Reply to reviewers comments on

„Overview of the first HyMeX Special Observation Period over Croatia"

by Ivančan-Picek, Tudor, Horvath, Stanešić and Ivatek-Šahdan

We appreciate the thorough and detailed review, with useful suggestions. We have done our best to improve the manuscript in a considerable number of corrections and modifications, according to the Reviewers comments. We have been asked to make major revisions mainly in the language and presentation.

- English has been corrected and red by a native English speaker. Language proofreading certificate is attached.
- In the revised manuscript, we agree with both Reviewers and have reformulated Section 3. Additionally, we heavily shortened Section 2 and removed unnecessary details. In order to improve readability of the manuscript, we arrange the figures. Instead of previously Figure 4 A, B, C and D, in the revised version we have Figure 5, 6, 7 and 9.

<u>Reply to Reviewer #1 comments:</u>

The authors would like to thank the Reviewer for the through review of the manuscript. We have done our best to improve the manuscript, according to the comments.

General comments:

1. We agree with the reviewer that that the manuscript would be more readable if English language native speaker would proof-red the manuscript and correct the grammar. English text has been corrected by a native English speaker.
2. Accepted. We appreciate the comments made by the Reviewer, which pointed that the description of the different IOPs is difficult to follow in the information flow (particularly in Subsection 3.1). In the revised manuscript we remedy the problem. We reorganise the text in accordance to the reviewer comments. In the Subsection 3.1 we also highlight the different physical proceses that produced HPE during the different IOPs.

Minor points:

1. Line 139-141; Line 364 – Locations of radiosounding stations, radar sites and other places mentioned in the text added in Fig. 1b
2. Line 144: Majority of SYNOP stations are also equipped with an automatic station ... how many? We change the sentences in Line 143-145 in: *The meteorological measurements and observations on 58 SYNOP stations (31 of them are automatic stations) are done every hour and reported in real time during the SOP1.*

3. Line 152: The number of climatological stations of the network in Croatia is 120. Average distance between stations are 20 km. We add this information in the text.
4. Line 153: why are the synoptic observations not taken at the main synoptic hours? Our high- resolution analysis are based on the dense network of climatological stations that make the observations three times a day (06, 13 and 20 UTC).
5. Lines 165-167: It is not clear what SAP refers to: is it a technique to select relevant parameters?

   Sensitive area prediction is a prediction of where might a more accurate definition of the initial state of the atmosphere benefit the quality of the forecast over the region in question. Sensitive areas are regions where extra observations are expected to have the largest impact on the forecasts for the verification area.

   We reformulated the sentence accordingly:
   The selection of sensitive area predictions (SAP), that is predictions of regions where observations are expected to have the largest impact on the forecasts for the verification, used methods developed by ECMWF and Meteo-France (Prates et al., 2009).
6. Line 199: Why is the convection parameterization employed at 2 km grid spacing? Why not using an explicit treatment?

   As explained in the text and more elaborately in references that describe the 2km resolution operational forecast and its parametrisations in more detail: ALADIN is a spectral model and operationally we are using quadratic truncation. This means that gridpoint resolution is 2 km but the shortest resolved wave has a wavelength of 6 km. The 3MT convection scheme can be run in multiple scales and substantial amount of literature shows that substantial part of convection remains unresolved even in 1km resolution (e.g. Kajikawa et al., 2016).
   Therefore, we add the reference: "*Kajikawa et al., 2016: resolution dependence of deep convections in a global simulation from over 10-km to sub-kilometer grid spacing. Progress in Earth and Planetary Science, DOI: 10.1186/s40645-016-0094-5*"

7. Accepted. Subsection 2.3.1 is devoted to the description of the well known operational 8 km ALADIN forecast. Therefore, we reduce the lenght of this section and remove unnecessary details which could find in the listed references. Details of the operational model characteristics are summarized in Table 1.
8. Line 218: What is biperiodization? The biperiodization is a numerical technique to facilitate spectral computations for dynamics in LAM Specific for spectral LAM uses FFT.
9. Line 312-316: We agree. The details about NAO are removed.
10. Line 390-391: Instead of sentence *„Large-scale conditions such as found in these IOPs help to generate mesoscale and local processes which modify additionally flow regimes leading to quite different precipitation patterns"* we propose *„Similar large-*

scale conditions such as found in these IOPs help to generate mesoscale and local processes leading to quite different precipitation patterns“

11. Line 434: Accepted. We add proposed sentence.
12. Line 459: No. To clarify this we propose to include in the text: *ALADIN model at 2km grid spacing during SOP1 was assessed by comparing forecasts from the nearest model point with respect to the observation location with the measurements from Croatian surface observation network.*
13. Line 471-499: We agree. The definition of the verification measures (indices) used in Tables 2 and 3 have done in Appendix.
14. We appreciate the comments made by the Reviewer, which reminded the authors to the reference Migletta et al. (2016). We refer to this paper which focuses on the IOP2 over northeastern Italy.
15. Figure 6 - What is ARPEGE resolution? Figure 6 in the revised version of manuscript become Figure 4. In 2012, ARPEGE resolution over the western Mediterrannean Sea was about 11 km and more than 14 km easward (stretched grid). This is gridpoint resolution since ARPEGE is also a spectral model.

Other points:

All accepted and problem corrected.

<u>Reply to Reviewer #2 comments:</u>

We appreciate the thorough review by the Reviewer and have done our best to improve the manuscript, according to the comments.

We agree with the reviewer that that the manuscript would be more readable if English language native speaker would proof-red the manuscript and correct the grammar. English has been corrected and red by a native English speaker.

We appreciate the comments made by the Reviewer, *„the paper lacks in clearly presenting the events making the readability quite low".* In the revised manuscript we remedy the problem and reorganise the text in accordance to the reviewer comments.

Regarding the Reviewer comment that the two sentences are the same as in Ferretti et al., 2014, we are very sorry for that and confirm that this is accidental. During our work on this manuscript we consulted a lot of relevant references (many are cited in the paper) in which we found similar sentences construction. The content of these two sentences is general description of the Mediterranean region and well known convection as major source of heavy precipitation over the sea, and therefore does not have any influence on the presented results. In the revised manuscript we rewrite the mentioned sentences in our own words.

General comments:

Accepted. We appreciate the comments made by the Reviewer, which pointed that the description of the observations and models should be shortened. In the revised manuscript we remedy the problem. We remove unnecessary details on observations and summarize models details in a separate table.

We agree with the Reviewer that the presentation of the events in the Section 3 is difficult to read. This section was rewritten in accordance to the reviewer comments.

Specific Comments:

Line 40-42: Accepted. We rewrite the sentence.

Line 98: To explain where is Adriatic TA we refer to the HyMEX (www.hymex.org/?page=target_areas*)* *where* identified 3 main Mediterranean target areas: North-West (NW), Adriatic (A) and South-East (SE).

Line 138: Agreed. We add a figure with the location of the observations in Croatia (Figure 1b).

Line 226-231: Accepted. We reduce the lenght of this section and remove unnecessary details which could find in the listed references. Details of the operational model characteristics are summarized in Table 1.

Section 2 has been shortened.

Line 316: Accepted. We add suggested references and remove details about the NAO.

Lines 351: Acknowledged. In the revised manuscript we l remedy the problem

Line 393: Agreed. Modified.

Line 464: Accepted. We will specify the IOPs.

Line 605: Accepted. The squares show the precipitation. We prepare Figure 11, now Figure 14, where the squares are distinguishes from the shaded background.

Line 640: We agree. The information about the data used in the data assimilation has been added.

Overview of the first HyMeX Special Observation Period over Croatia

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Abstract

The HYdrological cycle in the Mediterranean EXperiment (HyMeX) is intended to improve the capabilities ~~to predict~~~~for~~of predicting high-~~-~~impact weather events. ~~In~~ Within its framework, the aim of the first Special Observation Period (SOP1), 5 September to 6 November 2012, was ~~aimed~~ to study heavy precipitation events and flash floods. ~~Here~~ Here, we present high-~~-~~impact weather events over Croatia that occurred during SOP1. ~~A p~~Particular ~~articular~~ attention is given to eight Intense Observation Periods (IOPs),~~s~~ during which high precipitation occurred over the ~~e~~Eastern Adriatic and Dinaric Alps. During the entire SOP1, the operational model~~s~~ forecasts generally well represented ~~well~~ medium intensity precipitation, ~~while~~ but heavy precipitation was frequently underestimated by the ALADIN model at an 8 km grid spacing and was overestimated at a higher resolution (2 km grid spacing). During IOP2, intensive rainfall occurred ~~in~~ over a wider area ~~of~~ around the city of Rijeka in the N~~n~~orthern Adriatic. ~~Short~~The short-range maximum rainfall totals ~~achieved maximum values~~were the largest ever recorded at the Rijeka station since the beginning of measurements in 1958. The rainfall amounts measured in intervals of 20, 30 and 40 minutes ~~are~~ were exceptional, with return periods ~~of more than~~that exceeded a thousand, a few hundred~~s~~ and one hundred years, respectively. The operational precipitation forecast using the ALADIN model at an 8 km grid spacing provided guidance ~~on~~ regarding the event but underestimated the rainfall intensity. ~~Evaluation~~ An evaluation of numerical sensitivity experiments suggested that the forecast was slightly enhanced by improving the initial conditions through variational data assimilation. The operational non-hydrostatic run at a 2 km grid spacing using a configuration with the ALARO physics package further improved the forecast. This article highlights the need for an intensive observation period in the future over the Adriatic region~~,~~ to validate the simulated mechanisms and improve numerical weather predictions via data assimilation and model improvements in descriptions of microphysics and air-sea interactions.

Keywords: HyMeX SOP1, Adriatic TA, heavy precipitation, ALADIN mesoscale model, data assimilation

1. Introduction

The Special Observing Period 1 (SOP1) of the *HYdrological cycle in the Mediterranean Experiment – HyMeX* project was performed from 5 September to 6 November 2012 (Drobinski et al., 2014). The main objective of SOP1 was ~~improving~~ to improve the understanding and forecasting of the processes ~~leading~~ that lead to heavy rainfall and floods (Ducrocq et al., 2014). The Mediterranean region frequently is affected by heavy precipitation and flash floods, especially during the late summer and autumn. Daily precipitation amounts above 200 mm have been recorded during this season (~~e.g.~~ e.g., Romero et al. 2000; Buzzi and Foschini 2000; Jansa et al. 2001, Ducrocq et al 2008). Within small and densely urbanized areas, intensive and stationary precipitation events can rapidly result in dangerous floods, sometimes leading to disastrous consequences (~~e.g.~~ e.g., Silvestro et al., 2012; Rebora et al. 2013; Ivančan-Picek et al. 2014). This stresses the importance of such events through their impacts on the social and economic circumstances of local communities. Numerical weather prediction (NWP) models have made ~~a~~ significant progress through the development of convection permitting systems. However, the ability to predict such high-impact events remains limited because of the contribution of fine-scale processes that are not represented in NWP models,~~,~~ ~~and~~ their interactions with the large-scale processes~~, as well as~~ and limitations ~~of the~~in data assimilation, ~~and~~ especially ~~for the~~ convective-scale data assimilation. HyMeX aims to improve our understanding of precipitating systems, especially processes responsible ~~to~~ for their formation and maintenance, ~~as well as~~and to improve the ability of numerical weather prediction models ~~in~~ for forecasting the locations and ~~intensity~~ intensities of heavy precipitation events in the Mediterranean.

The orography and thermal contrasts of the Mediterranean basin together with approaching upper-level troughs frequently induce lee cyclogenesis (~~e.g.~~ e.g., Buzzi and Tibaldi, 1978; Horvath et al., 2006) and provide a trigger mechanism for a range of extreme weather phenomena~~,~~ such as local downslope Bora windstorms (known as Bura in Croatia) (~~e.g.~~ e.g., Grisogono and Belušić, 2009), strong ~~winds~~ Scirocco and Tramontana winds (Jurčec et al. 1996; Pandžić and Likso 2005; Jeromel et al., 2009), orographic precipitation, thunderstorms, supercells and mesoscale convective systems (Ivančan-Picek et al. 2003; Mastrangelo et al., 2011), and water-spouts (Renko et al., 2012). Heavy precipitation occurs preferentially downstream of~~ a~~ cyclones aloft (Doswell et al., 1998).

The seasonal distribution of heavy precipitation suggests the relevant role of the high sea surface temperature (SST) of the Mediterranean Sea during the autumn season, when the lower layer of the atmosphere is loaded with water vapour. The large thermal gradient between the atmosphere and the sea favours intense heat and moisture fluxes, which are the energy source for storms (Duffourg and Ducrocq, 2013). ~~As~~ Because the sea provides a large source of moisture and heat, the steep slopes of the surrounding mountains ~~in the vicinity of~~near the highly urbanized coastal areas of the Mediterranean are the key factors in determining ~~the~~ moisture convergence and the rapid uplift of moist and unstable air responsible for triggering condensation and convective instability processes (~~e.g.~~ e.g., Rotunno and Ferretti, 2001; Davolio et al., 2009). The coastal mountains, however, are not the only sources of lifting. Favourable synoptic upper-level settings, frontal lifting associated with quasi-stationary frontal systems and lower tropospheric mesoscale convective lines may also induce ~~the~~ convective instability.

~~One of the~~A key component~~s~~ of HyMeX is ~~the~~ experimental activity, which is ~~aimed at better quantification and understanding of~~intended to better understand and quantify the water cycle in the Mediterranean, with an emphasis on intense events. Over the ~~whole~~entire Mediterranean region, three target areas (TA) have been proposed for Enhanced Observational Periods (EOPs) to provide detailed and specific observations for studying key processes of the water cycle (http://www.hymex.org). ~~One of~~Among them is the Adriatic Sea and Dinaric Alps (Adriatic TA), which has been proposed for the study of heavy precipitation events and ~~flash-floods~~flash floods, and considerable effort from the Croatian meteorological community was put into the campaign (http://www.hymex.org/?page=target_areas).

The Adriatic Sea is a northwest–southeast elongated basin in the C~~c~~entral ~~Mediterranean sea~~Mediterranean Sea~~,~~ that is approximately 200 km wide and 1,200 km long and is almost entirely enclosed by mountains, namely the Apennines to the west and southwest, the Alps to the north and the Dinaric Alps to the east and southeast. ~~These~~ Those topographic features play a large role in the structure and evolution of the weather systems associated with heavy precipitation (~~e.g.~~ e.g., Vrhovec et al., 2001; Ivančan-Picek et al. 2014). This area is ~~one of~~among the rainiest in Europe, with expected annual amounts of precipitation greater ~~then~~than 5.000 mm in the mountainous hinterland on the southern ~~south~~ (end) part of the Adriatic Sea (~~Magaš~~Mages, 2002).

Although the Adriatic TA was not ~~a~~ part of the extensive experimental activity during ~~the SOP1~~SOP1, many events that affected the Western Mediterranean also expanded ~~at~~ into the Adriatic area~~ too~~. During SOP1, 16 IOPs were dedicated to heavy precipitation events (HPE) over France, Spain and Italy, and many of ~~these~~ those events subsequently affected the E~~e~~astern Adriatic Sea and Croatia.

The aim of the paper is~~:~~ to (1~~.~~) ~~to~~ provide a scientific overview of the HPEs that affected the Adriatic TA during SOP1~~;~~, (2~~.~~) ~~to~~ provide and examine the operational numerical model~~s~~ skill of the precipitation forecasts in Croatia~~;~~ and (3~~.~~) ~~to~~ provide a detailed description of the extraordinarily rare and heavy IOP2 precipitation event ~~IOP2~~.

The remainder of this paper is ~~organised~~ organized as follows. Section 2 describes the area of the Dinaric Alps and the Adriatic region~~,~~ and the measured and model data provided by the Croatian Meteorological and Hydrological Service (DHMZ). Section 3 analyses the events during HyMeX SOP1, ~~that~~ which produced more than 100 mm of precipitation during 24 hours on the ~~e~~Eastern Adriatic C~~c~~oastline. ~~Performance~~ The performance of the operational precipitation forecasts is assessed through the verification of forecasts, ~~mostly~~ primarily with the Croatian surface observation network. In Section 4, ~~an~~ additional attention is given to the extraordinarily rare and heavy precipitation IOP2 event ~~IOP2~~. Finally, we analyse and discuss the potential~~s~~ for improving numerical weather predictions through data assimilation using sensitivity experiments. The summary and conclusions are reported in Section 5.

2. HyMeX SOP1 in Croatia: observations and models

The Mediterranean is ~~one of~~among the most climatically ~~most~~ pleasant areas in the world. Nevertheless, the area is prone to high-impact weather phenomena~~, affecting~~ that affect people´s lives and activities and ~~causing~~ cause extensive material damage. This context was favourable for ~~an~~ the active participation of the Croatian scientific community in the HyMeX project. The Croatian research community was active in the preparation of the scientific programme, which included the identification of typical weather patterns over the regions and ~~the~~ target areas. During ~~the SOP1~~SOP1, the national meteorological service supported the main HyMeX Operational Centre (HOC) in Montpellier (France) by~~, through~~ visiting scientists and ~~their~~ providing their meteorological expertise,~~ as well as providing~~ observations, numerical modelling products and forecast data.

This section summarizes the observational network in Croatia that was operational during SOP1 and the operational forecasting modelling chain ~~producing~~ that produced numerical weather predictions during SOP1.

2.1. Observations

The instrumentation deployed over the Adriatic TA during ~~the SOP1~~SOP1 ~~belongs~~ belonged mainly to the DHMZ observational network~~ of DHMZ~~. DHMZ deployed a ground observation operational network that ~~includes~~ included automatic, climatological and ~~raingauge~~rain gauge stations, two radio-soundings (Zagreb-Maksimir (station ID = 14240, H = 123 m asl, $\varphi = 45^{0}49'$N, $\lambda = 16^{0}02'$E) and Zadar-Zemunik (station ID = 14430, H = 88 m asl, $\varphi = 44^{0}5'$N, $\lambda = 15^{0}21'$E)) and two radars (Bilogora and Osijek). ~~Indication of the~~The locations mentioned in the text ~~is shown in the~~are indicated in Figure 1b.

The meteorological measurements and observations ~~on~~ from 58 SYNOP stations (31 of ~~them~~ which ~~ware~~ ere automatic stations) ~~are done~~were made every hour and reported in real time during ~~the~~ SOP1. All the automatic stations measured data ~~with a~~at ~~10 minute~~10-minute ~~interval~~ intervals and reported the measured data in real time. However, not all 63 automatic stations measured all the meteorological parameters. ~~There are 21~~Twenty-one of the automatic stations ~~that report only the~~only reported wind parameters (average ~~10~~ 10-minute speed and direction, and wind gust speed measured in the ~~last~~ previous 10 minutes). Five ~~more~~ additional stations measured ~~measure the~~ wind parameters, temperature and relative humidity. All ~~real time~~real-time surface measurements (SYNOP~~,~~ and automatic station data)~~,~~ and available radar figures ~~are~~ were stored ~~in~~ at the HyMeX data centre.

The dense network of climatological stations (120 stations with an average distance of 20 km) ~~is~~ was the source of temperature, humidity and wind speed~~ –~~, cloudiness and visibility ~~are~~ were estimated ~~by~~ from observations only 3 times ~~a~~ per day at 0600, 1300 and 2000 UTC~~; –~~, and accumulated rainfall and snow height ~~are~~ were measured at 0600 UTC (~~there were~~ more than 500 stations ~~reporting~~ reported accumulated 24-hour~~ly~~ rainfall).

In addition to operational radio~~-~~soundings in Zadar-Zemunik at 0000 and 1200 UTC, several extra radiosoundings were deployed through the Data Targeting System (DTS) upon request of the HOC. ~~These~~ Those targeted radiosoundings, among others in the ~~w~~Western Mediterranean, were activated during IOP16, which caused heavy precipitation, strong winds and snow in the E~~e~~astern Adriatic. ~~The r~~Requests ~~equests~~ for additional radiosoundings at 0600 and 1800 UTC were carried out under the EUMETNET Observation Programme. Sounding data measured at Zadar-Zemunik, located on the eastern coast of the Adriatic Sea at the southern end of Velebit Mountain, provided information on the vertical structure of the troposphere ~~in order~~ to monitor the upstream flow of the precipitation events in the Adriatic region. The selection of sensitive area predictions (SAP), that is, predictions ~~of~~ for regions where observations are expected to have the largest impact on the forecasts for the verification, used methods developed by ECMWF and Meteo-France (Prates et al., 2009). The verification area selected for SAP calculations was centred over the N~~n~~orthern and/or C~~c~~entral Adriatic.

To complement the ground-based observations, the data from two radars in Croatia (Bilogora (H=270 m asl, φ = 44^{0}53´N, λ = 17^{0}12´E) and Osijek (H=89 m asl, φ = 45^{0}30´N, λ = 18^{0}34´E)) and one in Slovenia (Lisca; H=944 m asl, φ = 46^{0}04´N, λ = 15^{0}17´E) ~~are~~ were made available operationally in ~~a~~ graphical ~~graphic~~ form. ~~The estimation~~Estimates of the instantaneous surface rain rates from the Lisca and Bilogora radars were provided to the HyMeX web server in real time. Northwest Croatia, particularly Rijeka and Istria, are covered by operational radars in Croatia, Slovenia and Italy, but the area is on the edge of the ranges and behind a mountain obstacle.

~~The s~~Standard ~~tandard~~ Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI) data are available ~~with~~ in ~~an~~ interva~~l~~ls of 15 minutes, and Rapid Scan Service (RSS) data are available ~~with~~ in 5 minute intervals. The abundance of remote sensing data on the HyMeX server encourages detailed analyses of all the cases that produced HPEs over Croatia during SOP1.

Satellite-~~-~~derived precipitation data from the Tropical Rainfall Measuring Mission ~~are~~ were used ~~as provided from the Tropical Rainfall Measuring Mission~~ (TRMM, Huffman et al., 2007). In particular, we used the ~~3~~ 3-hour~~ly~~ accumulated precipitation data from the 3B42RT product to compute the 24 hourly accumulated rainfalls for the period from 0600 UTC to 0600 UTC the next day, and ~~1~~ 1-hour~~ly~~ precipitation data from the 3B41RT product ~~to compare it~~were compared with the precipitation forecasts ~~forecast by~~ developed using operational numerical weather prediction models.

2.3 Mesoscale models

A short description of the model~~s~~ characteristics and the operational ~~set up~~ setup during SOP1 is given here.

During ~~the~~ SOP1, DHMZ provided the products from the operational forecast (Tudor et al., 2013). At the time, the numerical weather prediction system (NWP) ~~is~~ was based on the hydrostatic and non-hydrostatic ALADIN models.

The ALADIN hydrostatic model (Aladin International Team, 1997; Tudor et al. 2013) ~~is~~ was run twice per day on a domain ~~in~~ with ~~8~~ 8 km resolution (Figure 1a), starting from 0000 and 1200 UTC analyses up to a ~~72~~ 72 hour~~s~~ lead time. The operational suite used lateral boundary conditions from the global model ARPEGE run operationally ~~in~~ by Meteo-France. The initial fields ~~are~~ were obtained using a data assimilation procedure (Stanešić, 2011). The operational ALADIN model is a limited-area model that applies Fourier spectral representation of the model variables using fast Fourier transforms (FFTs) in both directions with a quadratic elliptic truncation (Machenhauer and Haugen, 1987), ~~that~~ which ensures an isotropic horizontal resolution and that the nonlinear terms of the model equations are computed without aliasing. The forecast ~~in~~ at an ~~8~~ 8 km resolution ~~is~~ was run on a domain with 240x216 grid points that ~~includes~~ included a band of 11 points along the northern and eastern boundaries, with unphysical terrain created for the biperiodization (Figure 1a). The dynamical computations ~~are~~ were performed using semi-implicit semi-~~lagrangian~~ Lagrangian discretisation (Robert, 1982) to solve the hydrostatic dynamics and finite difference method on 37 levels of hybrid pressure type eta coordinates ~~coordinate~~ (Simmons and Burridge, 1981) in the vertical. The operational physics package at the time used prognostic TKE, cloud water and an ice, rain and snow and diagnostic scheme for deep convection. The prognostic equations for condensates ~~are~~ were solved using the barycentric ~~barrycentric~~ approach (Catry et al., 2007).

Upon numerous case studies of severe weather events (~~e.g.~~ e.g., Tudor and Ivatek-Šahdan, 2010), an additional operational forecast run was established in July 2011 that ~~uses~~ used ALADIN with non-hydrostatic dynamics and a complete set of physics parameterisations, including the convection scheme. The high 2 km resolution forecast using ALADIN model with non-hydrostatic dynamics (Benard et al 2010) with the physics package that included the convection scheme was running operationally during the HyMeX SOP1 campaign (Figure 1b). The convection scheme used in the high-resolution model is modular multiscale ~~misrophysics~~ microphysics and a transport (3MT) scheme for precipitation and clouds (Gerard and Geleyn, 2005; Gerard, 2007; Gerard et al., 2009). Both runs used SSTs from the initial file of the global model ARPEGE forecast. ~~More~~ Additional details ~~on~~ of the model characteristics can be found in Table 1.

3. Heavy precipitation events over the Adriatic TA during SOP1

In the late summer and early autumn of 2012 (from 5 September to 6 November), Hymex SOP1, which was dedicated to heavy precipitation and flash floods, ~~took place~~occurred over the W~~w~~estern Mediterranean (Ducrocq et al, 2014). During SOP1, 20 IOPs were declared, and 8 of ~~these~~ those events affected the Adriatic TA (Table 2). Most of ~~these~~ the events (6 IOPs) were related to HPEs over the ~~n~~Northern Adriatic (city of Rijeka).

Figure 2a shows the total precipitation amounts measured by the Croatian rain gauge network ~~cumulated~~ accumulated over the ~~whole~~ entire SOP1. The total precipitation for ~~the SOP1~~SOP1 was above the corresponding climatology (Zaninović et al., 2008) for September and October for the Adriatic TA. ~~Similar~~ A similar situation was found over the Apennine peninsula (Davolio et al., 2015). ~~Maximum~~ The maximum ~~of~~ precipitation during SOP1 was recorded ~~on~~ in the No~~no~~rthern Adriatic (city of Rijeka) and its mountainous hinterland of Gorski Kotar (~~more than~~exceeding 1000 mm at some locations). There were 15 days with daily rainfall accumulations exceeding 100 mm at locations in the Adriatic TA (Figure 2b). There were more IOPs dedicated to HPEs over the Adriatic TA in October than in September 2012, which was also the case in the W~~w~~estern Mediterranean (Ducrocq et al., 2014). Several of ~~these~~ those events caused local urban flooding (Rijeka, Pula and Zadar), with considerable material damage.

Some of the IOPs were embedded in a synoptic setting conducive to heavy rainfall and characterized ~~with~~ by cyclones over the Western Europe and Mediterranean (~~e.g.~~ e.g., Dayan et al. 2015). The storm tracks of these cyclones ~~coming~~ ~~traveling~~travelling from the North Atlantic to Europe depend on the direction and strength of the westerly winds that are controlled by the relative positions of the permanent Azores High and Icelandic Low. Based on Ferretti et al. (2014) and Pantillon et al. (2015), a small positive or negative North Atlantic Oscillation (NAO) index contributed ~~contribute~~ to the evolution of the weather systems associated with heavy precipitation and possibly reduced the ~~long term~~long-term predictability over the Mediterranean.

3.1 Overview of IOPs over the Adriatic TA

The influence of different meteorological characteristics and physical processes that produced HPEs over the Adriatic target area and Dinaric Alps are briefly analysed and summarized. Previous research on the occurrence of HPEs ~~occurrence~~ in the wider Adriatic region (~~e.g.~~ e.g., Doswell et al., 1998; Romero et a., 1998; Vrhovec et al., 2001; Kozarić and Ivančan-Picek, 2006; Horvath et al., 2006; Mastrangelo et al., 2011; Mikuš et al., 2012) highlighted cyclonic activity in the W~~w~~estern Mediterranean and ~~in the~~ Adriatic as a triggering mechanism for a range of extreme weather phenomena, including HPE. ~~Position~~ The positions of cyclones that appear in the Adriatic Sea basin strongly influence the climate and weather conditions in the area (Horvath et al., 2008).

During ~~the~~ SOP1, several upper-level troughs entered the W~~w~~estern Mediterranean and induced cyclogenesis over the Gulf of Genoa, ~~the~~ Tyrrhenian Sea and ~~over the~~ Adriatic Sea. Figure 3 shows the mean sea level pressures and low-level horizontal winds for IOP4, IOP9, IOP13, IOP16, IOP18 and IOP19. ~~While~~ Although most of the events were related to cyclone activity in the region, some events were not characterized ~~with~~ by a cyclone moving over the area. In the following text, we summarize the analyses of selected characteristic IOPs that affected the Adriatic area. ~~Similar large scale~~Large-scale conditions ~~such as~~similar to those found in ~~these~~ the IOPs helped ~~help to~~ generate mesoscale and local processes, leading to quite different precipitation patterns.

3.1.1 IOP4

This event was caused by a mesoscale cyclone associated with a potential vorticity (PV) anomaly over the Adriatic Sea~~,~~ and was enhanced by the low-level convergence of the Bora flow over the N~~n~~orthern Adriatic Sea and warm southerly wind ~~on~~ in the S~~s~~outhern Adriatic (Figure 3a). ~~Mesoscale~~ The mesoscale cyclone moved slowly southeastward, inducing instability over C~~c~~entral Adriatic Sea, with intense convective phenomena on both sides of the basin.

Several rain gauges stations reached maxima of over 150 – 200 mm/24 h along the E~~e~~astern Italian C~~c~~oast (Maiello et al., 2014), and more than 100 mm/24 h was recorded over the southeast coast of the Adriatic, with ~~the~~ a maximum over the Pelješac peninsula (Figure 1b). As inferred from the satellite data, there were also other local precipitation maxima ~~in precipitation above~~over the sea (Figure 4b). Previous studies (~~e.g.~~ e.g., Buzzi and Foschini, 2000; Ivančan-Picek et al., 2014; Davolio et al., 2016) ~~show~~ have shown that the largest component of the mountain-range-scale precipitation appears to be due to the orographic lifting ~~lift~~ of ~~the~~ moist and impinging low-level flows. Consequently, the vertical uplifts forced by the Dinaric Alps area were favourable for the initiation and maintenance of convection. However, the coastal ~~Coastal~~ mountains close to the Adriatic Sea were ~~however~~ not the only sources ~~source~~ of lift. ~~The l~~Low~~ow~~-level circulation over the sea frequently generates low-level convergence responsible for convective initiation (Jansa et al., 2001; Davolio et al. 2009). The mesoscale cyclone over the Adriatic and frontal system moved slowly ~~south-eastward~~southeastward and induced instability over the ~~c~~Central Adriatic Sea due to the strong low-level ***convergence*** between the southerly *jugo* (sirocco) and northeasterly *bora* winds~~wind~~. This ~~resulted in~~caused more than 100 mm/24 h to be recorded over the S~~s~~outheast Adriatic ~~c~~Coast and ~~above over~~ the open sea (Figure 4b).

In IOP4, heat loss caused by a strong *bora* wind was very intensive. The *Bora* was severe on N~~n~~orthern Adriatic~~, exceeding~~ and exceeded 24 m/s. Strong *bora* winds ~~wind~~ bring ~~brings~~ cold and dry continental air over the warm Adriatic basin, which ~~generating~~ generate intense air-sea heat exchanges and a rapid sea surface cooling (e.g. e.g., Grisogono and Belušić, 2009). The proper representation of sea surface temperatures (SSTs) in the numerical models, especially in small and shallow basins, like such as the Adriatic Sea, is necessary for improving the short-range precipitation forecasts (e.g. e.g., Davolio et al., 2015b; Stocchi and Davolio, 2016; Ricchi et al., 2016). The response of heavy precipitation to a SS an SST change is complex and mainly involves the modification ofmodification to the boundary layer characteristics, flow dynamics and its interaction with the orography. In the numerical modelling, the SST representation is generally unrealistic and usually keeps the SST fixed at its initial value. FurthremoreFurthermore, especially in a narrow and inhomogeneous basin, like such as the Adriatic, small-scale SST variations cannot be properly represented in the coarse large-scale analysisanalyses, especially near the coasts. Figure 4a shows SST measured on at the station Bakar station close to the city of Rijeka for the whole entire SOP period. During IOP4 (13 – 14 September 2012), the SST rapidly decreased for by 10 °C on at the Bakar station Bakar in comparison to representation in the operational model which usethat used LBC from the global ARPEGE model ARPEGE. Therefore, the SST near the coast was colder than that in the ALADIN model forecast, affecting which affected the ability of the forecast model to properly forecast the meteorological fields there. In addition to operational SST, a control simulation is was driven by the SST field provided through from the OSTIA analyses (Donlon et al., 2012), which better corresponded to in-situin situ observations during this event. The daily accumulated precipitation for the operational 2 km model run and the control simulation with modified colder SST from OSTIA are presented at Figures 4d and 4e. -In this case, the control simulation using the OSTIA analysis is was more realistic (see Figure 4b) and generally drier than the operational with a warmer SST. Colder The colder SST resulted with decreasing ofcaused a decrease in precipitation over the mountainous Adriatic Ceoast.

IOP4 shows the needs for further improvements of in the role of SST and surface (latent and sensible) heat fluxes over the Adriatic Sea, which attain large values during strong *bora* events. However However, a more detailed analysis of the impact of SST on precipitation is ongoing.

3.1.2 IOP-13

Several events were characterized by frontal lifting associated with quasi-stationary ***frontal systems*** that which help the release ofhelped release convective instability (IOP9, IOP12, and IOP13). Here Here, we will focus on the IOP13 event, that which affected the entire Eeastern Adriatic c Coast and all three Italian target areas (Ferretti et al., 2014).

Smooth troughs entering the wWestern Mediterranean Sea that produced a south westerly flow over the Adriatic TA were observed producing a south westerly flow over the Adriatic TA. A cold front moved eastward, supporting the advection of moist air ~~on the~~at low levels towards the coastline. This warm and moist air ahead of the front organized intensive convective activity that formed a rain band stretching from Tunisia over ~~s~~Southern Italy to S~~s~~outheast Croatia. ~~In~~ During the evening of 15 October, a Genoa cyclone developed and with an associated frontal system moved rapidly over Italy. The advection of the moist air from over the sea caused deep convection and another cut off low that developed over ~~n~~Northern Italy and moved eastward. This weather regime (Figure 3c) provided a favourable environment for HPE, with thunderstorms over the N~~n~~orthern Adriatic Sea, where 127.4 mm/~~24h~~24 h was recorded in the city of Rijeka in the ~~n~~Northern Adriatic. Figure 5a shows the daily accumulated rainfall on 16 October recorded by the Slovenian and Croatian rain gauge networks and the interpolation with the 3B42RT product. The low-level wind field was dominated by a low-level jet stream that carried the warm and humid Mediterranean air to the Adriatic Sea (Figure 3c). This situation was favourable for the strong S-SE sirocco wind, which is known as the *jugo* in Croatian (~~e.g.~~ e.g., Jurčec et al., 1996). ~~Advection~~ The advection of warm and moist Mediterranean air caused intensive precipitation, ~~with more than~~which exceeded 100 mm/24 h ~~above~~ over the N~~n~~orthern Adriatic and open sea and several outermost islands (Mali Lošinj, Silba, Hvar, and Mljet).

In less than 24 h, intense precipitation exceeding 120 mm affected the N~~n~~orthern Adriatic area. The precipitation timing and the location of the maxima ~~are~~ were reproduced quite well in the model forecasts (Figures 5~~-~~b and 5c). ~~Operational~~ The operational forecast at a ~~2~~ 2 km grid resolution better simulated ~~better~~ the extreme amounts in the Rijeka area than operational forecast at an ~~8~~ 8 km grid resolution. However, both models overestimated the rainfall ~~above~~ over the S~~s~~outhern Adriatic M~~m~~ountains.

3.1.3 IOP16 and IOP18

These events represent excellent cases for the science issues identified in HyMeX program for ~~the western~~the Western Mediterranean (convection initiation, cloud-precipitation processes, and air-sea coupled processes). These situations produce favourable conditions for HPEs on the southern side of the Alpine ridge, including the N~~n~~orthern Adriatic region.

During these events, the Adriatic TA was strongly affected by the Genoa cyclone (IOP16) and the intensive W~~w~~estern Mediterranean cyclone (IOP18) inducing low-level southeasterly ~~south-easterly~~ and south~~-~~westerly flow over the Adriatic area.

Figures 3d and 3e show the sea level pressure and low-level wind vectors at 1200 UTC on 27 and 31 October. This situation was favourable for the strong S-SE *jugo* wind (IOP18), which carried the warm and humid Mediterranean air to the Adriatic Sea. The cyclone during IOP16 caused the lowest pressure recorded over the Adriatic TA during the ~~whole~~entirety of SOP1. ~~Advection~~ The advection of the warm air combined with intensive advection of cyclonic vorticity contributed to the strong upward motion in the area of the N~~n~~orthern Adriatic and the adjacent mountains, ~~resulted~~ resulting in ~~with~~ 180 mm of precipitation ~~in~~ over the city of Rijeka and the mountainous hinterland (Figure 6a). Very intensive convective activity during IOP18, with heavy showers and thunderstorms, again produced more than 170 mm/24 h ~~again~~ in Rijeka ~~more than 170mm/24h~~ (Figure 7a).

During IOP16, targeted radio-soundings ~~aimed at both~~intended for data assimilation, case analysis and verification were deployed over the C~~c~~entral Mediterranean area and Adriatic area. The time evolution of the vertical structure of troposphere on the ~~e~~Eastern Adriatic C~~c~~oast ~~is~~ was inferred by DTS deployed and standard radiosoundings at Zadar-Zemunik during 26-28 October (Figure 8). ~~Gradual~~ A gradual moistening of the lower troposphere occurred on 26 October during the occurrence of a ~~south-easterly~~southeasterly near-surface *jugo* wind in the Adriatic basin and ~~south westerly~~southwesterly flow aloft. The air column below 500 hPa was nearly saturated ~~and also~~ and rather moist above. On 26 October, this moistening was still not associated with significant values of convective available potential energy (CAPE). On the next day, however, CAPE increased to over 1200 J/kg on 1200 UTC and over 1000 J/kg on 1800 UTC 27 October. The winds strengthened throughout the troposphere, and the highest intensity was observed in the layer between 300 and 200 hPa. ~~Strong~~ A strong ~~south-westerly~~southwesterly shear of approximately 20 m/s in the first 2 km of the troposphere was also present over this area.

Both IOPs (IOP16~~,~~ and IOP18) were fairly well forecast (Figures 6 and 7). The precipitation timing and the location of the maxima were reproduced quite well in the model~~s~~ forecasts. In less than 24 h, intense precipitation exceeding 170 mm affected the N~~n~~orthern Adriatic area. ~~Operational~~ The operational forecast of the 2 km model resolution run overestimated rainfall above mountains, but it ~~is~~ was consequently closer to the extreme amounts in the Rijeka area.

The sirocco wind is the cause of a piling up of Adriatic water near the northernmost coasts that occasionally floods the city of Venice (Orlić et al., 1994). This was the case also during the IOP16 and IOP18. The Venice Lagoon was hit by ~~the~~ “acqua alta” (high water), the warning level was exceeded twice, with more than 120 mm on 27 and 28 October (Ferretti et al., 2014), and more than 140 mm was measured on 1 November 2012.

3.1.3 IOP19

During the ~~whole~~entirety of IOP19 (3-5 November 2012), the ~~south westerly~~southwesterly advection of warm and humid air produced convection over the ~~n~~Northern Adriatic and orographic precipitation along the Kvarner B~~b~~ay. A south–westerly flow over the ~~whole~~entire region of the W~~w~~estern Mediterranean was produced by a baroclinic wave that formed over N~~n~~orthwest Europe to N~~n~~orthern Africa due to weakened westerlies and low NAO. Strong southwest flow in the lower troposphere ahead of the cold front supported the advection of moist and warm air. ~~A more detailed~~Additional details on the synoptic situation ~~is~~ are described in Ferretti et al. (2014) and Davolio et al. (2016). ~~-~~More rainfall was recorded on rain gauges on the ~~north eastern~~N~~n~~ortheastern Adriatic C~~c~~oast. During this event, 177.0 mm/~~24h~~24 h was recorded in Klana, the hinterland of the city of Rijeka (Figure 9), and the precipitation was mainly ~~orographic~~ orographic-forced with a strong southeast *jugo* (sirocco) wind (Figure 3f). This represents a typical event in this area, which are generally well forecasted by operational models that ~~are able to~~can describe the main orographic forcing properly. Both versions of the ALADIN operational models (8 and 2 km resolution) produced maximum precipitation over the mountainous hinterland of the city of Rijeka (Figures 9~~-~~b and 9c). The amount of precipitation was slightly underestimated. In addition, the 2 km non-hydrostatic version of the model produced the second maximum over the Velebit mountain, which was not observed. This result implies that ALADIN 2 km overestimated the orographic forcing associated with the higher Dinaric Alps ridges.

3.2. Verification of the precipitation forecasts during SOP1

~~Performance~~ The performances of the operational precipitation forecasts with the ALADIN model at 8 km and ALADIN model at 2 km grid spacing during SOP1 w~~was~~ere assessed by comparing the forecasts with the measurements from the Croatian surface observation network. ~~Model~~ The model results were compared with 24-hour accumulated precipitation measured by the rain gauges. Before the calculation of the verification scores results for ALADIN 2 km, the model was upscaled to an ALADIN 8 km grid to avoid double penalty errors and make a more direct comparison. Contingency tables (Tables 3 and 4) were evaluated with three categories defined according to the amount of ~~24h~~24 h accumulated precipitation and classified as dry, medium and strong. An event was defined as dry if the 24 h accumulated precipitation~~s~~ on the rain gauge station ~~were~~ was less or equal 0.2 mm/~~24h~~24 h. The ALADIN model at a 2 km grid spacing during SOP1 was assessed by comparing the forecasts from the nearest model point with respect to the observation location with the measurements from the Croatian surface observation network. The border between the medium and strong categories was defined as the 95th percentile of the measured ~~24h~~24 h accumulated precipitation (50.42 mm/~~24h~~24 h) during the ~~the SOP1~~SOP1 period, but with the dry events excluded.

Figure 10 presents the 24~~-~~-hour accumulated precipitation histograms from both the models and rain gauges during the ~~whole~~entire SOP1 period and during the specific days corresponding to the 8 IOPs indicated in Table 1. The ~~Measurements~~ measurements show that~~ during the entire SOP1 period,~~ a large percentage of the events ~~was~~ were dry (64.7%) during the entire SOP1 period. ~~Value~~ The value corresponding to the 95^{th} percentile (50.4 mm) is indicated ~~at~~ on the graph, and it appears ~~as~~ to be a reasonable threshold for the heavy precipitation events that we want to verify. ~~Histogram~~ As expected, the histogram for only the IOP days ~~only~~ (8 IOP cases) ~~as expected~~ show that the number of dry events ~~is~~ was reduced (18.1%) and the relative frequency of events ~~shifts~~ shifted towards events with higher amounts of precipitation.

~~While for~~Although ~~the whole SOP1 period~~ the ALADIN 8 km model distribution ~~is~~ was in rather good agreement with the rain gauge measurements during the entire SOP1 period, with the exception of the ~~except for~~ most intensive rain, the model distribution for the IOP days only shows that the model ~~tends~~ tended to underestimate the ~~frequency~~ frequencies of ~~week~~ the weak and strong precipitation events, ~~while~~ whereas it ~~overestimates~~ overestimated the frequency of moderate precipitation events. For ALADIN 2 km SOP1 and IOP days only, the histograms show~~s~~ similar results; ~~where~~ the model ~~tends~~ tended to underestimate moderate precipitation, ~~while~~ whereas at the same time it ~~tends~~ tended to overestimate strong precipitation. ~~Comparison~~ A comparison of the two models shows ~~a~~ that the ~~better agreement of~~ ALADIN 22~~km~~ km model ~~with~~ better agreed with the measurements, especially for very ~~week~~ weak and strong precipitation.
~~In Table 3 and 4~~The verification measures (Wilks, 2006) calculated from the comparison of the ~~24 hour~~24-hour accumulated precipitation from the rain gauges and model, for the three categories and ~~for~~ different periods are summarized in Tables 3 and 4. The ~~definition of the~~ indices used here ~~is available~~are defined in Appendix. ~~As~~ Because most of the measures are Base Rate (BR) sensitive and ~~they~~ can be safely used only to compare two models for the same event, the polychoric correlation coefficient (PCC; Juras and Pasarić, 2006) as an additional measure was calculated because PCC does not depend on BR or ~~on~~ frequency bias (FBIAS). For both ALADIN models, PCC showed rather high levels of association between the observations and forecast for the ~~whole~~entire SOP1, ~~while~~ whereas it ~~has~~ had a smaller value for only the IOP days.
For both models, the smallest value of PCC ~~is~~ was for IOP 9, where both models overestimated the number of strong precipitation events, especially ALADIN 2 km, which can be seen from the much higher FBIAS than ~~the one~~that from the ALADIN 8 km model. Comparing the performances of the two ALADIN models, it can be ~~seen~~ observed that ALADIN 2 km ~~has~~ had higher levels of association between the observations and forecasts for IOP13 and IOP19 compared to ALADIN 8 km. For IOP13, ALADIN 2 km w~~is~~ as relatively more accurate in all three categories, which can be

seen from the higher values of the critical success index (CSI). For IOP19, the FBIAS values show that ALADIN 2 km ~~overestimates~~ overestimated the frequency of strong precipitation, but at the same time it ~~is~~ was relatively more accurate for the other two categories (higher CSI). For the dry category, ALADIN 2~~2km~~ km ~~has~~ had better scores for almost all the selected cases (higher CSI; FBIAS closer to 1). For medium precipitation, ALADIN 8 km ~~has~~ had better scores, except for IOP13 and IOP19. For the strong category, the scores show that ALADIN 2 km ~~tends~~ tended to overestimate the frequency of strong events, whereas ~~while~~ ALADIN 8 km ~~tends~~ tended to underestimate the frequency of strong events, with ~~only exception for~~the sole exception of IOP19, where both models overestimated the number of strong precipitation events (especially ALADIN 2 km).

4. IOP2 over the ~~north-eastern~~N~~n~~ortheastern Adriatic TA

Although the Adriatic TA was not ~~a~~ part of the extensive experimental activity during ~~the~~ SOP 1, many events that affected the Western Mediterranean also expanded ~~at~~ into the Adriatic area~~ too~~. During ~~the~~ IOP 2, in the late evening hours of September 12, a rainy episode with very heavy rainfall ~~rain falling~~ over only a few hours ~~have been~~was recorded over the city of Rijeka, ~~at~~ on the northern coast ~~cost~~ of Kvarner Bay in the E~~e~~astern Adriatic ~~s~~Sea and ~~in~~ its mountainous hinterland of Gorski K~~k~~otar. According to ~~the~~ a report ~~of~~ from the Municipal Water and Sewer Company of the city of Rijeka, ~~-~~some major city roads became rivers and streams, sewage manhole covers were discharged, ~~and~~ massive caps flew into the air up to two~~-meter~~ metres, and ~~then~~ a spate of them were then carried up to one hundred~~-meter~~ metres ~~away~~ from ~~the~~ their shafts.

Ferretti et al. (2014) described IOP2 in ~~north-eastern~~N~~n~~ortheastern Italy (NEI) and analysed the meteorological characteristics and synoptic situation. A shallow orographic cyclone developed in the lee side of the Alps, extending from the Genoa Gulf to the N~~n~~orthern Adriatic. ~~Simultaneously~~ Simultaneously, with the Genoa cyclogenesis, a twin type of cyclone (Horvath et al., 2008) developed in the N~~n~~orthern Adriatic (Figures 11~~-~~a~~,~~ and 11b). The Croatian C~~c~~oast of the N~~n~~orthern and ~~middle~~ Central Adriatic was influenced by the strong moist southwestern ~~south-western~~ flow on the leading side of the cyclone(s). The air was moist due to southwest advection and evaporation from the Mediterranean. Below 2 km, there was strong convergence over the N~~n~~orthern Adriatic. Due to its specific position deep in Kvarner bay, which is open from the southwest and, at the same time, in the very pedestal of the Velebit mountain chain, the city of Rijeka and its surroundings have ~~the~~ geographic preconditions for pronounced convection, with extensive precipitation ~~in~~ under such specific synoptic conditions (~~e.g.~~ e.g., Ivančan-Picek et al., 2003).

During the day in the late afternoon, cold air ~~irrupted~~ erupted along the Alpine slopes, and together with the passage of the cold front over NEI and the ~~north eastern~~N~~n~~ortheastern Adriatic Sea, resulted ~~with~~ in intensive convective processes.

4.1. Extreme value analysis of the short-term precipitation maxima

~~Spatial~~ The spatial distribution of the daily rainfall amounts for the IOP2 rain episode indicates that the largest amounts ~~fall~~ fell over the city of Rijeka (220 mm at the Rijeka meteorological station, which is ~~Rijeka~~ located 120 m above sea level)~~,~~ and the surrounding mainland hilly slopes and mountainous hinterland. According to the ~~recorded~~ rainfall data recorded by ombrograph at the Rijeka meteorological station, ~~Rijeka the more~~a ~~-detailed~~better-detailed insight into the temporal rainfall distribution during the short-term interval of this heavy rainfall event is possible (Figure 12). The rainfall episode that occurred during the six-hour period between 6 pm and midnight~~,~~ ~~experienced its most intense part~~was most intense between 9 pm and 11 pm. ~~Maximum~~ The maximum 20, 30, 40, 50, 60 and 120 minute~~s~~ rainfall totals, which ~~belong to this~~would have been ~~within~~ the most intense part of the rainfall episode, have not been recorded at the Rijeka station since the beginning of measurements in 1958 (Table 5). ~~Especially intense were the~~The rainfall intervals of 20, 30 and 40 minutes were ~~-~~especially intense and ~~that~~ could be expected once in a more than a thousand, a few hundred~~s~~ and a hundred years, respectively, and ~~they belong to the~~correspond to an extraordinarily rare event~~,~~ as computed ~~from~~ over the period 1958 – 2011 (Patarčić et al., 2014). The maximum amounts that ~~fall~~ fell in the ~~interval of~~ two- and four~~- hours~~ hour intervals could be expected ~~ones in~~every forty and fifty years, respectively.

4.2 Observational analysis

On 12th September 2012, a sequence of convective events hit the northeastern part of Italy and, in particular, the eastern part of the Veneto region and the plain of the Friuli Venezia Giulia region~~s~~. During ~~the~~ that day, at least two of the events could be classified as supercells, and the first one ~~being~~ was also associated with ~~a~~ heavy hail ~~fall~~ (Manzato et al., 2015; Miglietta et al., 2016). ~~-~~After a few hours, a third storm system~~,~~ that ~~resembling~~ resembled a ~~squall-line~~squall line, although of limited dimensions, swept over the area.

EUMETSAT was conducting its first experimental 2.5-minute rapid scan with the MSG-3 satellite, ~~with~~ and data are available from early morning until 0900 UTC of the IOP2 day. Unfortunately, the MSG-3 satellite (renamed Meteosat-10) experimental rapid scan data, which have intervals of ~~with~~

2.5 minutes~~ interval~~, ~~taken by MSG-3 satellite (renamed to Meteosat-10) were~~are available ~~only~~ until only 0900 UTC on 12 September 2012.

~~Nearby~~ The nearby area of Istria and Rijeka ~~received the first~~first received rain in the early afternoon, which ~~that~~ soon stopped before the torrential rain in the evening~~,~~ between 2100 and 2300 UTC. The last one ~~is~~ was connected to ~~the~~ a third storm over Italy (as discussed in Manzato et al. 2015), which ~~that~~ was an elongated storm moving along the coast of the N~~n~~orth Adriatic. Convection developed over the N~~n~~orthern Adriatic, and warm and moist advection produced intensive precipitation triggered by the orography inland.

Satellite data show that~~formation of~~ cumulonimbus clouds formed (Figure 13). This intensive rainfall band reached Trieste and Slovenia according to the radar figures (not presented) and merged with the rainfall band that formed above Trieste at 1800 UTC. Another rainfall band formed above the Istria peninsula at 1930 UTC. Intensive rainfall spread to Rijeka and ~~remained~~ persisted there for several hours. During that time, other rainfall bands formed and moved over Rijeka, intensifying the precipitation and prolonging the period of high precipitation intensity.

According to the hourly amounts, the largest precipitation intensity ~~was the highest~~occurred from 2100 to 2200 UTC (85.3 mm/h), with 20.6 and 51.7 mm/h in the previous and ~~the next~~following hour (Figure 12).

Sounding data measured at Zadar-Zemunik, which is located ~~about~~ approximately 150 km south-southeast of the area where the largest rainfall was recorded, ~~are shown to~~can provide information on the vertical structure of the troposphere. Although the ~~thermodinamic~~ thermodynamic profile characteristics are not completely representative of the pre-convective environment over the study area, this is the only available sounding data ~~on~~ for the E~~e~~astern Adriatic. The soundings featured a low-level moist atmospheric layer from the surface to approximately 850 hPa that was connected with SE *jugo* wind, confirming ~~a~~ that there was a suitable environment for strong convective activity (not presented). ~~Winds~~ The winds strengthened throughout the troposphere, and the highest intensity was observed at 400 hPa.

4.3. Operational model forecasts

During ~~the SOP1~~SOP1, DHMZ made available the operational forecast ~~by~~ from the ALADIN operational forecast~~s~~ model ~~in~~ at 8 km and non-hydrostatic 2 km horizontal resolutions (Section 2.3). ~~A comparison between~~The two versions of the ALADIN model ~~is presented~~are compared here, and the comparison ~~and~~ shows the capability ~~in~~ for forecasting ~~the~~ intense convective activity in the area.

~~Short~~The short-range forecasts well reproduced ~~well~~ the large-scale and mesoscale features responsible for the event (Figure 11). The low-level wind field ~~is~~ was dominated by two low-level jet ~~stream~~ streams (LLJs) and caused the appearance of the low-level wind convergence over the North Adriatic ~~and~~ that was associated with the main Genoa cyclone (Figure 11b). In this case, the performance of the model ~~is~~ was rather successful in comparison with the ECMWF reanalysis (not presented). One SW LLJ was elongated from Italy towards the middle Adriatic ~~that carry the~~and carried warm and humid Mediterranean air to the Adriatic Sea, and another NE LLJ (*bora* wind) was modified and intensified by the pressure gradient across the southern flank of the Alps (Figure 11a). This convergence was responsible for the convective triggering in the late afternoon. Although the mesoscale characteristics ~~are~~ were correctly reproduced, the location and timing of the precipitation ~~was~~ were not as well ~~so~~ predicted~~good~~. The intensive precipitation event was predicted by both models, with precipitation close to or exceeding 100 mm/24 hours inland of Rijeka (Figure 4), but the amount of precipitation was underestimated for the city of Rijeka, ~~that~~ which lies on the coastline ~~for~~ in all operational models, possibly due to an absence of the cold pool that formed after the showers in the early afternoon or the ~~low level~~low-level wind from northeast that started earlier than in the model forecast.

~~Operational~~ The operational forecast ~~set up~~ setup of the ALADIN 2 km resolution run ~~overestimates~~ overestimated the rainfall above mountains (at least when compared to the 3B41 products from the TRMM data server), but it ~~is~~ was consequently closer to the extreme amounts measured in the Rijeka area (Figure 14). Although the 3B41 product is an estimate of precipitation intensity that also suffers from errors, the rain over the S~~s~~outhern Velebit Mountain was ~~an overestimate~~overestimated, ~~while~~ although it was correct for the mountains inland of Rijeka. In the hours of peak precipitation intensity in Rijeka, the satellite measurement data-derived precipitation (TRMM 3B41RT product available from NASA's Giovanni web service) was also considerably lower than ~~the one~~that measured ~~in-situ~~in situ.

The ~~high resolution~~high-resolution, non-hydrostatic operational forecast ~~shows~~ showed upward motions along the coastal mountains of Croatia ~~and associated to~~that were associated with the convergence line and the rain band over the sea (Figure 15). The wave of ~~the~~ upward motion ~~moves~~ moved from the Po valley eastward and ~~reaches~~ reached Rijeka area one hour after the recorded maximum intensity in precipitation,~~s~~ ~~so~~ and the model might, ~~be little~~therefore, have been slightly ~~late behind~~later than the real weather events. ~~There is also a~~A permanent wave formed over S~~s~~outhern Velebit (and several other mountains) ~~that~~ and persisted ~~persist~~ throughout the night. ~~This~~ That wave ~~is~~ was responsible for triggering the precipitation there, and its intensity ~~is~~ was probably overestimated. Apparently, small but tall topographic obstacles ~~are able to~~can trigger too much precipitation; ~~and~~ this issue ~~remains an issue to solve~~must still be solved.

Figure 16 presents a scatter plot of the ~~24h~~24 h accumulated precipitation from rain gauges over Croatia and the forecast values from the ALADIN model taken from the nearest grid points for IOP 2. The ALADIN 8 km model underestimated precipitation and forecasted up to 92 mm/~~24h~~24 h of rainfall, ~~while~~ whereas the measurements reached 220 mm/~~24h~~24 h. Much better results ~~ware~~ ere obtained ~~for~~ from the ALADIN 2 km model; ~~where~~ the values predicted by the model ~~were~~ reached 200 mm/~~24h~~24 h. A location error is also evident for both models, especially for the area where the most intense precipitation occurred (Istria peninsula; red dots), but it ~~is~~ was smaller for the ALADIN 2~~2km~~ km model. ~~Medium~~ The medium precipitation amounts ~~are~~ were better forecast than the strong precipitation amounts ~~one~~ but were still slightly overestimated for the ALADIN 8 km model, and much more spread ~~is noticeable~~can be seen for the ALADIN 2 km model, with both overestimation and underestimation, but with better results for the Istria peninsula. From Tables ~~Table~~ 3 and ~~Table~~ 4, it can be ~~seen~~ observed that ALADIN 2 km was relatively more accurate (higher CSI) for the dry and strong categories, but not for the medium category, than ALADIN 8 km. FBIAS ~~is~~ was better for ALADIN 2 km for the medium category in addition to the dry and strong categories ~~but also for medium category~~ compared to the ALADIN 8 km results.

4.4 Influence of the data assimilation

~~Since,~~Because the lack of model skill ~~in~~ when simulating HPE ~~may~~ could be partially attributed to imperfect initial conditions, we performed ~~perform~~ several numerical weather prediction experiments to assess the impact ~~that~~ of data assimilation ~~had~~ on the IOP2 forecast accuracy.

~~Comparison~~ A comparison of the measurements with an operational forecast and simulations without data assimilation is shown in Figure 17. ~~Rain~~ The rain gauges showed that ~~along Croatia-Slovenia border~~ an elongated area of stronger precipitation along the Croatia-Slovenia border ~~is~~ was present, and ~~this~~ that pattern ~~is~~ was better forecasted ~~with~~ by the operational run that ~~incorporating~~ incorporated data assimilation. ~~Also~~ In addition, ~~over Istria peninsula~~ higher amounts of the medium rain category over the Istria peninsula ~~are~~ were found in the operational run, which ~~is in~~ better accorded ~~accordance~~ with measurements. This ~~is also visible at~~can also be seen in Figure 13, where for the run with data assimilation the points are less scattered, and more points with higher values of precipitation over Istria are present. ~~Maximum~~ The maximum recorded around the town of Rijeka ~~is~~ was not adequately represented by either ~~of the~~ models.

~~Verification~~ The verification measures (Table 3) show that ~~slightly better results are found for~~the simulation with data assimilation produced slightly better results. ~~Scores~~ The scores for the entirety of Croatia show that the strong precipitation category results ~~in strong precipitation category are~~were improved for the operational run (CSI=0.28) compared to the run without data assimilation (CSI=0.23). ~~Also~~ In addition, PCC ~~shows~~ showed that ~~there is~~the ~~better association of~~ model and observations for the run with data assimilation were better associated. ~~Impact~~ The impact of data assimilation for ~~this~~ that ~~IOP~~ was ~~is~~ rather small, but it ~~still gives~~yielded an improvement in the 24-hour~~s~~ precipitation forecast. It should be ~~taken into account~~considered that for the selected case, better results were obtained with the higher resolution model and that the data assimilated in the operational ALADIN 8 km model ~~is~~ was mainly synoptic data. Thus, implementing data assimilation in the higher resolution model and adding additional ~~high resolution~~high-resolution temporal and/or spatial data to the data assimilation system ~~seems as~~are apparently good ways to ~~good way to~~ further enhance operational forecasts.

Summary and conclusions

In this paper, an overview of the IOPs that affected the Adriatic TA during the SOP1 HyMeX campaign (5 September to 6 November 2012) is presented. During SOP1, 20 IOPs were declared, and 8 of ~~these~~ those events affected the EOP Adriatic TA. ~~All of~~All ~~these~~ the events produced localized heavy precipitation and often were properly forecast by the available ALADIN operational model, ~~ALADIN~~ but uncertainties existed in the exact prediction of the amounts~~amount~~, precise times ~~time~~ and locations ~~location~~ of maximum intensity. The total precipitation amounts~~s~~ for ~~the SOP1~~SOP1 ~~were above~~exceeded the corresponding climatology for the Adriatic TA. ~~Maximum~~ The precipitation maximum ~~of precipitation~~ (more than 1.000 mm in 61 days at some locations) was recorded ~~on~~ in the N~~n~~orthern Adriatic (city of Rijeka) and its mountainous hinterland of Gorski Kotar. This region experiences climatic maxima of ~~the~~ annual precipitation greater than 3.000 mm on average. ~~Analysis~~ The analysis was ~~done mostly by the~~performed primarily using measurements from the operational meteorological network maintained by the Meteorological and Hydrological Service of Croatia.

There were 15 days when the accumulated rainfall ~~on any of the~~at ~~at~~ least one ~~raingauge~~rain gauges in the Adriatic TA exceeded 100 mm in 24 hours. Most the HPEs contained similar ingredients and synoptic settings but ~~of~~ had different ~~intensity~~intensities as follows: an ~~a~~extensive deep upper level ~~through~~, cyclone strengthening over the Mediterranean (or developing over the Gulf of Genoa, Lyon or the Tyrrhenian ~~Tyrhennian s~~Sea), a strong southwesterly low-level jet stream that advects

~~the~~ moist and warm air towards the orographic obstacles along the Mediterranean coastline and destabilizes the atmosphere as the strong wind picks up the moisture from the sea.

~~Verification~~ The verification of the operational precipitation forecasts during SOP 1 suggests the operational ALADIN ~~at 8 km grid spacing~~ model with 8 km grid spacing may be useful for issuing early warnings ~~to~~ for severe precipitation events in the region. For most of the events, ~~there was high level of association between~~ the precipitation forecast and measurements were highly associated. From the verification statistics and different precipitation related figures, it can be seen that ~~one~~ an obvious limitation of the ALADIN 8 km model is its inability to produce high amounts of precipitation and ~~also~~ its tendency to underestimate the frequency of dry events. ~~Having~~ Both issues can be ameliorated using a non-hydrostatic model at a higher resolution (ALADIN 2 km) ~~brings improvement for both of those issues~~. ~~Still~~Nevertheless, the exact precipitation amounts ~~are~~ were not always well simulated. ~~Verification~~ The verification methods used in this work ~~have their limitation where for~~are limited because the utilized ~~calculation of~~ score~~s~~ calculation method ~~used~~ is a point based comparison and is thus ~~it is~~ prone to location errors, and other methods that are used are based on subjective comparisons ~~comparison~~ of different precipitation plots. ~~Next~~ A next step would be ~~implementation~~ to implement an~~of~~ object-based verification method, e.g., SAL (Wernli et al., 2008), which could provide more objective verification measures, but for this local spatial precipitation analysis, the method must first be developed~~ first~~.

During ~~the~~ IOP2 on 12 September 2012, several thunderstorms formed, including a supercell and a possible tornado outbreak. The warm and moist air advected ~~at~~ in the low levels over the Adriatic (and Mediterranean before that) ~~was feeding~~fed the storms, ~~while~~ but ~~apparently~~ one storm apparently produced downdrafts that would in turn ~~form~~ have formed a convergence zone with ~~the~~ moist flow from the sea and triggered ~~trigger~~ the next storm. ~~Intensive~~ The intensive precipitation event in Rijeka and the surrounding area resulted from the influence of the coastal mountains on the movement of a convergence line. The atmosphere contained ~~a lot of~~ much moisture~~, being close to saturated~~ and was nearly saturated up to 6 km. The air flow converged above N~~n~~orthern Adriatic in the layer up to 2 km. The convergence line moved ~~south-eastward~~southeastward, ~~while~~ whereas rainfall intensified in the Rijeka area due to local terrain. The peak intensity was underestimated by the model forecast.

Such a chain of events poses a challenge with respect to predictability. The fact that the surrounding mountains represent physical obstacles that modified the flow and determined the position of the convergence zones made forecasting the location of such a chain of events more predictable. An~~A~~

abundance ~~bundance~~ of available real-~~-~~time ~~available~~ measured data, including radar measurements, aircraft data and targeted radio soundings, can improve the initial conditions for the NWP models. The ambiguities in the sea surface fluxes, ~~that pose~~ which were an important source of energy for this event, could be the factor that limits the abilities of ~~a~~ deterministic forecasts~~forecast~~.

The numerical sensitivity experiments with respect to the mesoscale data assimilation suggested the precipitation forecast during IOP 2 was improved by using data assimilation to produce initial conditions, compared to forecasts when initial conditions were derived from the global model data. ~~Use~~ The use of mesoscale data assimilation for initial conditions enhanced ~~both~~ the precipitation structure and intensity. This is also evident ~~also through~~given the improvement ~~of~~ in the objective verification measures, ~~such as~~including the critical success index and PCC. ~~Data~~ The data assimilation system could be further enhanced by using additional observations (e.g., radar ~~data,~~ and ground based GNSS data), shorter data assimilation cycles (e.g., 3 hours instead of 6 hours) or a B matrix computed ~~with~~ using more advanced methods (an ensemble B matrix instead of NMC based). ~~Also work on~~Work also continues ~~on~~to implementing a data assimilation system to a higher resolution model ~~is ongoing~~. Furthermore, the operational non-hydrostatic model at a 2 km grid spacing ~~is~~ was able to predict the intensity of an HPE more accurately than the hydrostatic model at an 8 km grid spacing. Nevertheless, a higher resolution forecast can misplace the position of the peak precipitation and overestimate the precipitation over ~~a~~ narrow but high mountains such as the ~~s~~Southern Velebit. This may be an artefact of the excessive sea surface temperature in the model in that region. These results suggest that precipitation forecasts in the Adriatic TA may be improved by both using mesoscale data assimilation and by decreasing the grid spacing of the model.

Heavy precipitation~~s~~ over the Adriatic area ~~are~~ is often associated with sirocco (*jugo*) or *bora* winds~~, thus involving~~ and thus involves intense air-sea interactions. ~~In IOP4 was an~~ IOP4 provided an excellent example ~~for~~ of very intensive heat loss caused by a strong *bora* wind. In ~~this~~ that case, the control simulation run was more realistic with colder SSTs and was generally drier than the operational run with ~~a~~ warmer SSTs. IOP4 ~~shows~~ illustrates the need~~s~~ for further improvements of the role of the SST and surface (latent and sensible) heat fluxes over the Adriatic Sea, which attain large values during strong Bora events. ~~However~~ However, a more detailed analysis of the impact of SST on precipitation is ongoing.

~~Therefore, this~~This paper, therefore, highlights the need ~~for enforcement~~to enforce an intensive observation period in the future over the Adriatic region~~,~~ to better understand the relevant processes, ~~and~~ validate the simulated mechanisms ~~as well as to~~and improve numerical forecasts via data assimilation and improvements ~~of~~ in model representations ~~representation~~ of moist processes and sea-land-atmosphere interactions~~interaction~~. There is also a need for collaborative efforts ~~effort~~ within the Italian and other HyMeX scientific and forecast communities to achieve a better understanding of the complex processes ~~caused the~~that cause extreme events over the Adriatic region.

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APPENDIX

~~Indices~~ The indices used in the statistical analysis of verification quality are briefly described and defined below. ~~-~~All the indices mentioned in Tables 2 ~~and Table~~ 3 ~~was~~ were calculated from a 3x3 contingency table, ~~with~~ the general form ~~indicated~~ of which is shown in Table 6. ~~Contingency~~ A contingency table with three categories (dry, medium~~,~~ and strong) was defined according to the amount of 24 h accumulated precipitation (Table 6). An event was defined as dry if the 24 h accumulated ~~precipitations~~ precipitation on the rain gauge station was less than or equal to 0.2 mm/~~24h~~24 h. The border between the medium and strong categories was defined as the 95th percentile (50.42 mm/24 h) of measured 24 h accumulated precipitation during the ~~the SOP1~~SOP1 period, but with dry events excluded.

Table 6: *General form of a multi-category (3x3) contingency table ~~along~~ with a marginal distribution.*

		OBSERVATIONS			
		Dry	Medium	Strong	∑
FORECAST	Dry	a	b	c	d
	Medium	e	f	g	h
	Strong	i	j	k	l
	∑	m	n	o	p

~~Formulas~~ The formulas for calculating the verification measures used in Tables 2 and ~~Table~~ 3 are ~~given hereafter~~provided here, ~~were~~ where the subscripts D, M and S indicate dry, medium and strong ~~category~~ categories, respectively.

BASE RATE (BR) – provides information on the observed event frequency. Does not depend on the forecasted values.

$BR_D = ; BR_M = \frac{n}{p}; BR_s = \frac{o}{p};$

FREQUENCY BIAS (FBIAS) – indicates how well the forecast frequency of an event corresponds to the observed frequency of the event. ~~Perfect score is~~ FBIAS=1 for a perfect score. If FBIAS>1, the model has a tendency to overforecast events, ~~while~~ whereas FBIAS<1 indicates that the model has a tendency to underforecast events.

$FBIAS_D = \frac{d}{m}; FBIAS_M = \frac{h}{n}; FIAS_s = \frac{l}{o};$

CRITICAL SUCCESS INDEX (CSI) – measures the relative accuracy of a forecast. It is defined as the ratio of the number of correct forecasts of an event for some category and the sum of the number of correct forecasts -of the event in that category, the number of events that were forecasted in that category and that were not observed and the number of observed events that were not ~~forecasted~~ forecast in that category. CSI has values in the interval [0,1], ~~with~~ and 1 ~~being~~ is a perfect forecast.

$CSI_D = \frac{a}{m+d-a};\ CSI_M = \frac{f}{n+h-f}; -CSI_S = \frac{k}{o+l-k};$

POLYCHORIC CORRELATION COEFFICIENT (PCC) – represents a measure of the association between an observation and forecast in the contingency table. ~~Main~~ The main idea is to make appropriate transformations of forecasted and observed values together with category thresholds and then to seek the parameter (PCC) of the bivariate density function for which the volumes of the discretized bivariate distribution is equal to the corresponding joint probabilities of the contingency table, with the assumption that their joint probability density function is ~~the~~ bivariate normal. For contingency tables with more than two categories, several methods for estimating PCC exist. In this work, the Maximum Likelihood method (Olsson, 1979) was used. ~~More~~ Additional information on using PCC for the verification of meteorological fields can be found in Juras and Pasarić, 2006. PCC has values in the interval [-1,1].

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Table 3: *Verification measures calculated for the ~~24~~ 24-hour accumulated precipitation and for the ALADIN ~~8~~ 8-km model (second column) for three categories (first column) and for the ~~whole~~ entire SOP1 period (5 September to 6 November 2012), only IOP days (IOPavg) and for selected ~~(~~IOP~~)~~s corresponding ~~to~~ to the time periods indicated in ~~-~~Table 1 and for IOP2 without data assimilation experiment (IOP2 no DA). ~~Verification~~ The verification measures include Base Rate (BR), Frequency Bias (FBIAS), Critical Success Index (CSI) and polychoric correlation coefficient (PCC). Due to zeros in the contingency table, some PCC scores could not be calculated (IOP4 and IOP16 for the ALADIN 8-km model).*

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Figure 6: ~~-~~*same as Figure 5 but for IOP16 (28 October)*

Figure 7: *same as Figure 5 but for IOP18 (1 November)*

Figure 8: *Radiosounding data for Zadar 26 October 2012 at 0600 and 1200 UTC (first row), 26 October 2012 at 1800 and 27 October 2012 at 0000 UTC (second row).*

Figure 9: *same as Figure 5 but for IOP19 (4 November)*

Figure 10: *Normalized histogram of rain events (~~24h~~24 h accumulated precipitation on rain gauge station greater or equal 0.2 mm/~~24h~~24 h) for the ~~whole~~entire SOP1 period (5 September to 6 November 2012) (left column) and for days of selected (IOP)s within the same period (right column). ~~In order to~~To have readable histogram first histogram bin starts from 0.2 mm, ~~while~~ whereas the number of dry days ~~for~~for a given period is indicated ~~at~~ on the graph. ~~Location~~ The location of the 95th percentile of the SOP1 rain events distribution (50.42 mm/~~24h~~24 h) is shown. ~~Area~~ The area of the histogram after the 95th percentile is ~~zoomed~~ enlarged and shown as an inset to ~~enhance~~ improve readability. ~~Frequency~~ The frequency of the precipitation events for rain gauge is ~~coloured~~ coloured in blue and in ~~, for model~~ light green for the model, ~~while~~ whereas dark green indicates the overlapping of the model and rain gauge data. First row: ALADIN 8 km, Second row: ALADIN 2 km upscaled to an ALADIN 8 km grid.*

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Figure 17: The ~~*24h*~~*24 h accumulated precipitation from 12 Sep 0600 UTC until 13 Sep 0600 UTC (IOP12). Left: rain gauge measurement, middle: ALADIN 8 km operational forecast with data assimilation, right: ALADIN 8 km forecast without data assimilation.*