

Variability of moisture sources in the Mediterranean region during the period 1980–2000

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[1] In this study, seasonal and interannual variability of the main atmospheric moisture sources over eight regions in the Mediterranean basin were investigated along a 21 year period. The Lagrangian dispersion model FLEXPART, developed by Stohl and James [2004, 2005], was applied to identify the contribution of humidity to the moisture budget of each region. This methodology is used to compute budgets of evaporation minus precipitation ($E - P$) by calculating changes in the specific humidity along backward trajectories, for the preceding 10 day periods. The results show clear seasonal differences in the moisture sources between wet and dry seasons. The Western Mediterranean Sea is the dominant moisture source for almost all the regions in the Mediterranean basin during the wet season, while the local net evaporation dominates during the dry season. The highest interannual variability is found in contributions to the Iberian Peninsula, Italy, and the Eastern Mediterranean. It is seen that the role of teleconnections is more limited than for the precipitation recorded in the region.

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1. Introduction

[2] Precipitation, evaporation, and the transport of atmospheric moisture are important elements of the atmospheric hydrological cycle. Currently, there is a great interest among meteorologists and hydrologists in understanding the origin of the moisture and precipitation that occurs in a region because of the importance to water resources. Understanding moisture transport processes requires knowledge of how water vapor, which accounts for approximately 0.25% of the total mass of the atmosphere, is distributed.

[3] The characteristics of precipitation depend, among other factors, on the available moisture. In general, it is commonly accepted that the precipitation that occurs in a region comes from one of the three possible sources [Brubaker *et al.*, 1993]: the moisture that is already present in the atmosphere over the region, the moisture advected by the wind into the region, and local evaporation from the Earth's surface (recycling). Although the definition of recycling varies, it is commonly defined to refer to that part of the water that evaporates from a given area and that con-

tributes to the precipitation in that same area [Eltahir and Bras, 1996]. Averaged over long periods, the contribution of moisture that is already present in the atmosphere over a given region is negligible. Trenberth *et al.* [1999] pointed out that the moisture contribution for the heavy and moderated precipitation does not result from local evaporation, but it is associated with large distance transport. Hence, the observed atmospheric moisture in a given region mostly depends on advection and recycling. Thus, it is important to identify the sources of the moisture that become precipitation in a given region.

[4] The Mediterranean Sea is an important source of atmospheric moisture, and the local water budget influences the amount of moisture that flows into northeast Africa and the Middle East [Peixoto *et al.*, 1982; Ward, 1998]. Evaporation in the Mediterranean region is the largest term in the Mediterranean freshwater budget and annual precipitation is about half the evaporation [Mariotti *et al.*, 2002]. It is known that in recent decades (1957–2007) evaporation has increased in the Mediterranean, while regional precipitation has decreased both in land and over the sea [Mariotti, 2010; Allan and Zveryaev, 2011]. These two trends have resulted in a significant net loss of water from the Mediterranean Sea into the overlying atmosphere.

[5] A number of previous authors investigated the geographical sources and sinks of moisture over the Mediterranean Sea using a range of different methodologies, mostly based on Eulerian analysis. For instance, Mariotti *et al.* [2002] analyzed contributions to the fresh water flux into the Mediterranean Sea over the last 50 years, including atmospheric inputs and river discharges, using an atmospheric reanalysis from the National Centers for Environmental Prediction (NCEP) and observational data sets from the Climate Research Unit (CRU), the University of

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Wisconsin Milwaukee (UWM), and the Comprehensive Ocean-Atmosphere Data Set (COADS). A different approach was employed by *Fernández et al.* [2003] who integrated the atmospheric moisture fluxes across the region boundaries. This type of analysis using Eulerian methods to study the divergence of moisture fluxes is not capable of identifying sources of moisture because it calculates the variations in moisture transport only in the boundaries of a specific area. Such methods do not compute the actual trajectories of atmospheric particles. The Lagrangian formulation basically follows trajectories of air parcels, so it can provide more precise information about the trajectories of air masses and the variability of the physical properties, such as moisture content, along them. A wide variety of studies using Lagrangian approaches for the assessment of the moisture source-receptor relationship can be found in the literature [*Stohl and James*, 2004; *Sodemann et al.*, 2008; *Gimeno et al.*, 2010b, 2012, 2013; *Durán-Quesada et al.*, 2010]. As an example, *Dirmeyer et al.* [2009] estimated the source regions of evaporation supplying precipitation of the most of nations of the world using a quasi-isentropic back-trajectory scheme to track water in the atmosphere.

[6] The Lagrangian diagnostic method developed by *Stohl and James* [2004, 2005] gives a good link between moisture sources and sinks. In their FLEXPART model, the net changes in specific moisture are diagnosed along the trajectories, allowing the precise identification of moisture sources and sinks. Previous works have applied this methodology to investigate the moisture sources for the Mediterranean region. *Nieto et al.* [2010] and *Schicker et al.* [2010] analyzed the main sources and sinks of moisture over the basin based on a 5 year period of data (from 2000 to 2004). They have identified the Mediterranean Sea as an

important moisture source for the region and provided an overview of the annual mean source patterns for different regions surrounding the basin. In their work, *Nieto et al.* found that the Western Mediterranean Sea contributes as a moisture source for the Iberian and Balkan Peninsulas, Italy, France, and Northern Africa, while the Central Mediterranean Sea is a source for the Italian Peninsula and Northern Africa. *Drumond et al.* [2011] extended the work of *Nieto et al.* [2010] by focusing on the seasonal variations of moisture sources during drier and wetter years for different Mediterranean target regions during 2000–2004. The contribution of the North Atlantic as a moisture source was apparent for Iberia, France, and Central Africa. In the summer months (JJA), they found that the contribution of the Atlantic reduces and the moisture sources are located over the Mediterranean basin and continental Europe. *Gimeno et al.* [2010a] identified Tropical South North Atlantic (TSNA) as the main moisture source for the Iberian Peninsula. *Nieto et al.* [2007] and *Sodemann et al.* [2008] verified its importance for north Western European regions based on analysis of a 5 year period.

[7] However, the long-term variability of the moisture sources has not yet been evaluated because all previous analysis discussed here is based on 5 years of data. Our purpose is to expand previous analysis [*Nieto et al.*, 2010; *Drumond et al.*, 2011; *Schicker et al.*, 2010] for a 21 year period in order to investigate the seasonal and interannual variability of the main climatological moisture sources for eight target regions in the Mediterranean basin.

[8] The outline of the paper is as follows. Section 2 explains the methods and data. In section 3, a seasonal and interannual analysis of the main moisture sources in the Mediterranean basin and their relationship with the main

Table 1. Main Moisture Sources Identified for Each Target Region and Their Relative 10 Days Integrated Contribution Normalized by the Source Area in Both Seasons^a

Target Region	Wet Season		Dry Season	
	Contributors	Contributions ^b	Contributors	Contributions ^b
IbP	WMS (2–5)	118.03	Local evaporation (0–9)	310.70
	GB (0–2)	87.67	WMS (0–9)	205.82
	TSNA (5–10)	44.18	GB (0–3)	126.86
It	WMS (0–6)	75.52	Local evaporation (0–4)	159.01
	CMS (6–10)	62.06	WMS (4–10)	77.59
	Local evaporation (0–3)	58.60		
Fr	WMS (2–5)	29.99	Local evaporation (0–4)	142.68
	CMS (0–2)	19.83	WMS (4–10)	58.69
	TSNA (5–10)	19.61		
BcP	CMS (0–10)	73.02	Local evaporation (0–10)	231.19
	WMS (1–10)	56.33	CMS (2–4)	40.72
WA	Local evaporation (0–7)	23.71	Local evaporation (0–7)	53.34
	TSNA (7–10)	3.14	CMS (7–10)	10.84
EA	CMS (0–10)	344.84	CMS (0–10)	526.44
CA	WMS (0–10)	306.88	Local evaporation (0–3)	657.70
	Local evaporation (0–3)	159.48	CMS (3–10)	601.61
EM	CMS (3–10)	154.44		
	CMS (3–10)	102.34	Local evaporation (0–4)	199.52
	EMS (0–3)	36.36	BS (4–8)	156.56

^aThe Regions of Study are the Iberian Peninsula (IbP), Italy (It), France (Fr), the Balkan Peninsula (BcP), the Eastern Mediterranean (EM) and Three Regions of the North Africa: West (WA), Central (CA), and East (EA). The brackets indicate the range of the days when a specific moisture source is important.

^bContributions are expressed in $10\text{E-}12 \text{ mm yr}^{-1} \text{ km}^{-2}$.

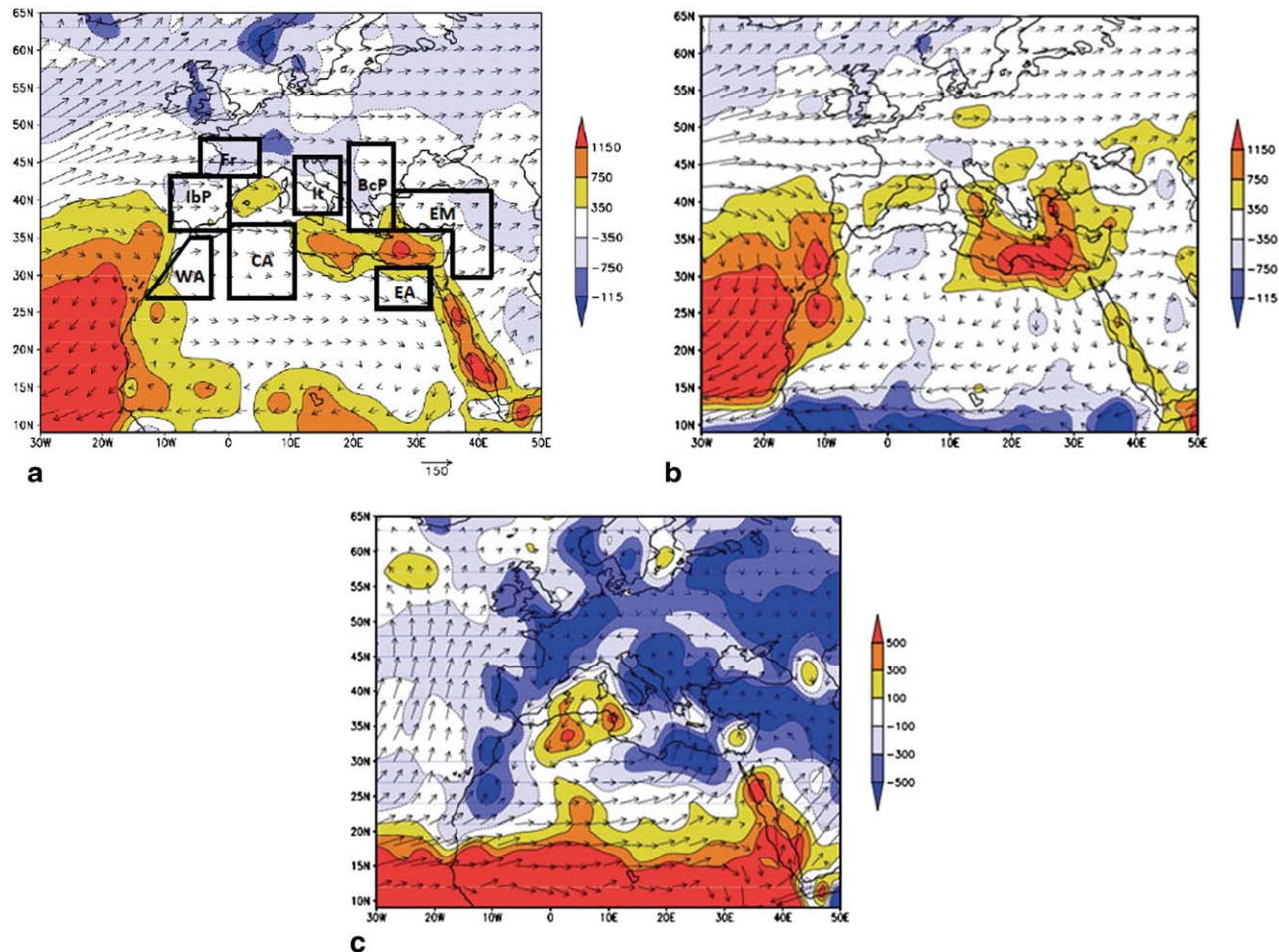


Figure 1. Climatological seasonal vertically integrated moisture flux (vector) ($\text{kg m}^{-1} \text{s}^{-1}$) and its divergence (shade) (mm yr^{-1}) for the (a) wet season, (b) dry season, and (c) the difference between both seasons for the period 1980–2000. This figure shows the eight regions of study: Iberian Peninsula (IbP), Italy (It), France (Fr), the Balkan Peninsula (BcP), Eastern Mediterranean (EM), Eastern (EA), Central (CA), and Western Africa (WA).

teleconnection patterns is presented. Section 4 summarizes the main findings.

2. Data and Methodology

[9] Our study is based on the method developed by *Stohl and James* [2004, 2005], which use the Lagrangian dispersion model FLEXPART to determine the main moisture sources and their contributions for different target regions. FLEXPART 8.0 was integrated using the European Centre for Medium-Range Weather Forecast (ECMWF) 40 year reanalysis (ERA-40) data set [*Uppala et al.*, 2005] available every 6 h with a $1^\circ \times 1^\circ$ resolution on 60 vertical levels. As we are interested in atmospheric moisture, the specific humidity was interpolated to the position of the particle at a given time.

[10] There are different Lagrangian dispersion models and methods. For instance, *D'Abreton and Tyson* [1995] used simple back trajectories from areas of precipitation to infer the origin of air masses. *Dirmeyer and Brubaker* [1999] and *Brubaker et al.* [2001] considered the uptake and loss of moisture and used large sets of back trajectories

to determine the sinks and moisture sources. They computed the back trajectories from each grid square at which precipitation had occurred. This method allows a detailed budget of moisture along the trajectories and provides estimate of precipitation recycling. The methodology applied here differs from *Dirmeyer and Brubaker* [1999] in several points, since it includes information of the turbulence [*Stohl and James*, 2005], it is obtained from a particle dispersion model and it uses different inputs such as the changes in specific humidity with time.

[11] The main reason for using FLEXPART is its robustness for studies of moisture transport, supported by a long list of publication [*Stohl et al.*, 1998, 2004, 2005; *Spichtinger et al.*, 2001; *Viste and Sorteberg*, 2012, 2013; *Chen and Taylor*, 2002; *Sodemann and Stohl*, 2009; *James et al.*, 2003; *Queralt et al.*, 2009]. FLEXPART was successfully applied in studies of sources of moisture for different regions, including the Sahel [*Nieto et al.*, 2006], Iceland [*Nieto et al.*, 2007], China [*Drumond et al.*, 2012], the Orinoco River basin [*Nieto et al.*, 2008], the South American Monsoon System and Northeastern Brazil [*Drumond et al.*, 2008, 2010], Central America [*Durán-*

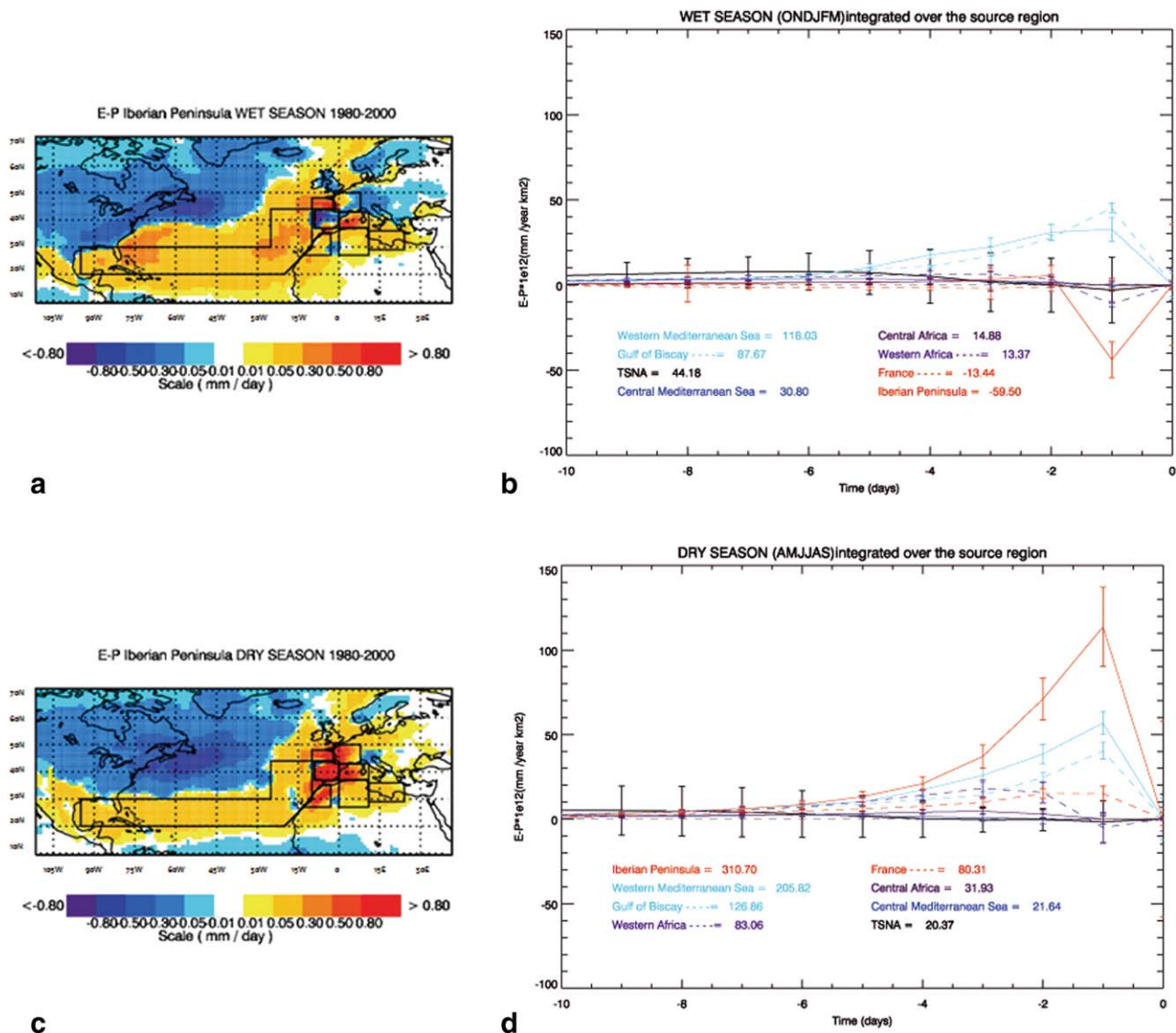


Figure 2. Ten days integrated ($E - P$) values observed during the (a) wet and (c) dry seasons in the period 1980–2000, for all the particles bound for the Iberian Peninsula, determined from backward tracking and expressed in absolute values. The scale is mm d^{-1} . (b) Wet and (d) dry seasons time series of $(E - P)_n$ calculated backward for moisture over Iberian Peninsula and integrated over the source regions selected (values normalized by the source area). The bars represent the interannual standard deviation for each day backward over the 21 year period.

[Quesada *et al.*, 2010], the Mediterranean region [Nieto *et al.*, 2010; Schicker *et al.*, 2010], the Indian Subcontinent [Ordóñez *et al.*, 2012], and the Iberian Peninsula [Gimeno *et al.*, 2010a]. It has also been applied to investigate the main oceanic sources of global continental precipitation [Gimeno *et al.*, 2013].

[12] We have also investigated the seasonal variability of moisture transport over the Mediterranean basin from an Eulerian perspective. The vertically integrated moisture transport ERA-40 reanalysis data set on a $1^\circ \times 1^\circ$ grid was defined as $\frac{1}{g} \int_0^{P_s} q v dp$ where g is the acceleration due to gravity, q is the specific humidity, P_s is the surface pressure, and v is the horizontal wind vector and computed for the 21 year period of study as well as the

divergence of moisture flux which was computed using finite differences.

[13] A detailed monthly analysis of precipitation (figures not shown) indicated that two seasons could be identified: October to March and April to September. The distribution of precipitation in two seasons agrees with the climatological analysis of *Xoplaki et al.* [2004] for the period 1950–1999, which showed that 80% of the annual precipitation in Southern Europe and the Mediterranean basin is recorded during October to March, hereafter considered the wet season. Similar definitions were applied by *Mariotti and Struglia* [2002] and *Eshel and Farrell* [2000].

[14] Eight target regions were defined following the results obtained by *Nieto et al.* [2010]: the Iberian

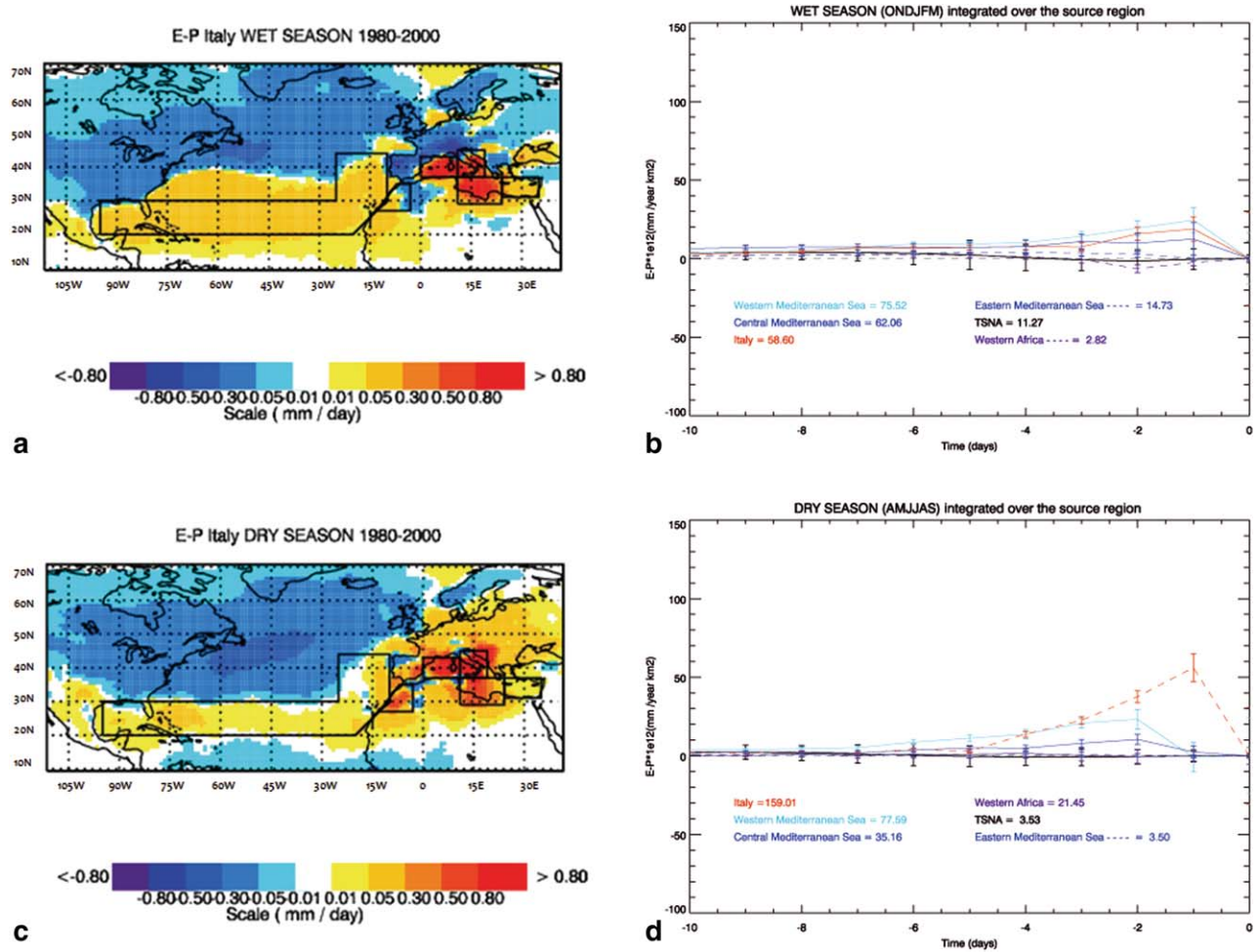


Figure 3. As Figure 2, for Italy.

Peninsula (IbP), France (F), the Italian Peninsula (It), the Balkan Peninsula (BP), Eastern Mediterranean (EM), Western North Africa (WA), Central North Africa (CA), and Eastern North Africa (EA) (Figure 1a).

[15] A backward analysis allows us to identify the major climatological sources of moisture for each one of the target regions during both seasons. The FLEXPART data set comes from a global simulation dividing the entire globe atmosphere into 1.9 million three-dimensional finite elements (hereafter “air particles” or “particles”). These particles are advected by the model using ERA-40 3-D winds in backward mode. To calculate both the grid scale advection and the turbulent and convective transport of particles, other ERA-40 variables were also used as inputs from every time step.

[16] The positions and specific humidity (q) values of the particles were temporally interpolated from ERA-40 data at 6 h intervals. The increases (e) and decreases (p) in moisture along the trajectory of a given particle were calculated from changes in (q) with time using the equation $e - p = m(dq/dt)$, where m is the mass of each air particle. Adding ($e - p$) for all the particles in the atmospheric column over an area yields ($E - P$), where the surface freshwater flux (E) is the evaporation rate and (P) is the precipitation rate. All the particles observed over the target

area are tracked 10 days backward (the average residence time of water vapor in the atmosphere [Numaguti, 1999]). According to Stohl and James [2004], the limitations of the method are mainly due to the fact that fluctuations in q along individual trajectories also occur for numerical reasons. Such random errors may cancel each other out given the large number of particles in an atmospheric column. Full details of the method are provided in Stohl and James [2004, 2005].

[17] We designed $(E - P)_n$ as the net freshwater flux of the selected particles for any prior day n . Analysis of $(E - P)$ fields shows where and when those particles acquire or lose moisture before reaching the target regions. So all particles residing over each target region were tracked backward for 10 days and identified every 6 h. Because target and source regions may have very different area sizes, we have applied two different normalization methods.

[18] In the first analysis, we computed the moisture contributions to a given target area from different sources. Consequently, each contribution was normalized by the area of the respective source (values in Table 1 and Figures 2a and 2d to 9b and 9d), in order to compare the relative contribution to the target region. Then, we computed how the moisture of a given source is distributed among

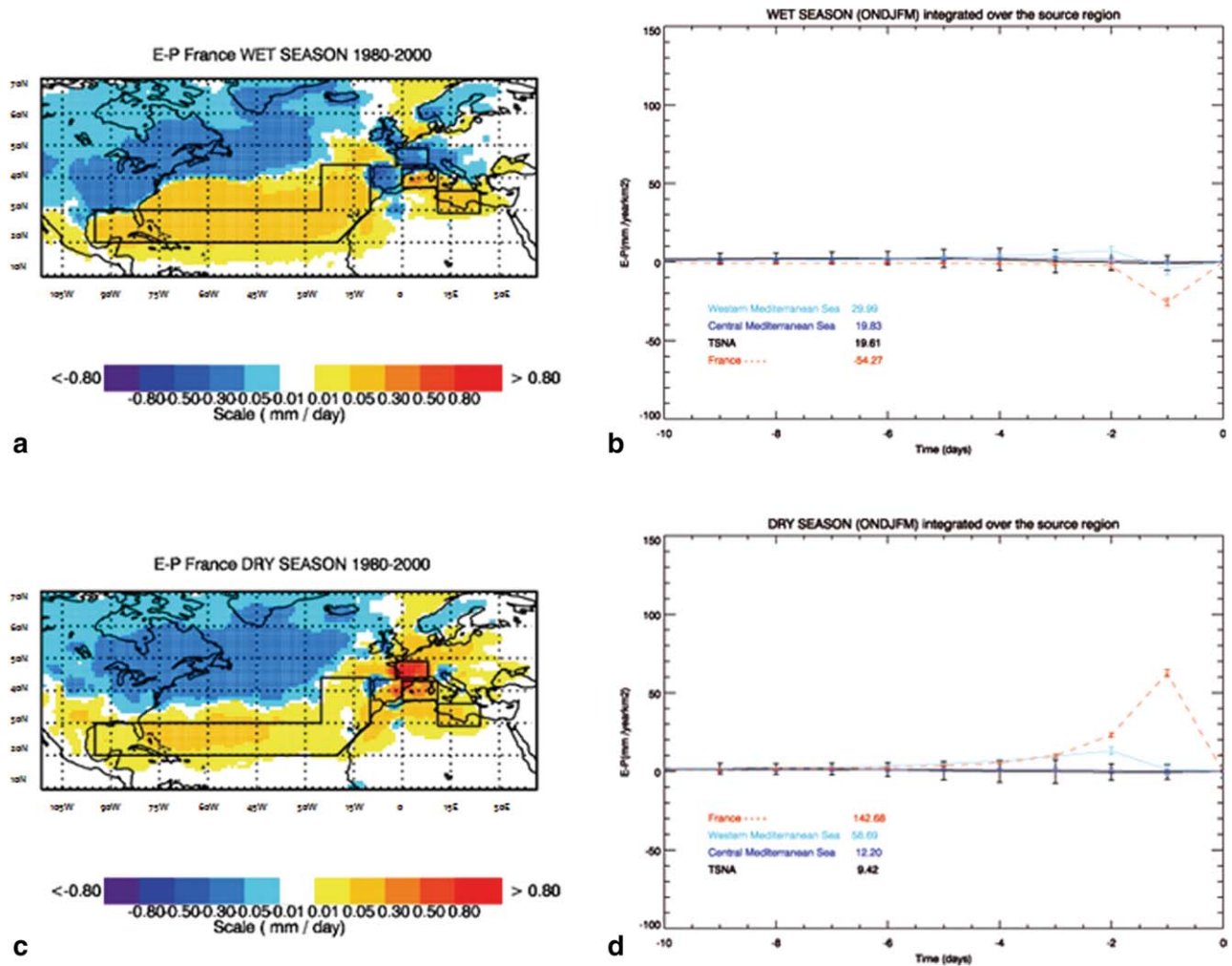


Figure 4. As Figure 2, for France.

different target regions. Thus, we normalized the absolute contributions of the sources by the area of each target region and they are shown in Table 3.

[19] The precipitation in the Mediterranean is influenced by different low-frequency patterns of large-scale variability [Pinhas *et al.*, 2006], so we have analyzed their possible influence in the behavior of moisture sources. The relationship between the different teleconnection indices and the 10 days integrated moisture sources contributions was investigated through linear correlation. Seasonal averages were computed for the following indices.

[20] The North Atlantic Oscillation (NAO) index data were obtained via the monthly NAO index (station-based) [Hurrell, 1996] provided by the Climate Analysis Section, NCAR. El Niño-Southern Oscillation (ENSO) index was obtained from the NCEP reanalysis data from El Niño 3.4 index that uses a centered 30 year base period. The South Asian Monsoon index (SAM) is an areal average of rainfall over India, defined as an average of total rainfall observed during June, July, August, and September and obtained from <http://grads.iges.org/india/allindia.html>. The West African Summer Monsoon Index (WASMI) was taken from <http://ljp.lasg.ac.cn/dct/page/65579> within the West Africa Monsoon domain [Li and Zeng, 2002, 2003]. Lastly,

the Scandinavian Pattern Index (SCAND) was obtained from the reanalysis NCEP data normalized considering the 1980–2010 monthly means of the SCAND index and standard deviations.

3. Results

[21] Figure 1 shows the vertically integrated moisture flux (VIMF) and its divergence for the period 1980–2000. For the wet season, the divergence expands over the Western and Central Mediterranean Sea, whereas during the dry season it is observed over the Eastern Mediterranean Sea. So, during the dry season the flux of moisture and its divergence seem to extend toward the continental areas where, as will be shown in the next figures, the process of local evaporation predominates in comparison with the moisture contribution from remote areas. Figure 1 is also helpful for interpreting the next figures since moisture sources coincide with regions presenting divergence of VIMF.

[22] The main moisture sources for the eight target areas were identified through seasonal ($E - P$) maps. Figures 2a and 2c to 9a and 9c show ($E - P$) averages for the period 1980–2000 in absolute terms for the wet and dry seasons, respectively. The contribution of moisture from the major

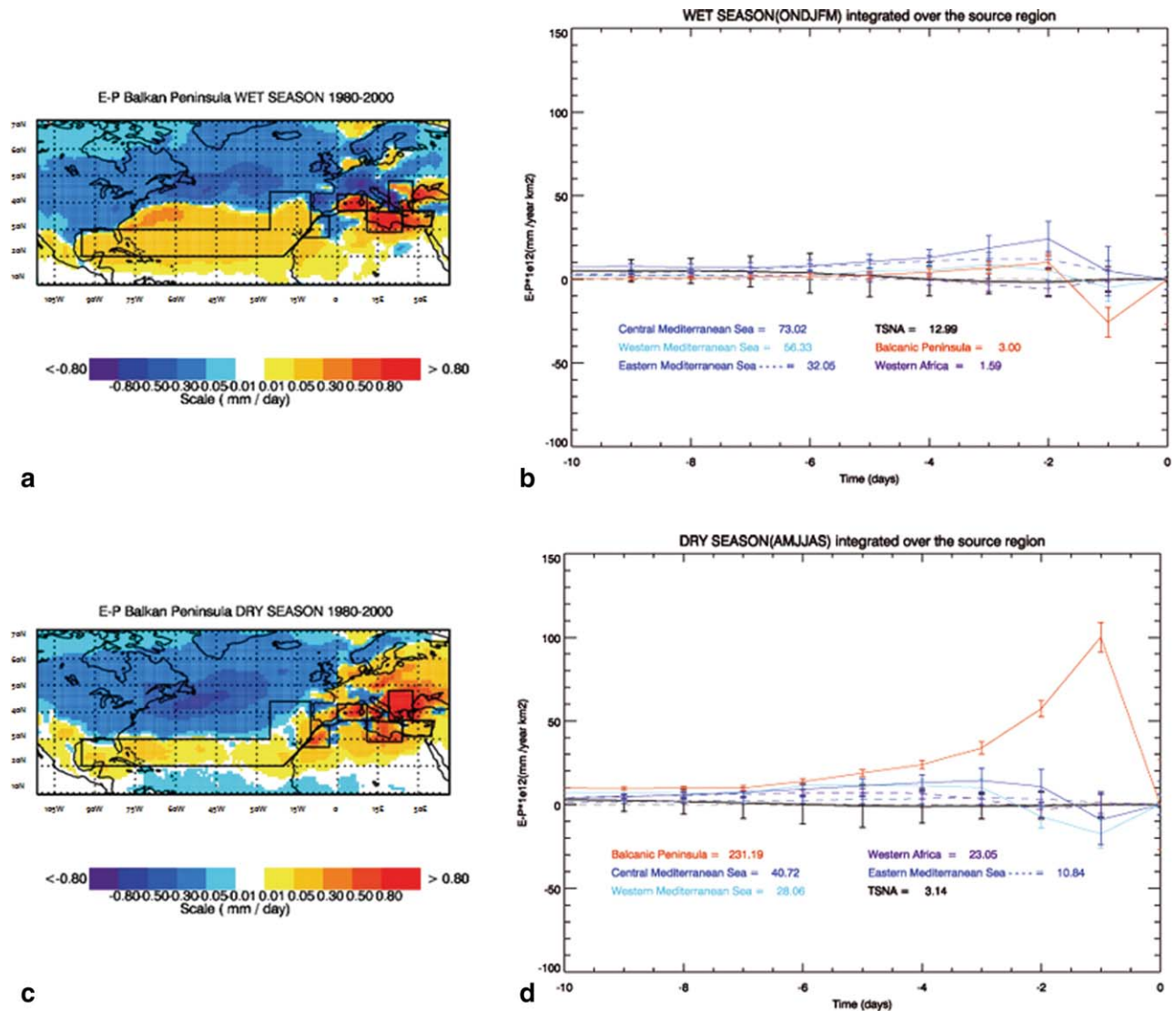


Figure 5. As Figure 2, for the Balkan Peninsula.

sources identified for each target region is shown in Figures 2b and 2d to 9b and 9d and Table 1. The seasonal time series of daily $(E - P)_n$ values were calculated backward and integrated over the major moisture sources to quantify the contribution of these sources to the target areas. The values were normalized as described above.

[23] Before discussing the results, it is important to understand how to interpret the figures. In Figures 2a and 2c to 9a and 9c, the areas characterized by reddish colors represent regions where $(E - P) > 0$, meaning that evaporation exceeds precipitation in the net moisture budget and these regions act as moisture sources. Bluish colors represent areas where $(E - P) < 0$, these are regions where precipitation exceeds evaporation in the net moisture budget. These regions may be considered as moisture sinks. In Figures 2b and 2d to 9b and 9d, the contributions of the main moisture sources for each target region 10 days backward in time are plotted. The bars represent the interannual standard deviation ($\pm\sigma$) of each day backward in time for the whole period of 21 years.

[24] Figure 2 shows that the WMS is the most relevant moisture source for the Iberian Peninsula during the wet season ($118.03 \times 10^{-12} \text{ mm yr}^{-1} \text{ km}^{-2}$), and it is the dominant source between 2 and 5 days backward in time (Figure 2b). From Figure 2b, we can see that the Tropical South North Atlantic (TSNA) appears to be the main moisture source between 5 and 10 days backward (10 days integrated contribution is $44.18 \times 10^{-12} \text{ mm yr}^{-1} \text{ km}^{-2}$). Besides, the contribution of WMS is higher during the dry season by approximately 54% in comparison with the wet period (Table 1). Local evaporation seems to be the most important moisture source during the dry season (10 days integrated contribution is $310.70 \times 10^{-12} \text{ mm yr}^{-1} \text{ km}^{-2}$). The contribution of the Gulf of Biscay (GB) is higher during the dry season than during the wet one.

[25] For Italy (Figure 3), WMS is the main moisture source during the wet season and it prevails between days 0 and 6 backward (Figure 3b). The Central Mediterranean Sea (CMS) is also an important source in this season. During the dry season, local evaporation plays an important

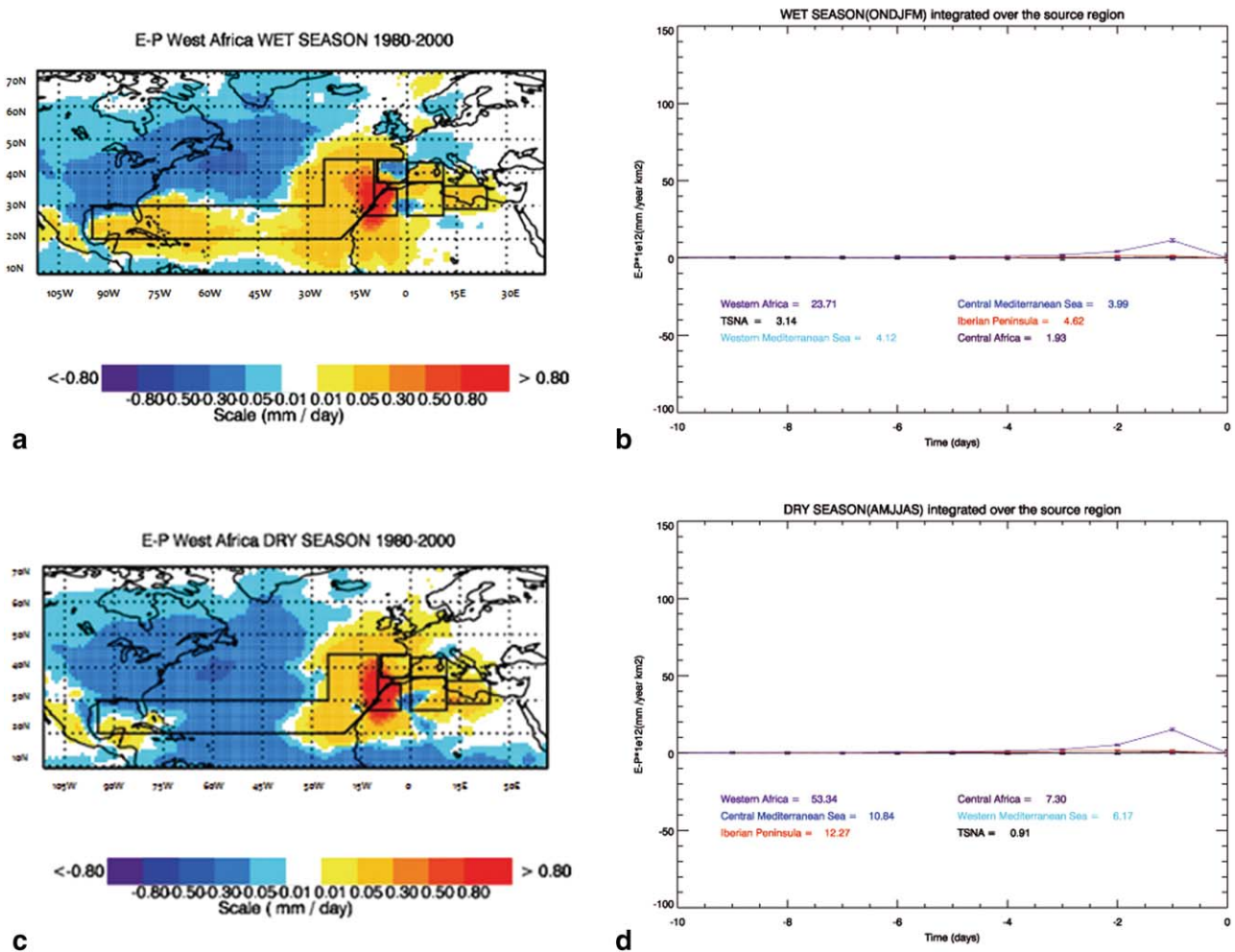


Figure 6. As Figure 2, for West Africa.

role during the previous 4 days (10 days total contribution $159.01 \times 10^{-12} \text{ mm yr}^{-1} \text{ km}^{-2}$ and Figure 3d), while the highest contribution comes from the WMS in the earlier days.

[26] For France (Figure 4), WMS appears the main remote moisture source in both seasons (10 days integrated contribution is $29.99 \text{ mm yr}^{-1} \text{ km}^{-2}$ for the wet season and $58.69 \text{ mm yr}^{-1} \text{ km}^{-2}$ for the dry) (Figures 4b and 4d, respectively). During the dry season, local evaporative processes seem to prevail until 4 days backward in time (10 days integrated contribution of $142.68 \times 10^{-12} \text{ mm yr}^{-1} \text{ km}^{-2}$) (Figure 4d).

[27] For the Balkan Peninsula (Figure 5), CMS is the main moisture source in the wet season (10 days integrated contribution of $73.02 \times 10^{-12} \text{ mm yr}^{-1} \text{ km}^{-2}$), and its contribution prevails during the previous 10 days (Figure 5b). During the dry season, local evaporative processes seem to be the main moisture source (10 days integrated contribution of $231.19 \times 10^{-12} \text{ mm yr}^{-1} \text{ km}^{-2}$). CMS still supplies less moisture than that observed during the wet season (10 days integrated contribution of $40.72 \times 10^{-12} \text{ mm yr}^{-1} \text{ km}^{-2}$) (Table 1).

[28] For West Africa (Figure 6), the contribution from local evaporative processes prevails during the wet (10 days integrated contribution of $23.71 \text{ mm yr}^{-1} \text{ km}^{-2}$) and

dry season (10 days integrated contribution of $53.34 \times 10^{-12} \text{ mm yr}^{-1} \text{ km}^{-2}$) (Figures 6b and 6d, respectively). Besides, IbP and Central Africa provide moisture during the whole year. The contribution from the maritime regions of WMS and CMS increases during the dry season, while the contribution from TSNA is then reduced (Table 1). In East Africa (Figure 7), CMS is the dominant moisture source in both seasons, presenting a higher contribution during the dry period ($526.44 \text{ mm yr}^{-1} \text{ km}^{-2}$). It dominates during the 10 days backward (Figures 7b and 7d and Table 1). For Central Africa (Figure 8), WMS appears as the most important moisture source during the wet season (its 10 days integrated contribution is approximately 50% higher than that from local evaporation process and the Central Mediterranean Sea) (Table 1). However, the local evaporative process dominates during the dry season (10 days integrated contribution is $657.70 \text{ mm yr}^{-1} \text{ km}^{-2}$). It is interesting to note that the contribution from the Mediterranean Sea increases during the dry season, while that from TSNA reduces.

[29] For the Eastern Mediterranean (Figure 9), CMS is the most important moisture source for the wet season, followed by the EMS between the first and third day backward (Figure 9b) (Table 1). Local evaporation dominates during the dry season between the first and fourth day backward.

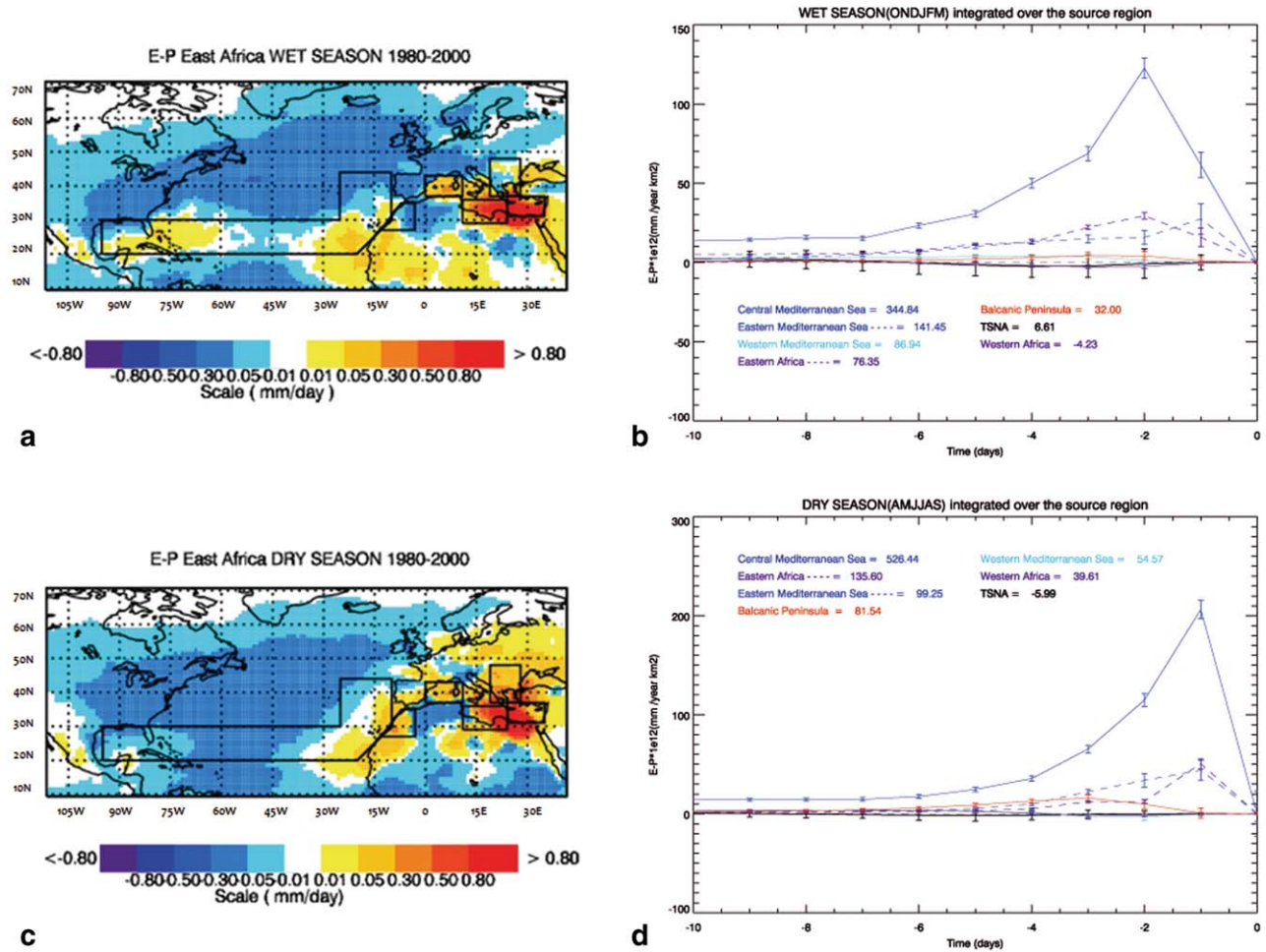


Figure 7. As Figure 2, for East Africa.

BS is also a relevant moisture source in the dry season (Figure 9d).

[30] Additionally, we also computed the main moisture sources for the entire year (figures not shown). The results are shown in Table 2 and it was observed that the local evaporative processes and Western Mediterranean Sea are the most important moisture sources for almost all the target regions. These results are in agreement with *Dirmeyer et al.* [2009] who computed the evaporative source regions for each individual country. They obtained that for our regions the local evaporative processes and Western Mediterranean Sea are the dominant moisture sources, except for Eastern Africa, where the Central Mediterranean Sea is the main moisture source, which is in agreement with our results. Besides the oceanic sources also play an important role. Our results suggest that the Atlantic Ocean supply moisture to the Iberian Peninsula, whereas the Black Sea does the same for the Eastern Mediterranean. This result agrees with *Dirmeyer et al.* [2009].

[31] Next, we analyze how the contribution of a certain source is distributed among different targets areas. Table 3 shows 10 days integrated contributions normalized by the area of the respective target regions. It is seen that IbP is the main destination of TSNA (with a 10 days contribution of $633.71 \text{ mm yr}^{-1} \text{ km}^{-2}$ during the wet season and $292.19 \text{ mm yr}^{-1} \text{ km}^{-2}$ during the dry season). The transport from

this oceanic source is probably associated with the tropospheric rivers and extratropical cyclones that are responsible for most of the precipitation on the western side of the extratropical continental latitudes [*Ralph et al.*, 2004, 2005; *Bao et al.*, 2006]. On the other hand, CA ($176.90 \text{ mm yr}^{-1} \text{ km}^{-2}$) is the main receptor of moisture from WMS, while most of the moisture from CMS arrives to EA ($655.49 \text{ mm yr}^{-1} \text{ km}^{-2}$).

[32] When comparing Tables 3a and 3b, it is seen that the role of local evaporative processes is more relevant during the dry season. The local contribution for CA is almost four times larger than in the wet season ($657.70 \times 10^{-12} \text{ mm yr}^{-1} \text{ km}^{-2}$).

[33] We have also estimated the total moisture supply reaching each target region (Table 4), obtained by adding all the source contributions. It is seen that during the wet season the total contributions are much lower for all the target regions apart from It and BcP. During the dry season, the target area receiving the lowest supply is Western Africa, while the highest is recorded in Central Africa. For the wet season, Eastern Africa and Central Africa are the main receivers. Besides, there are seasonal differences in the total moisture supply for the different target regions. During the dry season, some of the values of total contribution are twice (IbP, WA) or three times (CA) higher than in the wet one. For the Iberian Peninsula, Western, and

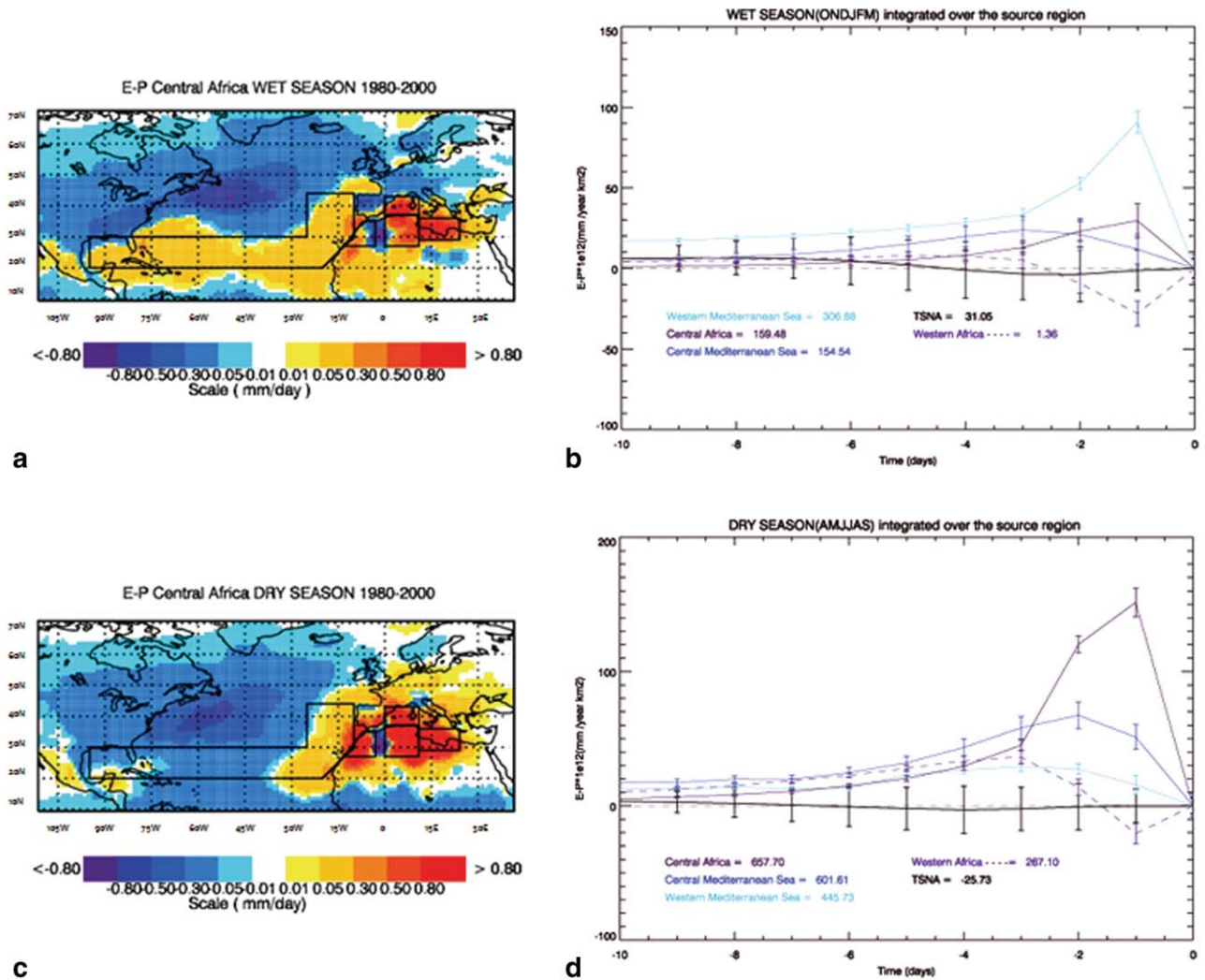


Figure 8. As Figure 2, for Central Africa.

Central Africa the contribution of moisture from the Mediterranean Sea (especially from WMS and CMS) increases during the dry season (between 2 and 4 factor), whereas for the other target regions this contribution decreases. Moreover for the Iberian Peninsula and Central Africa, the contribution of Western Africa suffers an important decrease during the wet season, showing higher values during the dry one.

[34] The interannual variability of the moisture contribution for a given region (Figures 2b and 2d to 9b and 9d) depends on the supplying source and the backward step. The highest variability, computed as Pearson's coefficient of variation ($\frac{\sigma}{\bar{x}}$), which ranges between 0.10 and 52.63 for all targets and sources, is recorded in days 1–2 backward of the TSNA contribution to IbP and EM, and in the first day of the WMS contribution to It. This could be due to the fact that those regions, where the air masses gain or lose moisture during the first and second day before their arrival in the IP, are very near their destination area, with a mixture of processes: ocean evaporation over Atlantic areas close to the IP, the process of recycling (terrestrial evaporation over the IP) and lost moisture (precipitation) over the IP. On the other hand, these regions are very homogeneous in

terms of evaporation/precipitation, being ocean evaporation for major oceanic sources the dominant process.

[35] The variability of the contributions integrated along the backward trajectories is more limited, as can be seen in Table 5. It shows different measures of variability for IbP, with WA, local sources, and TSNA showing the highest interannual changes. This is because actual moisture supply depends on the moisture provided by a given source and number of the particles trajectories reaching the target region.

[36] The impact of the main teleconnection patterns NAO, ENSO, SAM, WAM, and SCAND in the moisture variability was also evaluated. We have analyzed how the moisture supply from every source is correlated (coefficients of $r > 0.43$ are significant at the level of 95%) with the corresponding teleconnection patterns. Results show a wide range of possible influences, as seen in Tables 6 and 7. In general terms our results de-emphasize the potential importance of the NAO, the most important teleconnection in region and its correlations with the transport of moisture toward the Mediterranean regions are poor, even during the wet season, when NAO is the dominant teleconnection pattern. Then, there is a pool of significant but low

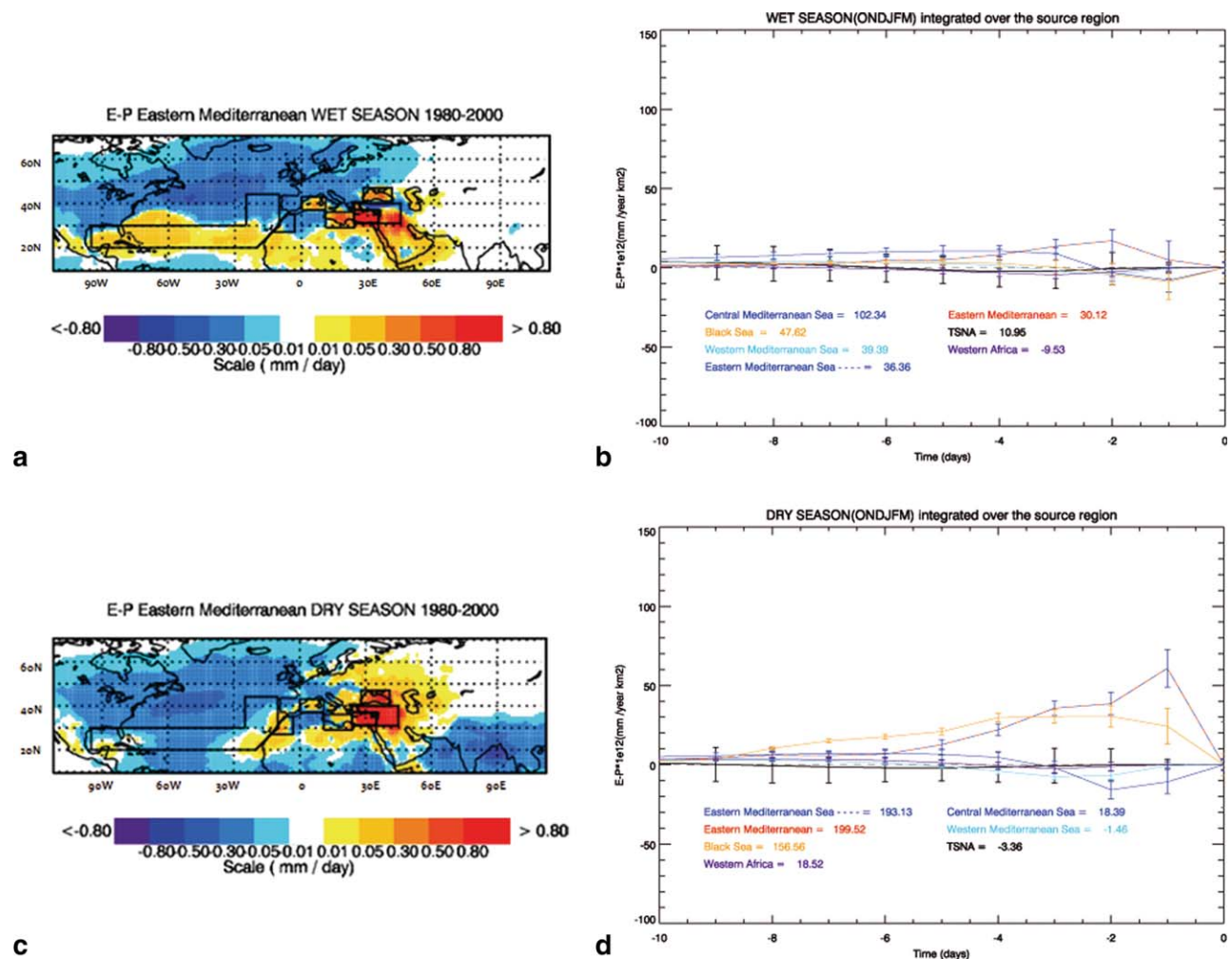


Figure 9. As Figure 2, for the Eastern Mediterranean.

correlations, such as those between El Nino and the moisture transport from the WMS to several target regions during the dry season, and finally, there are high correlations

Table 2. Main Annual Moisture Sources for Each Target Regions^a

Target Region	Contributors
IbP	WMS (4–6) Local evaporation (0–4) TSNA (6–10)
It	WMS (0–4) Local evaporation (4–10)
Fr	WMS (2–10) Local evaporation (0–2)
BcP	Local evaporation (1–6) WMS (1–10)
WA	Local evaporation (0–10)
EA	CMS (0–10)
CA	Local evaporation (0–3) CMS (3–5)
EM	WMS (5–10) Local evaporation (0–3) EMS (0–3) BS (3–9) CMS (9–10)

^aThe brackets indicate the range of the days when a specific moisture source is more relevant.

difficult to interpret in terms of changes in circulation patterns (e.g., between WASM and the transport of moisture to several target regions, both during the wet and dry seasons). The known effect of any of these teleconnections on Mediterranean precipitation (<http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml>) seems to be more related to changes in instability mechanisms (that force the moist air to rise) than to changes in the supply of moisture. There are any clear exceptions, such as the high correlation between SCAND and the transport of moisture from WMS to Italy; it is known that the positive phase of the SCAND is associated with above-average precipitation across southern Europe, so this is a clear example of combined effect transported moisture instability. The lack of more results in this direction could be due to the fact that our analysis accounts for all the transported moisture not only for that precipitating. An analysis of only precipitating trajectories could result in different conclusions (e.g., as those reached between the influence of NAO on transport of moisture precipitating in Scandinavia, *Stohl et al.*, 2008). We must also take into account that our analysis was limited to identify only linear relationship between atmospheric modes and moisture sources variability through correlation coefficients. We believe that a better understanding of the physical mechanisms linking changes of moisture transport must

Table 3. Distribution of the Moisture Provided From the Main Sources Among the Different Target Regions (Values Normalized for the Respective Area of the Target Region) for the (a) Wet and (b) Dry Seasons^a

Moisture Source	IbP	It	Fr	BcP	WA	EA	CA	EM
<i>Wet Season</i>								
TSNA	633.71	204.80	379.92	146.20	36.90	118.50	276.85	74.40
WMS	109.45	88.76	36.68	40.99	4.69	100.84	176.90	65.86
CMS	41.85	106.87	35.52	87.08	12.06	655.49	145.99	65.86
Local evaporation	59.50	58.66	142.68	3.00	53.34	76.35	159.48	36.36
<i>Dry Season</i>								
TSNA	292.19	64.20	178.14	35.39	10.76	−107.55	−229.48	−26.35
WMS	190.88	91.20	71.77	20.42	4.86	63.30	256.93	−0.74
CMS	29.40	106.87	21.85	43.42	12.08	894.61	508.08	13.65
Local evaporation	310.70	159.01	142.68	231.19	53.34	135.60	657.70	199.52

^aContributions are expressed in $10\text{E}–12\text{ mm yr}^{-1}\text{ km}^{-2}$.**Table 4.** Total Moisture Supply Reaching the Target Region the Wet and Dry Seasons^a

Target Region	Wet Season	Dry Season
IbP	295.54	569.99
It	166.40	141.23
Fr	69.43	80.31
BcP	175.98	105.81
WA	17.80	37.49
EA	607.61	795.42
CA	493.83	1288.71
EM	223.13	381.78

^aValues normalized by the source region for each region source. Contributions are expressed in $10\text{E}–12\text{ mm yr}^{-1}\text{ km}^{-2}$.

be further investigated with details in the future to further study the linear and nonlinear links between large-scale modes and water vapor transport in a more detailed way.

4. Concluding Remarks

[37] This paper analyzes for the first time the moisture sources in the Mediterranean basin over a long period (21 years) using the sophisticated Lagrangian approach based on FLEXPART model.

[38] We have defined wet and dry seasons based on the precipitation distribution in the region. This allows identifying significant seasonal differences in the main moisture sources for every target except for EA. During the wet season, the WMS is the main moisture source for all target

Table 5. Main Moisture Sources During the Wet Season for the Iberian Peninsula With the Maximum and Minimum Values and Years of Contributions (in Brackets), the Standard Deviation, the Average and Pearson's Coefficient of Variation^a

Moisture Source	Maximum	Minimum	Standard Deviation	Average	$\frac{\sigma}{\bar{x}}$
TSNA	91.54(1993)	41.11(1988)	37.36	44.18	0.84
GB	97.50(1980)	−19.69(1993)	5.00	87.67	0.06
WMS	210.09(1990)	53.21(1991)	42.94	118.03	0.36
CMS	107.52(1993)	6.67(1980)	23.47	30.80	0.76
WA	56.58(1984)	−47.72(1996)	32.75	13.37	2.44
IbP	83.05(1989)	−198.14(1995)	58.44	−59.50	0.98
Fr	20.77(1984)	−41.78(1993)	17.58	−13.44	1.30
CA	51.07(1988)	−9.98(1994)	18.69	14.88	1.26

^aValues were normalized by the target area. Contributions are expressed in $10\text{E}–12\text{ mm yr}^{-1}\text{ km}^{-2}$.**Table 6.** Pearson Coefficient of Correlation Between the Temporal Series of the 10 Days Integrated Contribution of the Main Moisture Sources of Each Target Region and the Main Teleconnection Patterns During the Wet Season

Target Region	Contributors	r (Teleconnection Pattern)
IbP	WMS	Not significant
	CS	Not significant
	TSNA	0.61 (WASM)
It	WMS	0.80/0.51 (SCAND/WASM)
	CMS	−0.56 (NINO)
	Local evaporation	Not significant
Fr	WMS	0.44 (WASM)
	CMS	0.56 (SCAND)
	TSNA	0.64/0.45 (WASM/SAM)
BcP	CMS	0.64 (WASM)
	WMS	0.48/−0.56 (NAO/NINO)
	Local evaporation	Not significant
WA	TSNA	0.56/−0.54 (WASM/NINO)
	CMS	0.59 (WASM)
EA	WMS	Not significant
	Local evaporation	Not significant
	CMS	−0.49 (NINO)
CA	CMS	0.63 (WASM)
	BS	Not significant

regions except for the Balkan Peninsula, East Africa, and the Eastern Mediterranean, where the CMS is the dominant moisture source. During the dry season, local evaporative processes seem to be the most important source jointly with WMS and CMS. In terms of an annual study, the local evaporative processes and Western Mediterranean Sea are the dominant moisture sources for almost all target regions apart from Eastern Africa which has the Central Mediterranean Sea as the dominant evaporative source.

[39] When the contribution of a source among different targets areas is analyzed, it is seen that IbP is the main destination of TSNA in both seasons, while CA is the main receptor for WMS and EA for CMS. During the dry season, the moisture from the local evaporative processes reaches the highest values in CA and IbP.

[40] The total moisture supply reaching every target region was also studied and CA (EA) appeared as the target region which received more moisture during the dry (wet) season. The lowest values appeared for WA. During the dry season the total supply of moisture is higher for all target regions (except for It and BcP) than in the wet,

Table 7. Same as Table 6, But for Dry Season

Target Region	Contributors	r (Teleconnection Pattern)
IbP	Local evaporation	Not significant
	WMS	Not significant
It	CS	Not significant
	Local evaporation	−0.44 (NAO)
Fr	WMS	−0.51 (NINO)
	Local evaporation	Not significant
BcP	WMS	Not significant
	Local evaporation	Not significant
WA	CMS	0.57/Not significant (SCAND/NINO)
	Local evaporation	Not significant
EA	CMS	−0.47 (NINO)
	Local evaporation	Not significant
CA	CMS	0.49 (WASM)
	Local evaporation	−0.46 (NINO)
EM	EMS/local evaporation	0.56 (NINO(+))
	BS	Not significant

probably because the higher air temperature during the dry season increases air water vapor content.

[41] The interannual variability of the contributions from the moisture sources along the 21 year period was also assessed through the standard deviation and the Pearson's coefficient of variation. The highest variability was recorded in days 1–2 backward of the TSNA contribution to IbP and EM, and in the first day of the WMS contribution to It.

[42] The impact of the main teleconnection patterns is limited. Analysis of the linear joint variability between the teleconnection patterns and the contribution of the main moisture sources for each target region reveals that despite of obtaining significant correlations during the wet season, the low coefficients suggest that there might be more changes in instability mechanism than changes in the supply of moisture. An analysis taking into account only the precipitating trajectories could result in different conclusions. A more detailed analysis (e.g., including modeling) might be also helpful to identify and to further study the linear and nonlinear links between large-scale modes and water vapor transport in a more detailed way.

[43] The contribution of the moisture sources to the precipitation is currently being analyzed. We are also studying the associated trends of precipitation and individual contributions, by extending the analysis to the domain of ERA-interim data. In addition, the main mechanisms responsible for the moisture transport, the role of atmospheric rivers, and changes observed during extreme events, will be also analyzed.

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