A Lagrangian identification of the main moisture sources and sinks affecting the Mediterranean area

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Abstract: - In this work the Lagrangian diagnosis method used by Stohl and James [1, 2] was applied to identify the main moisture sources and sinks affecting the Mediterranean area, as well as the contribution of this basin in the atmospheric moisture of adjacent and remote regions. The transport of particles is calculated with the Lagrangian particle dispersion model FLEXPART, which uses data from the ECMWF operational analysis. In this framework a large number of air particles were moved freely using 3D wind data. The flow is described by the position of the particles and the time. To identify the contribution to the moisture budget over a target region the specific humidity (q) was retrieved also from the ECMWF analysis. The increases and decreases in moisture along the trajectory can be calculated through changes in q with time (being recorded every 6 hours). Adding these changes for all the air particles residing in the atmospheric column over an area, we can obtain a measure of the surface freshwater flux E-P (the evaporation minus the precipitation rate). We traced (E-P) forwards trajectories over 3 areas over the Mediterranean Sea and backwards trajectories over 8 regions surrounding the basin during 2000–2004, all these areas selected based on the climatological atmospheric moisture flux divergence. The method supports a very high precise tool to determine how the Mediterranean Sea can affect the surrounding areas and also remote regions as the Sahel, as well as to reveal the importance of remote moisture sources as the Tropical-Subtropical North Atlantic to the studied region.

Key-Words: - moisture sources and sinks, Lagrangian approaches, precipitation, Mediterranean basin, FLEXPART, moisture flux divergence

1 Introduction

There is considerable interest in the meteorology and hydrology communities on understanding the origin of the moisture and the precipitation that occurs over a given region, due to the dependence of our life on water resources. In addition, it is known that the water vapour is the most important contribution to the natural greenhouse effect and any kind of change in those regions with maxima support of moisture to the atmosphere could modify its general distribution.

About 90% of the water in the atmosphere emanates from the oceans, lakes and other open water bodies [3]. Through atmospheric transport and associated transfer processes, some of the water that evaporates over the oceans reaches the land and may precipitate.

According to Gimeno et al. [4], understanding of moisture transport processes requires knowledge of how water vapor, which accounts for approximately 0.25% of the total mass of the atmosphere, is distributed. Water vapor concentration is highly variable both in space and time. The large scale distribution pattern of water vapor largely parallels that of temperature because equilibrium vapor pressure is dependent on temperature (Clausius-Clapeyron equation). Therefore, the greatest variations in water vapor in space occur with increasing height above the surface; specifically, water vapor concentrations decrease markedly with increasing height. Important variations also occur close to the surface, where concentrations vary by more than three orders of magnitude from 10 parts per million by volume in the coldest regions of the Earth's atmosphere to as much as 5% by volume in the warmest regions [3]. Most of the water vapor is concentrated in the tropical atmosphere, which contains more than three times as much water as the extratropical atmosphere. However, these moisture climatological distributions can be significantly different from daily humidity distributions, which are more sensitive to prevailing wind fields than to temperature.

It is now commonly accepted that the precipitation occurring in a region has one of the following origins: 1) moisture already present in the atmosphere, 2) advection of moisture into the region by the winds or, 3) recycling. Over long periods, the first source contributes little, so there are two major sources in the troposphere that govern the moisture transport, evaporation and advection.

Different approaches can be used to identify the moisture geographical sources, but all of them suffer some kind of limitation. Such methodologies can be grouped into four categories: a) studies that calculate recycling ratios (e.g. [5]; [6]), and their main limitation is that they cannot determine the specific origin of non-local water; b) studies that use general circulation models and water vapour tracers to assess the major evaporating regions that contribute to water precipitating in a different region (e.g. [7]; [8]). In this approach the source regions must be specified and the results are dependent of the quality of the model data; c) studies based on integrating the atmospheric moisture fluxes across the region boundaries (e.g. [9]; [10]; [11]) also fail in providing information about the geographical sources of moisture; and d) studies that quantify the transport based on trajectories (e.g. [12]; [13]). These studies are capable of providing full 3D details of where the air mass originated, but provide no information on how the moisture increases and decreases along the trajectories affect the moisture in the target region.

The Mediterranean is positioned at the border between the tropical climate zone and the mid latitude climate belt, presenting a large environmental meridional gradient [14] (figure 1). The temperate climate of this region is characterized by mild and humid winter months and most dry summer months. An extended area is influenced by the northern Atlantic atmospheric river. Those belts of moisture transport most of the water vapor in the lower troposphere. So, the precipitation pattern in its western continental margin is determinate by this mechanism due to the fact that the coastal line is perpendicular to the most frequent flow direction of the atmospheric river [15].

The Mediterranean Sea is almost a completely closed basin with an area of 2.5 million km^2 and an average depth of 1,500 m, being connected to the Atlantic Ocean through the narrow Gibraltar Strait (14.5 km wide and less than 300m deep). The region presents a complicated morphology, due to the presence of many sharp orographic features, the presence of distinct basins and gulfs, islands and peninsulas of various sizes. High mountain ridges surround the sea on almost every side and the highest ridge is the Alps, reaching a maximum high of 4,800 m and containing permanent glaciers. Islands, peninsulas and many regional seas and basins determine a complicated land-sea distribution pattern with a large spatial variability of both sea and atmospheric circulation with many subregional and mesoscale features [14].

The Mediterranean climate is exposed to the South Asian Monsoon in boreal summer and the Siberian high-pressure system in winter [14]. The southern part of the region is mostly under the influence of the descending branch of the Hadley cell, while the northern part is more linked to the mid-latitude variability as the North Atlantic Oscillation (NAO) [16]. The teleconnections in the region present a large amount of both spatial (ranging from synoptic to mesoscale) and time variability (with a strong seasonal cycle modulated on multi-decadal to centennial time scales), so the climatic variability present regional characteristics [17]. It is also important to consider the role of the Mediterranean Sea as a heat reservoir; as a source of energy and latent heat for cyclone development [18] and its possible effect on remote areas (such as the Sahel, [19]) and on the Atlantic overturning circulation [20].

The Mediterranean hydrological cycle is especially sensitive to the timing and the location of the winter storms as they move into the region [21]. Studies have showed a relationship between the NAO and precipitation over this area, especially at lower frequencies [22]. The influence of El Niño Southern Oscillation (ENSO) has also been identified mostly in winter during its extreme episodes, although its impact varies regionally ([23]; [24]). In boreal summer, when the advection of moisture from the Atlantic is weaker and the Hadley cell moves northwards, there are evidences of connections with the Asian and African monsoons [14].

The Mediterranean Sea is also an important source of atmospheric moisture and the characteristics of the local water budget influence the amount of moisture that flows into northeast Africa and the Middle East ([25]; [26]). Past and future global climate changes affecting, for example, storm track characteristics [27], as well as changes in the land surface conditions [28], may be linked to significant changes of the hydrological cycle in the Mediterranean region [29], with impacts in the available water for different purposes [30]. In this way, an improved knowledge of the Mediterranean hydrological cycle and its variability could offer important socioeconomic benefits to these areas.

Several previous studies were published identifying geographical sources or sinks of moisture over the Mediterranean Sea based on different methodologies (most of them attaining information in an Eulerian framework) and input data with results varying significantly among authors [31].

As an example, Mariotti et al. [31] performed a budget analysis to study contributions to the freshwater flux into the Mediterranean Sea, including atmospheric as well as river discharge inputs, during the last 50 years using recent atmospheric reanalyses and observational datasets. The analysis gives a moisture flux from west to east year-round, but with a southward component during summer, from the eastern Mediterranean into northeast Africa and the Middle East.

A different approach was employed by Fernández et al. [11] that have based their method on integrating the atmospheric moisture fluxes across the region boundaries. These authors have clearly shown that the precipitation variability within the Mediterranean basin is closely related to the structure of the vertically integrated moisture transport fluxes, inside the domain and at the borders.

Although this type of analysis with Eulerian method or using moisture divergence flux are capable to identify sources of moisture, they are not able to calculate them with high precision, in part because they do not imply real trajectories of atmospheric particles. Believing that the Lagrangian method can give more precise information concerning the trajectories of air masses and their moisture variability in comparison to the traditional Eulerian techniques, the purpose of this work is investigate the sources and sinks of moisture over the Mediterranean basin through the FLEXPART 3-D Lagrangian method. It is important to note that the Lagrangean analyses are very useful for other different geophysical applications, as studies concerning pollution transport [32] or works about transport of superficial and deep waters [33]. We considered a standard 5-year period that lacked extreme phases of the major modes of climate variability at the global climate scale, such as ENSO or NAO.

The Lagrangean model FLEXPART and the vertically integrated moisture flux divergence data used in the analysis are described in Section 2. Section 3 shows the results for the forward and backward trajectories analyses. In Section 4 we discuss our main results.

Fig. 1: Orography of the Mediterranean region. (From: www.euratlas.com/Atlasphys/Orography.htm)

2 Methodology

To determine from where the moisture over the Mediterranean Basin come from our study was based on the method developed by Stohl and James [1,2], which used the Lagrangian particle dispersion model FLEXPART [34]. FLEXPART uses the meteorological analysis data from the European Centre for Medium-Range Weather Forecasts [35] to track different meteorological parameters for the entire atmosphere along trajectories. We focus this study on the atmospheric moisture, so we used the equivalent humidity interpolated to the position of the trajectory at a given time.

In order to identify each particle trajectory, the atmosphere is divided homogeneously into a large number of particles at the model start. These particles have a constant mass and are distributed homogeneously in the atmosphere according to the distribution of atmospheric mass. In the model these particles are advected using operational three dimensional (3-D) ECMWF winds. To calculate both the grid scale advection as well as the turbulent and convective transport of particles, operational ECMWF data were also used as inputs to the model. Their positions and specific humidity values (q) were temporally interpolated from the ECMWF data, which was recorded every 6 h. The increases (e) and decreases (p) in moisture along the trajectory can be calculated from changes in (q) with time (e-p = m dq/dt), where m is the mass of the particle. When adding (e-p) for all the particles in the atmospheric column over an area it is possible to obtain (E-P), where the surface freshwater flux (E) represents evaporation and (P) is the precipitation rate per unit area. The method can also track (E-P) from any specific region backwards in time along the trajectories, choosing those particles that reach the target region at the time of interest, to identify sources of moisture and precipitation.

To ensure exact mass balances, vertical winds are calculated using spherical harmonics data as part of the data retrieval procedures at ECMWF. To account for turbulence the FLEXPART model calculates the trajectory of the particles using analyzed winds plus random motions. In the planetary boundary layer (PBL) these random motions are calculated by solving Langevin equations for Gaussian turbulence [36]. These equations use Lagrangian timescales and the standard deviations for wind components, which are computed from ECMWF PBL parameters [37]. The PBL height is determined using a combination of the Richardson number and the lifting parcel technique [38]; turbulence outside the PBL is assumed to be very small. Global datasets do not resolve individual convective cells, but do reproduce the large scale effects of convection. FLEXPART has various options for the generation of particles and what they represent. In this case the atmosphere was "filled" homogeneously with particles, each representing a fraction of the total atmospheric mass. Particles were then allowed to move freely (forward in time, but this is arbitrary) with the winds for the duration of the simulation.

The limitations of the method mainly concern the accuracy of the trajectories and the use of a time derivative of humidity, where unrealistic fluctuations in humidity could be interpreted as moisture fluxes. However, the use of sufficiently long time periods minimizes the effects of unrealistic fluctuations. Full details of the method and its limitations are described by Stohl and James [1] and [2].

In the work reported here we used the tracks of 1.3 million particles over a 5-year period (2000–2004), computed using ECMWF operational analysis available every 6 hours (00, 06, 12 and 18 UTC) at a 1º x 1º resolution in latitude and longitude on all 60 vertical levels.

A data base with the trajectories was performed from the model FLEXPART for several sub-regions within the extended Mediterranean basin (50ºN–28ºN lat, 10ºW–40ºE lon). The integration of the data from ECWMF analysis determined the spatial and temporal position of the particles and the value of their moisture was computed. We traced (E-P) backwards or forwards from the extended Mediterranean region limiting the transport times to 10 days, which is the average time that water vapour resides in the atmosphere [7], assessing the location of the most important sources or sinks of moisture observed along the period for eleven sub-regions selected through to a climatological atmospheric moisture flux and moisture divergence analysis (Fig. 2). The vertically integrated moisture transport is defined as $1/g\int_0^{Ps} qvdp$, 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. ECMWF Re-Analysis (ERA-40; [39]) on a 1° x 1° grid was used to compute flux divergences for the period from September 1957 to August 2002.

Figure 2 shows in grey contours the annual vertically integrated moisture flux divergence based on the entire atmospheric mass, as well as the boreal summer and winter fields. The origin of air-masses residing within the atmosphere over 8 different continental regions surrounding the Mediterranean Basin (trying to cover the maximum area around the sea) was tracked. The analyzed areas for backward trajectories (in red capital letters in Fig. 2) are: the Iberian Peninsula (IbP), France (F), the Italian Peninsula (ItP), the Balcanic Peninsula (BP), Eastern Mediterranean (EM), and three regions over North Africa: Western, Central and Eastern North Africa (WA, CA and EA). Over the Mediterranean Sea the areas for compute the forward trajectories were defined using the moisture divergence analysis. The local net water flux from the surface to the atmosphere is indicated by the positive values of atmospheric moisture divergence. Although the moisture flux in the Mediterranean region comes mostly from the Atlantic Ocean [31], over the Mediterranean Sea the flux is more intense than in surrounding land regions, being more intense eastward, from the west (near the Iberian Peninsula)

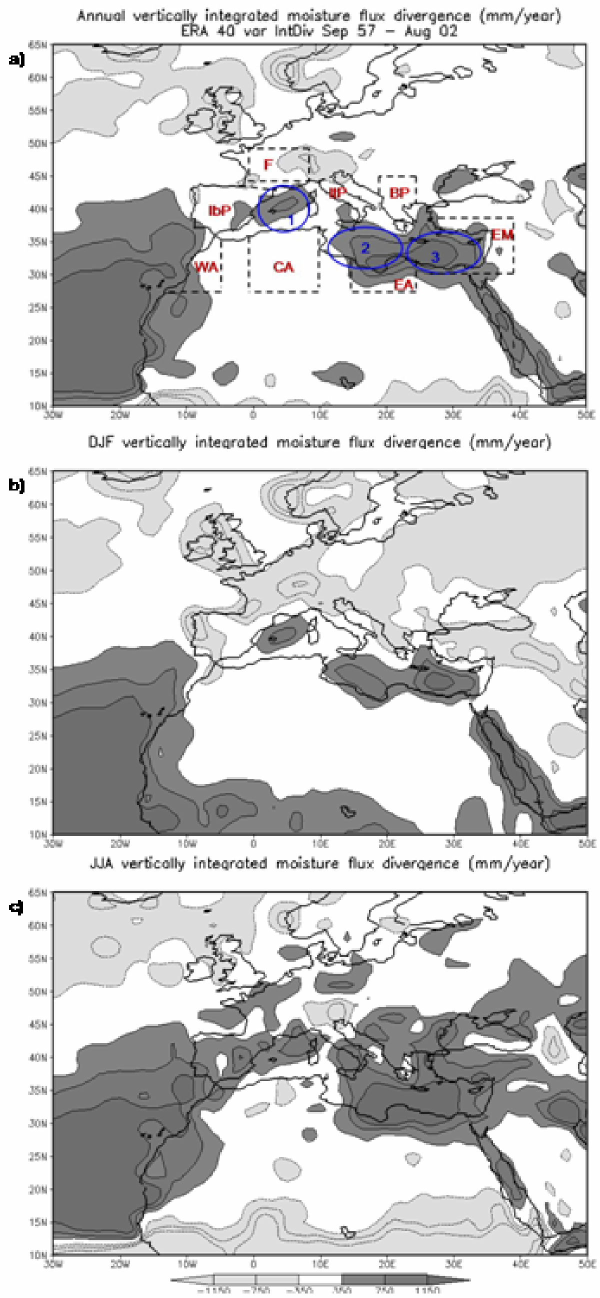


Fig. 2a: Climatological annual vertically integrated moisture flux divergence (shaded and contour lines, in mm/year). The boxes indicate the moisture regions studied through the integrations (red, backward trajectories; blue, forward trajectories); 2b: the same as a), but for the boreal winter; 2c: the same as a), but for the boreal summer.

to the east coast. In this way, 3 areas provide maximum water supply to the atmosphere: the Levantine Sea (the western of the Mediterranean), the southern Ionian Sea (between Italy and the African coast), eastern Mediterranean into northeast Africa and the Middle East. So, for forward trajectories the areas selected were the Western, Central and Eastern Mediterranean Sea (numbered 1, 2, and 3, respectively, in blue capital letters in Fig.2a). This structure was found along the years, though seasonal positional and quantity variations could be found for these sea areas (figures 2a, 2b and 2c for annual, boreal winter and boreal summer, respectively).

This work presents the results of (E-P) values averaged over 5 year periods and integrated over 10 days, from the first to the tenth day of the trajectory. We designated $(E-P)^{1,10}$ for backward trajectories and $(E-P)_{1,10}$ for forward trajectories. Despite the relative complexity of the tracking method, the interpretation of these patterns is straightforward. So, we will track the moisture from the Mediterranean Sea forward to see in which regions water from originally Mediterranean air masses is lost. And we will track the air masses residing over 8 surrounding land Mediterranean areas back in time to see where the moisture was originated.

This methodology follows the same one applied in various climatic regions, including the Sahel [40], the Iberian Peninsula [41], the Antarctic [42], the South American Monsoon System [43], and Central America [44]. Those recently diagnoses show the robustness of this approach.

3 Results

The high spatial discretization of the Mediterranean region allows for a detailed view on the moisture sources and sinks for the different regions of the extended Mediterranean area under study. Fig. 3 shows the annual $(E-P)_{1,10}$ values for the 3 Mediterranean sea areas, and Fig.4 displays the annual $(E-P)^{1,10}$ values for the 8 land Mediterranean regions. Before discussing the results, it is important to understand how to interpret de figures. Results corresponding to regions characterised by E-P>0, where evaporation dominated over precipitation (reddish colours in Figs. 3 and 4), indicate that air particles located within that vertical column and in transit from (to) the analyzed area gain moisture in a forward (backward) trajectory. These regions are therefore identified as moisture source regions. It is important to note that we define the “moisture source region” as an area in which an air parcel absorbed significant amounts of moisture before reaching the atmosphere over the target. Otherwise, E-P<0 reveals regions where precipitation dominates over evaporation (bluish colours in figs. 3 and 4). Consequently, air masses located over these regions in transit from (to) the analysed area in a forward (backward) trajectory display a net loss of moisture, and these regions are identified as moisture sink.

As we commented, Fig. 3 illustrates the forward tracking for the 3 sea regions with strongest net source of water vapour. The results presented suggest that moisture transport processes to different target regions undergo significant changes with the meridional position of each region. In general, results from the forward air-masses tracking (Fig.3) showed that for each region the main influence to the moisture budget is the owner surrounding area, and being throughout the local dominant flows the way to transport the air masses over the continental areas. Results from the western Mediterranean Sea (region 1, Fig. 3a) show that this region contributes directly in the precipitation (bluish colours) over the Alpine region, the Levantine coast (east of Iberian Peninsula) and the Strait of Gibraltar, playing an important role in the humidity transported to Algeria and Libya.

The central (region 2, Fig. 3b) and eastern (region 3, Fig. 3c) Mediterranean Sea show higher values of (E-P) due the bigger basin recorded. The central Mediterranean Sea affects with more importance the precipitation over the Hellenic Peninsula and Islands, and over the central part of North Africa. On the other hand, the eastern Mediterranean Sea has its influence on regions over the Middle East and Egypt.

Fig. 4 shows that the moisture sources for each continental area differ due the different location of the target regions around the Mediterranean Basin. Briefing discussing the results obtained for each target region, we can see, in general, the importance of the surrounding areas in providing the moisture. Although nearest areas are the most important sources of moisture it is necessary to note that for the western limits of the Mediterranean Basin (IbP, F, and WA) the contribution of the from the Tropical – Subtropical North Atlantic Ocean, including the Gulf of Mexico. For the Iberian Peninsula (IbP, Fig. 4a) the western Mediterranean Sea area appears as one of the main moisture sources, but it is this target region the most affected by the moisture gained along the Tropical –Subtropical North Atlantic Ocean. The importance of the western Mediterranean as moisture source is also observed for France (F, Fig. 4b), as well as the contribution from surrounding areas, including the Iberian Peninsula region, and from the Tropical-Subtropical North Atlantic.

The contribution of the Subtropical-Tropical North Atlantic is still observed for the Italian Peninsula (ItP, Fig. 4c). For this region all the Mediterranean Basin acts as a moisture source, especially the western and central regions, accompanied by the Southern Europe and Northern Africa. These same moisture sources can be identified for the Balcanic Peninsula region (BP, Fig. 4d), though their contributions are weaker than the ones observed for the Italian Peninsula (Fig. 4c).

All the Mediterranean Basin contributes as a moisture source for the Eastern Mediterranean region (EM, Fig. 4e), specially the surrounding sea. In addition, we can see the contributions from Eastern Europe, Middle East, Eastern North Africa and even the Subtropical-Tropical North Atlantic.

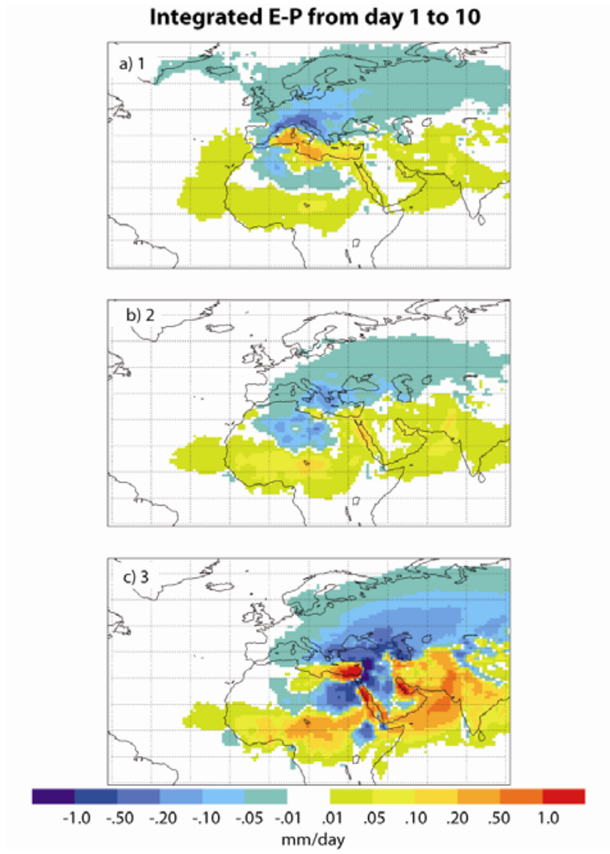
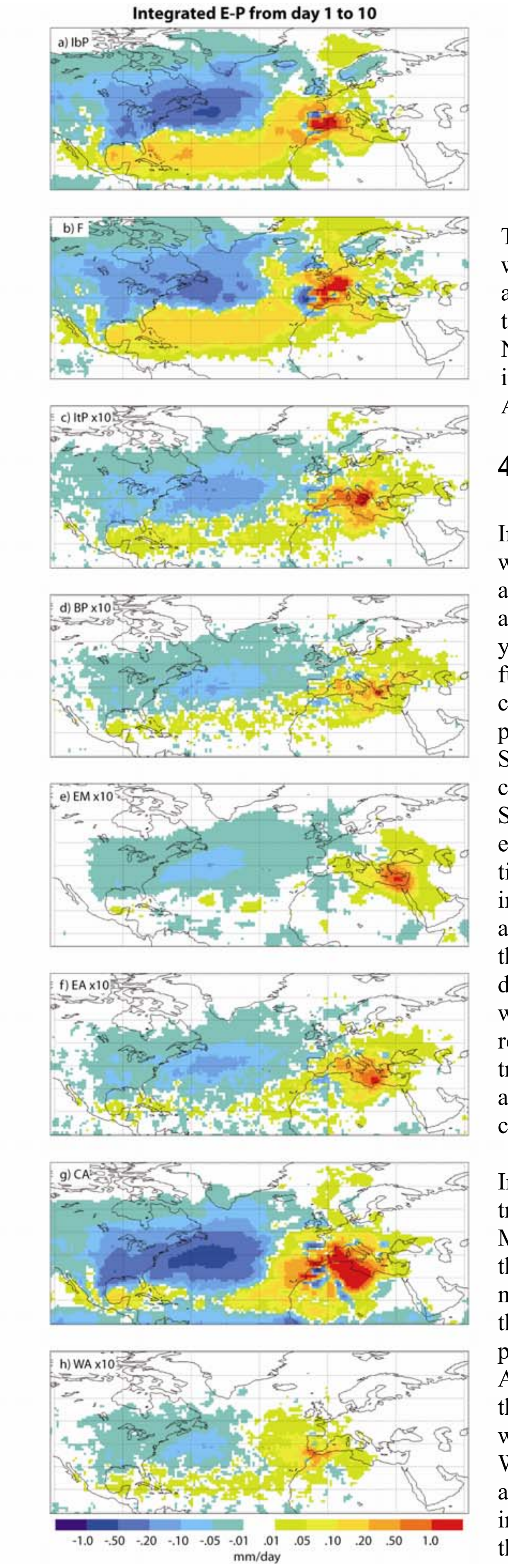


Fig. 3: Annual average values of $(E\text{-}P)_{1,10}$ for the period 2000–2004 determined from forward tracking for the: a) Western Mediterranean Sea (1), b) Central Mediterranean Sea (2) and c) Eastern Mediterranean Sea (3) regions. Scale in mm/day (scale multiplied by a factor of 10 in b).

For the Eastern North Africa target region (EA, Fig. 4f) the results indicate the importance of the Mediterranean Basin, specially the western and central regions, besides the contributions from the Southern and Eastern Europe, North Africa and Subtropical-Tropical North Atlantic. The western and Central Mediterranean regions are also moisture sources for the Central North Africa area (CA, Fig. 4g), together with Europe and northern and north western Africa. However, the general pattern of the obtained moisture sources for the Western North Africa target region (WA, Fig. 4h) differ from the ones observed for the other African studied areas.



← Fig. 4: Annual average values of $(E\text{-}P)^{1,10}$ for the period 2000–2004 determined from backward tracking for the: a) Iberian Peninsula IbP, b) France F, c) Italian Peninsula ItP, d) Balcanic Peninsula BP, e) Eastern Mediterranean EM, f) Eastern North Africa EA, g) Central North Africa CA and h) Western North Africa WA regions. Scale in mm/day (scale multiplied by a factor of 10 in c-e), f) and h)).

The contribution from Europe is reduced to the western continent, specially the Iberian Peninsula, and the contribution from Mediterranean comes from the western and central areas. On the other hand, the North Atlantic region close to Europe becomes an important moisture source, together to northern Africa and the Subtropical-Tropical North Atlantic.

4 Concluding remark

In this work a sophisticated 3-D Lagrangian method was used to determine the major moisture sources and sinks affecting the Mediterranean area through an analysis of the annually average conditions over a 5-year period (2000-2004). The method considers the full transport pathway of an air particle. We calculated the evaporation and the precipitation processes along the entire trajectory every 6 hours. So, the method allows us take into account the contribution of each process back or forward in time. So, we traced (E-P) backwards or forwards from the extended Mediterranean region limiting the transport times to 10 days, assessing the location of the most important sources or sinks of moisture observed along the period for eleven sub-regions selected through to a climatological atmospheric moisture flux divergence analysis. The origin of air-masses residing within the atmosphere over 8 different continental regions surrounding the Mediterranean Basin was tracked through backward trajectories, while three areas were selected over the Mediterranean Sea for computing the forward trajectories.

In general, results from the forward air-masses tracking showed that for the three studied Mediterranean regions the main influence occurs over the surrounding areas, being transported the air masses throughout the local dominant flows. From the backwards trajectories results, the observed patterns of (E–P) > 0 show, in general, that the North Atlantic basin and the western Mediterranean Sea are the main moisture source regions affecting the western target regions, Iberian Peninsula, France and Western North Africa. The eastern target regions are affected by each surrounding sea areas, being important the supply of moisture by recycling due to thermodynamic structure and soil factors in the

Eastern Mediterranean or in the Eastern North Africa. In central Mediterranean regions both type of sources of moisture (remote and recycling) are important. It is remarkable the role of the subtropical and tropical North Atlantic Ocean source of moisture (extending from the Gulf of Mexico to Africa) in the western and central regions. The tropical–subtropical source of moisture for the south western North Atlantic continental areas has been reported in studies of other western Europe regions at latitudes higher than the Iberian Peninsula [45, 46]. This tropical source is probably associated with tropospheric rivers, which are also related to extratropical cyclones that are responsible for most of the precipitation on the western side of the extratropical continental latitudes [47].

The Lagrangian diagnostic can be applied to other data set as the re-analysis of the ECMWF with a higher time covering, around 40 years. This is particularly important for studying interannual variability of moisture transport and the influence of the large-scale climate modes that affect the Mediterranean region, for instance the NAO. This topic constitutes one of the fundamental understandings for the future to know with more detail the hydrological cycle of the Mediterranean Sea.

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