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Analysis of air mass trajectories in the northern plateau of the Iberian Peninsula

Isidro A. Pérez*, M. Luisa Sánchez, M. Ángeles García, Nuria Pardo

Department of Applied Physics, Faculty of Sciences, University of Valladolid, Paseo de Belén, 7, 47011 Valladolid, Spain

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ABSTRACT

Air masses reaching the Iberian Peninsula, which is located between two continents and two seas, have been classified. 24-h backward air trajectories were calculated each hour for three years using the METEX model at a site in the centre of the northern plateau of the Iberian Peninsula where the air flow has scarcely been investigated to date. Rather than the usual Euclidean geometry, spherical trigonometry, together with the kernel regression method, was considered to calculate trajectory distances to the site. Numerical indicators allow for an accurate description of the results. Ranges surrounding the site from E to S evidenced a restriction in the movement of the arriving flow. However, the range to the N showed only a slight effect. A noticeable seasonal contrast was observed between winter, whose distances were the greatest, and summer, which displayed the shortest distances. Trajectory clusters, initially not considered in the METEX model, were obtained with different metrics to determine the air mass pathways reaching the site. Five clusters of trajectories were selected so as to easily explain the directions and distances covered. Regional and long range transport were observed in clusters from the NE, NW and SW. The NE cluster presented an orographic deviation and local processes were limited to the SE cluster. Finally, seasonal analysis revealed singular behaviour during autumn, when local processes centred on the N–S direction.

1. Introduction

In recent years, air mass trajectories have been applied extensively in different research fields, such as meteorology, air chemistry, transport of hazardous substances or effects on humans and animals (Pérez et al., 2015). This paper investigates air mass pathways in the northern plateau of the Iberian Peninsula by means of trajectories calculated with the METEX model (Zeng et al., 2010), which has scarcely been used to date (Kuramoto et al., 2008; Reddy et al., 2008). The main features of this model are its flexibility and ease-of-use, as well as the format of its output files, which may be readily employed in subsequent applications.

The first problem that arises when dealing with a large number of trajectories is deciding how to group them. The simplest and perhaps most widely used procedure to group trajectories is by considering one common property, such as direction. By adopting this approach, trajectories may be classified into sectors with the same angle, forming eight (Donnelly et al., 2012; Tang et al., 1987), or twelve sectors (Ahmed et al., 2014; Khan et al., 2010). However, previous inspection of observations may advocate considering a rough classification based on sectors with different angles. Witt et al. (2010) presented a simple classification with only three sectors. Four sectors are often used (Guo et al., 2011; Kanawade et al., 2012; Tseng et al., 2012), even for long distances (Kim et al., 2007; Lujanienė et al., 2012), with classifications of five or six sectors proving to be less commonplace (Garcia et al., 2011; Đurašković et al., 2012). Sector borders are usually straight lines, although curved lines have occasionally been used (Borbely-Kiss et al., 1999; Zhang et al., 2014a).

Another simple classification of trajectories is based on the date, since air flow is related with the synoptic pattern, which presents a temporal evolution (Atwood et al., 2013). Sometimes only two intervals are considered (Prijith et al., 2012; Osada et al., 2002; Shin et al., 2014), although more time periods may be taken into account (Kaskaoutis et al., 2014; Qin et al., 2012). One modification of this procedure is the classification made from the time spent over certain sectors (Marconi et al., 2014; Wang et al., 2010a).

A classification based on geographical criteria has been widely used. Three regions (Costa et al., 2014; He et al., 2013; Minejima et al., 2012; Müller et al., 2012) or four regions (Artuso et al., 2010; Ma et al., 2013; Nair et al., 2011; Tan et al., 2012) are often taken, with five types of air masses occasionally being employed (Xue et al., 2013). One particular case of this classification is the division

* Corresponding author. Fax: +34 983 423 013.
E-mail address: iaperez@fa1.uva.es (I.A. Pérez).

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between the marine or terrestrial origin of air masses (Avery Jr. et al., 2013; Li et al., 2011; Yan and Kim, 2012).

Another possibility for forming trajectory groups is by means of the target variable of the analysis, such as heavy snowfalls (Bednorz, 2013), ion concentration in precipitation (Osada et al., 2007), or mixing the geographical region and another variable, such as observed changes in ozone levels (David et al., 2011), the precipitation pH (Satyanarayana et al., 2010), or aerosol concentration (Marx et al., 2014). Specific classifications consider the shape of the trajectories (Nzotungicimpaye et al., 2014) or the heights (Osada et al., 2006) and more elaborate criteria include a meteorological classification (Hondula et al., 2010; Wilson et al., 2013).

In contrast to the classification procedures presented, clustering techniques are also frequently used. These methods are more complex than those previously mentioned, since computer calculations are required. Their main advantage is that results are obtained from the application of mathematical equations and are, consequently, essentially objective. The current paper explores this procedure applied to air mass trajectories affecting the northern plateau of the Iberian Peninsula.

The location of the Iberian Peninsula between two continents, Europe and Africa, and two bodies of water displaying different features, the Atlantic Ocean and the Mediterranean Sea, means that it receives a wide variety of air masses. Air mass trajectories have frequently been calculated in the Iberian Peninsula in recent years although most applications of single or clustered trajectories focus on coastal or peripheral sites where land-sea interactions condition the air flow. Several examples may be found following the peninsular coast counter-clockwise. To the SW, transport of air masses from wildfires to the NW determined a pollution event (Adame et al., 2012a). The influence of radionuclides emitted after the Fukushima accident has also been studied in this area (Hernández-Ceballos et al., 2012; Lozano et al., 2011) as has the vertical behaviour and meteorological properties of air masses (Hernández-Ceballos et al., 2013). To the S, polar maritime air masses have been linked with low activities of ^{7}Be and ^{210}Pb (Dueñas et al., 2011). To the NE, a red-dust-rain event whose source was the Sahara has been observed (White et al., 2012) and the main transport patterns have been identified in the Barcelona area (Jorba et al., 2004). To the N, the transport of the bluetongue virus from the S has been analysed (García-Lastra et al., 2012). To the NW, this area's climate does not favour photochemical ozone generation although regional scale transport may determine episodes (Saavedra et al., 2012). Finally, the contrast between terrestrial and marine air masses in rainwater composition has been observed at a western coastal site (Santos et al., 2013, 2014).

Certain trajectory applications have considered sites at some distance from the coast. To the SW, trajectories corresponding to desert dust and forest fire situations have been studied (Obregon et al., 2012), and regional ozone episodes have been described (Domínguez-López et al., 2015). The potential origin of certain kinds of pollen and their transport have been analysed to the SW and S (Fernández-Rodríguez et al., 2014; Hernández-Ceballos et al., 2014a, 2015, 2014b). To the SE, biomass burning particles transported from Canadian forest fires have been observed (Ortiz-Amezcua et al., 2014), radiative properties of aerosols from African desert dust intrusions classified (Valenzuela et al., 2012) and their spatial and temporal distributions modelled (Stein et al., 2011).

The number of recent air mass trajectory applications in the peninsula remains scarce and most focus on the southern plateau. One exceptional ozone episode in Madrid (in the centre of the peninsula) could not be explained by a stratospheric intrusion event suggested by trajectory analysis (San José et al., 2005), and the Eyjafjallajökull volcanic plume was also observed in this city (Revuelta et al., 2012). In the rest of the southern plateau, air mass trajectories have been introduced in the meteorological overview prior to describing air pollution in an industrial area (Adame et al., 2012b). The contribution of northern Africa dust to particulate matter concentration has been studied (Escudero et al., 2006), and air mass patterns have been determined in five provincial capitals (Notario et al., 2014). Contrastingly, few studies have considered air flow in the northern plateau, such as the influence of long range transport on ozone concentrations (García et al., 2005), and the link between night-time CO_2 concentrations and air mass trajectories (Pérez et al., 2012a). This latter research provides the basis for the current paper, which considerably extends the number and length of trajectories in an effort to gain insights into air mass pathways, a topic which has thus far been the subject of scant investigation in the region.

The current paper is divided into two complimentary parts. The first considers the extent of the trajectories calculated by the kernel regression method. The second is devoted to a cluster analysis to investigate air mass pathways affecting the measurement site in the centre of the northern plateau. A key point is that distances were calculated using spherical trigonometry rather than the usual Euclidean metric.

2. Materials and methods

2.1. Experimental description

The measurement site was the Low Atmosphere Research Centre (CIBA), located at 41° 48′ 50.25″ N, 4° 55′ 58.56″ W, at 850 m above MSL in the centre of the northern plateau of the Iberian Peninsula (Fig. 1), which is surrounded by three mountain ranges (Cantabrian, Iberian and Central) with some peaks reaching around 2500 m. One day backward trajectories were calculated with the METEX model each hour for three years, beginning on 15 October 2010. This was done in order to combine the results of the current study with CO_2 concentrations in further research (Pérez et al., 2014), analysis of which lay outside the scope of this paper. One day back trajectories are known to be on the border between mesoscale (short trajectories) and macroscale (long trajectories) processes.

The height of the CO_2 monitor, 8 m above ground, was used for trajectory calculations, and wind direction measurements, 10 m above ground, were used for comparison with values provided by the trajectory model.

2.2. Theoretical considerations

2.2.1. Distance analysis

METEX provides the coordinates (x, y, longitude and latitude respectively) for each point of every trajectory calculated. The distance and direction of every point B (x,y) of the trajectory to point A at CIBA (x_1,y_1), was determined with the aid of a third point, the North Pole, C, which together form a spherical triangle presented in Fig. 2(a). In this triangle, arcs a and b are part of the meridians. Arc c, which represents the distance between A and B, is calculated by the Sinnott equation (Snyder, 1987)

$$\sin\left(\frac{c}{2}\right) = \left\{\sin^2\left[\frac{(y-y_1)}{2}\right] + \cos y_1 \cos y \sin^2\left[\frac{(x-x_1)}{2}\right]\right\}^{\frac{1}{2}}. \quad (1)$$

The difference in longitude between points A and B is given by the angle associated with point C by the equation

$$\cos c = \cos b \cos a + \sin b \sin a \cos C. \quad (2)$$

The direction for point B is obtained from angle A.

Once distances and directions were calculated, a kernel regression was used to obtain distance d associated with direction θ.