AVHRR WARM-SEASON CLOUD CLIMATOLOGIES UNDER VARIOUS SYNOPTIC REGIMES ACROSS THE IBERIAN PENINSULA AND THE BALEARIC ISLANDS

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ABSTRACT

In this study we retrieved the spatial distribution of mid-afternoon clouds under various synoptic regimes across the Iberian Peninsula and the Balearic Islands for the warm/convective-season, from May through October. Accurate daily cloud masks were derived by applying a daytime over land multispectral convective cloud detection algorithm spanning 15-years (1997-2011) of Advanced Very High Resolution Radiometer (AVHRR) HRPT data. We processed a total of 2094 afternoon overpasses (between 1230 and 1720 UTC) corresponding to the NOAA-14, NOAA-16 and NOAA-18 spacecrafts, and stratified daily cloud masks as a function of: (i) the automated circulation-typing scheme of Jenkinson and Collinson, and (ii) the prevailing wind field at 850 hPa. The AVHRR warm-season cloud climatology with high spatial resolution (1.1-km) identified six representative areas (regions of interest; ROIs) with intensified cloud activity (hot spots). The results also revealed the typical spatial distribution of clouds for each synoptic regime across the whole region, identified the synoptic patterns and wind regimes under which high amounts of clouds occur for each ROIs, and showed that strong boundary layer winds in general increase the frequency of clouds. The regional cloud climatology presented here could be useful, for instance, to improve convective short-term forecasting by identifying active cloud areas for each atmospheric type.

KEY WORDS: NOAA AVHRR; warm-season cloud climatologies; synoptic regimes; Iberian Peninsula and Balearic Islands
1. INTRODUCTION

Mid-afternoon clouds are generally associated with non-frontal convective processes and represent a common feature mainly over the mountainous areas of both the Iberian Peninsula (IP) and the Balearic Islands (BI) during the warm-season of the year (May-October), (Sánchez et al., 1998). Convective cells develop with high frequency across portions of this temperate mid-latitude region, in particular northeastern Spain over the Pyrenees and the Iberian System Mountains (Romero et al., 2001) where summertime maxima of precipitation occurs (Martin-Vide and Olcina-Cantos, 2001). The diurnal cycle of clouds is particularly strong over land surfaces because of the small heat capacity compared to the ocean surfaces (Grawoski et al., 2006). Thus convective clouds and precipitation are mainly driven by the intense diabatic solar heating and intensified far more quickly at high temperatures (Berg et al., 2013). This thermodynamic process enhances: (i) the destabilization of the boundary layer by mixing out low-level inversions; (ii) the development of sea breezes and other local winds (e.g., anabatic valley wind circulations on heated south-facing mountain slopes, Azorin-Molina et al., 2011) in an area of complex terrain which enhances orographic lift and the transport of Atlantic and Mediterranean warm moist surface air to mountains in the daytime (Millan et al., 2005); and (iii) the establishment of a quasi-permanent thermal low over the Iberian plateau (Hoinka and De Castro, 2003). In order for convective clouds to become thunderstorms it is necessary that conditional instability exists: for example, from the passage of short-wave troughs which bring cold air aloft and sometimes passing cold fronts over the northern fringe of the IP (Romero et al., 2001).
During dry summer months, clouds producing rain are often the only source of precipitation over the region and are beneficial to agriculture directly as well as indirectly through the recharge of streamflow, aquifers and reservoirs (Millan et al., 2005). However, more organized and long-lasting convective thunderstorms (e.g., mesoscale convective systems) can become more intense and extensive and sometimes be extraordinarily severe, causing heavy rain (i.e., flash floods), large hail, straight line winds, lightning discharges, and rare tornadoes, producing serious socioeconomic impacts with damages and economic loss (Llasat-Botija et al., 2007), preferably over the Mediterranean region. On the evening of 7 August 1996, rainfall in excess of 200 mm in a 3 hour period caused a flash flood that killed 86 and injured 93 at a camping site in Biescas in Huesca, Spain (Romero et al., 2001) or the “Montserrat-2000” flash flood event that caused material damaged estimated at over 65 million euros (Llasat et al., 2003). Additionally, the short-term forecasting of the location, timing and intensity of isolated thunderstorms represents a challenging task in numerical weather prediction (Azorin-Molina et al., 2014), mainly due to (i) the uncertainties in the initial conditions, (ii) the limited knowledge about the cloud microphysical processes, and (iii) the difficulties in resolving low-level convergence and convection with fairly coarse horizontal resolution operational models (Mazarakis et al., 2009). Furthermore, isolated thunderstorm cells with severe weather can develop unexpectedly under weakly defined synoptic-scale or mesoscale precursor disturbances (Wilson, 2008), and may be missed by forecasts. Satellite cloud monitoring could provide valuable information for improving the forecasts of these meteorological hazards and the climate monitoring of storms. Moreover, knowledge of the distribution of mid-afternoon clouds under various synoptic regimes is useful for other fields such as solar energy, hydrology and agriculture activities.
Despite the benefits and risks associated with the development of mid-afternoon clouds and thunderstorms, the impact of synoptic regimes on the spatial distribution of convective clouds using remote sensing data across the IP and the BI has not been reported in the literature. Previous studies focussed on the location of areas with the most frequent convection. For instance, Ramis and Alonso (1988) used geostationary visible imagery on 11 May 1987 to show the development of a sea breeze front in the isle of Mallorca. Pascual (1999) used geostationary infrared imagery to develop convection climatologies in Catalonia (northeastern IP). Pascual et al. (2004) examined polar 1.1 km VIS and IR satellite imagery from NOAA-16 and 17 to infer the existence of boundary layer convergence lines for sea breeze and coastal range interaction in Catalonia. More recently, Azorin-Molina et al. (2009) used high-resolution daytime Advanced Very High Resolution Radiometer (AVHRR) data for retrieving the spatial distribution of convective areas associated with low-level sea breeze convergence and consequently sea breeze front development, and provided statistics about the impact of prevailing large-scale flows on the sea breeze convection. Furthermore, it should be noted that most studies on high-resolution regional cloud climatologies have been computed by the Regional and Mesoscale Meteorology Branch (RAMMB; http://rammb.cira.colostate.edu/research/satellite_climatologies/; last accessed 1 June 2014) for the United States, Central America, the Caribbean region and Spain.

The main goal of this study lies in objectively quantifying for the first time the impact of large-scale atmospheric circulation on the spatial distribution of mid-afternoon cloud frequency observed from high-resolution AVHRR satellite-registered radiances; the stratification of daily cloud masks as a function of various synoptic regimes and the use of 15-years (1997-2011) of AVHRR data are advances of the work published by Azorin-Molina et al. (2013). This paper is organized as follows: Section 2
describes the AVHRR data, and Section 3 shows the cloud frequency statistics and the 
two synoptic classifications; Section 4 displays the mid-afternoon cloud frequency 
composites for various synoptic regimes across the IP and the BI during the warm 
months (May to October) of the 15-yr period 1997-2011; and lastly a summary and 
conclusions are drawn in Section 5.

2. DATA

2.1. AVHRR data and pre-processing

AVHRR data from the NOAA-14 (AVHRR/2 instrument onboard; 5-spectral channels), 
NOAA-16 and NOAA-18 (AVHRR/3 instrument onboard; 6-spectral channels) polar 
orbiting satellites were collected from the High Resolution Picture Transmission 
(HRPT) receiving ground station placed at the National Institute for Aerospace 
Technology (INTA, Maspalomas, Gran Canaria, Canary Islands, Spain) and supplied by 
the Centre for Reception, Processing, Archiving and Dissemination of Earth 
Observation (CREPAD program; http://www.crepad.rcanaria.es/en/index-en.html; last 
accessed 1 June 2014) for the warm season May-October spanning the 15-year study 
period 1997-2011. We choose these NOAA satellites because their afternoon 
overpasses are ideal for capturing the active hours of the life cycle of convection.

AVHRR scenes used for this study were acquired from 1230 UTC till 1720 UTC; 
NOAA-14 between 1310 and 1720 UTC, NOAA-16 between 1244 and 1501 UTC and 
NOAA-18 between 1230 and 1437 UTC. The most frequent acquisition intervals 
occurred between 1300 and 1400 UTC. Regardless the instability of polar satellite orbits 
(Karlsson, 2003), we used all the available AVHRR scenes since the time window of all
of them covers the active hours of convection. A fully automated pixel-by-pixel pre-
processing routine using the header files (metadata) of L1B ESA SHARP data (binary
file; SHARP is the European Space Agency – Earthnet format for AVHRR data) was
designed in Environment for Visualizing Images (ENVI) + Interactive Data Language
(IDL) 4.7 package, also including a geometric correction; for details see Azorin-Molina
et al. (2009). A set of 2094 AVHRR scenes (75.9% of the theoretically available
satellite scenes) were analyzed in this study. The 24.1% not used were thrown out
because of (i) reception and technical processing problems, (ii) archiving-tape failures,
(iii) calibration errors, (iv) georreferencing problems, and (v) missed portions of the IP
and the BI. Table I summarizes the monthly number of AVHRR scenes for each
satellite for 1997-2011.

3. METHODS

3.1. Cloud detection algorithm and frequency statistics

We used a newly proposed daytime over land algorithm for computing AVHRR
convective cloud climatologies for the IP and the BI (Figure 1a); for details see Azorin-
Molina et al. (2013). The convective cloud frequency composites presented in section 4
are based on the cloud frequency (in percentage) regarding the complete available
scenes. Additionally, we used these high resolution cloud frequency maps to identify
active convective hotspots as those displaying the maximum frequency values (i.e.,
Regions of Interest, ROIs; see section 4.1) in relation to topographical features such as
altitude, and land/water boundaries (Klitch et al., 1985). Centered over the selected
ROIs, we computed cloud frequency statistics for a 50x50 pixel array, which Azorin-
Molina et al. (2009) identify as an area large enough to quantify the impact of various synoptic regimes on cloud frequency.

Azorin-Molina et al. (2013) employed the term “convective” cloud frequency composites because the algorithm was specifically defined for identifying convection and most clouds developed within the mid-afternoon overpasses; these clouds are mostly associated with convective processes during the warm-season May-October. However, it should be noted that composites presented in this study not only include cloud masks that include larger Cumulus and Cumulonimbus clouds, but also convection embedded in multilevel cloud cover, and mid-afternoon clouds linked to other synoptic-scale situations (e.g., frontal passages). A detailed description of the daytime over land cloud masking algorithm can be found in Azorin-Molina et al. (2013).

3.2. Synoptic regimes

With the aim of analyzing the impact of atmospheric circulation on the spatial distribution of mid-afternoon cloud patterns, the 2094 cloud masks were stratified resulting in cloud frequency climatologies as a function of: (i) the automated circulation-typing scheme of Jenkinson and Collison (1977) based on Sea Level Pressure (SLP), and (ii) the prevailing low-level boundary layer wind field at 850 hPa.

3.2.1. Automated circulation-typing scheme of Jenkinson and Collison
We choose the Jenkinson and Collison (1977) circulation-typing scheme as an objective synoptic classification method (hereafter JC) because it has been successfully applied to study the relationship between climate variables and atmospheric circulation over the IP (Goodess and Palutikof, 1998; Trigo and DaCamara, 2000; Goodess, 2000; Spellman, 2000; Martin-Vide, 2001; Vicente-Serrano, 2004; Azorin-Molina et al., 2011; among others) and the BI (Grimalt et al., 2013). The grid-point employed consisted on 16 points of daily SLP reanalysis data (p(n)) at a 5º latitude by 10º longitude (Jones et al., 1993; Chen, 2000; Linderson, 2001). The area is bounded by 30.0º and 50.0ºN, and 20.0ºW and 10.0ºE, essentially centred over the IP as can be found in Azorin-Molina et al. (2011). The SLP dataset was obtained from the National Centres for Environmental Prediction (NCEP) and the National Centre for Atmospheric Research (NCAR) reanalysis project (http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml; Kalnay et al., 1996; last accessed 1 June 2014) for the 15-yr study period (1997-2011). The JC method is based on objective rules concerning the calculation of seven equations or circulation indices (for details see Azorin-Molina et al., 2011). The synoptic catalogue identifies 27 weather types grouped into 4 categories: (i) directional flow types (N, NE, E, SE, S, SW, W and NW); (ii) anticyclonic (A) and cyclonic (C) types related to the rotation of the atmosphere; (iii) hybrid types (AN, ANW, AW, ASW, AS, ASE, AE, ANE, CN, CNW, CW, CSW, CS, CSE, CE and CNE); and (iv) the unclassified type (UD), which was resolved and classified by extending the original grid basis of Spellman (2000) and Martin-Vide (2001). Therefore, 26 weather types were used for stratifying daily cloud frequency composites.

3.2.2. Wind field at 850 hPa
The prevailing direction and strength of wind in the low-level troposphere have been used in satellite climatology for stratifying remote sensing data and investigate the impact of large-scale flows on cloud patterns (Connell et al., 2001; Combs et al., 2001; Azorin-Molina et al., 2009). Previous studies found that the direction and strength of low-level synoptic winds along with the shape of coastline and complex terrain are the most influential factors for sea breezes and local winds (Estoque, 1962; Blanchard and Lopez, 1985; Azorin-Molina and Chen, 2009), which in turn directly control the development of convection and the evolution of storms over land (Gould and Fuelberg, 1996).

The daily 850 hPa u-wind and v-wind data from the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) reanalysis project (http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml; Kalnay et al., 1996; last accessed 1 June 2014) were used to designate the synoptic-scale flow regimes described below. The grid at 40.0°N–5.0°W was chosen as the most centered point and therefore considered representative of large-scale ambient flow over the whole study area. The 850-hPa wind was assumed to be representative of the low level synoptic forcing because the layer 0–1.500 m is the one where local and mesoscale circulations trigger convective clouds (Banta et al., 1993; Helmis et al., 1995).

We classified synoptic-scale flows in 16 types in relation to (i) the wind direction (8 directional flow types), i.e., NE (22.6°-67.5°), E (67.6°-112.5°), SE (112.6°-157.5°), S (157.6°-202.5°), SW (202.6°-247.5°), W (247.6°-292.5°), NW (292.6°-337.5°) and N (337.6°-22.5°) regimes, and (ii) the wind speed (2 intensities), i.e., light to moderate (0 to 5.14 m s⁻¹) and strong (Str, >5.14 m s⁻¹) categories according to Gould and Fuelberg (1996) and Connell et al. (2001). A diagram of the near surface synoptic regimes is displayed in Figure 1b.
4. RESULTS

4.1. Seasonal Cloud Climatology and Identification of the Region Of Interest

Figure 2 displays the seasonal (i.e., May-October) and monthly mid-afternoon cloud frequency composites for 1997-2011. The present study of warm-season cloud climatology (Fig. 2a) is ideal for identifying the areas most likely to receive convection and therefore paying particular attention by, for instance, forecasters. Apart from the marked latitudinal gradient found in cloudiness with the maximum (73.8%) over the northernmost fringe of the Atlantic-Cantabrian area and the Pyrenees, partly attributed to low-stratiform clouds linked to large-scale northwesterly winds and the influence of cold fronts (Azorin-Molina et al., 2013), and the minimum in cloudiness (12.4%) over the southern region of the IP caused by the suppression of convection under the influence of the Azores high pressure system; we identified six Regions of Interest (ROIs) as those displaying high cloud frequency amounts. These ROIs basically correspond to the main mountainous areas of the IP and the BI: (i) the Cantabrian mountains (ROIs1; maximum cloud amount 66.2%), (ii) the Pyrenees (ROIs2; 67.6%), (iii) the Central system (ROIs3; 41.5%), (iv) the eastern Iberian system mountains (ROIs4; 44.5%), (v) the Betic mountains (ROIs5; 43.9%), and (vi) the centre of the isle of Mallorca (ROIs6; 41.2%) as a result of the low level convergence of sea breezes in the centre of the isle (Ramis and Alonso, 1988). All the ROIs are shown by squares in Fig. 2a, except for ROIs6 where cloud frequency statistics are computed for the whole isle of Mallorca because the 50x50 square includes sea pixels that are out of our area of interest. Along with these six convective hotspots, these high resolution cloud
frequency maps reveal other areas with high cloud frequency amounts which are important for forecasting. In contrast to these zones, large cloud-free regions dominate around southern coastal areas, bays, and particularly across main river valleys in relation to subsident divergent flows over nearby water bodies (Connell et al., 2001).

Note that the spatial distribution of cloud frequency shown in Figure 2a is similar to that of seasonal (JJA) mean precipitation from observed and simulated grid datasets revealed by Cardoso et al. (2013). The inset transects #1 and #2 shown in Figure 2b are manifestations of orography on the cloud frequency. It is noteworthy that the cloud frequency lines display the same shape as the orography lines for both transects; i.e., high cloud amounts over the mountainous areas (ROIs; 55-60%) and low cloud activity along river valleys (e.g., Guadalquivir, Tajo and Ebro; 15-20%).

Figure 2 also shows a pronounced intermonthly cycle in cloudiness. The statistics computed in Table II confirm that May (Fig. 2b) is the second cloudiest month with a mean cloud frequency of 33.7% (max. 87.1% and min. 16.9%); due to the development of widespread clouds associated with convective processes during spring. The mean cloud frequency sharply decreases in June (Fig. 2c) with 23.6% (max. 86.4% and min. 5.3%). This declining trend continues and the mean frequency reaches the lowest level in July (Fig. 2d) with 16.5% (max. 76.9% and min. 1.3%), as a consequence of the subsident influence of the Azores high pressure system. A gradual increase in cloud activity was found in August (Fig. 2e) with mean cloud frequency of 20.1% (max. 74.8% and min. 3.6%). September (Fig. 2f) is the third cloudiest month with a mean cloud frequency of 32.2% (max. 68.1% and min. 11.2%). Finally, October (Fig. 2g) represents the cloudiest month with a mean cloud frequency of 39.4% (max. 63.4% and min. 22.7%) in accordance with the occurrence of cold fronts which represents an instability approaching from the Atlantic Ocean (Azorin-Molina et al.,
291 2013), and the development of mesoscale convective systems over the Mediterranean
292 area.

293 4.2. Cloud composites according to weather type

294 Figure 3 shows the 26 cloud frequency composites corresponding to (i) the anticyclonic
295 and hybrid weather types (Fig. 3a), (ii) the cyclonic and hybrid weather types (Fig. 3b),
296 and (iii) the directional weather types (Fig. 3c). The box-and-whisker plots shown in
297 Figure 4 summarize the cloud frequency statistics for each synoptic pattern for
298 comparison between the six identified ROIs. Both figures are particularly helpful in
299 identifying the typical spatial distribution of clouds associated with the weather types.
300 Overall, there is a clear difference in the total amount and the spatial patterns of
301 cloudiness among the three groups. The anticyclonic and hybrid weather types are
302 generally characterized by low cloud amounts across the region (with exceptions, see
303 description for each ROIs below), while the cyclonic and hybrid weather types are
304 associated with an unstable atmosphere and widespread high cloud amounts. Further,
305 the directional weather types present the well defined cloud composites because the
306 spatial distribution of mid-afternoon clouds is driven by flow direction and
307 corresponding moisture sources. Below we focus on analyzing the favourable weather
308 types to develop (or inhibit) cloud development for each ROIs.

309 ROIs1 representing the Cantabrian mountains receives the highest cloud
310 amounts under the CSW type (mean cloud frequency 79.2%) followed by the
311 directional N (74.3%) and NW (73.8%) types, the hybrid cyclonics CN (72.5%) and
312 CNW (70.0%), among others. As an exception, high cloud amounts also develop under
313 hybrid anticyclonic weather types such as the ANW (61.2%) and the AN (60.7%). It is
314 therefore clear that mid-afternoon clouds are mostly formed over the Cantabrian
mountains when weather types with southwesterly, westerly, northwesterly and northerly circulations bring high Atlantic moisture levels into the region. On the contrary, under the ASE (12.2%) and the AS (16.3%) convective clouds are unlikely to develop as dry and warm tropical air moves from the north of Africa and the subsidence exerted by the Azores high pressure system inhibits lifting. The ROIs2 located in the eastern Pyrenees displays the highest cloud amounts under the AN (68.0%), the N (63.6%), the ANE (63.3%), the NE (62.4%) and the CNE (62.2%) weather types; i.e., mid-afternoon clouds develop when cold northerly and humid northeasterly advections destabilize the atmosphere. Along with the ROIs1, this mountainous region also represents an exception of showing high cloud amounts under anticyclonic hybrid circulation types due to the upward deflection of large scale horizontal flow by the orography. In contrast, the ASW (15.2%), the CSE and the S (21.6%) represent the circulation types with lowest cloud amounts over the Pyrenees. The ROIs3 in the Central system mountains receives the highest cloud amounts under the CSW (82.7%) and the CW (71.4%) types, followed by the directional W pattern (63.2%). Westerly and southwesterly circulations favour Atlantic moisture advection towards the center of the IP and the upward vertical propagation of moist air up by the orography help convective clouds to develop. The most stable AE (7.8%) and ASE (10.8%) weather types, i.e. eastern Mediterranean circulations, almost inhibit the development of mid-afternoon clouds over this mountainous region.

Cloud development in the ROIs4 over the eastern Iberian system mountains is basically influenced by cyclonic types from both the Atlantic and the Mediterranean moisture sources, i.e. the CSW (68.9%), the CNE (62.5%), and the CN and the CW (61.9%). It is also characterized by presenting moderate to high cloud amounts for almost every weather circulation, except for the ASW (10.3%). The most southern
ROIs5 representing the Betic system mountains is much affected by the influence of
stable air masses (i.e., proximity of Africa and the subtropical anticyclone belt) and
mean cloud amounts only show moderate values for the CW (56.2%), the CNE (53.3%)
and the CSW (50.2%). Additionally, the stability induced by subsidence under the
ASW type (6.0%) produces the lowest mean cloud amount recorded among all ROIs.
Lastly, the ROIs6 representing the whole of the isle of Mallorca displays low to
moderate mean cloud amounts for all weather types, only being greater than 50% for
the CW type (57.1%), followed by the CN circulation pattern (44.8%). The lowest
mean cloud frequency value is recorded under the ASW type (9.6%) and the CS
(11.6%). A summary of the five cloudiest and cloudless weather types for each ROIs is
shown in Table III, and transects #1 and #2 for all the 26 weather types are displayed
in Figure 5 showing the spatial distribution of clouds in relation to the orography.

4.3. Cloud composites according to background flow direction and speed

Figure 6 displays the 16 cloud frequency maps as a function of (i) wind direction and
(ii) wind speed, i.e., light to moderate (left panel) and strong (right panel) intensities.
Figure 7 summarizes the cloud frequency statistics in form of box-and-whisker plots for
each synoptic-scale flow type and ROI. On the one hand, the NE, E, SE and S (i.e.,
more Mediterranean winds) synoptic-scale flow composites (Fig. 6a) are characterized
by developing mid-afternoon clouds in the eastern part of the IP, particularly over the
mountainous areas under light to moderate winds, whereas the strong flows surpass the
high eastern Iberian mountain barriers bringing moisture and enhancing the
development of more and much widespread clouds westward of the IP, even though
mountains lead to some Föhn effect to the western parts of the IP. On the other hand,
the N, NW, W and SW (i.e., more Atlantic winds) synoptic-scale flow composites display a clear latitudinal gradient in the spatial distribution of clouds, with higher amounts in the northern part and lower amounts in the southern-southwestern parts of the region under light to moderate flows. The mid-afternoon clouds are more frequent and more widespread over the whole region under strong boundary layer winds.

The frequency of mid-afternoon clouds in the ROIs1 is greater for strong W (mean cloud frequency 72.3%), N (67.0%) and NW (65.3%) flows which bring Atlantic moisture (e.g., in form of cold front passes or low-stratiform clouds) to the Cantabrian mountains, whereas the Mediterranean circulations from the E (23.4%) and SE (31.3%) directions inhibit cloud development resulting in low cloud frequencies due to the adiabatic heating which operates over the ROIs1 located in the leeward side of the IP. Note in Fig. 7 that for all wind regimes the strongest strength of the low level wind is linked with high amount of clouds, except for the abovementioned E and SE flows that exhibit fewer clouds for strong intensities than those under light to moderate flows. The ROIs2 presents a similar pattern with enhanced cloud development under the dominance of both the light to moderate (68.3%) and strong (70.7%) NW direction, followed by the strong N (62.1%) and W (61.2%) types. In contrast, as occurred for the ROIs1, the strong SE (28.8%) and E (30.0%) flows represent the types showing the minimum mean of cloudiness due to the dissipating effect exerted by the adiabatic heating; however, convective clouds can develop just over the Pyrenees mountains as shown in Fig.6a. It is also noteworthy over the ROIs2 that for N, NW and W directions (i.e., favourable types for clouds to develop), except for the SW, the strong flows develop much more clouds, whereas for all the strong NE, E, SE and S flows (i.e., unfavourable types) the opposite occurs. In the case of the ROIs3, the most characteristic feature corresponds to the low mean cloud amounts for almost all
regimes, hypothetically due to its location in the centre of the IP, i.e., far from both the
Atlantic and Mediterranean moisture sources. The strong SW (43.8%), S (43.2%) and
W (42.5%) flows, which bring Atlantic tropical moisture flux, are the cloudiest wind
regimes, whereas the light to moderate NE (13.1%) flows are the cloudless ones. Note
that for all wind regimes strong intensities develop much more widespread clouds, with
noticeable differences compared with the light to moderate winds for the S, SW, W and
NW types.

Over the ROIs4 in the Iberian system, moderate cloud amounts are found for all
wind regimes. The highest cloud frequency observed under the light to moderate NW
type (51.8%) is associated with the large surface convergence between Mediterranean
sea breezes and the NW flows, which strengthen vertical motion for convection
initiation (Azorin-Molina et al., 2014). For instance, convective clouds are well-
organized parallel to the Iberian Mediterranean coast as shown in Fig. 6b for the light to
moderate NW regime, whereas strong NW flows slightly weaken (45.8%) low level
sea breeze convergence (Azorin-Molina et al., 2009). The opposite occurs for the
strong W (47.3%), N (46.5%), and SW (41.5%) flows, which show greater amounts of
clouds than light to moderate winds. In the case of the ROIs5, the development of mid-
afternoon clouds is mainly associated with low-level moisture fluxes linked to the
strong NE (57.1%), S (37.5%), E (37.3%) and SE (33.9%), whereas the remaining four
wind regimes tend to inhibit convection, e.g. light to moderate W winds (15.9%). For
the Betic mountains, we also detected much more clouds under strong flows for all the
8 wind directions. Lastly, over the ROIs6 strong N (61.9%), NE (58.4%) and E (41.0%)
flows bring Mediterranean moisture and basically unstable cold air aloft enhancing
cyclogenesis and development of clouds over the western Mediterranean basin. The
cloudless wind regimes corresponds to the strong S (19.2%) and SE (19.9%) flows
which bring tropical air (i.e., warm inversion layer) from north of Africa. The inversion acts as a cap inhibiting mid-afternoon convection. A summary of the five cloudiest and cloudless synoptic-scale flows for each ROIs is shown in Table IV, and transects #1 and #2 for all the 16 weather types are displayed in Figure 8.

5. SUMMARY AND CONCLUSIONS

In this study we revealed the location of mid-afternoon clouds (1230-1720 UTC) across the IP and the BI through the warm season (May-October) during a 15-yr study period (1997-2011); mid-afternoon cloud composites were basically represented by isolated convective clouds, but also convection embedded in multilevel cloud cover and some other cloud types associated with large-scale synoptic disturbances. The novelty of this study resides in the stratification of 2094 NOAA-AVHRR overpasses as a function of (i) the automated circulation-typing scheme of Jenkinson and Collison (i.e., 26 weather types) and (ii) the prevailing wind field at 850 hPa (i.e., 16 wind regimes). The application of this technique led to 42 high spatial resolution (1.1-km) regional cloud composites which provide valuable information for identifying the areas most likely to receive clouds (hot spots). It is concluded that large-scale atmospheric circulation, land/water thermal contrast and orography play a role in determining the composites. With the use of seasonal and monthly cloud composites we identified six highly active convective zones referred to ROIs (i.e., main mountainous areas of the IP and the BI) and showed the synoptic patterns and low level wind regimes that are more favourable to develop convective clouds for each ROIs. Even though operational forecasters already pay particular attention over these identified zones, here we supply additional information such as spatial distribution of mid-afternoon clouds and where these
clouds tend to form under each weather type or wind regime. Moreover, here we focussed our analysis on the six identified ROIs (i.e., zones to be monitored closely by weather forecasters), but high-resolution regional cloud composites presented in this paper offer information about cloud development across the whole IP and the BI, enabling readers to look at the frequency of clouds under different synoptic patterns in areas other than the described ROIs. The main features of the six ROIs can be summarized as the followings:

(1) The Cantabrian mountains in the northernmost fringe of the IP (ROIs1) exhibits high cloud amounts for weather types and wind regimes associated with Atlantic moisture advections; e.g., preferably under northerly, northwesterly and westerly cyclonic, directional or even anticyclonic circulations.

(2) The eastern Pyrenees (ROIs2) are mainly influenced by northerly and northwesterly advections. Northeasterly humid Mediterranean flows under both anticyclonic and cyclonic circulations also play a role.

(3) The Central system mountains (ROIs3) display a high dependency on southwesterly and westerly flows, mainly under cyclonic weather types and associated Atlantic moisture flux.

(4) The eastern Iberian System mountains (ROIs4) are characterized by moderate to high amount of clouds for all weather types and wind regimes. However, cyclonic situations originated from both the Atlantic and the Mediterranean moisture sources tend to increase the cloud amount.
(5) The Betic system mountains (ROIs5) is much influenced by hybrid cyclonic weather types from the west, southwest and northeast, with enhanced cloud development for the Mediterranean wind regimes.

(6) Lastly, the isle of Mallorca (ROIs6) displays low to moderate cloud amounts for all weather types, being greater for cyclonic patterns from west and north directions, and also by northerly, northeasterly and easterly synoptic-scale flows.

An interesting feature identified by this study is that mid-afternoon cloud frequency is greater under strong winds at 850 hPa. This was observed for all the six ROIs with only a few exceptions, but in contrast we also detected that for those unfavourable large-scale flows strong winds resulted in lower cloud frequencies than light to moderate winds. Therefore, we noted that frequency composites of mid-afternoon clouds are spatially distributed as a function of (i) the prevailing direction (and strength) of low-level wind fields, (ii) their corresponding sea surface latent-heat flux, and (iii) the frictional effects produced by the complex terrain of this mid-latitude region, which causes convergence and enhances lifting processes (i.e., focussing convection in slope zones).

To conclude, the first stratified regional cloud frequency composites compiled in this study for both the IP and the BI represents a valuable information for improving convective short term forecasting, if numeric prediction of the atmospheric circulation indicators is available. The 15-year climatology could also have practical applications for those interested on the climate monitoring of storms, or for those that make decisions related to e.g. solar energy use, hydrology, agriculture, tourism, among many other spheres of application. This claims the usefulness in satellite
meteorology/climatology of stratifying remote sensing data as a function of different
atmospheric classifications; a technique little used so far in the scientific literature since
the 1960s but with high potential for many regional applications. For instance, satellite
data provide a greater spatial representation of cloud frequency than surface based
measurements. Finally, future work should also look at compiling regional cloud
composites stratified as a function of various synoptic regimes through the cold season,
i.e., November till April, and spanning the roughly 35-years of AVHRR imagery.

Acknowledgements

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reviewers for their detailed and helpful comments to the original manuscript.

REFERENCES


Llasat MC, Rigo T, Barriendos M. 2003. The “Montserrat-2000” flash-flood event: a comparison with the floods that have occurred in the northeastern Iberian Peninsula since the 14th century. *International Journal of Climatology* **23**: 453-469.


Table I. Monthly number of NOAA-14, NOAA-16 and NOAA-18 AVHRR scenes used for the six-month study period May-October 1997-2011

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<td>373</td>
<td>355</td>
<td>353</td>
<td>364</td>
<td>2094</td>
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Table II. Mean cloud frequency (in %) from the convective composites shown in Figure 2 for (a) the Iberian Peninsula and the Balearic Islands, and (b) the ROIs during the warm semester May-October (1997-2011)

(a)

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<td>17.0</td>
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<td>32.2</td>
<td>39.4</td>
<td>27.4</td>
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(b)

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<td>37.0</td>
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Table III. Summary of the five cloudiest and cloudless weather types for each of the six ROIs.

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<tr>
<td>ROIs3</td>
<td>CSW CW W SW CNW</td>
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<tr>
<td>ROIs4</td>
<td>CSW CNE CN CW CE</td>
</tr>
<tr>
<td>ROIs5</td>
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<tr>
<td>ROIs6</td>
<td>CW CN CSW C CNE</td>
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Table IV. Summary of the five cloudiest and cloudless large-scale synoptic flows for each of the six ROIs.

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<th>NW_str</th>
<th>SW_str</th>
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<th>E_str</th>
<th>E</th>
<th>SE_str</th>
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<td>N_str</td>
<td>W_str</td>
<td>N</td>
<td>SE_str</td>
<td>E_str</td>
<td>S_str</td>
<td>S</td>
<td>E</td>
</tr>
<tr>
<td>ROIs3</td>
<td>SW_str</td>
<td>S_str</td>
<td>W_str</td>
<td>NW_str</td>
<td>SE_str</td>
<td>NE</td>
<td>W</td>
<td>E</td>
<td>SW</td>
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<td>NW_str</td>
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<td>SW</td>
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<td>NW</td>
<td>N</td>
<td>SW</td>
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<tr>
<td>ROIs6</td>
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<td>N</td>
<td>NE</td>
<td>E_str</td>
<td>S_str</td>
<td>SE_str</td>
<td>SW</td>
<td>W</td>
<td>SE</td>
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</tbody>
</table>
LIST OF FIGURES

Figure 1. (a) Map of the study area showing locations named in the text (rivers are shown as dashed lines); and (b) Wind direction at the 850 hPa level.

Figure 2. Convective cloud frequency composites for mid-afternoon orbits for (a) May-October for 1997-2011. The number of images averaged is shown in the lower-left corner (n = sample size). Dashed-lines represents (i) transect#1 (from South -ROIs5- to Northwest -ROIs1-) and (ii) transect#2 (from South -ROIs5- to Northeast –ROIs2-). ROIs are shown by black squares of 50x50 pixels, except for the isle of Mallorca. Maximum and minimum cloud frequency statistics for both the IP and the BI are shown in the lower-right corner for each figure.

Figure 2. Convective cloud frequency composites for mid-afternoon orbits for (b) May, (c) June, (d) July, (e) August, (f) September, and (g) October for 1997-2011. The number of images averaged is shown in the lower-left corner of each image (n = sample size). The inset graphs represent the spatial distribution of clouds (blue solid line) in relation to the orography (black dotted line) for (i) transect#1 (from South -ROIs5- to Northwest -ROIs1-) and (ii) transect#2 (from South -ROIs5- to Northeast –ROIs2-) shown as dashed-lines in Fig. 2a (May-October 1997-2011). ROIs are shown by black squares of 50x50 pixels, except for the isle of Mallorca. Maximum and minimum cloud
frequency statistics for both the IP and the BI are shown in the lower-right corner for each figure.

Figure 3a. Cloud frequency composites for mid-afternoon orbits for the nine anticyclonic and hybrid weather types during the 15-yr study period 1997-2011. The individual composites are arranged in a clockwise manner, starting with the A type (upper left corner) and followed by the AN, ANE, AE, ASE, AS, ASW, AW and ANW (lower right corner). The standard deviation computed for the number of images averaged ($n =$ sample size; in parenthesis the % of images with respect to the total 2094 cloud masks), and the mean, maximum and minimum cloud frequency statistics for both the IP and the BI are shown for each composite.

Figure 3b. As in Fig. 3a but for the cyclonic and hybrid weather types.

Figure 3c. As in Fig. 3a but for the directional weather types.

Figure 4. Box-and-whisker plots of cloud frequency for comparison between (i) the anticyclonic and hybrid (left part of each figure), (ii) the cyclonic and hybrid (centre), and (iii) the directional (right) weather types for each of the six ROIs. The mean (red line), the median (black line), the 25th and 75th percentile range (boxes), the 10th and
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Figure 5a. Spatial distribution of clouds for the A (red solid line) and C (blue solid line with dots) weather types in relation to the orography (black dotted line) for transect#1 (from South -ROIs5- to Northwest -ROIs1-) shown as dashed-line in Fig. 2a.

Figure 5b. Spatial distribution of clouds for the A weather types (upper graphs), the C weather types (medium graphs) and the D weather types (bottom graphs) in relation to the orography (black dotted line) for transect#1 (from South -ROIs5- to Northwest -ROIs1-) shown as dashed-line in Fig. 2a. Note that the 24 weather types have been grouped in pairs.

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Figure 5d. The same as Fig. 5b but for the transect#2 (from South -ROIs5- to Northeast -ROIs2-) shown as dashed-line in Fig. 2a.

Figure 6a. As in Fig. 3a but for the NE, E, SE and S synoptic-scale flows.
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Figure 8a. Spatial distribution of clouds for the light to moderate (red solid line) and strong (blue solid line with dots) wind regimes at 850 hPa in relation to the orography (black dotted line) for transect#1 (from South -ROIs5- to Northwest -ROIs1-) shown as dashed-line in Fig. 2a.

Figure 8b. As in Fig. 8a but for transect#2 (from South -ROIs5- to Northeast –ROIs2-) shown as dashed-line in Fig. 2a.
Figure 1. (a) Map of the study area showing locations named in the text (rivers are shown as dashed lines); and (b) Wind direction at the 850 hPa level.

206x248mm (300 x 300 DPI)
Figure 2. Convective cloud frequency composites for mid-afternoon orbits for (a) May-October for 1997-2011. The number of images averaged is shown in the lower-left corner (n = sample size). Dashed-lines represent (i) transect#1 (from South -ROIs5- to Northwest -ROIs1-) and (ii) transect#2 (from South -ROIs5- to Northest –ROIs2-). ROIs are shown by black squares of 50x50 pixels, except for the isle of Mallorca. Maximum and minimum cloud frequency statistics for both the IP and the BI are shown in the lower-right corner for each figure. 152x122mm (300 x 300 DPI)
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296x219mm (300 x 300 DPI)
Figure 3a. Cloud frequency composites for mid-afternoon orbits for the nine anticyclonic and hybrid weather types during the 15-yr study period 1997-2011. The individual composites are arranged in a clockwise manner, starting with the A type (upper left corner) and followed by the AN, ANE, AE, ASE, AS, ASW, AW and ANW (lower right corner). The standard deviation computed for the number of images averaged (n = sample size; in parenthesis the % of images with respect to the total 2094 cloud masks), and the mean, maximum and minimum cloud frequency statistics for both the IP and the BI are shown for each composite. 289x227mm (300 x 300 DPI)
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289x227mm (300 x 300 DPI)
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289x227mm (300 x 300 DPI)
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299x167mm (300 x 300 DPI)
Figure 5a. Spatial distribution of clouds for the A (red solid line) and C (blue solid line with dots) weather types in relation to the orography (black dotted line) for transect#1 (from South -ROIs5- to Northwest -ROIs1-) shown as dashed-line in Fig. 2a.

161x118mm (300 x 300 DPI)
Figure 5b. Spatial distribution of clouds for the A weather types (upper graphs), the C weather types (medium graphs) and the D weather types (bottom graphs) in relation to the orography (black dotted line) for transect #1 (from South -ROIs5- to Northwest -ROIs1-) shown as dashed-line in Fig. 2a. Note that the 24 weather types have been grouped in pairs.
231x221mm (300 x 300 DPI)
Figure 5c. The same as Fig. 5a but for the transect #2 (from South -ROIs5- to Northeast -ROIs2-) shown as dashed-line in Fig. 2a.

161x118mm (300 x 300 DPI)
Figure 5d. The same as Fig.5b but for the transect#2 (from South -ROIs5- to Northeast -ROIs2-) shown as dashed-line in Fig. 2a.

231x221mm (300 x 300 DPI)
Figure 6a. As in Fig. 3a but for the NE, E, SE and S synoptic-scale flows.

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205x310mm (300 x 300 DPI)
Figure 7. As in Fig. 4 but for each of the 16 synoptic-scale flow types.

300x155mm (300 x 300 DPI)
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Figure 8b. As in Fig. 8a but for transect #2 (from South -ROIs5- to Northeast -ROIs2-) shown as dashed-line in Fig. 2a.

298x122mm (300 x 300 DPI)