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Weather types and spatial variability of precipitation in the Iberian Peninsula

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ABSTRACT: The relationship between circulation weather types (WTs) and the spatial variability of precipitation across the Iberian Peninsula were studied using a high density, quality controlled, homogenized monthly precipitation database with approximately 3000 stations and interpolated to a 10 km grid. The circulation WTs were computed using an objective version of the Lamb classification centered on the Iberian Peninsula. A total of 26 WTs were selected for the period 1948–2003. Daily WTs were grouped to obtain their monthly frequencies, and used as potential independent variables in a linear least-square non-negative regression model with a forward stepwise selection. Results show the impact of each WT on precipitation in the Iberian Peninsula with a spatial resolution which had never been achieved before and additionally were obtained on a monthly scale highlighting the large seasonal cycle observed in each class, and including significantly different patterns in winter and summer. Nevertheless, results confirm that most of the precipitation in the Iberian Peninsula is produced by just a few WTs, with W, SW and C being the most influential. The association between WTs and precipitation is more robust in winter months and for the western IP areas, while it is lower during summer months and for the eastern IP areas. Spatial analysis revealed that precipitation on the Mediterranean coastland is mostly related with easterly flows (NE, E, SE and their hybrid counterparts), while on the Cantabrian coastland. N and NW flows are the most influential WTs. In general, cyclone-related types are the least frequent ones and also the most efficient in generating precipitation; while anticyclone-related types have the highest frequencies, but also the lowest contribution to total monthly rainfall in the Iberian Peninsula.

KEY WORDS weather types; monthly precipitation; Iberian Peninsula

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1. Introduction

Rainfall variability is a well known characteristic of the Mediterranean climate, and it has been particularly well studied around the Mediterranean Basin (Corte-Real *et al.*, 1995; Kutiel *et al.*, 1996; Xoplaki *et al.*, 2004, among many others). An example is presented in Dünkeloh and Jacobeit (2003), when they demonstrated that their analyses of modes of variability captured 75% of precipitation variability in the Mediterranean, and they found up to five significant atmospheric patterns responsible for seasonal precipitation. Furthermore, the same authors point out that precipitation during the wet season was well defined by different large-scale atmospheric patterns in contrast with summer, as the sub-grid scale convection processes dominated the summer rain-generator mechanism. For those interested in a more comprehensive evaluation of the Mediterranean precipitation regime, trends and modes of variability, we suggest reading the books by Lionello *et al.* (2006) and Lionello (2012).

In the Iberian Peninsula (IP), the orography exerts a strong influence on how low pressure systems affect the climate on a more local scale, as mountain ranges shield regions from oceanic moisture advection (Gimeno *et al.*, 2010). This causes a relative disconnection from general circulation in some areas of IP, particularly concerning the Mediterranean fringe and the Ebro river basin to the east. In addition, local factors give marked regional variations as well as high internal variability of precipitation (Martin-Vide and Lopez-Bustins, 2006; Muñoz-Diaz and Rodrigo, 2006). Thus the Iberian Peninsula (IP) has been recognized as one of the best places for analysing spatial variability of precipitation (Romero *et al.*, 1998; Martin-Vide, 2004; Morata *et al.*, 2006; Muñoz-Diaz and Rodrigo, 2006; Valero *et al.*, 2009; Casado *et al.*, 2010, among many others), an objective of great interest, because water in the IP is the most important climate factor due to unequal amounts of precipitation and high demands in several regions (de Castro *et al.*, 2005).

Previous studies focusing on the regionalization of IP precipitation defined three main areas: northern and eastern coastlands (i.e. Cantabrian and Mediterranean coastland), and central-south, with the mountain chains acting as boundaries (Fernandez-Mills, 1995; Esteban-Parra *et al.*, 1998; Rodriguez-Puebla *et al.*, 1998; Serrano *et al.*,

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1999; Garcia *et al.*, 2002; Muñoz-Díaz and Rodrigo, 2004; Morata *et al.*, 2006; Queralt *et al.*, 2009), although authors do not coincide exactly on areas. The aforementioned variability presents difficulties for short-term precipitation forecasting (Shrestha *et al.*, 2012) and climate change studies (Boxel, 2001). Thus, forecasting precipitation over a limited region is often attempted through the identification of the dynamic-statistical links between regional precipitation features and large scale atmospheric circulation patterns. These links represent the basis of a downscaling approach (Quadrelli *et al.*, 2001; Trigo and Palutikof, 2001) in which Weather Types (WTs) offer many possibilities across the Iberian Peninsula (Trigo and DaCamara, 2000; Goodess and Jones, 2002; Ramos *et al.*, 2010).

There are several examples of precipitation analyses and approaches to atmospheric circulation in the Iberian Peninsula from the pioneering studies carried out in the late 1990s (Corte-Real *et al.*, 1995; Zhang *et al.*, 1997; Romero *et al.*, 1999). Analyses for the entire Iberian Peninsula were presented by Goodess and Jones (2002), Paredes *et al.* (2006), Muñoz-Diaz and Rodrigo (2006), and Casado *et al.* (2010).

A second set of articles studied the relationship between WTs and precipitation on a subregional scale in different areas of the IP, particularly to the southeast (Goodess and Palutikof, 1998), the Mediterranean coastal fringe (Romero *et al.*, 1999), Portugal (Trigo and DaCamara, 2000), northwest of Spain (Lorenzo *et al.*, 2008, 2011; Ramos *et al.*, 2010), and inland basins, such as the Duero catchment (Fernández-González *et al.*, 2012), and Ebro basin in the north-east inland areas (Vicente-Serrano and Lopez-Moreno, 2006).

It should be stressed that all the articles mentioned above deal with low station density datasets (IP is about 500 000 km^2), different periods, and are often focused on winter precipitation, while the number of studies for the spring and autumn is scarce, although across large areas of the IP, the bimodal spring-autumn rainfall regime is the most dominant one (de Luis *et al.*, 2010). Thus, the spatial detail is low and information for non-winter months is scarce. As a consequence, the spatial variability of precipitation in the IP is not entirely captured and transitional areas, relief barrier effects, altitudinal effect and subregional details, among other research targets, are not well known. Cortesi *et al.* (2013) tried to solve these caveats by using a much denser dataset with more than 3000 stations from the whole of the IP to model the relationship between WTs, using the approach initially undertaken by Trigo and DaCamara (2000) and monthly precipitation for the wet half of the year (October to May).

In this article, we analyze, in the highest detail currently available, the spatial distribution of the relationship between WTs and monthly precipitation in the IP between 1948 and 2003, with the aim of identifying the role played by all WTs in determining the spatial variability of monthly precipitation in the IP, at the highest spatial resolution possible using observed data.

To a certain extent, this analysis provides the logical continuation of the previous study devoted to the development of a precipitation statistical model for the entire IP based on WTs (Cortesi *et al.*, 2013). However, the focus of this previous work was to assess the feasibility of constructing models for the entire wet half of the year and to evaluate the amount of explained variance achieved and the number of predictors required. Here, we intend to go further in several ways, and start to provide an assessment of the impact of each individual WT on the precipitation regime for the entire IP. In addition, we will emphasize the large intra-annual cycle showing the contribution of each WT on a monthly scale, and evaluating the efficiency of the most important circulation patterns on the precipitation regime each month. This article is structured as follows: in Section 2 we present the database and the methods. In Section 3 we show the main results on a monthly scale first analysing the WT frequency (3.1.), the percentage contribution to precipitation of WTs (3.2.), the origin of precipitation according to the prevailing direction of flow (3.3.) and the efficiency of each WT (3.4.). In Subsection 3.5, we present detailed spatial analyses of the most prominent WTs. Finally, in Section 4 we present a brief discussion and summary of results.

2. Database and methods

2.1. Database

One of the major advantages of this study in comparison with most previous studies focused on IP precipitation variability and links with synoptic scale atmospheric circulation is due to the use the highest-density, completed, quality controlled and homogenized network for monthly precipitation in the IP. The database combines two national datasets developed independently in recent years. For Spain, we used MOPREDAS (Gonzalez-Hidalgo *et al.*, 2011) from original data of AEMet (Spanish Meteorological Agency) including 2644 monthly series, and for Portugal 386 series provided by INAG – Instituto da Água (Servicio Nacional de Informaçao de Recurcos Hídricos) (Lorenzo-Lacruz *et al.*, 2011). The selected period from original datasets was 1948–2003 with an overall spatial density of 1 observatory/200 km^2 distributed fairly evenly (Figure 1). Both datasets were combined in a high resolution grid of 10×10 km containing 5828 land pixels (interpolated with an Ordinary Kriging), and at present constitute the most valuable information available for monthly precipitation analyses covering the entire IP. This dataset was used by the authors in the preliminary study conducted for the entire wet season (Cortesi *et al.*, 2013).

Because one of the main aim of this article is to analyse at higher spatial detail as possible the relationship between WTs and monthly precipitation during the second half of the 20th century, MOPREDAS offers some advantages over others dataset as developed for Portugal (Belo-Pereira *et al.*, 2011) and for Spain (Herrera

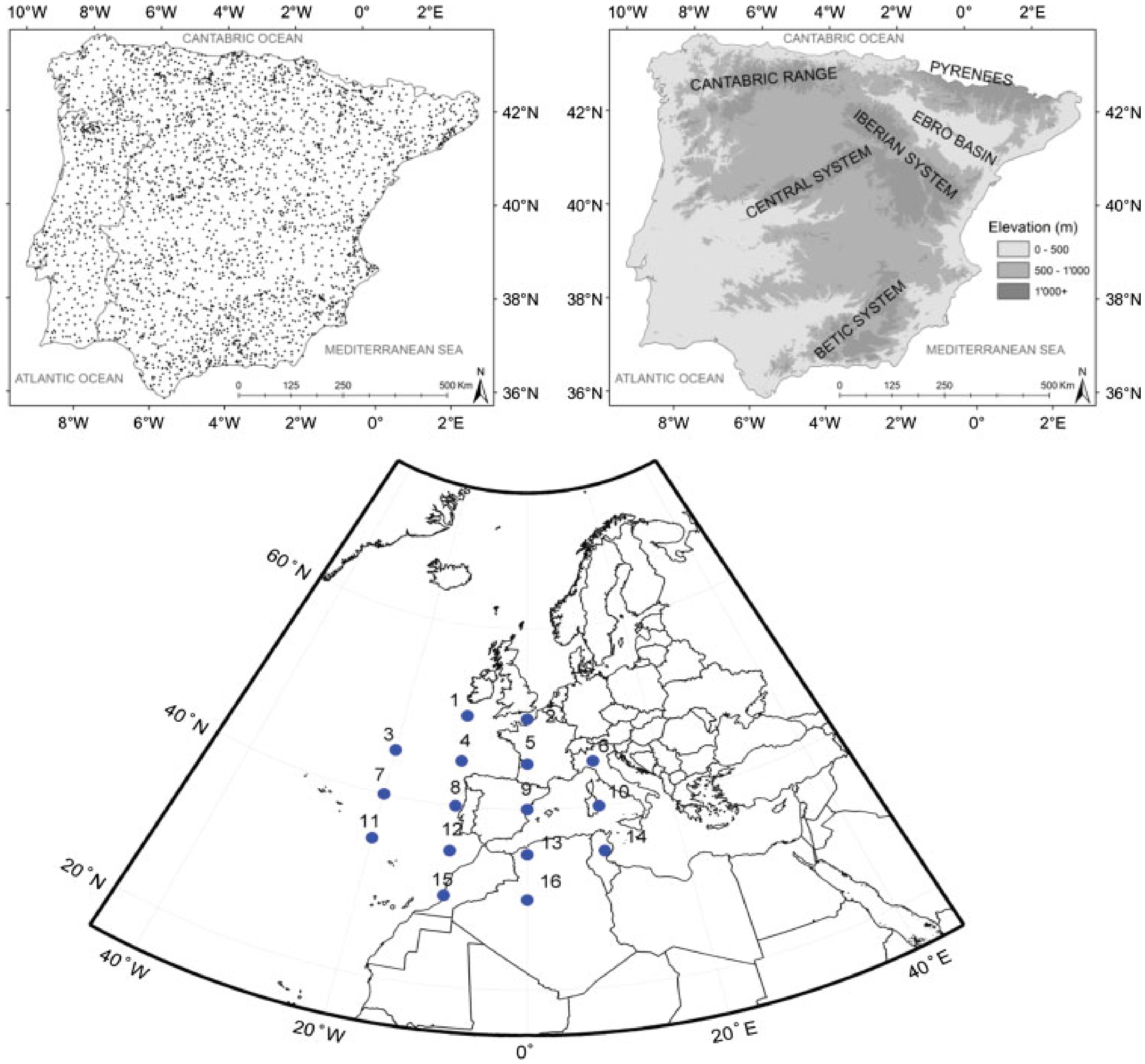

Figure 1. Upper left: spatial distribution of MOPREDASP precipitation series in the IP. Upper right: main mountain ranges of the IP. Bottom grid points for WTs calculation.

et al., 2012), because these daily dataset offer lower spatial resolution and the number of stations used throughout the period covered for grid performance varies between years, while MOPREDAS grid was performed after stations reconstruction and therefore using the same number of stations throughout the studied period.

2.2. Weather types approach

Our approach to daily WTs used a set of indices adopted by Trigo and DaCamara (2000) which takes into account physical or geometric characteristics, i.e. the direction and strength of airflow, the direction and vorticity of geostrophic flow, and the signal and intensity of cyclonicity. This approach is based on the corresponding objective Lamb classification defined for the British Isles (Jenkinson and Collison, 1977; Jones *et al.*, 1993). To determine the daily WTs, a set of 16 points centered on the IP was used to extract daily SLP series from EMULATE Mean Sea Level Pressure dataset (EMSLP), compiled by Ansell *et al.* (2006). Compared with Trigo and DaCamara (2000), these points were moved 5° to the east in order to center the entire grid in the middle of the IP (the area of this study, 40°N, 5°W for central point, Figure 1). The longitude–latitude gridded field resolution was $10^\circ \times 5^\circ$. A total of 26 WTs were defined, 10 pure types (NE, E, S, SE, SW, W, NW, N, C and A), and 16 hybrid types (8 for each C or A hybrid). We distributed the few cases (<1%) with possibly unclassified situations among the 26 classes.

We used this dataset because it shows a slightly better model performance, comparing the global mean absolute error obtained with EMULATE and with data from (1) NCEP/NCAR Reanalysis, (2) ERA reanalysis and (3) from 20th Century Reanalysis. The main reason for this better performance is out of the scope of this work but we reckon that it could be due to the EMULATE dataset only relies on observed data, and also because it is the only dataset that covers the entire period 1850–2003, making possible in principle to extend monthly rainfall reconstructions up to the 19th century. We should stress, however, that we are aware of the caveats of the EMULATE dataset, especially (1) the underestimation of the frequencies of some WTs such as the SW during the second half of the 19th century, and (2) the lack of direct pressure observations in the datas*et* along the Mediterranean coast of the Iberian Peninsula that hamper its effectiveness for downscaling.

The relative (%) contribution to total monthly Iberian rainfall by each WT was then modelled by means of a linear least-square non-negative regression model applied individually for each grid point (res.10 × 10 km) and for each separate month. The monthly frequencies of each of the 26 daily WTs were used as potential predictor variables while interpolated monthly rainfall totals, for each pixel and month, were used as the predictand variable. In this way, each regression coefficient is a positive number which represents the mean daily precipitation of its associated WT; it can then be multiplied for the mean monthly frequency of its corresponding WTs and normalized by the mean monthly observed precipitation at the grid point to get the mean relative % contribution to total monthly precipitation of a single WT.

Forward stepwise selection was employed to choose the best predictor WTs from among the large set of 26 WTs. The stepwise methodology begins by choosing a single predictor WT that gives the lowest Root Mean Squared Error (RMSE) for the given grid point and month over the 56-year dependent dataset. Having chosen the first predictor in this way, the methodology proceeds to choose from among the remaining potential predictor WTs the one that ensures the best score when combined with the first predictor.

To avoid over fitting the calibration data, we used a 'stopping rule' to determine at what point to stop adding predictors. By trial and error, it was found that the main error index [the Mean Absolute Error (MAE)] for the validation data was minimized when stepwise selection was terminated at the point at which the RMSE on the calibration data failed to decrease by 1% of observed mean monthly rainfall when adding another predictor WT.

Model validation was performed by means of a leave-one out cross validation over the same regression period 1948–2003 for all grid time series of monthly precipitation in the IP. More specifically, the validation was carried out for each grid point and month, as follows: 1 year of monthly precipitation data was excluded, and next we estimated the model coefficients for the remaining years to calculate the predicted value for the discarded year. For additional information, please refer to Trigo and DaCamara (2000) and Cortesi *et al.* (2013).

The WTs contribution for each month and grid point does not sum up to 100% because of the non-negative regression constant term that represents the mean monthly precipitation due to convective processes (which is highest during summer months). WTs should in theory explain 100% of the observed precipitation because there are no days with a WT different from the 26 ones included in Lamb's classification, so introduction of a constant term leads to a systematic underestimation of the rainfall contribution of each predictor WT. However, the stepwise selection employed to minimize over fitting subdivides monthly rainfall only to the chosen few (usually 1–7) selected predictor WTs, while in reality other WTs not selected by the stepwise selection can also contribute; they are discarded either because they are drier or because they are highly correlated with some predictor already selected. Such a shortcoming causes a systematic overestimation of the contribution of each predictor WT (and of the constant term) because the model tries to assign the whole monthly precipitation to them. The presence of the constant term helps in balancing the two opposite systematic errors, and was also found to reduce the overall MAE of the model for validation data.

3. Results

3.1. Frequency of WTs

An essential characteristic in determining the role played by each WT on the monthly precipitation regime is provided by how often they occur, i.e. by their frequency. The monthly frequency of WTs, expressed as number of days per month, is shown in Table 1. It is immediately noticeable that no WT occurs for more than 10 days in any given month. The most frequent WTs correspond to the pure A type, particularly during winter months. The N, NW, W, NE and E types have at least a frequency of more than 2 days during 5 months. Except W, the monthly frequency for these WTs is more than 1 day/month throughout the year. NE, N and E types are most frequent in summer, while W and SW occur mainly in winter.

However, the monthly frequency of C, ANW and AN types for at least 8 months is higher than 1 day. The ANW frequency remains relatively constant throughout the year, while the C type reduces its frequency to less than 1 day between June and September and the AN type frequency is reduced during winter. The other WT frequencies are usually lower than 1 day per month except for short periods, which suggests that these classes represent a less common synoptic pattern in the IP.

Generally speaking, WTs associated with N and E flows present maximum frequency during summer months, while WTs associated with W flows return higher frequencies in the winter months. It is worth mentioning that the mean frequency for A types is in general higher than C types.

3.2. Contribution to monthly Iberian precipitation

The mean relative (%) contribution of different WTs calculated using the statistical model on a monthly scale is presented in Table 2 as a regional mean value for IP, varying substantially throughout the year. In the IP, three WTs are responsible for more than 50% of total annual precipitation, namely W, SW and C types,

Table 1. Mean monthly WTs Frequency from 1948 to 2003 (days/month).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NE	*1.6*	*1.6*	*1.6*	*3.6*	*4.4*	*6.6*	*8.8*	*8.1*	*3.2*	*2.3*	*1.8*	*1.4*
E	*1.3*	*2.2*	*3.0*	*2.5*	*2.8*	*3.9*	*5.1*	*4.3*	*4.0*	*2.9*	*1.8*	*1.3*
SE	*1.1*	*1.0*	*1.7*	*1.0*	0.7	0.3	0.2	0.3	0.9	*1.3*	*1.0*	*1.3*
S	0.8	0.7	0.7	0.3	0.3	0.0	0.0	0.0	0.2	0.9	0.7	0.6
SW	*1.7*	*1.8*	*1.5*	0.8	0.7	0.1	0.0	0.0	0.5	*1.6*	*1.5*	*1.9*
W	*3.2*	*2.5*	*2.3*	*2.1*	*1.8*	0.5	0.1	0.3	*1.4*	*2.4*	*2.7*	*2.7*
NW	2.2	*1.9*	*1.8*	*2.3*	*2.7*	*1.9*	*1.1*	*1.4*	*1.8*	*1.6*	*2.2*	*2.1*
N	*1.1*	*1.2*	*1.9*	*2.7*	*3.1*	*3.6*	*4.5*	*4.5*	*2.2*	*1.5*	*1.5*	*1.6*
C	*1.4*	*1.2*	*1.6*	*2.7*	*1.8*	0.8	0.5	0.5	0.8	*1.2*	*1.5*	*1.7*
CNE	0.1	0.2	0.4	0.8	0.6	0.7	0.9	0.4	0.4	0.3	0.2	0.3
CE	0.2	0.2	0.4	1.0	0.7	0.7	0.5	0.4	0.7	0.6	0.3	0.3
CSE	0.1	0.2	0.3	0.3	0.2	0.1	0.1	0.1	0.2	0.2	0.3	0.4
CS	0.1	0.2	0.2	0.1	0.1	0.0	0.0	0.0	0.1	0.2	0.5	0.3
CSW	0.2	0.2	0.2	0.3	0.2	0.0	0.0	0.0	0.1	0.2	0.3	0.2
CW	0.3	0.3	0.1	0.2	0.3	0.1	0.0	0.1	0.1	0.3	0.1	0.3
CNW	0.1	0.2	0.1	0.3	0.2	0.2	0.1	0.0	0.1	0.1	0.3	0.2
CN	0.1	0.2	0.1	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0.2	0.1
A	*8.4*	*6.7*	*6.4*	*4.0*	*5.3*	*4.3*	*3.0*	*4.4*	*6.9*	*7.0*	*7.3*	*7.3*
ANE	0.6	0.6	0.7	0.8	0.9	*2.0*	*2.3*	*2.1*	*1.3*	0.8	0.6	0.8
AE	0.6	0.6	0.8	0.3	0.6	0.7	0.6	0.4	0.9	*1.0*	0.7	0.6
ASE	0.5	0.5	0.5	0.2	0.2	0.1	0.0	0.0	0.4	0.5	0.4	0.5
AS	0.3	0.3	0.3	0.1	0.0	0.1	0.0	0.0	0.2	0.5	0.3	0.3
ASW	0.6	0.6	0.6	0.2	0.2	0.1	0.0	0.0	0.1	0.6	0.5	0.7
AW	*2.1*	*1.5*	*1.4*	0.8	0.7	0.2	0.0	0.2	0.7	*1.0*	*1.3*	*1.6*
ANW	*1.6*	*1.3*	*1.4*	*1.2*	*1.2*	*1.3*	0.8	*1.1*	*1.5*	1.2	*1.4*	*1.6*
AN	0.8	0.7	*1.0*	*1.4*	*1.1*	*1.6*	*2.0*	*1.9*	*1.3*	0.9	0.9	*1.0*

In italics >1 day/month.

with this contribution being particularly large during the extended winter half from October to May. The W type is the highest contributor from September to May, and is related to more than 10% over 9 months (maximum in March), and for 5 months contributes with more than 20% of monthly precipitation. Interestingly, the C type also contributes considerably throughout most non-summer months (>10% of monthly precipitation during September–May except in February, with a maximum in spring (April–May). The third WT with the largest contribution is the SW type. From October to April this class is related to more than >5% of monthly precipitation, reaching 18.9% in January. As will be shown later, all these WTs spread their influence over extended areas of the IP, while the relationship between other WTs and monthly precipitation is mainly restricted to relatively narrow areas and also usually to a limited contribution to the total monthly precipitation, but which may be important on a local level.

On a seasonal scale, taking winter as the months of D–J–F, the highest contribution is achieved by SW and W (>15%), with the C and NW types also being important. In spring (March–May), the contribution of SW decreases and the highest contributions come from W and C. Meanwhile in summer, the highest contributions are provided by the NE and E types, with monthly contributions >5% from the NW, N, CNE, CE, CSE, CN and ANW types. Finally, during autumn months the highest contribution is associated with W and C types, with a contribution of >5% in some months from E, SW, NW, CE, CSW and CW types. All these types contribute with more than 5% of precipitation in June, July or August, and it is interesting to note that most of them have a directional component from north and east, except the ANW.

Figure 2 shows the mean percentage of monthly precipitation in the IP explained by the three and five WTs with maximum monthly contribution. From September to May, the contribution obtained from the three maximum WTs is higher than 40%, increasing to 50% if the five WTs with maximum contribution are taken (with an absolute maximum in January reaching 71.5%). The minimum contribution is observed in June with values below 40% for either three or five WTs. The results are stimulating in terms of potential performance of statistical models, because a relatively low number of WTs captures a high percentage of monthly precipitation variability.

3.3. The origin of precipitation according to the prevailing flow direction

The different WTs provide indications about flow direction under specific barometric patterns (pure directional WT, cyclonic WT and anticyclone WT). Thus we can perform the analysis using as simplification criteria the direction from which the air masses arrive to the IP irrespective of the pressure pattern (in a similar way as Goodess and Jones, 2002), or in other words *where does precipitation come from?*. Figure 3 shows the monthly percentage of precipitation explained by the different WTs according to the compass reading (using data from

Table 2. Relative contribution (in %) to total monthly Iberian precipitation by WTs.

	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
NE	0.0	0.4	1.2	0.8	0.2	1.8	23.8	17.8	1.5	1.1	0.9	0.2
E	0.8	3.9	0.6	0.1	0.0	3.0	21.8	0.6	7.5	0.2	0.1	0.0
SE	0.4	0.2	0.0	0.0	0.0	0.1	1.3	0.1	0.0	0.1	0.7	0.2
S	0.5	0.7	0.1	0.0	2.4	0.1	0.0	0.3	0.6	3.7	0.6	0.3
SW	18.9	14.6	8.8	6.0	3.3	0.0	0.0	0.3	1.7	8.1	7.3	15.9
W	27.9	28.7	31.1	13.2	13.4	2.3	1.2	2.4	23.9	19.0	19.0	23.8
NW	8.5	1.4	0.4	3.3	4.5	8.6	0.6	6.3	3.3	1.0	10.4	6.1
N	2.6	1.6	6.9	0.9	8.1	5.6	7.6	4.8	4.0	3.2	1.2	0.9
C	18.1	2.6	13.4	23.2	20.9	3.6	0.0	2.6	15.6	11.5	12.7	9.9
CNE	0.0	0.0	1.4	3.5	2.3	8.7	5.5	4.9	0.6	1.6	0.1	1.5
CE	0.1	0.7	0.2	1.0	0.4	1.0	1.7	6.9	5.6	4.2	1.8	2.5
CSE	0.2	1.2	0.5	0.4	0.2	0.0	0.0	5.6	1.9	0.7	2.4	4.2
CS	0.1	0.1	1.0	0.0	0.3	0.3	0.0	0.0	1.0	0.7	3.4	0.2
CSW	1.1	4.1	1.6	0.4	0.1	2.4	0.0	0.0	1.3	2.7	6.3	3.2
CW	1.0	0.5	0.3	0.0	0.7	1.3	0.2	1.8	0.0	6.5	2.2	0.6
CNW	0.1	1.2	0.0	0.8	0.8	3.0	0.0	0.5	0.9	1.2	0.0	1.1
CN	0.0	3.0	0.0	0.0	0.2	6.5	0.6	0.2	0.4	0.3	0.5	0.4
A	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.5	0.0	0.0	0.0	0.0
ANE	0.1	0.0	0.0	0.6	1.5	0.2	0.0	0.0	0.0	0.8	0.0	0.0
AE	0.0	0.4	0.0	0.0	0.5	0.0	0.1	0.0	0.1	0.0	0.2	0.0
ASE	0.0	0.0	0.0	0.4	0.1	0.3	0.1	0.0	0.0	0.0	0.0	0.1
AS	0.0	0.2	0.5	0.5	0.0	0.3	0.2	0.0	0.0	0.0	0.0	0.0
ASW	0.6	0.2	0.1	0.0	0.0	0.1	0.0	0.0	0.3	0.0	0.0	0.1
AW	0.1	0.2	2.4	1.8	0.0	1.5	0.0	1.2	2.1	0.4	0.8	0.4
ANW	0.8	0.1	0.1	0.4	0.1	0.0	10.3	7.3	0.0	1.4	1.4	1.3
AN	0.1	0.2	0.0	0.7	0.0	0.0	3.5	0.8	0.9	0.1	0.7	0.4
All WTs	82.0	66.2	70.6	58.0	60.0	50.8	78.5	64.9	73.2	68.5	72.7	73.3

Table 2). As an example, contribution from N is calculated by adding the WT contribution relative to N, AN and CN (Note that added contribution from different directions does not sum to 100 because A and C types are not included in the compass wind; and also the constant term, see Section 2.2.).

During winter months, Figure 3 shows the outstanding contribution of Westerly and Southwesterly air masses; a predominant westerly flow remains in March, but decreases abruptly in April and May. Summer rainfall is mainly due to the contribution of NW, N, NE and E flows, while in autumn the Westerly flow rises as the dominant direction.

3.4. The efficiency of WTs

Additional analyses on the role of different WTs can be obtained if we cluster them according to their primary characteristic, i.e. dominated by the geostrophic flow (directional types) or dominated by the geostrophic vorticity (broadly speaking, the cyclonic and anti-cyclonic

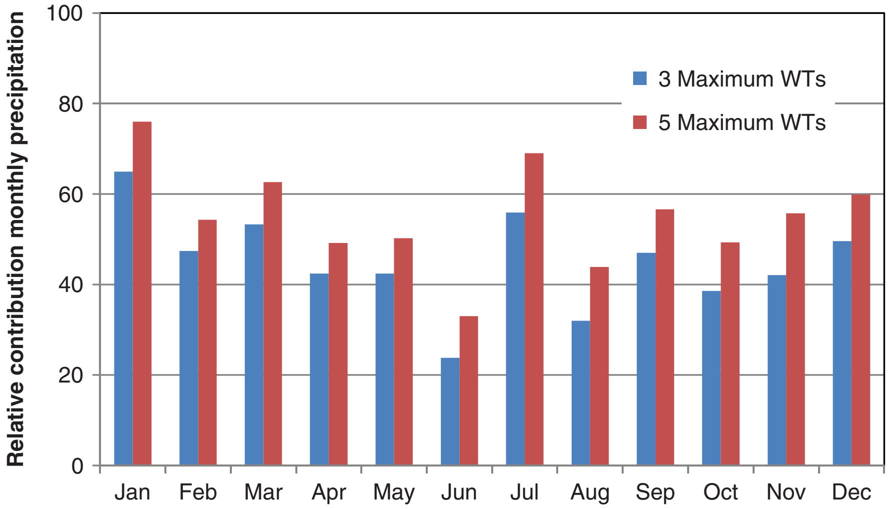

Figure 2. Sum of the relative contribute (in % of monthly Iberian precipitation) of the three and five most influent WTs.

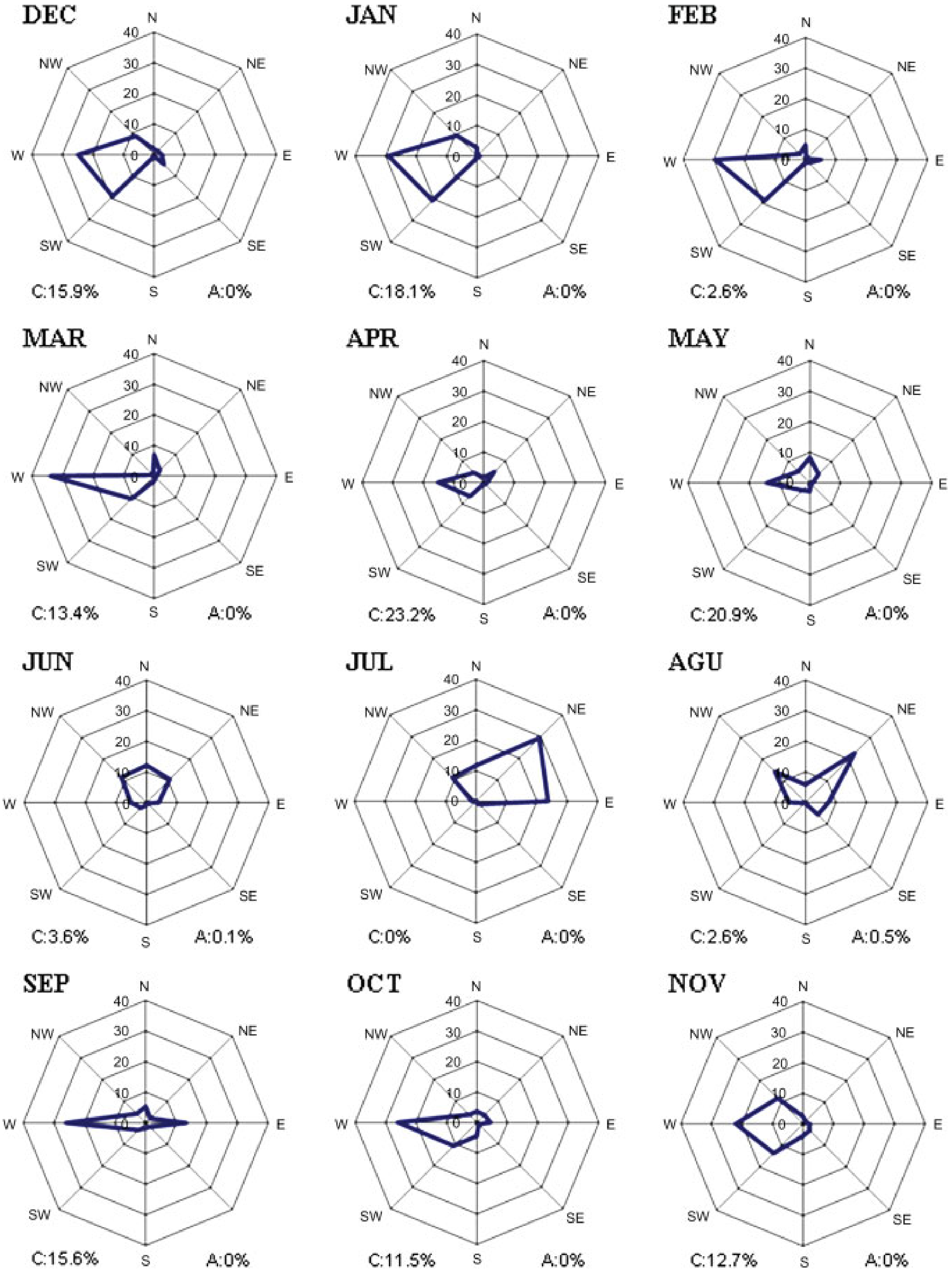

Figure 3. Relative contribute (in % of monthly Iberian precipitation) of WTs grouped by direction.

classes). If one takes into account the entire IP, monthly precipitation is more than 50% dependent on directional and cyclonic WTs (Table 3). The dependence increases during winter, spring and autumn and is considerably lower in summer. Anti-cyclonic WT contribution is the lowest and their overall maximum contribution is centered in peak summer months (July and August). Given that the frequency of cyclonic WTs is lower than directional WTs group, the effects of cyclonic WTs in terms of efficiency (i.e. the ratio between the relative contribution by the WT, from Table 2, and the WT monthly frequency from Table 1) are clearly higher than any other WT groups, and related to more precipitation when they occur than directional WT. The high frequency of anti-cyclonic days and its scarce contribution to monthly precipitation is due to their low efficiency overall. In addition, it is interesting to note that the highest values of efficiency for all C types arise in summer, particularly in August

Table 3. Frequency, relative contribution and efficiency by main WTs groups.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Directionals	*C*	59.6	51.5	49.1	24.3	31.9	21.5	56.3	32.6	42.5	36.4	40.2	47.4
	F	13.1	12.8	14.5	15.2	16.5	16.9	19.9	19.0	14.2	14.4	13.1	13.0
	E	4.6	4.0	3.4	1.6	1.9	1.3	2.8	1.7	3.0	2.5	3.1	3.7
Cyclonics	*C*	20.7	13.4	18.4	29.3	25.9	26.8	8	22.5	27.3	29.4	29.4	23.6
	F	2.6	2.8	3.4	5.9	4.4	2.9	2.4	1.8	2.6	3.2	3.6	3.7
	E	8.1	4.8	5.4	5.0	5.9	9.4	3.4	12.7	10.5	9.3	8.1	6.4
Anti-cyclonics	*C*	1.7	1.3	3.1	4.4	2.2	2.5	14.2	9.8	3.4	2.7	3.1	2.3
	F	15.3	12.7	13.1	9.0	10.1	10.3	8.8	10.2	13.2	13.4	13.3	14.4
	E	0.1	0.1	0.2	0.5	0.2	0.2	1.6	1.0	0.3	0.2	0.2	0.2

C, relative contribution (from Table 2); F, frequency (days) (from Table 1); E, efficiency (C/F).

Table 4. Efficiency of WTs (as Table 3).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SW	11.1	8.0	6.0	7.5	4.7	0.0	0.0	15.0	3.3	5.0	4.9	8.2
W	8.7	11.5	13.4	6.3	7.4	5.0	13.3	8.0	17.3	7.9	7.0	8.9
C	13.0	2.2	8.3	8.6	11.8	4.7	0.0	5.7	19.7	9.7	8.5	6.0

and September, and autumn. On the contrary, the highest efficiency of directional WTs is observed in winter months (Table 3).

This overall presentation of WT effects can be further refined by examining specific types. As we have shown previously in general tables (Tables 1 and 2), just a few ‘wet’ WTs dominate the precipitation over large parts of the IP, particularly W, SW and C. Combining the results from Tables 1 and 2, the efficiency of these three most prominent WTs is shown in Table 4. Cyclonic pure type efficiency is higher in autumn and spring (except March) and January, while precipitation efficiency for W and SW types is higher in winter months. The high efficiency of W type in July and September is also noticeable. Thus the global high efficiency of cyclonic types (Table 3) is not only due to the pure C type but also to Hybrid C types, suggesting that their monthly impact is confined to small areas (see Section 3.5.).

There are obvious changes associated with the mean seasonal intensity of the atmospheric motion that can help to explain the differences in the efficiency of each WT for the different months. These changes in the seasonal intensity will only have impact in the intensity of the geostrophic indices used in the computation of the WTs, but the spatial pattern is maintained relatively similar from month to month. As an example, the cyclones that strike the region, in the summer, are in general less intense than the ones that strike the region in the winter (Trigo, 2006), and therefore the efficiency of the C will obviously change accordingly.

Furthermore, the methodology to compute our method to obtain the WTs only requires that these are only computed taking into account the Sea Level Pressure level therefore the upper levels of the atmosphere are not well represented. For example, frequent spring and autumn Cut off Low can be associated with intense precipitation events. Usually these systems are associated with reduced thermodynamic stability beneath, hence enhancing the convection in the region, however, quite often these systems have no signature in the SLP field therefore they are not depicted well by any WT class (Nieto *et al.*, 2005; Nieto *et al.*, 2007; Ramos *et al.*, 2011).

3.5. Spatial analyses

As stated previously, the effects of each WT on the precipitation regime of the IP are related to its monthly frequency (Table 1), efficiency and total area affected. All these aspects are crucial in understanding the recent behaviour of precipitation in the IP, and constitutes a useful tool for detailed downscaling analyses. The WTs could then be classified according to their general effects (i.e. those WTs affecting a minimum percentage of land) or local effects. However, a more detailed analysis requires visualization of the spatial distribution of their impact on precipitation covering the entire Iberian Peninsula.

The analysis of WTs that follows illustrates the spatial distribution of the effects on monthly precipitation relative to the five most prominent (i.e. wettest) WTs, namely the W, SW and C, and the N, NW by their specific effects. Other locally important WTs, will be shown in less detail. Each composition includes the area affected by the specific WT on a monthly scale (12 subplots), and the SLP pattern (central subplot).

The most prominent WT affecting IP precipitation on a monthly level is the W type (Figure 4). The pattern consists of high pressure centered west of the Canary Islands and a low pressure system placed on average just west of Ireland. As a consequence, Atlantic westerly flows enter the IP from west to east without any mountain barriers until they reach the mountain arc to the east (Iberian mountains) and then affect the central-southern areas of the IP. This pattern substantially affects precipitation from September to March. The highest effects are seen in the northwestern areas where more than 50% of

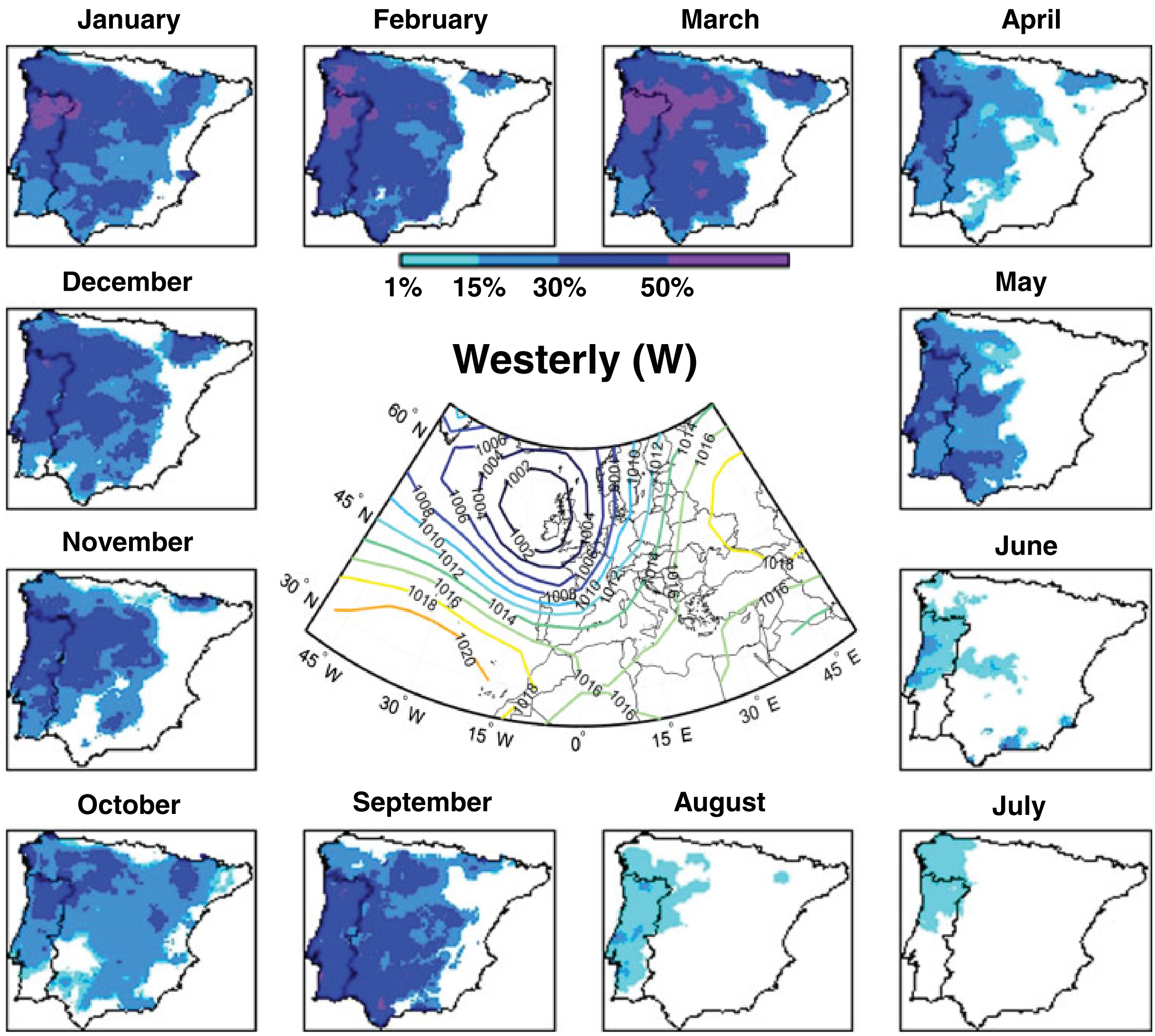

Figure 4. Spatial distribution of the relative contribution (in % of monthly Iberian precipitation) of W type.

January, February and March precipitation depends on this WT. There are two areas in which the effects of W type do not significantly help to explain monthly precipitation: the Cantabrian coastland to the north, and the Mediterranean fringe to the east, including the northern, inland Ebro basin. On the contrary, in summer months this WT is not related to large amounts of precipitation, as it is confined to the western Atlantic facade.

The SW type pattern consists of a low center located to the west of Ireland but extending further south than the average patterns for the W type. Its effects on a spatial and monthly scale are less widespread than those described previously for the W type. Thus, the effect on the fraction of land affected is lower throughout the year and the highest effects are restricted in time, particularly from December to February (Figure 5), again predominantly covering the central and western areas of IP. In same way, the SW is quite similar to W type in terms of the area affected, but the percentage of monthly precipitation explained is lower; also its temporal effects are restricted to a shorter period (October–April), and the area affected is not as continuous as for the W type. Nonetheless, this WT is capable of contributing more than 10% of the total monthly Iberian precipitation from December to February.

Pure Cyclonic WT monthly spatial distribution and relative contribution to monthly precipitation is shown in Figure 6. The composite SLP pattern is dominated by a low pressure center over the IP. The spatial impact of this WT type is different from the W and SW types described previously. Its maximum effects on monthly Iberian precipitation correspond to spring (March and May), and also between September and January. However, the area affected differs from what was found for W an SW, being on average higher than 60% from September–May (except February). This implies that efficiency varies substantially from month to month (Table 4). In addition, the spatial distribution of the affected area differs, and exhibits a diagonal orientation from north-east to southwest, i.e. precipitation in the northwest and southeast sectors of the IP is not related to this WT. The highest effects of C type on precipitation

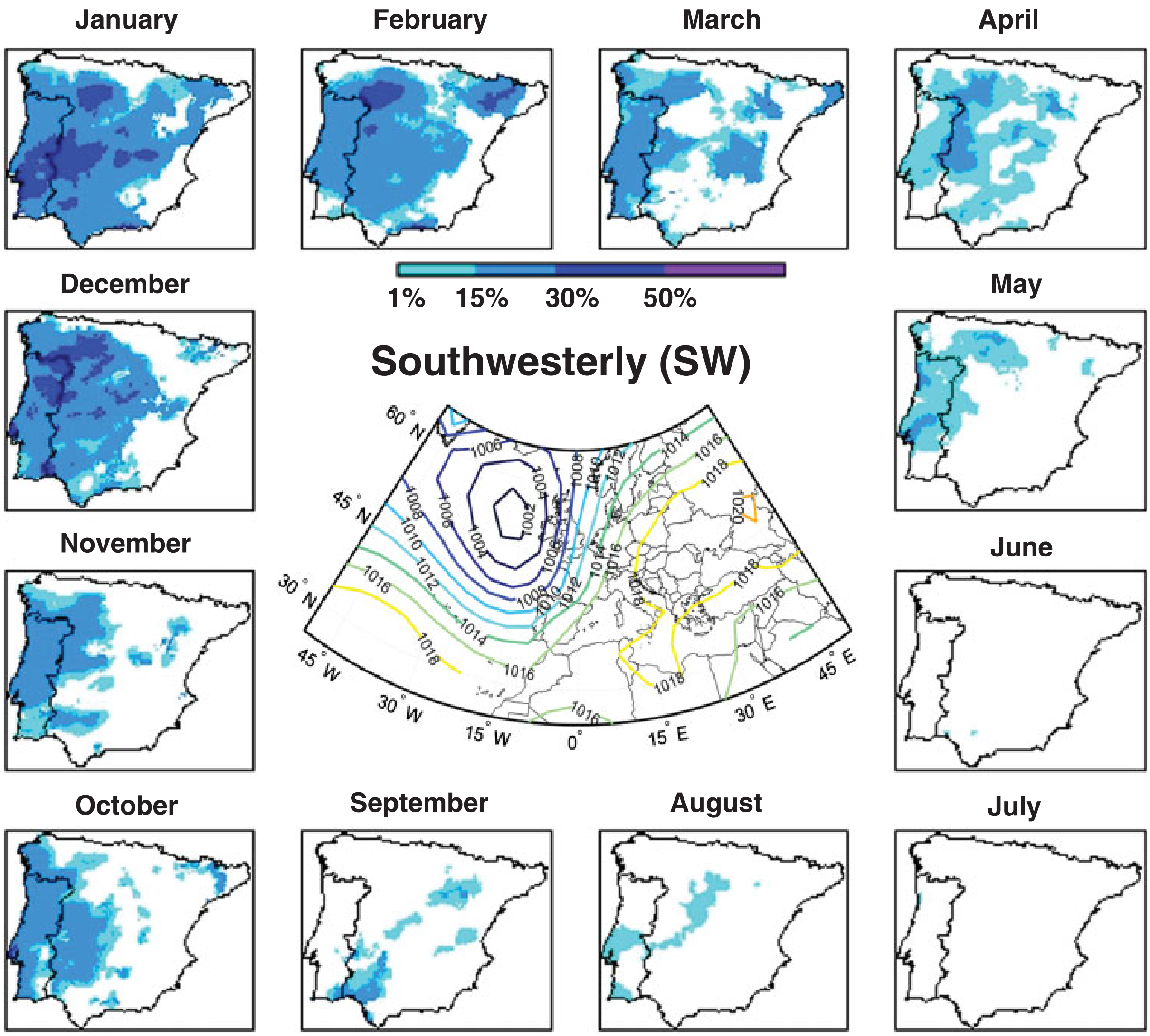

Figure 5. Spatial distribution of the relative contribution (in % of monthly Iberian precipitation) of SW type.

are located in different areas, depending on the month. In January and March, the maximum precipitation variance explained is located in northeast areas. However, in April the same percentage of precipitation is also seen in the central southwest areas. Finally, in May the maximum percentage of precipitation is clearly located in the southwest. We noticed that, in February, the area in which effects have been identified is confined to a narrow band along the Mediterranean fringe and lower part of Ebro basin to the northeast. This result appears to be slightly at odds with the rest of the months where this C type plays a much more relevant role.

It is worth stressing the significant contribution (albeit on a more regional scale) of a few other WT classes with a northern component. Among these, two WTs present very clear sub regional effects, namely the N and NW. The N type consists of a high pressure system centered west of Portugal, over the Azores archipelago (Figure 7). Under this synoptic situation, the northern coastland areas of IP are affected throughout the year, but particularly during spring, autumn and summer. The Cantabrian mountain chain in this case acts with the opposite effect exhibited for westerly types, thus acting as a barrier preventing the spread of its effects southwards inland. During some spring and summer months, the N type also significantly affects the Mediterranean coastland and areas of Pyrenees. The main pressure systems observed in the NW pattern (Figure 8) are basically similar to those observed for the N class. Under this WT, the northern coastland is also affected, although to a lesser extent during summer months. Unlike the N, the effects of the NW type also extend to the western coastland (Galicia and Portugal) and often to more southern areas, but not to the Mediterranean eastern coastland and Pyrenees range.

In a previous paper (Cortesi *et al.*, 2013), we found that the overall capacity of simple regression models, using WT monthly frequency as predictors in reproducing monthly precipitation, decreased significantly from west to east of the IP. In this regard, the identification of the most prominent WTs in the Mediterranean fringe and Ebro basin is more complex in some particular months since the mesoscale processes often dominate

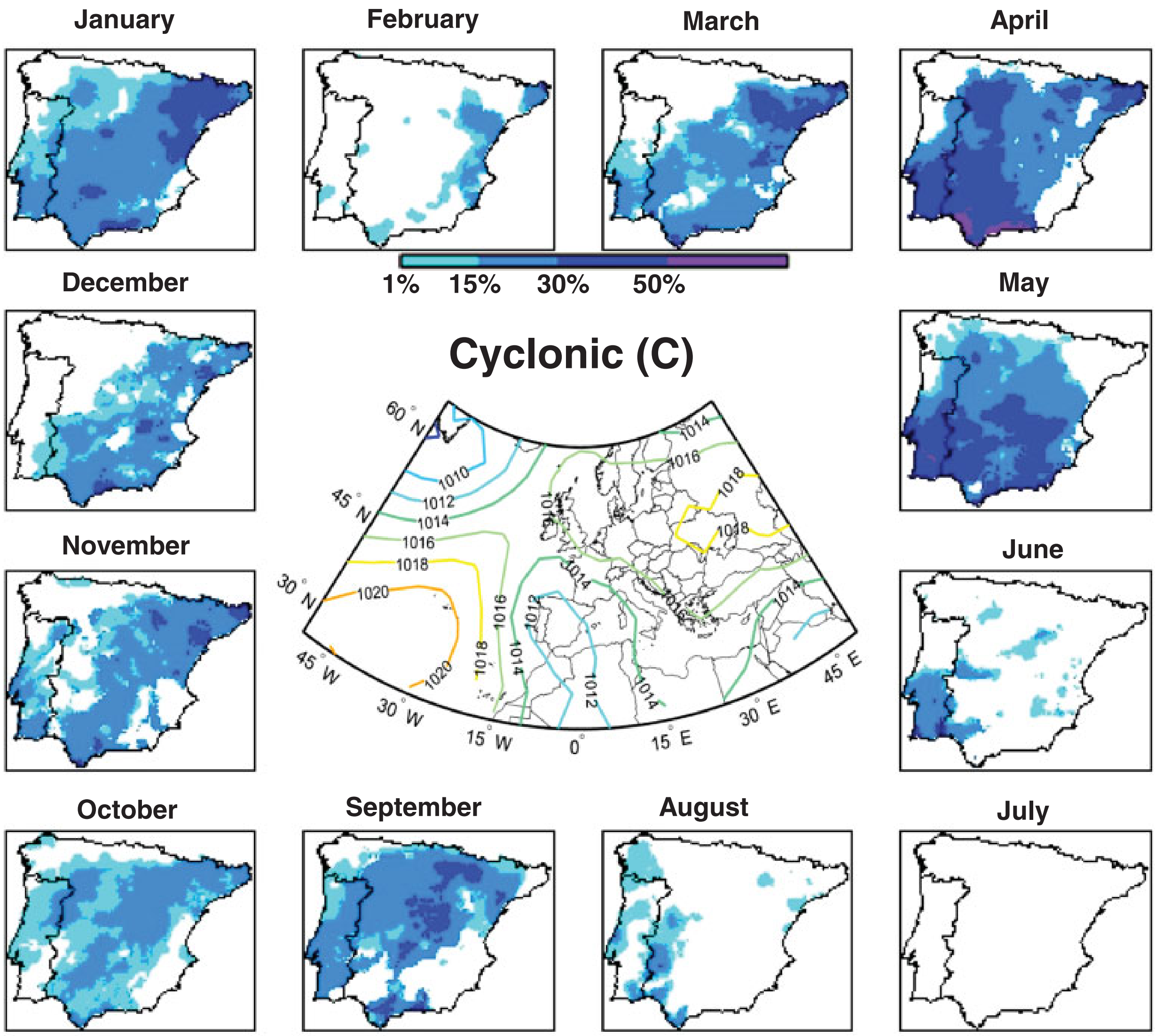

Figure 6. Spatial distribution of the relative contribution (in % of monthly Iberian precipitation) of C type.

over the synoptic processes and therefore are not well characterized by the different WTs of atmospheric circulation obtained on the synoptic scale. As a consequence, the Mediterranean versant of the IP (including the Ebro inland areas) is fragmented into several subsectors in which different WTs contribute differently to monthly precipitation. As an example, we show the contribution from six different WTs along the Mediterranean fringe in different months of the year. The contribution of NE, CNE and ANE types is shown in Figure 9. In general, their effect is confined to sectors of the Mediterranean fringe and Ebro basin, but they usually do not affect the north-eastern areas or inland to the west (except some months under CNE). The spatial effects of these WTs seem to be controlled by the mountain chains located parallel to the eastern coast and to mesoscale processes (not well picked up by the WTs).

The contribution from E, CE and CSE types is shown in Figure 10. The same facts as in Figure 9 can be observed: their contribution is restricted into very small areas on the eastern coastland and their spatial pattern varies substantially every month. The effects of E type during February and September are particularly noticeable, contributing more than 50% of total precipitation in areas of the extreme southeast of the IP. Analyses of the spatial distribution of WT effects suggest that precipitation in the western IP depends mainly on a moderate number (4–7) of WTs, with varying percentages of monthly precipitation (Cortesi *et al.*, 2013), while to the eastern areas, including the Ebro basin to the north-east inland, the amount of monthly precipitation at a given site depends mostly on just a few 1–2–3 WTs, which usually affect smaller areas and the time scale is more restricted to few months.

4. Discussion and conclusions

The subregional and local climate is generally more variable than on a hemispheric or global scale (Giorgi, 2002). This is especially true for precipitation, because

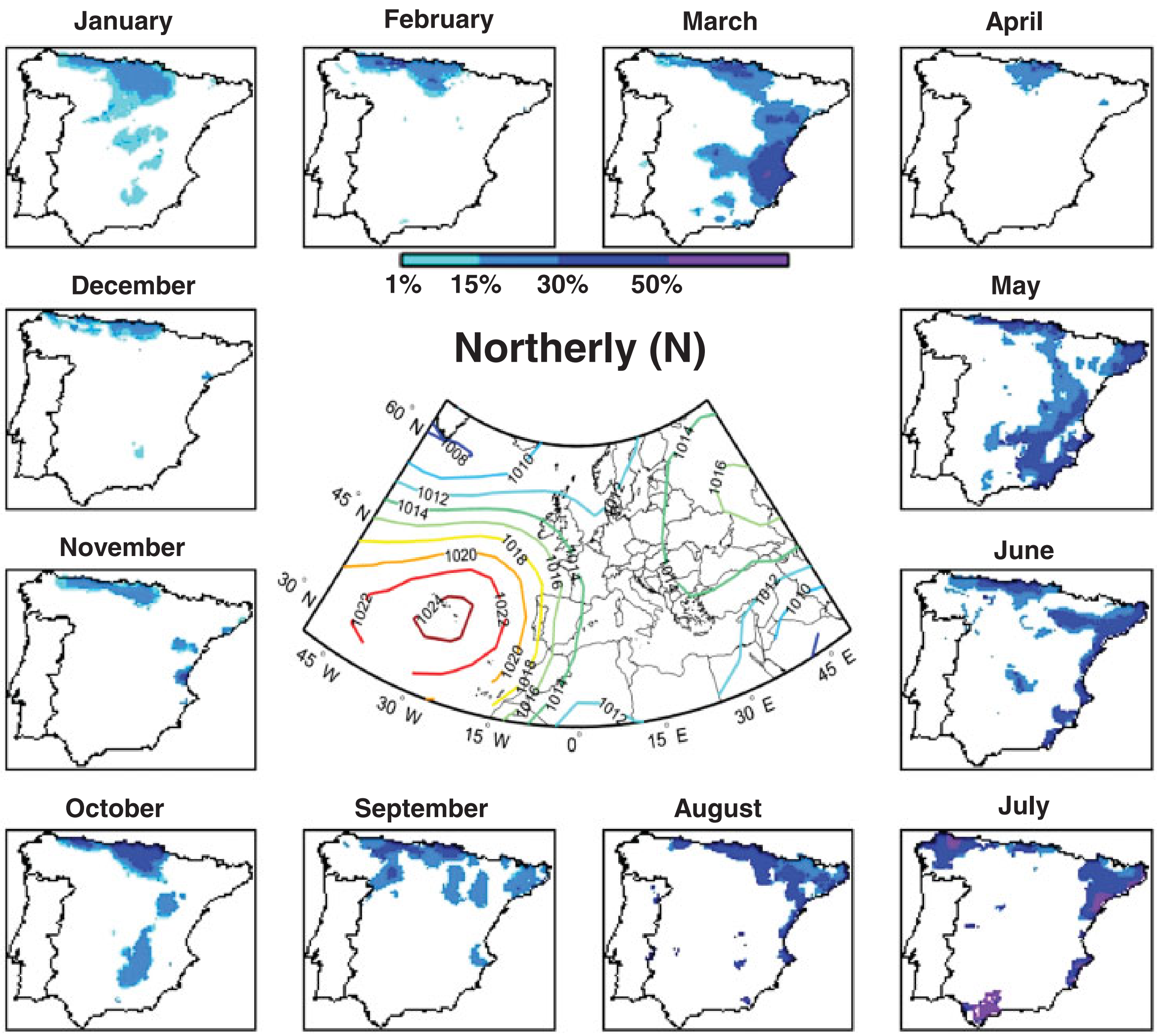

Figure 7. Spatial distribution of the relative contribution (in % of monthly Iberian precipitation) of N type.

its variability shows less spatial averaged predictability than any other climate elements (Quadrelli *et al.*, 2001; Xoplaki *et al.*, 2004), and because different spatial scale processes, from hemispheric to local convective, are related to precipitation. Thus, research on precipitation on subregional and local scales depends more than other climate elements on both: (1) the availability of spatially dense datasets (Lana and Burgueño 2000; Huntington, 2006; Trenberth *et al.*, 2007), and (2) the duration of the series (Llasat and Quintas, 2004; Xoplaki *et al.*, 2004). We have applied this approach in this study to analyse the relationship between WTs and monthly precipitation in the IP using the longest high resolution dataset available, detecting the areas in which precipitation exhibits robust links with different WTs.

The novel results presented here can be summarized as follows. The most frequent WT in the IP during 1948–2003 is the Anticyclone (A). This atmospheric pattern was also mentioned as the most frequent by Trigo and DaCamara (2000), Lorenzo *et al.* (2008) and Queralt *et al.* (2009), among other researchers, and can be seen as mostly responsible for scant precipitation in the IP, given that is has the lowest efficiency in precipitation. Grimalt *et al.* (2013) showed recently that the most frequent WT in the western Mediterranean basin is also the A type, and they suggest that A type frequency is at a maximum during summer and C most frequent in winter. These results are in contrast to ours because we found that the A maximum frequency is achieved in winter, and C maximum frequency is displaced to spring. We believe that such discrepancies could result from different choices in methodology, such as different location of grid points (showing land–sea contrast behaviour), number of points and values of the constants used to compute the geostrophic indices.

The global efficiency of WTs is dominated month by month by C types (pure and hybrid), particularly in summer months (because this is when the relative contribution of the C type is high, even if the absolute summer IP precipitation is only a few mm.), and to a lesser extent by directional types (particularly in winter months). Nevertheless, the efficiency of C types is higher in all months, confirming that C types are more clearly associated with precipitation when they occur.

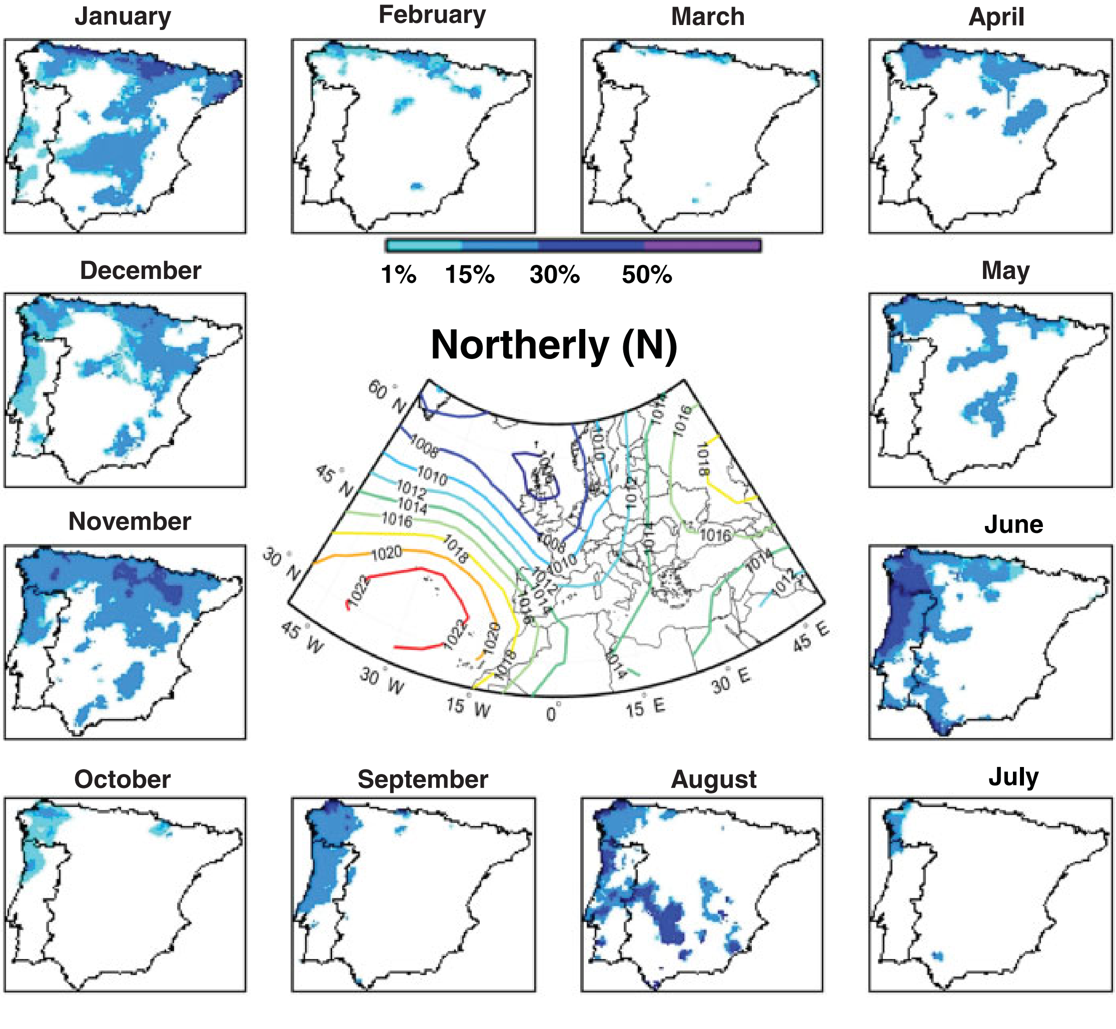

Figure 8. Spatial distribution of the relative contribution (in % of monthly Iberian precipitation) of NW type.

The WTs that prevail during winter months (D–J–F) in central, western and southwestern areas of the IP are pure C, directional W and SW. These results are in overall agreement with those presented by others researchers for the IP (Trigo and DaCamara, 2000; Muñoz-Diaz and Rodrigo, 2006). However, on the Mediterranean coastland the winter precipitation is related mostly to easterly flows, also noticed by Queralt *et al.* (2009) and Muñoz-Diaz and Rodrigo (2006). During winter months, C types and directional ones are the most efficient WTs.

Summer monthly precipitation is usually associated with northerly or easterly flows in the IP as suggested by Lorenzo *et al.* (2008) in northwest, or Muñoz-Diaz and Rodrigo (2006) for the whole IP. During summer months, the analyses show that the effects of different WTs are restricted to relatively narrow areas and during short periods (1 or 2 months), suggesting that local factors such as relief and an increase in convective processes could play a major role in precipitation across the whole IP (Mosmann *et al.*, 2004). However, we noticed that summer is clearly the season in which the WTs approach returns the lowest relationship between WTs and precipitation, probably associated with local convective processes, particularly in the eastern areas of the IP. During summer months the highest efficiency is related to C types.

Monthly precipitation during spring and autumn depends mainly on just two WTs, namely W and C. We did not observe a clear distinction at IP scale previously noticed between these two seasons, as suggested by Lorenzo *et al.* (2008), Muñoz-Diaz and Rodrigo (2006).

Three contrasting areas according to different WT-precipitation relationships can be delimited:

- Northern Cantabrian coastland, from the sea line to the mountain line, extending from west to east, where precipitation depends particularly on N and NW, WTs. Interesting to note is the low relationship with the most frequent and efficient WTs, as W or SW.
- Central-southwest, in which the relationship between W, SW and C with precipitation is highest. The area extends from western coastland to the inland mountain line to the east.
- Mediterranean coastland and Ebro basin, delimited by the Iberian System and Betic System mountain chain (to the west), the Pyrenees (to the north) and the sea

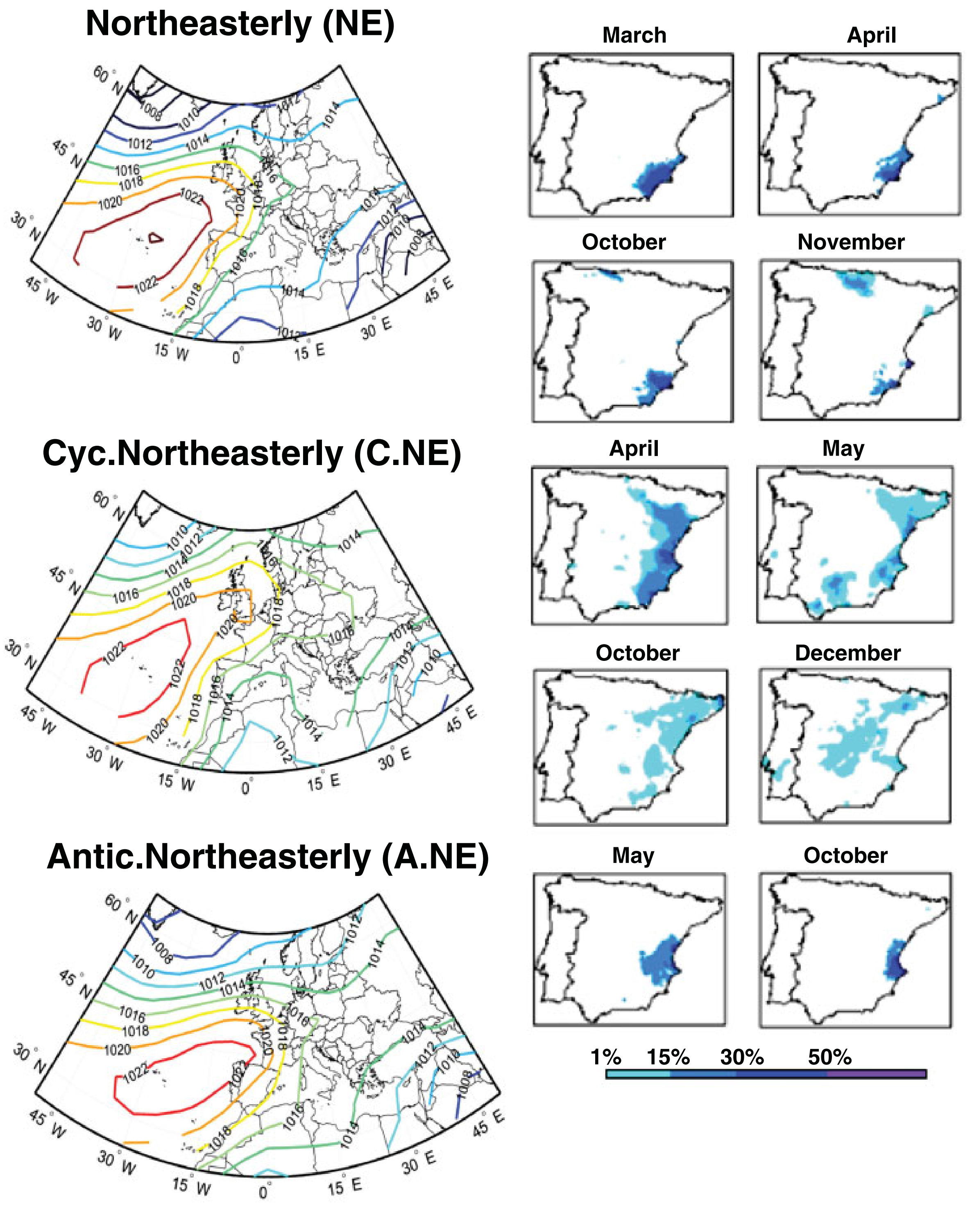

Figure 9. Spatial distribution of the relative contribution (in % of monthly Iberian precipitation) of NE, C-NE and A-NE types for selected months.

line (to the east). In this area, the monthly precipitation relationship with WTs shows a variety of situations, in which different WTs relate to precipitation during short periods (months) and in a very small areas.

These three areas coincide with most of the IP precipitation divisions suggested by different authors (Esteban-Parra *et al.*, 1998; Rodriguez-Puebla *et al.*, 1998; Serrano *et al.*, 1999; Muñoz-Diaz and Rodrigo, 2004), with the WT analyses presented here being a new set of arguments and explanations.

The alignment of the main mountain chains in the IP, i.e. from west to the east, have been attributed as one of the main factors promoting the spatial distribution of precipitation and its trends (Gonzalez-Hidalgo *et al.*, 2011), and we believe that they also contribute to

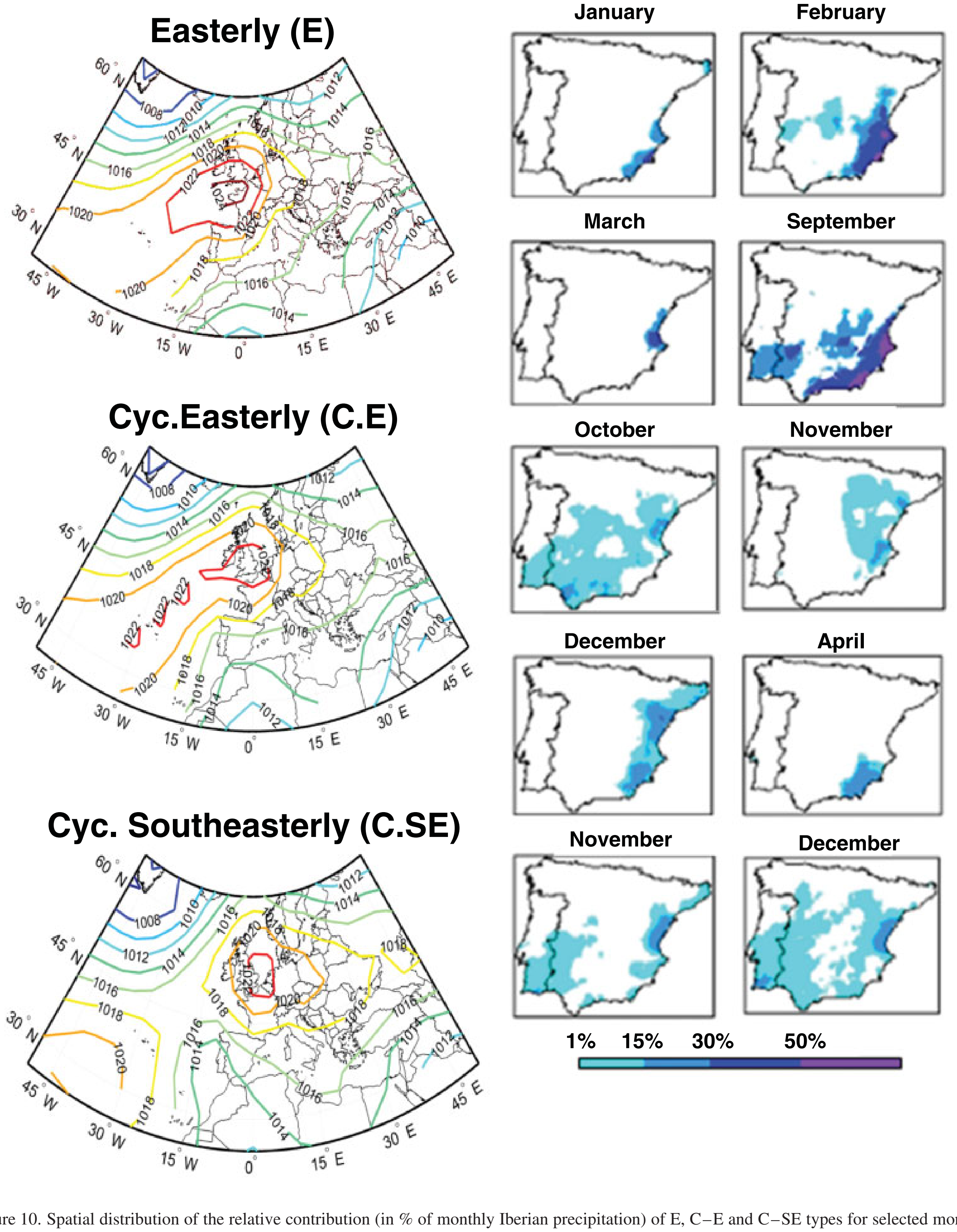

Figure 10. Spatial distribution of the relative contribution (in % of monthly Iberian precipitation) of E, C–E and C–SE types for selected months.

establishing clearly delimited areas with respect to the relationship between WTs and precipitation. This can be seen in the westerly flow that does not affect the Cantabrian coastland to the north, the Ebro basin inland, north-east areas and the Mediterranean fringe to the east. A second example corresponds to northern flows that only affect the Cantabrian coastland areas along a narrow fringe delimited to the South by the Cantabrian mountain barrier; or the Easterly flows that do not affect the inland areas because the Iberian System stops them.

This study shows that the WT approach could help to explain the spatial variability of precipitation in the IP. The results presented also include information valuable for spring and autumn, especially if we take into account the fact that two-third of total IP territory has a spring or autumn rainfall regime (de Luis *et al.*, 2010).

The results presented here come from a statistical model in which WTs have been introduced as monthly frequency to derive precipitation. Using monthly data instead of daily data offers advantages and disadvantages. Among the former, monthly data reduces the existing uncertainties in precipitation records, given the difficulties of having a high quality dataset with high spatial density. However, we also know that monthly data have important disadvantages, because they mask the occurrence of extreme events that can be crucial for monthly total amounts (Vicente-Serrano *et al.*, 2009). This is important, particularly in areas where monthly precipitation is highly dependent on the amounts of few daily precipitation events per month (i.e. Ebro basin, Mediterranean coastland areas, etc).

Finally, research in progress on temporal variability of all monthly WT series will provide more reliable physical mechanisms to explain the different monthly precipitation trends and their spatial distribution in the IP, as identified by Gonzalez-Hidalgo *et al.* (2011).

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