLEXPART we can identify from where the moisture observed over DRB comes from through the backward analysis. The backward analysis allows us to identify where the air masses gain humidity along their trajectories. In this case, when evaporation exceeds precipitation in the atmospheric moisture budget over a given area, we know that air masses gain moisture and this indicate the sources of moisture. On the other hand, the Lagrangian forward experiment identifies those air masses that left each moisture source region to reach the basin losing moisture (moisture sinks). In this case, precipitation exceeds evaporation.

The main reason for us to choose this methodology is because this methodology was widely used in many studies e.g., [13,21,22].

3. Results

In order to identify the boundaries of the moisture source regions, we used the 90% percentile of the annual averages of (E-P) > 0 for the backward experiment (Figure 2), which corresponds to the contour line of 0.06 mm day-1. Even though the definition of the threshold is arbitrary this statistical procedure is valid and successfully applied in many previous research studies with the same approach e.g., [23].

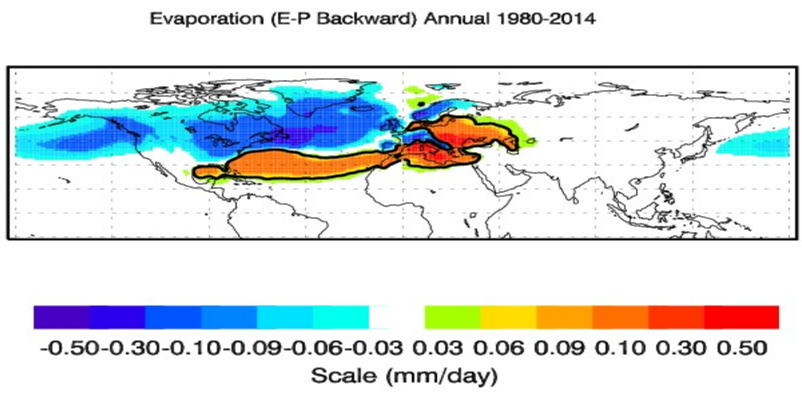


Figure 2. Climatological annual 10-day integrated (E-P) obtained from backward Danube River basin experiment for the period October 1980 to September 2014. The black contour line indicates the sources areas selected using the 90th percentile of the (E-P) > 0 values: 0.006 mm/day.

According to this threshold, the DRB receives moisture mainly from seven different oceanic, maritime and terrestrial moisture source regions: North Atlantic Ocean (NATL), North Africa (NAF), Mediterranean Sea (MED), Black Sea (BS), Caspian Sea (CS), Danube River Basin (DRB) and Central and Eastern Europe (hereafter Rest of Land). Those regions are shown in Figure 3.

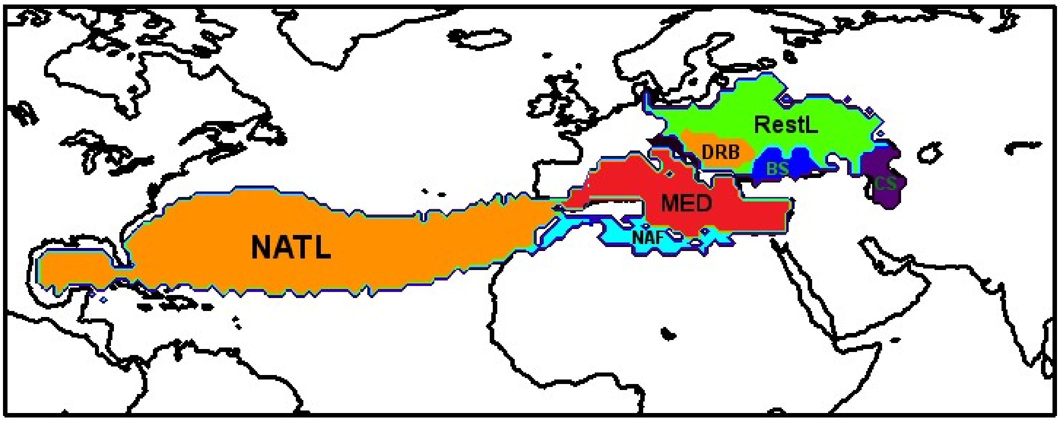


Figure 3. Schematic representation of moisture sources over Danube River Basin identified in the Figure 2.

Due to the seasonality of precipitation, it is likely a different pattern of moisture sources along the year. Figure 4 shows the annual cycle of precipitation (PRE), the potential evapotranspiration (PET), and the difference between them (P-E), calculated with CRU (TS3.23) climate data set with a spatial resolution of 0.5 degrees. The annual cycle of P-E can help us to justify the definition of two seasons: a Wet season when P-E > 0 (from October to March), and a Dry season when P-E < 0 (from April to September).

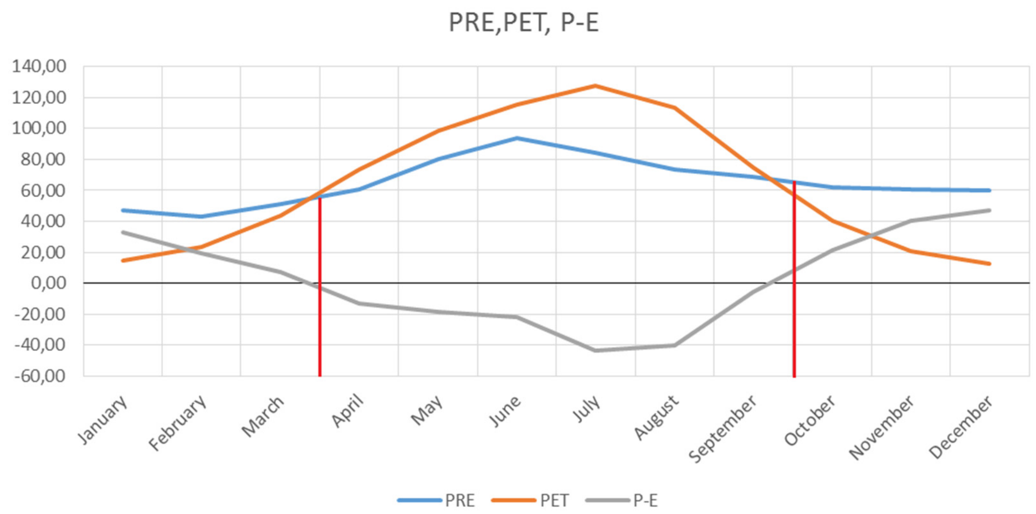
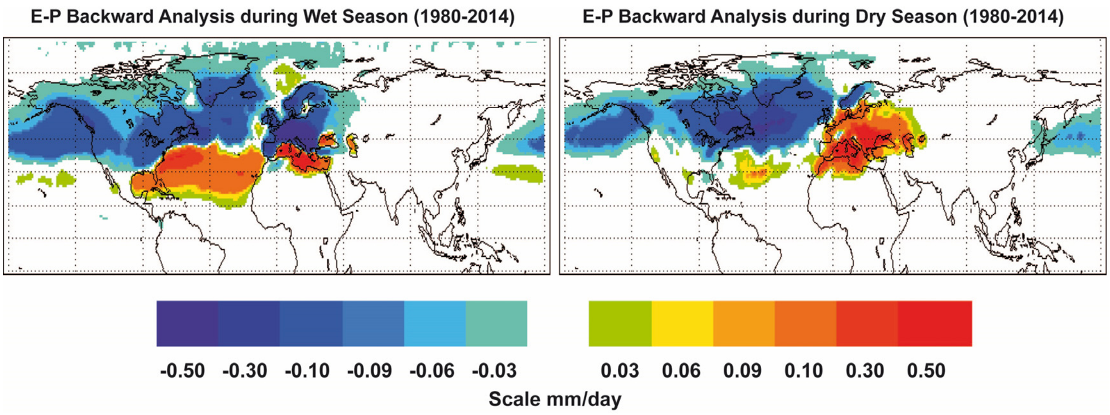


Figure 4. The climatological annual cycle of precipitation (PRE, blue line), potential evapotranspiration (PET, orange line) and their difference (P-E, grey line) average over the DRB for 1980–2014. Data from CRU. Scale in mm/day. Vertical red lines indicate the two identified season: Dry season from April to September and Wet season from October to March.

The Lagrangian analysis of moisture sources at this seasonal scale (Figure 5) shows that during Wet season the dominant source of moisture for Danube River Basin is the Mediterranean Sea, where the moisture uptake (E-P > 0) is greater than 0.3 mm·day^{-1}, while during Dry season the main source is the Danube basin itself where the moisture uptake exceeds 0.5 mm·day^{-1}. Results illustrate that (E-P > 0) over North Atlantic was greater than 0.1 mm·day^{-1} during the Wet season and less than

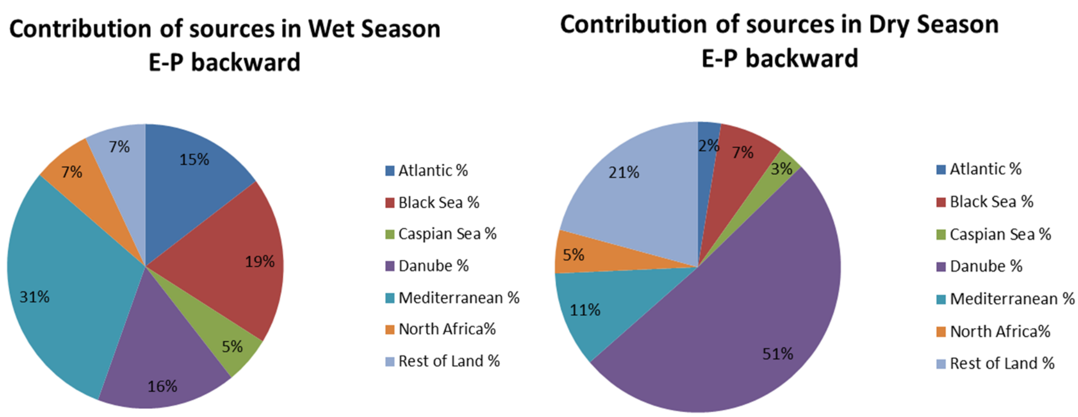
0.09 mm·day^{-1} for the Dry season. The uptakes over the Rest of Land sources and the Black Sea moisture are higher in the Wet season (approximately 0.3 mm·day^{-1}) than in the Dry one, when they are insignificant. North Africa and the Caspian Sea are minor sources in both seasons.



(**a**) (**b**)

Figure 5. Climatological seasonal values of 10-day integrated atmospheric moisture budget (E-P) obtained via backward trajectories from the Danube River Basin for (**a**) Wet and (**b**) Dry season.

Figure 6 shows the contribution of each source in percentage. From a overview of the figure it is possible to observe that in Wet season the Mediterranean Sea is the major source (31%) following by the Black Sea, the Danube and the North Atlantic, and three minor: the North Africa, Rest of Land (Central and Eastern Europe) and the Caspian Sea. The contribution of the sources in the Dry season is quite different, being the own DRB the most important one (51%), following by the Rest of Land (21%) and the Mediterranean Sea (11%) as intermediate sources. The other sources contribute a much smaller percentage.



(**a**) (**b**)

Figure 6. Moisture uptake over the sources obtained from E-P backward analysis for Danube River Basin for (**a**) Wet and (**b**) Dry season in percentage (%).

The several moisture sources regions considered can contribute in a different way for the precipitation in diverse subregions inside the Danube basin and this can also vary along both studied seasons. An estimation of the moisture provided by the air particles coming from each source region for precipitation in the basin can be done by using forward trajectories during 10-days of (E-P) for the 34-year period (Figure 7). The Lagrangian forward experiment identifies those air masses that leave each moisture source reaching the basin and lose moisture inside (moisture sinks). As we are interesting in precipitation only negative values of E-P budget are displayed (white areas of maps represent regions where the (E-P) fields have low or positive values).

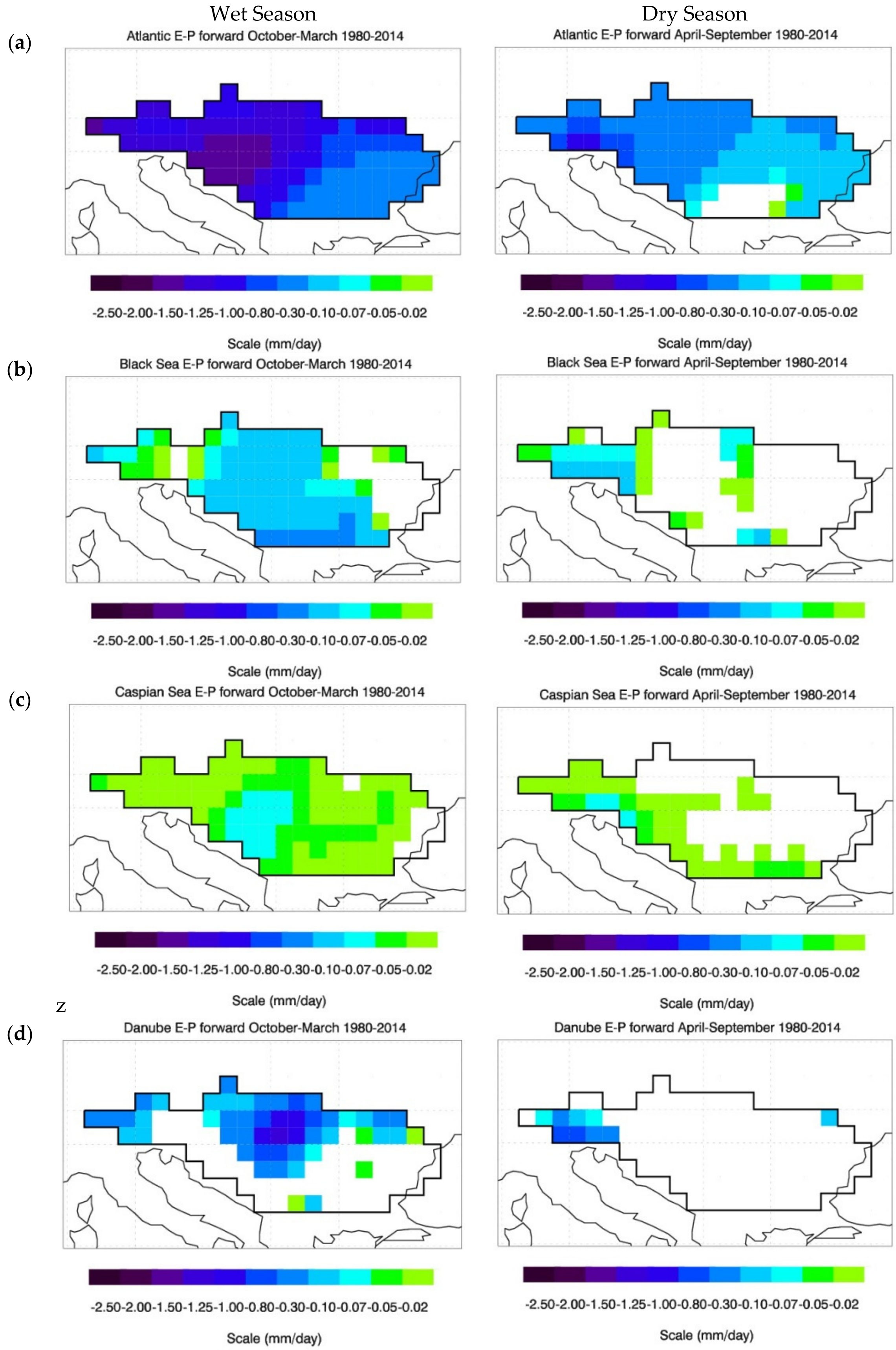


Figure 7. *Cont.*

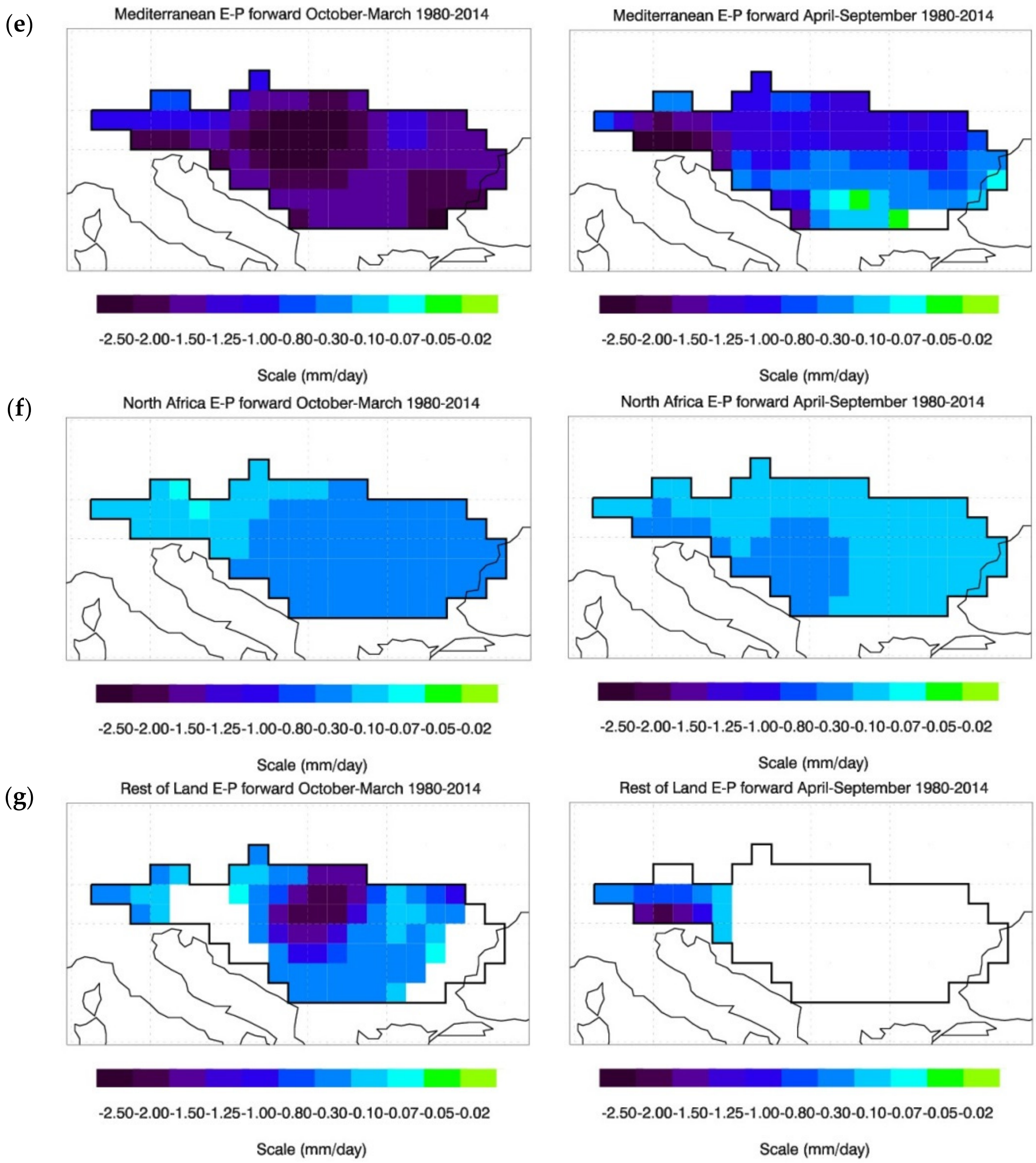


Figure 7. Seasonal average values of (E-P) < 0 for the period 1980–2014 determined from the forward Lagrangian experiment for the: (**a**) NATL; (**b**) BS; (**c**) CS; (**d**) DRB; (**e**) MED; (**f**) NAF; and (**g**) Rest of Land. Only negative values are shown to detect sink regions of moisture. Black contour line indicates the Danube River Basin area. Scale in mm/day.

We will now briefly describe the contribution of each moisture source:

The North Atlantic Ocean source: Figure 7a shows that the Atlantic Ocean has a different contribution on the target area during Wet and Dry season. In Wet season, Atlantic has astrong impact on the whole basin region, being the strongest one in the southwestern subregion. During the Dry season, the spatial pattern is quite similar but with less intensity, and the Atlantic source does not have impact on the south part of the basin.

The Black and Caspian Sea sources: The particles from the both sources (Figures 7b,c) lose moisture almost over whole basin area during the Wet season, but with lower amounts than the Atlantic. The Black Sea losses more moisture than the Caspian Sea, especially in the centers of the river basin. During the Dry season, these sources have a poor impact on the basin area.

The Danube source: The most considerable contribution provided by the same area (Figure 7d) ocurres during the Wet season in the norther-central part of the basin.

The Mediterranean Sea source: Although the Mediterranean source is the most significant source for the whole basin in both seasons (Figure 7e), the stronger influence occurs in the Wet season. During the Dry season, maximum values are located over the northwestern and northern parts of basin.

The North Africa source: This source has an impact over the whole target area during the Wet and Dry season (Figure 7f) but with low values.

The Rest of Land source: The moisture contribution during the Wet season (Figure 7g) reaches the central and northern part of the basin, but during the Dry season only reaches the western part of DRB.

4. Conclusions

In this paper, we used a Lagrangian approach based on FLEXPART model to track water vapor in the atmosphere and diagnose its sources and sinks for DRB. The approach consists of applying the method of Stohl and James [11,12] together with the Era-Interim dataset [12].

Results showed that the DRB receives moisture mainly from seven different oceanic, maritime and terrestrial moisture source regions: North Atlantic Ocean, North Africa, Mediterranean Sea, Black Sea, Caspian Sea, Danube River Basin and Rest of Land (Central and Eastern Europe). For each source, we calculated the percentage of contribution on the total moisture supplied for DRB. The contribution of these sources differs seasonally. During the Wet season (October–March) the main moisture source for the DRB is the Mediterranean Sea while during the Dry season (April–September) the dominant source of moisture in the own DRB.

Moisture coming from each source has a different contribution for the precipitation in the Danube. Results show that the air particles coming from the Mediterranean Sea provides the highest moisture losses in the basin during both seasons, extending to the whereas the whole basin for the Wet season and more confined to the western side during the Dry one. Moisture coming from the Caspian Sea and the Black Seawas that less contribute to precipitation in the Danube basin both seasons.

The own Danube river basin was a major source of moisture for itself during the Dry season but this moisture does not contribute in a major way to the precipitation over the region.

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Author Contributions: R. Nieto, A. Drumond and L. Gimeno conceived and designed the experiments; D. Ciric and M. Stojanovic performed the experiments and analyzed the data; D. Ciric, M. Stojanovic, L. Gimeno, R. Nieto, and A. Drumond wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

BS	Black Sea
CRU	Climatic Research Unit
CS	Caspian Sea
DRB	Danube River Basin
E	Evaporation
ERA	European Centre for Medium-Range Weather Forecasting Re-Analysis

FLEXPART	FLEXible PARTicle dispersion model
MED	Mediterranean Sea
NAF	North Africa
NATL	North Atlantic Ocean
P	Precipitation
PET	Potential evapotranspiration
PRE	Precipitation

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