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**Multi-scale Observations of Atmospheric Moisture
Variability in relation to Heavy Precipitating Systems in the
north-western Mediterranean during HyMeX IOP12**

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3 **Multi-scale Observations of Moisture Variability in relation to Heavy Precipitating**
4 **Systems in the north-western Mediterranean during HyMeX IOP12**
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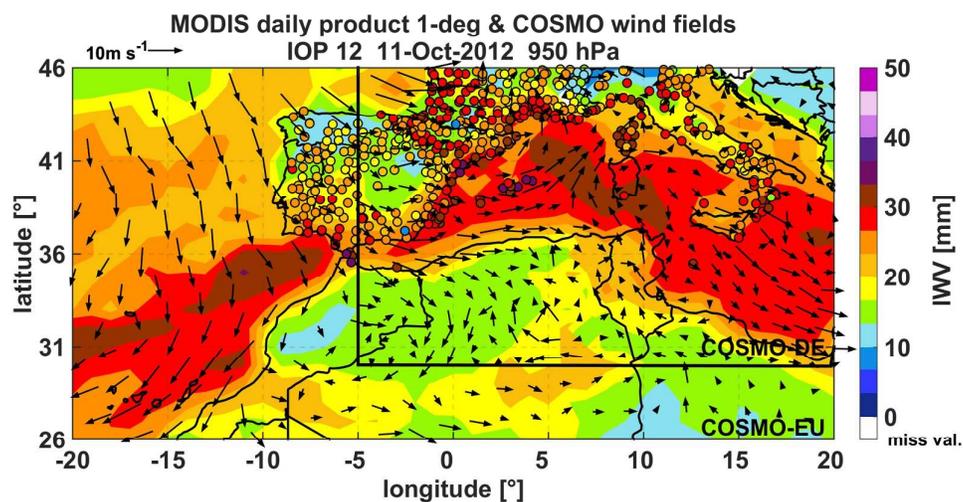
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This article investigates the spatio-temporal variability of atmospheric water vapour across scales in relationship with the occurrence of heavy precipitation systems in the north-western Mediterranean. Synergies between different instruments, Global Positioning System (GPS) stations, radiosondes, airborne and ground-based Lidars and space-borne observations from the Moderate Resolution Imaging Spectroradiometer (MODIS), among others, are used. High-resolution convection permitting simulations complement the observational network.



Daily mean spatial distribution of total column Integrated Water Vapour (IWV) from MODIS (background) and GPS (circles) observations. Simulated COSMO-7 km and COSMO-2.8km 950 hPa winds at 1200 UTC are superimposed.

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3 **Multi-scale Observations of Atmospheric Moisture Variability in relation to Heavy**
4 **Precipitating Systems in the north-western Mediterranean during HyMeX IOP12**
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Abstract

1 The deployment of special instrumentation for the Hydrological Cycle in the Mediterranean
2 Experiment (HyMeX) provides a valuable opportunity to investigate the spatio-temporal
3 variability of atmospheric water vapour across scales in relationship with the occurrence of
4 Heavy Precipitation Systems (HPSs) in the north-western Mediterranean (WMed) during the
5 Intensive Observation Period (IOP12), which is the focus of this investigation. High-
6 resolution convective permitting COSMO simulations complement the observational network
7 and allow the calculation of online trajectories.

8 In addition to the presence of a favourable large-scale situation and low-level convergence,
9 atmospheric moisture changes resulting in conditionally unstable air are identified as
10 responsible for convective initiation (CI). All HPSs within the north-WMed form in
11 periods/areas of maximum Integrated Water Vapour (IWV; $35\text{-}45\text{ kg m}^{-2}$) after an increase of
12 about $10\text{-}20\text{ kg m}^{-2}$. The most intense events receive moisture from different sources
13 simultaneously and show a sudden increase of about 10 kg m^{-2} between 6-12 h prior to the
14 event, whereas in the less intense events the increase is larger, about 20 kg m^{-2} , over a period
15 of at least 24 h-36 h. Changes in the lower ($\sim 900\text{ hPa}$) and mid-troposphere ($\sim 700\text{ hPa}$)
16 control the evolution of the atmospheric moisture and the instability increase prior to CI.
17 Spatial inhomogeneities in the lower boundary layer determine the timing and location of
18 deep convection, whereas enhanced moisture in the mid-troposphere favours intensification.
19 Moister and deeper boundary layers, with updraughts reaching up to 2 km are identified in
20 those pre-convective environments leading to HPS, whereas dry, shallow boundary layers are
21 found everywhere else. The build-up time and vertical distribution of the moisture changes
22 are found to be crucial for the evolution and severity of the HPSs rather than the amount of
23 total column atmospheric moisture.

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25 Key Words: HyMeX, Heavy Precipitation System, convection, multi-scale water vapour
26 variability, observations

For Peer Review

1. Introduction

Every year, the Mediterranean region is affected by high impact weather mainly in the form of Heavy Precipitation Systems (HPSs). These come often in the form of severe storms bringing, in addition to heavy precipitation and flooding, strong wind gusts, intense lightning, large hail and even tornadoes. Most of the HPSs with the accompanying flash floods occur between September and November and are caused mainly by Mesoscale Convective Systems (MCSs; Riosalido 1990).

Although the large-scale processes governing the occurrence of convection producing HPSs in the western Mediterranean (WMed) have long been studied and are generally well understood (e.g. Nuissier et al. 2008), there still are open questions concerning the role of enhancing factors affecting the initiation, the development, the type or the severity of convective storms. Among these, atmospheric water vapour is crucial for the occurrence of deep convection.

It is well known that besides a triggering mechanism, large-scale lifting and/or low level convergence allowing the release of the potential energy, small convective inhibition, and an conditionally unstable atmosphere, the main ingredient required for the occurrence of deep convection is a moist atmosphere (Doswell et al. 1996). Particularly relevant is the presence of sufficient moisture in the low- and mid-trosposhere (e.g. Khodayar et al 2010, 2013). The availability of moisture for precipitation is controlled by a number of processes including mixing on small scales, convective processes on different scales, and advection on the mesoscale and large-scale.

Former studies (e.g. Nuissier et al. 2011) pointed out that HPSs in the WMed often occur under the influence of a synoptic pattern that is quasi-stationary in time and favours a steady low-level moist flow towards the coast. This transport of moisture provides the large amounts of water vapour needed to feed the precipitating systems producing huge quantities of

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3 69 precipitation recorded during these events. Modelling studies in the last years also suggest
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5 70 that the main moisture sources for HPSs in the north-WMed are evaporation from North
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7 71 Africa, the Mediterranean and the Atlantic (e.g. Winschall et al. 2012; Duffourg and Ducrocq
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9 72 2013; Ramos et al. 2016). The time scale of the moisture transport was assessed to be about 2
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11 73 days for local sources, and 2 to 5 for contributions from the Tropics. Few observational
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13 74 investigations have been conducted to confirm these results (e.g. Chazette et al. 2016a; Lee et
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15 75 al. 2016). Furthermore, humidity shows large spatial and temporal variability on the
16
17 76 mesoscale (Crook 1996; Lauscaux et al. 2004; Weckwerth et al. 1996, 2000; Khodayar et al.
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19 77 2010, 2013, 2016a). The small-scale variations of humidity can directly influence convective
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21 78 initiation (CI), as well as its further development potential (Sherwood et al. 2010). Moisture
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23 79 variations of about 1 g kg^{-1} in the Planetary Boundary Layer (PBL) can make the difference
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25 80 between no initiation and intense convection (Crook 1996). Weckwerth et al. (1996) showed
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27 81 that this magnitude of variability occurs regularly in the PBL on distances of a few kilometres
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29 82 only.

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35 83 The combination of the various processes and scales discussed above results in a high
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37 84 variability in both space and time, whose exact knowledge is essential for both Numerical
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39 85 Weather Prediction (NWP; e.g. Weckwerth et al. 1999) and climate modelling (e.g. Bony et
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41 86 al. 2006). Advances have been achieved in the last years concerning convective processes
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43 87 modelling; however, the scarcity of water vapour observations at the mesoscale and smaller
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45 88 scales still hampers progress. The origin, pathways and time scales of transport of the large
46
47 89 amounts of moisture necessary for HPSs in the WMed are still open questions. Additionally,
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49 90 our understanding of the distribution, and variability of water vapour in relationship with
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51 91 convection is still far from being complete.

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56 92 Due to its importance, the characterization of water vapour has been a crucial aspect in the
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58 93 first of the two field campaigns of the Hydrological cycle in the Mediterranean Experiment
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60 94 (HyMeX; Drobinski et al. 2014). The Special Observation Period (SOP1; Ducrocq et al.

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3 95 2014) provided the unique opportunity of using the synergy of a dense network of
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5 96 observations, available on routinely basis, but homogenized for HyMeX, or especially
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7 97 deployed during the measurement campaign, to investigate the spatio-temporal variability of
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9 98 atmospheric water vapour in the north-WMed area in relationship with convection
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11 99 development. Previous studies analysed the consistency between the different water vapour
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13 100 data sets during the SOP1 (Chazette et al. 2016b). Few studies focused on the assessment of
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15 101 small-scale integrated water vapour (IWV) variability (< 10 km / < 1 day) and/or on the
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17 102 relationship between water vapour and precipitation systems on a larger-scale (> 1000 km / $>$
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19 103 1 day; e.g. Van Baelen et al. 2011; Winschall et al. 2012; Chazette et al. 2016a; Lee et al.
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21 104 2016, 2017).

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26 105 Using a multispatial scale approach, in this study, we use the synergy of moisture-measuring
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28 106 instruments available during the Intensive Observation Period 12 (IOP 12) to document the
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30 107 evolution and distribution of tropospheric water vapour in relation to the occurrence of HPSs
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32 108 in the north-WMed. Ground-based and airborne observations, as well as space-borne
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34 109 retrievals are combined to obtain a 3-D representation of atmospheric moisture. High-
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36 110 resolution convection permitting numerical weather prediction COSMO model simulations
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38 111 are used to complement the observations and the recent online trajectory module of COSMO
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40 112 helps us calculate online air parcel trajectories in relation with the convection activity in the
41
42 113 area. The goal of the present study is to investigate several aspects of the moisture variability-
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44 114 HPSs relationship during IOP12 in the north-WMed, (a) the variability of tropospheric water
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46 115 vapour and the ability of available observations to properly sample this on different scales,
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48 116 and (b) the role of water vapour as a precursor of heavy precipitation activity in the area. This
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50 117 paper is structured as follows: Section 2 outlines the experimental and modelling setup.
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52 118 Section 3 describes the synoptic situation that dominates over the investigation region
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54 119 between 9 and 14 October, as well as the convection activity and life cycle of the relevant
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56 120 storms in this period. The precipitation distribution, as well as the accompanying lightning
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3 121 activity, is also discussed. In Section 4, the pre-convective environment leading to HPSs in
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5 122 the investigation areas is assessed by detailed joint evaluation of observations and derived
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7 123 calculations. This part is followed by a detailed analysis of the spatial and temporal
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9 124 distribution of atmospheric humidity in Section 5. The transport, horizontal distribution and
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11 125 vertical stratification on different scales over the north-WMed are discussed. Section 6 closes
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13 126 this study with the summary of findings and conclusions.
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20 128 **2. Observational and modelling setup**

21 22 23 129 **2.1 Observations**

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26 130 Water vapour-related observations covering the north-WMed area between 9 to 14 October,
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28 131 including the IOP12, are used in this investigation, combining spaceborne and in situ
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30 132 observations from ground-based (Figure 1) and airborne platforms. A short description is
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32 133 provided in the following,
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36 134 (a) Spaceborne information

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39 135 • *Rapid Developing Thunderstorm product (RDT)*

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41 136 The RDT product is used in addition to lightning and precipitation information for a
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43 137 detailed analysis of the life cycle of convective storms during the selected investigation
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45 138 period. This product was developed by a team of specialists from the national
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47 139 meteorological institutes from Spain (AEMET), France (Météo-France), Sweden (SMHI)
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49 140 and Austria (ZMAG), as part of the Satellite Application Facility to support Nowcasting
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51 141 and Very Short range Forecasting (SAFNWC), hosted by the European Organisation for
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53 142 the Exploitation of Meteorological Satellites (EUMETSAT). It applies an algorithm to
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55 143 combine the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) onboard Meteosat
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57 144 second generation (MSG) and lightning data from ZEUS lightning detection network
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3 145 (operated by the National Observatory of Greece) to identify and track convective systems
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5 146 ranging from single isolated cells to mesoscale convective complexes (NWC SAF, 2014).
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8 147 The visualization tool developed by Météo-France uses colours to mark the development
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10 148 stadium of any identified storm. The available data is presented in an animated form in a
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12 149 15 min temporal resolution.

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15 150 • *Moderate Resolution Imaging Spectroradiometer (MODIS)*

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17 151 In this investigation, MODIS is utilized in order to study the IWV content of the
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19 152 troposphere from the radiance measurements performed by the imaging spectrometers on
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21 153 board the polar-orbiting platforms Terra (crossing the Equator at 1030 LT) and Aqua
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23 154 (crossing the Equator at 1330 LT). IWV is derived by applying an algorithm to IR spectral
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25 155 radiances retrievals obtained with clear sky conditions during either day or night-time
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27 156 (Gao and Kaufman 2003). The result is a highly spatially resolved gridded data set (5x5
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29 157 km) of IWV, mapping the whole Earth's surface every one or two days. The employed
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31 158 data set for this study is a daily average of both Terra and Aqua observations made
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33 159 available on a grid spacing of $1^{\circ} \times 1^{\circ}$.

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37 160 • *NOAA CPC Morphing Technique (CMORPH)*

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39 161 This product provides precipitation estimates during the investigation period in a gridded
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41 162 data set derived from microwave observation instruments placed in different low orbiter
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43 163 satellites. Microwave measurements from the Special Sensor Microwave Imager (SSM/I)
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45 164 aboard the Defence Meteorological Satellite Program satellites (DMSP-13, -14 and -15),
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47 165 the Advanced Microwave Sounding Unit-B (AMSU-B), on-board the National Oceanic
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49 166 and Atmospheric Administration spacecraft's (NOAA-15, -16, -17 and -18 spacecraft's),
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51 167 the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) of
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53 168 the Aqua spacecraft and the passive Microwave Imager of the Tropical Rainfall
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55 169 Measuring Mission satellite (TMI-TRMM) are combined by means of the Morphing
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57 170 Technique (Joyce et al. 2004). This procedure makes use of infrared derived motion

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3 171 vectors to propagate the microwave imagers' features to locations where no microwave
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5 172 data were obtained at a specific time (Stampoulis et al. 2013). This renders the technique
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7 173 flexible regarding its applicability to any microwave satellite source. In addition, it offers
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10 174 a wide coverage (60°S to 60°N), and a high temporal and spatial resolution, 30 minutes
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12 175 and 8 km at the Equator. The data set is produced by the Climate Prediction Center (CPC)
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14 176 of the National Weather service (NWS) of the USA and covers the period between 1998
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17 177 and 2015.

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20 178 *(b) Ground-based information*

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23 179 • *Radiosondes*

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25 180 Measurements from about 25 radiosounding stations in the HyMeX investigation area
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27 181 (Figure 1) are used for this research effort. On a regular basis, these measurements
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29 182 provide atmospheric profile information at least twice a day (0000 UTC and 1200 UTC).
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31 183 During SOP1, several of these stations either launched additional sondes at 0600 and 1800
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33 184 UTC and/or conducted high-resolution soundings (meaning here the vertical sampling of
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35 185 the collected data being less than 1 hPa (about 100 vertical levels) in comparison to
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37 186 regular soundings with generally about 20 vertical levels), all in order to provide a more
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39 187 detailed picture of the vertical distribution of atmospheric variables prior to and during the
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41 188 IOPs. Among these, seven stations were newly established for the purposes of the HyMeX
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43 189 SOP1 campaign.

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46 190 The network of radiosonde stations is additionally used to calculate convection-related
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48 191 parameters as indicators of the atmospheric degree of stability/instability, namely the
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50 192 Convective Available Potential Energy (CAPE; Moncrieff and Miller 1976), the
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52 193 Convective Inhibition (CIN; Colby 1984) and the KO-index (Andersson et al. 1989). The
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54 194 KO-index is estimated based on the equivalent potential temperature at 500, 700, 850 and
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56 195 1000 hPa (following the recommendations by Bolton 1980), it describes the potential of

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3 196 deep convection to occur as a consequence of large-scale forcing (Andersson et al. 1989;
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5 197 Khodayar et al. 2013). Generally, regions with KO-index < 2 K and large-scale lifting are
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7 198 identified as favourable for deep convection. Parcel theory (50 hPa ML (Mixed Layer)
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9 parcel) and virtual temperature correction (Doswell and Rasmussen 1994) are applied to
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12 200 these calculations.

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15 201 • *Ground-based GPS*

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18 202 A dense network of Global Positioning System (GPS) stations, which provide IWV
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20 203 information, covering the north-WMed were jointly reprocessed by IGN LAREG (Institut
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22 204 National de l'Information Géographique et Forestière - Laboratoire de Recherche en
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24 205 Géodésie) and e-GEOS S.p.A., ASI/CGS (Agenzia Spaziale Italiana/Centro di Geodesia
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26 206 Spaziale) and made available for the HyMeX scientific community (Bock et al. 2016).
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28 207 One of the highlights of this dataset is its dense and large coverage, provided it was
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30 208 obtained by commonly processing the raw measurements of 25 European, national and
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32 regional GPS networks. The post-processing GIPSY/OASIS II v6.2 software was used to
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34 209 process the total delays in the zenith direction (ZTD) and surface level pressure and mean
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36 210 temperature at the stations location were obtained from the AROME model in its west-
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38 211 Mediterranean configuration (AROME-WMED) and ERA-Interim analysis respectively.
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40 212 The dataset is available up to a 5 minute temporal resolution (the nominal sampling
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42 213 frequency) and also in 1-hourly and 3-hourly averaged data sets. In this study, the 1-
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44 214 hourly averaged product is used.
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51 216 • *Boundary Layer pressurized balloons (BLBP)*

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54 217 Lagrangian trajectories of specific humidity, temperature, pressure and horizontal wind
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56 218 can be obtained by means of Boundary Layer Pressurized Balloons (BLPBs) flying at a
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58 219 nearly constant height (Doerenbecher et al. 2016). For HyMeX SOP1, the Centre National
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60 220 d'Études Spatiales (CNES) measured and processed the *BLPB BAMED SOP1* dataset

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3 221 which is made available in 2.5 minute averages of 30-second samples, excluding time
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5 222 windows with less than four measurements available. The different launch dates were
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7 223 selected according to the forecasted conditions which were most propitious to reach
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9 224 targeted heavy precipitation areas during the campaign. Specifically, for IOP12 a total of
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11 225 4 balloons were launched from the Mahon site ($4^{\circ} 15' - 39^{\circ} 51'$; Balearic Islands); two on
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13 226 the 11 October 2012, at ~ 0200 and 0400 UTC and two on the 14 October 2012, at 0600
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15 227 and 0800 UTC, respectively. An inter-comparison between water vapour mixing ratio
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17 228 derived from the BLPB trajectories and that obtained from the ground-based water vapour
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19 229 Raman Lidar (WALI) showed a root mean square error of less than 1.3 g kg^{-1} for the
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21 230 SOP1 period over the Balearic Islands (Chazette et al. 2016b). This highlights the good
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23 231 quality of the humidity measurements.

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29 232 • *Ground-based Raman lidars BASIL (Candillargues) and WALI (Menorca)*

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31 233 The Raman Lidar BASIL (Di Girolamo *et al.* 2006, 2009a) is very effective in the
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33 234 characterization of atmospheric temperature and water vapour mixing ratio profiles
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35 235 throughout the troposphere, both in daytime and night-time conditions, providing accurate
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37 236 and high time- and space-resolution measurements of these two thermodynamic
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39 237 parameters, with the main goal of characterizing the water vapour inflow in the Gulf of
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41 238 Lion, which is heavily feeding precipitating systems. The system was deployed in an
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43 239 atmospheric ‘supersite’ located in Candillargues (43°N , 4°E , elevation: 1m) and operated
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45 240 from 5 September to 5 November 2012 (Figure 1). Besides atmospheric temperature and
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47 241 water vapour, BASIL also provides measurements of particle backscatter at 355, 532 and
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49 242 1064 nm, particle extinction at 355 and 532 nm, and particle depolarization at 355 and
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51 243 532 nm (Di Girolamo *et al.* 2009b, 2012). During HyMeX-SOP 1, water vapour mixing-
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53 244 ratio measurements were calibrated based on the comparison with the simultaneous
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55 245 radiosondes, with the radiosonde launching facility being located approximately 100 m
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3 246 south-east of the lidar station. A mean calibration coefficient for water vapour mixing
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5 247 ratio measurements was estimated based on approximately 50 comparisons.
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8 248 The Water Vapour Lidar (WALI) described in Chazette et al. (2014) is additionally used
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10 249 to monitor the water vapour mixing in the lower troposphere over the WMed during the
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12 250 period of interest. The lidar was located in La Ciutadella (40°00'00" N and 3°50'20"E) on
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14 251 Menorca Island (Spain, see Figure 1). The measurement protocol is explained in Chazette
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16 252 et al. (2016b). During HyMeX SOP1, the absolute deviation between the water vapour
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18 253 mixing ratio profiles from WALI and derived from meteorological balloon soundings
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20 254 launched from Palma de Mallorca was assessed to be less than 0.5 g kg^{-1} for a vertical
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22 255 resolution of 30 m. The maximum range of the zenith-pointing lidar was ~6-7 and 1 km
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24 256 during night-time and daytime, respectively, depending on the atmospheric transmission,
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26 257 mainly limited by the presence of aerosols or/and clouds.
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31 258 • *Lightning Network*
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34 259 The European Cooperation for LIghtning Detection (EUCLID 2014) is a collaboration of
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36 260 national lightning detection networks with the aim to identify and detect lightning all over
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38 261 Europe. Within our investigation area, 32 sensors from different networks are positioned.
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40 262 All the lightning data are detected by means of electromagnetic sensors, which send raw
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42 263 data to a central analyser. Each sensor detects the electromagnetic signal emitted by the
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44 264 lightning return stroke. This technology uses GPS satellite signals for time information.
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46 265 For each lightning stroke, the main parameters are recorded, namely, the time of the event,
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48 266 the impact point (latitude and longitude), the current intensity and polarity, and the
49
50 267 number of subsequent strokes. This data provides information about the position and even
51
52 268 intensity of isolated and organised convective systems.
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57 269 (c) *Airborne Information*
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- 270 • *Airborne lidar LEANDRE 2 on board of ATR-42*

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3 271 The airborne differential absorption lidar (DIAL) LEANDRE 2 was installed on board the
4
5 272 ATR-42 aircraft of Service des Avions Français Instrumentés pour la Recherche en
6
7 273 Environnement (SAFIRE), which operated from the Montpellier airport during SOP1
8
9
10 274 (also see Chazette et al. 2016b; Di Girolamo et al. 2016; Lee et al. 2016, among others).
11
12 275 Details concerning the design of LEANDRE 2 and the standard DIAL signal processing
13
14 276 procedure are given in Bruneau *et al.* (2001a, 2001b). During IOP12, LEANDRE 2 was
15
16 277 operated mostly in zenith-pointing mode, except for a small portion of the flight
17
18 278 performed over the Gulf of Lion on 11 October when it performed nadir-pointing
19
20 279 observations. LEANDRE 2 carries out water vapour mixing ratio measurements with a
21
22 280 precision ranging from less than 0.1 g kg^{-1} at 4.5 km above sea level to less than 0.4 g
23
24 281 kg^{-1} near the surface for an along-beam resolution of 150 m and accumulation of 100
25
26 282 individual profiles, corresponding to an along-track resolution of approximately 1 km for
27
28 283 an ATR-42 flying speed of 100 m s^{-1} . Systematic errors associated with the LEANDRE 2
29
30 284 system are typically not exceeding 0.1 g kg^{-1} (Bruneau et al. 2001b).

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35 285 • *Do-128*

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37 286 Do-128 (Corsmeier et al. 2001) flew mainly around and over Corsica from 11 September
38
39 287 to 11 October 2012 as a part of the Karlsruhe Institute of Technology (KIT) participation
40
41 288 in HyMeX-SOP 1. It is equipped with instruments (in a nose boom attached on the front)
42
43 289 for measuring air temperature, humidity, wind direction and speed, among others.

44
45
46 290 **2.2 COSMO model and online trajectory module**

47
48
49 291 The non-hydrostatic limited-area weather prediction model Consortium for Small-scale
50
51 292 Modelling (COSMO), developed by the German Weather Service (DWD, Shättler et al.
52
53 293 2008), is employed in this investigation with horizontal grid spacing of about 7 km and
54
55 294 2.8 km, and 40 and 50 vertical levels, respectively. COSMO-2.8 km explicitly resolves deep
56
57 295 convection (Weisman et al. 1997) and shallow convection is parameterized with the help of
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1
2
3 296 the reduced Tiedtke scheme (Tiedtke 1989), whereas in COSMO-7 km convection is
4
5 297 parameterized with the Tiedtke scheme (Tiedtke 1989). Details about the setup for all
6
7 298 physical parameterizations are found in Baldauf et al. (2011). The European Centre for
8
9 299 Medium-Range Weather Forecasts (ECMWF) analysis data with a horizontal resolution of
10
11 300 about 0.25° is used as initial and boundary conditions for the COSMO-7 km run, while this is
12
13 301 used as forcing for the higher resolution COSMO-2.8 km. The COSMO-7 km and 2.8 km
14
15 302 model domains extend from about 15°W to 22°E - 25°N to 50°N and 10°W to 20°E - 30°N to
16
17 303 46°N , respectively.

21
22 304 Online Lagrangian trajectories based on grid-scale wind velocities are used to study
23
24 305 mesoscale flows in the COSMO model (Miltenberger et al. 2013). The Lagrangian depiction
25
26 306 of atmospheric processes largely contributed in the last years to advance our understanding.
27
28 307 Lagrangian studies allowed the identification of atmospheric rivers (e.g. Ramos et al. 2015;
29
30 308 2016) and warm conveyor belts (WCB; e.g. Wernli and Davis 1997), the evaporative and
31
32 309 moisture water sources for precipitation (e.g. Sodemann et al. 2008; Liberato et al. 2012) or
33
34 310 the origin of air parcels feeding convective cells (e.g. Wang and Xue 2012). We use in this
35
36 311 study the online Lagrangian trajectories module of COSMO to assess the most likely origin
37
38 312 and path of air parcels contributing to the occurrence of HPS during the IOP12 on the WMed.

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42
43 313 A great advantage of the online trajectory contrary to any other offline option is the
44
45 314 calculation of the trajectory with wind field inputs at every model time step (~ 25 s for the
46
47 315 high-resolution simulations, this value shortens with increasing model resolution), whereas
48
49 316 offline trajectories are calculated with temporal resolutions from 1 h to 6 h. Because of the
50
51 317 forward computation of the online trajectories, the specification of the starting points is not a
52
53 318 trivial task. A priori knowledge of the interesting starting regions and times is required.
54
55 319 Following Duffourg and Ducrocq (2013) we started the simulation about 4 days before
56
57 320 intense convection activity in the north-western Mediterranean to consider the moisture of the

1
2
3 321 low-level feeding flow provided by evaporation over the Mediterranean and the transport
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5 322 from remote sources such as the Atlantic Ocean and/or Africa. The whole simulation period
6
7 323 covers the 8 October 2012 to the 16 October 2012. To avoid missing relevant information we
8
9 324 start trajectories every 0.5° over the entire investigation domain every 12 h starting 4 days
10
11 325 before the event. In total more than 50000 trajectories are calculated. To identify from all
12
13 326 estimated trajectories the contributing air parcels to each HPS and their origins the following
14
15 327 criteria are applied, (a) all air parcels are started 10 m over the surface to capture moisture
16
17 328 uptake regions. We assume that at this height the trajectories start in the boundary layer and
18
19 329 trajectories intersection with the terrain is avoided (Miltenberger et al. 2013), (b) air parcel
20
21 330 trajectories have to reach at least ~ 7000 m (Wernli 1997), and (c) air parcels have to release
22
23 331 at least 5 g kg^{-1} of the specific humidity in a 6-hour interval within the target area (Winschall
24
25 332 et al. 2014; Sodemann et al. 2008; James et al. 2004).

333

334 **3. Meteorological situation**

335 **3.1 Large-scale situation**

336 The synoptic situation over the Mediterranean area during the analysed period was generally
337 dominated by a long-wave trough that approached from the west and remained over the
338 Iberian Peninsula for several days, producing favourable conditions for the development of
339 deep moist convection (Figure 2).

340 On 9 October, the WMed was under the influence of a slowly weakening ridge receding
341 before the appearance of a trough approaching from the eastern Atlantic, which developed
342 from a cut off low that moved across the ocean in the previous days (Figure 2a). It merged
343 with a quickly approaching and elongating trough over the north-western Atlantic in the
344 course of 10 October. On the following day, the trough over the Atlantic moved further south-

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2
3 345 eastwards (at 0000 UTC its axis stretched along the western Iberian coast). Until late 11
4
5 346 October, a weak low-pressure area moved eastwards along the southern French coast reaching
6
7 347 the Gulf of Genoa (Figure 2b). To the west of it, in the upper levels, a well pronounced short-
8
9 348 wave trough simultaneously crossed that area, advecting warm and humid air from over the
10
11 349 sea. Ahead of it moved an area of strong local lifting (between 20 and 40 hPa in 6 hours). A
12
13 350 slight Potential Vorticity (PV) anomaly that accompanied this short-wave trough (not shown)
14
15 351 additionally strengthened the already existing instability. During the day, the long-wave
16
17 352 trough moved further eastwards so that around 1800 UTC its major axis lay across central
18
19 353 France and the eastern coasts of Spain. It was swiftly followed by another secondary trough
20
21 354 approaching from the west. On 12 October, this secondary trough was located already on the
22
23 355 eastern side of the long-wave trough, crossing over Corsica, central Italy and the Balkan. At
24
25 356 0000 UTC, the weak surface low with accompanying fronts was located over the Gulf of
26
27 357 Genoa, in the area of strong convective activity of IOP12. It moved ahead of this secondary
28
29 358 trough, slightly weakening on its way, and reached the Balkan around midnight. Its presence
30
31 359 was related to strong convective activity as well as an HPS over central and southern Italy, as
32
33 360 well as over the Adriatic Sea. Westerly and north-westerly mid-tropospheric winds brought in
34
35 361 humid air. The upper level pattern from the previous day remained almost unchanged on 13
36
37 362 October (Figure 2c). The axis of the main long-wave trough moved further east and, by
38
39 363 approximately 1800 UTC, stretched along the western Italian coast.

364 **3.2. Convective activity**

365 Between 9 and 13 October 2012, covering the IOP12 period (11 and 12 October), the
366 convective activity in the WMed was very intense. During these days convective activity was
367 observed to move eastwards (Figure 3, Table 1).

368 Intense convective activity on 10 October was initiated in the early afternoon in the form of
369 several storms over central Spain. One of these, with the longest life span, started at ~ 1345

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3 370 UTC some 100 km to the west of Madrid and moved in the north-eastward direction. At ~
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5 371 2000 UTC, it began to weaken but approximately two hours later it merged with a newly
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7 372 developed storm, whereupon it turned south-east towards the north-eastern Spanish coast
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9 373 from where it continued eastwards until it dissipated over the sea at ~0945 UTC on the
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11 374 following day (marked "A"; Figure 3a). It lasted for about 19.5 h and its anvil grew in this
12
13 375 time to almost 39000 km². This storm produced relatively moderate amounts of precipitation,
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15 376 i.e. 50 mm of 24-h accumulated precipitation measured by rain gauges and CMORPH
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17 377 estimates, which occurred only over land. Lightning activity in this area was strong
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19 378 throughout the whole convective period, which lasted till the end of the day (Figure 4a).
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23 379 The main IOP12 MCS developed in the evening of 11 October over the north-WMed as two
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25 380 initially independent storms. By looking at the 15-min radar reflectivity scan images for this
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27 381 particular analysis (not shown), it could be observed that one of these storms (marked "B1" in
28
29 382 Figure 3b) initiated at ~1930 UTC also as two separate convective cells, one over the eastern
30
31 383 French Riviera and the other some 30 km to the south of it over the sea. The second storm
32
33 384 (marked "B2") resulted from the merging of three smaller cells, which occurred at ~ 2100
34
35 385 over the sea some 100 km to the west of Corsica. Before it happened, numerous single-cell
36
37 386 storms developed in the zone between the Balearic Islands and Corsica from approximately
38
39 387 1800 UTC embedded within and moving eastwards with a broad cloud band stretching from
40
41 388 southern France to northern Africa. Before those two main storms merged to form a MCS
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43 389 (marked "C"), the northern one lasted for about 7 hours growing up to 37000 km² and the
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45 390 southern one for around 4.5 hours reaching over 23000 km² cloud top surface. At around
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47 391 midnight, both storms merged creating a cluster with the anvil's area of over 130000 km².
48
49 392 CMORPH captured the initiation of the main IOP12 MCS as two separate storms (not
50
51 393 shown), which produced high and spatially concentrated amounts of precipitation (up to 75
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53 394 mm in 6 hours); precipitation visibly diminished as the storms merged and propagated
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55 395 eastwards developing in to the main IOP12 MCS existing till the early morning hours of 12
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3 396 October (Figure 4b). Storm "D" (Figure 3c) started as two cells between Corsica and Italy at
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5 397 around 0200 UTC on 12 October and within the following hour it merged with a storm over
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7 398 central Italy, which developed shortly before midnight on 11 October. In its 8-h-long life it
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9 399 crossed central Italy in south-eastern direction and grew up to 93000 km². This MCS was
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11 400 responsible for the HPS over central Italy on that day. On 12 October, an area of strong
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13 401 precipitation could be observed over the vast region stretching between Corsica, Sicily and
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15 402 the Balkan Peninsula, which was directly connected with the activity of the IOP12 MCSs
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17 403 (Figure 4c). Rain gauges in central Italy measured over 150 mm in about six hours, but about
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19 404 75 mm over the eastern Spanish coast, Majorca and Sicily. According to CMORPH data, the
20
21 405 convective storms over the south-WMed also caused HPSs, during which over 150 mm
22
23 406 precipitation could be measured in a period lasting between 6 and 12 hours. The lightning
24
25 407 pattern shows that dense lightning activity was present everywhere between southern France
26
27 408 and northern Sardinia where the main MCS developed. On 13 October convection occurred
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29 409 over the south-western and central Mediterranean (including northern Africa, southern Italy
30
31 410 and the Balkan area); however only over Sicily did a MCS develop and remained active and
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33 411 intense in the second half of the day (marked "M" in Figure 3d) producing about 50 mm
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35 412 accumulated precipitation over land in about 6 hours (Figure 4d), but more than 150 mm rain
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37 413 over the sea within the same time period (not shown). The lightning data show that the
38
39 414 majority of storms over the south-western and southern Mediterranean were merely
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41 415 continuations of convective activity that initiated on the previous day. Most of them were
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43 416 moving in the eastern direction and dissipated in the early afternoon.
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54 418 **4. Daily cycle of convection-related atmospheric conditions**

57 419 An assessment of the temporal evolution and potential dependencies of convection-related
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59 420 atmospheric conditions on sub-daily scale for those areas where HPS occurrence was

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3 421 registered is shown in Figure 5. The following areas are considered, Area1 covers the north-
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5 422 eastern Iberian Peninsula, Area2 covers Corsica, Area3 is located in central Italy, and Area4
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7 423 includes Sicily in southern Italy (Figure 1). We are particularly interested in assessing the
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9 424 similarities and differences between the Areal preconditions leading to heavy precipitation.
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11 425 For each region hourly lightning sums using cloud-to-ground lightning data measured by the
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13 426 EUCLID network, as well as the hourly rain rates from CMORPH measurements are
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15 427 considered. We selected one representative radiosounding station for each area (Barcelona for
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17 428 Area1, Figure 5a; KIT-INRA for Area2, Figure 5b; Pratica Di Mare for Area3, Figure 5c;
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19 429 Trapani Birgi for Area4, Figure 5d; positions of the radiosoundings are in Figure 1) to study
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21 430 atmospheric stability and humidity stratification. The radiosounding profile information were
22
23 431 used to compute CAPE, KO-index, CIN, as representative of atmospheric instability and
24
25 432 inhibition conditions and the mean relative humidity (RH) averaged in the layer between 850
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27 433 and 700 hPa, as a measurement of the humidity content in the mid-troposphere. Additionally,
28
29 434 we included the IWV data from the nearest GPS stations (all located at similar heights; Figure
30
31 435 1), which provided information on the humidity contained in the entire troposphere above the
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33 436 station with 1 hourly temporal resolution.

34
35 437 The general picture confirms a shift of convective activity and moisture maxima from west to
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37 438 east. Lightning activity was well correlated with maxima of precipitation as an indicator of
38
39 439 deep convection in agreement with previous observations (Soriano et al. 2001). In all cases
40
41 440 the convective activity occurred in periods of maximum IWV (~ 30 to 45 kg m^{-2}). An upper
42
43 441 threshold of about 45 kg m^{-2} was identified. Total column atmospheric humidity experiences a
44
45 442 notable increase prior to HPSs, mostly in relationship with a change, up to 5 g kg^{-1} , in the
46
47 443 lower and mid-levels of the atmosphere (below 700 hPa). The upper atmospheric levels
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49 444 (above ~ 500 hPa; not shown) do not reveal any significant variation. Changes in the lower-
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51 445 troposphere in the pre-convective environment were associated to winds predominantly from
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3 446 the south-southwest and from the west in the layers above. Those stations with higher
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5 447 moisture content in the lower troposphere reveal a lower Lifting Condensation Level (LCL)
6
7 448 and a smaller difference between the LCL and the Level of Free Convection (LFC), which is
8
9 449 conducive to a more rapid formation of thunderstorms (not shown). For example, an increase
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11 450 of about 4 g kg^{-1} in the lower PBL moisture, registered at southern France (NIM
12
13 451 radiosounding station) prior to CI resulted in a decrease of LCL-LFC from $\sim 175 \text{ hPa}$ on 10
14
15 452 October 1200 UTC to $\sim 50 \text{ hPa}$ on 11 October 1200 UTC. Furthermore, directly related with
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17 453 the increase of moisture in the lower tropospheric levels an increase in atmospheric instability
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19 454 and a decrease in atmospheric inhibition are also identified prior to HPSs.

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23 455 In the mid-troposphere the relative humidity was very high, $> 75 \%$, in all deep convection
24
25 456 events leading to HPSs. Observations of the convective evolution in Area1, after the main
26
27 457 event, show a dry mid-troposphere inhibiting deepening of convective systems despite a
28
29 458 further low-tropospheric moisture increase. This supports previous investigations which
30
31 459 showed that high amounts of moisture in the mid-troposphere, which could be also due to
32
33 460 convection itself, favour deepening of convection and precipitation intensity and its absence
34
35 461 constrains its evolution (e.g. Khodayar et al. 2010; Lee et al. 2016). Similar developments are
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37 462 identified in the pre-convective environments of all stations affected by HPSs, which
38
39 463 evidences the crucial role of water vapour horizontal distribution and stratification on the
40
41 464 initiation and intensification of convection.

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44
45 465 In all cases except Area4, the period of severe convection activity was followed by a humidity
46
47 466 decrease (back to values observed at least 24-h prior to CI) resulting from boundary layer
48
49 467 winds turning their direction to westerly. The advection of dry air, thus, the moisture decrease
50
51 468 was concomitant with an equivalent potential temperature decrease and an increase in
52
53 469 atmospheric stability ($\text{CAPE} \sim 0 \text{ J kg}^{-1}$; $\text{KO-index} \sim 1 \text{ K}$), not favouring further intensification
54
55 470 of convection and suppressing any possibility of CI. In Area4, westerly and south-westerly
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57 471 winds continued advecting moist air over southern Italy after the main convection activity

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3 472 developed in the area, which resulted in a further initiation of deep moist convection in this
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5 473 region on 13 October, primarily affecting the Balkans.
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8 474 Despite the important commonalities listed above relevant differences are identified regarding
9
10 475 the build-up time period of the moisture changes and the resulting vertical stratification.
11
12 476 Figure 6 helps us illustrate these findings showing the interdependence between atmospheric
13
14 477 instability and atmospheric moisture changes with respect to convective evolution at two of
15
16 478 the affected areas/radiosounding stations, Area1/Barcelona (deep convection was observed at
17
18 479 about 11 October at 0000 UTC; max prec ~ 50 mm day⁻¹) and Area4/Trapani Birgi (a MCS
19
20 480 developed in the morning and maintained until mid-day on 13 October; max prec ~ 200 mm
21
22 481 day⁻¹). Despite a strong Areal increase of IWV ~ 20 kg m⁻² prior to CI, maximum local
23
24 482 precipitation in Area1 did not exceed 50 mm day⁻¹ (this is the area registering the lowest
25
26 483 precipitation rates). This increase occurred in a period of 36 h and maximum IWV values
27
28 484 were up to 45 kg m⁻². All atmospheric levels up to 500 hPa were affected, particularly the
29
30 485 mid- and low-atmosphere. In this 36 h period, an increase of about 3 g kg⁻¹ was observed in
31
32 486 the 900 \pm 50 hPa layer in the last 24 h, the same increase occurred in the 700 \pm 50 hPa layer but
33
34 487 only in the first 12 h. With the increasing moisture the atmosphere became more unstable, as
35
36 488 testified by the raising CAPE values to about 1200 J kg⁻¹ (decreasing KO-index to -10 K).
37
38 489 Contrary to the observed increase in Area1 the episode of moisture build-up over Area4 was
39
40 490 rather sudden (about 10 kg m⁻² in ~ 12 h), short-lived (duration of maximum about 12 h) and
41
42 491 the maximum IWV did not reach more than ~ 35 kg m⁻², ~ 10 kg m⁻² lower than in Area1. In
43
44 492 this area the most intense precipitation event was registered, maximum precipitation of about
45
46 493 200 mm in 6 hours was measured around 1200 UTC on 13 October. In contrast to the other
47
48 494 regions considered, a rapid and significant moisture increase of about 5 g kg⁻¹ in 6 h
49
50 495 characterizes the low-troposphere (in Area1 the same maximum in the lower-PBL was
51
52 496 reached after a 24 h period), while a weaker change occurs in the mid-troposphere. This
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3 497 resulted in very high CAPE values of about 2000 J kg^{-1} , KO-index $\sim -14 \text{ K}$, in a period where
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5 498 no CIN constrains deep convection in the area.
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7
8 499 A similar situation is observed in Area2 and Area3, in which the IWV increase was sudden
9
10 500 and rather quick, $\sim 12 \text{ h}$, and the atmosphere did not remain this moist for more than $\sim 12 \text{ h}$
11
12 501 and did not exceed 35 kg m^{-2} . In Area2, between the surface and 700 hPa a specific humidity
13
14 502 increase over 3 g kg^{-1} is registered. Moderate CAPE $\sim 500 \text{ J kg}^{-1}$, and KO-index $\sim -9 \text{ K}$
15
16 503 suggest that deep convection is possible in the area only under strong large-scale forcing. In
17
18
19 504 Area3, the specific humidity increased by some 3.5 g kg^{-1} on average between 750 and 600
20
21 505 hPa, whereas an increase of about 2 g kg^{-1} is identified below 900 hPa resulting in a sudden
22
23 506 increase of CAPE to $\sim 800 \text{ J kg}^{-1}$. The combination of these changes with the lack of
24
25 507 atmospheric inhibition, CIN $\sim 0 \text{ J kg}^{-1}$, favoured deep convection and intense precipitation in
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27
28 508 the area. More than 150 mm in 6 h were measured in the area.
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32 33 510 **5. Moisture transport and distribution over the north Western Mediterranean**

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37 511 To complement the information provided by the single observations regarding the evolution
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39 512 of moisture with respect to convective activity in the selected subdomains, a combination of
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41 513 MODIS and GPS-derived IWV (Figure 7) and observations from the two ground-based water
42
43 514 vapour Raman Lidars, WALI at Menorca (Balearic Islands) and BASIL at Candillargues
44
45 515 (Southern France; Figure 10) and from the BLPBs (Figure 11a) and the airborne water vapour
46
47 516 lidar (Figure 11b,c,d) are investigated. These measurements should complement each other
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49
50 517 and their joint evaluation is expected to provide an improved representation of atmospheric
51
52 518 moisture variability and its implication for convective activity on different spatiotemporal
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55 519 scales.
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3 521 The combination of MODIS and GPS-derived IWV allows the reconstruction of the spatial
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5 522 distribution of tropospheric water vapour over a large area, being a well-known limitation of
6
7 523 observational networks such as the GPS (Khodayar et al. 2016b). To jointly evaluate both
8
9 524 data sets, comparisons have been performed at the location of each GPS-station. Maximum
10
11 525 differences of about 2 kg m^{-2} have been found, which could be related with cloud
12
13 526 contamination in the MODIS IR data (dry bias) and with the time sampling differences. No
14
15 527 bias correction has been applied in this case. This information is combined with simulated
16
17 528 high-resolution, 7 km and 2.8 km, COSMO winds at different levels (500, 700, 850, 950 hPa
18
19 529 and 10 m), in order to assess the most likely transport path of the atmospheric moisture during
20
21 530 IOP12. Furthermore, the computation of the COSMO online Lagrangian trajectories helped us
22
23 531 to further assess the trajectories that air parcels mostly contributing to the HPS followed
24
25 532 serving as a qualitative indicator of the most likely transport pathway (Figure 8a) and origin
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27 533 (Figure 8b) of moisture.

28
29 534 On the 9 October 2012, MODIS-derived IWV shows two hot-spots with IWV values reaching
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31 535 about 50 kg m^{-2} , over the Atlantic – between Portugal and north-Africa – and east of Tunisia
32
33 536 (Figure 7a). Following the south-westerly transport of humid air from the Atlantic towards the
34
35 537 centre and north of the Iberian Peninsula a gradual humidity surge of about 10 kg m^{-2} could
36
37 538 be observed throughout the day, from about 25 to 35 kg m^{-2} . On 10 October, moisture
38
39 539 advection continues over the Iberian Peninsula and the moisture amount over the already
40
41 540 relatively humid Mediterranean ($30 - 35 \text{ kg m}^{-2}$) rose up to 45 kg m^{-2} forming a humid zone
42
43 541 along the eastern Spanish coast bending eastward across the Balearic Sea up to Sardinia
44
45 542 (Figure 7b). Instability began to increase over the Iberian Peninsula, reaching CAPE values of
46
47 543 ca 1000 J kg^{-1} and KO-index of about $-15 \text{ K over Barcelona}$ (Figure 9a). The first storms
48
49 544 initiated over this area (Figure 3a) in the presence of some moderate CIN over Barcelona (ca
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51 545 80 J kg^{-1}) and a relatively strong one (250 J kg^{-1}) over Zaragoza, about 250 km apart. Several
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53 546 orographically induced convergence lines formed over central and eastern Spain on that day,
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3 547 some as early as 12 h prior to the formation of the first storms in the region. The position of
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5 548 these convergence lines did not change much during the day, but winds became stronger as
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7 549 the day progressed (a change from 1 to about 8 m s^{-1} was measured). This low-level wind
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9 550 convergence in addition to the presence of large scale lifting of about 20 hPa h^{-1} acted as
10
11 551 triggering mechanisms in the area. KO-index in the order of -15 to -20 K and high CAPE (\sim
12
13 552 900 J kg^{-1}) in combination with no CIN occur also over Corsica, in agreement with high
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15 553 moisture values observed e.g. at the INRA radiosounding station (Figure 5b). However, no
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17 554 convection developed in this area due to the absence of a triggering mechanism, contrary to
18
19 555 the previous situation on the north-eastern Spain.

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23 556 The eastward transport of moist air continued on 11 October (Figure 7c). This eastward
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25 557 gradual moisture increase was strongly correlated (spatially and temporarily) with the moist
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27 558 air advection associated with the surface low accompanied by the shortwave trough aloft
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29 559 (Figure 2). Accompanying the strong increase of moisture along the southern French coast
30
31 560 and Majorca, then over Corsica (reaching about 40 kg m^{-2} from a value of $\sim 20 \text{ kg m}^{-2}$ 24 h
32
33 561 before), CAPE levels increased (between 1000 and 1750 J kg^{-1} ; Figure 9b) particularly
34
35 562 between the Gulf of Lion and northern Algeria. CIN levels in that same region were the
36
37 563 highest in the south (up to 150 J kg^{-1} over Dar El Beïda) and the lowest in the north (between
38
39 564 0 and 10 J kg^{-1} over southern France) where deep convection initiated, which led to the
40
41 565 development of the main IOP12 MCS (Figures 3 and 4). Also in this case, a convergence zone
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43 566 could be identified from the near-surface wind and buoy observations (not shown) prior to CI,
44
45 567 also captured by COSMO 2.8 km. The convergence line southeast of the Gulf of Lion was
46
47 568 already present at about 1200 UTC because of the merging of north-easterly and south-
48
49 569 westerly winds, which additionally advected moist air from over the sea. The 500 hPa level
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51 570 was a region of strong air ascent (between 20 hPa h^{-1} over southern France and almost 40 hPa
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53 571 h^{-1} over the sea) associated with the short-wave trough. In agreement with these
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55 572 observations and complementing this information, the computation of the COSMO online

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3 573 Lagrangian trajectories showed four main regions from where air parcels contributed to the
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5 574 formation of the HPSs: a) the eastern Atlantic Ocean, b) the land over the Iberian Peninsula,
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7 575 c) the north-western Mediterranean, and d) the north-eastern Africa region. Regions a, b and c
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9 576 mainly contributed to the formation of the HPSs over central and eastern Spain on 10
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11 577 October, whereas regions c and d play this role for the main IOP12 HPS on 11 and 12
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13 578 October. Different time scales ranging from days to hours are needed for the air parcels
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15 579 originating at these regions to reach the target areas. Remote regions such as the Atlantic
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17 580 Ocean and Africa require about 3-4 days whereas closer regions such as the Mediterranean
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19 581 itself need few hours to a day to reach their destination.

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23 582 The ground-based water vapour Raman Lidars WALI and BASIL (Figure 10), the BLPBs
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25 583 (Figure 11a) and the airborne lidar LEANDRE 2 (Figure 11b1, 11b2, 11b3) additionally
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27 584 provided some valuable insight into the atmospheric moisture conditions directly over the
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29 585 region where the IOP12 MCS initiated. The south to north moisture gradient and the
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31 586 increasing moistening of the atmosphere preceding deep convection, which determined CI
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33 587 location in the area, was well captured with high resolution. At Menorca, WALI (Figure 10a)
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35 588 reveals a very moist low PBL, with specific humidity values up to about 15 g kg^{-1} and
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37 589 reaching up to ca 1.5 km, from 9 October until early morning on 12 October. At 0000 UTC on
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39 590 12 October, deep moist updrafts are seen, probably in relationship with strong updrafts
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41 591 transporting moist air from the lower levels. This is in contrast with the dry atmosphere in
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43 592 southern France as evidenced by the BASIL lidar observations for the period 10 to 12 October
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45 593 (Figure 10b). Maximum values of water vapour up to 10 g kg^{-1} are seen reaching about 1 km,
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47 594 in the period between 11 October at 1200 UTC and 12 October at 0000 UTC. The BLPBs
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49 595 captured a high level of variability in the area between the Balearic Islands and Corsica on 11
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51 596 October. In the initial part of their eastward trajectories, both balloons measured moisture
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53 597 amounts of roughly 10 g kg^{-1} . This changed as they both turned northwards where, in both
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55 598 cases, specific humidity levels increased to about 15 g kg^{-1} ($\sim 6\text{-}10 \text{ g kg}^{-1}$ moister than
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3 599 observations on the same region on the 14 October). On this day, a short Do-128 flight
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5 600 conducted from 0700 till 1100 UTC over the sea along the north-eastern Corsican coast
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7 601 clearly evidenced that the lower PBL (~ 200 m amsl) in this region was significantly drier, < 5
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9 602 g kg^{-1} , than the western coast.

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12 603 In agreement with this, the LEANDRE lidar on board of the ATR-42 (between ca 0600 and
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14 604 1000 UTC on 11 October over the eastern Gulf of Lion, upstream of convective systems
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16 605 developing over this region at about 1930 UTC) showed a very moist PBL, reaching up to ca
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18 606 1.5 km, with specific humidity levels between about 9 and 15 g kg^{-1} (Figure 11b1). On the
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20 607 contrary, on 12 and 14 October (as part of IOP13) in the same area, a shallow PBL reaching
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22 608 up to 0.5 km was observed with specific humidity values between 6 and 11 g kg^{-1} in this layer
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24 609 (Figures 11b2 and 11b3). Figure 7d shows that after this period moisture content decreases
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26 610 over the Iberian Peninsula, France and Corsica and Sardinia Islands (by 10 to 20 kg m^{-2} on
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28 611 average) in agreement with the south-eastward progress of notably drier air. In all those
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30 612 regions, it put an end to severe convection.

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33 613 A change to southerly winds in the lower-troposphere over eastern-Africa and over the sea
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35 614 east of Tunisia, starting at about 1800 UTC on the 11 October, is responsible for the transport
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37 615 of the moist air mass over the sea towards central Italy (an IWV increase of about 15 kg m^{-2}
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39 616 in less than 24 hours is registered). These changes were closely correlated with the drop in
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41 617 instability (CAPE and KO-index) in the western part of the investigation area, and a gradual
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43 618 increase everywhere in the east, beginning over Corsica and moving southeast towards
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45 619 southern Italy (Figure 9c). Under these conditions convection activity over central Italy
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47 620 started entering in its dissipation stage at around 1600 UTC on 12 October. Preceded by a
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49 621 IWV increase in the area of Sicily, from around 30 kg m^{-2} measured at 1800 UTC on 12
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51 622 October to around 40 kg m^{-2} at 0700 UTC on 13 October, and accompanying CAPE values in
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53 623 the range 1500-2000 J kg^{-1} , KO-index close to -20 K and almost no CIN, the severe MCS
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3 624 (Figures 3 and 4) producing another HPS, with precipitation sums up to 200 mm in 6 hours,
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5 625 occurred in southern Sicily. Several convergence lines were also present over western Italy
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7 626 and the northern Tyrrhenian Sea prior to the onset convection in the night between 11 and 12
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9 627 October. In this case, these formed only some 3 h prior to convective CI. Their effect was
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11 628 strengthened by a shortwave through aloft and the orography of the area which played an
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13 629 important role in this case. The front approaching from the northwest forced the moist air
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15 630 ahead of it ($IWV \sim 40 \text{ kg m}^{-2}$) to rise over the western slopes of the mountain ranges
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17 631 stretching along the Apennine Peninsula. On 13 October (Figure 7e), dry air masses
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19 632 continued to flow in from the north-western direction over Spain, France, and north- and
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21 633 central Italy. By the end of the day the IWV levels dropped to values as low as 10 - 15 kg m^{-2} .
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23 634 The most humid air was concentrated over the south-eastern part of our investigation area
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25 635 (Algeria and Tunisia to the south), and over the Tyrrhenian Sea and to the south and west of
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27 636 Sicily, where till noon moisture levels rose up to 40 kg m^{-2} . In this area, a low-level wind
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29 637 convergence zone could be identified resulting from the merging of southerly winds
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31 638 transporting moisture from the sea east of Tunisia, and northerly winds transporting moisture
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33 639 from the Mediterranean area between Sardinia and central Italy. This convergence zone
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35 640 favoured the concentration of the convective activity around Sicily, especially west of it over
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37 641 the sea. Everywhere the humidity started to decrease in the early evening and remained low in
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39 642 the following days. Figure 9d shows that instability decreased in almost the whole region and
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41 643 CIN increased by 50 to 70 J kg^{-1} with respect to the values measured 24 hours earlier.
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43 644 Convection was still active over the Tyrrhenian Sea and Apennine Peninsula in the afternoon
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45 645 and evening of 13 October, but it was no longer as intensive as on the previous day.
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647 **6. Conclusions**

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3 648 The investigation of the spatio-temporal evolution of atmospheric moisture variability
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5 649 contributing to the HPS over the WMed region is an open question whose progress is
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8 650 generally hampered by the lack of water vapour observations, thus mostly restricted to
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10 651 modelling studies. This study profits from the rare opportunity to gather a diverse set of
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12 652 observational data sets providing a representation of atmospheric moisture across spatial and
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14 653 temporal scales in the framework of HyMeX. This helped us demonstrating that the sampling
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16 654 of water vapour spatial inhomogeneities on different scales is crucial for the understanding of
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18 655 the timing and location of deep convection. With this purpose, we use three types of
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21 656 observations, passive remote sensing water vapour observations such as MODIS, ground-
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23 657 based in-situ measurements such as radiosounding profile information, BLPB, ground-based
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25 658 water vapour Raman lidars and GPS-derived IWV, as well as airborne water vapour DIAL
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28 659 measurements. We combine this information with high-resolution COSMO model simulations
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30 660 to provide insight into the origin and pathways of air parcels contributing to the occurrence of
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32 661 the MCSs and their triggering mechanisms. Regarding this last point, the identification of
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34 662 low-level wind convergence lines prior to each deep convection episode in the area turned out
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36 663 to be crucial for the initiation and location of convection in the area, which is in agreement
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38 664 with previous investigations in different mid-latitude regions (e.g. Khodayar et al. 2013).

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43 665 Four areas of intense deep convection activity affect the investigation area during IOP12.
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45 666 Convective activity starts in north-east Spain (Area1) moving eastward toward Corsica
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47 667 (Area2), where intensification is observed and finally affecting central (Area3) and southern
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49 668 Italy (Area4). Italy was the most affected area, with intense precipitation being registered, ~
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51 669 150-200 mm/6 h, while precipitation rates in the range 50 to 100 mm in 24 h were recorded in
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53 670 the other affected areas.

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57 671 The main findings of this study are summarized below,
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3 672 • The high spatial and temporal coverage of GPS-IWV observations allowed to
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5 673 adequately sampling the west-to-east moisture transport within the north-WMed. All
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7 674 convective episodes leading to HPS occurred in environments with IWV values
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9 675 between 30 and 45 kg m⁻², being these upper threshold values common in the region
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11 676 for the autumn period of 2012 (e.g. Khodayar et al 2016a).
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14 677 • Large moisture changes, up to 20 kg m⁻², were identified prior to each convective
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16 678 episode leading to HPS. More intense events were not related to the situations in
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18 679 which higher IWV is reached, but rather the build-up time and vertical distribution of
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20 680 these increases were found to be crucial for the evolution and intensification of the
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22 681 HPS, thus on the severity of the event.
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24 682 • The most intense events reveal a rapid, 6-12 h, IWV increase in the order of 10 kg m⁻²
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26 683 (Area2, Area3 and Area4), whereas less intense events show a larger increase, ~ 20 kg
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28 684 m⁻² but in a longer time period 24h to 36 h (Area1).
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30 685 • Total column moisture changes were mainly related to differences in the lower and
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32 686 mid-troposphere. Almost no change in the atmospheric moisture distribution was
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34 687 observed at ~ 500 hPa or above. The mid-atmosphere, ~ 850 to 700 hPa, remained
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36 688 very moist during the pre- and convective periods, with RH values in excess of 75 %,
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38 689 favouring deep convection development. In the lower-troposphere, changes up to 5 g
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40 690 kg⁻¹ are observed.
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42 691 • The atmospheric stability conditions were as expected largely affected by these
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44 692 changes. The larger/faster the increase of the water vapour content in the low- and
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46 693 mid-troposphere, the stronger the impact on the atmospheric stability conditions and
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48 694 the strength of convection. Large-sudden increases in CAPE are identified preceding
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50 695 explosive convection yielding high precipitation amounts in a few hours.
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3 696 • A decrease of the LCL and a reduction of LCL-LFC are identified in those situations
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5 697 following an increase of moisture in the lower-troposphere. This suggests that moist
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7 698 air parcels become more easily buoyant, thus favouring initiation of deep convection
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9 699 and the rapid formation of deep thunderstorms.
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12 700 • Moister and deeper boundary layers with updraughts reaching up to 2 km are
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14 701 identified in those pre-convective environments leading to HPS, whereas dry, shallow
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16 702 boundary layers are found everywhere else with updraughts not higher than about 1
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18 703 km.
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21 704 • Spatial moisture inhomogeneities in the lower PBL, up to 4 g kg^{-1} in less of 100 km,
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23 705 have been shown to determine the location of CI over the sea.
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26 706 • Particularly for this IOP12, the more intense HPS is seen to receive air parcels, hence
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28 707 moisture contributions simultaneously from different sources resulting in a large-
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30 708 sudden increase of moisture in the lower atmosphere leading to explosive HPSs, as
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32 709 previously discussed. Whereas in the less intense events advection from a particular
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34 710 direction is seen to control moisture changes in the lower and mainly mid-troposphere
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36 711 probably in relation to synoptic conditions dominating the dynamics of the
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38 712 atmosphere. After the occurrence of heavy precipitation, a strong decrease of
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40 713 atmospheric moisture content is seen with the same or larger magnitude of the
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42 714 previous increase.
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48 715 We can conclude that the combined analysis of the available observational data sets provides
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50 716 on different scales adequate information about atmospheric moisture variability relevant to
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52 717 HPS occurrence. The synergetic analysis of the measurements helped us understanding the
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54 718 mechanisms and pre-convective conditions leading to deep convection in the area. Limitations
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56 719 on the use of single instrumentations are pointed out in this study. The development of a lidar
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58 720 network to measure water vapour could be of great help in the understanding and forecast of
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3 721 extreme events. The sampling of the interplay between the moisture evolution on different
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5 722 scales, from the large- to the smaller scale, as well as the lapse rate in which this occurs is
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7 723 crucial to improve our understanding of HPSs. Additionally, this study demonstrates that the
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9 724 misrepresentation of this variability in time and space should be carefully evaluated in model
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11 725 simulations as a crucial factor responsible for wrong CI and precipitation simulations. This
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13 726 study focuses on a complex single IOP; therefore, it would be of interest to extend the
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15 727 investigation to a large number of events, including other types of convective situations.
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17 728 Although the relevance of the vertical distribution of moisture and related changes for the
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19 729 occurrence of HPSs was already pointed out in the region in Khodayar et al. (2016c), the
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21 730 relationship with the severity of the event and the build-up time has not been previously
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23 731 discussed. Therefore, further analysis regarding these characteristics will be necessary to
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25 732 assess the generality of our results.
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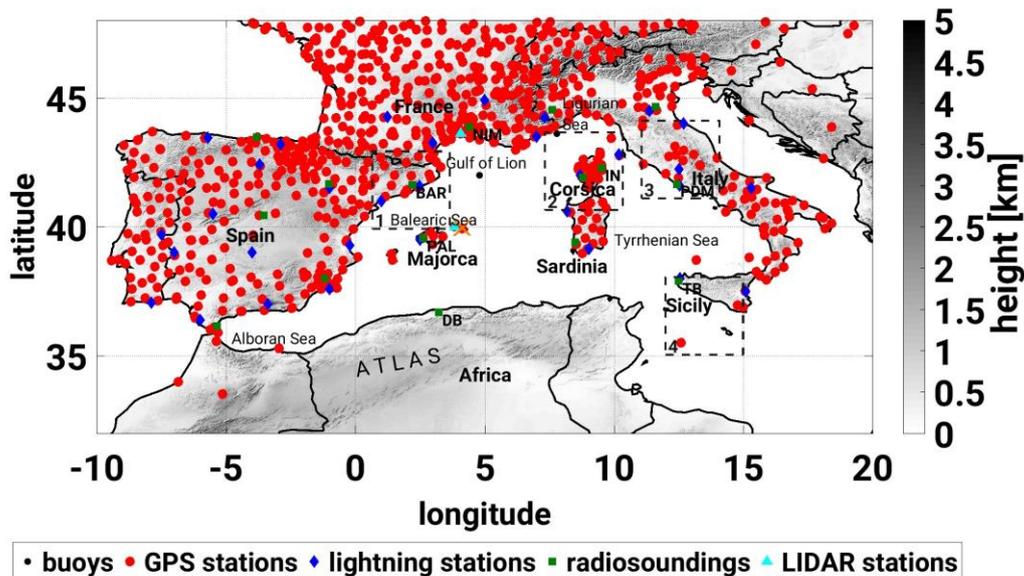
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1018 **Figures**

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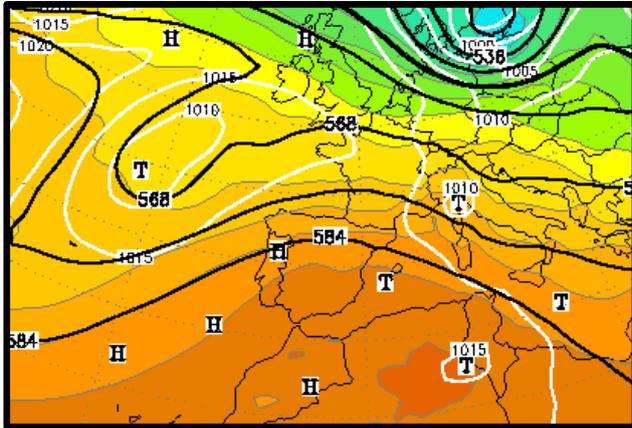
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Figure 1: Orography of the western Mediterranean region (black-white scale). Subdomains under investigation are delineated with dashed lines and numbered from 1 to 4. Observations are indicated as follows: GPS network (red), radiosoundings (green), lightning stations (blue), buoys (black), WALI lidar and BASIL lidar (light blue); the orange cross over the southeastern Menorca indicates the Boundary Layer Pressured Balloons (BLPB) launch site at the beginning of the balloon trajectories. Selected radiosounding stations are named as follows (from left to right) BAR (Barcelona), PAL (Palma), NIM (Nimes), IN (Inra), PDM (Pratica Di Mare) and TB (Trapani Birgi).

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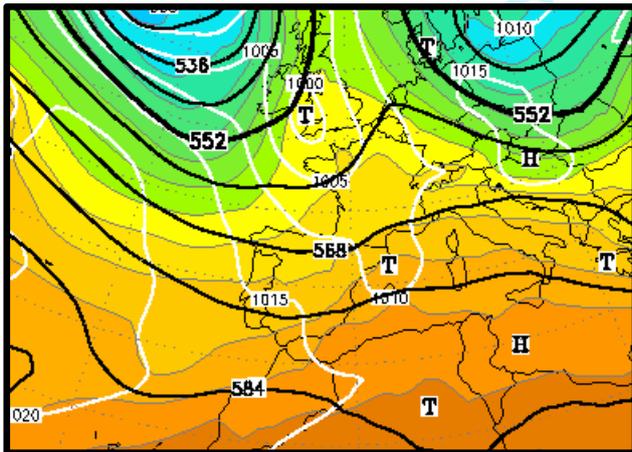
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1032 (a) 09.10.2012 1200 UTC



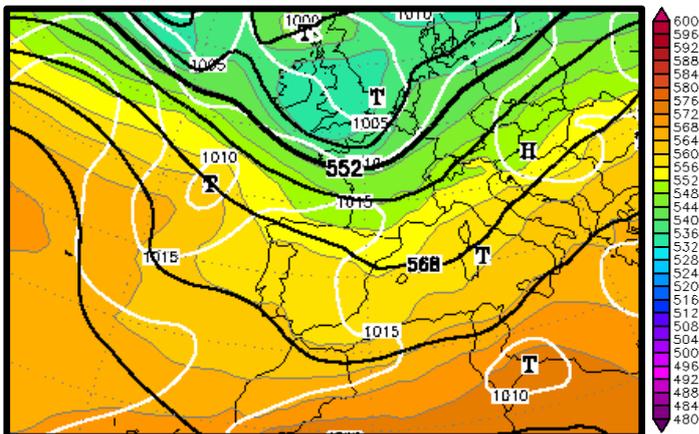
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1034 (b) 11.10.2012 1200 UTC



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1036 (c) 13.10.2012 1200 UTC



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Figure 2: GFS-analysis of 500 hPa geopotential height (gpdgm; black isolines), mean sea-level pressure (hPa; white isolines) and relative topography H500-H1000 (gpdgm; colour scale) at 1200 UTC on the 9, 11 and 13 October 2012 (source: wetter3.de).

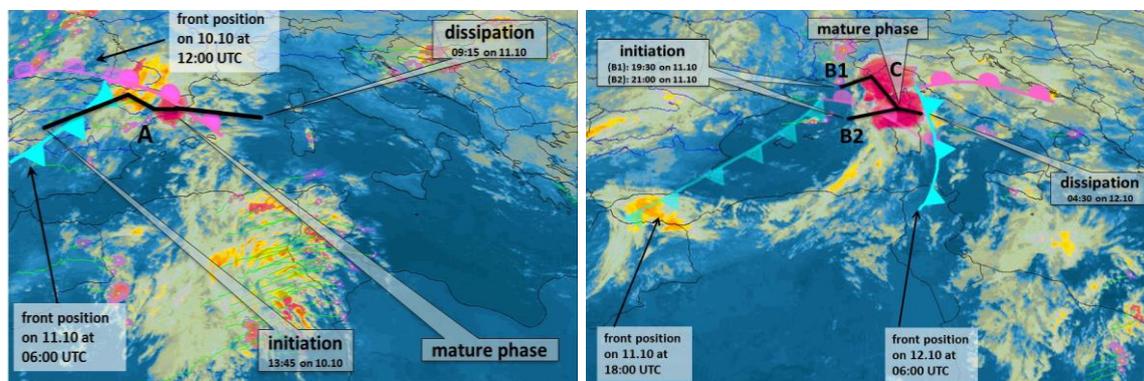
For Peer Review

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1059 (a) 11.10.2012 at 0000 UTC

(b) 12.10.2012 at 0000 UTC

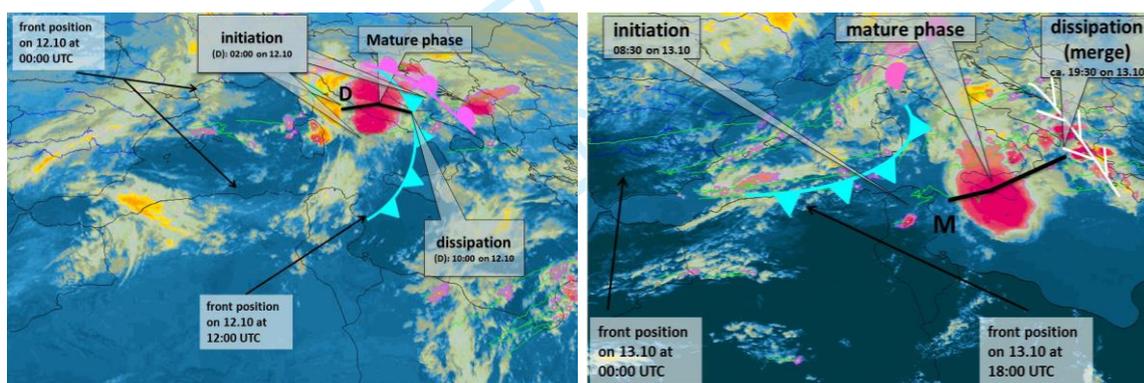
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1061 (c) 12.10.2012 at 0500 UTC

(d) 13.10.2012 at 1400 UTC

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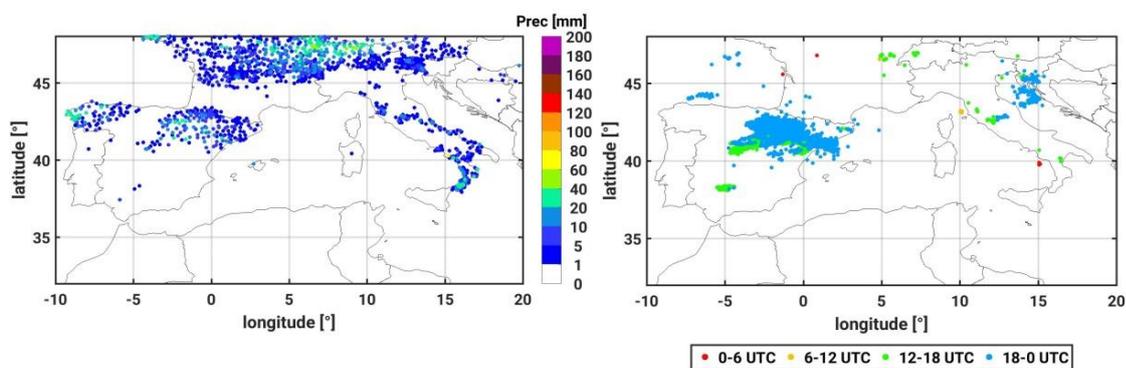


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1064 **Figure 3:** RDT (Rapid Developing Thunderstorm) products based on MSG SEVIRI
 1065 brightness temperature images at 10.8 μm showing the spatio-temporal development of
 1066 convective activity over the Mediterranean region for (a) 11 October 2012 at 0000 UTC, (b)
 1067 12 October 2012 at 0000 UTC, (c) 12 October 2012 at 0500 UTC and (d) 13 October 2012 at
 1068 1400 UTC. All development stages of storms are highlighted using different colours
 1069 (yellow=triggering, orange=growing, magenta=mature stadium, violet= split cases). The blue,
 1070 pink and white lines represent the position of fronts and convergence lines, respectively. The

1071 thick black lines locate the path of each storm and the captions indicate the stage of every
 1072 convective cell.

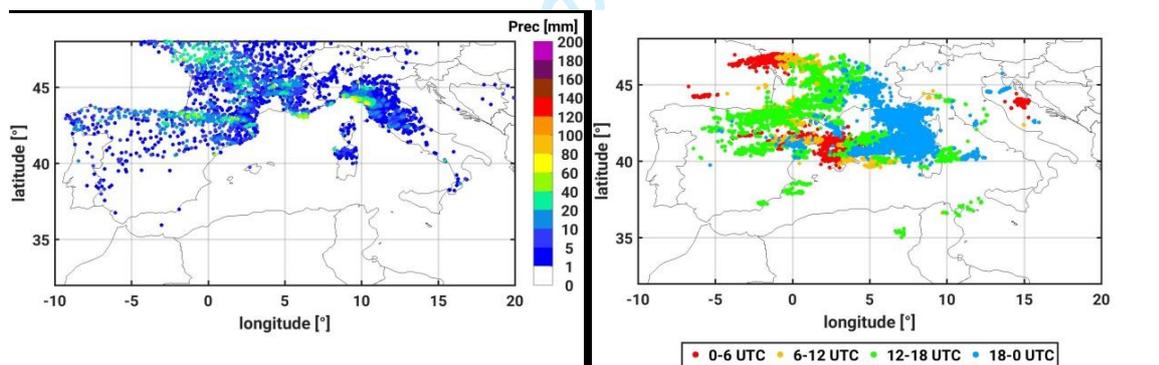
1073 (a) 10.10.2012



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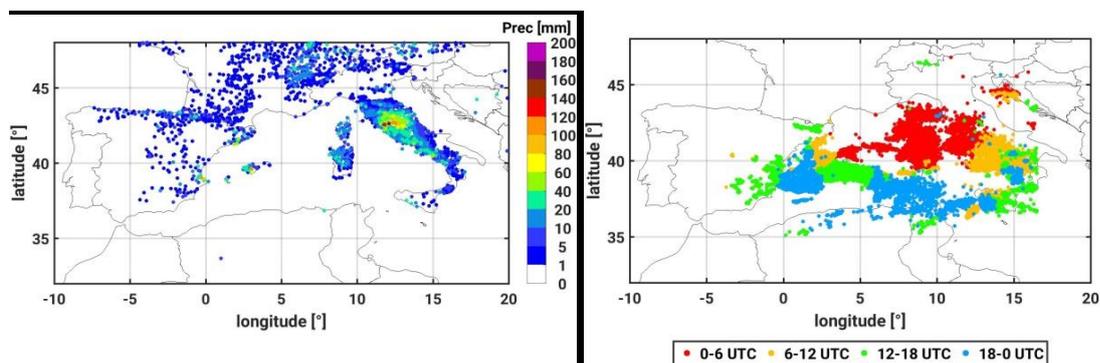
1076 (b) 11.10.2012



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1079 (c) 12.10.2012



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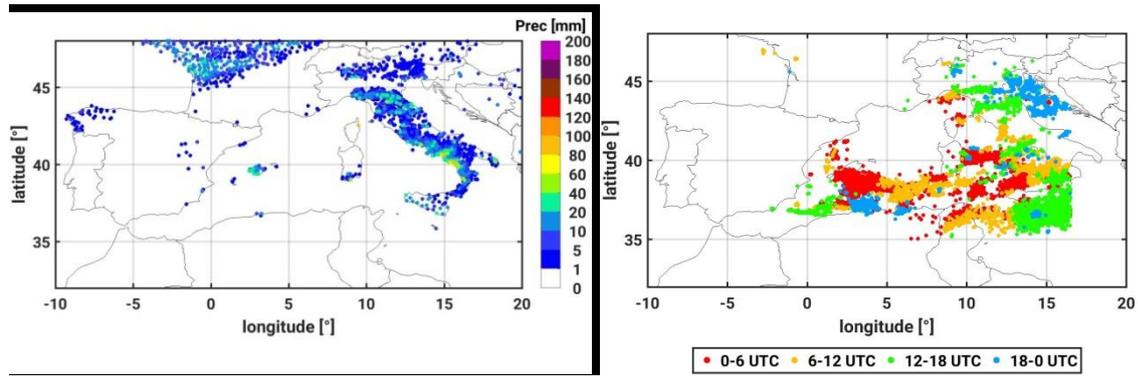
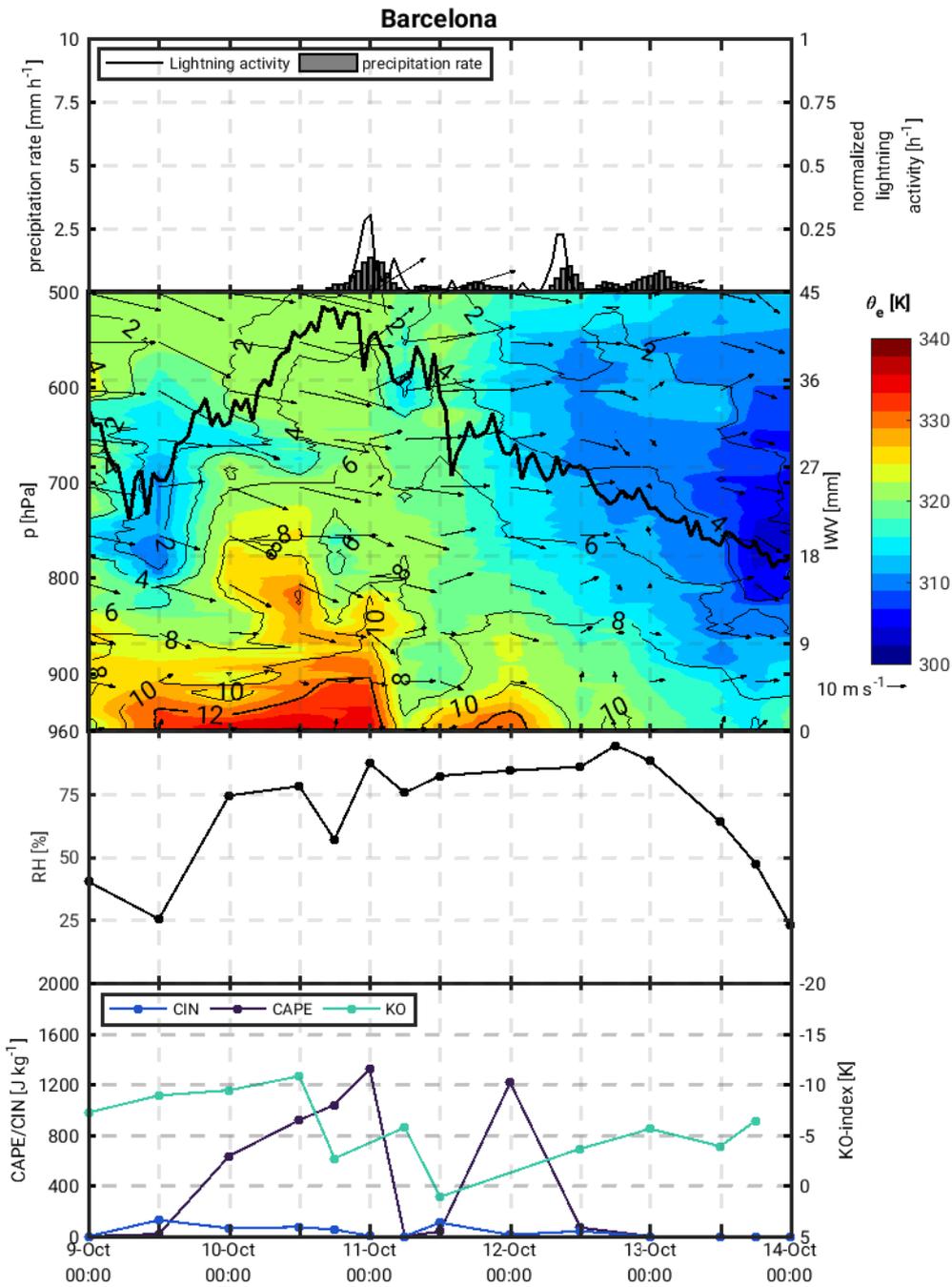


Figure 4: (a-d, left) Daily precipitation sums from 0600 UTC to 0600 UTC from 1 h rain gauge measurements and (right) EUCLID lightning observations (only available up to 16 °E).

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1099 (a)



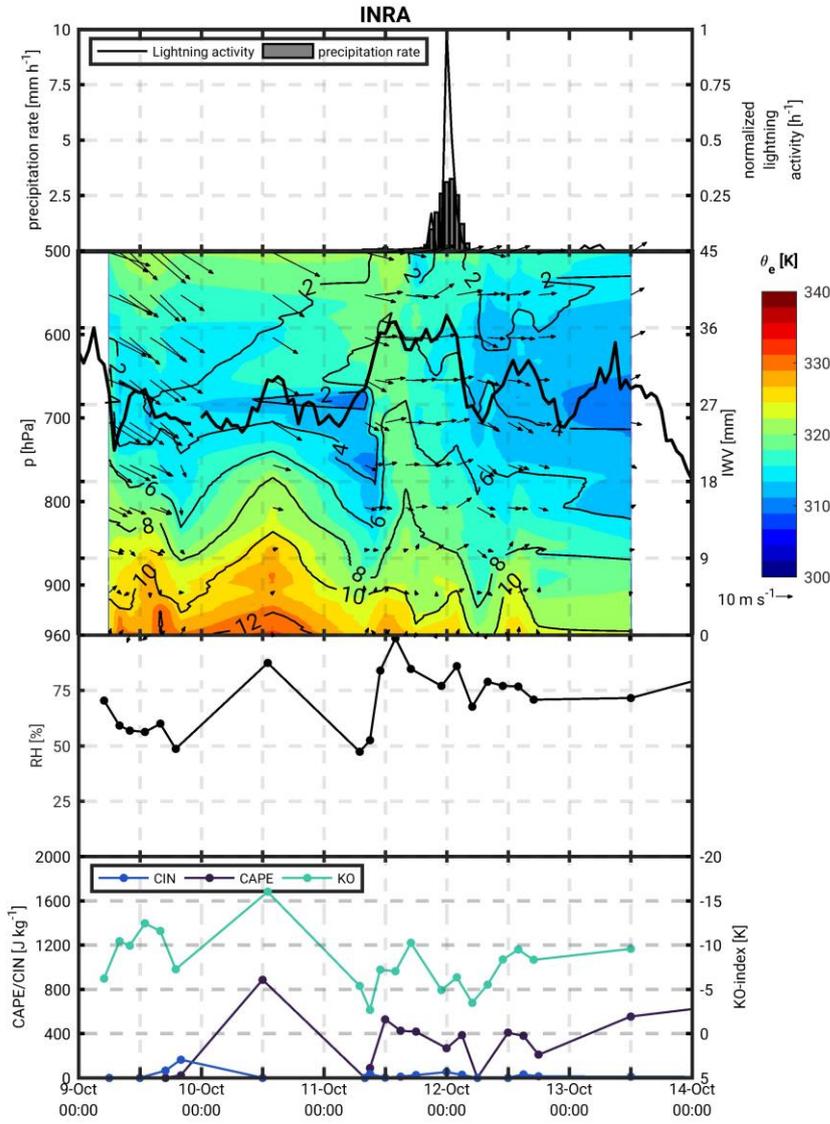
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1103 (b)

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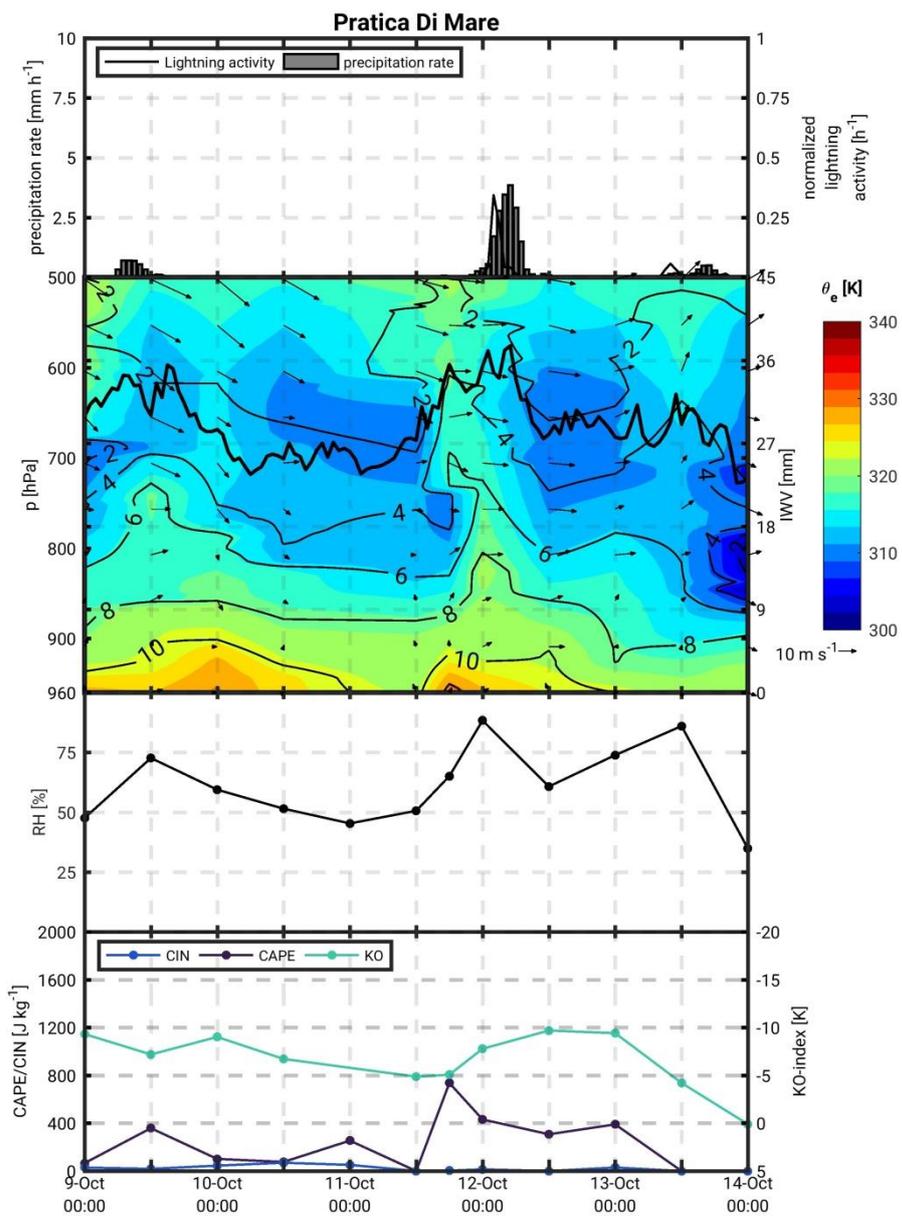
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1112 (c)



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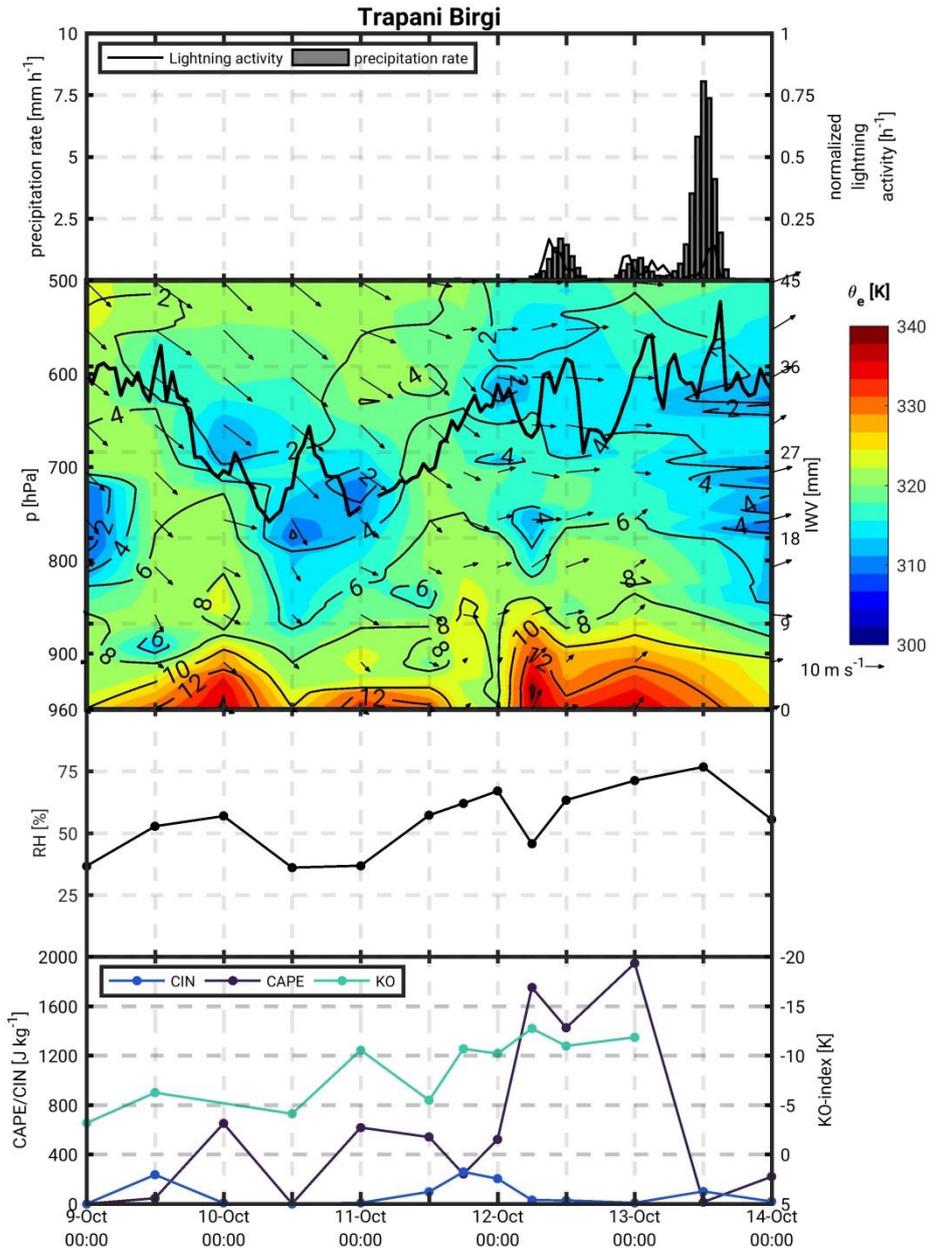
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1119 (d)



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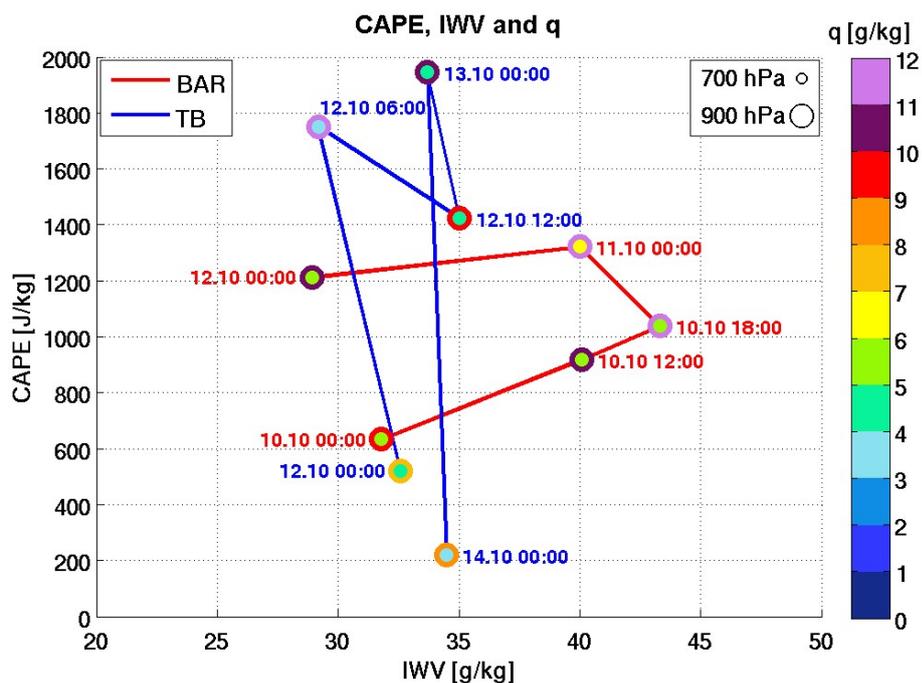
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3 1125 **Figure 5:** Temporal evolution of (from top to bottom): Areal mean CMORPH hourly
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5 1126 precipitation observations and EUCLID lightning; vertical cross-sections of equivalent
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7 1127 potential temperature, specific humidity and horizontal wind (north pointing upwards) for
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9 1128 selected stations using radiosounding data; IWV temporal evolution of the closest GPS station
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11 1129 is included, mean relative humidity (RH) averaged between 850 and 700 hPa and temporal
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13 1130 evolution of CAPE, CIN and KO-index calculated from corresponding radiosonde for: (a)
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15 1131 Barcelona, (b) KIT-INRA, (c) Pratica Di Mare, (d) Trapani Birgi. Position of stations and
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17 1132 selected areas are indicated in Figure 1.
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1142 **Figure 6:** Temporal evolution of CAPE in relation to IWV and specific humidity at 900±50

1143 hPa and 700±50 hPa using the Barcelona (BAR/AREA1; max prec ~50 mm day⁻¹ at about 11

1144 October at 0000 UTC), and Trapani Birgi (TB/AREA4; max prec ~200 mm day⁻¹ in the

1145 morning of the 13 October) radiosounding atmospheric profile information. As indicated in

1146 the legend, the inner circle indicates the 700 hPa specific humidity values and the outer circle

1147 the 900 hPa specific humidity values.

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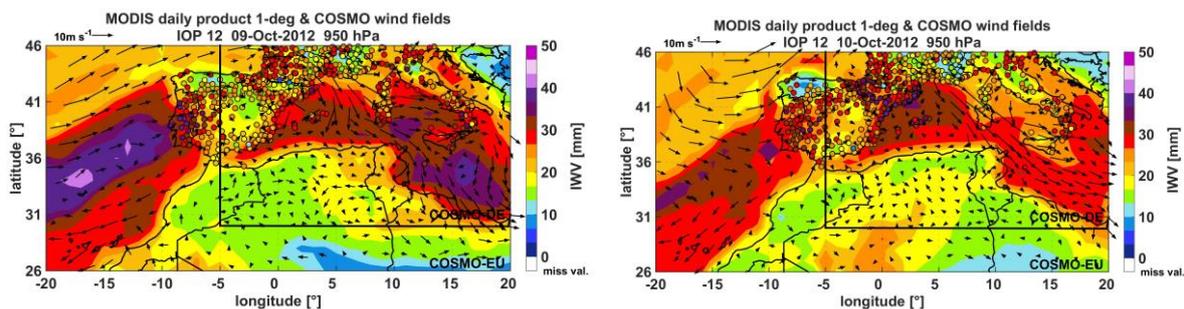
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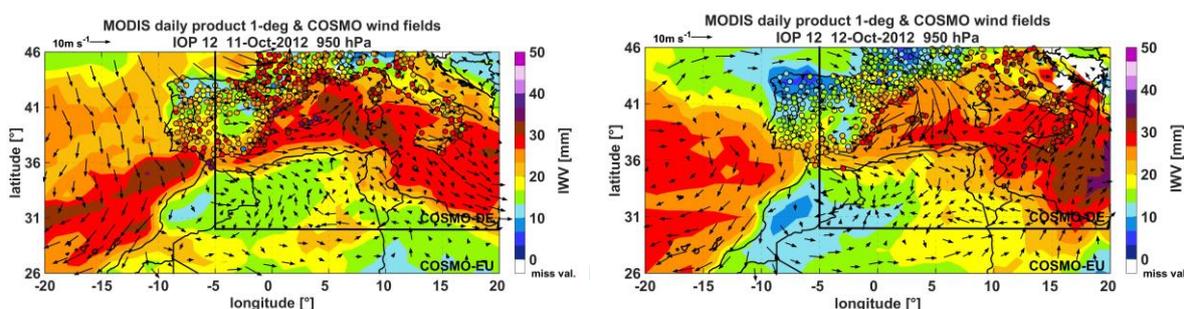
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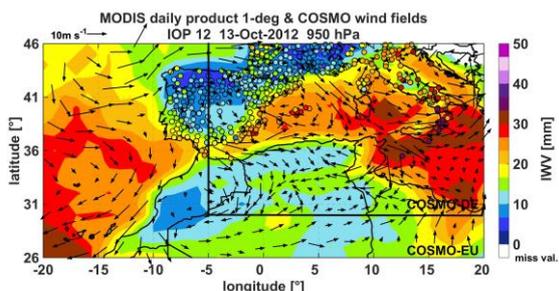
1153 (a) 09.10.2012 (b) 10.10.2012



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1155 (c) 11.10.2012 (d) 12.10.2012



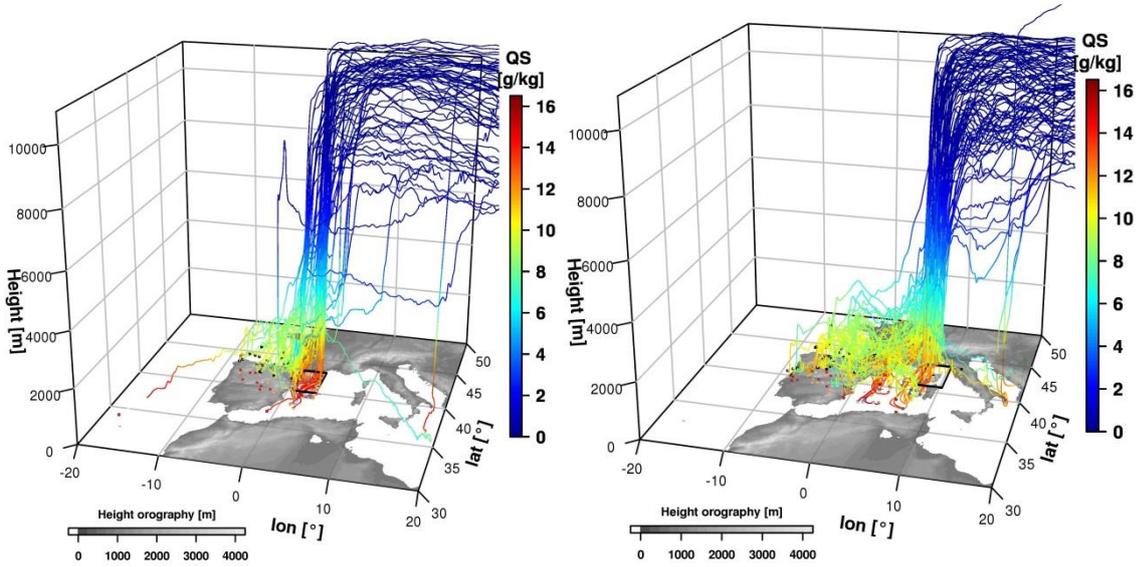
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1157 (e) 13.10.2012



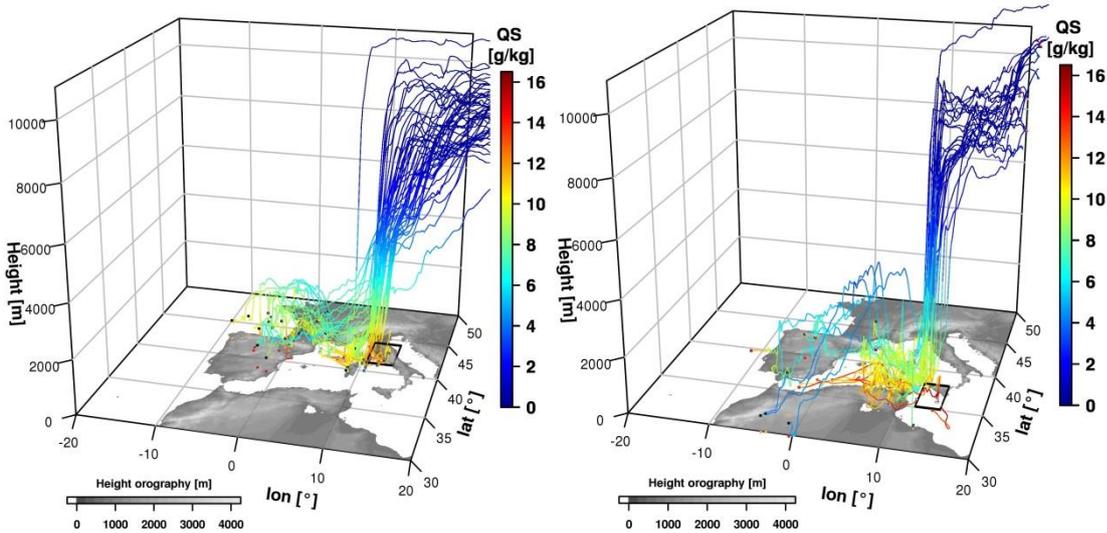
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1160 **Figure 7:** Daily mean spatial distribution of total column Integrated Water Vapour (IWV)
1161 from MODIS (background) and GPS (circles) observations for (a) 09 October 2012, (b) 10
1162 October 2012, (c) 11 October 2012, (d) 12 October 2012 and (e) 13 October 2012. Simulated
1163 COSMO-7 km and COSMO-2.8km 950 hPa winds at 1200 UTC are superimposed.

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1165 (a)



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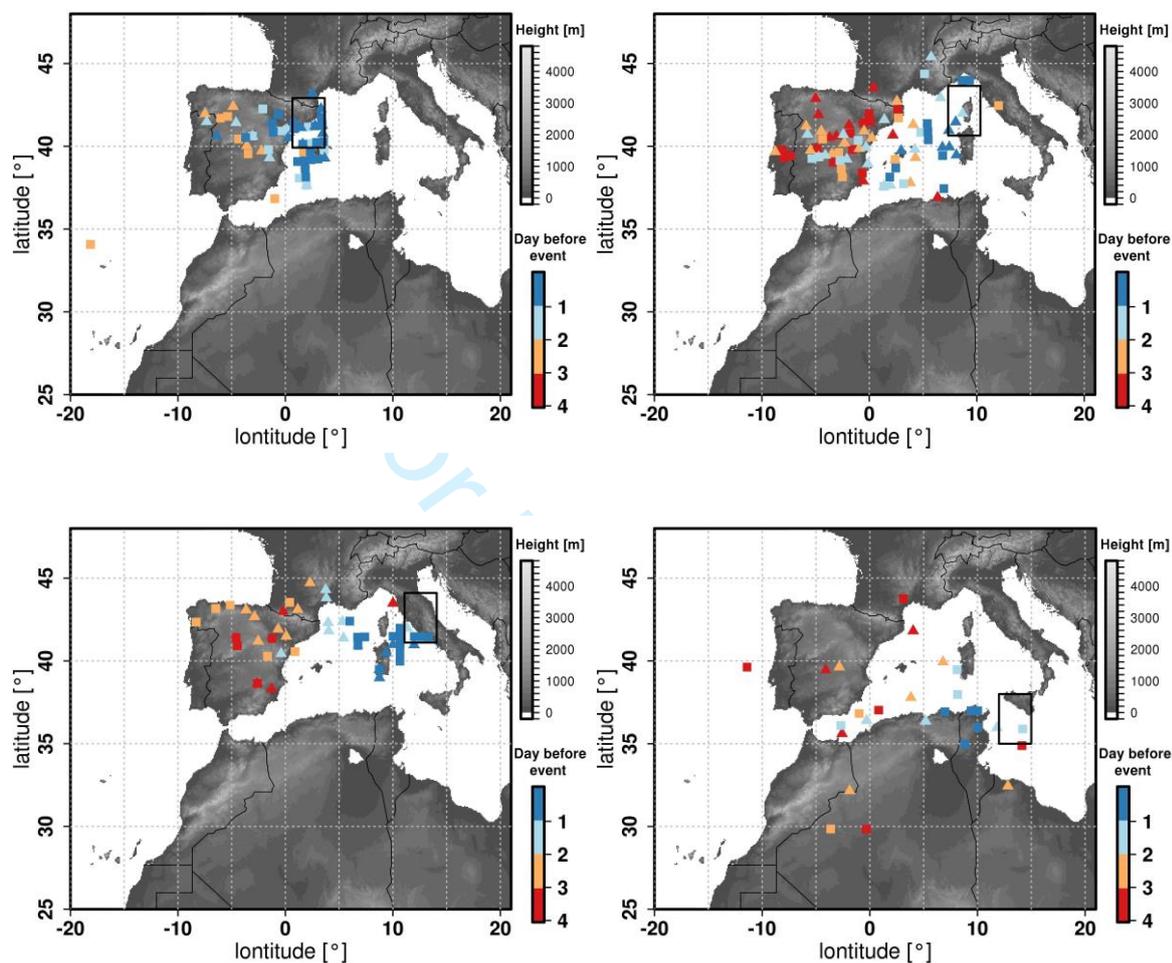
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1173 (b)



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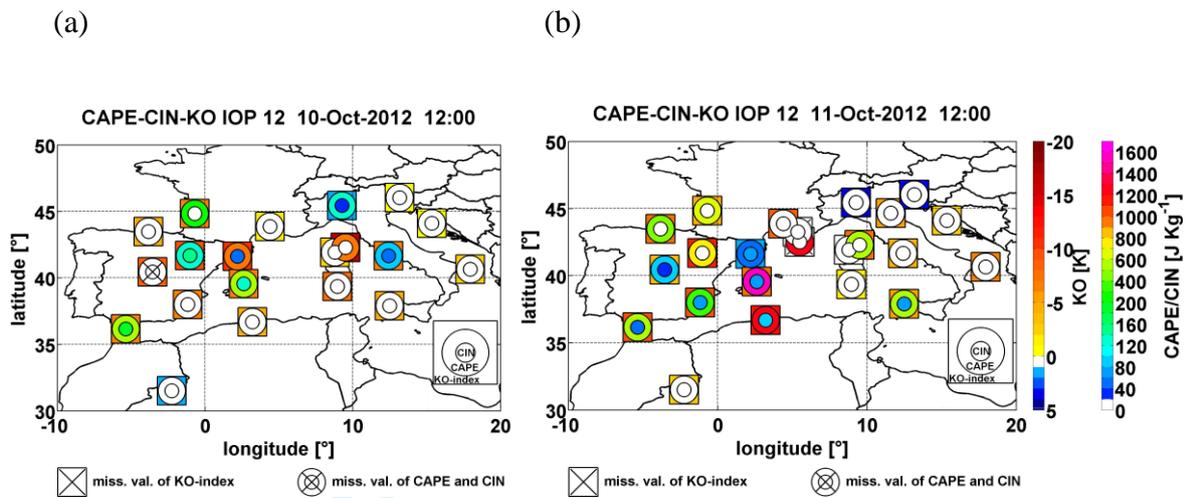
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1177 **Figure 8:** (a) Trajectory and (b) origin of air parcels contributing to the formation of the
 1178 heavy precipitation systems in each of the affected areas (black boxes) as determined from the
 1179 COSMO Lagrangian trajectories module. The orography of the region is depicted in white-
 1180 black scale. In (a) the colour scale indicates the specific humidity along the air parcel
 1181 trajectories. In (b) the symbols locate the origin of the air parcel trajectories and the colour
 1182 scale indicates the number of simulated days prior to the precipitation event. The symbols
 1183 themselves represent the starting time of trajectories (squares at 00UTC and the triangles at
 1184 12UTC).

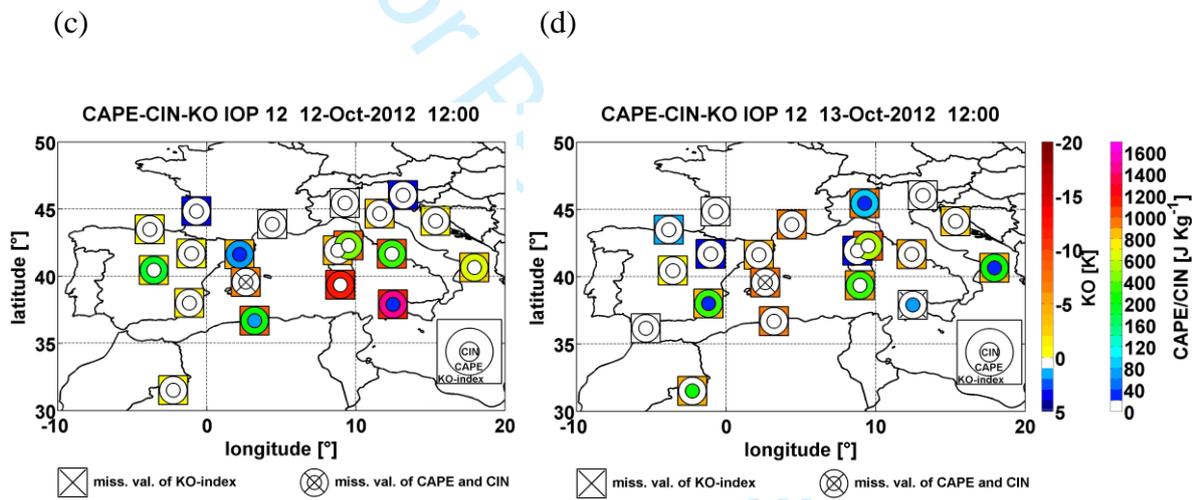
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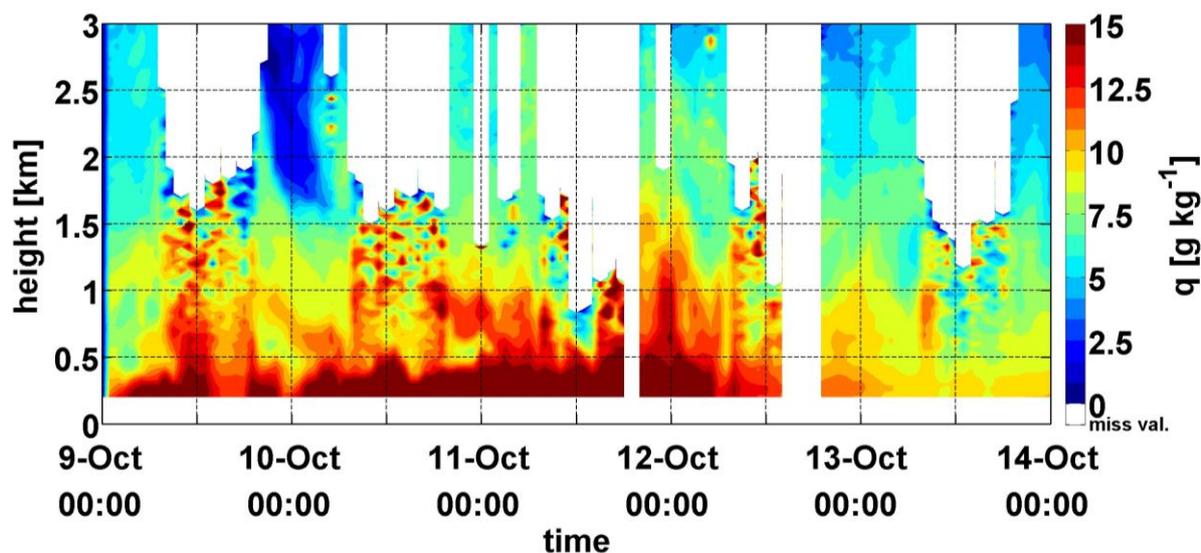
1191 **Figure 9:** Spatial distribution of CAPE, CIN and KO-index on the 10, 11, 12 and 13 October

1192 2012 at 1200 UTC. As indicated in the legend, the inner circle indicates CIN values, the outer

1193 circle represents the CAPE values, and the square reflects the KO-index values.

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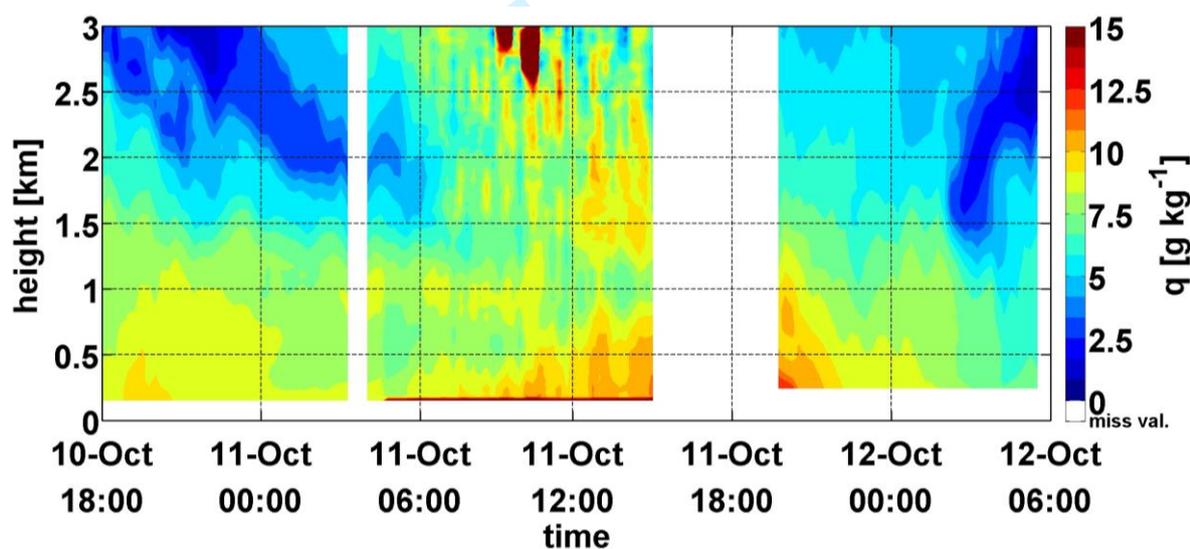
1195 (a)



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(b)



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1200 **Figure 10:** (a) Water vapour mixing ratio from 9 to 14 October 2012 over Menorca (Balearic

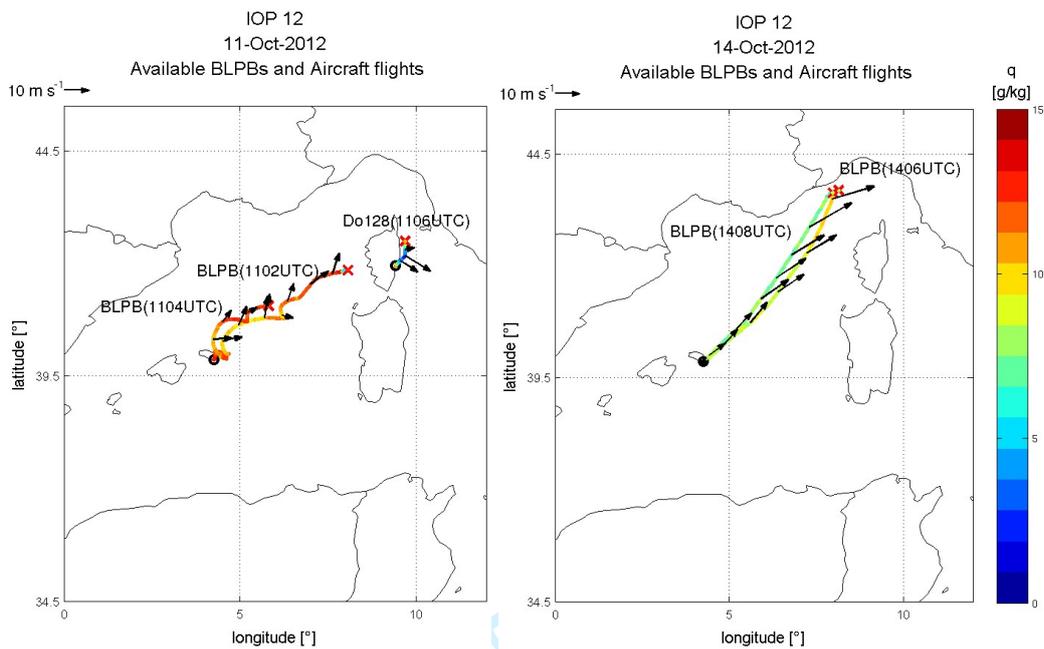
1201 Islands) as measured by the Raman lidar WALI. (b) Water vapour mixing ratio from 10 to 12

1202 October 2012 over Candillargues (south France) as measured by the Raman lidar BASIL.

1203 Please note the different time scales. The data gaps are due to cloud cover or heavy rain.

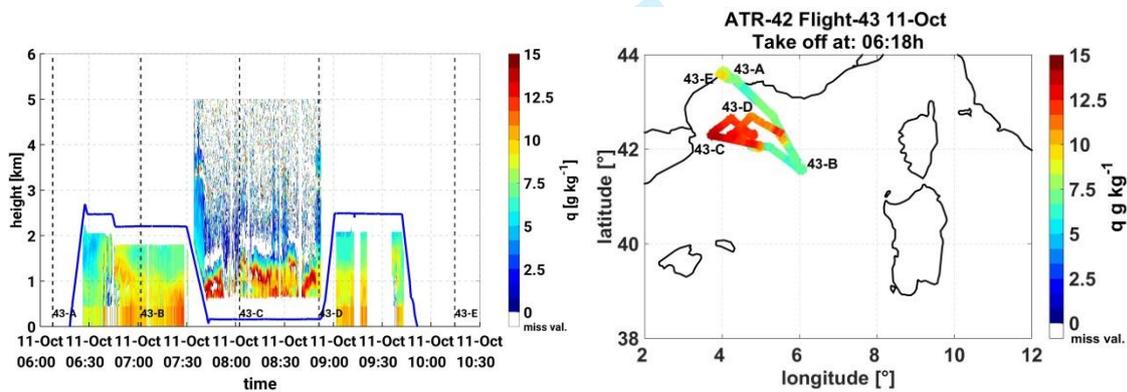
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1205 (a)



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1207 (b)



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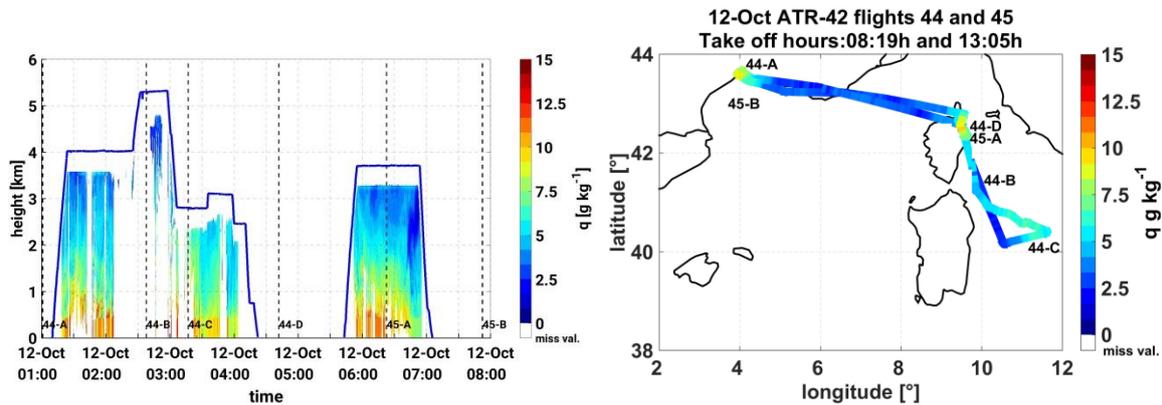
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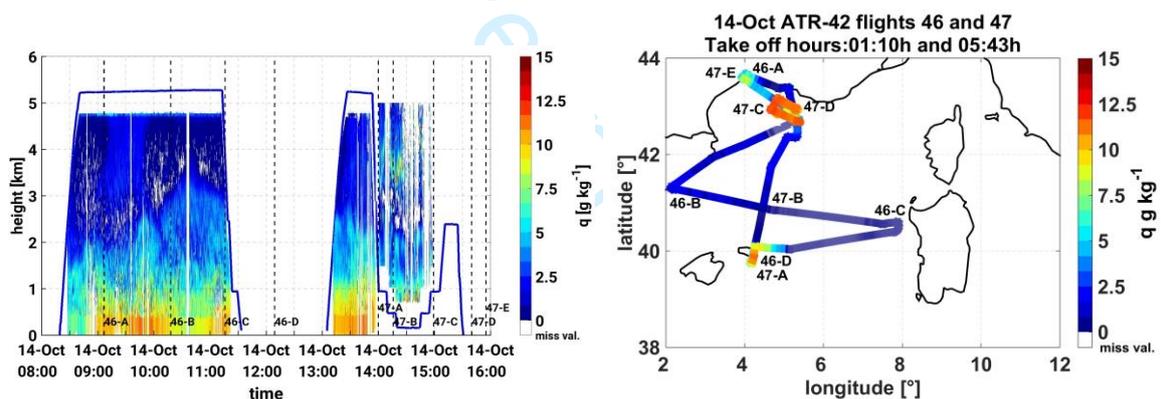
1214 (b2)



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1217 (b3)



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1219 **Figure 11:** (a) Boundary Layer Pressurized Ballons (BLPB) path depicting specific humidity
 1220 and horizontal wind at about 500-700 m amsl on 11 October 2012 and 14 October 2012. DO-
 1221 128 specific humidity and wind observations in the lower PBL for the 11 October are also
 1222 included. (b) Vertical-cross section of specific humidity measured by the LEANDRE 2 lidar
 1223 on board of the ATR-42 aircraft, on the 11, 12 and 14 October 2012 for the indicated periods.
 1224 Flight tracks and altitude are also indicated.

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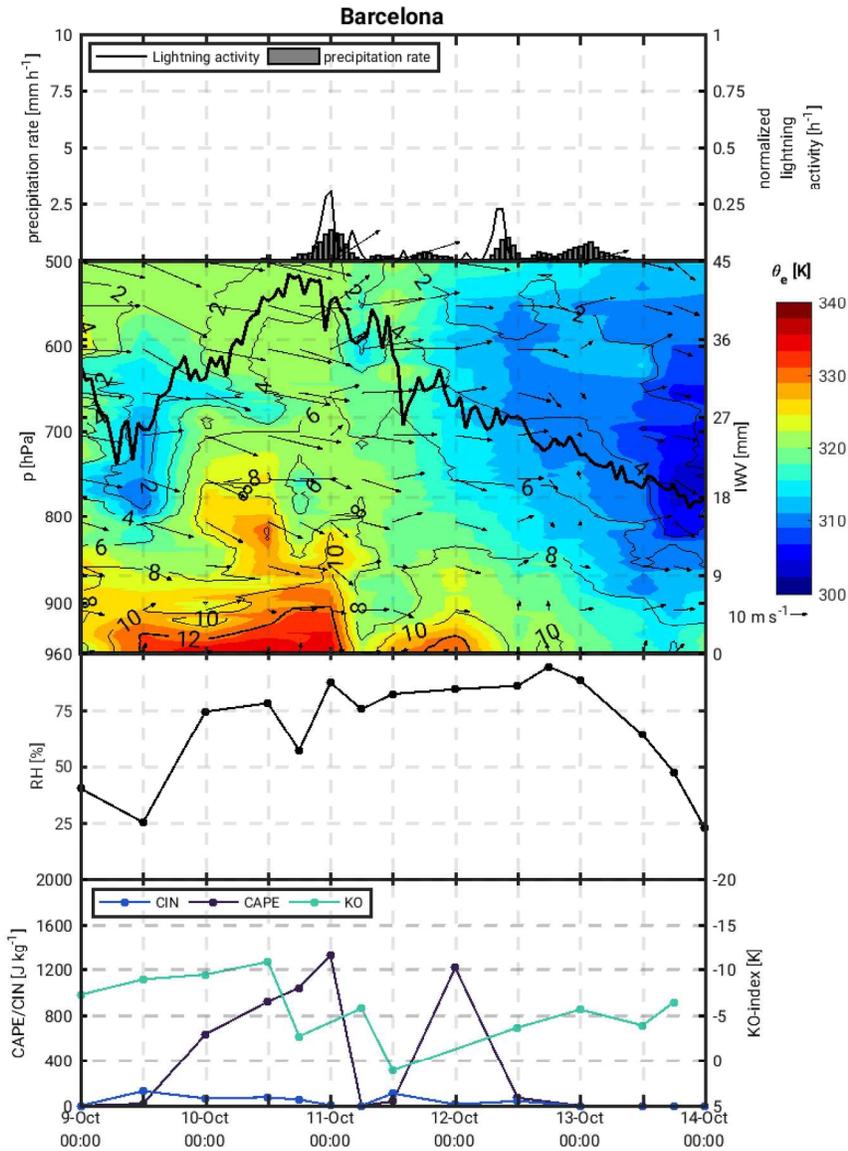
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1227 **Tables**

1228 **Table 1:** Complementary information on storms presented in Figure 3. The lifespan and
 1229 maximum anvil surface were estimated based on information contained in the RTD product
 1230 (accuracy is ± 15 min for the time estimates and ± 500 km² for maximum anvil expansion).
 1231 Maximum precipitation amounts are inferred from rain gauge measurements over land and
 1232 CMORPH satellite derived precipitation observations over the sea. Synoptic forcing
 1233 information is based on GFS model output and surface pressure charts (source
 1234 www.wetter3.de). Near-surface observations are based on SYNOP wind observations.

Storm	Lifespan [h]	Max. surface [x10 ³ km ²]	Max. prec [mm]	Forcing
A	19.5	39	50 /24h	Near-surface convergence line
B1	7	37	75/6h	Near-surface convergence line, secondary trough, surface
B2	4.5	23	40/6h	
C (merged B1&B2)	4	130	50/24h	cold front
D	8	93	150/6h	Near-surface convergence line, secondary trough, surface cold front
M	18	140	150-200/6h	Near-surface convergence line and secondary trough

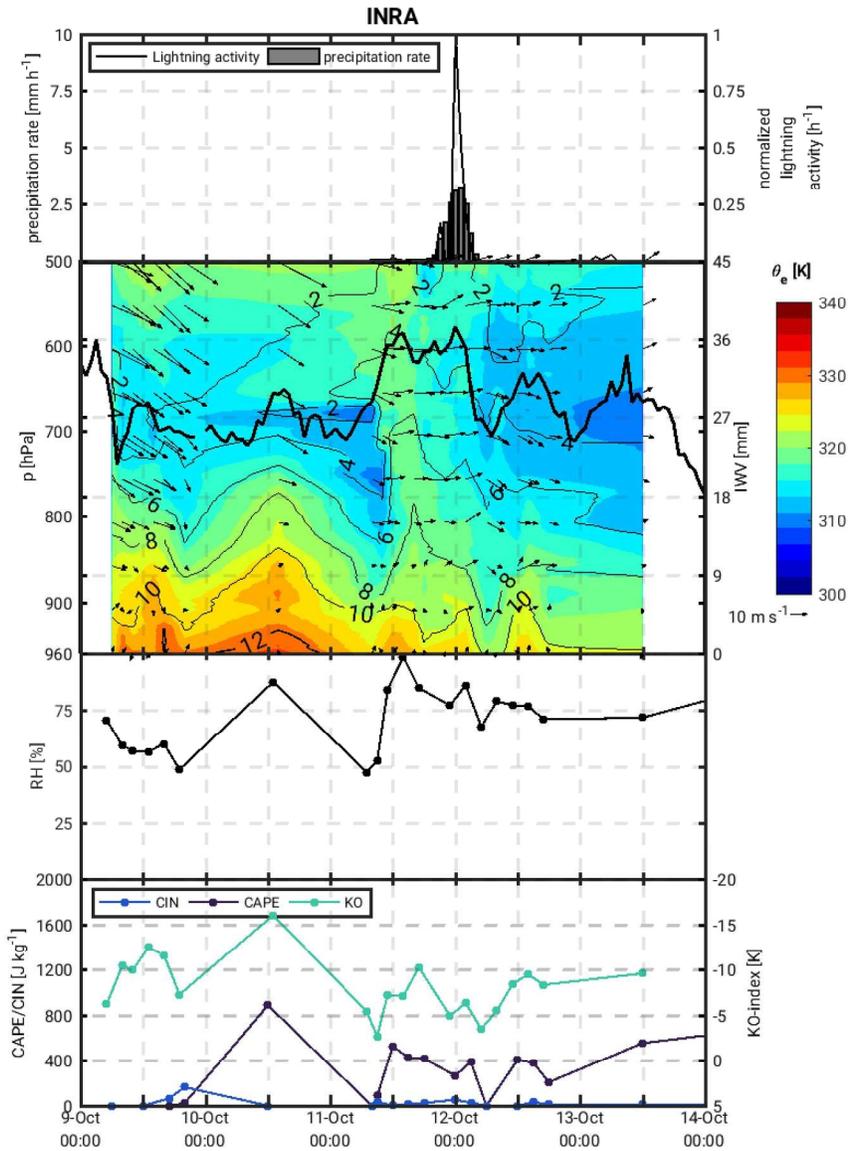
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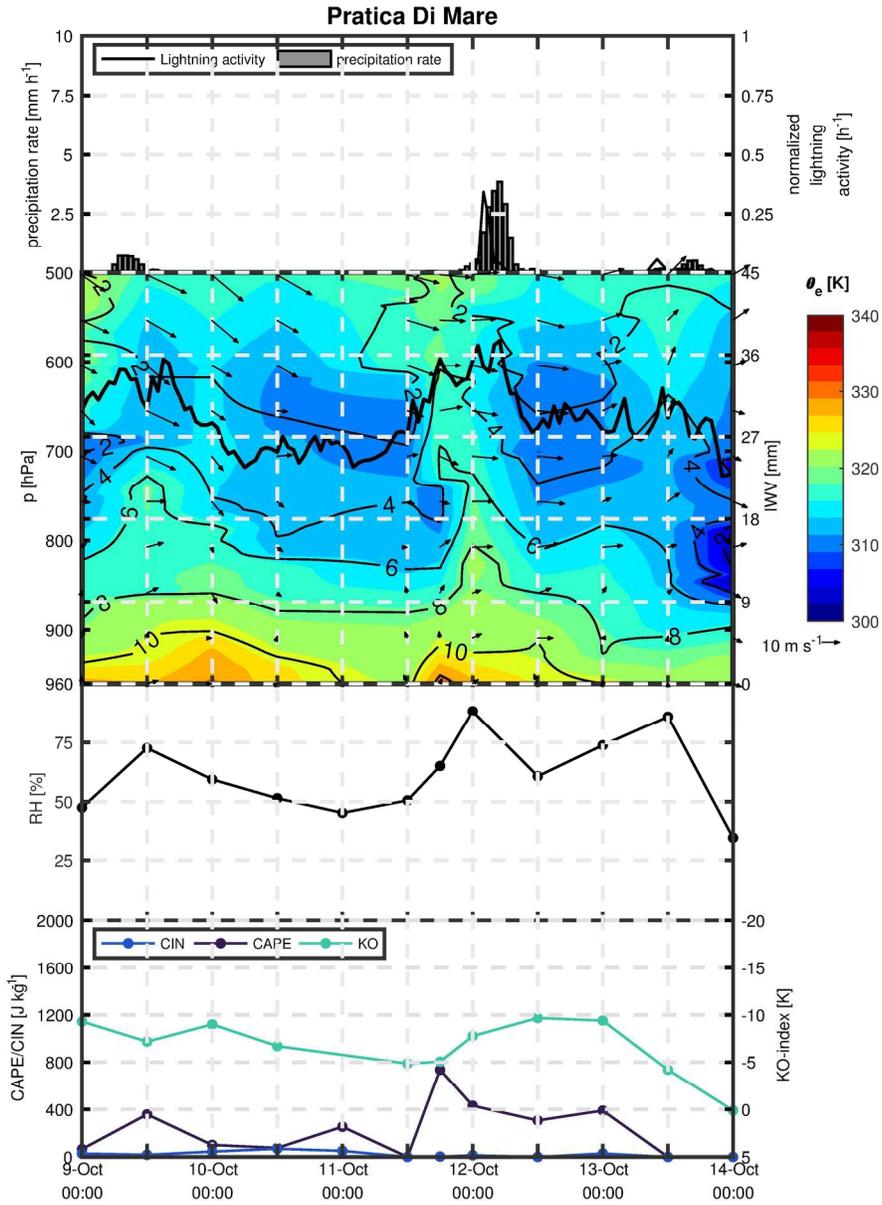
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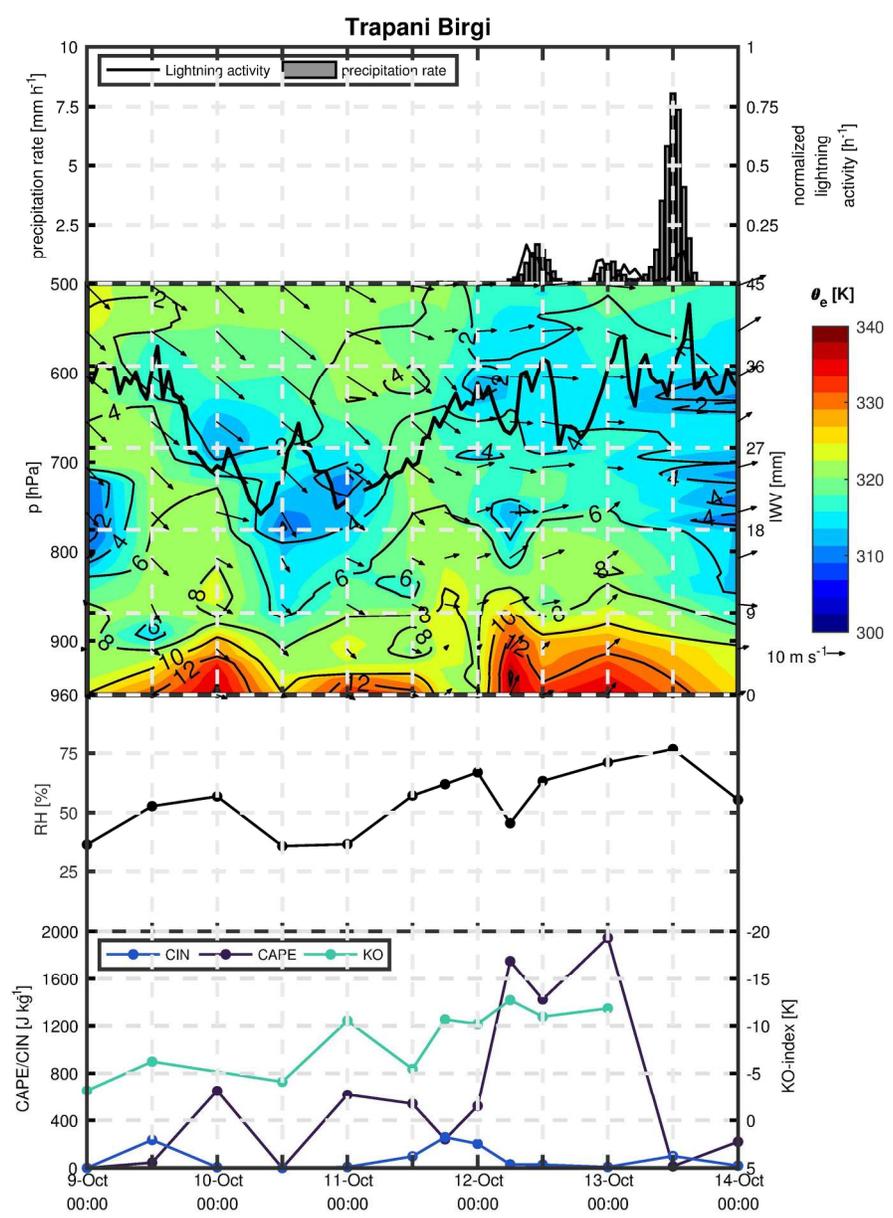
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