Hindawi Publishing Corporation
Advances in Meteorology
Volume 2016, Article ID 8026018, 10 pages
http://dx.doi.org/10.1155/2016/8026018

Research Article

Heat-Wave Events in Spain: Air Mass Analysis and Impacts on ^{7}Be Concentrations

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Received 7 March 2016; Accepted 23 May 2016

Academic Editor: Mastura Mahmud

The present paper describes and characterizes the air mass circulation during the heat-wave events registered during the period 2005–2014 over Spain, paying special attention to the role of the Saharan circulations. Backward trajectories at 500, 1500, and 3000 m in Seville (south), Madrid (centre), and Bilbao (north) during the thirteen heat-wave events identified are analysed. Finally, the impact of the heat-wave events and of each advection pattern on ^{7}Be activity concentrations is also analysed. The heat-wave events are characterized roughly by western, southern, and nearby advections, with a higher frequency of the first two types. The analysis shows an increase of African air masses with height, presenting a different spatial impact over Spain, with a decreasing occurrence and a decrease in the simultaneous occurrence percentage from south to north. On average, the ^{7}Be activity concentrations during these events show an increase of concentrations in central (21%) and southern (18%) areas and a decrease in northern (13%) Spain. This increase is not associated with Saharan air masses but instead with the arrival of distant westerly air masses.

1. Introduction

Climate change is recognized as a global key challenge for the 21st century. According to the IPCC (Intergovernmental Panel for Climate Change), the global mean surface temperature is projected to increase of about 0.3 to 4.8°C until 2100 in relation to the 1986–2005 baseline [1]. A general increasing trend in temperature has already been observed globally, with an increase of about 0.8°C since 1880 [2]. Associated with this tendency, it is currently recognized that extreme weather events, including in particular threshold-exceeding heat extremes but also cold spells, might increase in number, intensity, and duration under climate change [1, 3, 4].

Meteorologically, a "heat-wave" is defined as a prolonged hot weather event with respect to climatological means of the area at that time of year; in particular, the most used criterion is that a heat-wave exists when the maximum daily temperature exceeds the 95th percentile of the series of maximum daily temperatures for the summer months [5, 6]. Modelling studies indicate a 5 to 10% increased probability that more frequent and severe heat-waves will occur in a 40-year timeframe [7].

This meteorological scenario is dangerous not just because of its absolute temperature values but because of its duration, causing an immediate impact on human beings. It has been associated with increasing mortality [8] and morbidity [9], as well as very negative effects on socioeconomic activities, demography, acclimatisation to warmer temperatures [10], and the natural environment (e.g., [11, 12]).

The interest in this topic greatly increased after the 2003 European heat-wave that caused the hottest summer on record in Europe since 1540 [13], reaching the warmest temperatures in the historical temperature observations in many European countries from northern Spain to the Czech

Table 1: Year, starting and ending date, and maximum temperature for each heat-wave event identified in the Iberian Peninsula from 2005 to 2014 (source: State Meteorology Agency (AEMET), [25]).

Year	Start	End	Maximum temperature (°C)
2005	05/08/2005	08/08/2005	38.9
2005	14/07/2005	17/07/2005	36.8
2006	04/09/2006	06/09/2006	36.5
2006	24/07/2006	26/07/2006	35.3
2007	28/07/2007	31/07/2007	39.4
2008	03/08/2008	05/08/2008	36.9
2009	16/08/2009	20/08/2009	35.9
2011	19/08/2011	21/08/2011	37.1
2011	25/06/2011	27/06/2011	37.8
2012	17/08/2012	23/08/2012	36.2
2012	08/08/2012	11/08/2012	39.5
2012	24/06/2012	28/06/2012	38.3
2013	05/07/2013	09/07/2013	37.7

Republic and from Germany to Italy. Looking at more recent years, last July 2015 was the warmest July on record for Spain, Italy, Switzerland, and Austria (https://www.climate.gov/).

The intensity, origin, and impact of this kind of weather events in many countries across Europe have been analysed in several works (e.g., [14, 15]). The frequent synoptic pattern associated with heat-waves in Europe is the omega blocking, typically characterized by a low-high-low pattern arranged in the west-east direction, with the consequent blocking of high pressure systems over the same area for a long time period (days or even weeks), limiting the arrival of northern low pressure systems over Europe. In western Mediterranean, this stable synoptic configuration favours the displacement of high pressure systems developed in northern Africa, due to the intense heating towards high latitudes, and in particular towards the western Mediterranean, with the corresponding arrival of Saharan air masses in the upper atmospheric levels [16, 17].

The particular topography of Spain causes large spatial variations of the intensity of heat-waves both in terms of maximum temperatures and in terms of duration [18, 19] (Table 1). This spatial variability might also be linked to the impact of different meteorological patterns, and hence different air mass patterns. In this framework, the aim of this study is to characterize the air mass behaviour and to determine the occurrence and the spatial variability of Saharan air masses over Spain during heat-wave events.

In addition, and starting from the results obtained through this analysis, the general impact of the heat-wave events and of each air mass type identified during these periods on the ^{7}Be activity concentrations is discussed, paying special attention to its possible role as a tracer of Saharan intrusions over Spain. ^{7}Be is a cosmogenic radionuclide produced by nuclear spallation reactions in the stratosphere-upper troposphere [20]. After its production, ^{7}Be rapidly attaches to fine aerosol particles [21], with which it shares the removal mechanism (deposition). Previous studies (e.g., [22, 23]) have observed high ^{7}Be concentrations in southern Spain connected with the arrival of air masses from Africa but also from the Atlantic and from the north. In this sense, this study aims to complement such previous observations and to extend the analysis to central and northern regions. For this purpose the ^{7}Be activity concentrations stored in the Radioactivity Environmental Monitoring database (REMdb) during the heat-wave events in three reference sites (Seville, Madrid, and Bilbao) were analysed.

The following research issues are addressed in this work:

(i) Analysis of the latitudinal impact on the air mass behaviour during heat-wave events over Spain.

(ii) Relationship between heat-waves and Saharan air masses over Spain.

(iii) Impact of heat-waves and air masses associated on ^{7}Be activity concentration in Spain.

(iv) The use of ^{7}Be as tracer of Saharan air masses.

2. Materials and Methods

2.1. Sampling Sites. Figure 1 illustrates the location of the three Spanish sampling sites considered in this study, Seville (8 m a.s.l), in the south, Madrid (715 m a.s.l), in the centre, and Bilbao (380 m a.s.l), in the north. The complex topographic distribution of Spain produces a wide climatic variability with complicated wind patterns, different rainfall regimes, gradients of temperature, and so forth [24]. Due to their locations and their different altitudes, the three stations are affected by different meteorological conditions, being considerably heterogeneous to provide an adequate degree of representativeness of the results obtained in this work.

2.2. Air Mass Analysis. Hourly backward kinematic 3D trajectories at Seville, Madrid, and Bilbao were calculated during the 13 heat-wave events identified by the State Meteorological Agency in the period of 2005–2014 [25]. The trajectories were calculated with a run time of 120 h at three different initial heights (500 m, 1500 m, and 3000 m above ground level) with the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model [26, 27]. The choice of the three heights was based on two objectives: (1) to simulate the typical height at which Saharan air masses are observed over the Iberian Peninsula, between 1500 m and 3000 m [28, 29], and (2) to simulate the air mass circulation below and above the ABL (Atmospheric Boundary Layer) height. GDAS-NCEP meteorological data of the NOAA/ARL (Air Resources Laboratory), with a temporal resolution of three hours, spatial resolution of 1° × 1° (in latitude and longitude), and 23 vertical levels (from 1000 to 20 hPa), were used as meteorological inputs.

Backward trajectories with similar horizontal and vertical path were grouped together using the cluster methodology implemented in the HYSPLIT model, based on variations of the total spatial variance (TSV) between the different clusters formed and the spatial variance (SPVAR) between each cluster component [26]. This methodology minimizes

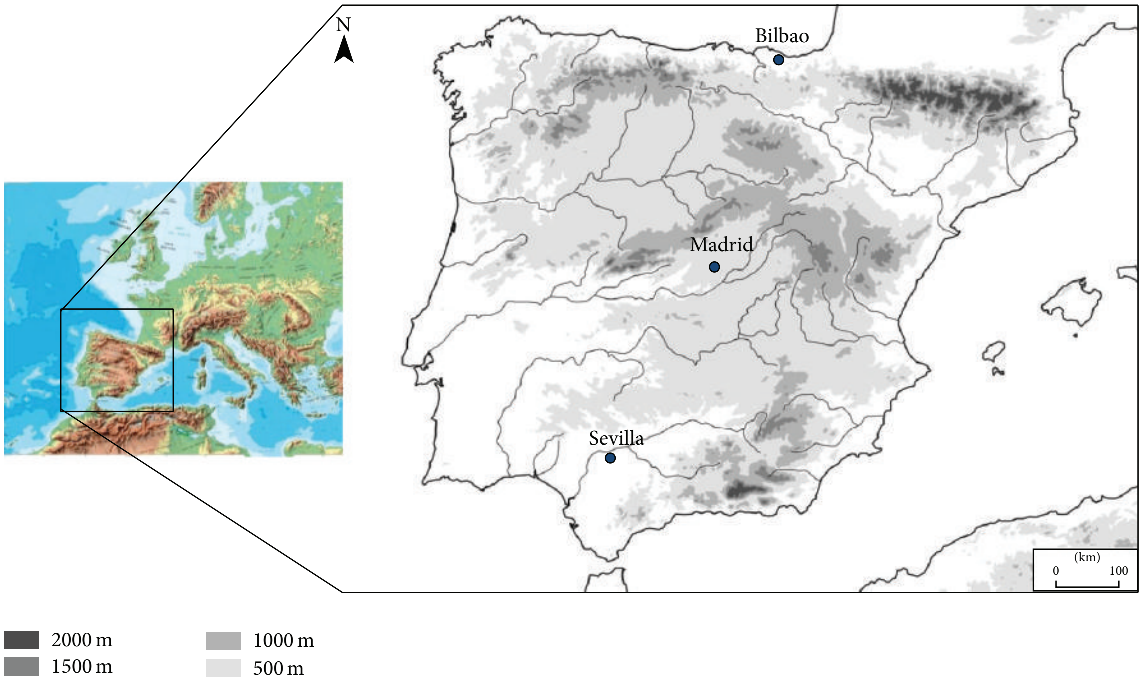


Figure 1: Map with the location of the stations and orographic characteristics of the Iberian Peninsula.

the differences among individual elements belonging to the same cluster and maximizes the differences among members of different clusters. For other details about the methodology applied to identify the optimal number of clusters, based on associating the optimal number with the first variation of the TSV above 40%, the reader is referred to Stunder 1996 [30].

2.3. ^{7}Be Database. ^{7}Be activity concentrations data recorded in the three selected Spanish stations (Figure 1) during the set of heat-waves were extracted from the sparse Radioactivity Environmental Monitoring database (REMdb) (https://rem.jrc.ec.europa.eu/RemWeb/Activities.aspx?id=REMdb). At all the sampling sites, ^{7}Be was measured by means of γ spectrometry analysis carried on airborne particulate matter filters sampled through high-volume samplers. Further information on the procedure to collect aerosol samples, with a roughly weekly temporal resolution (time ranging from 6 to 8 days), is available in Hernández-Ceballos et al. [31]. The ^{7}Be database stored in the REMdb is public until 2006, and the access to the data corresponding to the 2007–2011 period can be granted only after explicit request.

Here we have considered only ^{7}Be samples collected during or immediately after one heat-wave event, with a maximum delay of 2 days. Applying this criterion, all heat-wave events were associated with one value of ^{7}Be activity concentration at each sampling site.

2.4. Heat-Wave Events in Spain. The State Meteorological Agency (AEMET) has recently defined and applied the following criterion to identify heat-wave periods in Spain during the period of 1975–2014: "A Heat-wave event in Spain exists when at least 10% of the monitoring stations recorded maximum temperatures higher than the 95th percentile of daily maximum temperatures registered in July and August during the period of 1971–2000 for at least three consecutive days." Applying this criterion, the agency identified 13 heat-wave events in Spain during 2005–2014 [25] (Table 1). These 13 events presented different duration (Figure 2) and spatial extent and constitute the basis of the present analysis.

Figure 2: Yearly number (number of columns in each year) and duration (y-axis) of identified heat-wave events in Spain in the period of 2005–2014 (source: State Meteorology Agency (AEMET), [25]).

3. Results

3.1. Air Mass Clusters during Heat-Wave Events. Figure 3 shows the mean trajectories for each sampling site and at each height during the 13 heat-wave events analysed (total of 1272 backward trajectories for each site and height). Taking into account the uncertainties associated with trajectories (typically of the order of 20% of the travel distance [32]), this result clearly indicated that, on average, Atlantic advections dominated the heat-wave events at lower levels (500 m) in

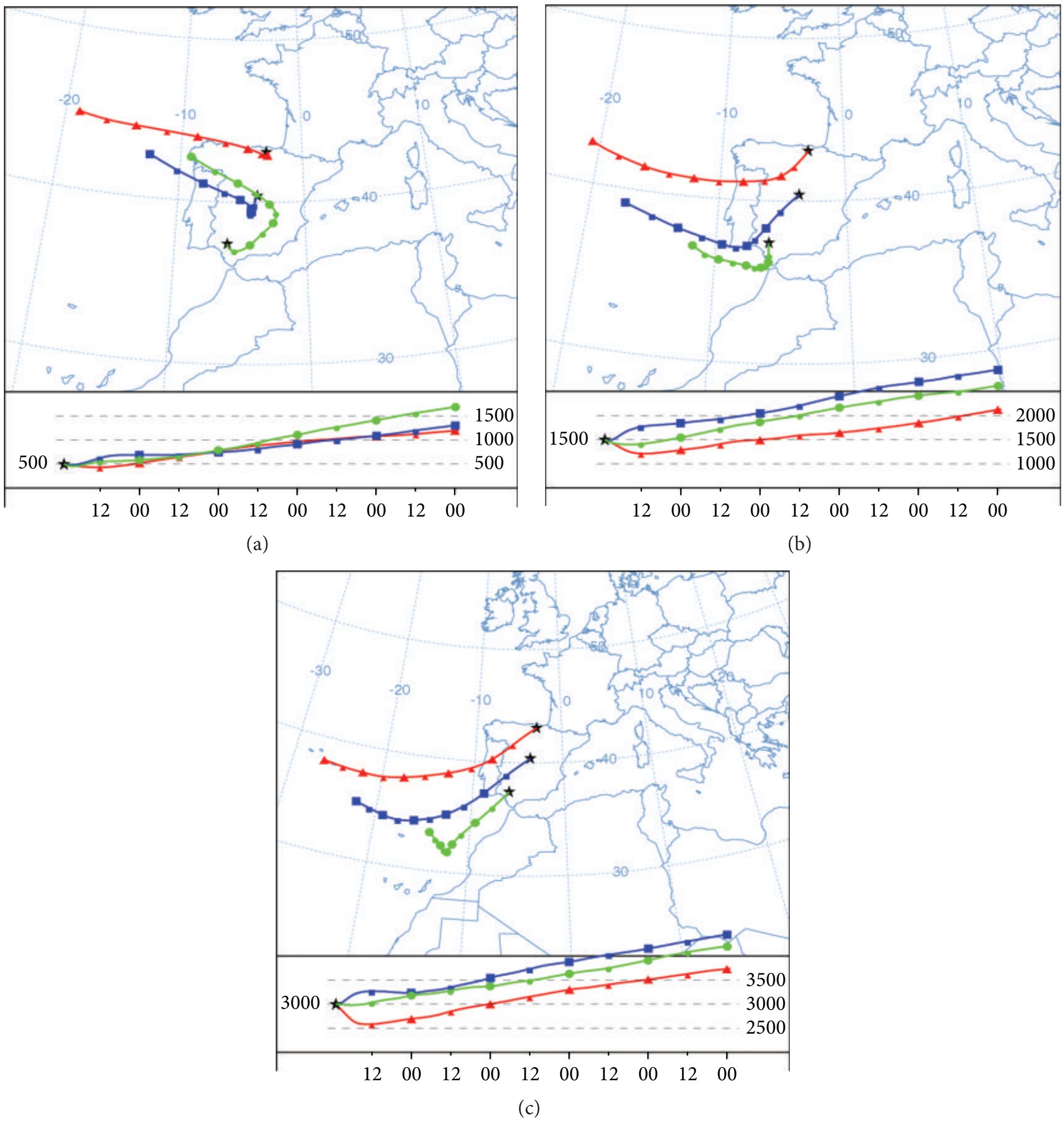


Figure 3: Mean trajectory (centroid) of the backward trajectories at Seville (green), Madrid (blue), and Bilbao (red) at (a) 500 m, (b) 1500 m, and (c) 3000 m during the whole set of identified heat-wave events.

northern and central Spain (Bilbao and Madrid), while, on the contrary, the southern site (Seville) was influenced by a continental circulation from the north to the south. At higher altitudes, advections from the Atlantic Ocean dominated at all the sites, with an increasing influence of southern circulation with the height especially in Madrid and Seville. In fact, mean trajectories showed a clockwise movement from west to east and from lower to higher latitudes with increasing height, with a pathway much closer to northern Africa.

After showing these mean advection patterns, Figure 4 displays the centroids of each cluster identified at each height and at each reference site, applying the methodology explained in Section 2.2. The number of identified clusters at each site presented a wide variability, with an increasing trend with increasing latitude. In fact, while six and four clusters were identified at 500 m and 3000 m, respectively, in Seville, seven and eight clusters were instead identified at 500 m and 3000 m in Bilbao. This latitudinal impact on the number of clusters was possibly due to the influence of the topographic characteristics and to the spatial variability of the meteorological conditions affecting Spain during heat-wave events.

Taking as reference the origin, pathway, and the distance travelled of each cluster, it is possible to define three main sets of common air mass patterns for the three sites, that is, from the west, south (southwest and Saharan), and nearby (local), with the first two as the most frequent ones. This combination of different flows was in agreement with previous results of Hernández-Ceballos et al. [33], analysing the vertical behaviour of air masses in south-western Iberian Peninsula, of Saavedra et al. [34], investigating the air masses associated with ozone peaks in the north-western area, and of

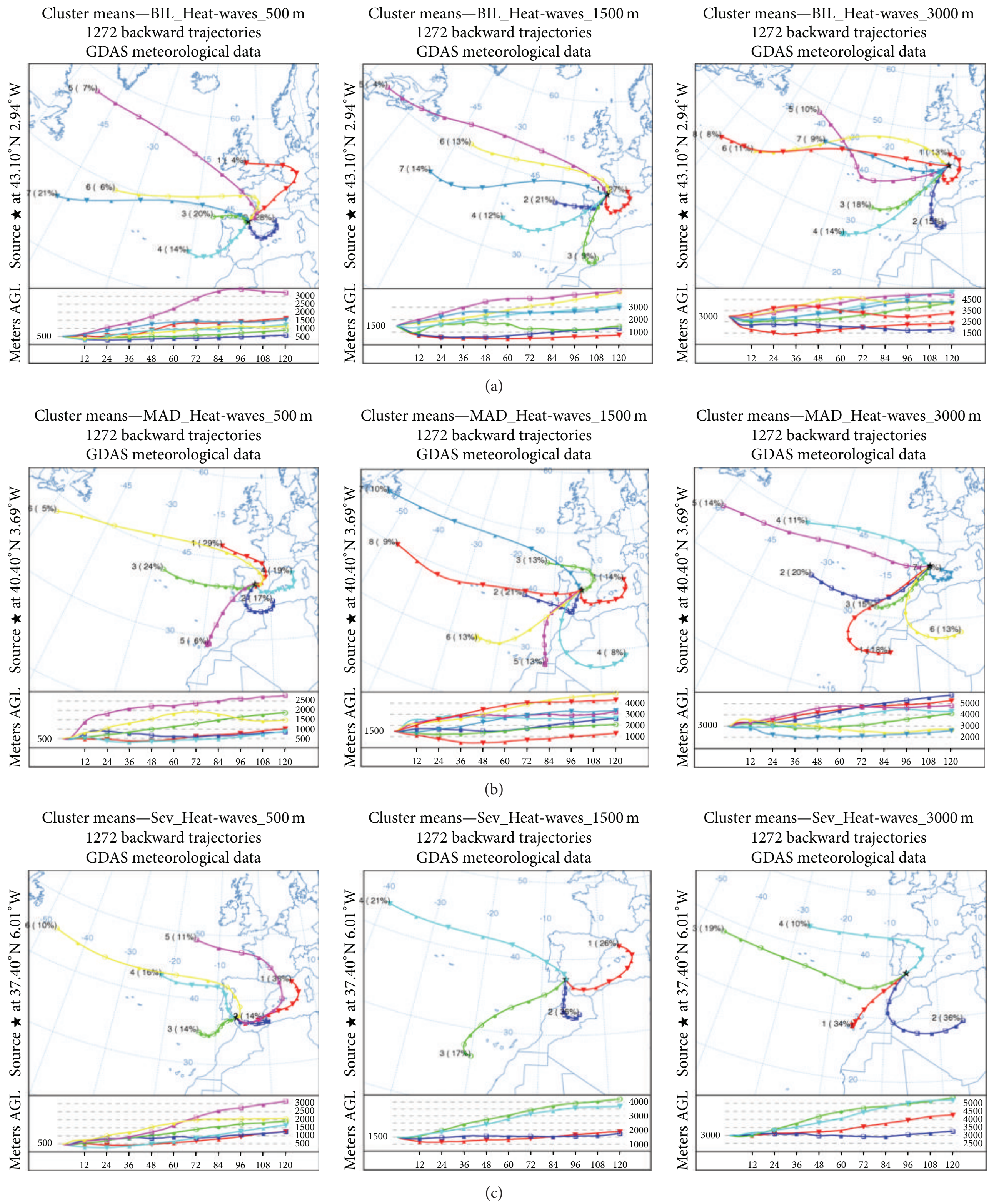


FIGURE 4: Centroids of the backward trajectories (vertical profile and horizontal pathways) at (a) Seville, (b) Madrid, and (c) Bilbao at 500 m, 1500 m, and 3000 m during the whole set of heat-wave events.

Pérez et al. [35], characterizing 24 h backward air trajectories arriving at a site located in the centre of the northern plateau.

The results obtained in the present work showed a wide predominance of westerly advections at each site, associated with the elevated influence of the zonal circulation from the west, typical of mid-latitude Northern Hemisphere sites. These circulations were originated in the Atlantic Ocean, with a main maritime pathway until arrival to each reference site, and they presented a frequency tending to increase with the altitude, due to the reduced influence of topographical elements. A similar increase in the frequency with height was also registered by circulations arriving from the south, comprehending both maritime circulations from the southwest as well as North African circulations. Regarding North African circulations, they were mainly observed at higher altitudes (1500 m and 3000 m), in agreement with the typical height at which Saharan air masses are observed over the Iberian Peninsula. Finally, a higher variability among the three sites was registered for the clusters originating close to the Iberian Peninsula, representative of nearby circulations with prevailing advections from the east and overpassing the Mediterranean Sea.

These results showed that the heat-wave events in Spain were characterized by a large variability of air mass circulations, with a general and large impact at lower levels of Atlantic air masses and an increase of African air masses with height in all the regions. This last behaviour showed the need for a better characterization of the arrival of Saharan air masses in connection with heat-wave events in Spain.

3.2. Impact of Saharan Air Masses over Spain during Heat-Waves. This section analyses further the behaviour of the Saharan air masses during the heat-waves. In fact, it is recognized that this particular advection largely affects the warmest periods of Spain (e.g., [36]). For this purpose, and considering again the error percentage associated with the computation of backward trajectories, here, for the general analysis, we considered only those clusters clearly originated over the Sahara desert and with a main previous continental pathway (Figure 3). For this reason, cluster 2 (9%) and cluster 3 (15%) in Bilbao, cluster 4 (8%) and 6 (13%) in Madrid, and cluster 2 (36%) and cluster 2 (36%) in Seville were selected at 1500 and 3000 m, respectively. These percentiles were in agreement with previous analysis carried out in Spain in which the impact of Saharan air masses over different areas was reported: for instance, it was quantified of 22% in the southwest [33], 13% in northeastern (predominantly during summer) [29], and 27% in the central area [37].

The time required for Saharan air masses to reach Spain depends on (1) the source region [17] and (2) the receptor site (Figure 1). The average time required for this type of air masses to reach each sampling site considered in our analysis can be estimated from Figure 4. Taking as reference the results obtained at the 3000 m height and the time when the trajectory was located over northern Africa, the average time taken for air masses to reach Spain from the Sahara varies on average between 48 and 120 hours for Seville and 60 and 120 hours for Madrid and Bilbao.

Based on this selection, the occurrence of this kind of advection presented latitudinal as well as height variability. In fact, this cluster was well observed only in upper layers (1500 m and 3000 m) at the three reference sites and it showed its maximum occurrence in Seville at 3000 m, while the minimum occurrence was instead observed in Madrid at 1500 m.

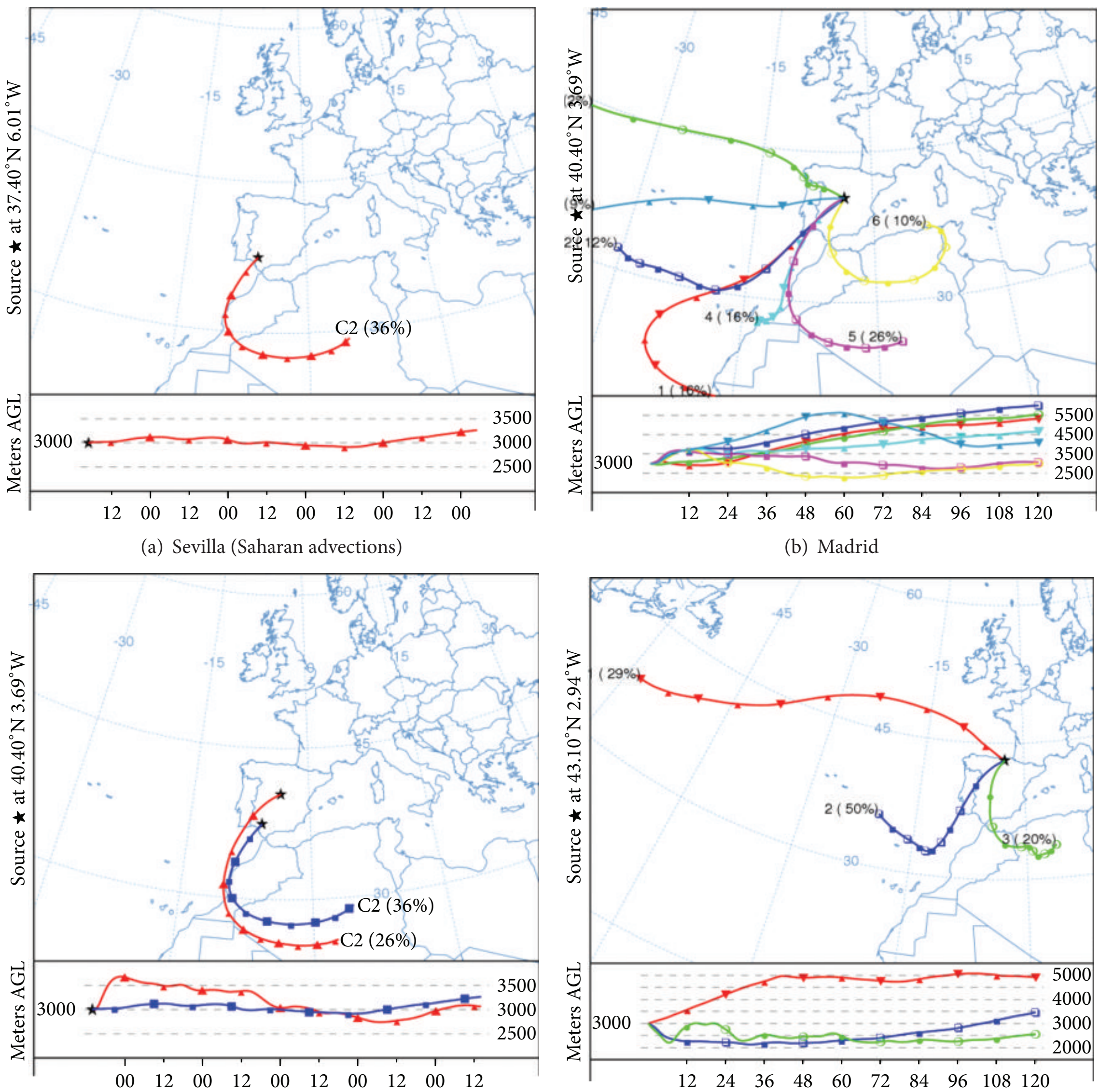
This general pattern indicates that this warm advection did not have the same spatial impact throughout Spain during the analysed heat-wave events. To investigate its spatial variation during these events we applied a selection procedure in order to extract only those periods with a simultaneous influence of Saharan air masses at the three sites. To this aim we applied the following methodology: firstly, we identified the hours in which Saharan air masses simultaneously impacted Seville and Madrid calculating the clustered back trajectories arriving in Madrid in the same periods that Sahara was observed in Seville. Secondly, from the new clusters obtained in Madrid, we selected only those strictly representing Saharan circulations, defining in this way a new set of days with an influence of Saharan circulations over both Seville and Madrid. Finally, we calculated and clustered the trajectories reaching Bilbao during this new set of days, of which only the clusters representing Saharan air masses were selected. The application of this recursive methodology is therefore able to identify periods with a strong influence of Saharan air masses at all locations.

Trajectories belonging to cluster 2 (36%) at 3000 m in Seville were firstly selected: this choice was based on the fact that (1) the highest percentages of Saharan air masses was observed at 3000 m and (2) Seville is the closest site to the source region, and therefore the most adequate to identify the arrival of Saharan air masses over Spain in the present study. Cluster analysis was applied to the set of backward trajectories calculated during the hours in which Saharan air masses were simultaneously observed in Madrid (Figure 5(b)) and in Seville (Figure 5(a)) at 3000 m.

The results illustrated how the arrival of Saharan air masses over southern areas was associated with a combination of Atlantic flows and south circulations with maritime and continental pathways over central areas of Iberian Peninsula. The arrival of southerly air masses dominated in Madrid, with a clear identification of the cluster originated in the Sahara desert (cluster 5 with 26%), evidently displaced along northern Africa.

On the basis of the previous analysis, after selecting the cluster arriving in Madrid from the Sahara (cluster 5 in Figure 5(b)) at 3000 m, the cluster analysis was applied to the set of backward trajectories calculated during the same hours in Bilbao at 3000 m. Figure 5(d) shows the cluster results for Bilbao and for Seville (cluster 2) and Madrid (cluster 5) (Figure 5(c)).

In this case, the results of the cluster analysis in Bilbao presented three clear air mass patterns, with a combination of westerly, south-westerly and southerly circulations, clearly indicating the spatial variability of air masses over northern



(a) Sevilla (Saharan advections)

(b) Madrid

(c) Sevilla and Madrid (Saharan advections)

(d) Bilbao

Figure 5: (a) Saharan cluster mean at Seville and (b) the corresponding cluster means (vertical profile and horizontal pathways) at Madrid at 3000 m during the same period. (c) Saharan cluster means at Seville and Madrid and (d) the corresponding cluster means of the backward trajectories (vertical profile and horizontal pathways) at Bilbao at 3000 m during the same period.

Spain under the arrival of Saharan air masses over southern and central areas. In this case, however, a cluster with a clear origin over the Sahara desert was easily identified (cluster 4 with 20%).

These results indicated that, during the heat-wave events, the simultaneous impact of Saharan air masses over the three sites was observed only during 20% of the hours. Moreover, the simultaneous occurrence percentage of Saharan air masses decreased with increasing latitude (36% in Seville, 26% in Seville and Madrid, and 20% in Seville, Madrid, and Bilbao), which confirmed the different spatial impact of these air masses over Spain during heat-wave events, with a latitudinal decreasing gradient from south to north. This spatial variability in the arrival of Saharan flows might be mainly related to a combination of factors, such as the large geographical distance between the south and north (almost 1000 km) and the topography of the Iberian Peninsula, that cause a different impact of the synoptic configurations associated with Saharan advections over the territory.

3.3. ^{7}Be Activity Concentrations during Heat-Wave Events.

As we previously commented, the Sahara desert is a source of hot air masses. Due to the intensive turbulent circulations created by its thermal capacity, the particles can ascend to the upper layers of the atmosphere where the sprays of ^{7}Be encountered there can adhere to them. Once attached, fine particles can travel over long distances and then settle to the surface due to deposition processes. Previous studies have proven that the production of ^{7}Be is primarily controlled by latitude [38, 39].

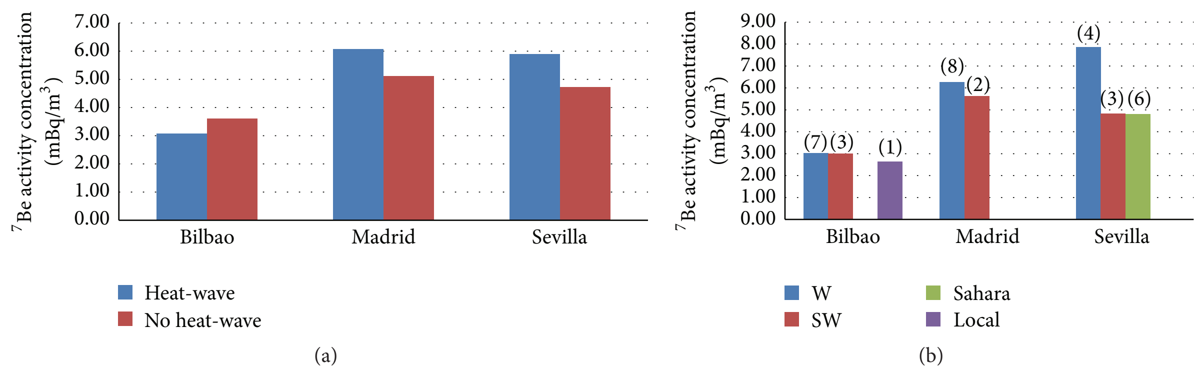


FIGURE 6: Comparison of ^{7}Be activity concentration in each sampling site observed during (a) the whole set of heat-wave events and the remaining ^{7}Be values registered during the same month and (b) the contribution of each air mass circulation considering the "pure" heat-waves events. In brackets is the number of pure heat-wave events associated with each ^{7}Be activity concentrations. W: westerly and SW: south-westerly.

In this line, Hernández-Ceballos et al., 2015 [31], obtained one of the highest European mean values of ^{7}Be in La Laguna (Canary Island), which is located in similar latitude of Sahara desert. Following this reasoning, ^{7}Be activity concentrations in Sahara desert would have to be higher than in the three sampling points taken as reference in this work, and, hence, it would be considered as a source of ^{7}Be for Spain.

This process suggests that the arrival of Saharan air masses might be linked with an increase of ^{7}Be activity concentrations, and, hence, ^{7}Be could be used as tracer of this type of air masses. With the aim to analyse this potential relationship, the ^{7}Be surface concentrations measured at the three sites during the heat-wave events and associated with each advection pattern were studied.

Figure 6 compares the mean ^{7}Be activity concentrations calculated at each site during the heat-wave events with that calculated during the same months excluding these events. This figure indicates that, on average, the occurrence of heat-wave events had a positive impact on ^{7}Be concentrations in central and southern areas and a negative one in the northern area. This difference can be associated with a larger air mass variability registered in Bilbao rather than in Madrid and Seville (Figure 4).

To better understand the impact of each type of circulation identified during the heat-waves events on ^{7}Be activity concentrations, we have selected "pure" heat-waves events, defined as those in which the number of hourly trajectories associated with each pattern was larger than 55%. Applying this methodology, Figure 6(b) shows the ^{7}Be activity concentrations registered during pure heat-wave events associated with westerly (W), south-westerly (SW), Sahara, and local advections. The total number of pure heat-waves in Seville was 4 for W, 3 for SW, and 6 for Saharan and in Madrid was 8 for W and 2 for SW, while in Bilbao was 7 for W, 3 for SW, and 1 for local.

Figure 6(b) displays that, on average, westerly and south-westerly circulations were associated with the highest ^{7}Be activity concentrations in all the sites. In fact, the concentrations observed during Saharan intrusions (pure heat-waves associated with Sahara advections were identified only in Seville) were lower than those observed during other advections. In this sense, this result was in agreement with the reduced impact of Saharan air masses over central and northern Spain.

This result suggested that during the heat-wave events an increase on ^{7}Be activity concentrations was registered in central and southern areas of Spain. However, this increase cannot be associated with the arrival of Saharan air masses, since it seems mostly connected with westerly advections. In this sense, the high percentage of Atlantic advections observed during these periods is in agreement with the previous analysis of ^{7}Be peaks in southern areas of Spain [23] that related the highest ^{7}Be concentrations to the arrival of Atlantic air masses due to the combined effect of the omega block configuration extending over the northern Atlantic Ocean (close to Greenland) and of the presence of the Azores high pressure system in the west of Spain.

4. Conclusions

The analysis of the backward trajectories at three sites (Seville, Madrid, and Bilbao) in Spain during the set of heat-wave events during the period 2005–2014 displayed that this meteorological scenario was characterized by a large variability of air mass circulations, with air masses coming mainly from the west, south, and nearby areas. The western circulations presented the highest frequency in all of the three sites, registering also a large occurrence of Saharan air masses in all of the regions. The impact of Saharan air masses showed an increasing frequency with height and a decreasing occurrence from south to north. This behaviour is associated with the geographical distance between southern and northern stations (1000 km) as well as with the topography of the Iberian Peninsula, favouring the establishment of different meteorological conditions under heat-wave events along the territory.

^{7}Be activity concentrations recorded during the heat-wave events displayed an increase in Seville (south) and Madrid (centre). This increase was mainly associated with the arrival of westerly advections and to a lesser extent with the arrival of Saharan air masses. On the basis of these results, ^{7}Be cannot be considered as an unambiguous tracer of Saharan advections over Spain.

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

The authors would like to thank all the Spanish National Competent Authorities (Nuclear Safety Regulator, CSN) for having sent the data of each of the countries to REMdb. They acknowledge NOAA/ESRL Physical Sciences Division, Boulder, Colorado, for providing the HYSPLIT trajectory model and the NCEP/NCAR reanalysis data used in this study.

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