Classification of air masses arriving at Cáceres (Spain) and its relationship with their aerosol load

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Abstract —Although the air masses reaching the Iberian Peninsula have been extensively studied, to establish an objective criterion for the classification remains a main problem which is specific for the particular purposes of each study. In the case of being interested in the aerosols transported by the air mass, the interest focuses on the origin of air mass, but also on the flight time and the path along which the air mass has traveled. Due to the difficulty to identify the effective source regions responsible for the aerosols arriving at Cáceres, in this study the air masses were clustered according to their backward trajectories. Daily 500 m above sea level (ASL) 5-day back-trajectories ending in Cáceres (Spain) over 5 years (2005 - 2010) were calculated using HYbrid Single Particle Lagrangian Integrated Trajectory model (HYSPLIT_4). This cluster analysis will identify the most frequent paths and origins for the air masses reaching the station of Cáceres. The cluster analysis used in this study combines two types of methodologies: hierarchical method and non-hierarchical method, so as to take profit from the advantages of each method. Clusters of trajectories have been related with the aerosol optical properties, such as aerosol optical depth and Ångström exponent α, obtained from measurements provided by photometers CIMEL in Cáceres station. Once applied this methodology, three different groups of trajectories were identified: on one side, trajectories coming from the Atlantic and Northern Europe, associated to low turbidity; on the other side, trajectories from continental areas, with a greater turbidity; and finally, Saharan dust events characterized by a remarkably high turbidity and very low Ångström exponent α.

Keywords — Aerosol, HYSPLIT, air-masses, trajectories.

1 INTRODUCTION

The study of atmospheric aerosols is of great interest because they affect the Earth´s radiation balance by directly interacting with solar radiation through scattering, absorption or emission processes, and indirectly by acting upon cloud formation. Additionally, high concentration of aerosols at low levels can be very harmful for the human health by favoring allergies and respiratory diseases [1]. Therefore, their study is very important, and although there has been significant progress in recent years, its current knowledge is still insufficient by their great complexity, due to the high heterogeneity in aerosol composition as well as their temporal and spatial variability. Hence, studies dealing with different aspects of aerosols are of high interest to improve their knowledge. Thus, nowadays, the analysis of back trajectories is widely used in order to identify the air masses arriving at a certain region and to relate the air masses characteristics with the aerosol properties retrieved from local measurements [2], [3], [4], [5], [6], [7], [8].

For studies involving air masses trajectories, it is advisable to know the most frequent typical air masses arriving the study area. In the case of the Iberian Peninsula, where this study is focused, air masses are well characterized and there are several different classifications according to their genetic origin (degree of continentality and latitude) and the associated synoptic situations, obtaining air masses types characterized by different humidity and temperature [9], [10], [11]. These principal types are:

- *tropical maritime* (**mT**). These air masses are very common and have a particularly warm and wet character. Their origin is located at the Atlantic Ocean and related to the Azores anticyclone. These air masses can arrive at Iberian Peninsula any time of year.
- *polar maritime* (**mP**). They have a wet character and low temperature. Their origin is the North Atlantic Ocean. The arrival at the Iberian Peninsula of this type of air mass is more frequent in winter.
- *arctic* (**A**). This type is colder and drier than mP, and is more common in winter and early spring.
- *polar continental* (**cP** or **c**). It corresponds to dry and very cold air masses arriving from Russia and Siberia. This type is rare, and only arrives at the

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Iberian Peninsula in winter.
- *tropical continental* (**cT**). These dry and warm air masses come from North Africa. They arrive at the Iberian Peninsula any time of the year, but predominantly in summer.
-*Mediterranean* (**Me**). They show a wet character and usually affect the Mediterranean coast.

Fig. 1 shows the main air mass types arriving at the Iberian Peninsula.

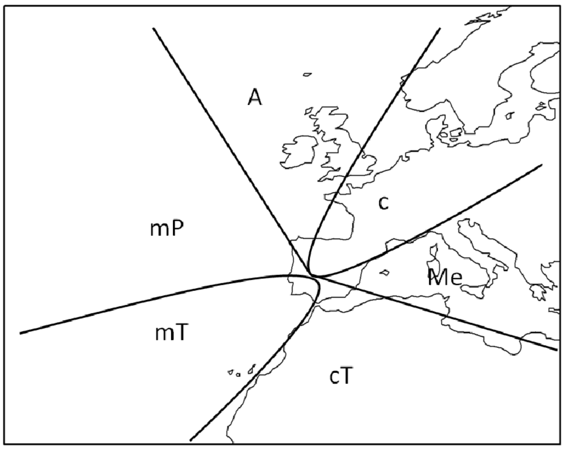

Fig.1. Sectors of origin of main air masses arriving at the Iberian Peninsula.

Although the type of air masses arriving at Iberian Peninsula have been extensively studied, one of the main problems found when trajectories are classified for a specific purpose, such as the study of aerosols, is to establish an objective criteria which fulfills such specific purpose. Being our main goal the study of aerosols transported by the air mass, it becomes essential to take into account the origin of air mass and its flight time. Another aspect to consider is the path travelled, as well as the time spent over the different regions. Due to the difficulty to propose a priori representative areas which effectively reflect the idiosyncrasies of the main air masses arriving at Cáceres, this study applies a cluster analysis to the daily backward trajectories in order to identify the most frequent situations. This analysis will allow to identify the main routes and most frequent sources air masses reaching the station of Cáceres.

The objective of this study is to characterize the spectral aerosol properties within each air mass type arriving at Cáceres (Spain). For this purpose, trajectories calculated with HYSPLIT_4 model (HYbrid Single Particle Lagrangian Integrated Trajectory model), [12], [13], have been classified using a cluster analysis (combining hierarchical and nonhierarchical methodologies). This analysis clusters air mass trajectories based on the geometric distance between their paths, which are defined by the latitude and longitude. Once trajectories have been classified to give the main air mass types, each type has been related with the resulting values of aerosol optical depth and Ångström exponent α measured by photometers CIMEL [14] at Cáceres station.

The period of study extends from July 2006 to June 2010 guaranteeing the reliability of the results and conclusions depicted in this study.

2 STUDY REGION AND INSTRUMENTATION

The aerosol optical properties used in this study have been obtained from measurements made with photometers CIMEL [14] located in Cáceres (Spain). This station is operatively working since July 2005 and is part of AERONET (AErosol RObotic NETwork) and RIMA (Red Ibérica de Medida Fotométrica de Aerosoles) networks, and it is managed by the AIRE (Atmósfera, cLima y Radiación en Extremadura) research group of Department of Physics, University of Extremadura (Spain).

Details about the CIMEL radiometers operation and the AERONET processing system can be found in [14].

This station is located at Western Spain, being the only one existing in Extremadura and, therefore, being representative for a wide region in the Iberian Peninsula. It is installed at the Campus of Cáceres (39.47ºN, 6.34ºW, 397 m a.s.l.) of the University of Extremadura, on the terrace of the Polytechnic School building, guaranteeing an open horizon free of obstacles. The area of study is predominantly rural, with no industry and where local pollution is mainly due to moderate road traffic.

Fig. 2. Location of the radiometric station of Cáceres.

The standard instrument of these networks is the CIMEL Electronique 318A automatic sun tracking photometer. It performs direct sun measurements using filters at 340, 380, 440, 500, 675, 870, 940 and 1020 nm wavelengths, and sky measurements at 440, 675, 870 and 1020 nm wavelengths. The

CIMEL radiometer is designed to perform series of automatic measurements throughout the day according to a certain schedule. The instrument measures only during daylight hours and under non-rainy conditions [14].

The radiation measured by CIMEL allows to retrieve radiation parameters of the aerosols related to their nature and size. These products are freely available at AERONET website (http://aeronet.gsfc.nasa.gov/) with three different quality levels: 1.0, 1.5 and 2.0. In this study level 2 aerosol optical properties, such as aerosol optical depth (τ) or Ångström exponent α, have been used, being the estimated uncertainty between 0.01 and 0.02 [14].

3 DATASET AND METHODOLOGY

The period of study extends from July 2005 to June 2010. During this period, the set of days for which level 2 data are available, has been used. For all these days, back-trajectories have been calculated.
Level 2 data have also been used in other studies to establish relationships between aerosol properties and their origin and path [15],[16].

Table 1 shows both the total number of days for Cáceres and the number of days for each season.

Table 1. Total number of days in Cáceres station and number of days for each season.

Total	Winter	Spring	Summer	Autumn
846	154	117	54	63

The first step of our study was to calculate120-hour back trajectories ending at Cáceres using the HYSPILT model. Back-trajectories have been calculated for arriving conditions corresponding to 12:00 UTC and height level of 500 m a.s.l. (corresponding to approximately 950 hPa). This height was selected because, in general, the aerosol concentration decreases with height, since the sources of aerosols tend to be close to the surface. Thus, trajectories at 500 m transport a greater aerosols load, often found within the mixed layer. Besides, these back-trajectories will be related to column integrated aerosol properties given by CIMEL photometers.

Once calculated the air masses back-trajectories, a cluster analysis was applied. Cluster analysis is a method used to classify items into homogeneous groups called clusters with respect to some predetermined selection criteria. The elements that make up each group (cluster) are similar one to each other (high internal homogeneity) and are different of the elements of the other clusters (high external heterogeneity). This analysis will result in clusters of trajectories with similar length and curvature, as it takes into account both the speed and direction of the trajectory [17]. In the literature there are different approaches on how to use this technique in the study of cluster grouping the trajectories of air masses [18].
In this work, the cluster analysis combines two methodologies, one hierarchical and the other nonhierarchical, to take advantage of both methods. Firstly, a hierarchical classification (which does not require a prior definition of the number of clusters) has been applied to the air-mass back-trajectories in order to determine the appropriate number of clusters and reliable seeds for the application of a non-herarchical methodology. This method aims to bring together clusters to form a new or an existing to separate in other, making a process of agglomeration or division. In the first part of the process it is necessary to establish the method used to calculate the distance between clusters. In this case we applied the average method, and the distance between clusters is calculated as the average distance between pairs of trajectories. The hierarchical method provides good representation of the results, being the clusters obtained neither too large nor too small. This information can be represented in a dendrogram that allows to determine the number of clusters depending on the distance between the clusters. Similar objects are connected by links whose position in the diagram is determined by the level of similarity or dissimilarity between objects.

Subsequently, a non-hierarchical analysis has been applied. The objective of this analysis is to make a single partition of the elements in k groups, which bind the other elements based on the distances between them. It means that previously one must calculate the matrix of distances between elements of the sample and determine the number of groups or clusters and their centroids, which correspond to the average trajectories of each cluster. The number of k groups and theirs corresponding centroids are provided by the hierarchical method. Once the number of clusters is known, it is necessary to establish the distance between points in the plane. In this case we have chosen the Euclidean distance. Each trajectory consists of 121 points on that plane, and the distance is calculated for all pairs of points.

After all trajectories have been assigned to each of the clusters, begins an iterative process to calculate the final centroids of these clusters. There are studies that propose a classification of air masses through a nonhierarchical analysis [19], [3].
Each cluster has been related with values of aerosol optical depth at 440 nm, because it is a standard wavelength in aerosol studies, and Ångström exponent α retrieved for the 440-870 nm spectral range [20].

4 RESULTS AND DISCUSSION

Once this method was implemented, the results obtained were evaluated. The cluster analysis resulted in five clusters of trajectories. The dendrogram obtained from the hierarchical analysis helped us to determine the proper number of clusters (Fig. 3). The dendrogram suggested to consider five clusters, since a larger number would result in non significantly different cluster with low distance values between them. Once this number is known, it is possible to calculate the centroids of these clusters and to classify all trajectories. The centroids of this classification are plotted in Fig. 4.

Fig. 5 shows the trajectories for each cluster and its centroid. These maps show that each cluster groups trajectories with similar length and path. Trajectories corresponding to cluster 1 come from the Atlantic Ocean and have the largest part of its path over the ocean. The trajectories of cluster 2 travel close to the Iberian Peninsula during the five days. Cluster 3 consists of trajectories coming from the northern regions, cluster 5 of trajectories that travel over the European continent, and cluster 4 groups trajectories coming from North Africa.

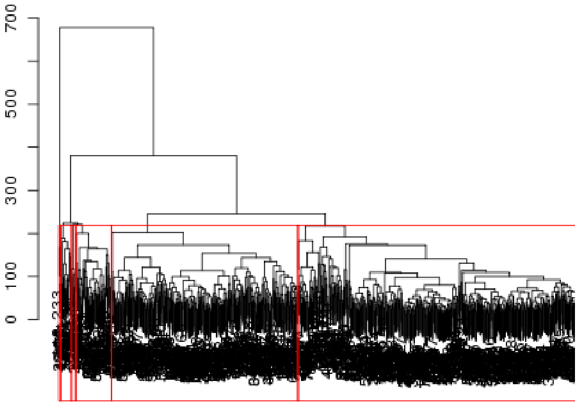

Fig. 3. Dendrogram corresponding to the hierarchical clustering and selected clusters.

The number of trajectories included in each cluster are summarized in Table 2.

Table 2. Number of trajectories corresponding to each cluster and season.

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
Winter	154	114	14	0	12
Spring	117	90	2	2	1
Summer	54	90	10	2	8
Autumn	63	75	13	11	14

At Cáceres, Atlantic and near air masses are clearly predominant (clusters 1 and 2). The most frequent clusters are 3 and 5, which correspond to trajectories coming from Northern and Eastern Europe, respectively. However, less common are those associated with cluster 4, which are trajectories with origin in North Africa.

Looking at the frequency of air mass trajectories by seasons, we find that air masses from the Atlantic (cluster 1) are more frequent during the winter and spring. Some of these trajectories can be related to maritime polar air masses whose origin is the North Atlantic Ocean and are common in winter. On the other hand, some of the trajectories of this cluster can be related to the maritime air masses called subtropical, which are more common on the Iberian Peninsula in the summer months. Trajectories from inland areas (cluster 2) are more frequent during the winter months, although it is noted that the frequency for the other three seasons is similar. The trajectories of clusters 3 and 5, from the north and east of Europe, are more frequent during winter and autumn, followed by the summer. The trajectories from North Africa (cluster 4) predominate in autumn, and the frequency is lower during the rest of the year, including winter, when no case was detected.

Fig.4. Centroids of the different clusters.

Once the air masses are classified into different groups, our goal is to relate each cluster of trajectories with some aerosol properties: optical depth, τ, and Ångström exponent, α.

For this purpose, τ values at 440 nm have been used and the α exponent was calculated using measurements of channels between 440 nm and 870 nm.

Subsequently, scatterplots of τ versus α with the values of these parameters closer to the time when the backward trajectory is calculated, 12 GMT have been represented.for each cluster separately, and for

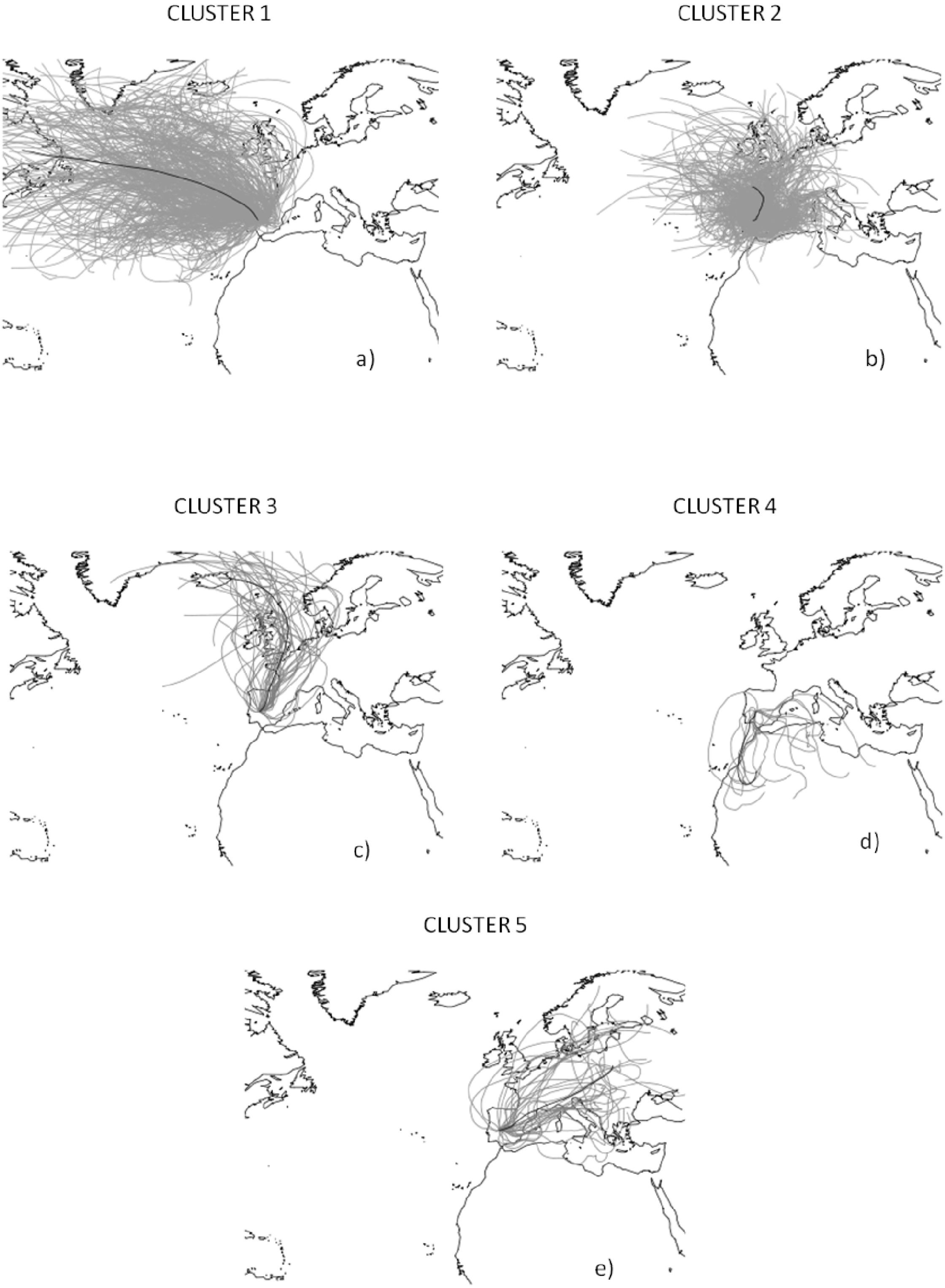

Fig. 5. Maps of 120 h back trajectories classified into each cluster.

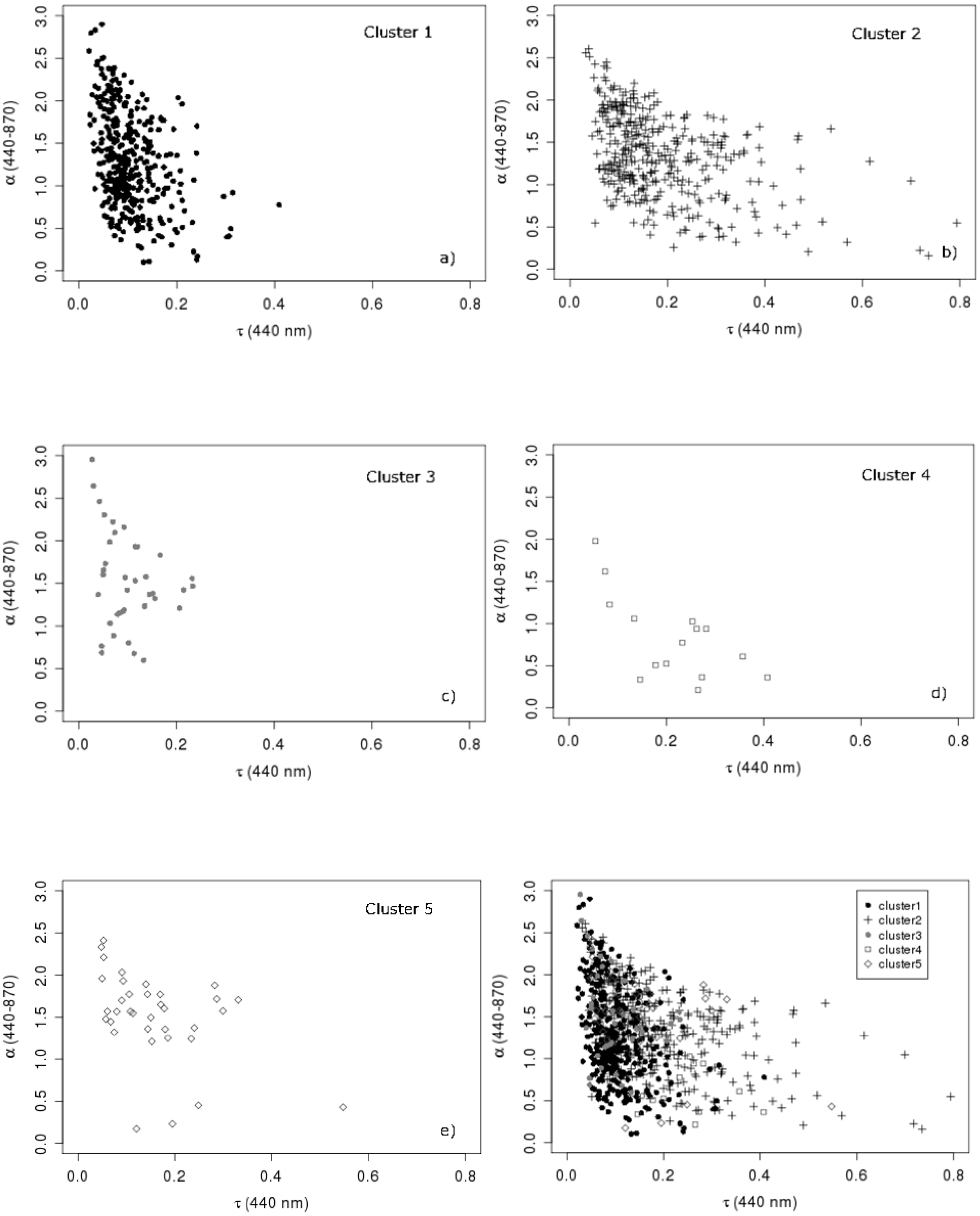

Fig. 6. Scatterplots of aerosol optical depth (440nm) vs Ångström exponent α for the five clusters, and for the whole dataset.

the whole dataset (Fig. 6). This figure shows that clusters 1 and 3 generally have lower aerosol optical depth values than the other clusters. The highest aerosol optical depth values are found in cases corresponding to clusters 2, 4 and 5, because they include trajectories coming from North Africa (cluster 4) and other ones that remain over the continental Europe (clusters 2 and 5), which have higher aerosol loading than trajectories coming from the ocean, which are cleaner.

As already mentioned, cluster 2 consists of trajectories that are circulating over inland areas close to Cáceres station during the five days used to calculate back-trajectories. As shown in Fig. 6, aerosol optical depth values of this cluster are high, between 0 and 0.8, although most cases are below 0.3 (median value=0.152). Additionally, Ångström exponent α values are moderate to high (median value=1.346) that is related to small continental particles or from fuel combustion. Similar values are obtained for cluster 5, because their trajectories are also influenced by continental pollution. In this case, Ångström exponent α values (median value=1.569) takes greater values than in cluster 2, indicating a smaller particle size.

Cluster 4 is also related to high aerosol optical depth values (median value=0.117), and low Ångström exponent α values (median value=0.774), that are typical characteristics of aerosols coming from North Africa [21], [22]. In the case of cluster 3, that include trajectories of northern Europe, the air masses are cleaner, with low aerosol optical depth values (median value=0.093) and Ångström exponent α values intermediate between values in the clusters 2 and 5. The cluster 1 also shows low values of aerosol optical (under 0.1), indicating that air masses coming from the Atlantic Ocean, due to its maritime character, are very clean. Ångström exponent α also has low median value (close to 1.2, although it can take values between 0.4 and 1.7 approximately), characteristic of larger size of sea salt particles.

In summary, there are three distinct sets of trajectories. On one side are the clusters 1 and 3, which include cases corresponding to trajectories from the Atlantic Ocean and northern Europe, with low turbidity. The second group, clusters 2 and 5, correspond to continental aerosols, with greater turbidity than in the previous group and finally, episodes of Saharan dust, cluster 4, which have a high turbidity and very low Ångström exponent α values. Each of these groups may be associated with air masses arriving at the Iberian Peninsula, as described above. For example, the Atlantic type may be associated with the mT (maritime tropical) and mP (maritime polar) air masses. The continental type is related to the c (continental) and Me (Mediterranean) air masses, and the Saharan episodes are associated with the cT (continental tropical) air masses.

5 CONCLUSIONS

Daily 500 m above sea level (ASL) 5-day back-trajectories ending in Cáceres (Spain) over 5 years (2005 - 2010) were computed using hybrid single particle Lagrangian integrated trajectory model (HYSPLIT_4). These trajectories of air masses have been classified by an improved cluster analysis which combines hierarchical and non-hierarchical methods, taking profit from the advantages of each method. The resulting clusters of trajectories have been related with the aerosol optical properties, such as aerosol optical depth and Ångström exponent α, obtained from measurements performed with CIMEL photometers in Cáceres station.

Five clusters have been obtained and they can be regrouped in three types: on one side, the cases belonging to trajectories coming from the Atlantic Ocean and northern Europe, with low turbidity; on the other side, continental aerosol cases, with a greater turbidity than the previous type; and, finally, Saharan dust events, which have a high turbidity and very low Ångström exponent α values. Each of these groups may be associated with specific air masses reaching the Iberian Peninsula. For example, the atlantic type may be associated with mT (maritime tropical) and mP air masses (maritime polar). The continental type is related to cT air masses (continental tropical) and M (Mediterranean). And dust episodes are associated with the cT (continental tropical) air masses.

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