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RESEARCH ARTICLE

A comprehensive analysis of hail events in Portugal: Climatology and consistency with atmospheric circulation

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A first hail climatology in mainland Portugal is provided, based on a network of 15 meteorological stations and over the period of 1971–2009 (39 years). Three hail sub-classes based on the SYNOP codes were considered (small hail, hail without thunder and hail with thunder). Furthermore, hail occurrences were also compared with thunderstorm, convection and precipitation days. Hail events are more frequent in northern Portugal during winter and spring (peaking in April). Both thunderstorm and convection events present a maximum in April–May and a secondary peak in autumn (October). This secondary peak is frequently associated with convective storms without hailfall at the ground, as no clear autumnal maximum is recorded in the hail frequency, particularly in the case of small hail and hail without thunder. The typically higher temperatures in October than in February–April may lead to excessively high-freezing level heights that hamper hailfall at the surface. The dynamical mechanisms underlying hail occurrence in mainland Portugal were also analysed using eight three-dimensional weather types. The atmospheric conditions associated with three weather types: Western European Trough, Blocking and Scandinavian Trough were responsible for ca. 75% of the hail events throughout Portugal. Overall, hail events are favoured either by extra-tropical depressions, with cold front passages over Portugal, or by upper-level troughs/lows over western Iberia, but preferably occurring in the period from December to May. These dynamical drivers promote instability conditions, which were also diagnosed by the convective available potential energy and total-totals index.

KEYWORDS

convection, hail, k-means, lightning, Portugal, small hail, thunderstorm, weather types

1 | INTRODUCTION

Hail is a widely known meteorological hazard, potentially causing severe damages to property, such as buildings, structures and automobiles (Brown *et al.,* 2015), crops (Sánchez *et al.,* 1996), aircrafts (Das *et al.,* 2009), wind turbines (Macdonald *et al.,* 2016), among others. Furthermore, hail-related economic losses have been increasing in different regions worldwide, for example, being recently estimated to be over $1 billion US dollars annually for the United States (e.g., Changnon, 1999; Cintineo *et al.,* 2012). In Europe, the insurance costs of the hailstorms occurred on June 8–10, 2014 were estimated to be of 2.3 billion EUR in France, Belgium and Germany (Punge and Kunz, 2016).

By definition, hail is the precipitation of transparent, partly or completely opaque particles of ice (hailstones), usually spherical, conical, or irregular in form, with a diameter generally greater than 5 mm (WMO, 2012). Smaller particles of similar origin may also be classified as small hail or ice pellets, but other frozen hydrometeors are often misinterpreted as hail. Hail commonly occurs in the form of showers and is typically observed during heavy thunderstorms

(WMO, 2012). As referred by Punge and Kunz (2016), the key elements for hailstorm formation are: high-convective energy to feed and maintain strong updrafts, sufficient vertical wind shear to organize convective storms and lift to overcome convective inhibition in the boundary layer. Hence, several sounding-derived parameters, such as convective available potential energy, lifted index, total-totals or vertical wind shear, have been used to describe the thermodynamic environment favourable to hail events (Groenemeijer and van Delden, 2007; Manzato, 2013; Mohr and Kunz, 2013; Tuovinen *et al.,* 2015).

Despite hail can be caused by various convective modes, the occurrence of severe hail events has been associated to organized convection, such as to supercells (e.g., Smith *et al.,* 2012; Peyraud, 2013; Tuovinen *et al.,* 2015; Belo-Pereira *et al.,* 2017) and to mesoscale convective systems (e.g., Sánchez *et al.,* 2003). These studies stress that hail size is largely dependent on the lifetime of the convective storm, which is in turn related to the updraft intensity. However, there are other factors, such as the aerosol concentrations (Ilotoviz *et al.,* 2016) or the melting level height (Dessens *et al.,* 2015), which may also play an important role.

The instability conditions, necessary to generate and maintain convective storms, can develop due to either low-level warming or cooling of air aloft. The instability conditions can thereby be favoured by large-scale weather patterns that promote cold advection at high-tropospheric levels and/or moist and warm advection at lower levels. For instance, the presence of an upper-level trough upstream of a certain location commonly promotes air lifting and thermal instability in that location (Punge and Kunz, 2016).

Hailstorms tend to be more frequent from April to September in Central and Eastern Europe (Rakovec *et al.,* 1990; Počakal *et al.,* 2009; Suwała and Bednorz, 2013; Burcea *et al.,* 2016). Nevertheless, in European regions where climates are more intensely influenced by the Atlantic Ocean, hail events tend to be more frequent during winter and early spring (Walsh, 2012), noticeably controlled by the large-scale atmospheric conditions. In effect, the important role played by large-scale circulation on triggering hail events has already been addressed by several authors (e.g., Aran *et al.,* 2011; Kapsch *et al.,* 2012; Suwała, 2013; Allen *et al.,* 2015a, 2015b). Furthermore, cold fronts (Schemm *et al.,* 2016) and orographic forcing (de la Torre *et al.,* 2011; Santos *et al.,* 2013) are important sources of lift that may promote hailstorms.

Reliable climatological data on hail events is critical for providing hail risk patterns to insurance companies and to many vulnerable socio-economic sectors, like the agro-forestry sectors (Changnon, 1999). Many regional hail climatologies have been produced worldwide using a large range of available data sources, namely weather stations and documentary sources, for example, newspapers and media alerts, weather logs or insurance loss data (Zhang *et al.,* 2008; Sánchez *et al.,* 2009; Tuovinen *et al.,* 2009; Mezher *et al.,* 2012; Berthet *et al.,* 2013; Hermida *et al.,* 2013; Baldi *et al.,* 2014; Rasuly *et al.,* 2015; Kahraman *et al.,* 2016; Li *et al.,* 2018), among others. However, substantial biases may occur, namely owing to the heterogeneous distribution of population and property or to the non-systematic nature of the reports. Therefore, remote sensing (radar and satellite) products have been frequently used for hail climatology and severe weather risk assessments (Gallus *et al.,* 2008; Cintineo *et al.,* 2012; Punge *et al.,* 2014; Skripnikova and Rezacova, 2014; Kunz and Kugel, 2015; Bowden and Heinselman, 2016). The analyses provided by numerical weather prediction models have also been used to develop hail climatologies over the globe (Hand and Cappelluti, 2011) and over Europe in particular (Mohr *et al.,* 2015). A detailed overview of hail-related studies in Europe is provided by Punge and Kunz (2016).

The climatological study of Tullot (2000), for Spain and Portugal, showed that in mainland Portugal and for the period of 1931–1960 hail occurs mainly northwards of the Tagus River, being very rare in the south (≤1 day per year). During the warm season (April–September) hail occurrences in Portugal are quite low when compared to Central Europe or to other Southern European regions (Punge *et al.,* 2014). Nevertheless, despite the comparatively low-hail frequencies, severe hail events do occur in mainland Portugal. For instance, on September 4, 2004, in Braga (northern Portugal) hailstones of 70 mm were reported to the European Severe Weather Database (ESWD) (Punge and Kunz, 2016). On December 7, 2010, large hailstones (egg-sized) were also reported during a long lived convective storm that produced a F3 tornado over central Portugal (Belo-Pereira *et al.,* 2017).

In Portugal, hail events are routinely recorded by the weather station network of the Portuguese Meteorological Office (*Instituto Português do Mar e da Atmosfera,* IPMA). Nonetheless, neither a systematic analysis of these hail records, nor a comprehensive analysis of their driving mechanisms, were carried out so far. Hence, the objectives of this study are threefold: (a) to develop a hail climatology for mainland Portugal based on the observations from a network of weather stations; (b) to compare hail records to thunderstorm, convection and precipitation days in Portugal; and (c) to evaluate their coherence with the large-scale atmospheric circulation using a three-dimensional (3D) weather typing approach. Section 2 will describe the data sources and the applied methodologies. Section 3 will be devoted to the presentation and discussion of the results. Lastly, Section 4 will summarize the main conclusions.

2 | DATA AND METHODS

2.1 | Weather station data

The hail data used in this study were obtained from the network of meteorological stations in mainland Portugal, routinely maintained by the IPMA. In order to ensure a relatively large period of data with acceptable quality that also presents a satisfactory geographical coverage, 15 stations were eventually selected for the period from 1971 to 2009 (39 years). All years, individually, with either more than 10% of missing data or with at least 1 month with ≥3 days missing are discarded. Similar criteria have been applied by Zhang *et al.* (2008) and Burcea *et al*. (2016). Thus, from the 15 selected stations, three stations cover the entire period without missing years (Table 1), 11 stations cover at least 30 years, one station covers 29 years (Sines), one station covers 24 years (Castelo Branco), one station covers 19 years (Porto) and one covers 15 years (Viseu).

The geographical locations of the 15 selected stations are plotted in Figure 1, along with the hypsometric chart of mainland Portugal. The station with highest elevation, Penhas Douradas (1,380 m), is located in Serra da Estrela (the highest mountain range in mainland Portugal). The second highest station is Bragança (690 m), located in Northeastern Portugal. The other stations located in mountainous regions are Portalegre (597 m), Viseu (636 m) and Vila Real (481 m). For the same weather stations, thunderstorm and convection days, as well as precipitation, were also analysed in this study.

2.2 | Hail, thunderstorm and convection days

At all selected stations the present weather and past weather are routinely encoded by a 2-digit code, according to SYNOP code (WMO, 2011; A356–A358). Hail records at the weather stations were made by meteorological observers, following the guides provided by WMO. The SYNOP codes related to hail are listed in Table S1 in Appendix S1, Supporting Information, as well as the corresponding frequencies of occurrence. Therefore, a day is classified as a hail day if hail is recorded at least in 1 hr of the day at a given weather station, that is, if one of the following SYNOP codes are recorded: 27, 87–90, 93, 94, 96 or 99. In order to infer the severity of hail, it is herein divided into three sub-classes: small hail (<5 mm), hail without thunder and hail with thunder. Small hail without thunder records correspond to the codes 87 and 88 (only small hail hereafter), hail without thunder records to 27, 89 and 90, and hail with thunder records to 93, 94, 96 and 99 (WMO, 2011). For the hail records, a Cumulonimbus (Cb) cloud should also be recorded in the SYNOP code for consistency. For the codes 87, 88, 90, 93 and 94, the 2 m air temperature (T2 m) should by higher than 3 °C. This criterion for T2 m is critical to distinguish hail from snow pellets or mixed snow. The frequencies of the different hail sub-classes by weather station are shown in Figure S1 in Appendix S1.

Following an analogous procedure as for hail, a day is classified as a thunderstorm day if at least one of the two following conditions is verified at any hour of the day at a given weather station: (a) thunderstorm was coded in past weather; (b) present weather coded as any of the numbers 13, 17, 29, 91–99 (WMO, 2011; A356-A358). Similarly, the two following conditions apply for a convection day at a given weather station: (a) an hourly precipitation record ≥20 mm; (b) present weather coded as any of the numbers 17–19, 25–27, 29, 79–99. Hail, thunderstorm or convection days in Portugal are considered when these events are recorded in at least one weather station.

In order to analyse the different types of hail it is important to consider several facts. The first is related to the thunder audibility, which can be affected by surface topography, noise (for instance, due to aircraft operations) and atmospheric conditions. Due to these factors, the distance for thunder audibility can vary from 8 to 24 km (Changnon, 2001). Therefore, when a hail event was reported with no thunder associated, it is possible that a lightning discharge occurred at a distance from the weather station greater than the maximum audible distance. The second fact to consider is the relationship between lightning activity and the strength and volume of the updrafts within a Cb cloud. Previous studies showed that Cb's electrification is caused by the collisions of certain hydrometeors (graupel and ice crystals) in the presence of supercooled water (Williams *et al.,* 1991). Moreover, the updrafts within the Cb's thermal layer from 0 to −20 °C must be sufficiently strong to uplift and generate large ice particles and riming conditions necessary for rapid electrification and lightning (Zipser and Lutz, 1994). Furthermore,

TABLE 1 List of the 15 weather stations in mainland Portugal considered in this study (cf. Figure 1), along with their corresponding time periods of hail records (first and last year), discarded years (see text for details) and the final length (number of years selected for the analysis)

Station	Discarded years	First year	Last year	Length
VIANA DO CASTELO	1971–1979	1980	2009	30
PORTO	1971–1987, 1989, 1990, 1993	1988	2009	19
VISEU	1971–1994	1995	2009	15
VILA REAL		1971	2009	39
PENHAS DOURADAS		1971	2009	39
BRAGANÇA	1995	1971	2009	38
CASTELO BRANCO	1971–1985	1986	2009	24
COIMBRA	1971–1973	1974	2009	36
LISBOA	1971–1979	1980	2009	30
PORTALEGRE		1971	2009	39
SINES	1971–1974, 1981, 1989	1975	2009	29
ÉVORA	1971–1978	1979	2009	31
BEJA	1971–1976	1977	2009	33
SAGRES	1971–1977, 1983, 1984	1978	2009	30
FARO	1984, 1985	1971	2009	37

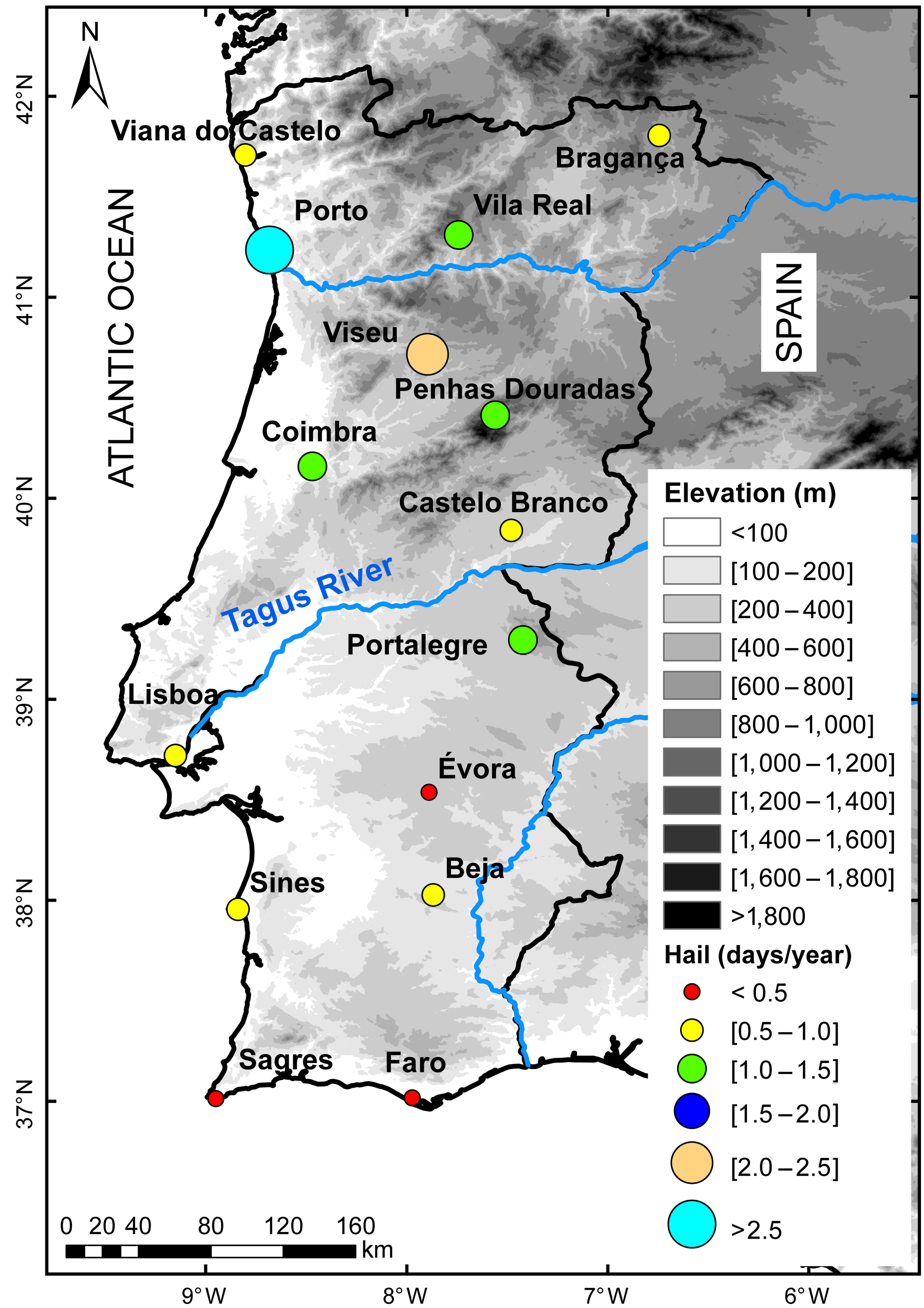

FIGURE 1 Map of the annual mean number of hail days (graduated circles in days year-1) at the 15 selected meteorological stations. The hypsometric chart for mainland Portugal (elevation in meters) is also shown along with the main rivers (the Tagus River is outlined) [Colour figure can be viewed at wileyonlinelibrary.com]

Lang and Rutledge (2002) showed that storms creating high cloud-to-ground lightning flash rates require a large volume of significant updrafts (>10 ms^{-1}) within the Cb's mixed phase region. Therefore, it is reasonable to assume that hail events with thunder are produced by severe storms, while hail events without thunder records may be produced by ordinary convective activity. A third factor is related to the spatial and temporal relations between hail and lightning. Hail reports are frequently not coincident with the location of cloud-ground lightning. Changnon (1992) showed that the distance between the lightning centres and hail streaks can range from 1.4 to 34 km.

2.3 | Weather typing and reanalysis

In order to assess the role of the large-scale atmospheric forcing on hail events in mainland Portugal, a *k*-means weather typing approach was applied. A clustering analysis, as in Santos *et al.* (2016), was followed, but adding the 500 hPa geopotential height (Z500) and the 250 hPa potential vorticity (PV250) to the mean sea level pressure (MSLP) used in the former study. The incorporation of these two additional atmospheric fields enable the identification of vertically coherent circulation weather types (3D approach). For that purpose, daily fields of MSLP, Z500 and PV250, for the available common period of 1979–2009 (no data exists prior to 1979), were retrieved from the ERA-Interim reanalysis dataset platform (Dee *et al.,* 2011). For an analysis of the thermodynamic conditions during hail days, the convective available potential energy (CAPE) and the total-totals index (TT) were also analysed. The former was directly retrieved from ERA-Interim, while the latter was computed using 850 hPa and 500 hPa temperatures and 850 hPa dew-point temperature (Miller, 1972). These two indices were widely applied in previous studies (e.g., Mohr and Kunz, 2013). The ERA-Interim fields were provided on a $0.75° \times 0.75°$ regular grid and extracted for a European-North Atlantic geographical sector (60°W–40°E, 20°–80°N). The 1200 UTC fields were chosen, as hail events are generally more frequent during the afternoon.

The *k*-means clustering was applied on the subspace of the leading principal components. However, seasonality was first removed from the datasets by subtracting the corresponding long-term daily means at each gridbox. In order to avoid adding noisy high-frequency variability to the analysis, these long-term means were smoothed out by a Lanczos low-pass filter (Yun and Rim, 2009), with 500 coefficients and cut-off frequency at 30 days. This option was taken after testing different cut-off frequencies, ranging from 10 to 60 days. The resulting gridded anomalies of each field (MSLP, Z500 and PV250) were then subjected to latitude weighting and principal component analysis. The resulting principal components that cumulatively represent at least 90% of the total variance of each field were retained for subsequent analysis. As the physical dimensions of these principal components are not the same (hPa for MSLP, gpm for Z500 and K m^2 kg^{-1} s^{-1} for PV250), they were scaled by the variance of the corresponding leading component of each field. For the *k*-means clustering, Euclidian distances to the centroids were used and seeding was based on an initial clustering on a 10% sub-sample of the full principal component matrix. Convergence to the best solution (minimization of the total intra-cluster variance) was achieved by 20 replications of the clustering approach. As in the previous study (Santos *et al.,* 2016), eight weather types were ultimately obtained and their centroids correspond to the composites of the three selected fields (3D weather types). Their detailed description and relations to hail events over mainland Portugal will be undertaken in Section 3.

3 | RESULTS AND DISCUSSION

3.1 | Climatology of hail in Portugal

The annual mean frequencies of hail occurrences over mainland Portugal are relatively low, highlighting that this is a scarce meteorological event, particularly in the south of the country (Figure 1). In fact, the highest values are found northwards of the Tagus River, mostly in Porto (2.6 days $year^{-1}$) and Viseu (2.1 days $year^{-1}$), while in the south frequencies are typically below 1.0 day $year^{-1}$. The higher frequency of hail events northwards of the Tagus River can be largely explained by two factors: the more complex orography in the northern half of the country (Figure 1) and the stronger exposure of northwestern Portugal to the North Atlantic frontal systems. Occurrences in the interval of 1.0–1.5 day $year^{-1}$ are found in Vila Real, Penhas Douradas, Coimbra and Portalegre. Bragança, Viana do Castelo, Lisboa, Castelo Branco, Sines and Beja show values in the interval of 0.5–1.0 day $year^{-1}$. In Évora, Sagres and Faro the frequencies of occurrence are indeed very low (<0.5 day $year^{-1}$), mainly in Sagres, where hail events are exceptional. These findings are generally supported by a previous climatology for the whole of Iberia (Tullot, 2000).

The monthly mean hail frequencies in mainland Portugal reveal strong seasonality, with a pronounced maximum in the period of February–April (late winter to early spring; ca. 0.2 day $month^{-1}$) and a clear minimum (virtually zero) in July–August (Figure 2a). With respect to the spatial variability in seasonality, despite some noteworthy differences among stations, hail days are largely confined to the period of December–May in the majority of the 15 selected weather stations (Figure 2b–p). The maximum monthly occurrence is found at Porto (0.75 day $month^{-1}$) in February (Figure 2e). The maximum hail occurrence is also recorded in February in Viana do Castelo, Viseu, Sines and Faro, thus showing no clear spatial organization. Hail is more frequent in March in Bragança and Coimbra (only residual occurrences). The maximum hail frequency is attained in April in Portalegre, with a pronounced maximum of approximately 0.55 day $month^{-1}$, as well as in Castelo Branco and Lisboa. In Penhas Douradas (a high-elevation station), hail is more frequent in May (Figure 2e).

Hail occurrences are uncommon in July and August, mostly due to the persistent influence of the Azores anticyclone, which typically extends over mainland Portugal as a high-pressure ridge (Martins *et al.,* 2016), thus favouring subsidence conditions and suppressing convection. In fact, summers in mainland Portugal are normally characterized by very dry and warm conditions (https://portaldoclima.pt/pt/, accessed on 10 February 2018). This can also be confirmed by the mean number of precipitation days (Figure 2), which shows a clear minimum in summer for all stations, with maxima in December–January and April. As it will be shown in the next section, hail events in Portugal are typically associated with extra-tropical cyclones and upper-level troughs or cut-off-lows, which provide a source of lift and favour moist air advection. In other regions significantly influenced by the Atlantic Ocean, such as Ireland, the highest hail frequency is also observed in winter and early spring (Walsh, 2012) instead of summer, as commonly occurs in Central Europe (Burcea *et al.,* 2016; Punge and Kunz, 2016).

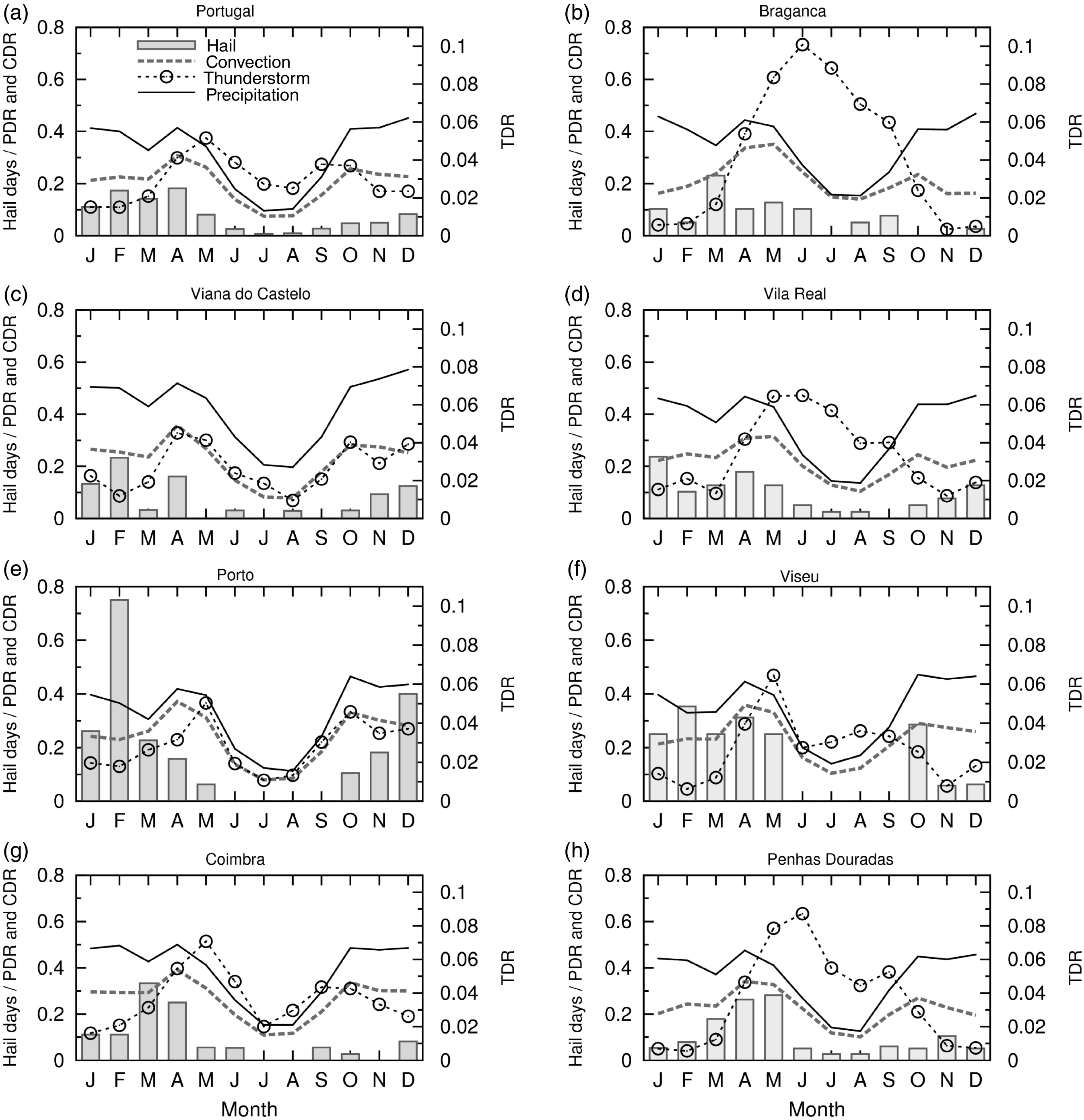

FIGURE 2 (a) Monthly mean number of hail, convection, thunderstorm and precipitation days in mainland Portugal (average over the 15 meteorological stations) for the period of 1971–2009 (cf. legend). For comparison purposes, the last three variables are normalized by the number of days in each month, thus representing the thunderstorm, convection and precipitation day ratios (TDR, CDR and PDR, respectively). TDR is read at the right *y*-axis and the other variables at the left *y*-axis. (b–p) The same as in (a) but for the 15 stations separately

Regarding the seasonal relative distribution of the hail occurrences and of its sub-classes (types) over mainland Portugal, hail occurrences peak in April for all hail types, but hail without thunder and in particular small hail are largely confined to winter and early spring, while 20% of hail with thunder occurrences are recorded from June to September (Figure 3). With respect to the daily cycle of the hail occurrences, there is a clear peak from 1500 UTC to 1800 UTC not only for total hail (Figure 4a), but also for each hail type (Figure 4b), particularly for hail with thunder, thus highlighting the contribution of the surface heating to convective destabilization. Although the seasonality of hail occurrences is not similar to other European regions, as previously shown, the daily cycle is in clear accordance with previous studies for Europe (Kaltenbock *et al.,* 2009; Burcea *et al.,* 2016). Similar distributions can be found for thunderstorm and convection days, though their concentration in the afternoon/evening is much less pronounced (Figure 4a).

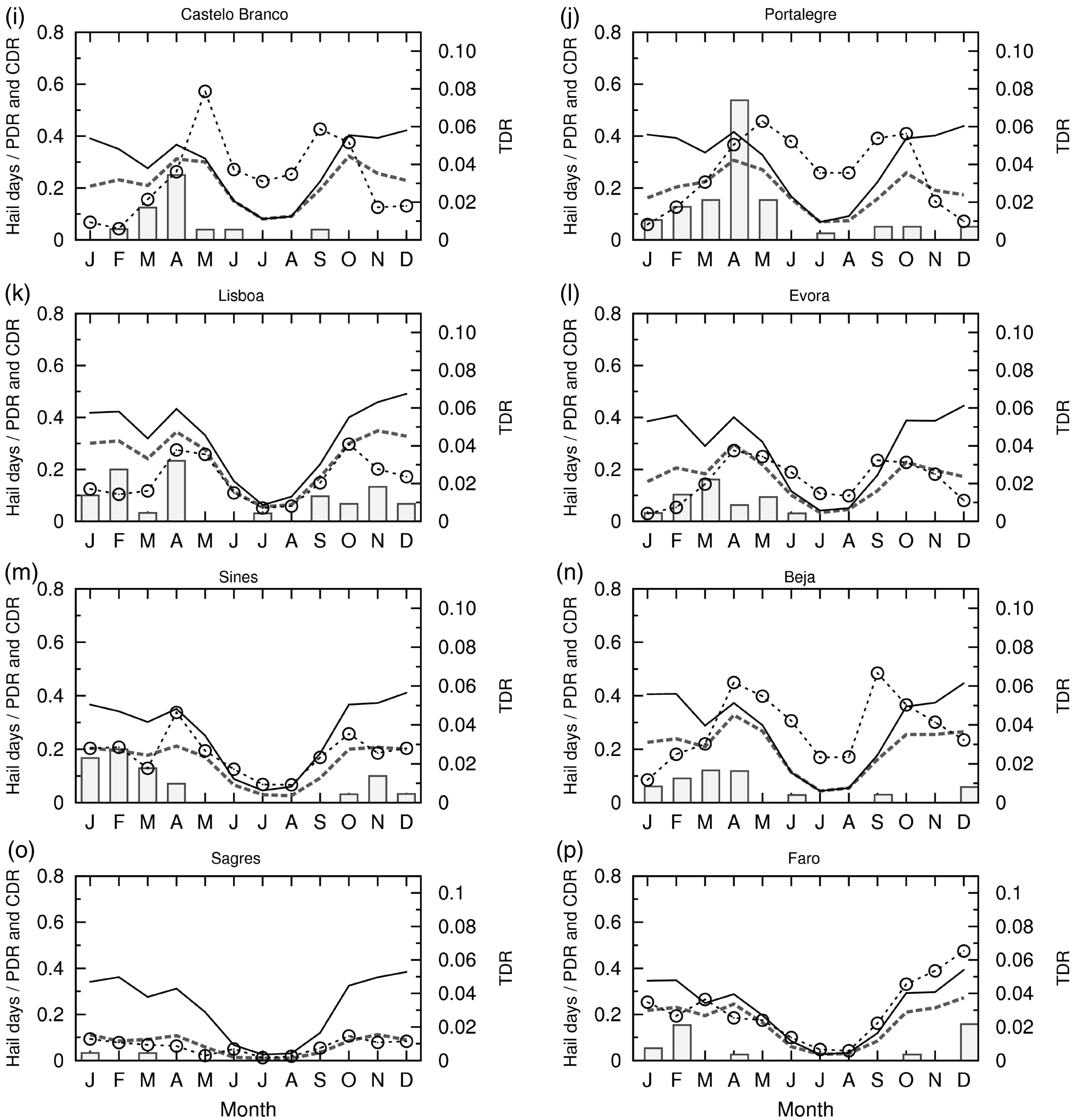

FIGURE 2 Continued

3.2 | Comparison with thunderstorm and convection days

Within the framework of the present study, the records of thunderstorm and convection events were also analysed so as to provide a comparative assessment. The convection events include thunderstorm, shower and hail events (see Section 2.2). Although these events are not herein discussed in detail, as they are out of its main scope, the seasonal cycle of thunderstorm and convection days over mainland Portugal and for each weather station are also shown (Figure 2). These totals are normalized (i.e., divided by the number of days in each month) to facilitate the comparison among the different curves.

The seasonal cycles of precipitation and convection are very similar and the number of days of precipitation or convection generally decreases from the north to the south. In Sagres (Figure 2o), and to a lower extent in Faro (Figure 2p), both located along the southern coast (Figure 1), the prevailing dry and stable weather conditions are remarkable, with a suppression of convection throughout the year and thunderstorms or hail occurring only sporadically (Figures 1 and 2). During summer months, convective systems are responsible for most of the precipitation in some stations, mainly in inland stations (Figure 2b,d,f,h,i,j,l,n). Conversely, the role of convection is less relevant during winter/autumn and in the northern coastal stations (Figure 2c).

The maximum thunderstorm occurrence in mainland Portugal shows a shift with respect to the hail events (Figure 2a), since thunderstorm frequency peaks in May rather than in February–April. Moreover, the thunderstorm events present a clear secondary maximum in September–October, which is not observed in the hail occurrences. This bi-modal behaviour in the thunderstorm days is consistent with Ramos *et al*. (2011) and Santos *et al*. (2012), who showed two maxima in the intra-annual lighting activity in Portugal, one centred in May and another in September. The maximum in autumn is also consistent with the findings of Anderson and Klugmann (2014) for the 30°–40°N latitude belt over Europe. Regarding the monthly mean convection days (Figure 2), there is a clear accordance with the thunderstorm events, including the bimodal distribution, though the frequency of convection days peaks in April (as hail events) instead of May (1-month lag).

In the northeast, Vila Real (Figure 2d), Penhas Douradas (Figure 2h) and mostly in Bragança (Figure 2b), the seasonal cycle of thunderstorms is clearly distinct from the rest of the country, showing a summer maximum, which is closer to the behaviour in Central Europe (Wapler, 2013; Anderson and Klugmann, 2014), though thunderstorms are more frequent in Central Europe and in the Mediterranean Basin than in mainland Portugal. In the northeast, this maximum in summer is mostly related to orographic forcing (Figure 1) and diurnal heating, as was already documented in previous research (Santos *et al.,* 2012). However, these early summer maxima do not have correspondence in the hail occurrences, since, for example, in Bragança the hail peak is in March, similarly to other stations throughout the country.

Besides the general suppression of convection by persistent and recurrent anti-cyclonic systems, the low-hail occurrences during the summertime half of the year (May–October) may also be partially explained by the excessively high-freezing levels, thus favouring hail melting before reaching the ground. In fact, Punge *et al*. (2017) referred that storms with high-freezing level height (>4,420 m) are less likely to lead to hailfall at the ground. In a proximity sounding study, Púčik *et al*. (2015) showed that for non-severe and severe hail events the median of the 800–600 hPa lapse rate is of 6.3 and 6.6 K km^{-1}, respectively. Assuming an average lapse rate of 6.6 K km^{-1} for a T2 m of 29 °C, the freezing level height is of 4.4 km. Considering that summertime diurnal T2 m commonly reach similar or higher values over mainland Portugal, this may explain that few thunderstorms lead to hailfall on the ground. In fact, ca. 75% of the thunderstorm events in mainland Portugal occur for T2 m above 12 °C (Figure 5a), while hailstorms tend to occur under cooler conditions (ca. 75% below 12 °C). Furthermore, the excessively high-freezing levels may also underlie the absence of a clear autumnal maximum in hailstorms, on the contrary to thunderstorms, as autumn temperatures are typically higher than spring temperatures. This hail melting process may also explain the 1-month lag between the hailstorm maximum in April and the thunderstorm maximum in May. Convection days reveal an intermediate (mixed) behaviour, as expected (Figure 5a). The preference of hail occurrences under cool conditions is more evident for hail without thunder events and particularly for small hail events, which are all associated to T2 m below 16 °C (Figure 5b). In contrast, 16% of hail with thunder events occurs for T2 m

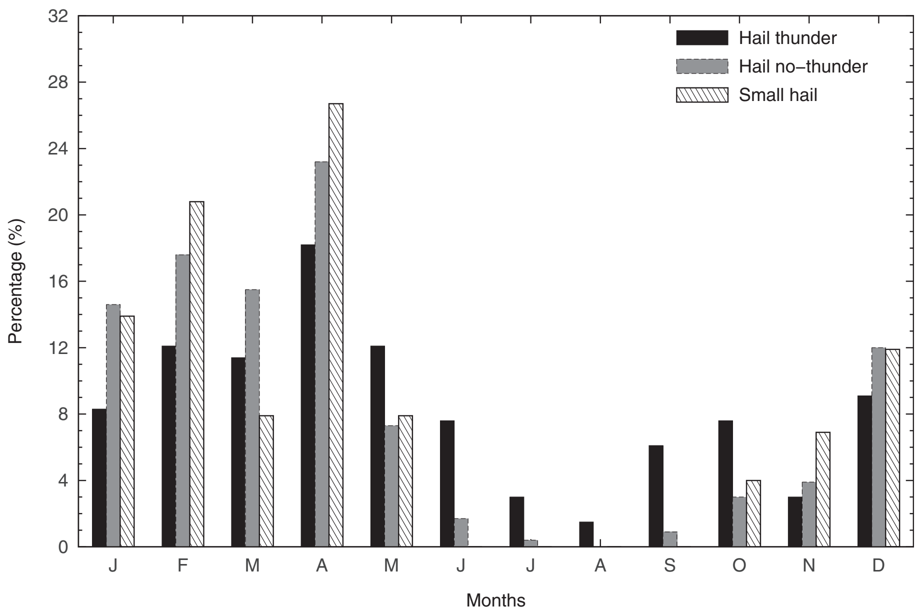

FIGURE 3 Monthly relative frequencies of occurrence (in %) of the three hail sub-classes (hail with thunder, hail without thunder and small hail) for the period of 1971–2009

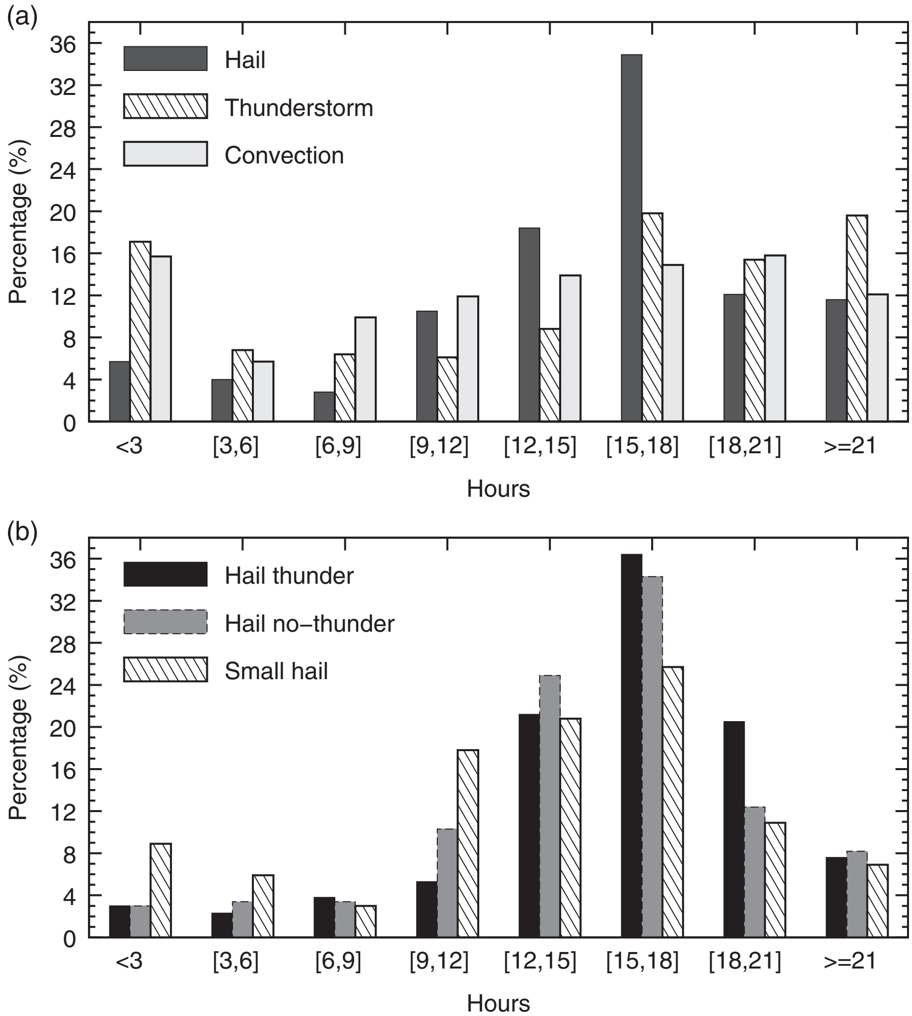

FIGURE 4 (a) Relative frequencies of occurrence (in %) of hail, thunderstorm and convection days, collected at the 15 meteorological stations in Portugal and over the period of 1971–2009, by different time periods of the day. (b) The same as in (a) but for the three hail sub-classes (hail with thunder, hail without thunder and small hail)

above 16 °C, suggesting that these events might be associated with larger instability (i.e., higher lapse rates) and, consequently, to stronger updrafts and to the formation of larger hail, which is thus less susceptible to melting.

3.3 | Large-scale dynamical forcing of hail

In order to better understand the hail-triggering mechanisms, the large-scale dynamical conditions associated with hail days in mainland Portugal will be analysed in this section. A hail day in Portugal corresponds to a day with at least one hail occurrence reported by the selected network of 15 meteorological stations. A weather typing approach was applied for analysing the large-scale conditions underlying hail days in Portugal. The composites of MSLP, Z500 and PV250 for all days keyed to each weather type in the period of 1979–2009 (Figure 6) highlight their corresponding typical dynamical features (average conditions or centroids). However, specific days farther away from centroid conditions can be significantly different (much less typical), as will be discussed below. Despite the different weather typing approach from Santos *et al*. (2016), the composites of the MSLP for the eight weather types (WT1–8, Figure 6) are similar to those obtained in the previous study using a two-dimensional approach (cf. their Figure 2). However, to avoid misinterpretations, the weather type designations used in Santos *et al*. (2016) will not be followed herein, as the purposes of the two studies are quite different. Although a detailed comparison between the two- and three-dimensional approaches is not within the scope of this study, it can be stated that WT1 clearly resembles the former WT S3, WT2 resembles W1, WT3 resembles S1, WT4 resembles S2, WT5 resembles W2, WT6 resembles B1, WT7 resembles B2 and WT8 resembles W3. The typical patterns of each weather type, as well as their seasonality (Figure S2), will be succinctly discussed in the following lines.

WT1 (European Ridge, Figure 6a) is characterized by a strong low-pressure system over the sub-polar North Atlantic, but confined by a high-pressure belt, extending from the subtropical North Atlantic to Eastern Europe, with two high-pressure cores. An anti-cyclonic ridge over Europe and a see-saw structure in PV250, with a positive core over the

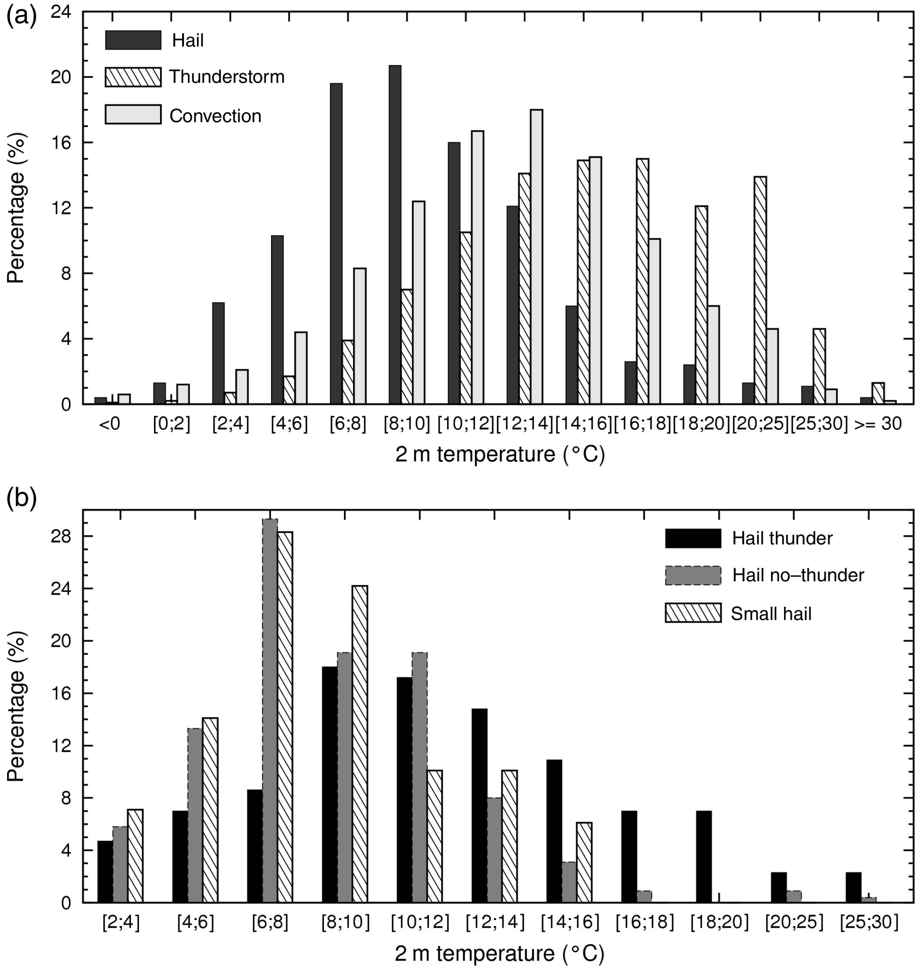

FIGURE 5 (a) Relative frequencies of occurrence (in %) of hail, thunderstorm and convection days, collected at the 15 meteorological stations in Portugal and over the period of 1971–2009, by 2 m air temperature intervals (in °C). (b) The same as in (a) but for the three hail sub-classes (hail with thunder, hail without thunder and small hail)

sub-polar North Atlantic and a negative core over northern Europe, are also apparent. This regime occurs throughout the year (Figure S2 in Appendix S1). WT2 (Figure 6b), more frequent in April–May and October (Figure S2 in Appendix S1), features a strong cyclonic trough over Western Europe, with a well-defined vertical structure throughout the troposphere. WT3 (Summer North Atlantic Ridge, Figure 6c), very common in July–August (Figure S2 in Appendix S1), is characterized by a ridge extending over a large area of the North Atlantic and Europe and by a middle and upper level trough over Iberia. WT4 (Figure 6d), predominant in summer (Figure S2 in Appendix S1), reveals a dipolar structure in PV250 similar to WT1, but of opposite signal (waves in phase opposition), with a strong ridge over the North Atlantic accompanied by a well-developed trough over Scandinavia. WT5 (Westerly Flow, Figure 6e), also more frequent in summer (Figure S2 in Appendix S1), discloses a typical north–south dipolar structure over the North Atlantic, with a sub-polar low-pressure system nearby Iceland and a subtropical high-pressure system over the Azores Archipelago, inducing prevailing westerly winds over Western Europe. WT6 (Figure 6f), less frequent in summer (Figure S2 in Appendix S1), depicts a positive core in PV250 over Iberia and a blocking-like dynamical structure, with a trough over Iberia at 500 hPa and a high-pressure system over the British Isles. WT7 (Winter British Ridge, Figure 6g), predominant from November to March (Figure S2 in Appendix S1), displays a strong wave-like pattern, with a robust anti-cyclonic ridge over Western Europe and centred over the British Isles. Lastly, WT8 (Winter North Atlantic Ridge, Figure 6h), also more frequent from November to March (Figure S2 in Appendix S1), reveals a ridge over the North Atlantic and southwestern Europe, along with a vast high-pressure system and a strong meridional wave-like pattern in PV250.

Hail days are expected to be more likely under specific dynamical conditions. Hence, it should be expected that hail occurrence is differently distributed by the different weather types. However, as the frequencies of occurrence of the weather types are not uniform and vary seasonally, the number of hail days in each WT is normalized by the number of WT days (empirical probability of occurrence within each WT, Figure 7). For mainland Portugal, the probabilities of hail occurrence for WT2, followed by WT6, are clearly above the climatological probability (ca. 2%), that is, above

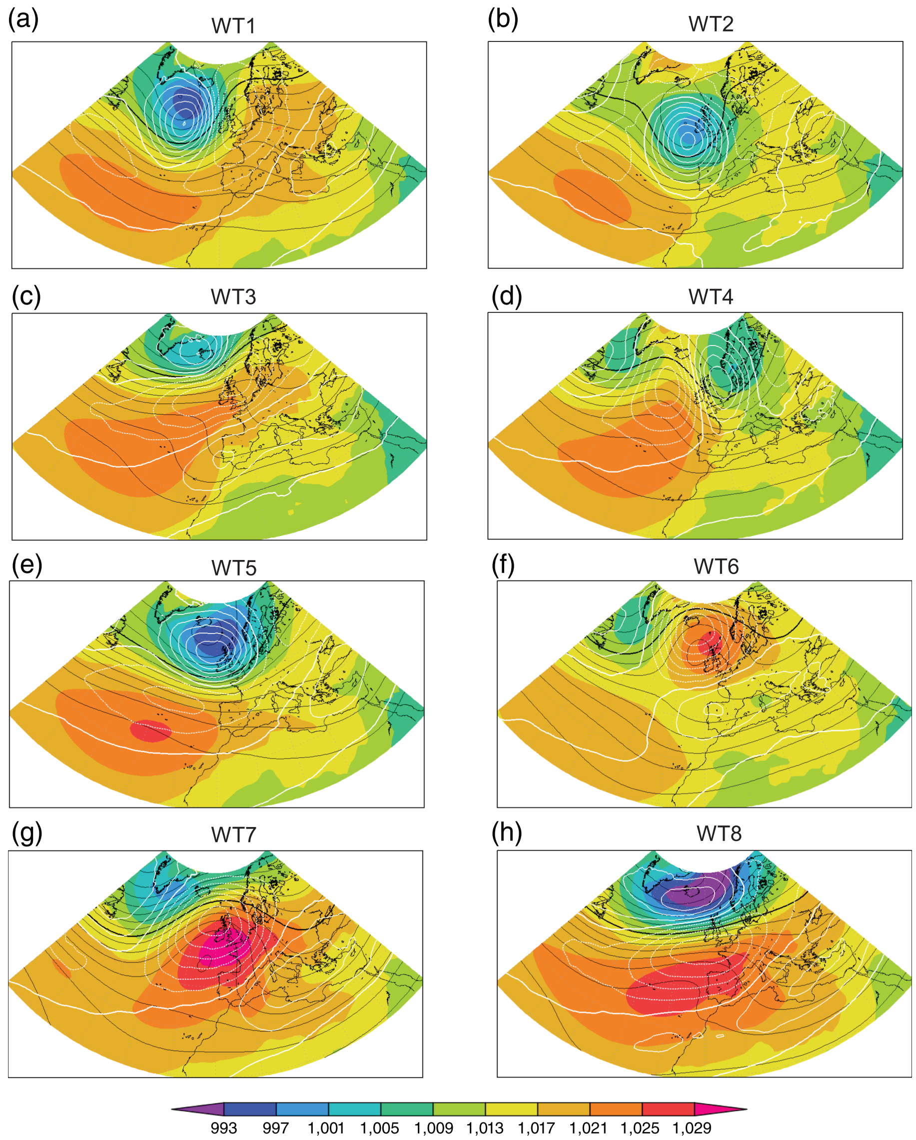

FIGURE 6 (a–h) Composites of daily SLP (shading in hPa, intervals of 4 hPa), Z500 (black contours in gpm, intervals of 50 gpm) and the PV250 anomalies (white contours in PVU—1 PVU = 106 K m2 kg-1 s-1—intervals of 0.05 PVU, solid/dashed contours for positive/negative anomalies) for each weather type (WT1–8) over the period of 1979–2009 (Data source: ERA-Interim). Thick black contours for 5,500 gpm and thick white contours for zero PV250 anomaly

the annual mean relative frequency of hail days (Figure 7). The hail probabilities are close to the climatological value for WT4. For the remaining WTs the probabilities are all below the climatological probability (Figure 7). Additionally, it is still worth noting the generally lower probabilities for the south (Figure 7), a much drier and warmer region, also much less exposed to the North Atlantic weather disturbances.

As seasonality is also shown to be an important factor to take into consideration for hail in mainland Portugal, the probabilities of occurrence of hail days were also analysed by season (Figure 8a). Apart from small differences in detail, WT2, WT4 and WT6 reveal the highest probabilities, as verified for the annual values. The maximum hail probability (nearly 20%) occurs under WT2 during winter. In addition, a similar analysis was carried out for thunderstorm (Figure 8b) and convection (Figure 8c) days in Portugal. As expected, thunderstorms and convection days are much more frequent than hail days, particularly the latter (Figure 8). In fact, the climatological probability of a thunderstorm day is of ca. 17% and of a convection day is of ca. 53%, which are remarkably higher than for hail days (2%). For thunderstorms (Figure 8b), their probability is higher under WT2 in winter (55%) and autumn (38%), while it is higher under WT6 in spring (> 40%). For convection (Figure 8c), much higher probabilities were found, but also showing clear maxima for WT2 and WT6. Overall, the dynamical regimes more favourable to thunderstorm and convection occurrences are also the most favourable to hail occurrences (WT2 and WT6). However, under these regimes, thunderstorm and convection probabilities are nearly as high in autumn as in spring, while hail is much less frequent in fall

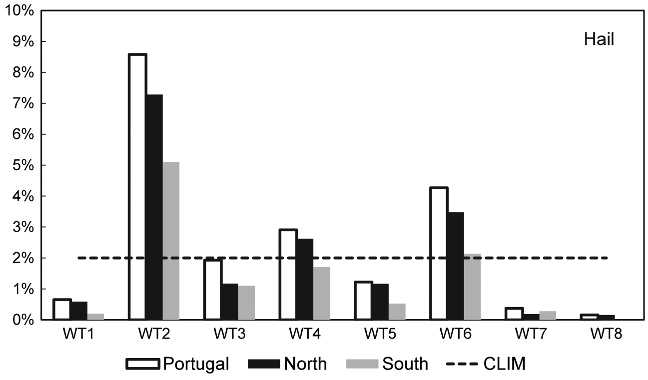

FIGURE 7 Empirical probabilities of occurrence of hail days by WT (ratio between the number of hail days in each WT and the number of WT days) over mainland Portugal, north and south of Portugal (separated by the Tagus River, Figure 1). The dashed line corresponds to the respective climatological probability of occurrence (CLIM) for the full time period (1979–2009), that is, the annual mean relative frequency of hail days

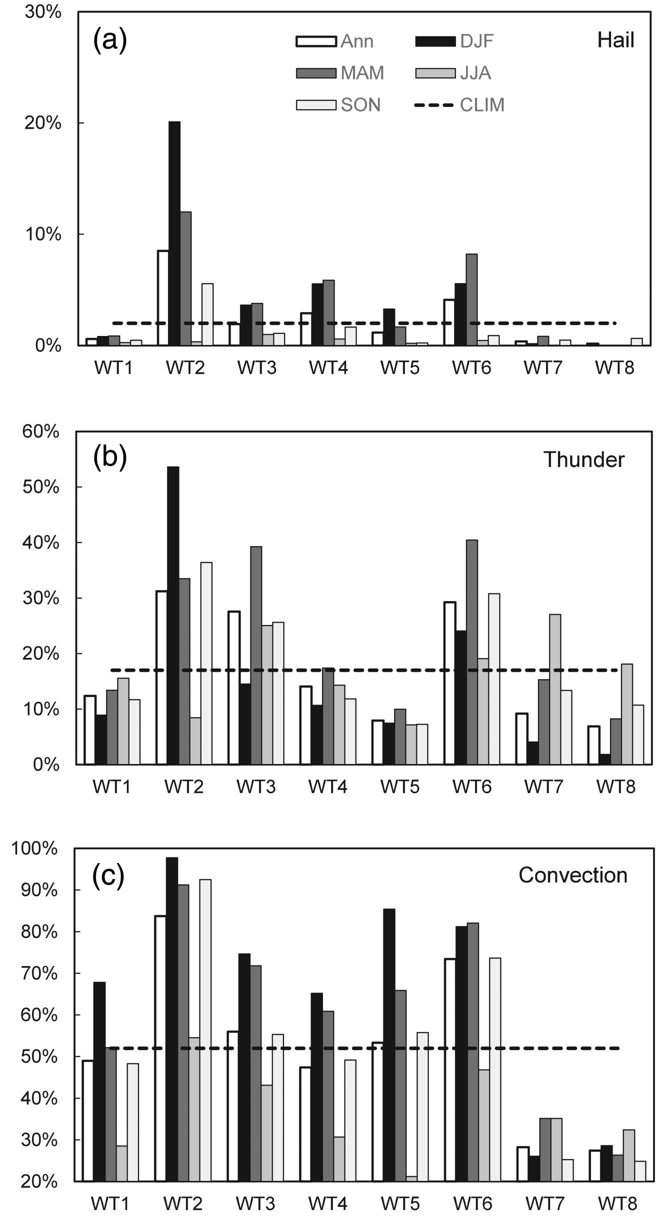

FIGURE 8 Empirical probabilities of occurrence of (a) hail, (b) thunderstorm and (c) convection days over mainland Portugal by WT (ratio between the number of the event days in each WT and the number of WT days) for the full year (Ann) and for each season separately (DJF, MAM, JJA and SON). Dashed lines correspond to the respective climatological probability of occurrence (CLIM) for the full time period (1979–2009), that is, the annual mean relative frequency of the event days

than in spring. Despite the above-referred differences, the results reveal a similar large-scale dynamical forcing for hail and thunderstorm events, which implies that other factors (e.g., local-to-mesoscale conditions) explain the absence of the autumnal maxima in hail days. The thermal conditions were already mentioned as an explanation factor for this divergence. However, further research should be envisioned to clarify this behaviour.

The composites of each WT for the hail days highlight the specific dynamical hail-driving conditions (Figure 9). Ranking these conditions as a function of the number of hail days in each WT, WT2 (Western European Trough) is by far the most relevant ($n = 105$), mostly during winter and spring (Table 2), as was described above (Figures 7 and 8). The corresponding composite for hail days (Figure 9b) reveals an extra-tropical depression and an enhanced trough over Western Europe (strengthened with respect to the WT2 centroid, Figure 6b), at middle and upper levels, with a remarkably strong positive core in PV250 (>6 PVU). This pattern is commonly linked to cold front passage, which is an important source of lift, thus generating favourable conditions for the development of convective storms.

WT6 ($n = 52$) is also an important driver of hail occurrences over Portugal. Again the strengthening of the centroid pattern (Figures 6f and 9f) leads to the emergence of a cut-off low, with a positive core in PV250 (>6 PVU) over northwestern Iberia, while the British Isles are under a strong high-pressure system. From these 52 hail occurrences, the vast majority also occurs in winter and spring (Table 2). For WT4 ($n = 51$) the typical middle and upper level trough is anomalously strong and extended towards the Iberian Peninsula (Figures 6d and 9d). For WT3 (Summer North Atlantic Ridge, $n = 28$), a strong mesoscale cut-off low develops over southwestern Iberia (>5 PVU), along the southern flank of the North Atlantic ridge (Figure 9d). In fact, nearly 40% of hail events in summer are associated with this dynamical pattern (Table 2). For WT5 (Westerly Flow, $n = 20$) and WT1 (European Ridge, $n = 9$) deep troughs over Western Europe, with some similarity with troughs in WT2, but zonally narrower (Figure 9a,e), are also fingerprints of the passage of frontal systems over mainland Portugal, mostly in the case of WT5. Lastly, WT7 (Winter British Ridge, $n = 4$) and WT8 (Winter North Atlantic Ridge, $n = 2$) are in general largely unfavourable to hail occurrences, owing to their typically strong anti-cyclonic circulation over mainland Portugal (Figure 6g,h). However, in some sporadic occasions, a marked positive core in PV250 (>4 PVU), linked to upper-level troughs or upper-level lows, develop over southwestern Iberia (Figure 9g,h), thus promoting deep convection. The

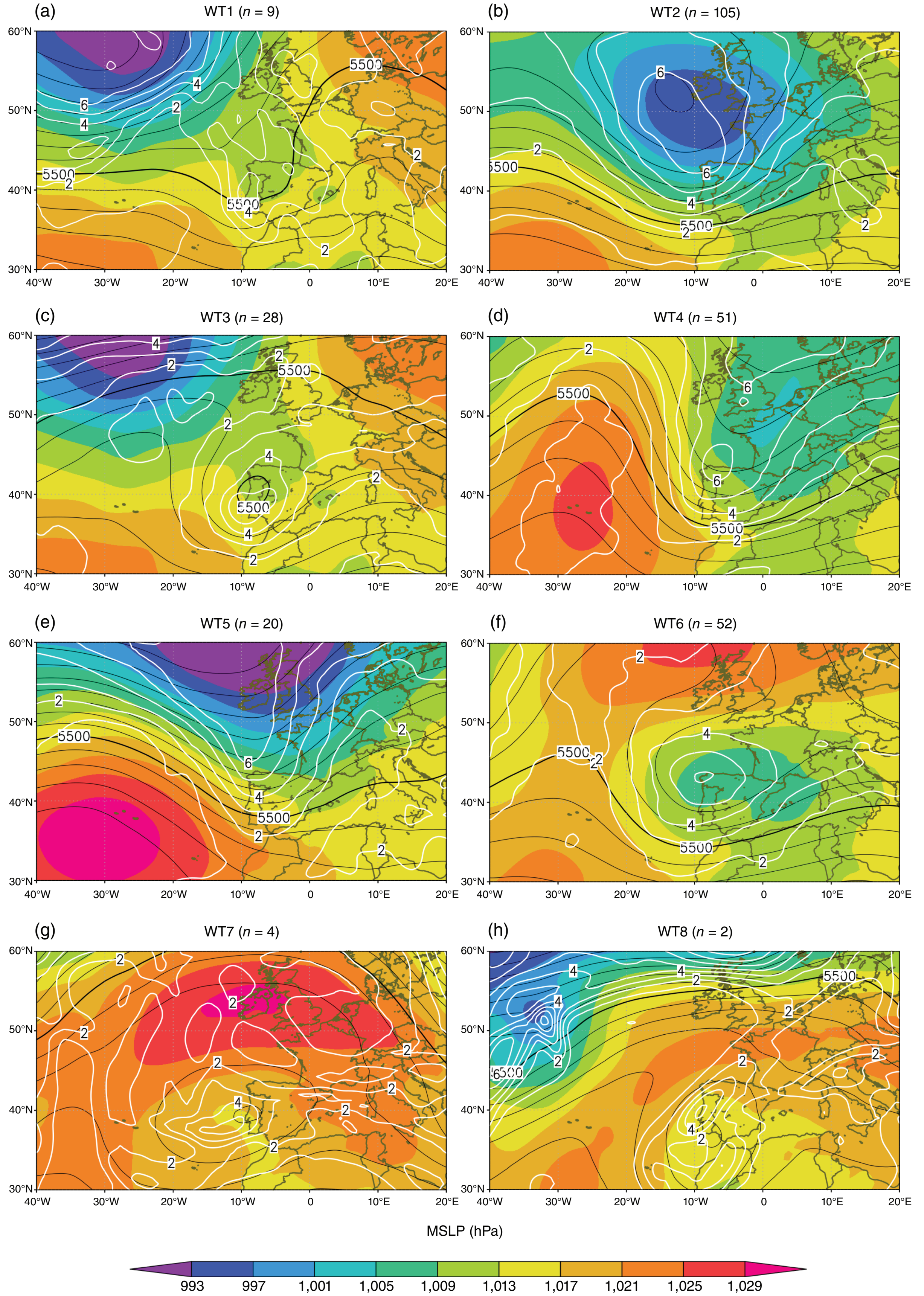

FIGURE 9 As in Figure 6, but only for hail days in each WT (a–h). The number of hail days in each composite (n) is also outlined. The colour scale is the same as in Figure 6. The extent of the geographical sector was reduced to improve readability

TABLE 2 Number of hail days over mainland Portugal in the period of 1979–2009 by weather type (WT1–8) and for the full year (ANN) or for winter (DJF), spring (MAM), summer (JJA) and autumn (SON), separately

Portugal	ANN	DJF	MAM	JJA	SON	Records	Records (%)
WT1	9	3	3	1	2	9	2
WT2	105	36	48	1	20	158	44
WT3	28	5	13	6	4	30	8
WT4	51	14	27	4	6	64	18
WT5	20	11	7	1	1	29	8
WT6	52	21	27	1	3	64	18
WT7	4	1	2	0	1	5	1
WT8	2	0	0	0	2	2	1

Note. The total number of hail records over Portugal (recorded at the selected 15 weather stations) by weather type is also outlined, along with the corresponding fractions of records (in %).

total number of hail records over Portugal (recorded at the 15 selected weather stations) also shows the leading role played by WT2, with a total of 158 records (44% of all hail records), followed by WT4 and WT6 (each with 64 records, 18%). Both WT7 and WT8 contribute to only ca. 1% to the total number of hail records (Table 2).

The spatial patterns of the CAPE and TT composites for each WT tend to show relatively high values over the more continental areas (inner Iberia) and much lower values over the surrounding maritime areas (Figure 10). However, some important differences among WTs can be outlined. For WT2, the type connected to the majority of hail occurrences in mainland Portugal (Figure 10b), the largest values of CAPE (>200 J kg^{-1}) and TT (>52 °C) are located over northwestern Iberia (cf. the rule-of-thumb scale for TT in Figure 10). For WT6 (Figure 10f), the second most important WT for hail occurrences, TT values are higher over inner-northern Iberia (>52 °C), while CAPE reveals a quite uniform pattern (~100 J kg^{-1}). For WT4 (Figure 10d), the third in the number of hail days, a maximum of CAPE (>200 J kg^{-1}) is located over northern Iberia, while TT achieves maximum values in the inner-north of the peninsula. For WT3 (Figure 10c), the fourth in the number of hail days, the largest values of CAPE (>250 J kg^{-1}) occur over northern Portugal, which are mostly related to spring and summer hail days (warmer conditions with higher available energy), as was shown above. For WT7 (Figure 10g) and WT8 (Figure 10h), for which hail occurrences are sporadic, the maximum values of CAPE and TT are found in southern Portugal. In WT7, values of TT larger than 54 °C and CAPE >500 J kg^{-1} are found in southern-inner Portugal, but much lower values are depicted in WT8. When only the hail with thunder events are considered in the composites, an overall strengthening of the patterns is observed (Figures S3 and S4 in Appendix S1). The locations of the hail occurrences over Portugal for each WT are also displayed in Figure S5 in Appendix S1. An analysis using atmospheric datasets with much higher spatial resolution than ERA-Interim, generated by regional models, may provide a better spatial correspondence between the local hail records and these indices (e.g., CAPE and TT, Figure 10 and Figure S4 in Appendix S1), including some insights into their potential forecast skill at local scales. However, these analyses and model simulations are out of the scope of the present study and will be undertaken in forthcoming studies.

In summary, the composite analysis for the different WTs reveals that hail occurrence in mainland Portugal is associated with either extra-tropical depressions or upper-level troughs/lows, which are more frequent during winter and spring associated with the WT2, WT4 and WT6 regimes. The hail occurrences under other WTs were shown to be mostly related to exceptional / atypical conditions of the corresponding WT, mainly driven by mesoscale systems embedded in the large-scale pattern. Similar results were obtained when considering only stations either northwards or southwards of the Tagus River, apart from some differences in detail (not shown). These outcomes not only give clues about the hail-triggering conditions in mainland Portugal, but also demonstrate a high coherency of the hail dataset with the underlying atmospheric dynamics. These findings are also in agreement with previous studies that showed that these upper-level systems act to enhance conditional instability (Juckes and Smith, 2000; Gold and Nielsen-Gammon, 2008), supporting the development of convective storms. Furthermore, the eastern side of the trough lift is favoured by advection of potential vorticity (Hoskins *et al.,* 1985). All these large-scale dynamical features are thereby precursors of hailstorms in Portugal, but local-to-mesoscale thermal conditions are also determinant for hail occurrences at the surface.

4 | CONCLUSIONS

This study provides a first comprehensive analysis of the hail events in mainland Portugal. This analysis extends over the period of 1971–2009 (39 years) and uses the records from a network of 15 meteorological stations. Three hail types were also considered separately: small hail, hail without thunder and hail with thunder. Not only the climatological characteristics of hail occurrences (spatial and temporal variability, including seasonality and daily cycle) are assessed, but also their connections to the large-to-mesoscale atmospheric drivers. The records of thunderstorm and convection events from the same network and over the same time period were also used for comparison purposes. Furthermore, the relationship between hail events and atmospheric circulation patterns was also analysed using a novel 3D weather type daily catalogue for the period of 1979–2009.

In mainland Portugal, hail occurs mostly northwards of the Tagus River, with an annual mean number of hail days larger than 2 days/year in Porto and Viseu. On average, hail frequency presents a maximum in the period from February

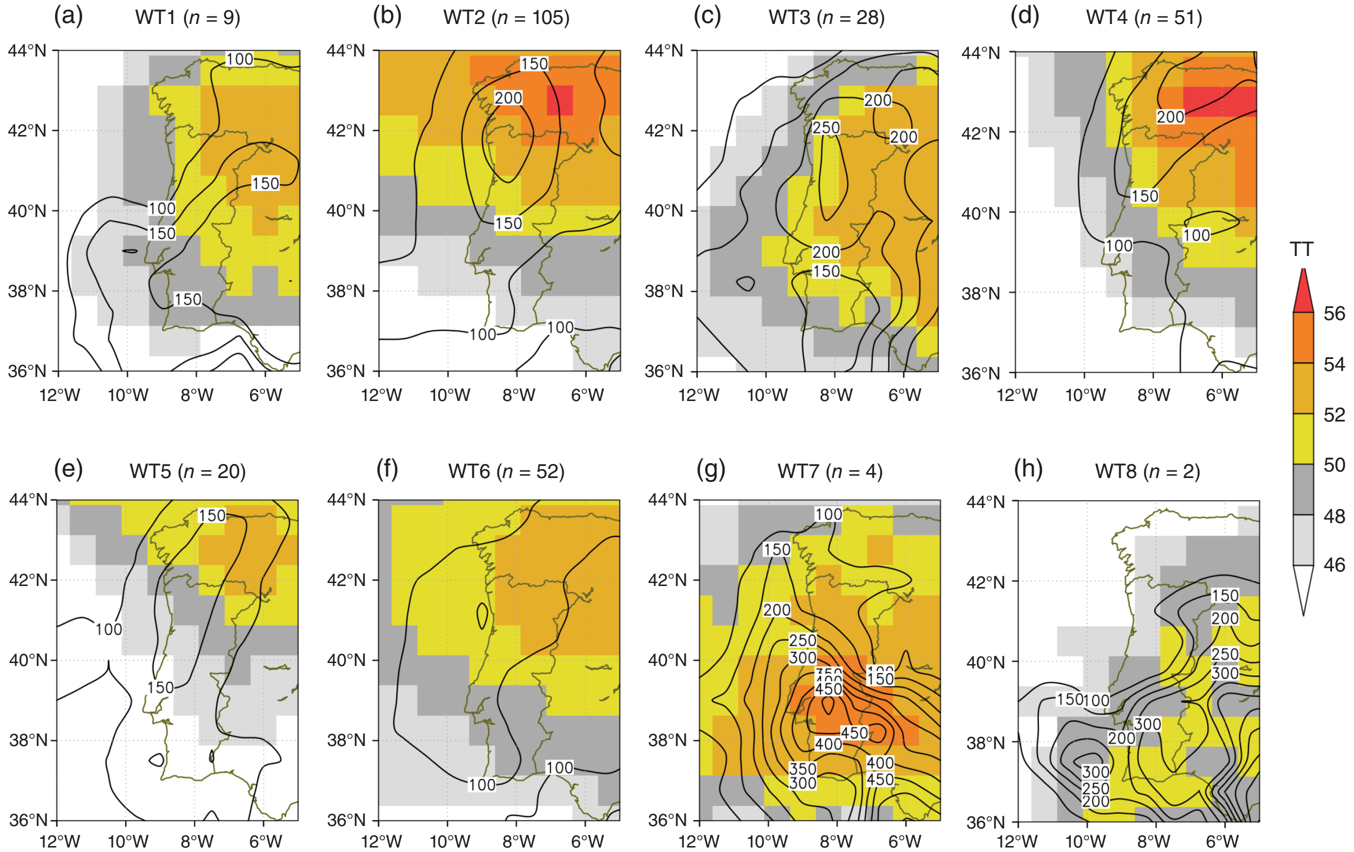

FIGURE 10 (a–h) Composites of the 1200 UTC CAPE (Convective Available Potential Energy, contours at 50 J kg-1 intervals) and TT (Total-Totals index, colour shading) for hail days in each WT over western Iberia for the period of 1979–2009. The number of hail days in each composite (n) is also outlined. TT rule-of-thumb scale: 46–50 °C (thunderstorms possible); 50–54 °C (thunderstorms most likely, possibly severe); >54 °C (severe thunderstorms most likely)

to April (late winter and early spring) and a minimum in July–August. Convection frequency peaks in April, while thunderstorm frequency is maximum in May (1-month lag). Both thunderstorm and convection events present a secondary peak in autumn (October), which is frequently associated with convective storms without hailfall at the ground, as no clear autumnal maximum is recorded in the hail frequency, particularly in the case of small hail and hail without thunder. The typically higher temperatures in October (second thunderstorm maximum) than in February–April (hail maximum) may lead to excessively high-freezing level heights that hamper hailfall at the surface, as was also mentioned by Punge *et al*. (2017). Therefore, this process may underlie the absence of a clear autumnal maximum in hail occurrences. This same process can also explain the 1-month lag between the hailfall maximum, in April, and the thunderstorm maximum, in May.

The seasonal distribution of hail events in mainland Portugal, with a peak from February to April, is considerably different from other regions of Europe, such as Finland (Tuovinen *et al.,* 2009) and Central Europe (Suwała and Bednorz, 2013; Burcea *et al.,* 2016), where hail occurs mainly from May to September. In mainland Portugal, nearly 58% of hail events reported at weather stations are associated with T2 m <10 °C, thus probably related to small hail events that are typically linked to much weaker and less organized convective cells than severe hail, which is also in agreement with previous studies (Sánchez *et al.,* 2009; Li *et al.,* 2018). However, in Portugal severe hail can also occur in the winter half of the year (Belo-Pereira *et al.,* 2017), when synoptic conditions are more favourable to severe convection, owing to the much warmer wintertime conditions than in, for example, Central Europe (Figure S6 in Appendix S1). On the other hand, summertime hail is much less frequent in Portugal than in Central Europe, mostly due to the influence of Azores high, commonly very pronounced in this season (Martins *et al.,* 2016), which also explains the very low-summer precipitation amounts when compared to Central Europe (Figure S6 in Appendix S1).

The analysis of the atmospheric circulation patterns associated with hail days over mainland Portugal also revealed high coherency between hail occurrences and the large-to-mesoscale dynamical conditions of eight 3D weather types. Hail events are clearly connected to specific dynamical drivers, either remote extra-tropical depressions, with cold front passages over Portugal, or local strong upper-level troughs/lows. Under strong anti-cyclonic circulations at low levels, the presence of mesoscale cut-off lows over western

Iberia also promotes instability conditions favourable to hailstorm occurrence. Similar relationships between weather type dynamical features and hail occurrence were found over other European regions (Aran *et al.,* 2011; Suwała, 2013; Merino *et al.,* 2014).

These results provide valuable information not only for upcoming research, but also for several socio-economic sectors in the country, such as viticulture and horticulture, for which hail represents a major natural peril, frequently entailing significant losses. This hail climatology is thereby a first step to support decisions involved, for example, in agricultural planning and in other relevant socio-economic sectors in Portugal. In addition, a more in depth analysis of the atmospheric drivers of hail events in Portugal, including an assessment of potentially predictive indices, such as in a previous research for lightning in Portugal (Sousa *et al.,* 2013), will also be the focus of a forthcoming study. The identification of these indices is of utmost relevance in operational weather forecasting, by assisting meteorologists towards a more accurate prediction of hail occurrences, also with evident benefits to many socio-economic sectors throughout the country.

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REFERENCES

Allen, J.T., Tippett, M.K. and Sobel, A.H. (2015a) An empirical model relating US monthly hail occurrence to large-scale meteorological environment. *J Adv Model Earth Syst*, 7, 226–243. https://doi.org/10.1002/2014MS000397.

Allen, J.T., Tippett, M.K. and Sobel, A.H. (2015b) Influence of the El Nino/-Southern Oscillation on tornado and hail frequency in the United States. *Nat Geosci*, 8, 278–283. https://doi.org/10.1038/ngeo2385.

Anderson, G. and Klugmann, D. (2014) A European lightning density analysis using 5 years of ATDnet data. *Nat Hazards Earth Syst Sci*, 14, 815–829. https://doi.org/10.5194/nhess-14-815-2014.

Aran, M., Pena, J.C. and Tora, M. (2011) Atmospheric circulation patterns associated with hail events in Lleida (Catalonia). *Atmos Res*, 100, 428–438. https://doi.org/10.1016/j.atmosres.2010.10.029.

Baldi, M., Ciardini, V., Dalu, J.D., Filippis, T.D., Maracchi, G. and Dalu, G. (2014) Hail occurrence in Italy: towards a national database and climatology. *Atmos Res*, 138, 268–277. https://doi.org/10.1016/j.atmosres.2013.11.012.

Belo-Pereira, M., Andrade, C. and Pinto, P. (2017) A long-lived tornado on 7 December 2010 in mainland Portugal. *Atmos Res*, 185, 202–215. https://doi.org/10.1016/j.atmosres.2016.11.002.

Berthet, C., Wesolek, E., Dessens, J. and Sanchez, J.L. (2013) Extreme hail day climatology in Southwestern France. *Atmos Res*, 123, 139–150. https://doi.org/10.1016/j.atmosres.2012.10.007.

Bowden, K.A. and Heinselman, P.L. (2016) A qualitative analysis of NWS forecasters' use of phased-array radar data during severe hail and wind events. *Weather Forecast*, 31, 43–55. https://doi.org/10.1175/WAF-D-15-0089.1.

Brown, T.M., Pogorzelski, W.H. and Giammanco, I.M. (2015) Evaluating hail damage using property insurance claims data. *Weather Clim Soc*, 7, 197–210. https://doi.org/10.1175/WCAS-D-15-0011.1.

Burcea, S., Cică, R. and Bojariu, R. (2016) Hail climatology and trends in Romania: 1961–2014. *Monthly Weather Review*, 144, 4289–4299. https://doi.org/10.1175/MWR-D-16-0126.1.

Changnon, S.A. (1992) Temporal and spatial relations between hail and lightning. *J Appl Meteor*, 31, 587–604.

Changnon, S.A. (1999) Data and approaches for determining hail risk in the contiguous United States. *J Appl Meteorol*, 38, 1730–1739. https://doi.org/10.1175/1520-0450(1999)038<1730:DAAFDH>2.0.CO;2.

Changnon, S.A. (2001) Assessment of the quality of thunderstorm data at first-order stations. *Journal of Applied Meteorology*, 40, 783–794. https://doi.org/10.1175/1520-0450(2001)040<0783:AOTQOT>2.0.CO;2.

Cintineo, J.L., Smith, T.M., Lakshmanan, V., Brooks, H.E. and Ortega, K.L. (2012) An objective high-resolution hail climatology of the contiguous United States. *Weather Forecast*, 27, 1235–1248. https://doi.org/10.1175/WAF-D-11-00151.1.

Das, M., Oterkus, E., Madenci, E. and Razi, H. (2009) Residual strength of sandwich panels with hail damage. *Compos Struct*, 88, 403–412. https://doi.org/10.1016/j.compstruct.2008.05.002.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Hólm, E.V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.J., Park, B. K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.N. and Vitart, F. (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Q J Roy Meteor Soc*, 137, 553–597. https://doi.org/10.1002/qj.828.

Dessens, J., Berthet, C. and Sanchez, J.L. (2015) Change in hailstone size distributions with an increase in the melting level height. *Atmos Res*, 158, 245–253. https://doi.org/10.1016/j.atmosres.2014.07.004.

Gallus, W.A., Snook, N.A. and Johnson, E.V. (2008) Spring and summer severe weather reports over the Midwest as a function of convective mode: a preliminary study. *Weather Forecast*, 23, 101–113. https://doi.org/10.1175/2007WAF2006120.1.

Gold, D.A. and Nielsen-Gammon, J.W. (2008) Potential vorticity diagnosis of the severe convective regime. Part III: the hesston tornado outbreak. *Mon Weather Rev*, 136, 1593–1611. https://doi.org/10.1175/2007MWR2092.1.

Groenemeijer, P.H. and van Delden, A. (2007) Sounding-derived parameters associated with large hail and tornadoes in the Netherlands. *Atmos Res*, 83, 473–487. https://doi.org/10.1016/j.atmosres.2005.08.006.

Hand, W.H. and Cappelluti, G. (2011) A global hail climatology using the UK Met Office convection diagnosis procedure (CDP) and model analyses. *Meteorol Appl*, 18, 446–458. https://doi.org/10.1002/met.236.

Hermida, L., Sánchez, J.L., López, L., Berthet, C., Dessens, J., García-Ortega, E. and Merino, A. (2013) Climatic trends in hail precipitation in France: spatial, altitudinal, and temporal variability. *Sci World J*, 2013, 1–10. https://doi.org/10.1155/2013/494971.

Hoskins, B.J., McIntyre, M.E. and Robertson, A.W. (1985) On the use and significance of isentropic potential vorticity maps. *Q J R Meteorol Soc*, 111, 877–946. https://doi.org/10.1002/qj.49711147002.

Ilotoviz, E., Khain, A.P., Benmoshe, N., Phillips, V.T.J. and Ryzhkov, A.V. (2016) Effect of aerosols on freezing drops, hail, and precipitation in a midlatitude storm. *J Atmos Sci*, 73, 109–144. https://doi.org/10.1175/JAS-D-14-0155.1.

Juckes, M. and Smith, R.K. (2000) Convective destabilization by upper-level troughs. *Q J R Meteorol Soc*, 126, 111–123. https://doi.org/10.1002/qj.49712656206.

Kahraman, A., Tilev-Tanriover, S., Kadioglu, M., Schultz, D.M. and Markowski, P.M. (2016) Severe hail climatology of Turkey. *Mon Weather Rev*, 144, 337–346. https://doi.org/10.1175/MWR-D-15-0337.1.

Kaltenbock, R., Diendorfer, G. and Dotzek, N. (2009) Evaluation of thunderstorm indices from ECMWF analyses, lightning data and severe storm reports. *Atmos Res*, 93, 381–396. https://doi.org/10.1016/j.atmosres.2008.11.005.

Kapsch, M.L., Kunz, M., Vitolo, R. and Economou, T. (2012) Long-term trends of hail-related weather types in an ensemble of regional climate models using a Bayesian approach. *J Geophys Res–Atmos*, 117, D15107. https://doi.org/10.1029/2011JD017185.

Kunz, M. and Kugel, P.I.S. (2015) Detection of hail signatures from single-polarization C-band radar reflectivity. *Atmos Res*, 153, 565–577. https://doi.org/10.1016/j.atmosres.2014.09.010.

de la Torre, A., Hierro, R., Llamedo, P., Rolla, A. and Alexander, P. (2011) Severe hailstorms near Southern Andes in the presence of mountain waves. *Atmos Res*, 101, 112–123. https://doi.org/10.1016/j.atmosres.2011.01.015.

Lang, T.J. and Rutledge, S.A. (2002) Relationships between convective storm kinematics, precipitation, and lightning. *Mon Wea Rev*, 130, 2492–2506. https://doi.org/10.1175/1520-0493(2002)130<2492:RBCSKP>2.0.CO;2.

Li, X., Zhang, Q., Zou, T., Lin, J., Kong, H. and Ren, Z. (2018) Climatology of hail frequency and size in China, 1980–2015. *J Appl Meteor Climatol*, 57, 875–887. https://doi.org/10.1175/JAMC-D-17-0208.1 in press.

Macdonald, H., Infield, D., Nash, D.H. and Stack, M.M. (2016) Mapping hail meteorological observations for prediction of erosion in wind turbines. *Wind Energy*, 19, 777–784. https://doi.org/10.1002/we.1854.

Manzato, A. (2013) Hail in northeast Italy: a neural network ensemble forecast using sounding-derived indices. *Weather Forecast*, 28, 3–28. https://doi.org/10.1175/WAF-D-12-00034.1.

Martins, J.P.A., Cardoso, R.M., Soares, P.M.M., Trigo, I.F., Belo-Pereira, M., Moreira, N. and Tomé, R. (2016) The summer diurnal cycle of coastal cloudiness over west Iberia using Meteosat/SEVIRI and a WRF regional climate model simulation. *Int J Climatol*, 36, 1755–1772. https://doi.org/10.1002/joc.4457.

Merino, A., Wu, X., Gascón, E., Berthet, C., García-Ortega, E. and Dessens, J. (2014) Hailstorms in southwestern France: incidence and atmospheric characterization. *Atmospheric Research*, 140–141, 61–75. https://doi.org/10.1016/j.atmosres.2014.01.015.

Mezher, R.N., Doyle, M. and Barros, V. (2012) Climatology of hail in Argentina. *Atmos Res*, 114, 70–82. https://doi.org/10.1016/j.atmosres.2012.05.020.

Miller, R. C. (1972). *Notes on analysis and severe storm forecasting procedures of the Air Force Global Weather Central.* Tech. Rept. 200(R). Headquarters: Air Weather Service, USAF, p. 190.

Mohr, S. and Kunz, M. (2013) Recent trends and variabilities of convective parameters relevant for hail events in Germany and Europe. *Atmos Res*, 123, 211–228. https://doi.org/10.1016/j.atmosres.2012.05.016.

Mohr, S., Kunz, M. and Geyer, B. (2015) Hail potential in Europe based on a regional climate model hindcast. *Geophys Res Lett*, 42, 10904–10912. https://doi.org/10.1002/2015GL067118.

Peyraud, L. (2013) Analysis of the 18 July 2005 tornadic supercell over the Lake Geneva Region. *Weather Forecast*, 28, 1524–1551. https://doi.org/10.1175/WAF-D-13-00022.1.

Počakal, D., Večenaj, Ž. and Štalec, J. (2009) Hail characteristics of different regions in continental part of Croatia based on influence of orography. *Atmos Res*, 93, 516–525. https://doi.org/10.1016/j.atmosres.2008.10.017.

Púčik, T., Groenemeijer, P., Rýva, D. and Kolář, M. (2015) Proximity soundings of severe and nonsevere thunderstorms in central Europe. *Mon Wea Rev*, 143, 4805–4821. https://doi.org/10.1175/MWR-D-15-0104.1.

Punge, H.J. and Kunz, M. (2016) Hail observations and hailstorm characteristics in Europe: a review. *Atmos Res*, 176, 159–184. https://doi.org/10.1016/j.atmosres.2016.02.012.

Punge, H.J., Bedka, K.M., Kunz, M. and Werner, A. (2014) A new physically based stochastic event catalog for hail in Europe. *Nat Hazards*, 73, 1625–1645. https://doi.org/10.1007/s11069-014-1161-0.

Punge, H.J., Bedka, K.M., Kunz, M. and Reinbold, A. (2017) Hail frequency estimation across Europe based on a combination of overshooting top detections and the ERA-INTERIM reanalysis. *Atmos Res*, 198, 34–43. https://doi.org/10.1016/j.atmosres.2017.07.025.

Rakovec, J., Gregorcic, B., Kranjc, A., Mekinda, T. and Kajfež-Bogataj, L. (1990) Some evaluations of hail suppression system efficiency in Slovenia, Yugoslavia. *Theor Appl Climatol*, 41, 157–171. https://doi.org/10.1007/BF00866439.

Ramos, A.M., Ramos, R., Sousa, P., Trigo, R.M., Janeira, M. and Prior, V. (2011) Cloud to ground lightning activity over Portugal and its association with circulation weather types. *Atmos Res*, 101, 84–101. https://doi.org/10.1016/j.atmosres.2011.01.014.

Rasuly, A.A., Cheung, K.K.W. and McBurney, B. (2015) Hail events across the greater metropolitan severe thunderstorm warning area. *Nat Hazard Earth Sys*, 15, 973–984. https://doi.org/10.5194/nhess-15-973-2015.

Sánchez, J.L., Fraile, R., de la Madrid, J.L., de la Fuente, M.T., Rodríguez, P. and Castro, A. (1996) Crop damage: the hail size factor. *J Appl Meteorol*, 35, 1535–1541. https://doi.org/10.1175/1520-0450(1996)035<1535:CDTHSF>2.0.CO;2.

Sánchez, J.L., Fernández, M.V., Fernández, J.T., Tuduri, E. and Ramis, C. (2003) Analysis of mesoscale convective systems with hail precipitation. *Atmos Res*, 67, 573–588. https://doi.org/10.1016/S0169-8095(03)00074-7.

Sánchez, J.L., Gil-Robles, B., Dessens, J., Martin, E., Lopez, L., Marcos, J.L., Berthet, C., Fernández, J.T. and García-Ortega, E. (2009) Characterization of hailstone size spectra in hailpad networks in France, Spain, and Argentina. *Atmos Res*, 93, 641–654. https://doi.org/10.1016/j.atmosres.2008.09.033.

Santos, J.A., Reis, M.A., Sousa, J., Leite, S.M., Correia, S., Janeira, M. and Fragoso, M. (2012) Cloud-to-ground lightning in Portugal: patterns and dynamical forcing. *Nat Hazard Earth Sys*, 12, 639–649. https://doi.org/10.5194/nhess-12-639-2012.

Santos, J.A., Reis, M.A., De Pablo, F., Rivas-Soriano, L. and Leite, S.M. (2013) Forcing factors of cloud-to-ground lightning over Iberia: regional-scale assessments. *Nat Hazard Earth Sys*, 13, 1745–1758. https://doi.org/10.5194/nhess-13-1745-2013.

Santos, J.A., Belo-Pereira, M., Fraga, H. and Pinto, J.G. (2016) Understanding climate change projections for precipitation over western Europe with a weather typing approach. *J Geophys Res–Atmos*, 121, 1170–1189. https://doi.org/10.1002/2015JD024399.

Schemm, S., Nisi, L., Martinov, A., Leuenberger, D. and Martius, O. (2016) On the link between cold fronts and hail in Switzerland. *Atmos Sci Lett*, 17, 315–325. https://doi.org/10.1002/asl.660.

Skripnikova, K. and Rezacova, D. (2014) Radar-based hail detection. *Atmos Res*, 144, 175–185. https://doi.org/10.1016/j.atmosres.2013.06.002.

Smith, B.T., Thompson, R.L., Grams, J.S., Broyles, C. and Brooks, H.E. (2012) Convective modes for significant severe thunderstorms in the contiguous United States. Part I: storm classification and climatology. *Weather Forecast*, 27, 1114–1135. https://doi.org/10.1175/WAF-D-11-00115.1.

Sousa, J.F., Fragoso, M., Mendes, S., Corte-Real, J. and Santos, J.A. (2013) Statistical–dynamical modeling of the cloud-to-ground lightning activity in Portugal. *Atmos Res*, 132–133, 46–64. https://doi.org/10.1016/j.atmosres.2013.04.010.

Suwała, K. (2013) The influence of atmospheric circulation on the occurrence of hail in the North German Lowlands. *Theor Appl Climatol*, 112, 363–373. https://doi.org/10.1007/s00704-012-0735-6.

Suwała, K. and Bednorz, E. (2013) Climatology of hail in central Europe. *Quaestiones Geographicae*, 32, 99–110.

Tullot, I.F. (2000) *Climatología de España y Portugal*. Salamanca, Spain: Universidad de Salamanca https://ediciones.usal.es/producto/978-84-7800-944-2.

Tuovinen, J.P., Punkka, A.J., Rauhala, J., Hohti, H. and Schultz, D.M. (2009) Climatology of severe hail in Finland: 1930-2006. *Mon Weather Rev*, 137, 2238–2249. https://doi.org/10.1175/2008MWR2707.1.

Tuovinen, J.P., Rauhala, J. and Schultz, D.M. (2015) Significant-hail-producing storms in Finland: convective-storm environment and mode. *Weather Forecast*, 30, 1064–1076. https://doi.org/10.1175/WAF-D-14-00159.1.

Walsh, S. (2012). *A summary of climate averages for Ireland 1981–2010.* Dublin, Ireland: MET Éireann. Technical Report: 14.

Wapler, K. (2013) High-resolution climatology of lightning characteristics within Central Europe. *Meteorol Atmos Phys*, 122, 175–184. https://doi.org/10.1007/s00703-013-0285-1.

Williams, E.R., Zhang, R. and Rydock, J. (1991) Mixed phase microphysics and cloud electrification. *J Atmos Sci*, 48, 2195–2203. https://doi.org/10.1175/1520-0469(1991)048<2195:MPMACE>2.0.CO;2.

WMO (2011). *Manual on codes: International codes.* Vol. I.1. Geneva, Switzerland: WMO. . Report no: 306.

WMO (2012). *Guide to meteorological instruments and methods of observation*, 7th editon. Geneva, Switzerland: WMO. Report no: 8.

Yun, B.I. and Rim, K.S. (2009) Construction of Lanczos type filters for the Fourier series approximation. *Appl Numer Math*, 59, 280–300. https://doi.org/10.1016/j.apnum.2008.02.005.

Zhang, C.X., Zhang, Q.H. and Wang, Y.Q. (2008) Climatology of hail in China: 1961-2005. *J Appl Meteorol Clim*, 47, 795–804. https://doi.org/10.1175/2007JAMC1603.1.

Zipser, E.J. and Lutz, K.R. (1994) The vertical profile of radar reflectivity in convective cells: a strong indicator of storm intensity and lightning probability? *Mon Wea Rev*, 122, 1751–1759. https://doi.org/10.1175/1520-0493(1994)122<1751:TVPORR>2.0.CO;2.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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