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Overview of the first HyMeX Special Observation Period over Italy: observations and model results

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Abstract

During the first Hymex campaign (5 September–6 November 2012) referred to as Special Observation Period (SOP-1), dedicated to heavy precipitation events and flash floods in Western Mediterranean, three Italian hydro-meteorological monitoring sites were activated: Liguria-Tuscany, North-Eastern Italy and Central Italy. The extraordinary deployment of advanced instrumentation, including instrumented aircrafts, and the use of several different operational weather forecast models has allowed an unprecedented monitoring and analysis of high impact weather events around the Italian hydro-meteorological sites. This activity has seen the strict collaboration between the Italian scientific and operational communities. In this paper, an overview of the Italian organization during the SOP-1 is provided, and selected Intensive Observation Periods (IOPs) are described. A significant event for each Italian target area is chosen for this analysis: IOP2 (12–13 September 2012) in North-Eastern Italy, IOP13 (15–16 October 2012) in Central Italy and IOP19 (3–5 November 2012) in Liguria and Tuscany. For each IOP the meteorological characteristics, together with special observations and weather forecasts, are analyzed with the aim of highlighting strengths and weaknesses of the forecast modeling systems. Moreover, using one of the three events, the usefulness of different operational chains is highlighted.

1 Introduction

The HYdrological cycle in the Mediterranean Experiment (HyMeX, http://www.hymex.org; Drobinski et al., 2013) is an international experimental programme that aims at advancing the scientific knowledge of the water cycle variability in the Mediterranean basin. This goal is pursued through monitoring, analysis and modelling of the regional hydrological cycle in a seamless approach. Its multidisciplinary research activity investigates phenomena at different temporal and spatial scales, from the interannual/decadal variability of the Mediterranean coupled system (atmosphere-land-

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ocean) to the single event of severe weather. In this context, a special emphasis is given to the occurrence of heavy precipitation and floods, considering also the associated impacts on society.

The motivation for improving our understanding and the predictability of hydro-meteorological hazards stems from the peculiar characteristics of the Mediterranean region, a nearly enclosed basin surrounded by both highly urbanized and complex terrain close to the coast that makes the Mediterranean area prone to natural hazards related to the water cycle. In particular, during the autumn season, when the sea is still relatively warm, the large thermal gradient with the atmosphere allows for intense heat and moisture fluxes (Duffourg and Ducrocq, 2011, 2013) and therefore the Mediterranean is often affected by heavy rainfall and floods, which are responsible for most of the natural disasters in the region.

Given the central position of Italy in the Mediterranean basin, it is particularly affected by severe weather phenomena and by the consequent hydro-geological effects; hence the interest in improving knowledge and forecasting of disastrous severe weather events is clear for both scientific research and the operational activities. Consistent with the HyMeX programme, within the Western Mediterranean Target Area (TA) three hydro-meteorological sites were identified over Italy (Fig. 1): Liguria-Tuscany (LT), North-Eastern Italy (NEI) and Central Italy (CI). These sites were selected because they are representative of the mechanisms responsible for most of the heavy precipitation and flood events affecting the Italian territory, which can be related to specific large-scale patterns (Tartaglione et al., 2009). For example, the severe weather events that occurred over the Alps in recent years (Rotunno and Houze, 2007; Mariani et al., 2009; Barbi et al., 2012) or in Liguria and Lazio during the autumn of 2011 (Buzzi et al., 2012; Ferretti et al, 2012; Parodi et al., 2012; Rebora et al., 2013), are directly (e.g. orographic precipitation) or indirectly (e.g. cyclogenesis Tibaldi et al., 1990), related to the influence of mountain ranges on atmospheric motions. The steep slopes of the Alps and the Apennines in the vicinity of large coastal areas of the Mediterranean, and the sea itself that acts as a large source of moisture and heat, are the key factors

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in determining the convergence and the rapid uplift of moist and unstable air, being responsible for triggering condensation and convective instability processes (Benzi et al., 1997; Rotunno and Ferretti, 2001). Heavy rainfall events are often associated with the development of intense convective systems (Davolio et al., 2009; Melani et al., 2013), whose scientific understanding and prediction is still an open problem (Weisman et al., 2008; Ducrocq et al., 2008; Bresson et al., 2012; Miglietta and Rotunno, 2012). Moreover, within several small and densely urbanized watersheds with steep slopes, which characterize the Italian area, precipitation events that persist over the same area for several hours can become devastating floods in a relatively short time (Silvestro et al., 2012). In addition, it is worth recalling that the national socio-economical impact of these kinds of events is quite important, as indicated by the number of causalities and damages reported (see, e.g., Guzzetti et al., 2005; Lastoria et al., 2006; Salvati et al., 2010, and references therein).

A key component of HyMeX is the experimental activity based on atmospheric, oceanic and hydrological monitoring for a period of ten years, from 2010 to 2020. Within this time frame, shorter periods of intensive monitoring, named Special Observation Periods (SOPs) are planned. The first field campaign, SOP1 (Ducrocq et al., 2013), dedicated to heavy precipitations and flash-floods, took place in autumn 2012 (5 September–6 November) over the western Mediterranean. It was characterized by an extraordinary deployment of advanced instrumentation, including instrumented aircrafts. In order to prevent or reduce societal losses, progress in the monitoring of and predictive capability for these severe events are needed. This requirement represented the strong motivation that resulted in the large and active participation of the Italian community in the first HyMeX SOP.

The aim of this paper is to provide a scientific overview of the events that affected the Italian area during the SOP1 (Sect. 3), and to highlight the large Italian community effort for the field campaign in terms of coordination and logistics. Moreover, an extraordinary monitoring activity as well as an outstanding number of implemented weather forecasting modelling chains, as described in Sect. 2, were carried out. The

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abundance of information available during the campaign from both observations and numerical models was of great help to the forecaster. The organization and the coordination of the Italian community during the HyMeX campaign are discussed in Davolio et al. (2013).

The activities carried out during the field campaign and planned for the upcoming years represent an important opportunity for exploiting the synergy between a unique database of observations and model simulations, for the study of intense orographic precipitation, in order to improve the knowledge and forecasting ability of high impact weather events. The present study represents just the first step towards a coordinated activity of the large Italian scientific and operational communities in the field.

2 HyMeX SOP1 activity in Italy: observations and models

This section summarizes the instrumentation collecting observations and the forecasting modelling chains producing numerical weather prediction data during the SOP1 in Italy. It must be noted that these include both operational and research instrumentation/model in some cases specifically deployed or implemented for SOP1.

2.1 Observations

Three hydro-meteorological sites of interest were identified over Italy in the HyMeX Implementation Plan (Ducrocq et al., 2010): LT, NEI and CI (Fig. 1). The hydro-meteorological site CI is located at the eastern boundary of the HyMeX North West Mediterranean TA and at the western boundary of the Adriatic TA (Fig. 1, CI). The area is densely populated and it includes the urban area of Rome, with some 4 million inhabitants. The orography of CI is quite complex, going from sea level to nearly 3000 m in less than 150 km. The CI area involves many rivers, including two major basins: the Aniene-Tiber basin (1000 km long) and the Aterno-Pescara basin (300 km long), respectively on the west and on the east side of the Apennines ridge. The

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instrumentation deployed over the CI area belongs to several institutions, including the Integration of remote sensing techniques and numerical modeling for the prediction of severe weather (CETEMPS), National Department of Civil Protection (DPC), Department of Information Engineering Sapienza University of Rome (DIETSap), the Institute of Atmospheric Sciences and Climate of the National Research Council of Italy (CNR ISAC), HIMET (High Innovation in Meteorology and Environmental Tech., L'Aquila), the University of Ferrara, the National Observatory of Athens (NOA), US National Aeronautics and Space Agency (NASA), the Abruzzo Regional Government (RegAb), and finally the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA). The instrumentation deployed over the CI area during the SOP1 is summarized in Table 1. Part of this instrumentation is permanent and run operationally. Conversely, several instruments were specifically deployed for the period of the SOP1 as a consequence of specific international agreements, such as with NASA and NOA. These include an X-band polarimetric mini-radar, a K-band micro 21 rain radar, and disdrometers of three kinds, namely, 2-D-video disdrometers, PLUDIX, and 22 laser disdrometers Parsivel2.

The LT hydro-meteorological site is located at the eastern boundary of the HyMeX North West Mediterranean TA (Fig. 1), in a coastal region where Alpine/Apennine chain is close to the Mediterranean Sea. The high elevation of the mountains – more than 2000 m a.m.s.l. – at few tens of km from the coast explains the complex orography of this area, with many densely populated catchments characterized by steep slopes and limited extents. The Liguria Region Meteo Hydrological Observatory (OMIRL) deployed a ground observation operational network that includes meteorological parameters sensors. Over Tuscany, the Hydrological Service, Consorzio LaMMA, and DPC manage a dense meteorological station network. All the instruments over the LT area that were operational during SOP1 and the Intensive Observation Periods (IOPs) launched in Italy are summarized in Table 2.

The North-Eastern Italy hydro-meteorological site covers an area of almost 40 000 km^2, including three regions (Veneto, Trentino-Alto Adige, and Friuli Venezia

Giulia; Fig. 1, NEI), characterized by multiple river system, with the longest rivers of Italy (Po and Adige), a wide flood plain area, and the eastern Alpine range. Orography plays a major role in extreme hydro-meteorological events, with altitudes reaching nearly 4000 m a.m.s.l. The instrumentation deployed over the NEI area during the SOP1 is summarized in Table 3 and it belongs to several institutions, including OSMER – ARPA FVG, Ufficio Idrologico of Bolzano, MeteoTrentino, ARPAV – Servizio Meteorologico, Areonautica Militare, Regional Civil Protection in Friuli Venezia Giulia. Most of the instruments run operationally, whereas a few of them were specifically deployed for the period of the SOP1, including the mobile X-band polarimetric radar from NOA, the K-band micro rain radar from NASA, and five disdrometers of two kinds (2DVD and Parsivel) from NOA.

For the whole Italian territory and the three hydro-meteorological sites in particular, measurements from the LINET VLF/LF lightning detection network (Betz et al., 2009), with 12 sensors located in Italy, were made available by the CNR ISAC (Rome branch), providing high-precision three dimensional location and time of occurrence of Intra-Cloud and Cloud-to-Ground strokes in real time during the IOPs discussed below.

During the campaign, DPC made available more than 3000 rain gauges in real time; such a richness of surface stations was never available before in a monitoring and forecasting campaign. They were all operational over Italy producing an exceptionally well distributed coverage for the rain measurements.

To complement the ground-based observations, instrumented aircrafts were deployed by the HyMeX international team. This is a crucial element of the HyMeX observational strategy for various reasons: (i) heavy precipitation events (HPE) may occur outside the hydro-meteorological sites and may not be adequately observed without aircraft, (ii) HPE are often related to offshore events and/or synoptic scale systems extending at least partially over the sea, (iii) in situ measurements are critically needed to assess and/or validate some of the products derived from the ground based observation systems, (iv) while ground-based systems provide continuity in time, aircrafts allow high temporal and spatial resolution measurements. Therefore, three instrumented

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aircrafts were deployed by the HyMeX French and German teams, and thus airborne measurements were available occasionally during IOPs over Italy. The following aircrafts were available for the North Western Mediterranean TA:

- SAFIRE FALCON 20 (France) (F20 hereinafter)
  - Payloads: RASTA radar, cloud microphysics sensors, dropsondes
- SAFIRE ATR-42 (France)
  - Water vapor lidar, cloud microphysics sensors, aerosol probe
- KIT 128 (Germany) (DO128 hereinfater)
  - In-situ sensors, turbulent fluxes, radiation, dropsondes

The DO128 and ATR42 were used to sample the upwind low-level flow, focusing on the pre-convective environment during the initiation phase. The F20 was used to observe the precipitating systems during the mature phase with its microphysical probes and radar systems.

Within the Northwestern Mediterranean domain, the airspace is controlled by several distinct authorities with different constraints with respect to the HyMeX aircraft flights. Well in advance of SOP1, the procedures for each aircraft were defined with the respective air traffic control authorities (HyMeX Operation Plan SOP1, 2012). In the flight information regions (FIR) over Italy, these include four flight plans for ATR42 and two flight plans for F20, while twelve flight patterns for the DO128 over Corsica (within the French FIR) are also of some interest for soundings of the upstream flow over Italy.

2.2 Numerical weather prediction models

In the framework of the HyMeX SOP1 a common platform has been implemented to upload products from different numerical weather prediction (NWP) models (available

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online at http://sop.hymex.org). These have been a fundamental means for the forecasting activity during the campaign, allowing for planning with adequate advance the observation strategy of the events of interest.

The Italian community assured several models in use by the different groups participating in the experiment. This provided the possibility of having many products available to refer to during the forecasting phase at the Italian operational center organized in L'Aquila which supported the HyMeX Operational Centre (HOC) in Montpellier (France), as well as to compare performances of different models and thus investigate their potentialities or deficiencies.

The abundance of operational weather prediction models turns out to be a precious help especially for the most difficult task, i.e. making decisions on the take off time for the flight measuring hydro particles in well developed convective cells.

Basically three different operational chains based on the following high resolution models were used: the Advanced Research version of the Weather Research and Forecasting (WRF-ARW) used by CETEMPS (WRF-CETEMPS), by CNR ISAC (WRF-ISAC) and by LaMMA (WRF-LaMMA); the BOlogna Limited Area Model (BOLAM) and the MOLOCH model both used by CNR ISAC (respectively BOLAM-ISAC and MOLOCH-ISAC), by ISPRA (respectively BOLAM-ISPRA and MOLOCH-ISPRA) and by ARPA Liguria, and the COSMO model by ARPA-SIMC producing the only limited-area ensemble forecasts available for Italy.

A short description of each model and of the different implementation schemes used during SOP1 is given in the next sections.

2.2.1 WRF ARW

Several operational chains using WRF-ARW model were implemented during HyMeX, they differentiate either by physical model configuration or domains and resolution. The WRF-ARW model is a numerical weather prediction system that is the result of a joint effort of different research institutes coordinated by the National Center for Atmospheric Research (NCAR, http://www.wrf-model.org). It has been developed both for research

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and operational purposes and it has been used over a wide range of scales for climate studies as well as for Large Eddy Simulations. It solves the fully compressible, non-hydrostatic Euler equations, using the terrain-following, hydrostatic-pressure vertical coordinate with vertical grid stretching. It is based on time-split integration using a 2nd- or 3rd-order Runge-Kutta scheme with smaller time step for acoustic and gravity-wave modes. The horizontal grid is staggered Arakawa-C. A variety of schemes are provided for the model physics: microphysics schemes ranging from simplified physics suitable for idealized studies to sophisticated mixed-phase physics suitable for process studies and NWP; cumulus parameterizations; multi-layer land surface models ranging from a simple thermal model to full vegetation and soil moisture models, including snow cover and sea ice; turbulent kinetic energy prediction or non-local K schemes for planetary boundary layer physics; atmospheric radiation physics. For further details, the reader is referred to Skamarock et al. (2008).

CETEMPS, CNR ISAC and Consorzio LaMMA use WRF-ARW but different operational chains are implemented. A nest-down configuration with two domains running independently and 37 vertical levels is used at CETEMPS (http://skynet.phys.uniroma1/Main_index.htm). The low resolution domain (12 km) covers Italy and part of the Mediterranean basin; it is initialized using ECMWF analysis at 0.125 deg. The highest resolution domain (3 km) covers Italy and it is initialized by the WRF simulation at 12 km. Explicit convection and six different hydrometeors are computed using the new-Thompson scheme (Thompson et al., 2008), together with a Mellor-Yamada 2.5 turbulence closure scheme (Janjic, 2002; Mellor and Yamada, 1982) for the Planetary Boundary Layer (PBL) parameterization. Details of the chain configuration are in Table 4.

Two daily runs (00:00 and 12:00 UTC) with a two-domain, one-way nested configuration initialized using GFS forecasts are operational at CNR ISAC. The father domain has a horizontal resolution of 15 km, 3 km for the innermost; 40 vertical levels are used. The same microphysical and boundary layer schemes as WRF-CETEMPS

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are used. The Kain (2004) cumulus parameterization is used only for the coarser grid (http://meteo.le.isac.cnr.it).

At Consorzio LaMMA two independent configurations are run daily at 12 and 3 km resolutions. The coarse domain (configuration 1 in Table 4) is initialized at 00:00 and 12:00 UTC using GFS analysis and the boundary conditions are upgraded every 6 h. The domain covers central Europe (200 × 300 grid points) and provides 120 h forecasts. Thirty-five vertical levels and a convective scheme are used. The fine resolution domain (3 km) is initialized at 00:00 and 12:00 UTC using ECMWF high-resolution (0.125 deg) analysis and the boundary conditions are upgraded every 6 h. It covers the Italian area (400 × 440 grid points) and provides a 60 h forecast. At this resolution the precipitation is explicitly (no cumulus scheme) computed and the new-Thompson scheme (Thompson et al., 2008) is used for microphysics (http://www.lamma.rete.toscana.it/meteo/modelli).

2.2.2 BOLAM and MOLOCH

The hydrostatic model BOLAM (Buzzi et al., 1994; Malguzzi and Tartaglione, 1999) and the non-hydrostatic model MOLOCH (Malguzzi et al., 2006) have been developed at CNR ISAC and together constitute a forecasting chain, with MOLOCH nested (1-way) into BOLAM. The model prognostic variables staggered on an Arakawa C-grid are wind, temperature, specific humidity, surface pressure and five water species. Hybrid terrain-following coordinates are used as vertical levels. MOLOCH integrates the fully compressible set of equations, with an explicit representation of convective phenomena, deploying a hybrid terrain-following coordinate, relaxing smoothly to horizontal surfaces.

The physical schemes for the two models are almost the same for: atmospheric radiation (a combination of the Ritter and Geleyn, and ECMWF schemes), sub-grid turbulence (E-l closure), water cycle microphysics (Drofa and Malguzzi, 2004), and a soil model with vegetation, as well as the same 3-D Eulerian weighted averaged flux (WAF) scheme for advection. However, in order to account for the complex processes

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characterizing convective systems, differences are found between MOLOCH and BOLAM. The Kain-Fritsch parameterization scheme is implemented in BOLAM for cumulus convection, whereas convection is explicitly computed in MOLOCH. Further details are available at http://www.isac.cnr.it/dinamica/projects/forecasts.

Several forecasting chains based on BOLAM-MOLOCH have been implemented for the SOP1. These chains differ in terms of initial and boundary conditions, horizontal grid spacing (see Table 4), vertical levels and domain extension. At CNR ISAC two different chains were operated, both driven by the GFS global model, but initialized at different times, namely 18:00 and 00:00 UTC. Moreover, the models were run at different horizontal grid spacings (Table 4) in the two chains. At ISPRA, a BOLAM-MOLOCH chain was specifically implemented for SOP1 (Table 4). This chain was initialized by 0.15° ECMWF analyses and forecasts from the 12:00 UTC run of the previous day. In addition, the ISPRA chain currently operational within the SIMM (Sistema Idro-Meteo-Mare) forecasting system (Speranza et al., 2007; Casaioli et al., 2013; http://www.isprambiente.gov.it/pre_meteo/simm.html) was also provided. This chain is based on BOLAM integrated in cascade over two (1-way) nested domains (Table 4) and it is driven by ECMWF global model at 0.5 deg resolution, using the 12:00 UTC run of the previous day. Although different, all the BOLAM domains deployed in the ISPRA chains include the whole Mediterranean basin.

2.2.3 COSMO

COSMO is the limited-area model used by COSMO consortium (http://www.cosmo-model.org) and is based on the primitive hydro-thermodynamical equations for a compressible non-hydrostatic flow in a moist atmosphere with no scale approximations (for an overview of COSMO, the reader is referred to Steppeler et al., 2003).

In the framework of HyMeX, two ensemble systems based on COSMO model were provided by ARPA-SIMC:

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- COSMO-LEPS (COSMO Limited-area Ensemble Prediction System) is the operational limited-area ensemble prediction system of the COSMO consortium, running on a daily basis since 2002 (Montani et al., 2011). It is a convective-parameterized ensemble and is run twice a day (starting at 00:00 and 12:00 UTC) at 7 km, with 40 vertical levels and a forecast range of 132 h. It is composed of 16 members, with initial and boundary conditions taken from elements of ECMWF EPS selected via a clustering analysis-selection technique.

- COSMO-H2-EPS (COSMO HyMeX 2.8 km Ensemble Prediction System) is a research ensemble system, designed for the HyMeX program (Marsigli et al., 2013); COSMO-H2-EPS is an atmospheric convection-permitting ensemble and is run once a day (starting at 12:00 UTC) at 2.8 km, with 50 vertical levels and a forecast range of 36 h. It is composed of 10 members, which take initial and boundary conditions from the first 10 COSMO-LEPS members.

Both COSMO-LEPS and COSMO-H2-EPS also benefit from model perturbations applied by varying few parameters of the COSMO physical schemes.

3 SOP-1: the intense observing periods

The first field campaign (SOP1, Ducrocq et al., 2013) of the HyMeX project was dedicated to heavy precipitation and flash-floods; it took place in autumn 2012 (5 September–6 November) over the western Mediterranean area. During the SOP1 twenty IOPs were launched, ten of which occurred in Italy (Table 5). During the campaign two main features were affecting the large scale regime of the Mediterranean region: a negative NAO index for most of the time and the long duration of the hurricane Nadine (Calas et al., 2013). The first factor made the weather regime favourable for precipitating system over southern Europe; the second factor strongly reduced the long term predictability for the first month of the campaign. From the water vapour supply point of view all the events were characterized by a prevailing cyclonic condition before the events. Based on Duffourg and Ducrocq (2011, 2013) the contribution to the water supply from the sea surface evaporation is expected to be reduced with respect to anticyclonic conditions.

During the campaign several troughs entered the western Mediterranean and swept the Italian regions after having affected Spain and/or France; only few events produced cyclogenesis over the Genoa Gulf or deep trough over the Tyrrhenian Sea (IOP13, IOP16c, IOP18). During the campaign, several smooth troughs entering the western Mediterranean Sea were often observed producing westerly-south-westerly flow over Italy (IOP2, IOP6, IOP7b, IOP12, IOP19); occasionally meso-low developed associated to PV anomaly (IOP4, IOP16a). Most of the events were fairly well forecasted. However, IOP4 was characterized by a low predictability of the exact position of the heaviest precipitation, which was highlighted by the large variability among the model forecasts.

Several events were characterized by convection over the sea followed by orographic precipitation: during IOP2 (12–13 September 2012) convection developed over the northern Adriatic, then warm and moist advection from the south produced precipitation inland; during IOP13 (15–16 October 2012) convection associated with a convergence line entered CI from the Tyrrhenian sea; during IOP19 (3–5 November 2012) southerly advection of warm and humid air produced either convection on the Liguria sea and/or orographic precipitation along the Maritime Alps. In this study, these three events will be analyzed from both observing and modelling points of view.

3.1 IOP 2 – NEI

IOP2 occurred on 12–13 September 2012 involving mostly North Eastern Italy. The event was characterized by a NAO index close to zero (0.2). In the following sections the meteorological characteristics of the event are described.

3.1.1 Synoptic situation

10 September 2012 was characterized by a smooth ridge extending from Scandinavia to the entire Mediterranean basin. During the following two days, the intrusion of a North

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Atlantic trough from the west weakened and pushed eastward the ridge producing cold and moist polar air advection toward Northern Italy. On 12 September, at 06:00 UTC, a shallow cyclone developed over the Gulf of Genoa and moved north-eastward. At the same time on the eastern side of NEI, dry air aloft, as shown by the reddish area on the northern Adriatic sea (Fig. 2), associated with a moderate southerly surface wind, advecting warm and moist air from the Adriatic Sea toward the eastern part of the Po Valley, produced an increase of the potential instability. The lower atmosphere was destabilized as confirmed by both observations (Fig. 4) and high resolution weather forecasts (Fig. 5a, b). During the afternoon, the low-tropospheric cold advection on the northern side of the Alps generated a significant pressure gradient, associated with a surface depression, which triggered northerly winds descending along the Alpine slopes and spreading into the eastern Po Valley during the passage of the cold front, as most of the operational high resolution weather forecasts confirmed (not shown). It is worth noting that in the three previous days a positive sea surface temperature anomaly of 1.5 °C was recorded over the northern Adriatic Sea (as observed at the Trieste meteorological station).

3.1.2 Observations

During 12 September several convective events affected the eastern part of Veneto and the plain of Friuli Venezia Giulia (FVG hereafter).

Figure 3 shows the areal distribution of the accumulated daily rainfall recorded in the Veneto region (source ARPAV) and in FVG region (source OSMER – FVG): a maximum of 97 mm/24 h (53 mm in only 1 h, between 13:00 and 14:00 UTC) was recorded at Crespano del Grappa (45.5028 °N, 11.5027 °E). In the mountain side a small area (Fig. 3, dark red) of precipitation exceeding 150 mm in 24 h is clearly shown, whereas the Surface Rain Intensity (SRI) retrieved by the Fossalon di Grado (45.73° N, 13.49° E) radar, calibrated with the rain gauge measurements, detected two small areas of precipitation exceeding 150 mm in 24 h (not shown). The daily accumulated precipitation reached up to 106 mm at Palazzolo (45.81° N, 13.05° E, Fig. 3b), with a detected hourly

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maximum of 52 and 13 mm in only 5 min. In the following, the hailstorm that hit Latisana (45.78° N, 12.99° E) at about 09:00 UTC will be analyzed in more detail.

In the morning of 12 September 2012, two thunderstorms developed in the area, hereafter called the "Northern Storm" (affecting the Rauscedo area 46.04° N, 12.83° E) and the "Southern Storm" (affecting the area west of Latisana). The Northern Storm was active by 06:30 UTC (08:30 local time) over the western part of FVG and moved south eastward; the Southern Storm started later (08:00 UTC) in the northern Adriatic coast of Veneto and moved inland toward NE. The south-easterly low level wind feeding moisture toward the orographic barrier of the Carnic Pre-Alps, is probably one of the factors leading to the development of the Northern Storm (Kerkmann et al., 2012). The map of both the Vertical Maximum Intensity (VMI) of the radar in Fossalon di Grado at 08:20 UTC and the surface station measurements at 08:25 UTC, overlapped with the cloud-to-ground lightning (source CESI-SIRF), clearly shows (Fig. 4a) the moist flow. This was evidenced by the high values of equivalent potential temperature (Θ_e) along the coast (Lignano, 45.70° N, 13.14° E) as high as 341 K, and inland (Palazzolo) as high as 342 K showing the localized high-Θ_e flux feeding the storms (Figs. 4, and 5a, b). A sudden reinforcement of the Southern storm as shown by the radar (Fig. 4b and c, 08:40 and 09:00 UTC, respectively) would suggest the convergence of the south-easterly low level wind with the downdraft produced by the Northern Storm (Fig. 4) as the mechanism for its reinforcement. This led to the formation of a storm with supercell features. High resolution forecasts (WRF-ISAC and MOLOCH-ISAC) further support this hypothesis, showing a weak convergence between the downdraft produced by the cells and the south easterly flow (not shown) at the time of the sudden reinforcement of the Southern storm. The *supercell* features are further confirmed by the radar image (Fig. 4c): the maximum reflectivity values (above 60 dBZ) are located at about 5 km a.m.s.l., with a very low cloud base (about 500 m high) and a top above 13 km. Moreover, a *meso-cyclone* signature in the Doppler field (not shown) was detected. Finally at 09:00 UTC strong hail was reported on the A14 highway near Latisana. At the same time a "convergence line" developed in the northern Adriatic as most of the

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operational high-resolution models predicted (not shown). Afterward, the “Southern” cell moved eastward, dissipating nearby Trieste at 11:00 UTC.

The Udine-Campoformido (46.03° N, 13.18° E) extra-soundings at 06:00 and 18:00 UTC, allow for profiles available every 6 h. During the morning, very high values of potential instability with Θ_e maximum above 330 K between 500 and 1000 m of altitude (Fig. 6) are detected. A strong rotation of the low level winds between the 06:00 UTC and the 18:00 UTC is also found, confirming a suitable environment for strong convective activity. The 06:00 UTC Udine sounding exhibits a Lifted Index of only −0.7 °C, but the difference in temperature between the Most Unstable Parcel ($\Theta_e = 336$ K) lifted pseudo-adiabatically at 500 hPa and the environmental air (DT500) was as low as −5.0 °C. CAPE was almost 1680 J kg^{-1} and the precipitable water (PWE) was 34 mm. These values of potential instability indices are very high for this time of year in FVG (mid-September).

Finally, the ATR42 flew over the north Adriatic Sea detecting the low level southerly flow by mid day which is after the super cell ended. LIDAR measurements (not shown) documented a well developed PBL (up to 2 km) over the Adriatic sea, characterized by high values of water vapour mixing ratio.

3.1.3 Peculiarities and model simulations

Short range forecasts fairly well reproduced the large scale and the mesoscale features responsible for the event. In fact, all the investigated high resolution operational models capture the convergence among the Low Level Jet (LLJ) close to the east coast of the northern Adriatic, the southwesterly flow across the Apennines (similar to alpine Foehn), the east-northeasterly barrier flow just inshore the FVG coast (Fig. 5a, b). This convergence was responsible for the convective triggering. A strong gradient of Θ_e over the Adriatic was produced by the warm and moist air associated with the LLJ and the dry SW airflow. The northern part of the LLJ reached the coasts of FVG, producing a tongue of high values of Θ_e and CAPE (Fig. 5a, b). Although the mesoscale environment is correctly reproduced, the exact location and timing of cells weakly depended

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on both the model and the initial condition. Indeed, small differences had a strong impact on the simulation of the convective cells that crossed the NEI area during the whole day. Focusing on the morning event, no model simulation was able to correctly reproduce the evolution of both storms. For example, the 2.3 km MOLOCH-ISAC run (initialized through the GFS forecasts starting at 00:00 UTC, 12 September) fairly well reproduced the southern cell (Fig. 7a) but missed the northern one, while the WRF run (initial conditions at 12:00 UTC, 11 September) captured only the northern cell (Fig. 7b).

3.2 IOP 13 – CI

IOP13 occurred on 15–16 October 2012. The weather system involved all three Italian target areas: LT, NEI and CI; it was characterized by a NAO index approximately zero (0.13 during 15 October, 0.6 during 16 October) . An overview of the event over CI area is presented in the following sections.

3.2.1 Synoptic situation

This IOP was selected as a typical situation of frontal precipitation affecting Central and North-eastern Italy. The precipitating events were associated with a wide upper level trough extending from northern Europe to Spain (Fig. 8) in the early morning of 15 October 2012. A cold front was moving eastward, advecting low level moist air towards Corsica and Italy. The main convective activity was located in the warm air ahead of the front, in the narrow cold frontal rainband and behind, under the upper cold low. During the morning of that day a secondary V-shaped trough started to form over France, and moved eastward. A strong PV anomaly (reddish area in Fig. 8) associated with the deep trough and the warm temperature advection at 700 hPa allowed for the development of several MCS in the central and south Tyrrhenian Sea (Fig. 8).

In the following hours the trough deepened and moved eastward, by 18:00 UTC of 15 October, a cyclone developed over Gulf of Genoa (not shown), with an enhancement of PV anomaly. The associated frontal system moved rapidly toward the Italian peninsula, causing moist air advection over the Tyrrhenian Sea and consequent deep convection on the Tyrrhenian coast, east of Rome. In the evening a cut-off low developed over Northern Italy, moving eastward and crossing the North-eastern part of the Italian peninsula by the early morning of 16 October.

3.2.2 Observations

During this IOP all the operational instruments and the ones purposely deployed over the CI site were operational, with the exception of the Monte Midia weather radar, which was out of order since 13 October. Figure 9 shows the 24 h accumulated precipitation on 15 October recorded by the Italian rain gauge networks: a maximum of 60 mm/24 h was reached. The inset in Fig. 9 shows the hourly precipitation recorded by one of the rain-gauges located north of Rome (Formello, 12°23′55.34″ E, 42°04′41.40″ N). It clearly shows that most of the precipitation occurred in the late afternoon (from 17:00 to 19:00 UTC) with a remarkable maximum of rainfall rate of 35 mm h^{-1} at 18:00 UTC, whereas little precipitation amounts were recorded at night and in the morning. The spatial distribution and the evolution of precipitation can be inferred from the radar reflectivity pattern (Fig. 10). Most of precipitation occurred on the western slope of the Apennines. Indeed the NASA Parsivel disdrometers purposely installed at L'Aquila (on the Eastern slope) and Pescara (on the East coast of CI) recorded only 9.8 and 5.0 mm, respectively, on that day. Conversely, the NASA 2D video disdrometer at "Sapienza" University, in Rome, recorded a total amount of 25 mm, 20 mm of rain, cumulated between 17:40 LST and 18:40 LST, being 114 mm h^{-1} the highest rain rate estimated in 1 min. Such measurements are consistent with measurements of operational rain-gauges available in Rome downtown.

In addition to the operational soundings available from the Global Telecomunication System (GTS), dedicated extra soundings were launched by the HyMeX Italian team as listed in Table 5. Two instrumented aircrafts (ATR42 and F20) were used to provide evidence of the moist south westerly flow and the vertical cloud structure. The ATR42 flew on 15 October over the Tyrrhenian Sea; the earlier flight (take off at 05:00 UTC

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from Montpellier to Bastia) crossed the cold front; the later one (take off at 08:00 UTC from Bastia to Sicily and back) crossed the south-westerly flow. The return flight took place from Bastia to Montpellier at the end of the morning. The flight was successful except for returning early (before reaching Palermo) because of the presence of cumulonimbus clouds over Sicily.

The F20 flight was dedicated to document the cloud properties of the precipitation systems, exploiting the joint coverage of X- and C-band radars in Central Italy, and measurements collected by the 94 GHz Doppler radar RASTA (Radar Aéroporté et Sol de Télédétection des propriétés nuAgeuses; Protat & Al, 2009) onboard the F20 aircraft. The main objectives of these joint observations were: (i) to intercompare the capabilities of dual polarized radars at C and X band having different specifications (i.e. different beam-widths, peak powers, central wavelengths, scanning modes); (ii) to compare the radar-derived microphysical retrievals with ground based network of the disdrometers in terms of particles size distributions and precipitation rates. Preliminary results (Marzano et al., 2013) show that path attenuation correction and clutter removal are critical steps in radar data processing especially at X band, whereas good agreements have been found between radar products and disdrometer data for the particle concentration and mean diameter estimation especially for stratiform rainfall.

The CNR radar Polar 55C was available during this IOP to provide, from the Rome site, both conventional volume scanning made of sweeps at different elevations and RHI mode, that is scanning with increasing elevation angle at a fixed azimuth direction, along both the directions of the HyMeX instrumented sites and along the F20 route. The reflectivity maps were collected by Polar 55C on 15 October at elevation angle equal to 1.6°. This angle allows both to avoid the influence on radar beam propagation of obstacles close to the radar and at the same time to keep the radar beam at low height. For a correct interpretation of the radar maps, it should be noted that a sector between the azimuth angles of 120 and 150 degrees is almost blocked by the Colli Albani hills. The reflectivity maps collected at 04:00, 07:00 and 10:00 UTC (not shown), show weak precipitation characterized by sparse convective systems. At 04:00 UTC convective cells developed over the Tyrrhenian Sea, and moved along the NE direction. Later on this system was replaced by a second one of smaller extent. The third system, characterized by more scattered cells, originated southward respect to the previous ones. No lightning activity was detected at these time steps either over the sea or around Rome (Fig. 11). In the afternoon, a well organized squall line, aligned NE-SW, developed and moved southeastward as shown by the radar (Fig. 10) and the lightning images (Fig. 11). The most intense part of the system moved very rapidly across Rome. The peak intensity of lightning activity in Rome occurred between 18:00 and 19:00 UTC, and it was associated with the most intense precipitation.

At 17:57 UTC Polar 55C operated in RHI mode along the direction of 293° azimuth. Figure 12 shows reflectivity and differential reflectivity (respectively a and b in Fig. 12) both corrected for rain attenuation effects) and it reveals the vertical extent (up to 10 km) of the convective cells (note that the apparent decrease of the height with distance from radar is an effect of both attenuation and reduction of minimum detectable signal with distance). The presence of a convection core at 4 km (Fig. 12b) is confirmed by the high differential reflectivity, while the trailing part of the convective systems exhibits a quite thick and not well defined bright band signature (Fig. 12c, d).

The F20 flight started as soon the most intense convection begun to decrease, supported by a correct forecasting of the convective activity well before its occurence. The F20 aircraft took off at 18:20 UTC from Montpellier, followed a flight plan over CI and reached the rainfall area over the Italian peninsula at 19:00 UTC (Fig. 13). To acquire as much valuable information as possible it performed two loops around the Rome-Pescara transect (Fig. 13); no dropsondes were launched. During the flight along the northern leg convective precipitation was observed close to CI, behind the cold front. Between 19:20 and 20:30 UTC the most interesting legs were performed; during the Rome-Pescara route, the height of the flight was around 10 km, just above the top of the cloud, confirming the height observed by the Polar 55C RHI scans. On the way back, both of the height and speed (see the white track on the top panel of Fig. 13) of aircraft decreased allowing in-cloud flights. The 94 GHz reflectivity recorded by the

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RASTA radar provides a clear signature of the melting layer. Figure 12 shows an RHI collected by Polar 55C during the F20 flight (position of F20 red circle in Fig. 12a). Both sensors detected a stratiform structure of precipitation. Differential reflectivity shows an increase around at 6 km height and 10 km from the radar, indicating the formation of oblate ice particles.

3.2.3 Peculiarities and model simulations

For this event both deterministic and ensemble forecasts were analyzed. This richness of products eased the operational forecaster's work. The fairly good agreement among the models in forecasting moderate precipitations over the western side of CI supported the decision for the flight planned on the afternoon of 15 October 2012. As will be pointed out inthe following, the models reproduced quite well the rain pattern from the Tyrrhenian coast to the western side of Apennine (Figs. 14, 15 and 17). The WRF-CETEMPS simulation initialized on 14 October 2012 at 12:00 UTC shows the onset of the low level south-westerly jet after midnight. The flux strengthened during the morning reaching a maximum of wet and warm advection in the late afternoon. The Θ_e map shows values over 330 K intruding into the middle Tyrrhenian coasts (Fig. 14a); the convergence between the south-westerly and the westerly flow allowed for triggering and developing a convective line. The radar detected between 17:00 UTC and 18:00 UTC (Fig. 10), a convective squall line over the west side of the CI target area. WRF-CETEMPS correctly reproduces the timing and the multi-cellular character of this structure as shown by the simulated radar reflectivity (Fig. 14b). The comparison between the 24-h precipitation by the rain gauges (Fig. 9) and the model (Fig. 15a) reveals a very good agreement in terms of both maximum value (approximately 60 mm/24 h) and location (north-east side of Lazio region). Similarly, MOLOCH-ISPRA (using the same initialization as WRF-CETEMPS) reproduced the growth of the Tyrrhenian low-level jet during the morning and the development of the two squall lines during the afternoon, but displaying some differences in the details of the rainfall fields. As a result, the 24 h precipitation forecast (Fig. 15b) provided a good forecast for the northern squall line

(Fig. 9), but differences in the forecast between MOLOCH-ISPRA and WRF-CETEMPS were instead larger over other areas: the former model seems to provide a better forecast over the northern Campania (41.5° N, 13–14.5° E, Fig. 15b), while the latter model performs better over the southern Tuscany (43–44° N, 10.5–11° E, Fig. 15a). A correct space-time forecast of multiple squall lines which grow into the warm sector of a Mediterranean cyclone during its passage on the Tyrrhenian Sea may crucially depend on the ability of the NWP model in reproducing the fine structure of the cyclone. This clearly appears comparing the synoptic forecasts provided by the 0.07 BOLAM-ISPRA (which drives the MOLOCH-ISPRA) with the corresponding ones provided by the 0.1° BOLAM-ISPRA (belonging to the low-res ISPRA forecasting chain). In particular, at 18:00 UTC on 15 October, the 0.07° BOLAM (Fig. 16, right panel) shows a more accurate forecast (in shape and in position) of the PV anomaly, evidenced as the reddish region in the SEVIRI AirMass RGB image (Fig. 8), than the 0.1° BOLAM (Fig. 16, left panel). This produced an increased skill in detecting the precipitation field. Indeed, the double convergence line over the Tyrrhenian Sea is found only for the 0.07° BOLAM forecast (not shown). As for the probabilistic prediction of this event, COSMO-LEPS provided an early indication of the possible occurrence of a HPE over the CI area. At the 72 h forecast range, the possibility of a heavy precipitation scenario was shown by some ensemble members (e.g. members 3, 7 and 8) with a good prediction in terms of amount and, to a lesser extent, location. This was confirmed by the probability maps of precipitation exceeding 10 and 50 mm in 24 h (Fig. 17a, b respectively), which indicated CI as an area possibly affected by moderate-to-intense precipitation with probability peaks of 70 % at the higher threshold. At shorter time ranges, the high-resolution information conveyed by COSMO-H2-EPS is shown in Fig. 17c and d. The 24 h predicted precipitation by the 10 ensemble members clearly showed a better localized area possibly affected by heavy rain: some ensemble members predicted the occurrence of precipitation above 50 mm in the region 41–42° N, 13–14° E. The probability maps for 24 h precipitation above 10 and 50 mm (Fig. 17c and d, respectively) indicated that the area most likely affected by the weather events was located more

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inland rather than near the coast, confirming the information provided by the deterministic systems (Fig. 15). Further investigation are necessary for IOP13 to evaluate why two deterministic model chains sharing the same ECMWF initialization provided an overall good forecast but with some differences. Further studies will be worthwhile to investigate whether these differences are a consequence either of the different models used (MOLOCH vs. WRF), or of the differences in the parent model design (0.07° BOLAM vs. 12 km WRF), or of a combination of both.

3.3 IOP 19 – LT

IOP19 was dedicated to HPE over LT-NEI on 3–5 November, which induced local flash-flooding. The event was characterized by a well defined negative NAO index, −2.7 during the first day and −3.3 during the second one, remaining negative or zero until the end of the year.

3.3.1 Synoptic situation

During 3 November 2012, a widespread upper-level low located over the Atlantic Ocean began to move southward, turning its axis anticlockwise while approaching Western Europe. A strong polar upper level jet (more than 70 $m\,s^{-1}$) associated with the trough, began to flow over the western Mediterranean, connecting to the subtropical jet (Fig. 18a, b). The Mediterranean Sea was affected by a strong south-westerly flow and a Warm Conveyor Belt ahead of the cold front advected very warm subtropical air (values of Θ_e at 850 hPa of more than 323 K, not shown), at mid and low levels (20 $m\,s^{-1}$ at 700 and 15 $m\,s^{-1}$ at 850 hPa). At the surface a cyclone developed on the evening of 4 November 2012 over the Lion Gulf, enhancing a strong southerly flow over the Tyrrhenian and Liguria Sea. By 21:00 UTC, WRF-ARW LaMMA shows the entrance of a south-westerly low level jet associated with a strong increase of Θ_e (Fig. 18c).

The synoptic situation remained unchanged until the morning of 5 November, because of the blocking induced by a high-pressure area over Russia. Then, the weakening of the ridge allowed the main cold frontal system to move eastward crossing Italy.

3.3.2 Observations

During IOP19 heavy precipitation occurred over both LT and NEI. On 3 November maxima of precipitation were recorded mostly on the Liguria side of the target area. At Novegigola station (lat = 44.22, lon = 9.89, 382 m a.m.s.l) precipitation reached 85 mm/24 h, with an hourly precipitation of 15 mm h^{-1} between 16:00 and 17:00 UTC (Fig. 19a). During the following day, the south-westerly flow moved southward shifting the maxima of precipitation towards Tuscany, especially over the Apuan Alps and the northern Apennine range. During this day, the Campagrina station (Apuan Alps, lat = 44.05, lon = 10.26, 832 m a.m.s.l) recorded 226 mm/24 h, with a maximum hourly precipitation of 33 mm h^{-1}, between 23:00 and 00:00 UTC (Fig. 19b). Most of the rain was recorded between 18:00 UTC on 3 November and 04:00 UTC on 5 November reaching 317 mm/3 days at Campagrina. The maximum hourly precipitation was 39 mm h^{-1} between 02:00 and 03:00 UTC on 5 November at Lago Scaffaiolo (lat 44.12, lon 10.81, 1811 m a.m.s.l), just after the entrance of a strong low level jet advecting warm air toward this area. The precipitation was mainly orographic, with an average hourly rate of around 6–10 mm and peaks of 30–40 mm. No deep convection was observed, since lightnings were not recorded.

In the following hours the system moved inland producing precipitation over the northern Apennines at Lago Scaffaiolo, between 02:00 and 03:00 UTC, 5 November 2012, two maxima were recorded: 124 mm/24 h and 39 mm h^{-1} (not shown).

During IOP19 additional observations were performed: the aircrafts (ATR42 and F20) flew in the upstream part of the flow, deploying dropsondes. At S. Giuliano (Corse) three hourly soundings were launched and two planetary boundary layer balloons from Balearic Islands flew toward Gulf of Genoa (Table 5).

The F20 took off from Montpellier to fly over LT area from 21:00 UTC, 4 November (flight number 3, Fig. 20b), measuring reflectivity by the Doppler radar RASTA

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(Fig. 20a) along the flight track. High reflectivity values were recorded between 22:00 and 23:15 UTC, when the F20 flew over the Genoa Gulf and the Apennine range; high values were detected over the whole atmospheric column up to 8–10 km, with maxima at approximately 5 km and over the mountains (Fig. 20a).

Also, two dropsondes were deployed in the Gulf of Genoa in DS1 (44.055° N, 8.689° E), and DS2 (44.052° N, 9.388° E) at 21:40 UTC and 21:45 UTC, respectively documenting a nearly saturated profile up to 700 hPa. DS1 showed a sharp low level inversion, below 900 hPa (Fig. 21a). This is probably produced by a northerly low level flow locally advecting cooler air from the Po Valley as the lowest level wind observation suggests (Fig. 21a, DS1). On the contrary intense south (south-westerly aloft) wind was recorded at DS2. This wind pattern, northerly out-flow on the western side of Liguria coast and southerly advection in the eastern part, is often observed in this area in correspondence with heavy precipitation events. Among the mesoscale models, the WRF-ARW LaMMA clearly showed cold air and easterly low level wind in the Po Valley producing an outflow in the eastern side of Liguria region (not shown). Several case studies of past events occurring in this area (IOP8 during MAP 19–22 October 1999, 5Terre and Genoa Floods, 25 October and 4 November 2011 respectively) produced this local wind structure (Rotunno and Ferretti, 2003; Buzzi et al., 2012; Ferretti et al., 2013), which was never confirmed before because of lack of observation. Finally, wind velocity at DS1 increased with height with a maximum of 30 $m\,s^{-1}$ over 500 hPa, whereas at DS2 and DS3 (Fig. 21b, c) the wind velocity reached a maximum (25 $m\,s^{-1}$) at 700–800 hPa.

Two PBL Balloons were launched from Minorca on 4 November at 11:00 UTC and at 14:30 UTC, respectively. Both reached the Gulf of Genoa (Fig. 22) measuring temperature, relative humidity, wind and pressure. Along the balloon track a temperature drop starting at 16:00 UTC associated with a wind intensity increase and a local depression was clearly recorded (Fig. 22a, b, c). At this time the balloon was out of the Gulf of Genoa and precipitation had already started.

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3.3.3 Peculiarities and model simulations

IOP19 was characterized by heavy precipitation occurring in the north western edge of Tuscany. This represents a typical event in this area, generally well forecast days in advance by operational models that are able to properly describe the main orographic forcing.

The main characteristics of the heavy precipitation occurring in this area are:

- south-westerly warm and moist air advection producing an unstable environment;
- topography plays a critical role either in lifting humid air above the Apennines (reaching 1800 m in less than 20–30 km from the coast) or in forcing the low level wind direction, possibly developing a local area of convergence. The correct reproduction of the low level convergence is crucial, because it determines the location where maxima of precipitation occur, leading to flash floods.
- low level cold air in the Po Valley, resulting in a very stable stratified boundary layer (ground thermal inversion) may lead to very intense local drainage flow or gap flow from the valley, restraining the inflow in the eastern edge of Liguria region or north western edge of Tuscany, and resulting in nearly opposite winds (in respect to the gradient flow) producing local convergence.

The previous characteristics are generally well reproduced if high resolution models are used.

The observed precipitation showed two distinct maxima (Fig. 19) over the two parallel mountain ridges (being the Apuan Alps on the west and close to shore, and the Apennines ridge on the east). Maxima values of precipitation reached approximately 220 mm over the Apuan and 130 mm over the Apennines. Most of the models correctly simulated the precipitation structure with the two maxima over the two mountain ridges, but most of them produced more precipitation over the Apennines than on the Apuan: WRF-ARW LaMMA overestimated the precipitation over the Apennines producing 150–200 mm and slightly underestimated the rain on the Apuan producing 100–150 mm

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(Fig. 23a). This result infer that WRF-ARW overestimated the orographic forcing associated with the highest mountain ridge (Apennines) which turned in an underestimation of the Apuan maxima of precipitation.

Beside different physics, characteristics and employed initial/boundary conditions (ECMWF or GFS for model configuration details see Sect. 2.2) most of the Italian operational models produced similar position and amount of the precipitation maxima, as will be discussed in the next section. Moreover, the +24 h and the +48 h WRF-ARW LaMMA forecast (Fig. 23a, b) showed very similar patterns suggesting a very high forecast reliability.

Leaving aside the incorrect position of the maxima, the weather forecast during IOP19 allows the assessment that heavy orographic precipitation in this area is quite well forecast by numerical models, especially in terms of predictability. As far as for precipitation distribution and amounts are concerned, differences between models and configurations exist, even though a direct comparison might also be influenced by initial conditions. The most interesting object of study for this IOP is the exact location of maxima of precipitation, a subject which needs further modeling investigation.

3.4 Operational chains during IOP19

To the aim of further investigating the usefulness of the operational chains during the campaign and to better understand the previously analyzed feature of IOP19 a gross comparison among all the Italian operational models is carried out for this IOP only. Because of the different configurations (domain, resolution, initialization, etc.) of the operational forecasts a rigorous inter-comparison among the models cannot be performed. However, the following exercise will allow the inferrence of a sort of spread of the precipitation forecast. The 24 h accumulated precipitation ending at 00:00 UTC of 5 November is shown for all the available models (Figs. 24, 25, 26). Figure 24 shows the 24 h accumulated precipitation for different MOLOCH operational chains. All of them caught the two observed maxima (Fig. 19) and the pattern of the precipitation distribution. The values of the two maxima differ among the MOLOCH chains varying from

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approximately 250 mm/24 h down to 100 mm/24 h, but as for the previously analyzed results of WRF-ARW LaMMA, the maximum is produced on the Apennines, suggesting again a too strong orographic forcing. As far as the WRF-ARW chains (Fig. 25) are concerned, again the precipitation pattern was well reproduced in terms of both intensity and distribution. Finally, regarding the ensemble forecast from COSMO (Fig. 26), the position where intense precipitation is expected agrees with the observations, thus reinforcing the deterministic models results. As for the other models the maxima are underestimated.

Being obtained using different models and different configurations (a sort of multi-model multi-analysis ensemble), these results suggest that the precipitation forecast for IOP19 was highly predictable both for the amount and location. However, different results from similar chains indicate that model settings may maintain remarkable variability in the precipitation forecasts. Anyway, this gross comparison indicates the usefulness of using different model chains for weather forecasting. A deeper analysis of the model results should be performed to understand model behaviours, but it is beyond the aim of this paper and is left to future work.

4 Conclusions

In this paper three events occurred during the SOP-1 HyMeX campaign (5 September–6 November 2012) are presented. During the campaign three hydro-meteorological sites were set on Italy: Liguria-Tuscany, North-Eastern Italy and Central-Italy. Operational instruments run in all the Italian hydro-meteorological sites, and over CI research instruments were also activated during selected IOPs. All events were characterized by a trough entering the Mediterranean region from the northwest and deepening while crossing the Mediterranean Sea, except for IOP2. All of them produced localized heavy precipitations and most of the operational models well forecasted the events. The three events are chosen because of their characteristics and because each of them affected

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one of the three Italian hydro-meteorological sites: IOP2 over NEI, IOP13 over CI and IOP19 over LT.

IOP2 occurred on 12 September 2012 producing several thunderstorms and a supercell. The storms produced heavy precipitation exceeding 50 mm h^{-1} and hail. The triggering and in particular the intensification of the cell, turning into supercell, seems to be related to the southerly low level flow advecting moist air from the Adriatic sea. The main characteristics of the cells were described by operational radars Moreover, the ATR42 flight detected the southerly flow advecting moist air at low level. High resolution models caught the main features of the storms, but failed in producing the very exact evolution of all the convective systems. Measurements and wind forecasts suggest the convergence of the southerly flow with the downdraft of one of the cells as the main mechanism responsible for supercell development.

IOP13 occurred on 15–16 October 2012 producing a convective line SW-NE oriented crossing the city of Rome. The event was characterized by a deep upper level trough and cyclogenesis over Genoa Gulf. The entrance of a south westerly low level jet advecting warm and humid air and the convergence with the westerly flow triggered the convective line. Moderate precipitation was recorded at several stations, but a high rain rate (35 mm h^{-1}) was recorded at the passage of the convective line. Both operational and research radars well documented the event. Moreover, Polar 55 radar operated at fixed azimuth and variable elevation angle along the F20 flight, operating together with the RASTA radar on-board. Also in this case the models well forecasted both the convergence line and the accumulated precipitation.

IOP19 occurred on 4–5 November 2012 producing heavy precipitation between Liguria and Tuscany. The event was characterized by orographic precipitation reaching a maximum of 220 mm/24 h over the Apuan Alps and of 130 mm/24 h over the Apennine. Also in this case a strong southwesterly low level jet advecting humid air and destabilizing the lower atmosphere was the most important feature. The model well reproduced the thermodynamics of the event and the accumulated precipitation. The comparison among all the available models highlights problems in the correct reproduc-

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tion of the orographic precipitation being strongly driven by the highest peak. Moreover, the spread in the location of the precipitation produced by the models was very small as well as for the amount of precipitation allowing for a strongly reliable forecast.

Noteworthy, the instrumentation deployed during the HyMeX SOP provided a wealth of unprecedented information for studying atmospheric processes, weather patterns, and NWP model parameterization over Italy. For example, the local wind structure often leading to HPE in LT, as predicted by NWP, has been confirmed by the dropsondes released from aircraft. Similarly, the simultaneous radar observations from ground and aircraft provide information on the droplet microphysics that can be inserted into the NWP parameterization to test the impact on the forecast. On the other hand, the availability of different operational weather forecasting chains allowed for highlighting similar models difficulties in spite of the different configurations employed.

Hence, this valuable dataset, together with the observations collected over Europe from the other HyMeX partners during the entire SOP1, provides an inestimable source of knowledge for statistically evaluating strengths and deficiencies of the deployed forecasting chains. This will be the aim of future works.

Finally, the most important lesson from the first HyMeX campaign from the Italian point of view is twofold: the ability of establishing a strong link between research and operational agencies, and to discover that the different operational chains are a great aid to the forecaster as is discussed in Davolio et al. (2013).

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Table 1. Instrumentation deployed over the CI area during the SOP1 (in brackets the responsible institutions).

Radars	– 1 C-band single-polarization radar, Mt. Midia, Abruzzo (CETEMPS, RegAb) – 1 C-band polarimetric radar, Il Monte, Abruzzo (DPC) – 1 C-band single-polarization radar, Monte Serano, Umbria (DPC) – 1 C-band dual-polarization radar, ISAC Atmosph. Obs., Rome (CNR ISAC) – 1 X-band single-polarization radar, Rome (DIETSap) – 1 X-band polarimetric mini-radar, L'Aquila (HIMET, CETEMPS) – 1 X-band polarimetric mini-radar, Rome (HIMET)
Rain gauges	~ 200 telemetered rain gauges and thermometers (Regional authorities)
Disdro meters	– 1 Parsivel laser disdrometer (DIETSap) – 1 Parsivel laser disdrometer (CNR ISAC) – 1 K-band micro rain radar in Rome (DIETSap, NASA) – 1 bidimensional video-disdrometers 2DVD in Rome (DIETSap, NASA) – 2 PLUDIX disdrometers at DIETSap and CNR ISAC (Univ. of Ferrara) – 5 Parsivel2 laser disdrometers (Pescara, L'Aquila, Avezzano, CNR ISAC, CNR-INSEAN) (NASA)
Soundings	– 1 research sounding station at L'Aquila (CETEMPS) – 1 tethersouding (CNR ISAC) – 1 operational sounding site at Pratica di Mare, Rome (CNMCA, Air Force)
Other	– 1 Raman lidar and 1 ceilometer, located in L'Aquila (CETEMPS) – 1 meteo station and VLF lightning sensor in Rome (DIETSap) – 2 SODAR (CNR ISAC) at ISAC Atmospheric Observatory and in the Castel Porziano Presidential Park – Micrometeorological Surface layer sensors (CNR ISAC) – AWS surface station (CNR ISAC) – 1 aerosol lidar and 1 ceilometer (CNR ISAC) – 3 sunphotometers (CNR ISAC) – 1 Microwave radiometer (CNR ISAC) – LINET VLF/LF lightning detection network a station (CNR ISAC) – weather station near Rome (ENEA)

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Table 2. Instrumentation deployed over the LT area during the SOP1 (in brackets the responsible institutions).

Radars	– 1 C-band dual polarization radar, Monte Settepani, Liguria (ARPA Piemonte & ARPA Liguria) – 1 C-band single-polarization radar, Monte Crocione, Tuscany (DPC)
Rain gauges	~520 telemetered rain gauges (Consorzio LaMMA, OMIRL)
Other	– 1 RASS (Radio Acoustic Sounding System), Florence (Consorzio LaMMA) – 45 stream level gauges (OMIRL) – 131 hydrometers (Consorzio LaMMA) – 190 thermometers (Consorzio LaMMA) – 209 anemometers (Consorzio LaMMA) – 156 hygrometers (Consorzio LaMMA) – 21 barometers (Consorzio LaMMA)

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Table 3. Instrumentation deployed over the NEI area during the SOP1 (in brackets the responsible institutions). FVG stands for Friuli Venezia Giulia.

Radars	– 1 C-band dual-polarization radar, Fossalon di Grado, FVG (FVG Regional Civil Protection) – 1 C-band single-polarization radar, Mt. Macaion, Trentino-Alto Adige (Meteotrentino) – 1 C-band single-polarization radar, Mt. Grande, Veneto (ARPAV) – 1 C-band single-polarization radar, Concordia Sagittaria, Veneto (ARPAV) – 1 mobile X-band polarimetric radar, Trafoi, Trentino-Alto Adige (NOA)
Rain gauges	~ 400 telemetered tipping bucket rain gauges (FVG Regional Civil Protection, ARPAV)
Disdro meters	– 5 disdrometers: 3 Parsivels, 1 2DVD (NOA) and 1 micro-rain radar (NASA)
Soundings	– 1 operational sounding site at Campoformido, Udine (CNMCA)
Other	– 2 Microwave radiometers in Padova and Rovigo (ARPAV) – 4 SODAR (ARPA Veneto) – 55 hydrometric stations (FVG Regional Civil Protection, ARSO Slovenia)

Table 4. Summary of the main characteristics of the models chains used by the different Institutions for SOP1. The COSMO ensemble size is given in the brackets. The last column indicates whether the model calculates the convection explicitly or needs a parameterization scheme.

Model [Chain]	Grid spacing (km)	Initial conditions	Boundary conditions	Forecast range	Convection permitting
WRF-CETEMPS	12	ECMWF 12:00 UTC	ECMWF forecasts	96 h	No
WRF-CETEMPS	3	WRF 12 km 00:00 UTC	WRF 12 km forecasts	48 h	Yes
WRF-ISAC [1 & 2]	15	GFS 0000 & 12:00 UTC	GFS forecasts	48 h	No
WRF-ISAC [1 & 2]	3	GFS 0000 & 12:00 UTC	WRF 15 km forecasts	48 h	Yes
WRF-LAMMA [1]	12	GFS 00 & 12:00 UTC	GFS forecasts	120 h	No
WRF-LAMMA [2]	3	ECMWF 00 & 12:00 UTC	ECMWF forecasts	60 h	Yes
BOLAM-ISAC [1]	11	GFS 00:00 UTC	GFS forecasts	72 h	No
MOLOCH-ISAC [1]	2.3	BOLAM 03:00 UTC	BOLAM forecasts	45 h	Yes
BOLAM-ISAC [2]	9	GFS 18:00 UTC	GFS forecasts	54 h	No
MOLOCH-ISAC [2]	1.5	BOLAM 00:00 UTC	BOLAM forecasts	48 h	Yes
BOLAM-ISPRA [1]	33	ECMWF 12:00 UTC of d-1	ECMWF forecasts	84 h (+12 h to +96 h)	No
BOLAM-ISPRA [1]	11	BOLAM 00:00 UTC	BOLAM forecasts	84 h	No
BOLAM-ISPRA [2]	7.8	ECMWF 12:00 UTC of d-1	ECMWF forecasts	48 h (+12 h to +60 h)	No
MOLOCH-ISPRA [2]	2.5	BOLAM 00:00 UTC	BOLAM forecasts	48 h	Yes
COSMO-LEPS (size: 16)	7	ECMWF-EPS members (00:00 and 12:00 UTC)	ECMWF-EPS members	132 h	No
COSMO-H2-EPS (size: 10)	2.8	COSMO-LEPS members (12:00 UTC)	COSMO-LEPS members	36 h	Yes

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Table 5. Summary of the Italian IOPs during the SOP1. In the table the affected hydro-meteorological sites, the duration, the instruments specifically activated, the flight and extra soundings are reported.

IOPs	Target area	duration	instruments (except operational)	flight	Extra RS
IOP2	NEI (HPE) LT (ORP)	12–13 September	Disdrometer and X-Band Radar	ATR42 (Italy4)	Bologna Udine 12 September at 05:30 UTC
IOP4	CI (HPE/FFE)	14 September	radar, sodar and microwave sensor	Dornier Flight (Corsica 5)	L'Aquila 13 September at 18: UTC, 14 September at 12:00 and 18:00 UTC
IOP6	LT & NEI(ORP)	23–24 September	Disdrometer and X-Band Radar	Dornier Flight (Corsica 9)	Data Targeting System (**DTS**) 23 September, 18:00 UTC Milano, Roma, Trapani, Cagliari, Udine 24 September, 06:00 UTC: Milano, Trapani, Cagliari 24September, 18:00 UTC: Udine, Milano, Roma, Trapani
IOP7b	LT (HPE) NEI (ORP)	26–27 September	Disdrometer and X-Band Radar		Data Targeting System (DTS) 25 September, 18:00 UTC: Cagliari 26 September, 09:00–06:00 UTC: Cagliari 26 September 18:00 UTC Udine 27 September, 06:00 UTC Udine
IOP12a	LT & CI (HPE)	11–12 October	Radar Polar 55 (Roma Tor Vergata – CNR ISAC), sodar, MW sensors	Falcon-DLR ATR42 (Italy3)	Bologna 11 at 12:00 UTC and 12 at 12:00 UTC L'Aquila 11 at 16:00 UTC and 12 at 09:00 UTC
IOP13	LT,NEI &CI (HPE)	15–16 October	Radar Polar 55 (Roma Tor Vergata – CNR ISAC), sodar, MW sensors	ATR42 (Italy1) & FALCON (CI)	L'Aquila 15 October at 12:00 UTC Udine 15 October at 06 and 18:00 UTC Bologna 15 October at 12:00 UTC
IOP16a & c	LT,NEI & CI (HPE/ORP)	26–29 October	Radar Polar 55 (Roma Tor Vergata – CNR ISAC), sodar, MW sensors	ATR42 (Italy1) & FALCON (CI)	L'Aquila 25 October at 16:00 UTC 28 at 18:00 UTC Udine every 6 h from 25 October at 18:00 UTC till 28 October at 12:00 UTC Bologna at 00:00 UTC and 12:00 UTC from 26 to 29 October at 00:00 UTC
IOP18	LT,NEI & CI (HPE)	31 October– 1 November	Radar Polar 55 (Roma Tor Vergata – CNR ISAC), sodar, MW sensors	ATR42 (modified Italy3) & FALCON (CI)	L'Aquila 31 October at 12:30 UTC 16:30 UTC (ending quickly) 20:30 UTC Udine, Bologna
IOP19	LT(ORP/HPE) & NEI (ORP)	3–5 November	2 BLP balloon	ATR42 (Hymex 10) & FALCON (LT)	Udine 4 November at 18:00 UTC 5 November at 06:00 UTC

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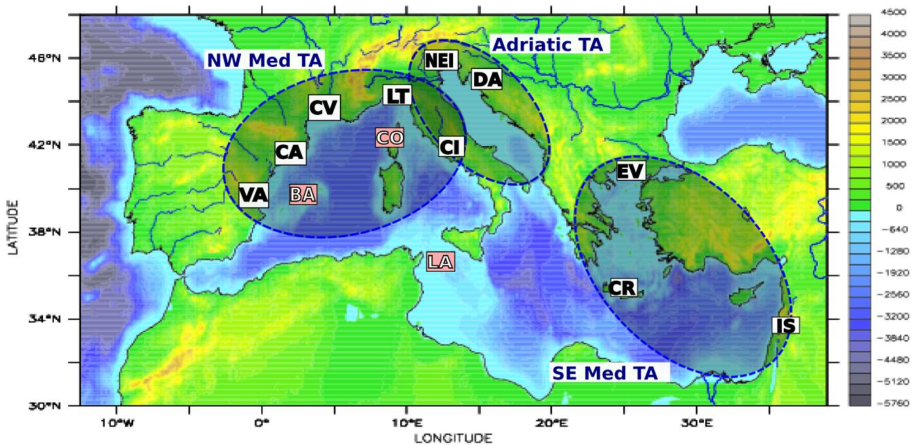

Fig. 1. HyMeX target areas (TA) in the Mediterranean basin and hydro-meteorological sites. Liguria-Tuscany (LT), North East Italy (NEI) and Central Italy (CI) are located within the Italian territory.

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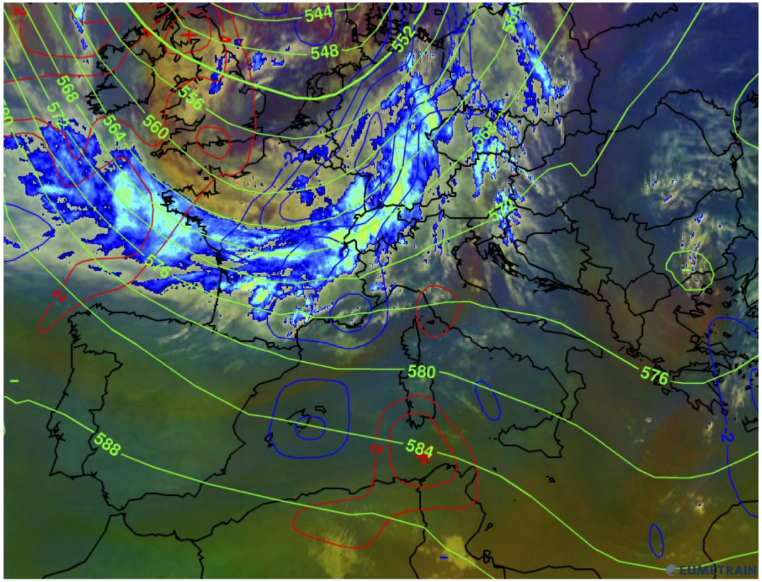

Fig. 2. Synoptic analysis at 06:00 UTC, 12 September 2012: ECMWF 500 hPa geopotential height (green lines), 700 hPa temperature advection (red warm and blue cold), MSG SEVIRI AirMass RGB composite EumetSat product and enhanced IR 10.8 µm temperature, ranging between 200 K (red) and 240 K (blue) – source: http://www.eumetrain.org.

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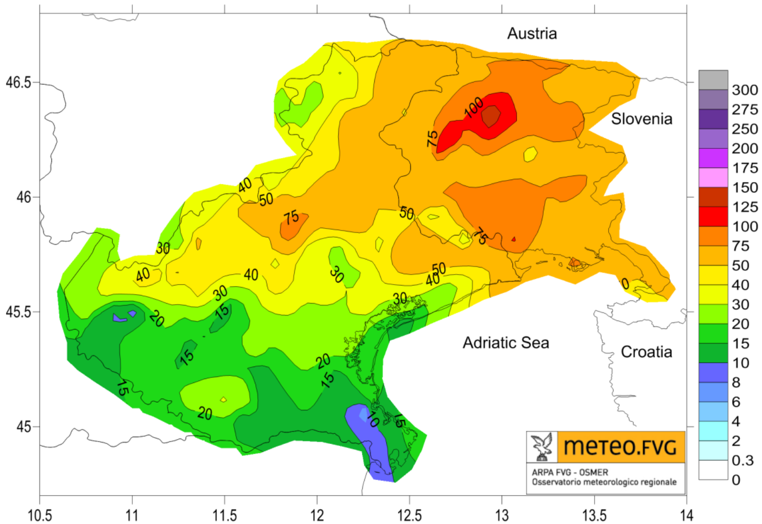

Fig. 3. 24 h accumulated precipitation for 12 September 2012, obtained from hourly raingauge data analyzed with the Kriging method: 163 stations in the Veneto region (ARPAV) and 111 stations in the Friuli Venezia Giulia region (OSMER-ARPA FVG). The figure is a courtesy of A. Cicogna (OSMER – ARPA FVG).

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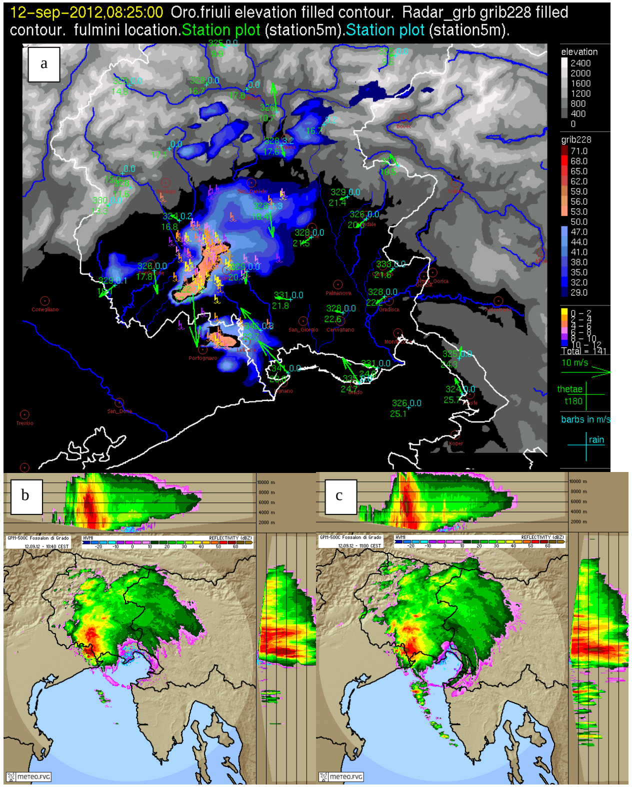

Fig. 4. **(a)** Vertical Maximum Intensity (VMI) from the Fossalon di Grado radar at 08:20 UTC with surface observations at 08:25 UTC and the C2G lightning fallen in the 12 previous minutes (courtesy of CESI-SIRF); **(b)** VMI with lateral projections at 08:40 UTC; **(c)** VMI with lateral projections at 09:00 UTC.

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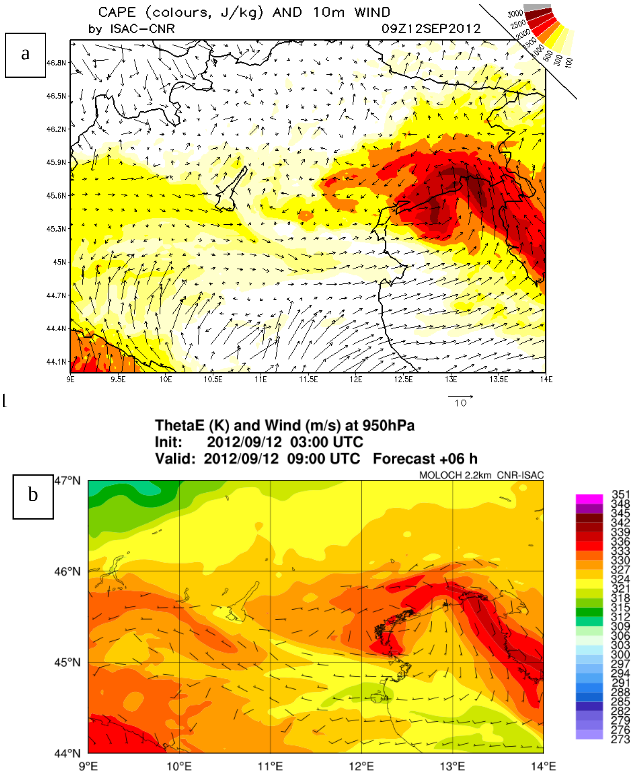

Fig. 5. (a): CAPE (J kg^{-1}) and horizontal wind at 10 m by WRF-ISAC run driven by GFS forecasts starting at 12:00 UTC, 11 September; **(b)**: equivalent potential temperature (K) and wind at 950 hPa by MOLOCH-ISAC at 2.3 km run driven by GFS forecasts starting at 00:00 UTC, 12 September.

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Interactive Discussion

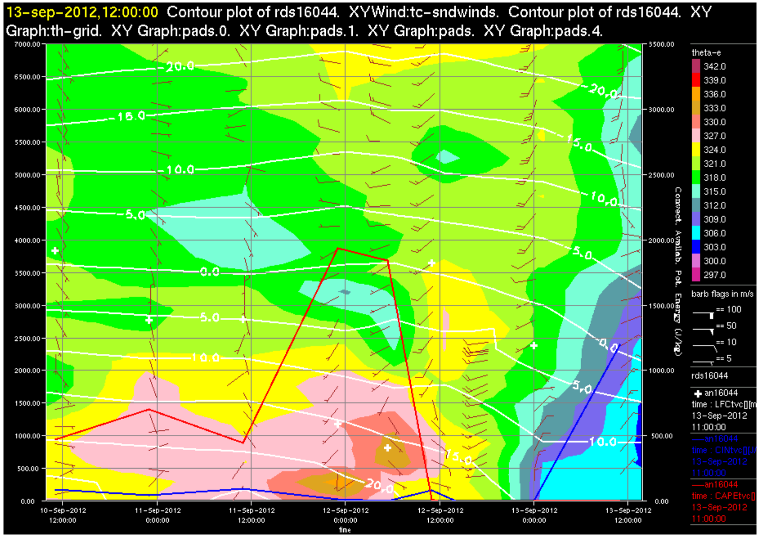

Fig. 6. 7 km vertical-time series of all the Udine soundings made by CNMCA with horizontal winds, Θ_e in shaded colors and overlapping CAPE and CIN estimations. Please note that the wind vectors at 18:00 UTC on 12 September 2012 are probably wrong.

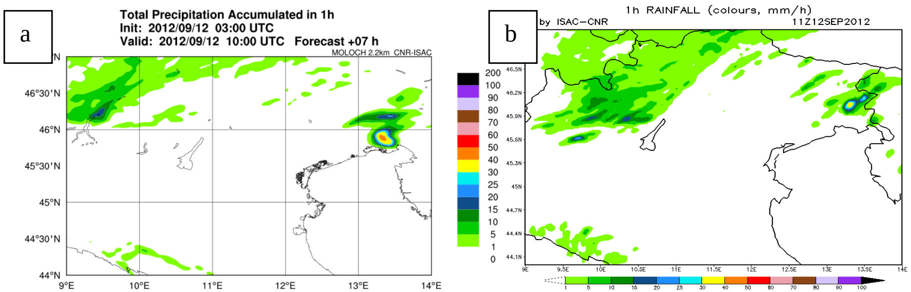

Fig. 7. Hourly accumulated precipitation on 12 September: **(a)**: at 10:00 UTC, forecast by MOLOCH-ISAC; **(b)**: at 11:00 UTC, forecast by WRF-ISAC.

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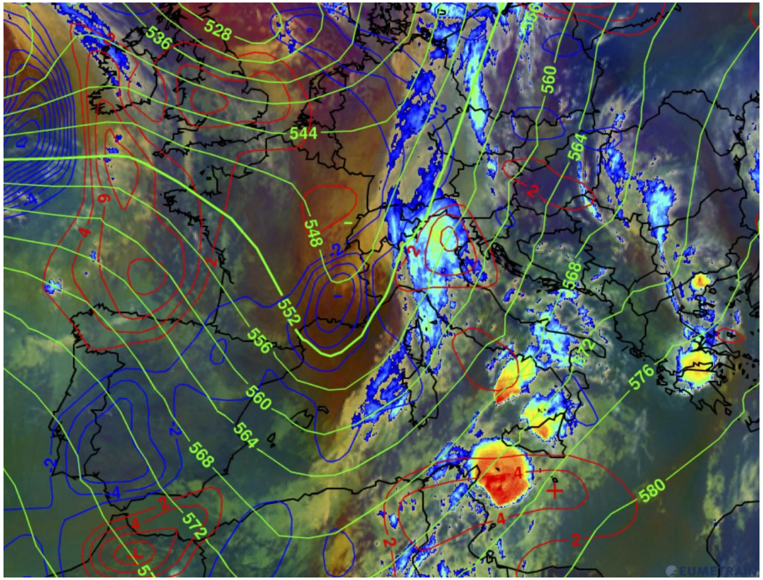

Fig. 8. As in Fig. 2, but at 12:00 UTC, 15 October 2012, source: http://www.eumetrain.org.

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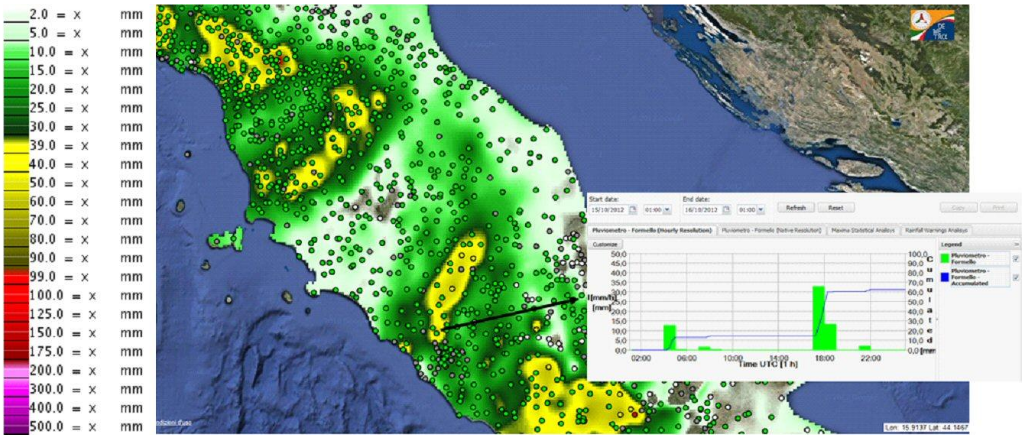

Fig. 9. Daily accumulated rainfall recorded by rain-gauges (green dots on the map) on 15 October 2012; the inset shows the hourly accumulated precipitation for the station of Formello (North of Rome) – Courtesy of DPC (DEWETRA system).

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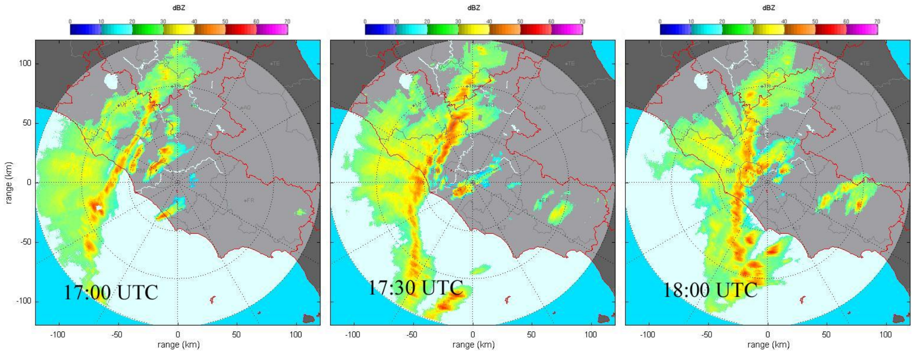

Fig. 10. Reflectivity images at different times (17:00, 17:30 and 18:00 UTC) collected by Polar 55C radar in Rome during 15 October 2012 (elevation 1.6°).

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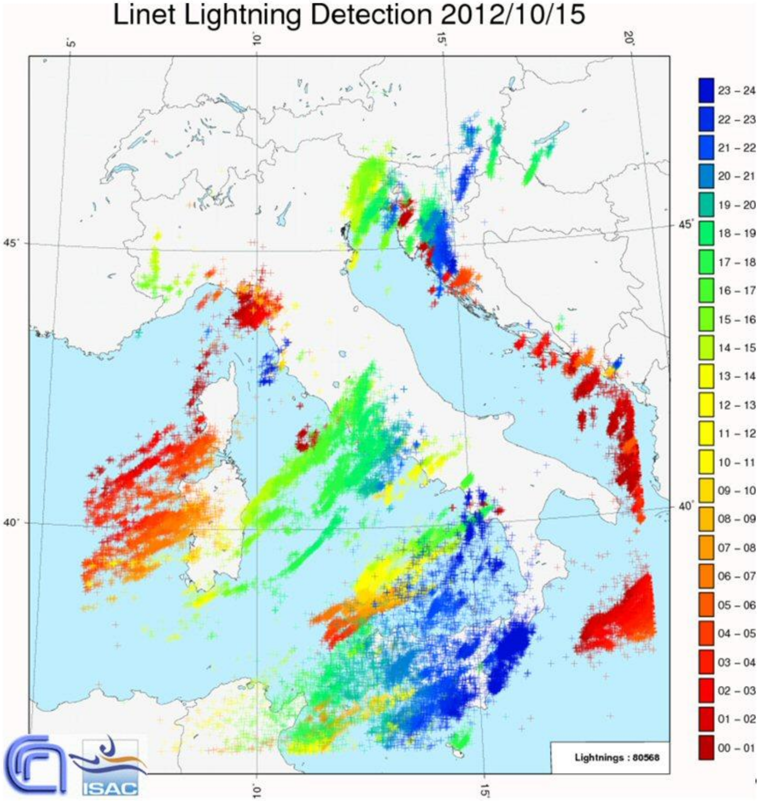

Fig. 11. LINET lightning activity measured on 15 October 2012. The map shows the Intra-Cloud and Cloud-to-Ground strokes registered in 24 h. Different colors are associated with different hours.

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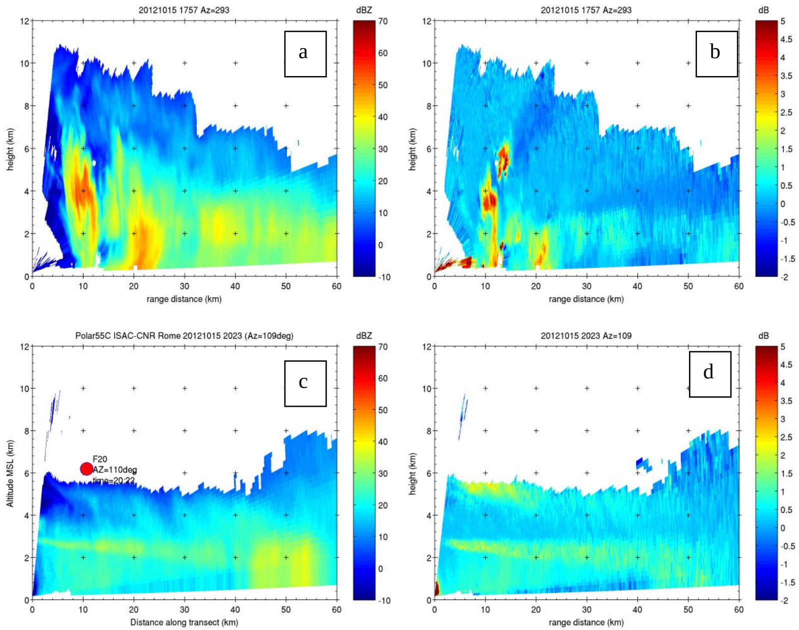

Fig. 12. Polar radar 55C in RHI mode on 15 October 2012 (azimuth 293°) at 17:57 UTC: **(a)** Sections of reflectivity; **(b)** differential reflectivity. Polar 55C pointing to a direction along the Falcon 20 route on 15 October 2012 at 20:25 UTC: **(c)** Reflectivity, the solid red circle indicates the aircraft position; **(d)** differential reflectivity.

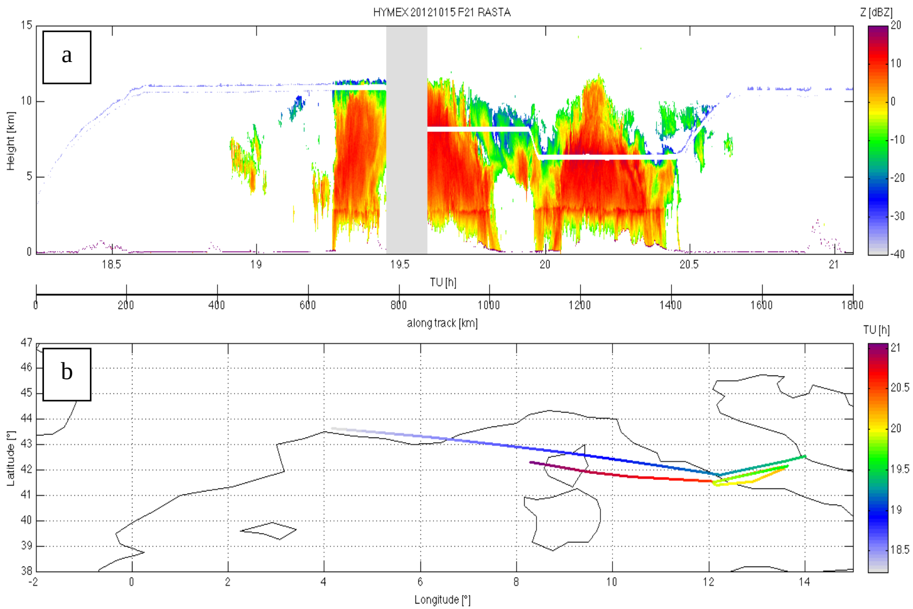

Fig. 13. Falcon 20 flight on 15 October 2012 (18:00 UTC to 21:00 UTC): **(a)** Reflectivity; **(b)** flight track. Courtesy of Julien Delanoe (LATMOS/IPSL/UVSQ, France).

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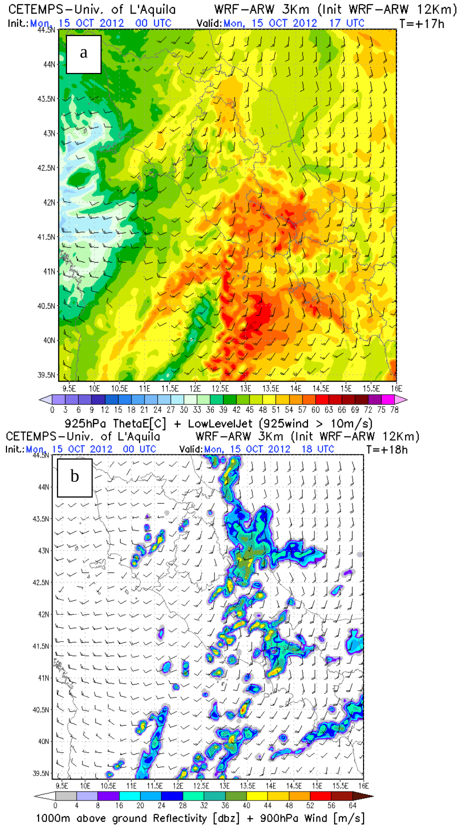

Fig. 14. (a): WRF Equivalent potential temperature (°C) and low level jet at 925 hPa; **(b)**: WRF Reflectivity at 850 hPa (dbz) and wind at 925 hPa (WRF-CETEMPS initialized by ECMWF at 12:00 UTC, 14 October 2012).

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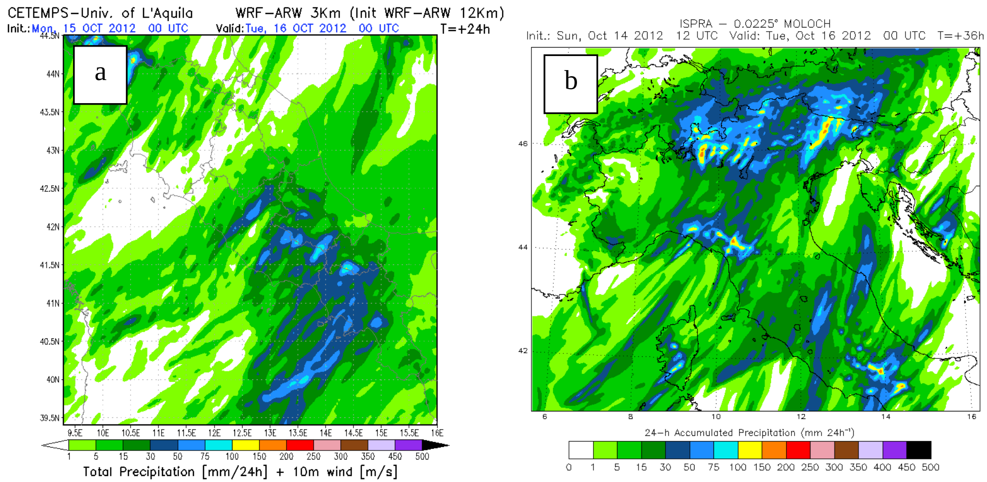

Fig. 15. Daily precipitation (mm $24\,h^{-1}$) valid at 00:00 UTC on 16 October 2012 simulated by: **(a)** WRF-CETEMPS; **(b)** MOLOCH-ISPRA both initialized by ECMWF at 12:00 UTC, 14 October.

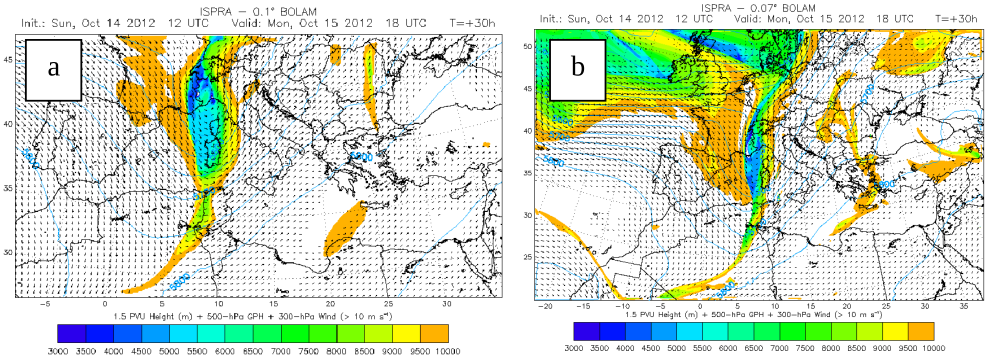

Fig. 16. 500 hPa GPH (blue contour lines), 300 hPa wind (> 10 m s^{-1}) and 1.5 PVU isosurface (color shaded area) for the forecast initialized at 12:00 UTC of 14 October 2012 and valid at 18:00 UTC of 15 October 2012 for: **(a)**: 0.1 ° BOLAM-ISPRA; **(b)**: 0.07° BOLAM-ISPRA.

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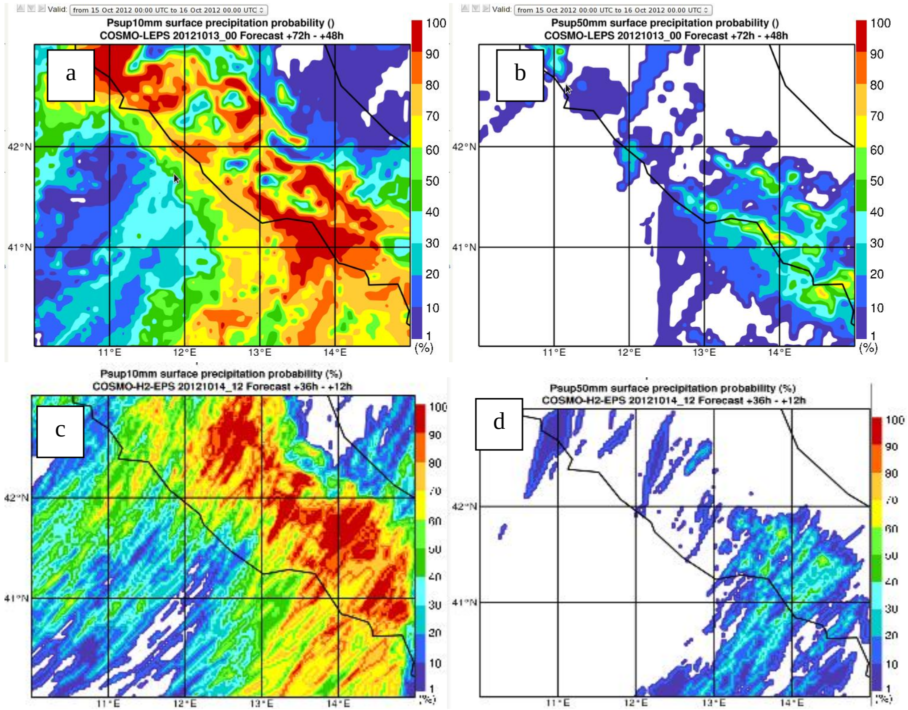

Fig. 17. COSMO-LEPS (emission time: 00:00 UTC of 13 October 2012, fcst +48–72 h) probability maps of 24 h precipitation exceeding: **(a)** 10 mm; **(b)** 50 mm. COSMO-H2-EPS (emission time: 12:00 UTC of 14 October 2012, fcst +12–36 h) probability maps of 24 h precipitation exceeding: **(c)** 10 mm; **(d)** 50 mm.

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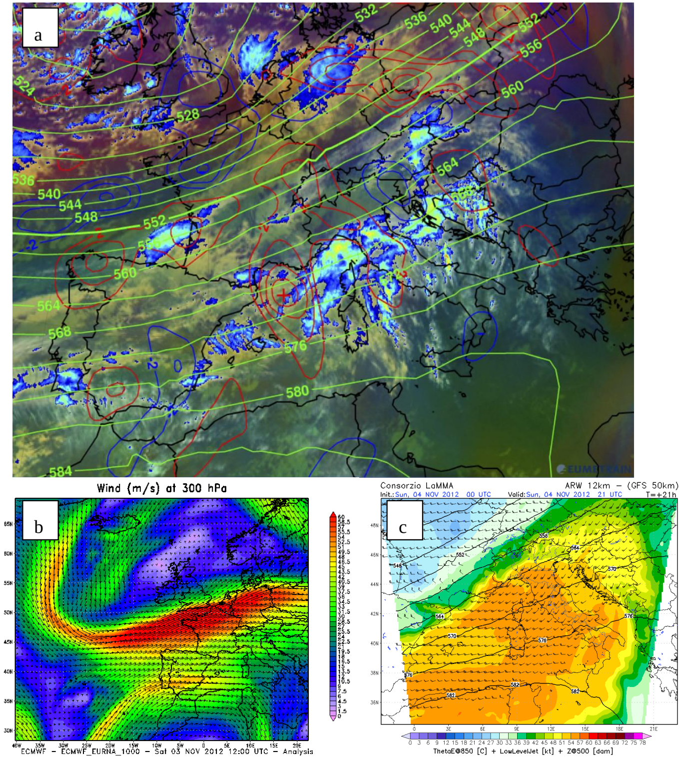

Fig. 18. (a) As in Fig. 2 but at 12:00 UTC, 3 November 2012 – source: http://www.eumetrain.org; **(b)** Wind speed at 300 hPa: ECMWF analysis, 4 November 2012 at 12:00 UTC; **(c)** Equivalent potential temperature and low level jet at 850 hPa, Geopotential height at 500hPa from WRF-ARW LaMMA.

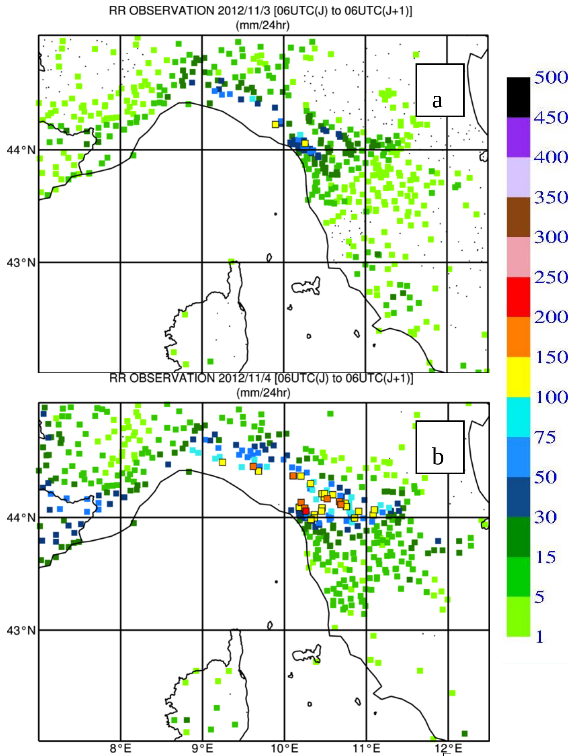

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Fig. 19. Observed 24 h accumulated precipitation ending at 06:00 UTC on: **(a)** 3 November; **(b)** 4 November 2012 (source: sop.hymex.org).

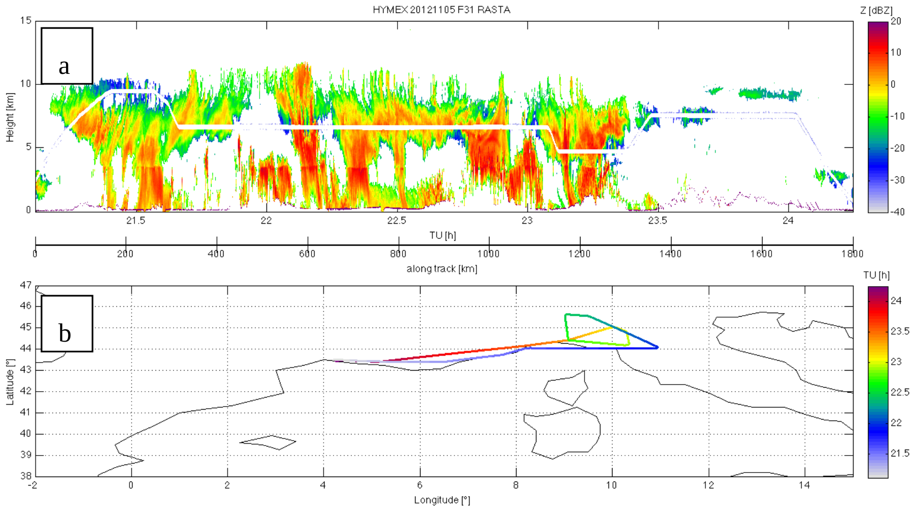

Fig. 20. Falcon RASTA radar: **(a)** reflectivity and **(b)** flight track on 5 November 2012. Courtesy of Julien Delanoe (LATMOS/IPSL/UVSQ, France).

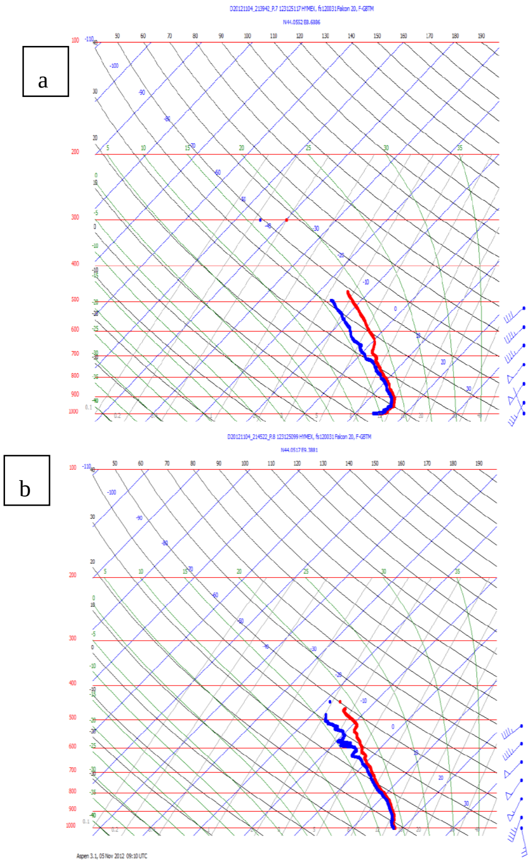

Fig. 21. Vertical profile from the two dropsondes deployed by the Falcon flight over the Gulf of Genoa at: **(a)** DS1 (44.055° N, 8.689° E) at 21:40 UTC; **(b)** DS2 (44.052° N, 9.388° E) at 21:45 UTC. Courtesy of Julien Delanoe (LATMOS/IPSL/UVSQ, France).

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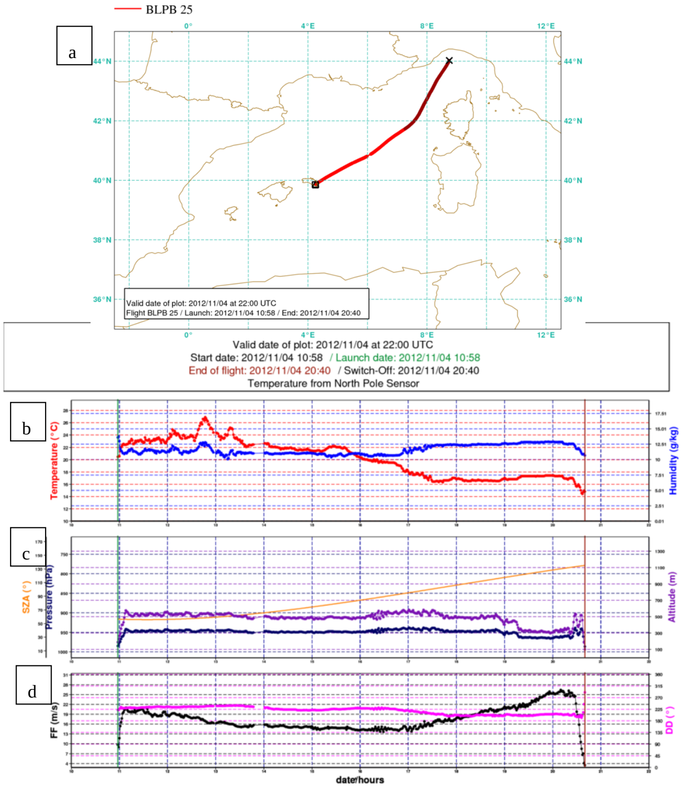

Fig. 22. (a) PBL balloon (#25) track; **(b)** temperature; **(c)** relative humidity; **(d)** pressure and wind intensity and direction along the balloon track. Courtesy of Alex Doerenbecher (CNRM-France).

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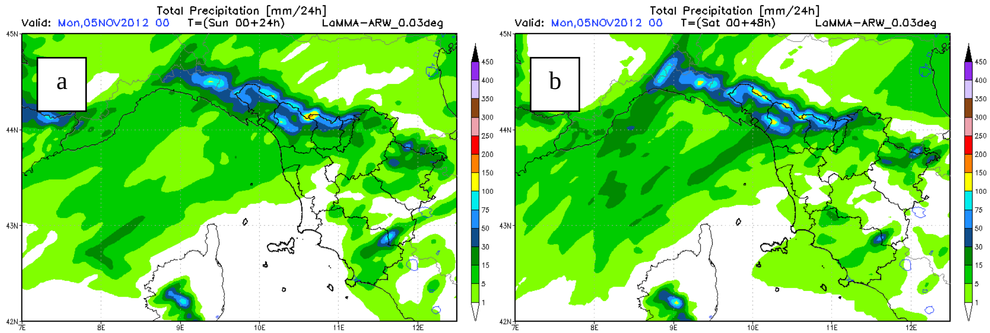

Fig. 23. WRF-ARW by LaMMA: 24 h accumulated precipitation for 4 November 2012. **(a)** +24 h forecast; **(b)** +48 h forecast.

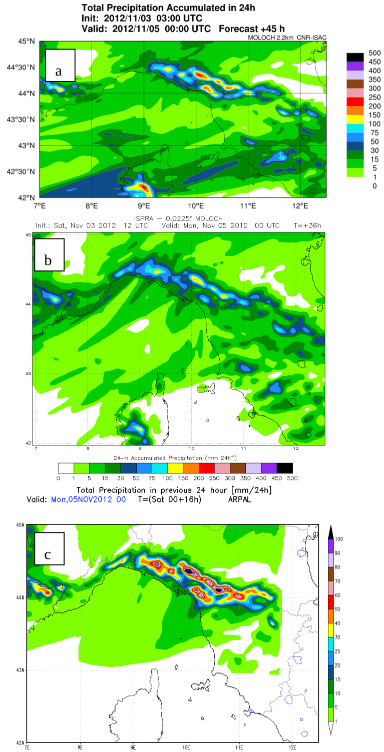

Fig. 24. 24 h accumulated precipitation at 00:00 UTC, 5 November 2012, forecast by different MOLOCH operational chains: **(a)** CNR-ISAC at 2.3 km starting at 03:00 UTC on 3 November; **(b)** ISPRA at 2.5 km starting at 12:00 UTC, 3 November; **(c)** ARPAL at 2.3 km, starting at 00:00 UTC, 3 November 2012.

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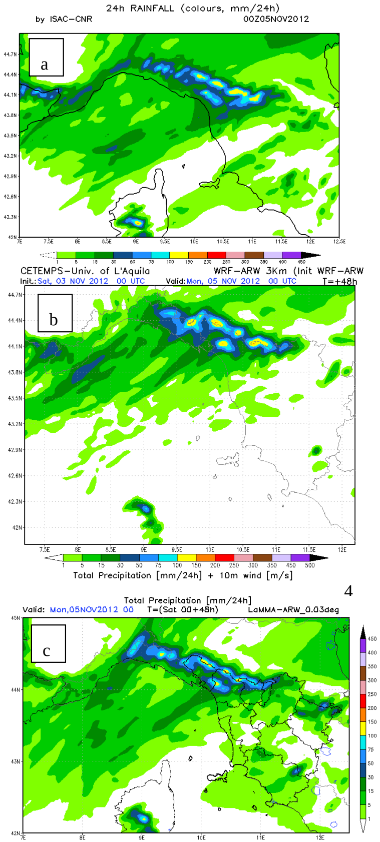

Fig. 25. 24 h accumulated precipitation forecast by different WRF-ARW operational chains: **(a)** CNR-ISAC at 3 km starting at 00:00 UTC 3 November; **(b)** CETEMPS at 3 km starting at 00:00 UTC 3 November; **(c)** LAMMA at 3km starting at 00:00 UTC 3 November.

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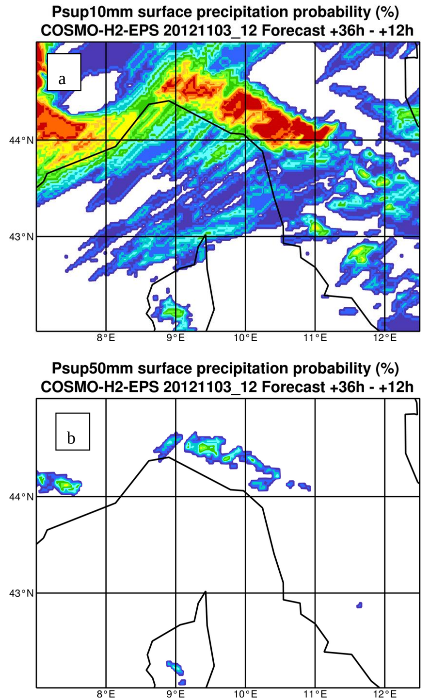

Fig. 26. COSMO-H2-EPS ensemble forecasts: **(a)** precipitation probability above 10 mm; **(b)** precipitation probability above 50 mm.

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