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Cloud to ground lightning activity over Portugal and its association with circulation weather types

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ABSTRACT

The Cloud to Ground lightning activity is analyzed for the Portugal mainland during the 2003–2009 period. Both inter-annual and intra-annual variability are clearly present. Winter months present a smaller number of Cloud to Ground discharges than the remaining warmer seasons. The highest density of discharges in the colder months is found in the coastal regions. On the contrary, for the remaining seasons, Cloud to Ground discharges tend to occur much more frequently in the interior areas of Portugal. A diurnal cycle of the Cloud to Ground discharges activity is clearly present in spring, summer and autumn, with maximum activity being found in the afternoon hours. The relationship between the Circulation Weather Types and Cloud to Ground discharges allowed us to distinguish which types are most frequently associated to lightning activity and also which types are the most favorable to present severe lightning episodes. Moreover, the analysis of additional meteorological fields allowed, at a seasonal scale, to discuss different mechanisms for lightning activity triggering: frontal activity, cut-off lows, and summer thermal lows are the most relevant in Portugal mainland. A case study is also provided for the most notorious event in terms of the total number of Cloud to Ground discharges (10th and 11th of September of 2007).

1. Introduction

Atmospheric circulation at the synoptic scale can be described in different ways and using a wide range of different sorts of circulation-based classifications (Philipp et al., 2010). Circulation weather types are generally specific to a given location and result from the examination of synoptic weather data usually on regular gridded fields, often based on sea level pressure (SLP) or geopotential height at 500 hPa (gpt500). They are typically defined for each day or group of consecutive days as a simple way to reflect the local circulation that actually occurred (e.g. Hess and Brezowsky, 1952; Jones et al., 1993; Kruizinga, 1979; Philipp et al., 2007). The availability of automated classification schemes coupled with the generalised use of several 3-D grid based reanalysis datasets (e.g. NCEP, ECMWF) in the last two decades has increased considerably the interest and applicability to establish links between circulation weather types and surface climate, environmental and socio-economic variables. In fact, recent applications of different circulation weather type classifications (CWT) can be found covering a wide range of purposes, such as climatological studies (e.g. Garcia-Herrera et al., 2007; Huth, 2001; Lorenzo et al., 2008; Pineda et al., 2010; Ramos et al., 2010), biometeorology (Laaidi, 2001), air quality (Buchanan et al., 2002; Demuzere et al., 2009), medium-range forecasting (James, 2008) and also to assess the accuracy of the Coupled Global Circulation Models (CGCMs), as well as for analyzing changes in CWT under

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future scenarios of climate change (Demuzere et al., 2008; Lorenzo et al., 2011).

Several studies point out that changes in the climate variables at the Earth's surface are often a result of changes in the frequency of occurrence of CWT (e.g. Fowler and Kilsby, 2002; Goodess and Palutikof, 2002; Jones and Lister, 2009; Kyselý, 2008; Paredes et al., 2006).

Nowadays, the classification of synoptic weather situations gains added importance within the context of the European Cooperation in Scientific and Technology (COST) Action (COST 733—http://www.cost733.org), the main objective of which is to develop different automated CWT classification and objective measures to compare these classifications when applied to different variables for various European (sub)regions. Readers interested in the outcomes of the project area referred to a special issue based on the COST 733 results and that were published recently (Huth et al., 2010).

In the study reported herein, we used an automated version of synoptic CWT that was initially developed for the British Isles (Jones et al., 1993), and later adapted to western Iberia (Paredes et al., 2006; Trigo and DaCamara, 2000). This classification describes the regional atmospheric circulation in terms of a small set of relatively simple circulation parameters, in this case, the mean flow and shear vorticity.

In recent years several studies have been published establishing objective links between CWT and lightning activity (e.g. Lericos et al., 2002; Pineda et al., 2010; Tomás et al., 2004). Lightning data constitutes a relatively new form of meteorological information due to the fact that most lightning location networks have only been installed in the last two decades, thus allowing a recent increase of studies on this topic. Lightning is associated to a number of significant meteorological factors. Physical mechanisms and associated theoretical models linking temperature with lightning are discussed in Williams et al. (2005). Relations between lightning activity and sea surface temperature (e.g. Altaratz et al., 2003; Holt et al., 2001) or atmospheric aerosol (e.g. Andreae et al., 2004; Orville et al., 2001; Steiger and Orville, 2002) have also been discussed in recent years. In addition, lightning activity can be used as a prognostic tool to estimate convective rainfall (e.g. Petersen and Rutledge, 1998; Rivas Soriano and de Pablo, 2003).

In terms of impacts, lightning plays not only a role as a major cause of natural forest fires in mid-latitudes regions (e.g. Podur et al., 2003; Vasquez and Moreno, 1998; Wierzchowski et al., 2002), but also as a source of nitrogen oxide, which by itself is related to tropospheric ozone formation (Bond et al., 2002; Kaynak et al., 2008; Martin et al., 2007). Lightning also has others socio-economical impacts, particularly in human casualties (Curran et al., 2000; Elsom, 1993), property damage, or even in electricity transmission and distribution (Holle et al., 2005; Mitsche, 1989; Mills et al., 2010).

Temporal and geographical variations in lightning activity in the Iberian Peninsula have been analysed over a 10 year period (1992–2001) by Rivas Soriano et al. (2005). More recently Pineda et al. (2010) studied the CWT related to lightning activity over Catalonia and the Principality of Andorra, two regions that have particularly high values of lightning activity. However, despite the large lightning dataset available for Portugal, an equally comprehensive assessment has not been attempted.

The major aim of this paper is to study the main characteristics (geographical distribution, intra and inter-annual variability, diurnal cycle, and first stroke peak current) of cloud–ground flashes recorded in Portugal mainland for the 2003–2009 period. In addition, the relationship between CWT and cloud–ground (CG) flashes occurrence is also provided.

The remainder of the paper is organized as follows. In Section 2, we describe the different data sets and the methodologies used in the analysis. In Section 3.1 we characterized the occurrence of CG discharges in mainland Portugal, while in Section 3.2 we analyze the impact of CWT on the CG discharges. In Section 3.3 we studied in more detail the synoptic fields of the unstable days and in Section 3.4 a case study is provided for the most notorious episode in terms of the total number of CG discharges. Finally, Section 4 presents the conclusions.

2. Data and methodology

2.1. Lightning data

The Portuguese Lightning Location System (LLS) has been in service since June of 2002 and is operated by the national weather service—*Instituto de Meteorologia* (IM). It is composed of 4 IMPACT 141T-ESP detectors, which are installed over Portugal in Braga, Castelo Branco, Alverca and Olhão (Fig. 1). Since 2005 the IM receives data from the Spanish National Meteorology Institute (AEMET, Spain) from five sensors located nearest to the border (Jerez de la Frontera, Armilla, Getafe, Matacán and Santiago—Fig. 1), thus improving the accuracy of the network.

According to Rodrigues et al. (2008), the software manufacturer indicates an error in spatial location, over the continental area of Portugal, which varies between 500 m and 1 km for the semi major axis of a 50% probability ellipse. The manufacturer also assures, for the same area, efficiency higher than 90% for strokes with peak current greater than 5 kA. These values were found by using the detection efficiency of each sensor (based on the threshold value and gain sensor), which was supposed to be the same for all sensors. In addition, detection efficiency varies over the continental area of Portugal. Consequently, and following the work of Rivas Soriano et al. (2005), we also did not attempt to correct the data for detection efficiency, considering the lightning data of the measured values. Therefore, annual and spatial variations may be slightly biased by the characteristics and changes in the lightning detection network.

The network uses a combination of time-of-arrival (TOA) and magnetic-direction-finding (MDF) to locate lightning. Furthermore, the system also estimates several other proprieties as: the current peak, multiplicity (number of strokes in a flash), and type of discharge (cloud–ground and cloud–cloud). In addition, according to Jerauld et al. (2005), current peaks are underestimated by lightning locating systems.

In this work we will only focus in the cloud–ground (CG) discharges that strike Portugal mainland, i.e., we will disregard all other discharges. Information about semi major axis (a measure of the location error) is also available in the dataset. An initial quality control was done in order to ensure that CG discharges with an error larger (semi major axis) than 25 km were excluded from the analysis (which

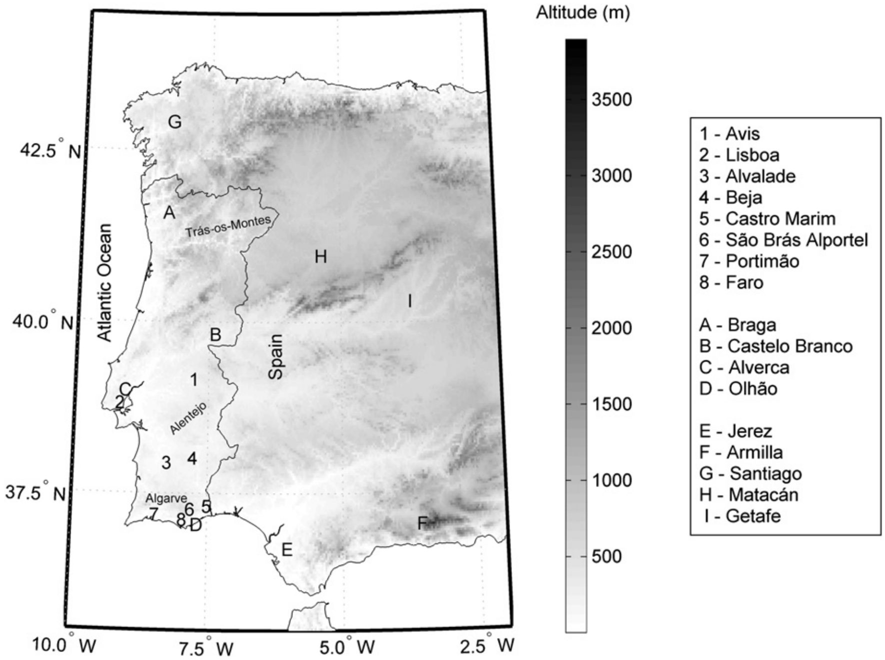

Fig. 1. The position of the nine (four in Portugal and five in Spain) Lightning Location System detectors are referred in capital letters, while the surface weather stations used for precipitation totals are represented by numbers. Portuguese regions referred in the text are also identified in the figure.

corresponds to 4% of all data). At the synoptic scale employed in this work, the 25 km threshold was considered sufficient. If we were analyzing a finer scale (e.g. CG discharges striking at transmission electric systems) a smaller threshold would be appropriate.

2.2. Large scale meteorological fields

All large-scale meteorological fields used in this work were obtained from the National Center for Environmental Prediction (NCEP) database. In this work we use two reanalysis datasets. First we use the daily mean data retrieved from NCEP/NCAR reanalysis data (Kalnay et al., 1996) on a 2.5° grid data resolution. The variables retrieved are: sea level pressure (SLP), relative humidity at the 925 hPa (hr925), 850 hPa (hr850), 700 hPa (hr700) levels, the temperature at the 925 hPa level (t925), and geopotential height at the 1000 hPa (gpt1000) and 500 hPa (gpt500) levels. Furthermore, and taking into account the necessity to use some type of instability indices, we have retrieved the *Convective Available Potential Energy* (CAPE) and the *Lifted Index* (LI) from the NCEP Final Analyses of the Global Tropospheric Analyses (NCEP FNL data; FNLDOC/NOAA/NWS/NCEP, 2000) at 1° grid resolution.

2.3. Daily circulation weather type classification

The classification used herein is an automated version of the Lamb weather type procedure, initially developed for the United Kingdom (Jones et al., 1993), and often named circulation weather types (CWT). This method has successfully been applied to Portugal mainland by Trigo and DaCamara (2000), where a comprehensive study linking these CWT to precipitation in the region was performed. Using an algorithm previously developed by Trigo and DaCamara (2000), we computed the daily CWT for the 1948–2010 period by means of the daily SLP retrieved from the NCEP/NCAR reanalysis data (Kalnay et al., 1996). Since the availability of the lightning data is restricted to the period spanning from 2003 to 2009 we extracted, for the correspondent period, the daily CWT from the initial 1948–2010 dataset. The circulation conditions were determined using the geostrophic approximation and adopting physical or geometrical parameters, such as the direction and strength of airflow, and degree of cyclonicity based on 16 grid points. In order to work out a practical, though reliable, statistical analysis scheme, the 26 circulation types were re-grouped into ten basic ones. To do so, we adopted a similar approach to Jones et al. (1993) and Trigo and DaCamara (2000): each of the 16 hybrid types was included with a weight of 0.5 into the corresponding pure directional and cyclonic/anticyclonic types (e.g. one case of ANE was included as 0.5 in A and 0.5 in NE). Therefore, we obtain 10 circulation types, eight driven by the direction of the flow (NE, E, SE, S, SW, W, NW, and N) and two by the shear vorticity (cyclonic or anticyclonic).

Ten distinct CWT are therefore considered, including 8 directional types dominated by strong non-rotational flow (within 45° sectors), and two other CWT dominated by high absolute values of vorticity (cyclonic and anticyclonic types). A comprehensive description of this methodology may be found in Trigo and DaCamara (2000).

3. Results and discussion

3.1. Characterising the occurrence of Cloud–Ground discharges

3.1.1. Inter-annual variability

The lightning observation dataset is characterised by large temporal and spatial variability in the number of occurrences and geographical distribution of CG discharges. The inter-annual variability of the spatial density distribution (given by the number of flashes/km^2) relative to all CG discharges from 2003 to 2009, on a 0.2°×0.2° grid, is shown in Fig. 2. It is immediately noticeable the existence of a high inter-annual variability of the CG discharges, with low activity years in 2003 and 2005, while a conspicuous maximum was achieved in 2007. Moreover, as pointed out earlier, there are clear

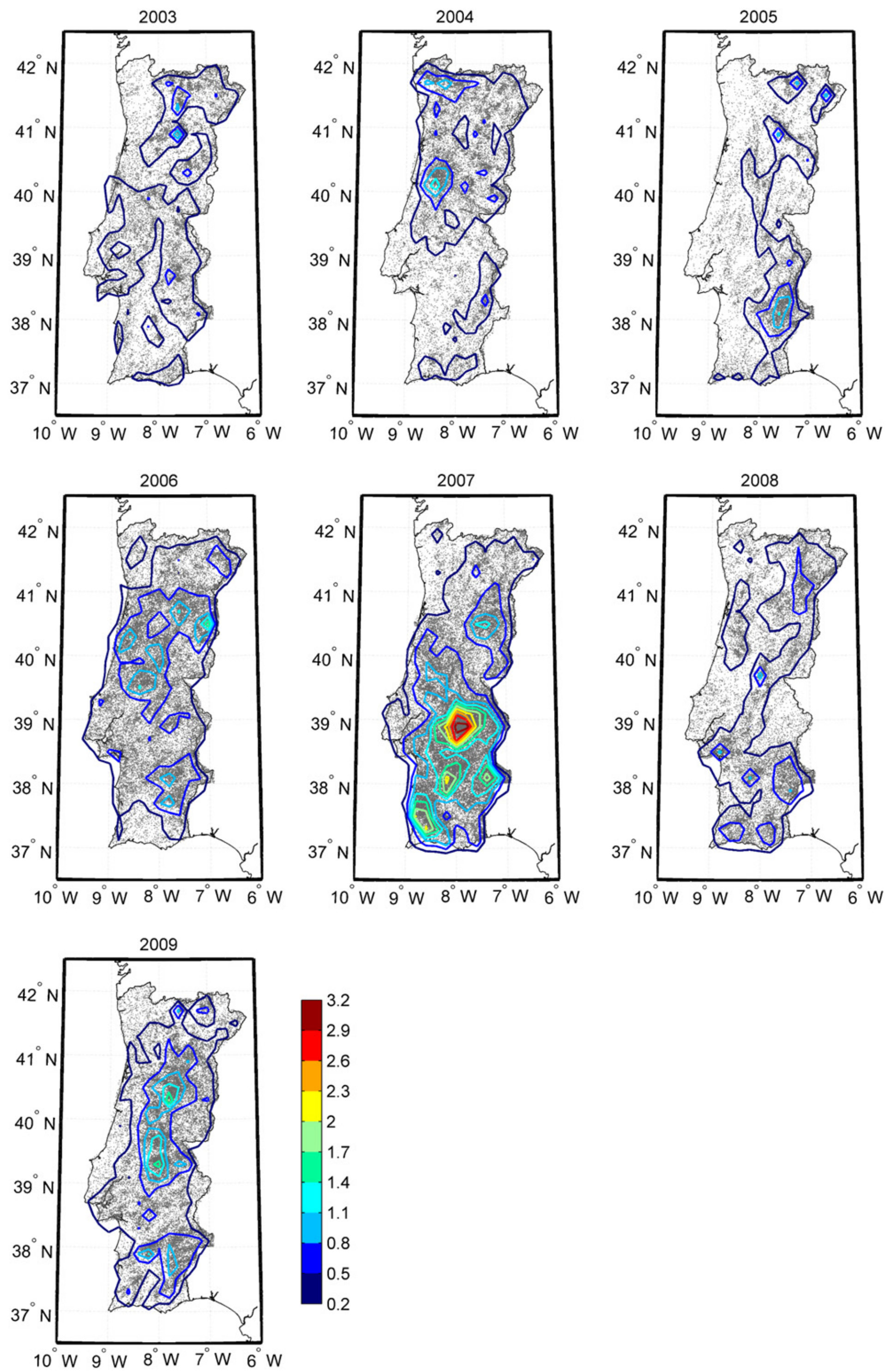

Fig. 2. Spatial density distribution of CG discharges in coloured contours. Values given as number of discharges/km^2 per year over a regular 0.2°×0.2° grid. All effective CG discharges for each year are represented by grey dots.

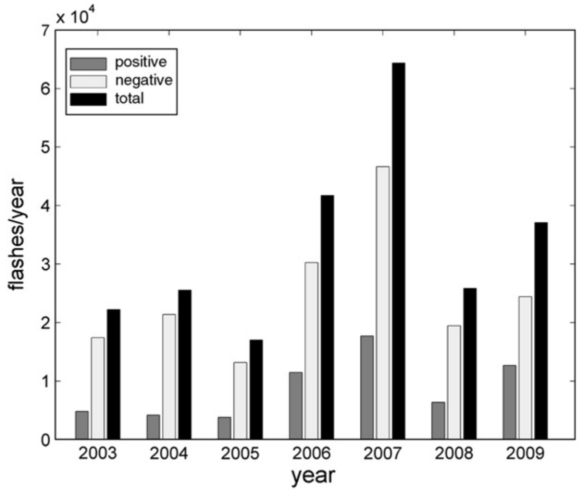

Fig. 3. Inter-annual variability of the number of CG discharges per year: positive (dark grey), negative (light grey) and total (black).

spatial inhomogeneities, particularly in what concerns the location of the maximum CG discharge occurrences being non-uniform throughout the years. Some years appear to be dominated by a meridional gradient (e.g. 2004 and 2007) while others present a more zonal configuration (e.g. 2005, 2008 and 2009). Despite this high variability in space, we can associate some regions with higher probabilities of showing high density CG discharge values (up to 1.4 flashes/km^2), namely in the southeast (southern part of Alentejo), northeast (Trás-os-Montes) and central Portugal (see Fig. 1 for region identification). Nevertheless, when compared to other regions in eastern and northern sectors of the Iberian Peninsula (especially the Pyrenees and the Mediterranean coastal sector), these values can be considered relatively low (Pineda et al., 2010; Rivas Soriano et al., 2005). Finally, Atlantic coastal areas present very low density of CG discharges.

The total number of CG discharges (positive and negative) per year is shown in Fig. 3. During the seven-year period, there is a clear separation in the number of positive and negative discharges, which corresponds to a total of 26.1% positive and 73.9% negative discharges. Results confirm that there is a minimum of CG discharges in 2005 (around 18,000 discharges) and a maximum in 2007 (roughly 65,000 discharges). However, it must be stressed that these discharges can often be clustered in a relatively small number of days of outstanding activity. In this regard, it is worth to notice that the two single days with the highest number of CG discharges within the considered domain have occurred on the 10th and 11th of September of 2007 (see Section 3.4). Moreover, the total number of discharges for these two 2007 days (near 15,000 discharges) is of the same order as the total discharges for the year 2005 (approximately 18,000). These two days are also responsible for the appearance of a maximum value of discharge density (3.2 flashes/km^2) in the year 2007 in the central/southern part of Portugal (Fig. 2).

To further analyse the frequency characteristics of CG discharges we have also computed the number of days per year with CG higher than 0, 7 and 127, with the results being shown in Fig. 4. Choice of threshold values (7 and 127) was based on the fact that these values correspond to the 80 and the 90 percentiles of the CG discharges distribution. Results show that days per year with CG higher than the 90 percentile are not very frequent, ranging between 20 days in 2005 and around 50 days in 2007. Despite this, the amount of days with CG discharges higher than 127 is relatively stable throughout the years, around 35 days per year. As expected, as we get to the lower classes of CG discharges (above 7 and above 0 CG discharges per day), the number of days per year increases with an average value around 120 days per year with at least one CG discharge.

3.1.2. Intra-annual variability

It has been shown before that the monthly Iberian Peninsula CG discharge regime varies considerably throughout the year, at both the seasonal and monthly scales (Rivas Soriano et al., 2005). The seasonal distribution of all individual CG discharges is given in Fig. 5, where the corresponding density distribution (representing the number of flashes/km^2) on a 0.2°×0.2° grid is also represented. The first obvious result is the large seasonal variability found in the density of the flash distributions, with winter months presenting much smaller number of CG discharges when compared with spring but particularly with summer and fall. Interestingly, one can notice appreciable differences in the spatial distributions of CG discharges by season. During the winter months (DJF) the highest number of CG discharges can be found in coastal areas, with a maximum just south of Lisbon (Setúbal Peninsula) with a density of 0.8 discharges/km^2. The main responsibility for this spatial pattern corresponds to the frequent travelling lows that cross the Atlantic in winter. However, if one applies a finer temporal comb it becomes immediately obvious that this particular maximum results from a large extent from a single event, namely an outstanding sequence of convection cells that affected the region on the 18 of February of 2008, provoking widespread flooding and traffic havoc (Fragoso et al., 2010). In spring (MAM), the spatial distribution is more homogenous through the entire domain, with the highest density being found in inland areas, especially in southern Portugal (Alentejo province).

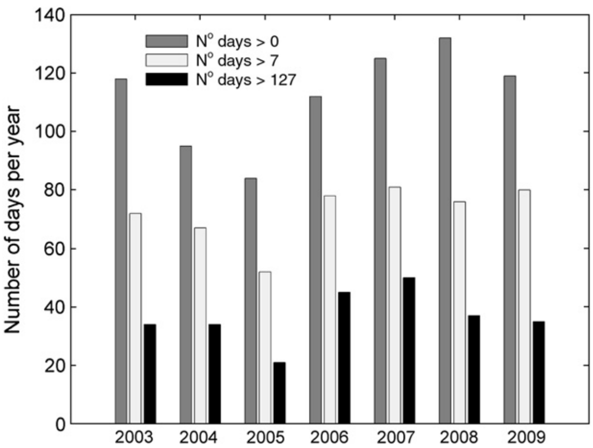

Fig. 4. Inter-annual variability of the number of days (per year) with: >0 (dark grey), >7 (light grey), >127 (black) CG discharges in a day.

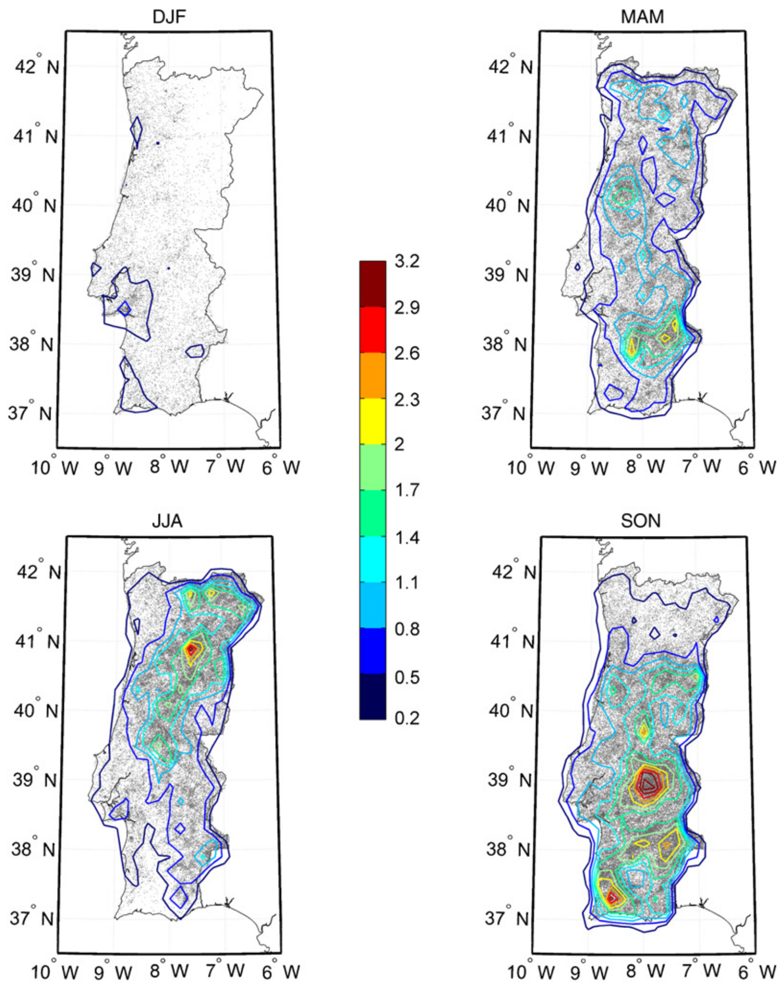

Fig. 5. Seasonal spatial density distribution of CG discharges in coloured contours. Values given as number of discharges/km^2 per year over a regular 0.2° × 0.2° grid. Geographical density distribution (0.2° × 0.2° grid) of CG discharges/km^2 per season. All effective CG discharges for each year are represented by grey dots.

In summer months (JJA), the highest values of CG density can be found in the north-eastern sector of Portugal (Trás-os-Montes), with lower values in the coastal regions and Algarve. The northeast of Portugal is characterized by a complex terrain, with orographic systems, which are favorable for the generation of uphill currents during the hot weather, thus allowing the creation of cumulonimbus clouds (Ćurić et al., 2003). Finally, during autumn (SON), the atmosphere is often characterised by colder and moister air masses advected from the Atlantic ocean, which can interact with the still reasonably warm Iberia continental mass (Martín et al., 2004; Valero et al., 2009). This situation can foster instability that favours thunderstorms, increasing CG discharges all over the country, although in a lesser extent over the north of Portugal. A more detailed synoptic analysis of the different mechanisms responsible for CG discharges will be presented later on (see Section 3.3).

Seasonal analysis often hide significant changes within each season, thus we present a more detailed desegregation at the monthly scale, for total, positive and negative discharges (Fig. 6a). This intra-annual analysis is dominated by a large peak in September (27.2% of the annual total and within that month corresponds to a total of 28.8% of positive discharges and 72.2% of negative discharges) and a smaller but clear secondary maximum in spring (April, May and June). This monthly assessment confirms that seasonal averages can conceal large differences between diverse months, this being particularly impressive for summer and fall months. On the contrary, winter months (December–March) reveal a consistent lower value of CG discharges, with less than 2% for all months. Interestingly, it can be seen that throughout the year (with the exception of December), the percentage of negative CG discharges is clearly higher than the percentage of positive CG discharges. Once again observed results for September can be slightly misleading (i.e. biased) because of the previously mentioned episode during the 10th and 11th of September 2007.

Even though the winter months have a particularly low frequency of CG discharges (Fig. 6a), the highest mean intensity values for the first stroke peak current are found for December, January and February (Fig. 6b), both for positive and negative discharges. On the contrary, minimum intensity values are found for the summer months. Moreover, the minimum for positive flashes (September) occurs clearly

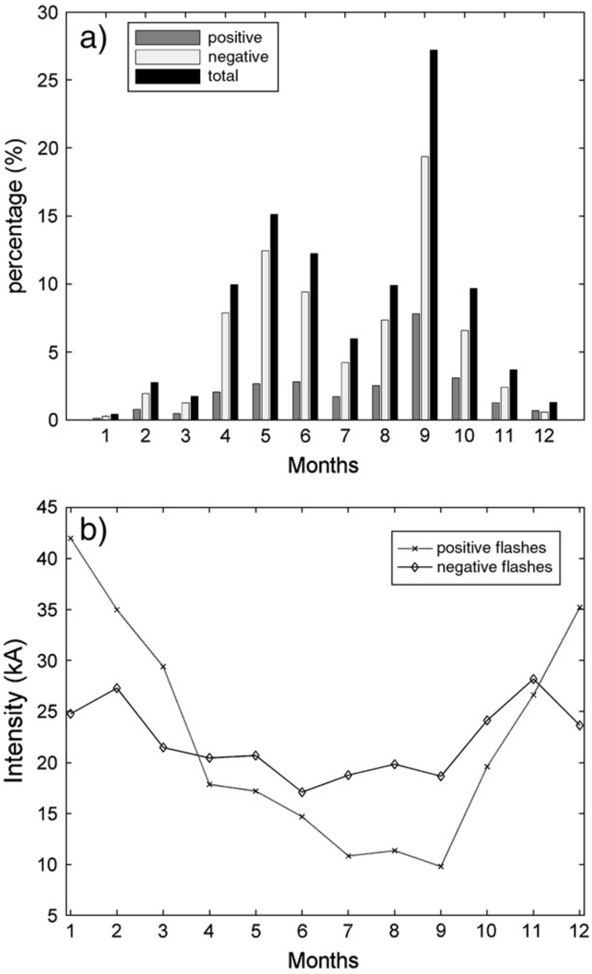

Fig. 6. a) Intra-annual variability (in percentage) of positive (dark grey), negative (light grey), total (black) CG discharges; b) the corresponding intra-annual variability of the mean intensity of positive and negative discharges.

later than the one found for negative flashes (June), confirming the results obtained for the Iberia Peninsula in the 1992–2001 period by Rivas Soriano et al., in 2005. One should note that lightning detection networks tend to misidentify cloud–cloud discharges by CG discharges for peak currents in the 10 to 15 kA range, a fact that may result in an underestimation of the mean peak current (Biagi et al., 2007; Cummins et al., 1998; Wacker and Orville, 1999).

Multiplicity results are not presented, since an exhaustive characterization of CG discharges physics is not the main purpose of this work. In addition, Rivas Soriano et al. (2005) found for the Iberia Peninsula that the average multiplicity is 2.0 for negative flashes and 1.1 for positive flashes, and that there is intra-annual variability for negative discharges but not for positive discharges.

3.1.3. Diurnal variability

The different synoptic mechanisms responsible for CG discharges at the seasonal level will have impact on the average diurnal cycle of the discharges. The total number of CG discharges over Portugal per hour for the 2003–2009 period is analyzed in Fig. 7, at the seasonal scale.

The diurnal cycle obtained for spring, summer and autumn shows the classic shape with a clearly defined maximum in the afternoon hours between 16 UTC and 18 UTC, decaying throughout the night, with minimum activity during early morning hours. Nevertheless, in summer and autumn months a secondary peak of activity appears near sunrise. The prominent afternoon peak in lightning activity is related to the enhancement of vertical motions after the hours of maximum daytime heating. The summer mean daily maximum is observed 1 h later than the one observed for spring and autumn. In any case, it is clear that convective activity over Portugal mainland responds to the diurnal cycle of solar radiation, which is in line with other results found for land areas in mid-latitudes (e.g. Altaratz et al., 2003; Lericos et al., 2002; Novák and Kyznarová, 2010). Contrasting with the previous description, the winter diurnal cycle is almost absent, presenting a modest peak early in the afternoon (13 UTC). This weak diurnal cycle during the coolest and less sunlit months once again reinforces the intimate relation between solar radiation and convective instability. A work by Lay et al. (2007) focused on this diurnal cycle issue at both global and continental scales, distinguishing lightning activity over land and sea areas. Over land areas it is clear that a large diurnal cycle exists, with peak activity during the afternoon hours. Overseas the authors state a much less pronounced cycle, with maximum activity near sunrise, having a flash density similar to continental areas during that period of the day. Bearing this in mind, and although we only considered CG discharges over land areas of Portugal, we must take into account the possibility that convective activity originated over sea and coastal areas (and later advected inland) could be responsible for the existence of a minor peak in lightning activity near sunrise over Portugal on summer and autumn months.

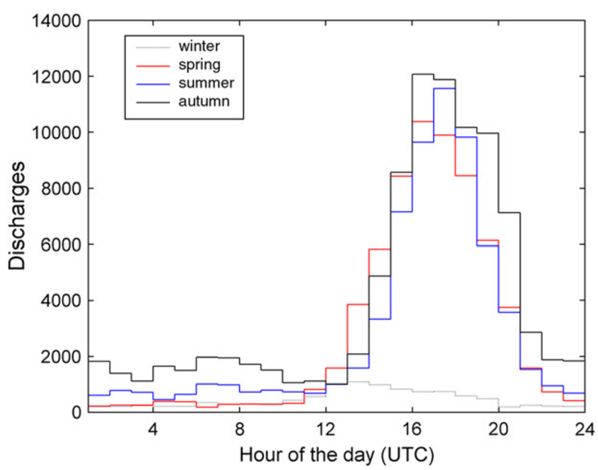

Fig. 7. Hourly (UTC) variability of the number of CG discharges for winter (grey), spring (red), summer (blue) and autumn (black).

3.2. The impact of atmospheric circulation types

3.2.1. Atmospheric circulation weather types (CWT)

The characterization of the atmosphere over most European regions, by means of CWT is, nowadays, a relatively easy procedure for obtaining a comprehensive description of the complex atmospheric circulation for a given day (Huth et al., 2008; James, 2007; Philipp et al., 2010). Each CWT, for a certain region, is often related with climatic variables at the surface, e.g. temperature and precipitation regimes (e.g. Jones and Lister, 2009; Trigo and DaCamara, 2000). Here we use the same methodology as Trigo and DaCamara (2000) to retrieve the daily CWT for the 2003–2009 period (see Section 2.3). The annual composites for that period for the 10 CWT are shown in Fig. 8 and the corresponding short description for the observed SLP features of each type is presented as follows:

- NE (northeasterly) are days characterized by an extended Azores high pressure to the northeast and by low pressure over the Mediterranean region;
- E (easterly) are synoptic situations characterized by an anticyclone between the British Isles and the Iberian Peninsula;
- SE (southeasterly) are characterized by low pressure regions extending from Madeira to the east of the Azores Islands and high pressure over Northern Europe;
- S (southerly) are situations characterized by low pressure east of Azores, and by high pressure over central Europe;
- SW (southwesterly) are days characterized by a weakening of the Azores high pressure and strong low pressure located between Iceland and the Azores;
- W (westerly) are days with weather circulation characterized by the setting of the Azores high pressure around 30°N and by low pressure centres west of the British Isles;
- NW (northwesterly) are characterized by the localization of Azores high pressure between the Azores and Madeira Islands and low pressure centres over northern France;
- N (northerly) are days characterized by the presence of the Azores high pressure near the Azores Islands and low pressure over southern Europe and the Mediterranean basin;
- C (cyclonic) are synoptic situations characterized by a low pressure centre over the western Portuguese coast, sometimes accompanied by a blocking anticyclone located between Iceland and the British Isles;
- A (anticyclonic) are days characterized by a extended high pressure centre between the Iberian Peninsula and the Azores Islands.

The annual and seasonal frequency (in percentage) for the 10 CWT during the 2003–2009 period are shown in Tables 1 and 2 (column identified as CWT). At the annual scale, the A and the NE types are most frequent, followed by the N type. In winter the dominant type is A, with a frequency of 45.8%, while none of the remaining patterns present frequencies above 10%. In spring, although the CWT frequency is more evenly distributed once again, the A type is the most frequent, followed by northern flow types such as NE and N. In summer, the NE and A types dominate, with roughly 25% each closely followed by the N type. Finally, in autumn, the A type is once again the most frequent CWT, followed by the NE and C types. To sum up, in general the A the NE types are the most frequent in Portugal.

3.2.2. Relationship between the Circulation Weather Types and Cloud to Ground discharges

An analysis of lightning events per weather type (CWT) for the period 2003–2009 is shown at both the annual (Table 1) and seasonal (Table 2) scales, respectively. As we mentioned before, the first column (CWT) represents the percentage of total days with each specific CWT; the second column represents the ratio of lightning days (rLD) for each specific CWT frequency; the third column simply shows the total number of lightning days (LD) for each CWT; and the last column shows the contribution (CG) of each CWT to the total CG discharges (in percentage). The last line of each table corresponds to the sum of all CWT type lines, except for the rLD column, where it corresponds to the absolute lightning days ratio. Note that the rLD, LD and the CG that occur during days characterized by a hybrid CWT (see Section 2.3) were redistributed with a weight of 0.5 into the corresponding pure directional and cyclonic/anticyclonic types, following the same approach adopted for the CWT (see Section 2.3).

The classification from columns rLD, LD and CG enables us to distinguish between CWT frequently associated to lightning episodes (regardless of these episodes being severe or not), and CWT that are favorable to severe lightning episodes (very high number of CG discharges by episode), apart from these events being rare or not. To be completely clear about the meaning of each number we can look in detail to the two CWT dominated by either anticyclonic (A) or cyclonic (C) vorticity, at the annual scale. The A type corresponds to 35% of all days, while C type represents only 8.4%, however the vast majority of A days are not related to CG discharges (ratio of only 11.0%) while most C type days are indeed characterized by some level of CG activity (ratio of 74.7%). As a consequence, the large number of A type days is responsible for only a small fraction of total CG discharges (6.0%) while the much smaller percentage of C type days contributes disproportionately higher (26.3%).

Considering the whole period at the annual basis (Table 1), we find that almost a third of the days registered (30.7%) at least one CG discharge over Portugal, with the highest number of thunderstorm days happening in autumn (38.9%) and spring (34.6%). Now focusing on CWT, we find that the NE and C types contribute with the highest number of lightning events in absolute terms: C with 160 days and NE with 123 days (total study period—2557 days). These CWT also present the two largest fractions of the total number of strikes (NE—37.6%; C—26.3%). As we can see, despite having a smaller number of thunderstorm days, the NE type is associated to a considerably higher amount of ground strikes than the C type. This means the latter is related to a superior number of days with not too severe events. Nevertheless, the NE type is not on the top three CWT in terms of lightning days ratio (rLD). Only 33.9% of NE days are associated to convective episodes. The SW, W, and NW types surpass the previous, but present a much smaller contribution for the percentage of CG discharges. This apparent contradiction reflects the fact that the latter types are frequently associated to weak thunderstorms with few discharges.

Looking more carefully at a seasonal level (Table 2), the C type, is fairly distributed by the four climatic seasons, and frequently associated to lightning activity, although ratios diminish considerably in summer months. On the other hand, episodes associated with the NE type are rare in winter months, but they are the most important in other seasons. In

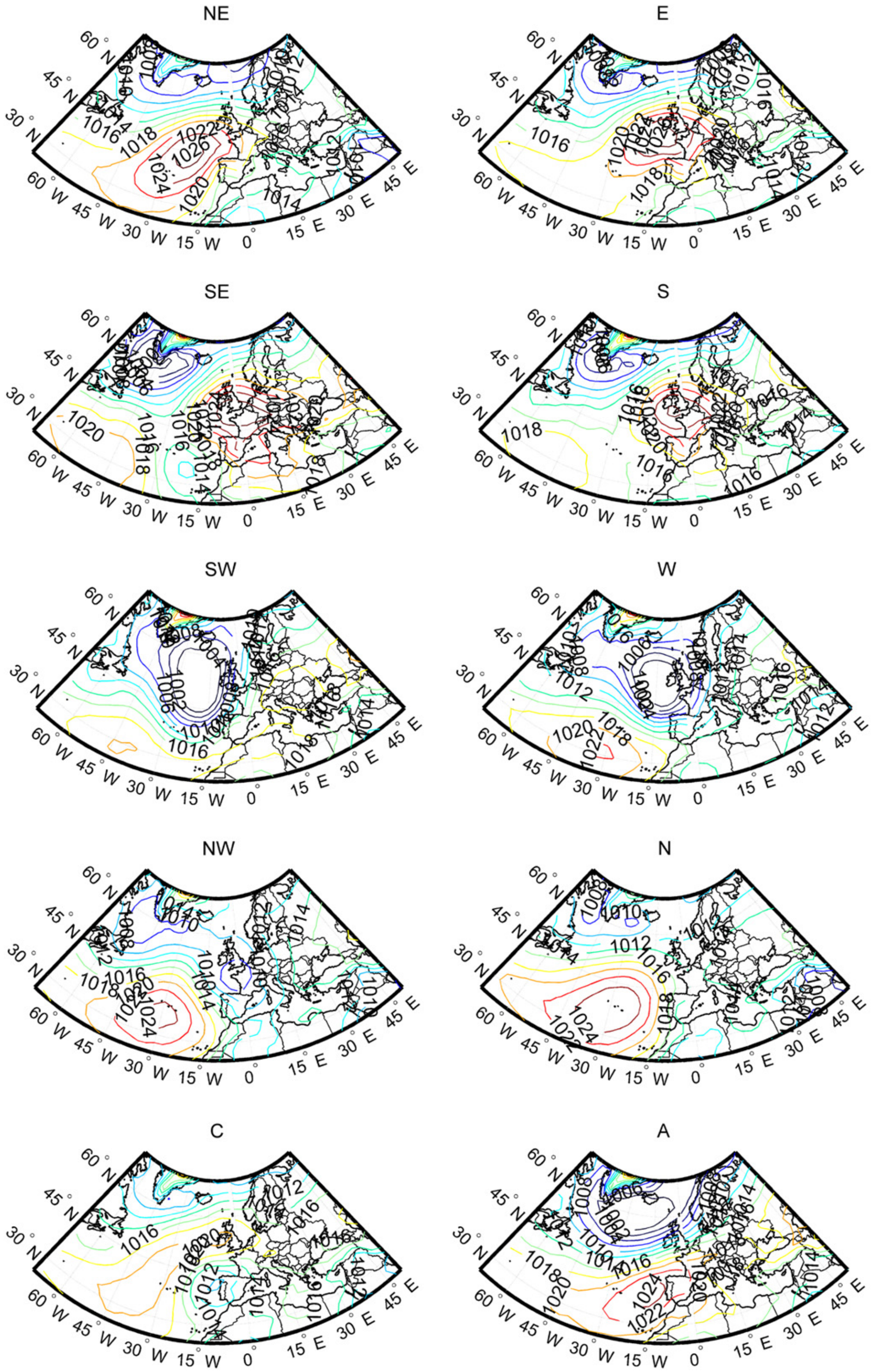

Fig. 8. Annual average composite SLP field of the 10 circulation types for the 2003–2009 period.

Table 1
Circulation weather type (CWT) frequency, lightning days ratio (rLD), total lightning days (LD) and Cloud–Ground discharges (CG) frequency during the 2003–2009 period, on an annual basis. The last line of each table corresponds to the sum of all CWT type lines, except for the rLD column, where it corresponds to the absolute lightning days ratio. (Bold values represent the three dominant situations).

	Annual average			
	CWT (%)	rLD (%)	LD	CG (%)
NE	14.2	33.9	**123**	**37.6**
E	6.5	32.1	53	7.4
SE	3.1	19.2	15	0.8
S	4.0	32.3	33	3.3
SW	5.0	**42.6**	55	3.4
W	7.7	**49.8**	98	3.0
NW	6.4	42.2	69	4.2
N	9.9	32.2	82	**8.3**
C	8.4	**74.7**	**160**	**26.3**
A	35.0	11.0	**99**	6.0
	100.0	*30.7*	*785*	*100.0*

summer it is responsible for 45.7% of strikes. The relation between this type (NE) and very active thunderstorms in warm months is evident. The C and W types are responsible for the highest number of thunderstorm days in winter (36 and 29 days respectively). The A type corresponds to the third highest number of thunderstorm days, but associated only to 1.1% of total winter CG strikes, which means this CWT is responsible for reasonably frequent, but very weak thunderstorms. As seen before (Section 3.1), the number of strikes in winter is much smaller than during the three warmer seasons. Nevertheless, there are some isolated cases of severe events in winter, with very high number of lightning strikes. These are essentially associated with the cyclonic C type CG column (46.7% of total winter discharges). The most prominent case corresponds to the 18th of February of 2008, where a very important convective episode occurred in the surrounding areas of Lisbon. In fact, this episode corresponds to the new absolute record precipitation in 24 h in Lisbon (129 mm) since 1863 (Fragoso et al., 2010).

In spring, the two most important types are C and NE, and as said before, the NE is related to thunderstorms with larger number of discharges (28.8%). In this season, the N type is also relevant, as it is responsible for 31 thunderstorm spring days (and 18.1% of total spring CG discharges). This CWT is highly related to thunderstorm outbreaks in this transition period, as this is the season where remaining important cold air masses at high levels can coexist with high solar radiation forcing. This will be seen in more detail in the next section. Once again, the NW and A CWT are responsible for relatively frequent weak thunderstorms.

We should once again stress that in summer the NE type is by far the most prominent pattern associated with thunderstorms over Portugal. It was responsible for thunderstorms in 44 summer days during the 2003–2009 period, and for 45.7% of total CG discharges. Other CWT, such as the C and N present some contribution, but less significant than the NE type. Nevertheless, some very active days with cyclonic circulation have occurred in summer, as this type is responsible for 23.6% of total strikes. Although responsible only for 10 thunderstorm days, the E type is the third in terms of CG percentage, which means that summer storms under this type of circulation are not very frequent, but rather strong.

The CWT responsible for most lightning episodes in autumn are somewhat similar to those found in summer, with the NE being responsible for most important events (42.1% of total autumn CG discharges). Once again the C type

Table 2
Same as Table 1, but on a seasonal basis.

	Winter					Spring			
	CWT (%)	rLD (%)	LD	CG (%)		CWT (%)	rLD (%)	LD	CG (%)
NE	6.1	19.5	8	1.7	NE	12.8	44.5	**37**	**28.8**
E	7.6	23.1	11	11.1	E	7.1	40.7	19	8.6
SE	6.1	18.2	7	0.5	SE	2.4	3.2	1	0.0
S	4.9	22.8	7	1.1	S	3.0	36.2	7	2.9
SW	6.3	35.4	14	**11.4**	SW	5.1	24.6	8	0.9
W	8.5	53.4	**29**	**15.3**	W	8.6	**55.4**	**31**	2.3
NW	4.3	**57.0**	16	8.0	NW	7.4	**53.9**	26	10.1
N	3.9	**62.9**	16	3.3	N	11.0	43.1	**31**	**18.1**
C	6.8	**84.4**	**36**	**46.7**	C	8.6	**80.3**	**45**	**26.7**
A	45.8	8.0	**23**	1.1	A	34.3	9.7	22	1.8
	100.0	*26.1*	*165*	*100.0*		*100.0*	*34.6*	*223*	*100.0*
	Summer					Autumn			
	CWT (%)	rLD (%)	LD	CG (%)		CWT (%)	rLD (%)	LD	CG (%)
NE	24.8	27.6	**44**	**45.7**	NE	13.2	41.8	**35**	**42.1**
E	4.6	**32.4**	10	**9.0**	E	6.5	34.1	14	4.9
SE	0.6	25.9	1	0.3	SE	2.9	35.2	7	1.7
S	1.0	16.3	1	1.1	S	7.3	39.0	18	5.2
SW	1.4	**44.4**	4	1.6	SW	7.6	**56.1**	27	5.7
W	6.9	29.5	13	2.9	W	7.4	**55.5**	26	2.1
NW	8.4	25.1	14	1.3	NW	5.6	40.6	15	1.6
N	19.3	17.3	**22**	7.6	N	5.1	43.5	14	2.4
C	7.9	**45.2**	**23**	**23.6**	C	9.9	**86.9**	**55**	**25.8**
A	25.4	9.5	16	7.1	A	34.9	17.3	**39**	**8.6**
	100.0	*22.7*	*146*	*100.0*		*100.0*	*38.9*	*248*	*100.0*

is the second most important in terms of percentage of CG discharges (25.8%), but it presents a very significant ratio of thunderstorm days (86.9% of total autumn days). This value shows that thunderstorm activity over Portugal is almost guaranteed when these synoptic conditions occur in autumn. In this particular season, the N type loses relevance, as at this time of the year there are no very important cold air masses at high levels being advected from the north. Curiously we find a significant number of thunderstorm days associated to the A type (39 days), but these events are not severe, as they represent only 8.6% of total CG discharges. Also note that autumn months present the highest ratio (and total number) of thunderstorm days (39).

We should once again stress that on the context of the Iberia Peninsula, the total number of CG over Portugal is relativity low when compared with other areas (Pineda et al., 2010; Rivas Soriano et al., 2005). Moreover, Rivas Soriano et al. (2005) concluded that the CG discharges spatial distribution pattern in central and east Iberia is clearly related to the orography, and the maximum lightning activity is related not only to the Pyrenees and the Sistema Ibérico mountain range, but also to the Mediterranean sea. In addition, Tomás et al. (2004) studied the relationship between the Lamb weather types (centred in the Iberia Peninsula) and the CG discharges between 1992 and 1994, and found out that on an annual scale, the C type presents the greatest flash frequency, and days with an easterly component (NE, E, SE) generate 30.7% of the total CG discharges in that period. We must of course carefully bear in mind that most of the CG discharges considered by Tomás et al. (2004) were located in northern and eastern Spain.

3.3. Characterization of synoptic fields on unstable days

In this section, we computed composites for each CWT in two separate situations: 1) days with more than five CG discharges; 2) days with no CG discharges. We are aware that we may lose some days with weak thunderstorm activity, but we want to clearly distinguish the mean synoptic fields in situations that can generate important lightning activity, and

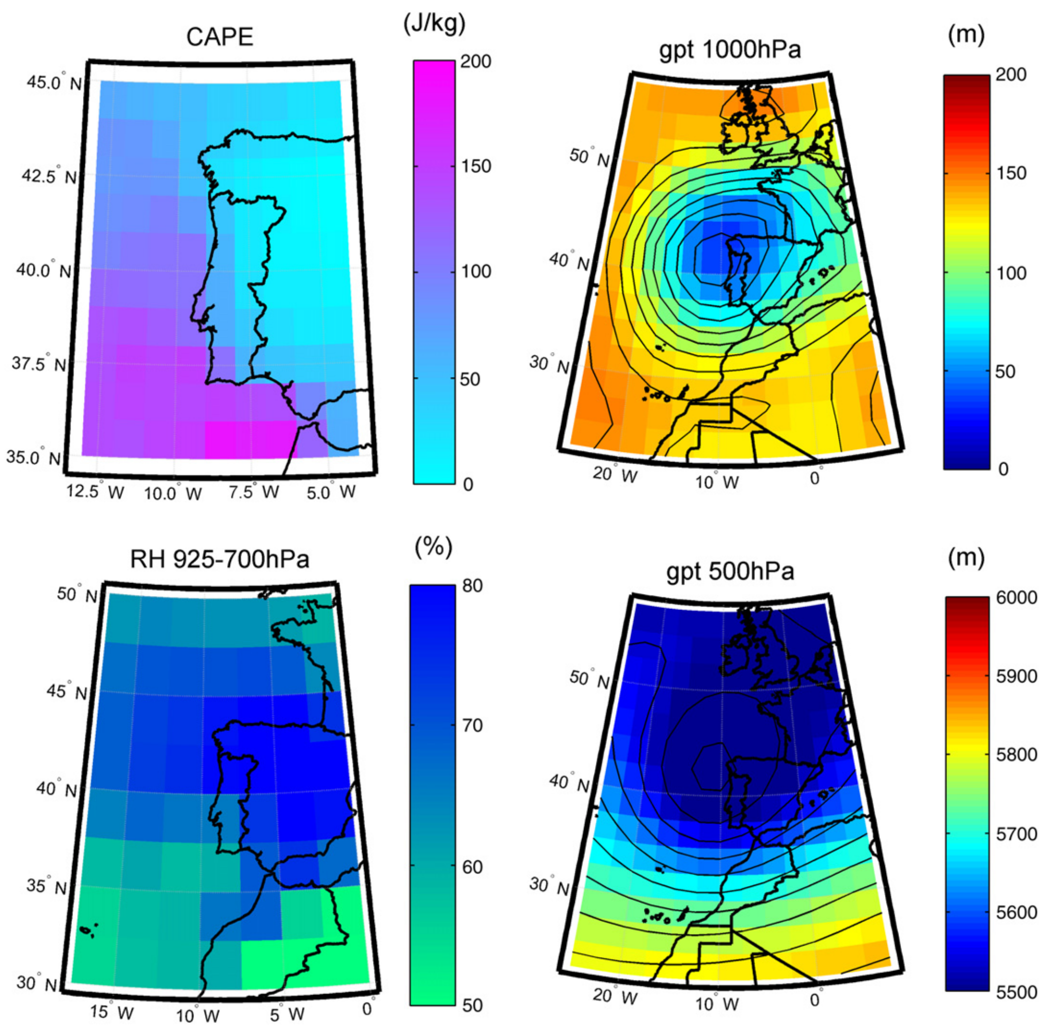

Fig. 9. Composites of unstable days in winter with the C circulation type—mean daily fields of CAPE (J/kg), gpt1000 (m), gpt500 (m) and RH (%).

days with stable conditions. We analyzed the maps of two instability indices: Convective Available Potential Energy (CAPE) and Lifted Index (LI); the geopotential near the surface (at the 1000 hPa) level and at high levels (500 hPa) to analyze large-scale circulation forcing; the mean relative humidity (RH) for the 925–700 hPa layer; the temperature at the 925 hPa level, to capture possible forcing due to low level warming, especially during summer months. Since we computed a large number of composites for both stable and unstable situations in all climatic seasons, we opted, for the sake of simplicity, to concentrate on those maps that offer more information (CAPE, gpt1000, gpt500 and RH) and are most significant and illustrative.

As seen in the previous section, in winter months, the CWT responsible for a larger number of thunderstorm days are the C, NW, SW and W. But as already stated, the last three are generally not associated to very active episodes. Cyclonic types are responsible for the largest share of CG discharges activity, and are associated with synoptic scale frontogenesis, which is well defined in the geopotential mean fields (Fig. 9). For these winter cases, convection is essentially forced synoptically, and not by afternoon convection by radiation, so thunderstorms can, and often are, formed in the Atlantic, and then advected towards Portugal. The ratio of lightning days for the cyclonic type (84.4%) during winter shows that these synoptic conditions are generally associated to at least some weak thunderstorm activity. In cold months, severe lightning episodes are rare, as naturally there is not an important radiative forcing. As we look at other seasons besides winter, this forcing is present and plays a major role in triggering huge thunderstorms, often promoting large amounts of CG discharges. Contrarily to winter months, most of the CG discharges in other seasons develop inland (see Section 3.1), far enough from inhibitive sea breezes. Inland, solar radiation during the day promotes soil heating and available energy for convection. On the contrary, close to coastal areas, this heating cycle is damped considerably reducing the amount of available energy for thunderstorm development. Even thunderstorms formed inland and advected to coastal areas tend to be dissipated, as the sea

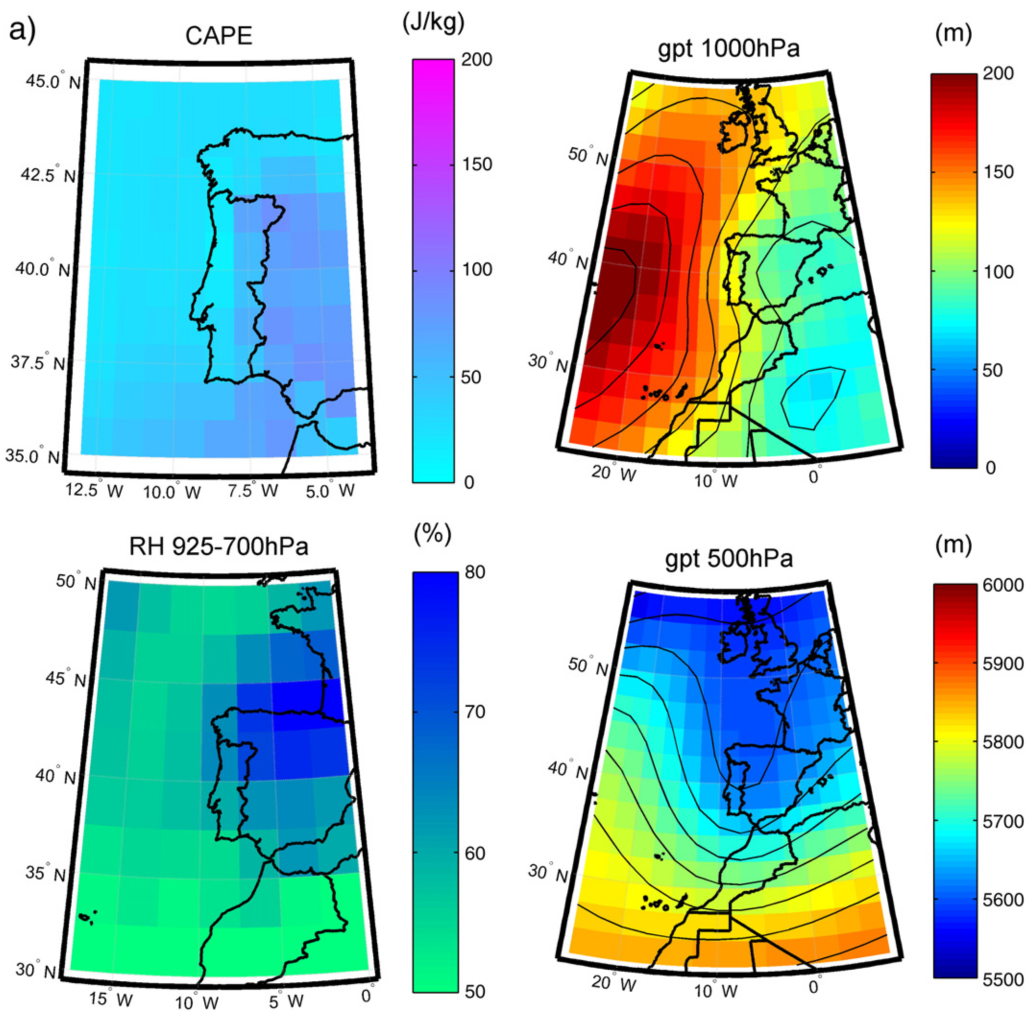

Fig. 10. Same as Fig. 9, but for (a) unstable spring days and (b) stable spring days with the N circulation type.

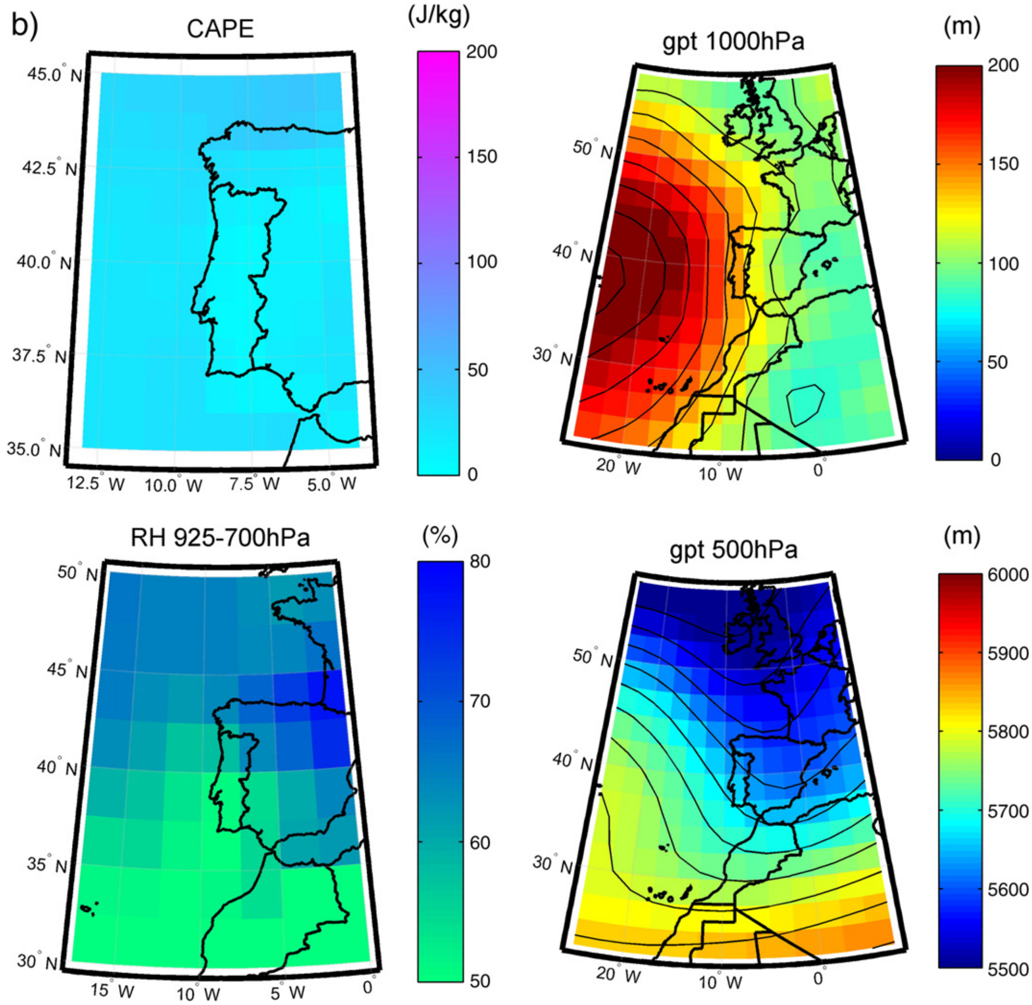

Fig. 10 (*continued*).

breezes cut the energy supply for convection and organization of convective cells.

Obviously, this heat source is very important in afternoon spring thunderstorms, but there is another quite important factor in this season. Although at low levels we may already have important heat content, frequently in early spring we still find very cold air masses at higher levels producing large lapse rate values that are favorable for deep convection (Pineda et al., 2010). Thus one can say that in this season, synoptic scale patterns still play a major role, particularly when allied to the triggering mechanism enabled by high solar radiation. This description fits well the N and NE types, responsible for a large number of thunderstorm days in this season. In Fig. 10 (composites for the N type) we can see a cold air mass over Portugal (in the form of a cut-off low or a pronounced trough) when we analyze the 500 hPa geopotential height composites. In addition, Nieto et al. (2007a), found that more than half of the cut-off low systems found in the European sector are associated to blocking events, particularly in spring and winter, when these quasi stationary anticyclonic patterns are more frequent. Comparing unstable (Fig. 10a) and stable days (Fig. 10b) for the N type in spring, we see the impact (on the CAPE values) of the trough being positioned over Portugal, or slightly to the east (over Spain), respectively. The N weather type loses influence in summer and autumn, as the high troposphere warms and these synoptic conditions occur less frequently, inhibiting the establishment of steep lapse rates.

In the summer months Portugal has small activity in terms of frontogenesis, as the storm-track is usually further north (Trigo, 2006). One can ask what drives summer thunderstorms in Portugal. Essentially, we find the development of afternoon thunderstorms in inland areas as the result of daily heating. Although radiative heating is usually required to trigger early convection stages, there are some other "ingredients" that must be present for thunderstorms to develop. In types like C or N, we can find a slightly colder air mass at high levels (not shown). Albeit not so important as in spring months, it can be enough to trigger important thunderstorms allied to soil heating, which can enable important CAPE values. However, as previously described, the CWT presenting the highest number of CG discharges days in summer is the NE. Still, in this particular case we cannot identify any cut-off low or very relevant trough over

Portugal in the composite. Again one can ask how thunderstorms can develop in these days. In this case, the other "ingredient" is essentially a small low pressure over Iberia, frequently forced by long periods of very warm weather (thermal lows), which induces a cyclonic circulation over Iberia (Hoinka and De Castro, 2003). Comparing NE days with and without thunderstorms for summer, we found slight differences in the temperature at 925 hPa (not shown) and in the mean RH at low-medium levels (both higher in thunder days), and also a slight difference in the mean 1000 hPa geopotential field, reflecting the thermal low. The composite for summer thunderstorm days with the NE type is shown in Fig. 11.

Autumn geopotential composites for the CWT with the most number of thunderstorm days (C) clearly reveal synoptic patterns typical of frontal systems crossing Portugal from west to east (as in winter). Nevertheless, we find more concentrated activity once again for the NE type days (42.1% of CG discharges). Here, and similarly to spring, we find a mix between synoptic forcing (cold air mass at the 500 hPa level) and a thermal low over southern Portugal. In this season, for the NE type, the 500 hPa composites reveal a less cold air mass aloft (when compared to spring cut-off lows), but on the other hand we find very interesting CAPE values, particularly over sea areas. At this time of the year, Sea Surface Temperatures (SSTs) are higher than in spring, a fact that compensates the lack of very cold air aloft, enabling once again steep lapse rates that are favorable for deep convection (the case study in Section 3.4 is illustrative of this pattern). This particular factor (only in autumn months) is probably the explanation for a more curious result: anticyclonic types present the second highest number of lightning days in autumn (39), but once again, the fraction of total CG discharges for this CWT is relatively small (8.6% of autumn strikes), meaning that these episodes are generally not particularly severe.

3.4. Case study—September 10–11, 2007

In this section we analyze a particular episode, the most notorious in terms of the total number of CG discharges for the period 2003–2009. The two most active days took place in September 2007 (on the 10th and 11th) and are the first and second days with the most CG during the 2003–2009 period.

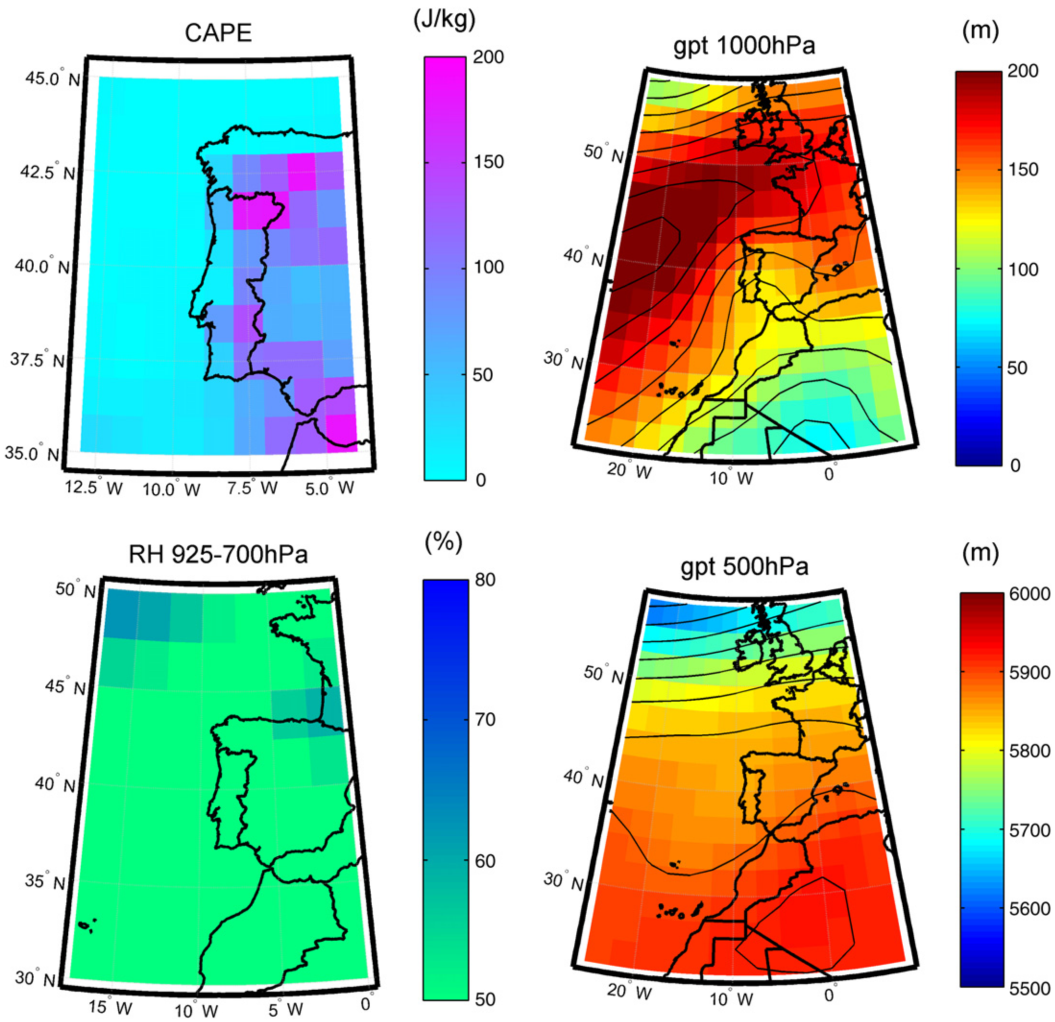

Fig. 11. Same as Fig. 9, but for unstable summer days with the NE circulation type.

The composites of CAPE (J/kg), LI (°C), gpt1000 (m), gpt500 (m), t925 (°C) and RH (%) synoptic fields for these two days are shown in Fig. 12. The associated type is from the NE, which is one of the most relevant CWT for thunderstorm episodes in autumn (see Sections 3.3 and 3.4). Looking at the surface synoptic fields, no clearly significant feature is present besides

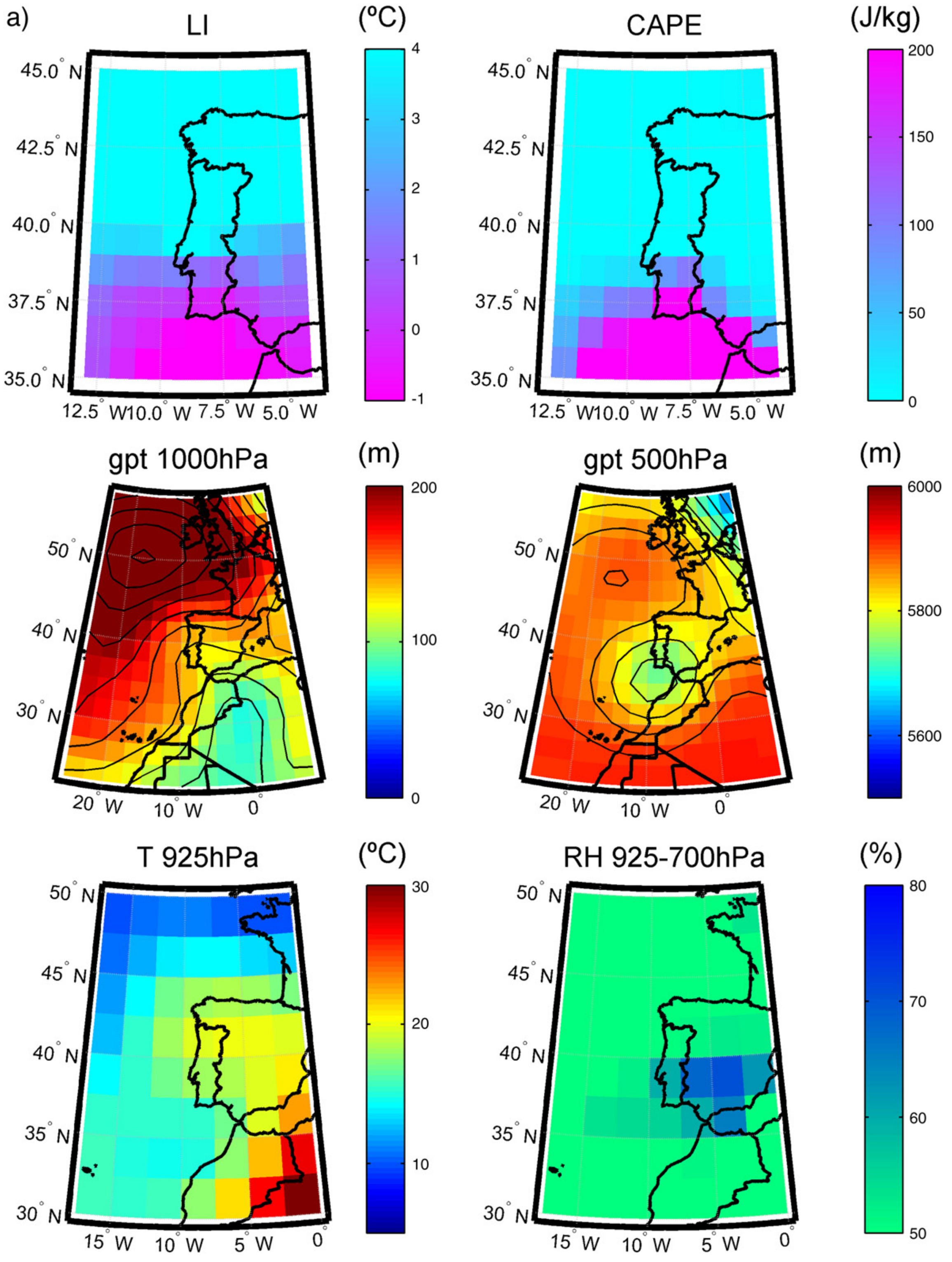

Fig. 12. Case study of 10–11 September 2007: (a) Composites of the two days episode of mean daily fields of LI (°C), CAPE (J/kg), gpt1000 (m), gpt500 (m), t925 (°C) and RH (%). (b) CG discharges of each day at the hourly scale.

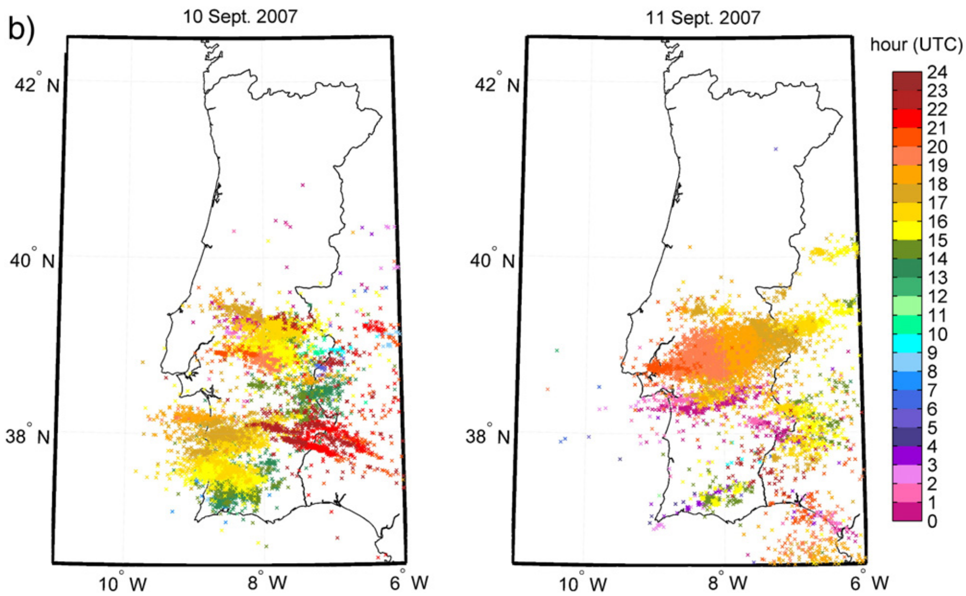

Fig. 12 (*continued*).

the NE flux over Portugal. But at the 500 hPa geopotential height level, we find a well defined cut-off low centered between southern Portugal (Algarve) and coastal Morocco. The existence of this cold air mass aloft, coupled with the usually high SST values observed at this time of the year, enables the establishment of an important lapse rate in the vertical section below the position of the cut-off. This can be identified in the interesting values of the LI and CAPE mean fields, especially in southern regions. Further north, the conditions were much more stable, and no thunderstorms developed. In Fig. 12a we can also notice the existence of reasonable amounts of moisture associated with the unstable area.

The first day registered 8304 CG discharges as we already mentioned in Section 3.1. To emphasize the magnitude of these numbers, we should stress that these values are not distributed homogeneously over Portugal, but concentrated essentially over southern Portugal (mainly over the Alentejo region). The majority of these lightning discharges took place in the period between the afternoon and the evening hours (Fig. 12b), as the low level heating during daytime enables the start of the convective process, further amplified by the favorable unstable synoptic conditions found over the region.

Very similar conditions remained on the following day, as a continuation of the event, and once again the southern half of Portugal maintained high rates of lightning activity (6361 CG discharges). Once more, the largest part of lightning strikes occurred in the afternoon and evening hours, although some strikes were registered before sunrise, as some of the previous day's thunderstorms remained active.

Cut-off low systems are responsible for the most severe convective episodes in Iberia (Nieto et al., 2007b). Since convective episodes are generally of localized nature, the highest precipitation values are rarely captured in a scattered weather station network. Nevertheless, station data from IM (see locations in Fig. 1) presents some medium to high accumulation values, especially in the Alentejo region, and during the second day. Some of the most prominent values are now detailed: 24 mm in Alvalade, 7 mm in Beja and 6 mm in Avis during the first day; 37 mm in Castro Marim, 17 mm in São Brás de Alportel, 15 mm in Portimão, 13 mm in Faro or 10 mm in Lisbon (airport station). As expected, taking into account the nature of the event, the highest precipitation values are found inland, where naturally thunderstorms were more active. However, we call attention to some moderate values in coastal stations (Lisbon, Portimão and Faro), meaning the storms spanned further west into the Atlantic. The localized nature of strong convective precipitation episodes is also reflected on the wide range of values registered on the second day of the event for stations located inside the urban area of the city of Lisbon (from 1 mm to 16 mm—as stated before, the main reference station in Lisbon, at the airport, registered 10 mm).

4. Conclusions

In this work we have studied the main characteristics (geographical distribution, intra and inter-annual variability, diurnal cycle, first stroke peak current) of CG flashes recorded in mainland Portugal for the 2003–2009 period. Moreover, the relationship between CWT and the CG discharges occurrence was also provided.

In the context of the Iberia Peninsula, the total number of CG discharges over Portugal is relativity low when compared with other areas of Iberia (Pineda et al., 2010; Rivas Soriano et al., 2005). Therefore, the limitation in the availability of good quality data for Portugal (confined to the 2003–2009 period) combined with the relative small number of CG discharges in the domain require a careful assessment, due to the heavy impact of just a few extreme days with outstanding thunderstorm activity. An example of these are the days of September 10–11, 2007, which alone, are responsible for the appearance of a very marked maximum value of discharge density (3.2 flashes/km^2) in the autumn season (Fig. 5) and also for the year of 2007 (Fig. 2).

A clear spatial density pattern emerges when comparing CG discharges occurrence at different seasons. The winter months present much smaller number of CG discharges than the remaining warmer seasons, and the highest density of discharges in this season is found in the coastal regions. On the contrary, for the other three seasons, CG discharges tend to occur much more frequently in the interior areas of Portugal. The diurnal cycle of the CG discharges is clearly present in spring, summer and autumn with maximum activity being found in the afternoon.

The relationship between the CWT and CG discharges (at an annual and seasonal scale) allowed us to distinguish which types are frequently associated to lightning episodes, and also the ones that are favorable to severe lightning episodes (very high number of CG discharges by event). We find two dominant types, which explain more than 60% of total registered strikes: the C type is most of the times associated to the occurrence of thunderstorms, as approximately 75% of the days with this pattern registered discharges, being responsible for the highest number of thunderstorm days (160 days during 2003–2009); NE is responsible for the most important thunderstorms, as it presents the highest number of discharges, but this activity only occurs in about 35% of the days with NE type, the second in number of thunderstorm days (123). Other CWT are responsible for a large number of thunderstorm days, especially the W, N and A, but for a small fraction of CG strikes, meaning these types are generally associated to isolated and not severe thunderstorms.

At a seasonal scale, results show different mechanisms for triggering lightning activity. In winter, the activity is mainly associated with synoptic scale frontogenesis, where thunderstorms are often formed in the Atlantic and then advected to Portugal. In spring, the combination of heat source inland of Portugal (as the result of the amplified daily heating cycle) and the presence of relatively frequent cold air masses at high levels (particularly in early spring) are very important in the formation of afternoon spring thunderstorms. In summer, we essentially find the development of afternoon thunderstorms in inland areas as the result of daily heating in association with a thermal low over Iberia (frequently forced by long periods of very warm weather), which induces a cyclonic circulation over Portugal. In autumn, frontal systems crossing Portugal from west to east are again responsible for lightning activity, while daily heating still plays a major role. In this particular season, and especially for September, higher SST values in the Atlantic can help enabling steep lapse rates that are favorable for deep convection.

A recent work done by Huth et al. (2008) intends to place circulation classifications in a broader context within climatology and systematize the various methodologies. In this work we used an automated version of the Lamb weather types, computed using 16 sea level pressure grid points. As mentioned previously, the mechanisms associated with lightning activity are often related to atmospheric features that do not have a clear signature at lower atmospheric levels, (e.g. sea level pressure fields), so their associated CWT alone cannot fully explain mechanisms in all cases. In these type of situations, distinguishing composites for stable and unstable days for several meteorological fields at different height levels revealed rewarding in the objective of identifying unstable patterns over Portugal. Nevertheless, CWT proved to be a very important tool to be related with climatic variables at the surface of the earth (in this work, the CG discharges), taking into account that in some cases, additional upper level meteorological fields may be needed for a deeper knowledge.

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