Dry and wet conditions in the Niger River Basin and its link with atmospheric moisture transport

Rogert Sorí[1,*], Raquel Nieto[1,2], Anita Drumond[1] and Luis Gimeno[1]

[1] Environmental Physics Laboratory (EPhysLab), Facultad de Ciencias, Universidade de Vigo, Ourense 32004, Spain; rnieto@uvigo.es (R.N.); anitadru@uvigo.es (A.D.); l.gimeno@uvigo.es (L.G.)

[2] Department of Atmospheric Sciences, Institute of Astronomy, Geophysics and Atmospheric Sciences, University of São Paulo, São Paulo 05508-090, Brazil

* Correspondence: rogert.sori@uvigo.es; Tel.: + 34-988-38-72-08

Abstract: In West Africa is located the Niger River Basin (NRB). Dry and wet conditions were investigated in this basin during the rainy (May-October) and dry (November-April) seasons, from 1980 to 2014. To do this was calculated the Standardized Precipitation-Evapotranspiration Index (SPEI) at the time scale of 6-months for the whole NRB. The Lagrangian model FLEXPART v9.0 has been used to compute over the main semi-annual climatological moisture sources of the NRB, the budget of evaporation minus precipitation *(E-P)* over 10-day backward in time the trajectories from the NRB itself. Positive (negative) *(E-P)* values indicate moisture uptake (loss). This approach permits evaluating the role of continental and oceanic sources of moisture separately for composites of extremely and severely dry and wet conditions in the basin. The results show for the dry season the negative trend of the April-SPEI6 values and the standardized anomalies of *(E-P)i10 > 0* values obtained over the tropical east-north Atlantic Ocean, the western Sahel and the Mediterranean region. On the contrary, for the rainy season, the October-SPEI6 values trend is positive. It also occurs for the standardized anomalies of the moisture uptake over the South Sahel (SSah) and the NRB itself. The moisture uptake anomalies for composites of seasons under severe and extremely dry and wet conditions indicate the direct response of these sources. Particularly, the anomalies of positive *(E-P)i10 >0* values for driest and wettest rainy season's composites suggest the importance of the SSah, SAtl, NEA and MEDT.

Keywords: Dry and wet conditions; moisture uptake, Niger River Basin

1. Introduction

The Niger River Basin (NRB) is located in West Africa (Figure. 1). In WA and particularly in the NRB the mean annual cycle of precipitation is characterized by minimum values at the beginning of the year, that increase month by month, reaching a maximum in August, to later decrease until December [1, 2]. An analysis of droughts during 1900–2013 indicated that droughts in Africa have intensified in terms of their frequency, severity and geospatial coverage over the last few decades [3]. Differences in the Sahelian precipitation rate are primarily a consequence of the contrasting circulation, together with recycling of local evaporation and moisture advected from the tropical North Atlantic Ocean and the Gulf of Guinea [4]. According to Belen et al. [5], at interannual time scales, a warming of the equatorial Atlantic and Pacific/Indian Oceans results in rainfall reduction over the Sahel. On the contrary, positive Sea Surface Temperature anomalies over the Mediterranean Sea tend to be associated with increased rainfall.

Utilizing a Lagrangian approach, Sorí et al. [2] identified and investigated the main sources of moisture for the NRB during the dry (November-April) and rainy season (May-October) (Figure 1). In the dry season these are: the "tropical east north Atlantic Ocean" (NAtl), the "tropical east south Atlantic Ocean" (SAtl), the "Western Sahel" (WSah), the NRB itself, the "Southern Sahel" (SSah), the "Eastern Sahel" (ESah), "Eastern Africa" (EA), and the "Mediterranean" (MEDT) region that mainly comprises the Mediterranean Sea and a small part of the Northern African continent. In the rainy season remain the same sources as for the dry season, but their spatial extents change and new sources are delimited; the northeast African region (NEA), in Central Equatorial Africa (CEA) and small sources located in the "Indian Ocean" (Ind) and the "Persian Gulf" (PGulf).

The aim of this work is to identify dry and wet conditions in the NRB and evaluate the role of the climatological moisture sources of this basin providing moisture to the basin during severe and extremely dry and wet seasons in the period 1980-2014. A similar approach has been implemented to investigate the role of moisture transport during drought episodes in the climatological sinks of the Mediterranean [6] and the Central United States [7]. We believe that the methodology here utilized may be successfully applied in further research on the hydrological cycle in other river basins worldwide.
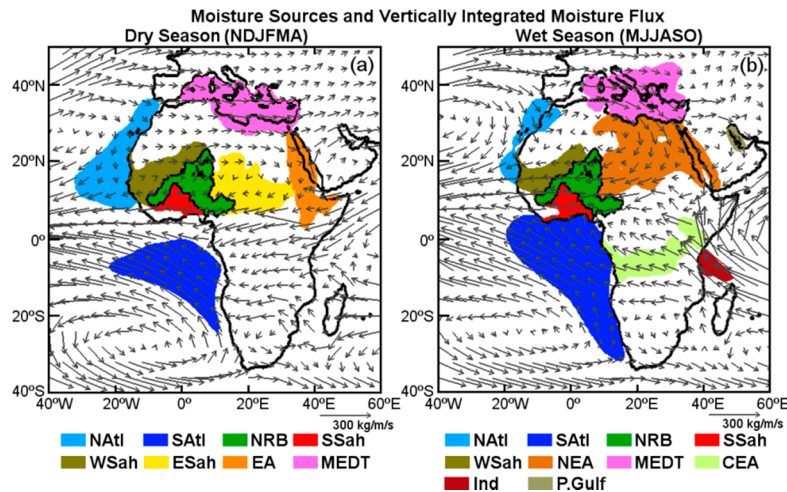

Figure 1. Schematic representation of moisture sources for the NRB and average Vertically Integrated Moisture Flux (VIMF) from ERA-Interim, for the period 1980–2014 during the dry (a) and wet (b) seasons. From: Sorí et al. [2].

2. Experiments

2.1. Method

In this study, we applied the Standardised Precipitation-Evapotranspiration Index (SPEI) [8] to identify dry and wet conditions in the NRB. SPEI is based on a standardization of the climatic water balance (Precipitation –P- minus Atmospheric Evaporative Demand –AED), which is computed on different time-scales. The PELT algorithm [9] was used to detect multiple changepoints (identifying changes in the mean) in the SPEI values at 6-months temporal scale (SPEI6). The study is mainly focused for the dry (November – April) and rainy season (May – October) at the basin. To do it we utilized the SPEI6 for April and October, which enable us to characterize the water balance conditions in the NRB for the previous 6 months (for the dry and wet season respectively). According to the criterion of Mckee et al. [10], we used an SPEI threshold of +/ -1.5 to identify severe and extreme drought and wet conditions in the basin.

To assess the average role of the climatological semi-annual NRB´s moisture sources, for severe and extremely dry and wet conditions, we used the Lagrangian particle dispersion model FLEXPART v9.0 developed by Stohl and James [11, 12]. In this approach, the atmosphere is homogeneously divided into N evenly distributed "particles" or "parcels", over the entire world. FLEXPART permits to compute the rate of moisture increase (through evaporation from the environment, *e*) or decrease (through precipitation, *p*) along the trajectory of the parcels are calculated by changes in the specific humidity (*q*) over time (*t*) by Equation (1), assuming a constant mass (*m*) of the particles:

$$(e - p) = m(dq/dt) \tag{1}$$

Integrating the *(e − p)* values of all parcels in a vertical column over an area A, is possible to obtain the surface freshwater flux, hereafter-denoted *(E − P)* in Equation (2):

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

where *E* represents the evaporation and *P* the precipitation per unit area. The transport time was set to 10 days, which is the average time that water vapour resides in the atmosphere [13]. Here we implemented a backward experiment, in which *(E − P) > 0* are regions where air masses in travel to the NRB uptake humidity. On the contrary *(E − P) < 0* values represent moisture loss. For this work, we calculated the moisture uptake *((E − P)i10 > 0)* over the climatological moisture sources of the NRB for the dry and rainy seasons. Thus, we can evaluate the role of these sources during composites of seasons under severe and extremely dry and wet conditions.

FLEXPART has been also applied for investigating the hydrological cycle for the NRB [2], the Sahel [14] and several river basins like the Amazon River basin [15], the Yangtze River Basin [16], the Danube River basin [17] and the Orinoco River Basin [18].

2.2. Data

To compute the SPEI, data of P and AED were obtained from the Climatic Research Unit (CRU 3.23TS) [19] with a resolution of 0.5° × 0.5°. The analyses were carried out using 35 years of data (1980–2014), ensuring that climatological results were obtained. FLEXPART uses data from the ERA-Interim reanalysis [20] every 6 h with a resolution of 1° in longitude and latitude on 60 vertical levels from 1000 to 0.1 hPa [11, 12].

3. Results and Discussion

3.1. The SPEI 6-months temporal evolution

The temporal evolution of the SPEI6, from 1980 to 2014 is shown in Figure 2. The values greater than 1.5 (severe and extreme wet conditions) and -1.5 (severe and extremely dry conditions) are separated by a dotted blue and red lines respectively. Few moments are appreciated under these conditions, like the droughts in 1983 and the beginning of 1984, while extremely wet conditions in 1991 and 1995. These results are in accordance with Massi et al. [3], who recorded many severe and prolonged droughts in the recent past such as the 1999–2002 drought in northwest Africa, 1970s and 1980s droughts in western Africa (Sahel). They also documented the most extreme droughts which occurred during past 50 years in 1983–1984 and 1991–1992. In accordance with these results, from 1980 to 2014 we identified two changepoint in the mean of the SPEI6 series; the first in July/1982 and later in April/1988 (Figure 2).
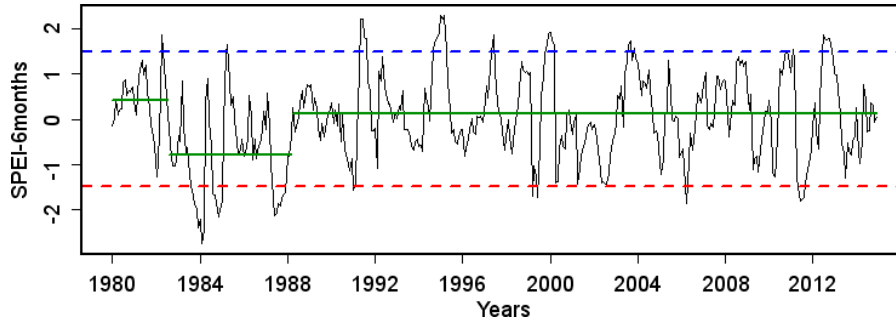
Figure 2. Temporal evolution of the SPEI6 for the NRB (black line). Period 1980-2014. The discontinued blue (red) line represents the threshold of the SPEI= 1.5 (SPEI= -1.5). The green line discontinuities represent the multiple changepoint of the mean.

The SPEI6 values for April and October and the standardized anomaly of the average moisture uptake over the sources during dry and wet seasons and the linear trend (and the equation) are shown in Figure 3 and 4 respectively. The evolution of the SPEI6 for April from 1980 to 2014 clearly reflects a negative trend, which indicates that dry season for the NRB is becoming drier (Figure 3). It is best observed after 1995. It should be related to a decrease of moisture arriving at the NRB from the NAtl, WSah and EA, which is revealed by the negative trend of the standardized anomalies of the moisture uptake over these sources. Sorí et al. [2], argue the key role of the NAtl and WSah regions for the NRB during November-April. Over the rest of the sources, the trend of the anomalies is not like similar. In the rainy season, the trend of the SPEI6 is positive (Figure 4). After 2007 positive SPEI6 values prevail, indicating wet conditions in the NRB. In this season, together with greater precipitation over the NRB, the $(E − P)i10 > 0$ values over the NRB are less than for the dry season [2]. However, the evaporation in the basin may be favoured if the rainfall increases, which could explain the positive trend of the standardized anomalies of the moisture uptake over the NRB itself and the SSah. From the rest of the sources the anomalies trend is negative; even over the SAtl, which is the most important moisture source of the basin in this season.
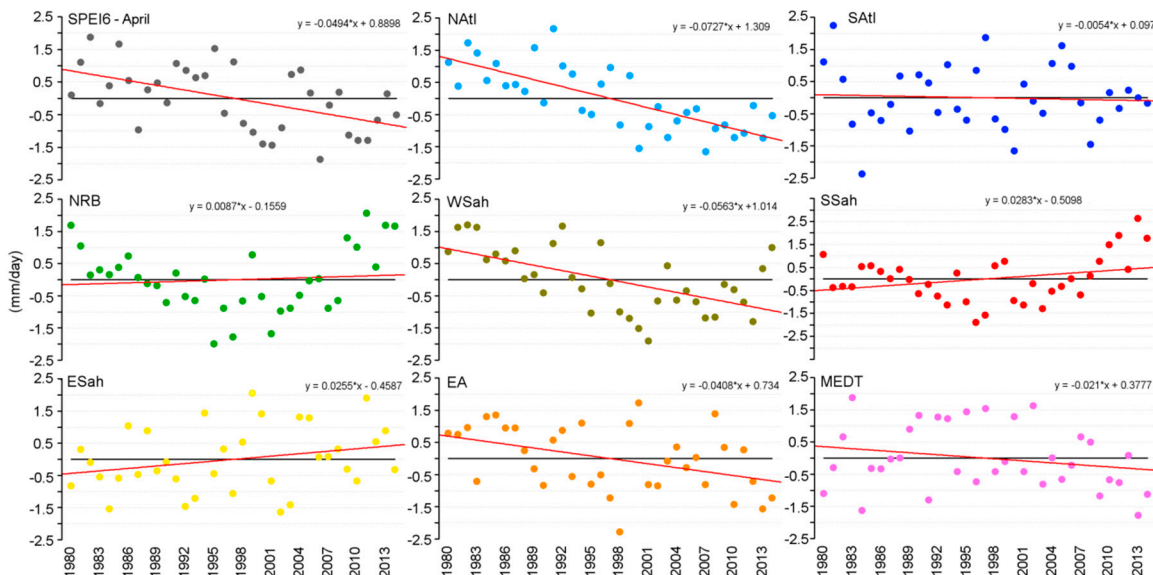

Figure 3. SPEI at 6-month temporal scale for April and standardized anomalies of $(E − P)i10 > 0$ values over the NRB´s moisture sources during the dry season. (The colours of the circles are in accordance with the colour representing the sources of moisture in Figure 1).
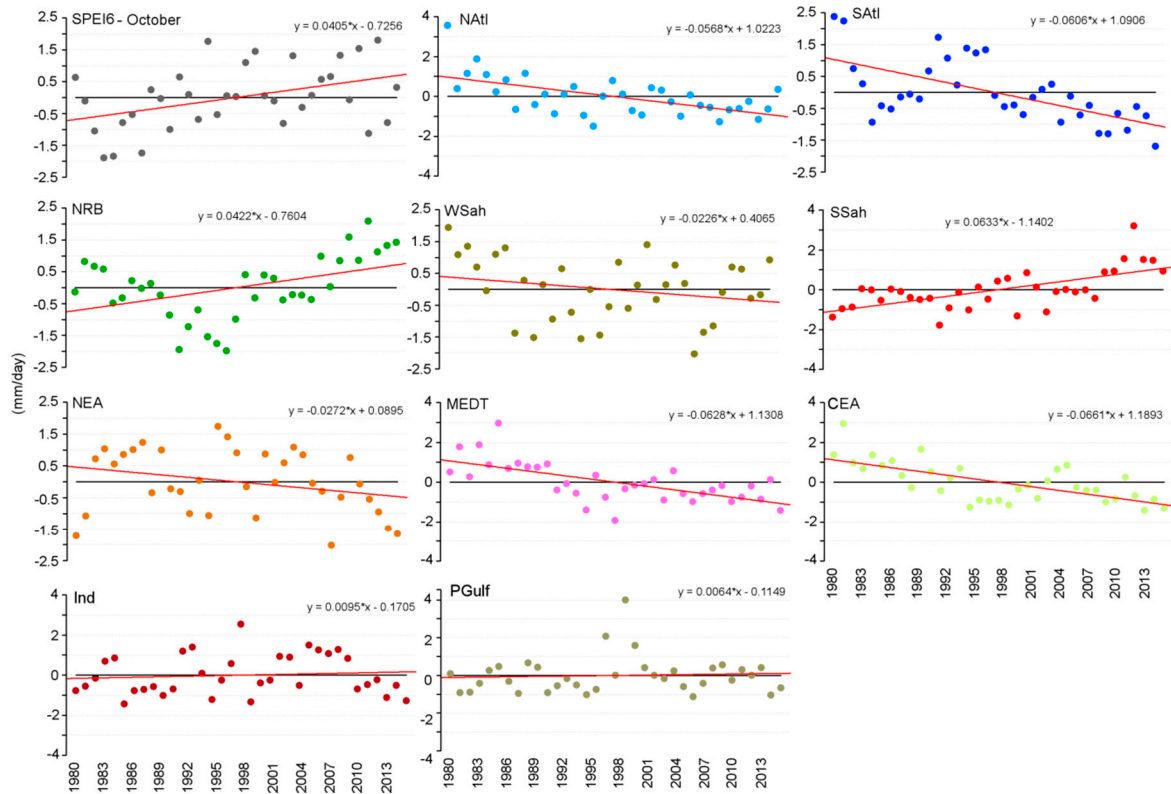
Figure 4. SPEI at 6-month temporal scale for October and standardized anomalies of *(E – P)i10 > 0* values over the NRB´s moisture sources during the wet season. (The colours of the circles are in accordance with the colour representing the sources of moisture in Figure 1).

The criterion of McKee et al. [10] was used to identify those seasons under severe and extreme drought and wet conditions in the NRB (according to the SPEI threshold of +/-1.5). The results appear in Table 1.

Table 1. Dry and rainy seasons under severe and extremely dry and wet conditions in the Niger River Basin. Period 1980 – 2014.

Dry Season (November-April)				Rainy season (May-October)			
Driest	**SPEI-6**	**Wettest**	**SPEI-6**	**Driest s**	**SPEI-6**	**Wettest**	**SPEI-6**
04/2006	-1.88	04/1995	1.52	10/1983	-1.89	10/2010	1.53
		04/1985	1.65	10/1984	-1.84	10/1994	1.76
		04/1982	1.87	10/1987	-1.75	10/2012	1.80

In Figure 5 are shown the anomalies of the total moisture uptake over the sources for composites of severe and extremely dry and wet conditions (according to cases in Table 1). For driest November-April, negative anomalies of *(E – P)i10 > 0* values occur from the NAtl, the WSah and the MEDT; which are the same sources responsible for wettest conditions for this season (Figure 5a). For the composite of rainy season under severe and extremely dry and wet conditions, the moisture uptake anomalies occur from the SAtl, WSah, and SSah (Figure 5b). In this season we can also

appreciate that when negative anomalies of moisture uptake occur from the SAtl, occur greatest positive anomalies from NEA and MEDT. To understand these values, it must be noted that source areas are not spatially of the same size and, thus, the amount of moisture uptake (and anomalies), over them are quite scale dependent.
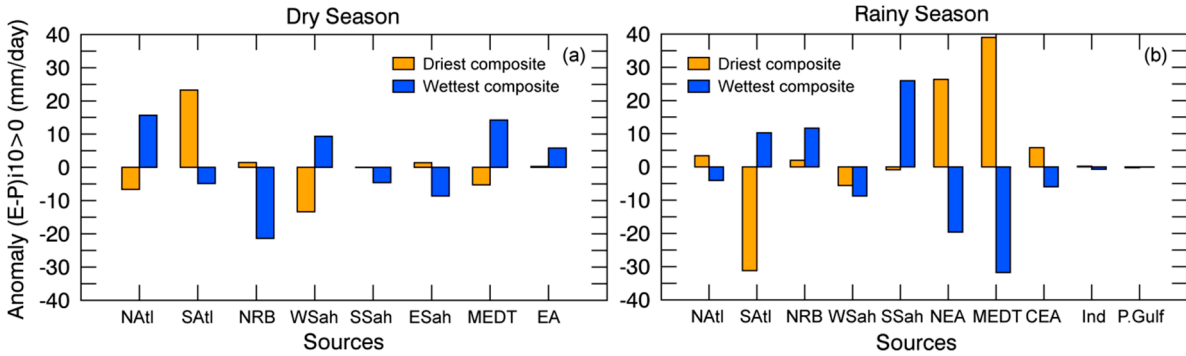

Figure 5. Anomalies of $(E − P)i10 > 0$ over the NRB moisture sources for composites under severe and extremely dry and wet conditions (cases of Table 1) for the dry (a) and rainy (b) seasons.

4. Conclusions

The Standardized Precipitation Index (SPEI) was utilized to identify dry and wet conditions in the Niger River Basin (NBR) in the period 1980-2014. Besides, the model FLEXPART was utilized to track air parcels backward in time from the NRB and to compute the moisture uptake $((E − P)i10 > 0)$ over the seasonal climatological moisture sources of this basin. The SPEI at temporal scale of 6-months (SPEI6) for April and October were utilized to characterize the NRB´s dry and rainy seasons. The results reveal that the NRB dry season is becoming drier, which seems to be related to a decrease of moisture uptake from the NAtl, WSah and EA. On the contrary, the positive trend of the SPEI6 for October reflects wettest conditions in the NRB mainly after 2007. For the rainy season, positive trend of the standardized anomalies of the moisture uptake occur over the NRB itself and the SSah. The anomalies of the moisture uptake over the sources, for composites of seasons under severe and extremely dry and wet conditions in the NRB were calculated. The results suggest that driest (wettest) November-April periods are related to negative (positive) anomalies of $(E − P)i10 > 0$ values over the NAtl, the WSah and the MEDT. For the rainy season composites, the SAtl, WSah, and appear to be responsible for driest seasons, while the SAtl and the SSah for wettest.

Author Contributions: R.N., and L.G. designed, proposed and conducted the research; R.S. performed the experiments and analysed the data; R.S., R.N., L.G., and A.D. 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, or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

NRB: Niger River Basin
SPEI: Standardized Precipitation-Evapotranspiration Index

NAtl: Tropical-east North Atlantic Ocean
SAtl: Tropical-east North Atlantic Ocean
WSah: Western Sahel
SSah: South Sahel
ESah: Eastern Sahel
EA: East Africa
MEDT: Mediterranean region
NEA: North-east Africa
CEA: Central-east Africa
Ind: Indian Ocean

References

1. Van der Ent, R.J. A New View on the Hydrological Cycle over Continents. Ph.D. Thesis, Delft University of Technology, Delft, The Netherlands, 2014.
2. Sorí, R.; Nieto, R.; Drumond, A.; Gimeno, L. The Niger River Basin Moisture Sources: A Lagrangian Analysis. *Atmosphere.* **2017**, 8, 38.
3. Masih, I., Maskey, S., Mussá, F.E.F., Trambauer, P. A review of droughts on the African continent: a geospatial and long-term perspective. *Hydrol. Earth Syst. Sci.* **2014**, 18, 3635–3649.
4. Druyan, L.M.; Koster, R.D. Sources of Sahel Precipitation for Simulated Drought and Rainy Seasons. *J. Clim.* **1989**, 2, 1438–1446.
5. Rodríguez-Fonseca, B., et al. Variability and Predictability of West African Droughts: A Review on the Role of Sea Surface Temperature Anomalies. *J. Clim.* **2015**, 28, 4034–4060.
6. Drumond, A.; Gimeno, L.; Nieto, R.; N.; Trigo, R.M.; Vicente-Serrano, S.M. Drought episodes in the climatological sinks of the Mediterranean moisture source: The role of moisture transport. *Global and Planetary Change.* **2017**, 151, 4–14.
7. Drumond, A.; Nieto, R.; Gimeno, L. A Lagrangian approach for investigating anomalies in the moisture transport during droughts episodes. *Cuadernos de Investigación Geográfica.* **2016**, 42(1), 113–125.
8. Vicente-Serrano, S.V.; Beguería, S.; López-Moreno, J. I. A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. *J. Clim.* **2010**, 23, 1696-1718.
9. Killick, R.; Eckely, I.A. changepoint: An R Package for Changepoint Analysis. *J. of Statistical Software.* **2014**, 58(3), 1-19.
10. McKee, T.B.N.; Doesken, J.Y.; Kleist, J. The relationship of drought frecuency and duration to time scales. Eight Conf. On Applied Climatology. Anaheim, CA. *Am. Meteorol. Soc.* **1993**, 179–184.
11. Stohl, A.; James, P. A Lagrangian analysis of the atmospheric branch of the global water cycle. Part 1: Method description, validation, and demonstration for the August 2002 flooding in central Europe. *J. Hydrometeorol.* **2004**, 5, 656–678.
12. Stohl, A.; James, P. A Lagrangian analysis of the atmospheric branch of the global water cycle: 2. Earth's river catchments, ocean basins, and moisture transports between them. *J. Hydrometeorol.* **2005**, 6, 961–984.
13. Numaguti, A. Origin and recycling processes of precipitating water over the Eurasian continent: Experiments using an atmospheric general circulation model. *J. Geophys. Res.* **1999**, 104, 1957–1972.
14. Nieto, R.; Gimeno, L.; Trigo, R.M. A Lagrangian identification of major sources of Sahel moisture. *Geophys. Res. Lett.* **2006**, 33, 1–6.
15. Drumond, A.; Marengo, J.; Ambrizzi, T.; Nieto, R.; Moreira, L.; Gimeno, L. The role of the Amazon Basin moisture in the atmospheric branch of the hydrological cycle: A Lagrangian analysis. *Hydrol. Earth Syst. Sci.* **2014**, 18, 2577–2598.
16. Bin, C.; Xiang-De, X.; Tianland, Z. Main moisture sources affecting lower Yangtze River Basin in boreal summers during 2004–2009. *Int. J. Climatol.* **2013**, 33, 1035-1046.
17. Ciric, D.; Stojanovic, M.; Drumond, A.; Nieto, R.; Gimeno, L. Tracking the Origin of Moisture over the Danube River Basin Using a Lagrangian Approach. *Atmosphere.* **2016**, 7, 162.
18. Nieto, R.; Gallego, D.; Trigo, R.M.; Ribera, P.; Gimeno, L. Dynamic identification of moisture sources in the Orinoco basin in equatorial South America. *Hydrol. Sci. J.* **2008**, 53, 602–617.

19. Harris, I.; Jones, P.D.; Osborn, T.J.; Lister, D.H. Updated high-resolution grids of monthly climatic observations—The CRU TS3.10 Dataset. *Int. J. Climatol*. **2014**, 34, 623–642.

20. Dee, D.P.; Uppala, S.M.; Simmons, A.J.; Berrisford, P.; Poli, P.; Kobayashi, S.; Andrae, U.; Balmaseda, M.A.; Balsamo, G.; Bauer, P.; et al. The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Q. J. R. Meteorol. Soc*. **2011**, 137, 553–597.