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Saharan dust intrusions in Spain: Health impacts and associated synoptic conditions

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ABSTRACT

Background: A lot of papers have been published about the impact on mortality of Sahara dust intrusions in individual cities. However, there is a lack of studies that analyse the impact on a country and scarcer if in addition the analysis takes into account the meteorological conditions that favour these intrusions.

Objectives: The main aim is to examine the effect of Saharan dust intrusions on daily mortality in different Spanish regions and to characterize the large-scale atmospheric circulation anomalies associated with such dust intrusions.

Methods: For determination of days with Saharan dust intrusions, we used information supplied by the Ministry of Agriculture, Food & Environment, it divides Spain into 9 main areas. In each of these regions, a representative province was selected. A time series analysis has been performed to analyse the relationship between daily mortality and PM_{10} levels in the period from 01.01.04 to 31.12.09, using Poisson regression and stratifying the analysis by the presence or absence of Saharan dust advections.

Results: The proportion of days on which there are Saharan dust intrusions rises to 30% of days. The synoptic pattern is characterised by an anticyclonic ridge extending from northern Africa to the Iberian Peninsula. Particulate matter (PM) on days with intrusions are associated with daily mortality, something that does not occur on days without intrusions, indicating that Saharan dust may be a risk factor for daily mortality. In other cases, what Saharan dust intrusions do is to change the PM-related mortality behaviour pattern, going from $PM_{2.5}$.

Conclusions: A study such as the one conducted here, in which meteorological analysis of synoptic situations which favour Saharan dust intrusions, is combined with the effect on health at a city level, would seem to be crucial when it comes to analysing the differentiated mortality pattern in situations of Saharan dust intrusions.

1. Introduction

1.1. Mechanisms of transport of the Sahara dust

The vast arid and semi-arid regions of Northern Africa represent the main sources of dust for the Earth's atmosphere (Prospero et al., 2002; Ginoux et al., 2012). It is now well established that airborne plumes of dust prevenient from the desert (Sahara) and semi-arid (Sahel) regions can be transported over long swathes, particularly the Atlantic Ocean (Prospero et al., 2002), as well as crossing the Mediterranean sea and affect the European continent (e.g. Moulin et al., 1997; Engelstaedter and Washington, 2007).

The transport of dust from North Africa occurs predominately over the Atlantic as a result of the powerful westward trade winds (Prospero et al., 2002), although characterised by an intense seasonal cycle (Engelstaedter et al., 2006). In recent decades several works have addressed the major mechanisms that can drive such transport towards higher latitudes, having found that these are frequently driven by more complex wind fields than in the case of the Atlantic transport and often include cyclonic activity inside and around the Mediterranean basin (Alpert and Ziv, 1989; Moulin et al., 1997). A number of preferential configurations favouring the transport of dust from North Africa towards the Iberian Peninsula are associated with location of low pressure systems close to the Canary Islands or off the coast of Portugal (Rodríguez et al., 2001).

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1.2. Why desert dust can affect health?

Not only does long-distance transport bring about a change in the respective atmospheric concentrations of the different sized particles and in the chemical composition of the particles present in the air (Pérez et al., 2008), but there is even evidence to show that desert dust itself transports biological matter harmful to health (Griffin et al., 2007). There are new papers that point that the agents involved in dust toxicity may differ from those of other PMs, raising further questions about mechanisms and implications. It has been hypothesized that the increase risk associated with Saharan dust exposure may be due in part to biological materials contained within the dust; transported Saharan dust may be an adequate medium for survival and proliferation of these microorganisms (Griffin et al., 2001; Griffin, 2007; McCarthy, 2001). The possibility that Saharan dust may contain toxic biological allergens of irritants is now supported by several studies (Garrison et al., 2006; Polymenakou et al., 2008). It is also possible that non-biologic compound in dust may generate adverse health effects or that local conditions change the toxicological properties of the dust. In that direction, recent research in Algeria has shown that desert dust may contain carcinogenic and mutagenic compounds (PAH and oxygenated organics such as phthalates) (Ladji et al., 2009).

Although only there is a little evidence of the different components of PM presents higher risks among them (Atkinson et al., 2015; Stanek et al., 2011). May be these two circumstances of change, i.e., in particulate matter (PM) concentrations and chemical composition, make for clearly differentiated morbidity-mortality patterns, which are observable on days with desert dust intrusions as compared to days without desert dust intrusions (Jiménez et al., 2010; Reyes et al., 2014).

1.3. Impact of desert dust on human health

The human health effects of dust storms range from respiratory disorders (including asthma, tracheitis, pneumonia, allergic rhinitis and silicosis), to cardiovascular disorders (including stroke), conjunctivitis, skin irritations, meningococcal meningitis, valley fever, diseases associated with toxic algal blooms, and mortality and injuries related to transport accidents (Goudie, 2014).

1.4. Researches in human health effects

Many studies have been conducted in different places around the world on the impact of desert dust on health (Crooks et al., 2016; Kanatani et al., 2016; Coulibaly et al., 2015; Diokhane et al., 2016; Abuduwailil et al., 2015; Merrifield et al., 2013; Taylor et al., 2013).

1.4.1. Impact on morbid-mortality in Europe

In the European setting, mention should be made of the study undertaken in 13 southern European cities (Stafoggia et al., 2016), including Madrid and Barcelona, which analysed the relationship between PM_{10} and hospital admissions and mortality on days with and without Saharan dust advections. The results obtained show that excess PM_{10}-related morbidity-mortality is similar for days with and without these advections.

In this line of inconclusive results regarding the effect of Sahara dust intrusion on mortality in Europe, is found the work Samoli et al. (2011a); conducted in Athens (Greece). In this study the PM effects were significantly higher during non-desert dust days cause of "that PM from traffic sources prevail on non-desert dust days, have more toxic effects than the ones originating from long-range transport, such as Sahara dust". Another paper conducted in Italy (Zauli Sajani et al., 2011) concludes that the days with Saharan dust intrusions increase mortality in person aged 75 years or more by respiratory causes but not by circulatory causes. This fact occurs for the whole year and the warm season. Moreover, in this paper there is no evidence of an effect modification of dust events on the concentration-response relationship between PM_{10} and daily deaths. At last, a study located in Nicosia (Neophytou et al., 2013) found a relation with the increment of mortality due to circulatory causes in days with desert dust, but not relation with respiratory causes was found. About the relation studied with Sahara dust intrusions on hospital admissions, one study located in Rome in which analysed specific causes, (Alessandrini et al., 2013) concludes that a clear enhanced effect of $PM_{2.5–10}$ on respiratory diseases and of PM_{10} on cerebrovascular diseases emerged during Saharan dust outbreaks. Another study located in Nicosia (Middleton et al., 2008), that is not so specific as the Rome study´s, established that there was an increased risk of hospitalization on dust storm days, particularly for circulatory causes.

1.4.2. Impact on morbid-mortality in Spain

In Spain, relatively few studies have analysed the health impact of Saharan dust intrusions, and, at a city level, have focused on Barcelona and Madrid. In the case of Barcelona, a recent study linked Saharan dust intrusions to an increase in cases of meningococcal disease in the 4 weeks after the intrusion (Tobías et al., 2011a). Studies have also examined whether Saharan dust intrusions might be related to complications in pregnancy, though no conclusive associations have been established in this respect (Dadvand et al., 2011). With regard to daily mortality, another study conducted in Barcelona (Pérez et al., 2008) reported an increase in mortality on days with versus those without Saharan dust intrusions, with this being linked to the coarse $PM_{10\text{-}2.5}$ fraction, and no statistical association being detected between mortality and $PM_{2.5.}$ Along these same lines, though in relation to daily mortality due to different specific causes and various sizes of PM, attention should be drawn to Pérez et al. (2012) study, which detected a differentiated effect on mortality due to different diseases, according to the size of the particles and the presence or absence of Saharan dust intrusions. In the case of the city of Madrid, a number of studies have addressed this subject in the last few years. Hence, a study conducted into daily all-cause mortality on days with and without intrusions reported a differentiated mortality behaviour pattern, with PM_{10}-related mortality being higher on days with than on days without Saharan dust intrusions (Pérez et al., 2008). Other studies undertaken in Madrid, for both the general population and the segment aged over 65 years (Jiménez et al., 2010), indicate that on days without Saharan dust intrusions it is $PM_{2.5}$, a pollutant having its main source in road traffic, which displays a stronger association with daily mortality: in contrast, on days with Saharan dust intrusions, this association assumes greater statistical significance for PM_{10}. This pattern detected for mortality has likewise been seen for emergency hospital admissions (Reyes et al., 2014). Lastly, as regards studies conducted into the influence of Saharan dust on health in the Canary Islands, there was one such study which targeted emergencies in Santa Cruz de Tenerife (García et al., 2001). The results indicated that the presence of Saharan dust in suspension in the air brought about an increase in the demand for emergency health care for respiratory diseases, anxiety disorders and atypical chest pains. Similarly noteworthy is a recent study (López-Villanueva et al., 2012) conducted in two Canary capital cities, which analysed the impact of $PM_{2.5}$ and $PM_{10\text{-}2.5}$ on daily mortality and linked increases in this particulate matter to increases in mortality due to both circulatory and respiratory causes.

1.5. Synoptic patterns in relation with Sahara dust intrusion

Several studies have been conducted on the influence of meteorological patterns on PM dispersion in southwestern Europe (e.g. Russo et al. (2014) for O_3, PM10 and NO_2 in Portugal; Pey et al. (2013), Gaetiani and Pasqui (2014) and Salvador et al. (2014) for PM in the Mediterranean). These applications associate a certain type of circulation pattern to the long-range transport, linking a particular air mass to dispersion conditions and also to the mesoscale meteorological behaviour that controls the regional transport of air pollution (Russo et al., 2014). Pey et al. (2013) characterised the occurrence of African dust outbreaks across the whole Mediterranean Basin, analysing the levels of dust concentration as well as seasonal patterns and frequency of the events in the study area. This study served as base for the study of Salvador et al. (2014), where the main atmospheric processes which give rise to the dust outbreaks were characterised and the source areas of dust identified using different objective statistical procedures.

1.6. Research aim of this study

It is evident that the inflow of dust from the Sahara into Spain causes an increase in PM levels in the atmosphere: this, along with the change in the composition of PM present in the atmosphere, brings with it a modification in the morbidity-mortality pattern associated with airborne PM levels. The relative frequency with which these intrusions occur in the atmosphere of Spanish cities and their presumable increase as a consequence of desertification attributable to climate change (Evan et al., 2016), renders their consideration and analysis of special interest in these latitudes, not only from a health standpoint, but also in terms of the synoptic conditions that are present when these advections occur. Appropriate characterisation of such meteorological patterns is crucial for predicting them and, by extension, for adopting preventive measures designed to minimise the health impact of PM.

Although these studies make very thorough analysis on the influence on weather and circulation patterns on the occurrence of dust intrusions, none of them has the goal of also analysing how intrusions' impact on human health. On the other hand, researches in Europe about the impact of PM on mortality are based in specific cities, but there are no studies that analyses the impact on the whole country.

Accordingly, the main aims of this study were threefold: a) to assess the significance of aerosol/dust intrusions in all the Spanish regions considered; b) to examine the effect of Saharan dust intrusions on daily mortality in different Spanish regions; and, c) to characterise the large-scale atmospheric circulation anomalies associated with such dust intrusions.

2. Methods

2.1. Days with dust Saharan intrusions

For determination of days with Saharan dust contributions, we used information supplied by the Ministry of Agriculture and Fishing, Food & Environment (MAPAMA, 2016) (*Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente,* http://www.mapama.gob.es/es/calidad-y-evaluacion-ambiental/temas/atmosfera-y-calidad-del-aire/calidad-del-aire/evaluacion-datos/fuentes-naturales/default.aspx).

It divides Spain into 9 main areas, namely, North, North-east, North-west, Centre, South-west, South-east, Levant, Balearic Isles and Canary Islands (Fig. 1). A robust procedure was used to identify the occurrence and duration of Saharan dust episodic days (dusty days) over each main area. It is based on the daily interpretation of air mass back trajectories, synoptic meteorological charts, satellite imagery (maps of aerosol index of Ozone Monitoring Instrument-OMI and NASA SeaWiFS images) and daily consultation of dust forecast models, namely: SKIRON-University of Athens, BSC-DREAM8b v2.0-Barcelona Supercomputing Centre and NAAPS-Naval Research Laboratory (NRL), Monterey, CA. This procedure also allows quantifying the dust contribution to the PM_{10} daily records during each potential dusty day by means of a statistical analysis of the time series of PM_{10} values registered at regional background monitoring sites. Hence, the higher the dust contribution levels, the more intense the dusty day. The feasibility of this method was demonstrated by different approaches in (Escudero et al., 2007) and (Viana et al., 2010). This methodology became the Spanish and Portuguese reference method to identify and quantify Saharan dust contributions to PM_{10} levels since 2004. The method is also applicable across the whole Southern Europe, as demonstrated by (Pey et al., 2013). Currently, this is one of the official methods recommended by the European Commission for evaluating the occurrence of African dust intrusions and quantifying its contributions (Commission Staff Working Paper, 2011).

2.2. Air pollution and mortality data

In each of these regions, a representative province was selected on the basis of the availability and quality of the air pollution and mortality data. Chemical air pollution data corresponded to the mean daily values of each of the pollutants at stations situated in each province, as supplied by the MAPAMA for the period 2004–2009.

The independent variable was mean daily PM_{10} concentrations measured in $\mu g/m^3$. Only the Provinces of Madrid, Las Palmas and Santa Cruz de Tenerife had $PM_{2.5}$ measures. In these 3 cases, we also included these concentrations in the analysis.

As control variables, we used the mean daily concentrations of SO_2, NO_2 and O_3, obtained from the same site as those corresponding to PM.

Given that Saharan dust advections in the summer period are linked to heat waves in Spain (García-Herrera et al., 2005), we controlled for the effect of the maximum daily temperature in heat waves.

It is widely known that temperature displays a U-shaped relationship with mortality (Alberdi et al., 1998), in which the left-hand side corresponds to the effect of low temperatures and the right-hand side to the effect of high temperatures. This effect of heat and cold on mortality is exacerbated in so-called heat and cold waves. Determination of the threshold temperatures ($T_{threshold}$) used in the heat- and cold-wave definitions is different in each provincial capital, with these being established in previous studies undertaken for each Spanish province for heat (Díaz et al., 2015) and cold waves respectively (Carmona et al., 2016). Bearing this in mind, the variable "temperature" was parameterised as follows:

Heat:
$T_{heat} = 0 \quad \text{if } T_{max} < T_{threshold}$
$T_{heat} = T_{max} - T_{threshold} \quad \text{if } T_{max} > T_{threshold}$

Cold:
$T_{cold} = T_{threshold} - T_{min} \quad \text{if } T_{min} < T_{threshold}$
$T_{cold} = 0 \quad \text{if } T_{min} > T_{threshold}$

Maximum (T_{max}) and minimum daily temperature (T_{min}) data for each provincial capital were provided by the State Meteorological Agency (*Agencia Estatal de Meteorología/AEMET*).

The dependent variable was daily mortality due to all causes except accidents: "natural- cause" (International Classification of Diseases 10th Revision (ICD-10: A00-R99) for the period 2004–2009 in Spanish towns of over 10,000 inhabitants, grouped by provincial capitals and by geographical location into the above 9 main areas, i.e., North, North-east, North-west, Centre, South-west, South-east, Levant, Balearic Isles and Canary Islands.

The daily mortality data were obtained from microfiches containing death data broken down by cause of death and supplied under a data loan agreement by the National Statistics Institute to the Carlos III Institute of Health (Ministry of Economic Affairs & Competitiveness/*Ministerio de Economía y Competitividad*), for the purpose of undertaking a "Study of influenza-related mortality in Spain".

2.3. Impact of air pollution on mortality: Methodology of analysis

We conducted a longitudinal ecological time series study to analyse the relationship between daily mortality and PM_{10} levels in the period from 1 January 2004 to 31 December 2009, using generalised linear models (GLMs) with the Poisson regression link, and stratifying the analysis by the presence or absence of Saharan dust advections.

To take into account the seasonal effect on mortality, the analysis for PM_{10} has been done in different stages: a) the whole year, b) in

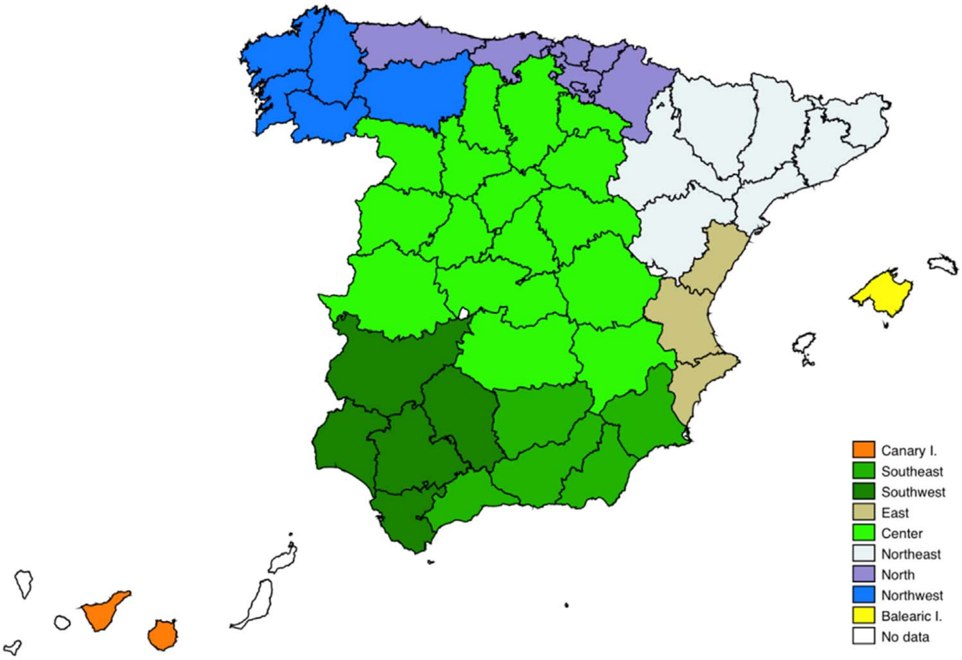

Fig. 1. Geographical location of the 9 main areas in Spain.

summer months (considering June to September) and c) rest of the year.

In addition to the above-described air pollution variables and heat and cold wave temperatures, in these models we controlled for trend of the series, day of the week, annual, six-monthly and quarterly seasonalities, and the autoregressive nature of the series. For controlled seasonalities of an annual, six-monthly and quarterly nature, we used the sine and cosine functions with these same periodicities. For time trend a variable called n1 has been introduced. This variable was defined as n1 = 1 for January 1st, 2004, n1 = 2192 for December 31th, 2009.

In view of the fact that the effect of PM and other control variables may be lagged in time, we created lags for the pollution variables up to order 4 for pollutants and heat, and up to order 11 for cold (Díaz et al., 2015; Carmona et al., 2016).

Variables were selected using the Backwards-Step procedure, eliminating those that were not significant at $p < 0.05$. The models were constructed for days with and without Saharan dust intrusions, based on data supplied by the MAPAMA for the days on which there had been (NAF = 1) or had not been an intrusion (NAF = 0).

Poisson modelling makes it possible to ascertain the relative risks (RRs) of mortality in respect of those variables which prove statistically significant. Based on these RRs, the percent increase in mortality per 10 $\mu g/m^3$ increase in PM_{10}, and is obtained as: IRR = (RR-1)*100.

2.4. Climate data and analysis

In order to identify the most favourable synoptic conditions for intrusions to take place, several surface, low- and mid-tropospheric meteorological variables were considered. We used European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyzes (Dee et al., 2011) to characterize the atmospheric circulation associated with the dust intrusions across the period 1981–2012. The choice of variables and levels used is similar to previous analysis performed by the authors when evaluating the impact of atmospheric circulation patterns in mortality (García-Herrera et al., 2005) or wildfires (Pereira et al., 2005) in Iberia. Thus, the meteorological data used are:

- 500 and 850 hPa geopotential height
- Relative humidity at 850 hPa
- Temperature at 850 hPa
- Sea level pressure
- 10 m wind height (u and v components)
- Maximum temperature at 2 m

For the identification of the preferential synoptic conditions composites were computed of the different meteorological variables which consisted of arithmetic means evaluated for a sub-sample of the original daily values from the reanalyzes dataset. This subset included only the days when intrusions occurred for each region. Anomaly fields for intrusion days are obtained after removing the long-term climatological mean from the intrusions composites.

Anomaly fields of surface or low troposphere climate variables are interpreted on the basis of large-scale physical mechanisms, namely, the advective anomalous mean flow (characterised by 500 hPa geopotential height and surface wind). Anomalies were computed for the period from June to September, including relative humidity and temperature at 850 hPa, sea level pressure, 500 hPa geopotential height, 10 m wind height (u and v components). The period with dust data is considerably shorter than the reanalyses available: on being restricted to 9 years of data 2004–2012), we removed the long-term climatology computed from 1981 to 2010.

3. Results

3.1. Increase in mortality associated with Sahara dust intrusions

Tables 1, 2 show the descriptive statistics for each of the 52 provincial capitals across the total period considered, in which the mortality (Table 1) and PM_{10} values (Table 2) are included.

In order to perform an in-depth analysis of the variables of interest in this paper, we selected the days with intrusions versus days without intrusions, and grouped the results by region. Accordingly, Table 3 shows the daily mortality values for days on which there were intrusions and for those on which there were no intrusions, by region, along with the percentage of days on which intrusions appeared with respect to the total number of days analysed. It should be noted that the frequency of appearance was higher in the southernmost regions of

Table 1
Descriptive statistics of daily Natural-cause mortality (ICD–10: A00-R99) on days with and without Saharan dust advections, for all provincial capitals in Spain: 2004–2009.

Capitals	Natural-cause mortality			
	Days with advections		Days without advections	
	Mean	95% CI	Mean	95% CI
Albacete	8.8	8.5–9.09	9.1	8.95–9.25
Alicante	35.4	34.78–35.99	36.2	35.77–36.53
Almería*	11.2	10.93–11.49	11.8	11.62–12
Ávila	5.0	4.78–5.22	4.8	4.72–4.94
Badajoz	16.7	16.36–17.10	17.2	17.01–17.49
Barcelona*	113.0	111.30–114.63	116.6	115.65–117.56
Bilbao	28.0	27.14–28.75	28.1	27.80–28.39
Burgos	9.2	8.87–9.54	9.1	8.99–9.28
Cáceres	10.5	10.16–10.84	10.4	10.20–10.53
Cádiz*	22.4	21.90–22.80	23.1	22.80–23.42
Castellón	12.1	11.81–12.46	12.5	12.33–12.70
Ciudad Real	13.1	12.71–13.47	13.4	13.19–13.58
Córdoba	18.6	18.20–19.04	18.9	18.65–19.18
Coruña	32.8	31.89–33.68	31.8	31.53–32.14
Cuenca	5.0	4.82–5.26	4.9	4.79–5.01
Gerona	14.92	14.52–15.32	14.82	14.62–15.02
Granada	19.8	19.38–20.17	20.4	20.10–20.65
Guadalajara	4.6	4.37–4.8	4.6	4.47–4.67
Huelva	10.8	10.52–11.10	11.1	10.89–11.25
Huesca	5.8	5.53–6.03	6.0	5.84–6.08
Jaén*	14.7	14.34–15.00	15.5	15.31–15.78
Las Palmas de GC*	17.2	16.73–17.69	16.5	16.23–16.67
León	15.2	14.60–15.71	14.8	14.57–14.95
Lérida	10.3	9.95–10.70	10.7	10.56–10.89
Logroño	7.3	6.99–7.53	7.2	7.05–7.30
Lugo	12.0	11.52–12.57	12.2	12.01–12.36
Madrid*	58.4	57.45–59.41	60.0	59.48–60.51
Málaga*	29.9	29.47–30.39	31.4	30.98–31.71
Murcia*	25.2	24.82–25.64	26.7	26.38–27.02
Orense	11.7	11.14–12.15	11.7	11.51–11.85
Oviedo	33.6	32.69–34.53	33.1	32.75–33.41
Palma de Mallorca	20.1	19.66–20.59	20.5	20.22–20.69
Pamplona	14.0	13.41–14.49	13.5	13.33–13.68
Pontevedra	21.4	20.69– 22.07	21.3	21.07–21.55
Salamanca	10.4	10.09–10.75	10.1	9.91–10.22
San Sebastián	16.4	15.78–16.98	16.0	15.82–16.25
S. C de Tenerife*	18.7	18.21–19.10	17.1	16.86–17.31
Santander	14.3	13.78–14.86	14.6	14.44–14.83
Segovia	4.1	3.9–4.31	4.0	3.94–4.13
Sevilla*	37.5	36.85–38.15	39.2	38.78–39.65
Soria	2.8	2.67–3.01	2.8	2.7– 2.86
Tarragona*	15.7	15.28–16.17	16.4	16.22–16.63
Teruel	4.4	4.19–4.61	4.2	4.06–4.25
Toledo	14.0	13.58–14.35	13.8	13.61–14.01
Valencia*	55.4	54.58–56.25	57.9	57.38–58.47
Valladolid	12.5	12.11–12.86	12.6	12.40–12.77
Vitoria	6.0	5.63–6.30	6.2	6.04–6.27
Zamora	6.3	6.06–6.54	6.1	5.99–6.23
Zaragoza	24.3	23.76–24.91	24.5	24.25–24.79

* Statistically significant differences.

Table 2
Descriptive statistics of mean PM_{10} concentrations on days with and without Saharan dust advections, for all provincial capitals in Spain: 2004–2009.

Capitals	PM10			
	Days with advections		Days without advections	
	Mean	95% CI	Mean	95% CI
Albacete*	55.5	53.16–57.85	40.0	39.25–40.70
Alicante	–		–	
Almería*	44.5	41.04–47.92	32.8	31.27–34.23
Ávila	–		–	
Badajoz	27.1	26.08–28.07	19.2	18.68–19.64
Barcelona	–		–	
Bilbao*	45.6	42.72–48.58	33.26	32.53–33.99
Burgos*	33.8	32.45–35.07	24.9	24.37–25.33
Cáceres*	25.2	24.02–26.36	16.9	16.48–17.26
Cádiz	–		–	
Castellón	–		–	
Ciudad Real	–		–	
Córdoba*	55.7	53.27–58.07	35.5	34.71–36.28
Coruña*	46.4	41.47–51.39	32.2	31.06–33.26
Cuenca*	43.1	39.68–46.44	28.1	26.88–29.22
Gerona	–		–	
Granada*	52.9	50.71–55.09	37.6	36.74–38.48
Guadalajara*	44.1	41.67–46.59	26.0	25.34–26.71
Huelva*	44.6	42.89–46.24	30.6	29.94–31.19
Huesca	–		–	
Jaén*	50.4	48.13 – 52.74	35.7	34.73 – 36.61
Las Palmas de GC*	62.0	55.88 – 68.14	31.3	30.77 – 31.86
León*	43.7	41.38 – 46.10	35.5	34.81 – 36.17
Lérida	–		–	
Logroño*	36.3	34.61–38.02	25.5	24.84 – 26.06
Lugo	–		–	
Madrid*	43.7	41.98–45.51	28.7	28.08–29.38
Málaga*	40.9	38.85–42.99	25.2	24.53–25.77
Murcia*	33.7	32.37–35.07	27.3	26.39–28.15
Orense	26.2	22.18–30.17	21.3	20.27–22.33
Oviedo*	46.8	44.21–49.38	40.2	39.35–41.03
Palma de Mallorca*	38.0	36.14–39.81	26.3	25.85–26.67
Pamplona*	44.2	41.86–46.48	29.9	29.34–30.53
Pontevedra	–		–	
Salamanca*	29.6	28.12–31.00	23.9	23.41–24.41
San Sebastián*	34.9	32.59–37.31	26.4	25.85–26.97
S. C de Tenerife*	117.5	102.13–132.91	48.9	47.92–49.87
Santander*	40.6	38.72–42.56	31.3	30.85–31.83
Segovia*	34.2	32.13–36.20	22.5	21.84–23.18
Sevilla*	49.6	47.69–51.53	37.8	36.94–38.57
Soria*	37.3	35.82–38.72	25.3	24.69–25.84
Tarragona	–		–	
Teruel	–		–	
Toledo*	48.3	45.92–50.70	33.9	33.21–34.69
Valencia*	34.5	33.33–35.72	28.2	27.56–28.90
Valladolid*	20.5	19.40–21.62	16.4	15.96–16.80
Vitoria*	37.1	34.63–39.62	23.6	22.96–24.19
Zamora*	36.0	34.38–37.56	28.2	27.67–28.74
Zaragoza*	55.5	52.97–57.99	40.4	39.49–41.38

* Statistically significant differences.

mainland Spain, with values of 30.1% in the south-east and 25.3% in the south-west regions, followed by the Canary Islands with a 22.4% frequency of days with intrusions. The north-west region, the furthest from the Sahara, was that which registered the lowest percentage of days with intrusions, with a figure of 9.6%.

Table 3 also shows the mean natural-cause mortality for each of the regions, plus -marked with an asterisk- those regions in which mortality proved statistically significantly different on days with versus those without Saharan dust intrusions.

A noteworthy finding was that the three regions which displayed differences in mortality were those which displayed the highest percentage of days with intrusions, yet it was only in the Canary Islands that mortality was higher on days with than on those without intrusions.

Table 4a shows the mean daily PM_{10} concentrations in the whole year (as well as mean daily $PM_{2.5}$ concentrations in the case of the Centre and Canary Islands regions). It will be seen that in all regions, the presence of a dust intrusion meant that the concentration of all particulate matter increased statistically significantly. The same pattern can be observed in Table 4b and Table 4c for summer months and the rest of the year.

In general, days with Sahara dust intrusions are more frequent in rest of the year (Table 4c) than in summer months (Table 4b), except in Centre, South-west and South-east regions. PM concentrations are higher in rest of the year than in summer months except in North-east and South-west.

From the above-mentioned results in relation to Tables 3, 4a, it seems clear that there is no evident relationship between an increment

Table 3
Natural-cause mortality by regions and days with and without Saharan dust advections and percentage of days on which such advections appear.

Days with Saharan dust advections					Days without Saharan dust advections		
Region	**Capitals** Total	**Days** Total	**Days %**	**Mean Natural-cause (95% CI)**	**Days** Total	**Days %**	**Mean Natural-cause (95% CI)**
North-west	5	210	9.6	18.60 (18.04–19.16)	1982	90.4	18.35 (18.17–18.53)
North	6	220	10.0	19.69 (18.13–19.26)	1972	90.0	18.58 (18.39–18.77)
North-east	7	346	15.8	26.93 (25.48–28.38)	1846	84.2	27.61 (26.95–28.26)
Centre	16	398	18.2	11.54 (11.18–11.91)	1794	81.8	11.63 (11.45–11.81)
South-west[*]	5	554	25.3	21.20 (20.81–21.59)	1638	74.7	21.91 (21.67–22.16)
South-east[*]	5	660	30.1	20.16 (19.88–20.45)	1532	69.9	21.16 (20.95–21.36)
East	3	481	21.9	34.31 (33.33–35.29)	1711	78.1	35.53 (34.97–36.99)
Balearic Isles	1	448	20.4	20.13 (19.66–20.59)	1744	79.6	20.46 (20.22–20.69)
Canary Islands[*]	2	491	22.4	17.93 (17.60–18.26)	1701	77.6	16.77 (16.61–16.93)

[*] Statistically significant differences at $p < 0.05$.

Table 4a
PM_{10} and $PM_{2.5}$ concentrations (μg/m^3) by regions and days with and without Saharan dust advections in the whole year.

		Days with Saharan dust advections		Days without Saharan dust advections	
Region	**Capitals** Total	**Mean PM10 (95% CI)**	**Mean PM2.5 (95% CI)**	**Mean PM10 (95% CI)**	**Mean PM2.5 (95% CI)**
North-west[*]	5	40.74 (38.70–42.78)		31.94 (31.40–32.48)	
North[*]	6	41.52 (40.50–42.54)		30.77 (30.49–31.05)	
North-east[*]	7	55.50 (52.97–57.99)		40.43 (39.49–41.38)	
Centre[*]	16	37.88 (37.27–38.49)	21.81 (21.05–22.57)	26.20 (26.00–26.40)	16.08 (15.73–16.42)
South-west[*]	5	44.38 (43.37–45.40)		30.87 (30.48–31.26)	
South-east[*]	5	45.83 (44.75–46.92)		32.09 (31.65–32.52)	
East[*]	3	34.53 (33.33–35.72)		28.23 (27.56–28.90)	
Balearic Isles[*]	1	37.97 (36.14–39.81)		26.26 (25.85–26.67)	
Canary Islands[*]	2	78.97 (72.36–85.57)	23.45 (21.72–25.17)	37.36 (36.78–37.95)	11.50 (11.31–11.70)

[*] Statistically significant differences at $p < 0.05$.

in the concentration of particles associated with Saharan dust intrusions and increased mortality, a finding that justifies the performance of statistical analyses of greater sensitivity than mere comparisons of mortality means. To this end, and given that some of the regions studied extend over a very wide area, we decided to select a single province for each region in order to perform the statistical analysis with Poisson regression, which would enable us, in the event of there being an association, to quantify this effect. The selection criteria were: the quality of existing PM data; and the fact that the daily mortality values were sufficiently high to enable statistically representative results to be obtained.

The provincial capitals chosen are listed in Table 5. This table shows the relative and attributable risks for each of these provinces in relation to the PM variable that had proved significant in the modelling process, controlling for the rest of the above-mentioned variables.

From the analysis in Table 5a, the following different behaviour patterns can be observed:

1. Cities which displayed no association between mortality and PM on days without intrusions but which did display such an association on days with intrusions, e.g., Coruña and Las Palmas de Gran Canaria.
2. Cities which did not display an association between mortality and PM, regardless of the fact that there might or might not have been an intrusion, e.g., Palma de Mallorca; or alternatively, which displayed an association between daily mortality and PM on days without intrusions but not on days with intrusions, e.g., Bilbao.
3. Cities which displayed an association between PM and daily mortality on days with and without intrusions, e.g., Madrid, Malaga and Seville.

In other words, in 5 of the 7 cities analysed, the effect of Saharan dust intrusions had on an impact on daily mortality.

Tables 5b, 5c show the effect on mortality of PM concentrations in summer months and the rest of the year. The pattern showed in Table 5b (summer months) is very similar to the whole year pattern (Table 5a).

Table 4b
PM10 and PM2.5 concentrations (μg/m^3) by regions and days with and without Saharian dust advections in summer months (June-September).

Summer months (june–september)		Days with Saharian dust advections			Days without Saharian dust advections		
Region	**Capitals** Total	**Days** Total	**Mean PM10 (95% CI)**	**Mean PM2.5 (95% CI)**	**Days** Total	**Mean PM10 (95% CI)**	**Mean PM2.5 (95% CI)**
North-west[*]	5	91	33.51 (31.40–35.63)		641	27.05 (26.36–27.74)	
North[*]	6	89	38.52 (37.20–39.83)		643	30.02 (29.60–30.43)	
North-east	7	159	56.09 (52.96–59.22)		573	41.92 (40.34–43.49)	
Centre	16	204	37.18 (36.35–38.02)	21.32 (20.30–22.34)	528	27.53 (27.16–27.89)	16.06 (15.54–16.58)
South-west[*]	5	289	45.36 (44.04–46.68)		443	33.60 (32.85–34.35)	
South-east[*]	5	350	45.66 (44.53–46.80)		382	33.78 (33.06–34.49)	
East[*]	3	231	33.12 (31.73–34.51)		501	26.90 (25.90–27.91)	
Balearic Isles[*]	1	184	38.34 (36.07–40.61)		548	26.86 (26.19–27.54)	
Canary Islands[*]	2	122	61.67 (54.24–69.07)	16.98 (15.55–18.40)	610	39.81 (38.75–40.87)	12.37 (11.99–12.75)

[*] Statistically significant differences at $p < 0.05$.

Table 4c
PM10 and PM2.5 concentrations (μg/m3) by regions and days with and without Saharian dust advections in the rest of the months of year.

Rest of the year		**Days with Saharian dust advections**			**Days without Saharian dust advections**		
Region	**Capitals** Total	**Days** Total	**Mean PM10 (95% CI)**	**Mean PM2.5 (95% CI)**	**Days** Total	**Mean PM10 (95% CI)**	**Mean PM2.5 (95% CI)**
North-west*	5	119	46.12 (43.12–49.11)		1341	34.31 (33.60–35.02)	
North*	6	131	43.59 (42.14–45.04)		1329	31.13 (30.77–31.50)	
North-east*	7	187	54.96 (51.13–58.78)		1273	39.77 (38.60–40.93)	
Centre*	16	194	38.61 (37.73–39.50)	22.33 (21.20–23.45)	1266	25.64 (25.40–25.88)	16.09 (15.65–16.53)
South-west*	5	265	43.34 (41.78–44.90)		1195	29.87 (29.42–30.32)	
South-east*	5	310	46.03 (44.11–47.95)		1150	31.53 (31.01–32.06)	
East*	3	250	36.06 (34.09–38.03)		1210	28.71 (27.87–29.55)	
Balearic Isles*	1	264	37.73 (35.05–40.40)		1196	25.99 (25.48–26.50)	
Canary Islands*	2	369	84.45 (76.12–92.77)	25.52 (23.30–27.74)	1091	35.97 (35.29–36.66)	11.02 (10.80–11.25)

* Statistically significant differences at $p < 0.05$.

Next, a model corresponding to Sevilla city is showed during summer months in days with Sahara dust intrusions.

The GLM Poisson regression models equations for the baseline model (M0) for each region, and the models with the temperature variables added (M1) are the following showed below, in which:

$\hat{\mu}$: Daily Natural Mortality
$\hat{\mu}1$: Autoregressive order 1 of $\hat{\mu}$.

The subscripts in air pollution variables are referred to the lags in which the statically association is found. Sine and Cosine functions are control variables to seasonality's that results statically significant ($p < 0.05$).

$$\mathrm{Ln}\ (\hat{\mu}) = 3.295 - 0.144\cos365 + 0.040\cos90 + 0.001PM10 + 0.040Tcal2 + 0.002NO23$$

3.2. Synoptic patterns characteristic of dust intrusions

In the previous section we have shown that, independently of the sub-region considered, days classified as intrusion days were in fact characterised by statistically significant higher values of PM10 (and PM 2.5 when available) when compared to non-intrusion days. However, no information was provided regarding the atmospheric processes associated with such transport, namely are these processes associated with very similar anomalous circulation patterns affecting the southern and northern Spanish provinces? Likewise, the entire assessment provided so far does not mention any seasonal breakdown, but from a synoptic circulation perspective it may be important to separate intrusions occurring during different seasons as the climatological circulation over northern Africa and Iberia varies considerably throughout the year (e.g. Lionello, 2012).

In this section we try to address these two issues, starting by showing the seasonal cycle of the number of intrusions observed during the considered period (2004–2009) for the different Spanish sectors considered (Fig. 2). Most of the regions do reveal a marked seasonal cycle, with a clear maxima (minima) during summer (winter) months, particularly the southern and central sectors (South-east, Levant, South-west Centre) and less clear cut in two out of three northern sectors (North-west, North). The Balearic Islands present a higher intrusion season spanning between April and October, while the Canary Islands archipelago present a rather different seasonal evolution with more (less) events during the winter (summer) half of the year. As mentioned previously, from the atmospheric circulation standpoint it is important to separate the analysis for different periods of the year, as extreme events in Iberia, such as heatwaves (García-Herrera et al., 2005) or cold events (Sánchez et al., 2004; Orlowsky·and Seneviratne, 2011) are usually separated between the hot (summer) and cold (winter) corresponding seasons.

Taking into account the predominance of the intrusion phenomena during summer months for the vast majority of Spanish sectors we provide a more detailed characterisation of the large-scale atmospheric circulation for the region Surest centred in summer (Jun, Jul, Aug) months (Fig. 3). In the left panels we can observe the composite (for the variables mentioned above) for those days characterised with aerosol intrusions, while the right side panels present the corresponding

Table 5a
PM variables that proved significant in the Poisson regression models fitted for each provincial capital in each of the regions considered for the whole year.

		Days with Saharan dust advections			**Days without Saharan dust advections**		
Region	**Capital**		**RR (95% CI)**	**IRR* (%) (95% CI)**		**RR (95% CI)**	**IRR*(%) (95% CI)**
North	Bilbao		–		PM_{10} (lag 2)	1.006 (1.000–1.012)	0.63 (0.04–1.22)
North-east	Zaragoza		–			–	
North-west	Coruña	PM_{10} (lag 3)	1.050 (1.024–1.077)	5.00 (2.36–7.71)		–	
Centre	Madrid	PM_{10} (lag 2)	1.007 (0.999–1.015)	0.67 (−0.12 to 1.46)	$PM_{2.5}$ (lag 1)	1.026 (1.018–1.034)	2.59 (1.80–3.41)
South-east	Málaga	PM_{10}	1.006 (1.000–1.012)	0.58 (0.00–1.18)	PM_{10} (lag 1)	1.010 (1.002–1.018)	1.00 (0.21–1.79)
South-west	Sevilla	PM_{10}	1.009 (1.004–1.015)	0.94 (0.35–1.53)	PM_{10}	1.007 (1.003–1.011)	0.70 (0.31–1.09)
East	Valencia		–			–	
Canary Islands	Las Palmas de G.C.	$PM_{2.5}$	1.010 (1.001–1.020)	1.04 (0.05–2.03)		–	
Balearic Isles	Palma de Mallorca		–		4.	–	

(*) For these chemical air-pollutant variables increases of 10 $\mu g/m^3$, for maximum temperatures increases of 1 °C, and for minimum temperatures decreases of 1 °C.

Table 5b
PM variables that proved significant in the Poisson regression models fitted for each provincial capital in each of the regions considered in summer months (June-September).

Summer months (june-september)		**Days with Saharan dust advections**			**Days without Saharan dust advections**		
Region	**Capital**		**RR (95% CI)**	**IRR* (%) (95% CI)**		**RR (95% CI)**	**IRR* (%) (95% CI)**
North	Bilbao		–		PM_{10} (lag 2)	1.017 (1.006–1.027)	1.69 (0.64–2.75)
North-east	Zaragoza		–			–	
North-west	Coruña		–			–	
Centre	Madrid	PM_{10} (lag 2)	1.018 (1.004–1.032)	1.79 (0.38–3.22)		–	
South-east	Málaga	PM_{10}	1.014 (1.004–1.025)	1.44 (0.36–2.53)	PM_{10} (lag 1)	1.015 (1.001–1.029)	1.48 (0.12–2.87)
South-west	Sevilla	PM_{10}	1.013 (1.003–1.022)	1.28 (0.31–2.25)	PM_{10}	1.018 (1.006–1.030)	1.79 (0.62–2.97)
Levante (east)	Valencia		–			–	
Canary Islands	Las Palmas de G.C.		–			–	
Balearic Isles	Palma de Mallorca		–			–	

(*) For these chemical air-pollutant variables increases of 10 $\mu g/m^3$, for maximum temperatures increases of 1 °C, and for minimum temperatures decreases of 1 °C.

anomalous patterns, obtained for the very same days, but after removing the corresponding daily averages obtained for the climatological longer period (1981–2010). The standard assessment of these days based on the 500 hPa geopotential height shows a weak ridge inclined towards eastern Iberia, with high temperature in the lower troposphere (as depicted by the 850 hPa temperature field). These ridges are associated with clear skies, additional solar radiation and even adiabatic subsidence, all processes that are known be associated with summer hot months in the western (Trigo et al., 2004; Pereira et al., 2005) and eastern Mediterranean. The corresponding anomalous fields confirm that these days are characterised by positive temperature values and negative relative humidity values considered over eastern Iberia and eastern Mediterranean, with the statistically higher temperatures also including most of northern Morocco and Algeria. At the surface level, the combined analysis of SLP and surface wind shows an intensified northern branch of the Azores Anticyclone and also anomalous winds in northern Africa reflecting the advection of hot air that is also impinging the additional load of dust into southern Iberia. These results are in accordance with Russo et al. (2015) and Querol et al. (2009) which state that advection of hot and dry air masses are associated with the additional transport of dust into Iberia.

It is important to stress that, despite their differences, most of the remaining Spanish sectors considered are characterised by relatively similar large-scale atmospheric circulation patterns. The main difference is related to the location and strength of the high ridge that can be centred further east or (e.g Baleares) or to the west (e.g. North-west, South-east).

4. Discussion

4.1. Spatial changes in the PM concentrations

The proportion of days on which there are Saharan dust intrusions in Spain, with places where this figure rises to 30% of days (south-east region), means that this is a problem that must be analysed from a public health standpoint, owing to the related potential health effects (Goudie, 2014) and impact on daily morbidity-mortality (Stafoggia et al., 2016). The frequency of days with intrusions is similar to that found in other European cities in which these values are reported to range from 28.5% in Palermo to 8.8% in Emilia-Romagna (Stafoggia et al., 2016).

In Spain, the frequency of days with intrusions is marked by the distance to the emission source, though also are influenced by the meteorological conditions in synoptic pattern. The places lying nearest (south-east 30.1%) have a higher frequency of days with dust intrusions than do those lying furthest away (north-west 9.6%). However, this is not the only factor that influences the frequency of days with Saharan dust intrusions. It is also the synoptic situations and air-mass trajectories, as described in this study, that are decisive when it comes to generating or not generating Saharan dust intrusions. Indeed, this would account for the fact that, whereas the proportion of days with intrusions in Milan, a city situated at 2800 km from Morocco, is 11.7%,

Table 5c
PM variables that proved significant in the Poisson regression models fitted for each provincial capital in each of the regions considered in the rest of the months of year.

Rest of year		**Days with Saharan dust advections**			**Days without Saharan dust advections**		
Region	**Capital**		**RR (95% CI)**	**IRR* (%) (95% CI)**		**RR (95% CI)**	**IRR* (%) (95% CI)**
North	Bilbao		–			–	
North-east	Zaragoza		–			–	
North-west	Coruña	PM_{10} (lag 3)	1.046 (1.016–1.077) 4.39	4.59 (1.57–7.69)		–	
Centre	Madrid		–		$PM_{2.5}$ (lag 1)	1.028 (1.019–1.038)	2.84 (1.93–3.76)
South-east	Málaga		–			–	
South-west	Sevilla		–		PM_{10}	1.005 (1.000–1.010)	0.51 (0.004–1.02)
Levante (east)	Valencia		–			–	
Canary Islands	Las Palmas de G.C.		–			–	
Balearic Isles	Palma de Mallorca		–			–	

(*) For these chemical air-pollutant variables increases of 10 $\mu g/m^3$, for maximum temperatures increases of 1 °C, and for minimum temperatures decreases of 1 °C.

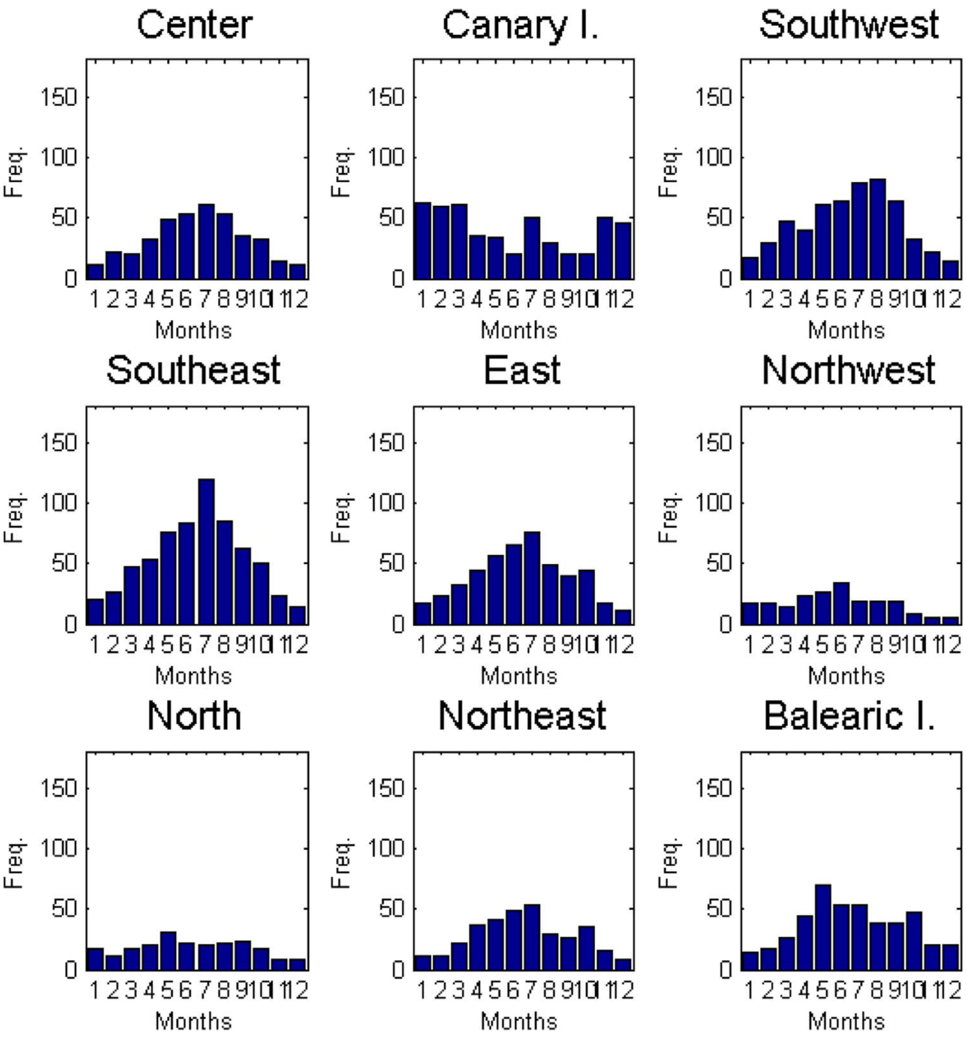

Fig. 2. Annual cycle of average monthly values of dust intrusions between 2004 and 2009.

in Corunna, situated at a distance of only 870 km from Morocco, it is 9.6%.

The results in Table 4a indicate that, when there is an intrusion, this is accompanied by an increase in particle levels in all regions, with this increase rising as high as 111% for PM_{10} and 104% for $PM_{2.5}$ in the case of the Canary Islands. These results indicate that PM values produced by Sahara dust are added to the air polluted by local emissions. These increases observed by us are similar to those found in other studies undertaken in the Mediterranean Basin (Querol et al., 2009). This natural inflow of PM, which occurs in southern European countries in particular, is taken into account in the current European Union Directive governing PM limit values: in cases of non-compliance with the statutory standards, the Directive permits days on which there are Saharan dust episodes to be discounted (Official Journal of the European Union, 2008), though from a health stance this decision may well be questionable (Linares et al., 2010).

A remarkable fact comparing Tables 4b, 4c is that in days with Sahara dust intrusion are more frequent in the rest of the year than in summer months, except in Centre, South-west and South-east regions. However, the highest PM_{10} concentration occurs in rest of the year. This fact is justified because in summer months, the weather conditions at a synoptic scale (Yuval et al., 2012), with the formation of thermal low by the strong solar irradiation, produce ascending movements that are more favourable for the dispersion of pollutants with lower PM_{10} concentration values. In the rest of the year, are more frequent the anticyclonic situations that block the ascending movements that do not permit the dispersion of air pollutants (Díaz et al., 1999).

4.2. Different patterns between PM and daily mortality

With regard to the daily mortality behaviour pattern shown in Table 3, only the Canary Islands region registers statistically significant higher mortality on days with versus days without intrusions. Needless to say, there are multiple factors which influence daily mortality (Alberdi and Díaz, 1997) and, though PM concentrations may be one such factor, this relationship is not evident. Accordingly, a statistical analysis of the type performed by us is necessary to detect these associations, which in many cases are inconsistent with the hypothesis of the impact of Saharan dust on daily mortality (Karanasiou et al., 2012).

The results of the modelling processes shown in Table 5a tend towards such inconsistency. In some cases, PM on days with intrusions are associated with daily mortality, something that does not occur on days without intrusions, indicating that Saharan dust may be a risk factor for daily mortality, as occurred in studies conducted in Barcelona (Pérez et al., 2012) and Madrid (Jiménez et al., 2010; Reyes et al., 2014). In other cases, what Saharan dust intrusions do is to change the PM-related mortality behaviour pattern, going from $PM_{2.5}$ being associated with mortality on days without intrusions to PM_{10} being associated with mortality on days with intrusions. This pattern is presumably related to the fact that $PM_{2.5}$ is fundamentally of anthropic origin, which is the type of PM that predominates on days without

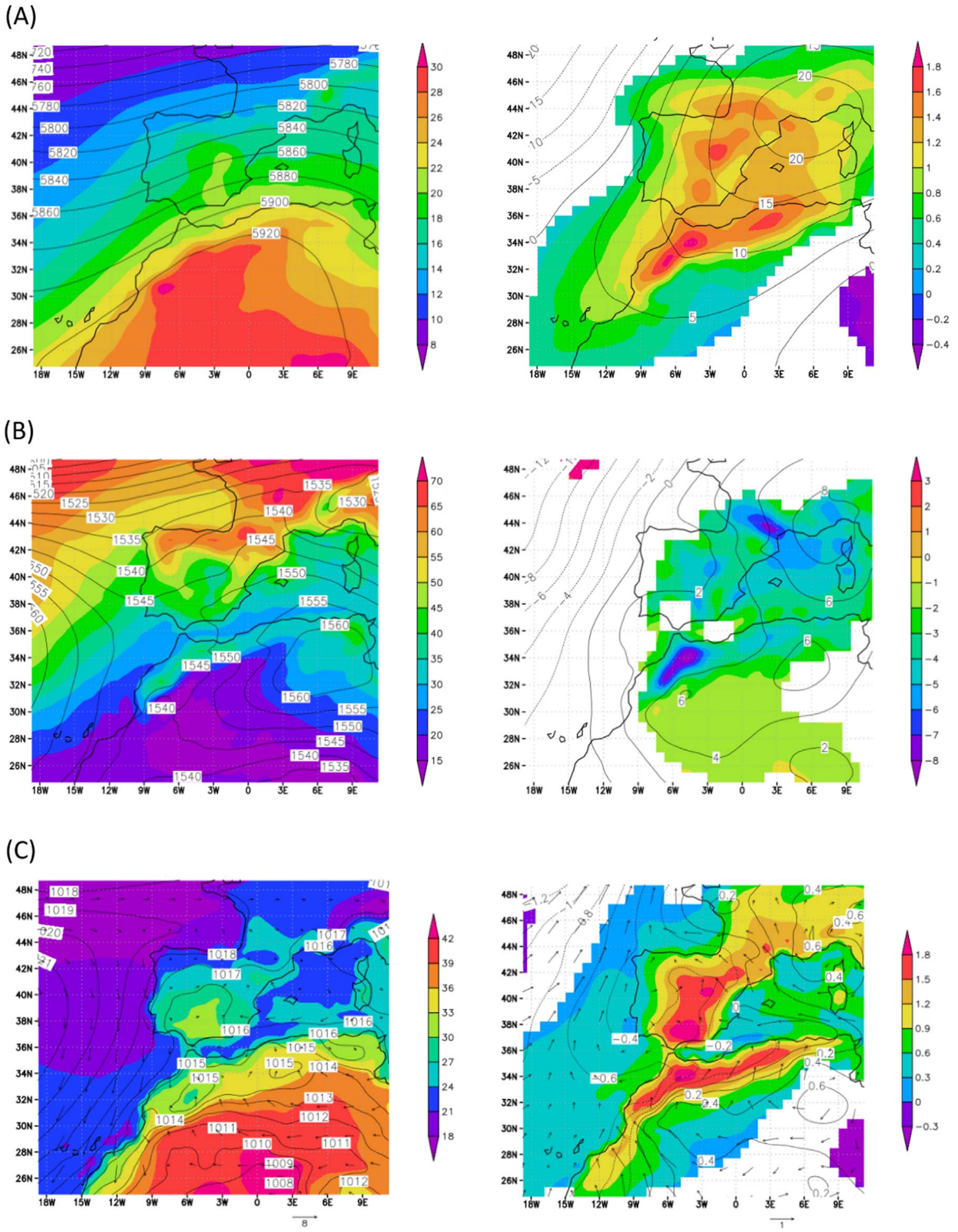

Fig. 3. (A) Air temperature fields (°C) at 850 hPa for composite for intrusion days (left panel) and for the corresponding anomaly regarding the 1981–2010 period (right panel). Contour lines show the corresponding geopotential height (gpm) at 500 hPa. (B) Relative humidity (%) at 850 hPa for composite for intrusion days (left panel) and for the corresponding anomaly regarding the 1981–2010 period (right panel). Contour lines show the corresponding geopotential height (gpm) at 850 hPa. (C) Maximum temperature (°C) at 2 m height for composite for intrusion days (left panel) and for the corresponding anomaly. Contour lines show the corresponding SLP and arrows the 10 m wind vector. Climate anomalies are only represented where such anomaly is significant at the 5% level computed with a two-tailed *t*-test.

intrusions, whereas natural sources produce larger-sized particles, which are the type of PM that predominates on days with Saharan dust intrusions (Jiménez et al., 2010; Reyes et al., 2014). Lastly, there are cities in which the presence or absence of intrusions does not modify the association, as occurred in studies undertaken in Athens (Samoli et al., 2011a, b) or even in those in which the association is found only on days without intrusions, something that was also detected in a study undertaken in Emilia-Romagna (Zauli Sajani et al., 2011). In Samoli´s paper the authors explain this lack of association for the toxic effect of PM produced by traffic during the days without Saharan dust intrusions. Otherwise, in Zauli Sajani´s paper, there is an association for respiratory causes but not for circulatory explained by “the seasonal variations characterising the synoptic transport of Saharan dust towards northern Italy, both in terms of source basin and transport pathway. However, an interaction with other environmental factors not included in the analysis is another possible explanation”.

Similar conclusions to those obtained in this study, not only in terms of the inconsistency of results by city, but also from a quantitative point of view in terms of IRR values and the lags at which the associations occur, have recently been reached by the study conducted in 13 southern European cities (Stafoggia et al., 2016).

One of the possible causes of this heterogeneity in results might perhaps lie in the fact that all the studies were conducted in isolated cities separated by hundreds of kilometres. Accordingly, conducting a study that covered all the cities in each region could make for greater uniformity in the pattern of association between PM and mortality in relation to days with intrusions.

Tables 5b, 5c, show a strong seasonal pattern in the effect of PM in days with Saharan dust intrusion. In regions Centre, South-east and South-west, in which the advections of dust were more frequent in summer months, are the only ones in which exist a statically significant association with mortality in the model procedure. An exception occurs in the North-west region. Lastly, mention should be made of the fact that various authors have reported that the different regions of the Sahara have different mineralogical properties (Moreno et al., 2006; Stafoggia et al., 2016), which might affect the toxicological composition of the particles and, by extension, their health effects. Determination of synoptic situations, both on the surface and at altitude, could determine the source of the different air masses and contribute to their identification.

A study such as the one conducted here, in which meteorological analysis of synoptic situations which favour Saharan dust intrusions, is combined with the effect on health at a city level, would seem to be crucial when it comes to analysing the differentiated mortality pattern in situations of Saharan dust intrusions.

4.3. Weakness of the study

A limitation to our work is that, we had no explanatory variables, a part from sex, age and the address of the subjects, at the individual level. In particular, we cannot control for factors, such as individual socioeconomic data, lifestyles and comorbidities that may differ between the mortality in people in different cities (Vodonos et al., 2015). These factors may also act as confounders or effect modifiers of relations between air pollution and daily mortality (Barceló et al., 2016). Historically, research on environmental inequality has emerged in the United States (US) following the Environmental Justice Movement (Morello-Frosch et al., 2011; Bowen, 2002). Repeatedly, US studies reported that lower socioeconomic or minority groups were more likely to be exposed to higher traffic-related air pollution exposure such as nitrogen dioxide (NO_2) or PM (Hajat et al., 2015). However, results from US studies cannot be extended to European countries because of very different socio-spatial characteristics, specifically in urban areas (Musterd, 2005) as a paper recently published in Europe showed (Temam et al., 2017). In this study, an equal distribution to air pollution exposure according to socioeconomic position groups is complex in European cities and no general pattern exists across cities, but rather inequalities need to be specifically assessed in each city, so for Europe is not so clear the association obtained by Hajat in US (Hajat et al., 2015).

Exposure measurement error is an inherent disadvantage of time-series studies, because the average of selected fixed monitoring stations does not reflect the true average exposure of the population. Nevertheless, there is some evidence that exposure measurement error in time-series analysis tends to bias estimates downward (Zeger et al., 2000).

Furthermore, no specific validation was performed within the project to assess the representativeness of spatial variability in air pollutants. Our study suffered from Berkson-type measurement error, among other biases associated with ecological exposure, as is common in most time-series studies, which leads to no or little bias but decreases statistically power. Not only do the concentrations of the respective air pollutants have different spatial distributions, but how well outdoor levels reflect indoor levels also varies. This leads to different degrees of measurement error -and therefore of power- for each of these, and may influence which associations are detected.

Otherwise, most of the air pollution studies assessing the long-term effects of noise address the misalignment problem (albeit only implicitly) using a two-stage modelling procedure, or plug-in approach,- where predictions from an exposure model(first stage) are used as covariates in a health effect model(second stage) (Barceló et al., 2016). Although predictions in a few cases are obtained from exposure models that explicitly incorporate spatial structure, even in these cases the plug-in approach does not take into account the uncertainty in the exposure predictions. This leads to a complex form of measurement error, resulting in bias of the health effect (Wannemuehler et al., 2009; Ingebrigtsen et al., 2015).

Another of the limitations of this study resides in not having performed the analysis according to the specific causes of mortality, both respiratory and circulatory, that have displayed a differentiated behaviour pattern with respect to total mortality in other studies which have targeted, not only mortality (Pérez et al., 2012; Díaz et al., 2012; Tobías et al., 2011b; Mallone et al., 2011), but also hospital admissions (Reyes et al., 2014).

5. Conclusions

While many studies have considered this topic previously, the analysis conducted here broken down by region and city, makes it especially relevant in the research background. Sahara dust intrusions produce an increment of PM concentrations in all regions of Spain. This increment has in some regions impact on daily mortality and in future makes necessary to carry out studies at finer spatial level, introducing specific causes of mortality.

Disclaimer

This paper presents independent results and research.The views expressed are those of the authors and not necessarily those of the Instituto de Salud Carlos III.

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