# Climate Dynamics

## A first-of-its-kind multi-model convection permitting ensemble for investigating convective phenomena over Europe and the Mediterranean

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| **Abstract:** | A recently launched project under the auspices of the World Climate Research Program's (WCRP) Coordinated Regional Downscaling Experiments Flagship Pilot Studies program (CORDEX-FPS) is presented. This initiative aims to build first-of-its-kind ensemble climate experiments of convection permitting models to investigate present and future convective processes and related extremes over Europe and the Mediterranean. In this manuscript the rationale, scientific aims and approaches are presented along with some preliminary results from the testing phase of the project. Three test cases were selected in order to obtain a first look at the ensemble performance. The test cases covered a summertime extreme precipitation event over |

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| | Austria, a fall Foehn event over the Swiss Alps and an intensively documented fall event along the Mediterranean coast. The test cases were run in both "weather-like" (WL, initialized just before the event in question) and "climate" (CM, initialized one month before the event) modes. A total of 22 ensemble members, representing six different modeling systems with different physics and modelling chain options, was generated for the test cases (26 modeling teams have committed to perform the longer climate simulations). Results indicate that, when run in WL mode, the ensemble captures all three events quite well. They suggest that the more the event is driven by large-scale conditions, the closer the agreement between the ensemble members. Even in climate mode the large-scale driven events over the Swiss Alps and the Mediterranean coasts are still captured, but the inter-model spread increases as expected. In the case over Mediterranean the effects of local-scale interactions between flow and orography and land-ocean contrasts are readily apparent. However, there is a much larger, though not surprising, increase in the spread for the Austrian event, which was weakly forced by the large-scale flow. The preliminary results illustrate both the promise and the challenges that convection permitting modeling faces and make a strong argument for an ensemble-based approach to investigating high impact convective processes. |

# A first-of-its-kind multi-model convection permitting ensemble for investigating convective phenomena over Europe and the Mediterranean (submitted)

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**Abstract**

A recently launched project under the auspices of the World Climate Research Program's (WCRP) Coordinated Regional Downscaling Experiments Flagship Pilot Studies program

(CORDEX-FPS) is presented. This initiative aims to build first-of-its-kind ensemble climate experiments of convection permitting models to investigate present and future convective processes and related extremes over Europe and the Mediterranean. In this manuscript the rationale, scientific aims and approaches are presented along with some preliminary results from the testing phase of the project. Three test cases were selected in order to obtain a first look at the ensemble performance. The test cases covered a summertime extreme precipitation event over Austria, a fall Foehn event over the Swiss Alps and an intensively documented fall event along the Mediterranean coast. The test cases were run in both "weather-like" (WL, initialized just before the event in question) and "climate" (CM, initialized one month before the event) modes. Ensembles of 18-21 members, representing six different modeling systems with different physics and modelling chain options, was generated for the test cases (27 modeling teams have committed to perform the longer climate simulations). Results indicate that, when run in WL mode, the ensemble captures all three events quite well with ensemble correlation skill scores of 0.67, 0.82 and 0.91. They suggest that the more the event is driven by large-scale conditions, the closer the agreement between the ensemble members. Even in climate mode the large-scale driven events over the Swiss Alps and the Mediterranean coasts are still captured (ensemble correlation skill scores of 0.90 and 0.62, respectively), but the inter-model spread increases as expected . In the case over Mediterranean the effects of local-scale interactions between flow and orography and land-ocean contrasts are readily apparent. However, there is a much larger, though not surprising, increase in the spread for the Austrian event, which was weakly forced by the large-scale flow. Though the ensemble correlation skill score is still quite high (0.80). The preliminary results illustrate both the promise and the challenges that convection permitting modeling faces and make a strong argument for an ensemble-based approach to investigating high impact convective processes.

## Introduction

Recent years have witnessed an explosive increase in climate simulations being run at convection permitting scales (so-called convection permitting regional climate modelling (CP-RCM)). The types of models used in these experiments are generally, though not exclusively, limited area models with grid spacings under 4 km (Prein et al. 2015). Convection, and its related impacts, is of high interest to atmospheric scientists, climate impacts researchers and the public due to the role it plays in driving damaging extreme events such as heavy precipitation, floods, landslides, windstorms (Carvalho et al., 2002; Jakob and Weatherly, 2003; Beniston, 2006; Ducrocq et al., 2014; Stucki et al., 2015). It is also the dominant type of precipitation in many parts of the world, such as the tropics, and influences the general circulation of the atmosphere through tropospheric mixing and cloud - circulation interactions (e.g., Bony et al. 2015). Unfortunately, parameterization of convection, which is required at the grid spacing of most Global Climate Models (GCMs) and Regional Climate Models (RCMs), contributes to errors in climate simulations (Dirmeyer et al., 2012; Klein et al., 2013). Poor representation of convection and related processes also likely contributes to the uncertain response of the atmospheric circulation to changing greenhouse gas concentrations (Shepherd, 2014; Sherwood et al., 2014; Webb et al., 2015). In addition to errors related to convection, along with clouds and circulations associated with it, many other physical parameterization schemes interact with models' convection schemes, raising the potential for consequences in other aspects of a climate simulation (Stevens and Bony, 2013). These twin desires, the reduction of model errors associated with parameterized convection and a more detailed representation of present and future regional climate, have strongly motivated the recent increase in modeling activities at convection permitting scales.

There is a rich history in the Numerical Weather Prediction (NWP) and mesoscale meteorology communities of using convection permitting simulations for process and case studies (e.g., Benoit et al., 2002; Milovac et al., 2016; Schwitalla et al., 2017). These researchers have decades of experience running simulations at these resolutions and have shown the added value of resolving convective scale phenomena such as complex interactions with orography (e.g., Grell et al., 2000; Pontoppidan et al., 2017), precipitation intensity (e.g., Ducrocq et al. 2002, 2008; Davis et al., 2006) and severe weather (e.g., Weisman, et al., 1997; Mass et al., 2002; Done et al., 2004; Khodayar et al., 2016). Although, it should be noted that some authors advocate  for a severe change of data assimilation approaches, physics (e.g., microphysics), parameterizations and numerical methods to be used at convection resolving scales (Yano et al., 2015; Yano et al., 2017). Until recently there has not been as much attention to longer and scenario-based experiments (Kendon et al. 2012; Fosser et al. 2014; Prein et al. 2015). Further, climate change detection and attribution studies at convection permitting scales have only just begun. This has been due mainly to computational limitations and costs. With recent advances in processing speed and efficiency, research teams with an eye towards improving our understanding of processes driving societally relevant climate impacts, have begun developing and running CP-RCMs at climate time scales.

A number of decade-long simulations have been completed in recent years with impressive results (Kendon et al., 2012; Warrach-Sagi et al., 2013; Fosser et al. 2014; Ban et al., 2014; Brisson et al., 2016; Déqué et al. 2016; Tölle et al. 2017). The benefits of running climate simulations (~10 years or more) at convection permitting grid spacings are far reaching. Among the improvements, compared to coarser resolution simulations, are a more accurate representation of diurnal cycles, hourly precipitation intensities, local-regional circulations, seasonal average precipitation, convective downdrafts, and the representation of cold pools (Prein et al., 2013a, Ban et al., 2014; Fosser et al., 2014; Kendon et al., 2012, 2014; Rasmussen et al., 2014; Brisson et al., 2016; Déqué et al. 2016; Fumière et al., this issue). In addition to the direct effects of resolving convective processes, - there are additional benefits through e.g., more accurate representation of interactions with complex topography, urban effects, land-ocean contrasts and land surface heterogeneities, which play a key role in forcing or triggering convection (Prein et al., 2013b). Convection-permitting climate simulations also allow the study of complex and fine scale aerosol-cloud-precipitation interactions as shown in Heinzeller et al. (2016). Finally, there are indications that CP-RCM simulations have positive indirect effects on the representation of regional climate through various feedback mechanisms such as soil moisture - precipitation (Hohenegger et al., 2009) and soil moisture/vegetation - temperature (Tölle et al. 2014) and urban effects (Argüeso et al., 2014). For example, there is indication for reduced mid-Europe summer warming (in its mean and extremes) in CP-RCM simulations (Tölle et al. 2017). There is also evidence that explicitly representing deep convection qualitatively modifies the response of summertime convective extremes to climatic changes (Kendon et al., 2014; Meredith et al., 2015; Giorgi et al. 2016; Tölle et al. 2017). For a comprehensive review see Prein et al. (2015).

However, there are limitations to CP-RCM. At these scales, shallow convection is not explicitly resolved (e.g. Soares et al. 2004; Khairoutdinov and Randall 2006; Siebesma et al., 2007) and is crucial in providing moisture and energy from the planetary boundary layer to the free atmosphere, which sustains the development of deep convection (e.g. Holloway and Neelin 2009). On one hand, summertime convective systems over land are strongly determined by the transition from shallow to deep convection (Teixeira et al., 2008; Wu et al., 2009), and on the other hand, shallow convection is directly linked to tropical deep convection and other atmospheric phenomena like the Madden-Julian oscillation (Teixeira et al., 2011; Chen et al., 2016). Consequently, CP-RCM results are highly model-dependent. This poses problems not only for developing a stronger process-based understanding of the present climate but also for assessing robustness in future change signals. Also, single model experiments are not particularly robust and do not sample the range of natural variability (e.g., Tebaldi and Knutti, 2007; Deser et al., 2012). Up to now assessments of uncertainties in future projections at km-scales have not been possible due to the prevalence of single model, single realization experiments. This issue related to internal variability is moreover exacerbated at finer spatial scales where local interactions play a more prominent role (Hawkins and Sutton, 2009; Deser et al., 2014). Therefore, ensemble based approaches will be needed in order to investigate convective extremes and related uncertainties in a climate change context. Further to this point, "coordinated modeling programs are crucially needed to advance parameterizations of unresolved physics and to assess the full potential of CPMs" (Prein et al., 2015).

The confluence of activities around CP-RCM at climate scales, recent field campaigns covering heavy precipitation and associated extreme events, and computational advancements, suggest that the time is right for coordinated multi-model ensemble CP-RCM experiments. In early 2016 a consortium of modeling groups from the Med-CORDEX and Euro-CORDEX initiatives submitted an application for a targeted Flagship Pilot Study (FPS, Gutowski et al. 2016) to the WCRP CORDEX (Coordinated Regional Downscaling Experiment, Giorgi et al. 2009) program (http://cordex.org/experiment-guidelines/flagship-pilot-studies/). The aim is to develop a set of first-of-their-kind, multi-model ensemble experiments at CP-RCM scales over Euro-Mediterranean region.

However, the project is much more than a set of multi-model ensemble experiments. We aim to answer questions related to drivers of convective extremes across scales, event attribution under changing climate conditions and more (see Scientific Aims below). For example, even at convection permitting scales turbulence and other fine scale processes are not resolved and model errors will still exist. Also, computational costs limit the length of simulations which limits their utility in assessing uncertainty and trends. In this case, combined dynamical-statistical approaches and process-informed bias correction may be of use (see, Maraun et al., 2017). As mentioned previously, event detection and attribution is also just beginning and this task likely requires a more nuanced approach to interpreting projections. One promising avenue that the project will pursue is the construction of so-called “storylines” (e.g., Meredith et al., 2015; Shepherd et al., 2014). Storylines’ may be thought of as an alternative way to interpret large multi-model ensembles, where regional impacts are assessed over, for example, a range plausible scenarios of atmospheric circulation change (as and example see, Zappa and Shepherd, 2018).

The FPS was awarded in spring 2016. The first annual meeting was held in November of 2016 at the Abdus Salam International Centre for Theoretical Physics in Trieste, Italy. Work began on finalizing scientific aims, developing an experimental protocol and selecting representative test cases to be examined prior to launching into expensive decade-long simulations. The primary objectives of the present manuscript are to 1) introduce the project, 2) describe its scientific goals and approaches and 3) show some preliminary results, which illustrate both the promise and peril of CP-RCM in a multi-model ensemble context.

The next section provides background information on the FPS (motivation, aims, timeline), followed by sections detailing methods and presenting preliminary results. The paper finishes with a discussion of the way forward and an invitation for contributions to the broader CP-RCM community.

## FPS description

*Motivation*

Much of the motivation for the project is provided in the previous section. In short: Climate change can alter the character of convection, making extreme precipitation more extreme, and also potentially modify large-scale conditions (atmospheric circulation and stratification) that favor convection. This can then induce changes in, e.g., return periods of precipitation extremes, spatial and temporal distribution of events, the effects of convection-induced feedback processes.

The study of convective events and their evolution under human-induced climate change is therefore of particular importance, and it is also timely not least due to the following:

- Large field campaigns dedicated to the study of heavy precipitation events such as HyMeX (Ducrocq et al., 2014), and gridded high-resolution precipitation datasets (typically hourly, kilometer scale), often merging station and radar data (Wüest et al. 2010, Tabary et al. 2012, Delrieu et al. 2014) now provide a wealth of observations;
- Computer capacity and model development now allow limited-area convection-permitting climate simulations at longer time-scales (Kendon et al., 2012, 2014; Ban et al., 2014, 2015), enabling a leap in climate modeling capacity;

- Homogeneous observation data sets collected over the years can unveil emerging trend signals in most extreme precipitation events, particularly at sub-daily time scales (Westra et al., 2014), in Mediterranean coastal areas (Vautard et al. 2015) and in Alpine mountain ranges (Scherrer et al. 2016)
- Several issues linked to detection, attribution and downscaling of the very localized consequences of extreme convective events can now benefit from recent progress in advanced statistical methods combined with advances in dynamical modeling (Beaulant et al., 2011).

Convective extreme events are also a priority under the WCRP Grand Challenge on *weather and climate extremes*, because they carry both society-relevant and scientific challenges that can be tackled in the coming years.

The proposed work in the Convection FPS also reflects a number of criteria identified by the CORDEX-FPS Scientific Advisory Team (SAT) such as: i) run RCMs at a broad range of resolutions, down to convection-permitting; ii) promote side-by-side experimental design and evaluations of both statistical and dynamical downscaling techniques at scales more typical of vulnerability-impacts-assessment applications; iii) Design targeted experiments aimed at investigating specific regional processes and circulations; iv) investigate the importance of regional scale forcings; v) Compile and use high quality, high resolution (both spatial and temporal), multi-variable observation datasets for model validation and analysis of processes.

The makeup of the consortium is diverse, both institutionally and with respect to expertise (Table 1). Though many participants come from climate background, others bring significant NWP experience to the challenge. The FPS mobilizes the Euro-CORDEX and Med-

CORDEX communities but is also open to new partners who bring fresh perspectives and expertise.

*Scientific questions*

The project was conceived with three general and open-ended scientific questions to allow some flexibility in the analyses while also providing sufficient structure to keep the consortium working towards some common goals. The general aims and specific challenges/questions can be summarized as:

**1. How do convective events and associated damaging phenomena (heavy precipitation, wind storms, flash-floods) respond to changing climate conditions in different climatic regions of Europe?**

- Identify trends in intensity, scale and duration in past observations, in underlying processes, and understand how these are simulated by convection permitting RCMs;
- Explain major events in the context of climate change, via "storylines" of individual events under different climatic conditions, but conditional on a fixed state of the large-scale atmospheric circulation (e.g., Meredith et al., 2015; Shepherd et al., 2014) in addition to a more robust assessment of uncertainties using an ensemble-based approach;
- Investigate life cycles of convective phenomena and related processes in the context of a changing climate;

- Identify the added-value of convection-permitting models in simulating such trends with respect to standard resolution regional climate models, including the investigation of relevant underlying processes;
- Include additional processes/phenomena such as high altitude snow and related hydro climatic impacts, mesoscale processes such as low-level wind convergence, orographic interactions, land-atmosphere interactions and hydrological impacts;
- Identify the added value of CP-RCM scenario simulation;

**2. Does an improved representation of convective processes and precipitation at convection permitting scales lead to upscaled added value?**

- How improved are CP-RCM aggregated precipitation statistics compared to lower-resolution models up to the resolution of GCMs?
- Do CP-RCMs and parameterized models have the same temperature-precipitation intensity relation (as formulated in Lenderink & van Meijgaard, 2008)?
- Can CP-RCMs serve as reference to improve convection parameterizations, from shallow to deep?
- Are there differences in the representation of key feedback processes between parameterized and explicit convection (e.g. Hohenegger et al. 2009)?
- Are there improvements in the aggregate statistics of other near-surface variables such as temperature and wind?

**3. Is it possible to augment costly convection-permitting experiments with physically defensible statistical downscaling approaches such as "convection**

**emulators" that mimic CP-RCMs and are fed by output of conventional-scale RCMs?**

- Can the variability of local-scale convective precipitation be sensibly predicted by statistically downscaling 0.11° area-averages of variables that are typically provided by RCMs?
- Can the corresponding response to climate change be sensibly predicted by corresponding 0.11° resolution RCM predictors?
- Can statistical methods be advanced to include temporal discretization that elucidates sub-daily rainfall;
- Can these approaches be expanded to include temperature and wind?

*Expected impact*

- Improved understanding of mechanisms and factors that influence location, intensity, frequency and extent of convective precipitation events under changing climate conditions;
- Better constrained estimates of future changes in convective extremes and associated processes, phenomena and feedbacks across Euro-Mediterranean regions;
- Bridge the spatial scale gap between regional climate models and impact models (hydrological models, ecosystem models, etc.)
- Provide added value for the decision-making process through analysis of risks and opportunities associated with changes in extreme convective events.

*Timeline/Experiment Protocol*

*2017: First set of simulations*: RCM simulations will be run at convection-permitting resolutions for selected test periods

- Mandatory domain centered on the Alpine chain (1°-17° longitude East, 40°-50° latitude North) (Figure 1);
- Individual model sub-groups coordinate multi-physics options internally and conduct short tests;
- Perform test case study experiments with model systems run in weather like (WL) and climate mode (CM), see Methods for more details.
- Finalize the definition of the other FPS domains.

*2018: Begin ERA-Interim evaluation simulations*

- Perform simulations that will systematically assess the ability of the CP-RCMs to represent the present climate period chosen to overlap with recent high resolution observation campaigns: 2000-2014 (minimum 10 years), ERA-Interim.
- Develop a statistical convection model that will be employed to identify mechanisms of long-term changes in convective precipitation and serve to evaluate the representation of underlying processes, assess added value and emulate convective precipitation.

*2019-2021: Third set of simulations, event interpretation, detailed analyses and intercomparisons*

- Scenario simulations (10 year time slices of selected CMIP5 GCM projections, CMIP6 if available; Periods: 1996-2005, 2041-50, 2090-99 (HIST and RCP8.5)
- Additional simulations focusing on extreme events under present and future conditions for the purpose of event interpretation;
- open access to the CP-RCM output data through the ESGF
- Link to the impact community: Impact models forced by CP-RCM output for past and future climate periods, and compared with recent databases (Llasat et al., 2013).

**Methods**

An ensemble of CP-RCMs has been created with each model coming from one of the European RCM groups. The models and institutes participating to the FPS effort are reported in Table 1, and more contributors are foreseen in the near future. All these models will produce the set of experiments mentioned above and for the purpose of this paper a set of test case simulations have been completed with the main purpose of testing this nascent multi-model ensemble (MME). The purpose of this initial set of experiments is to:

- reproduce convection explicitly at convection permitting scales (many models never carried out such an exercise before) and assess the model performance in such experiments
- assess what can be expected from climate-type simulations with CP-RCMs with respect to heavy precipitation (HP) events
- set up a test platform for new models entering the project.

For this particular exercise three case studies have been identified in what we defined as two modes:

1. the weather like initialization (WL)
2. the climate mode initialization (CM)

For each case study ERA-Interim is used to provide boundary conditions (Dee et al., 2011). Twenty of twenty-three modeling teams used the same nesting strategy, which was to nest (one-way) the convection permitting domain within a 0.11 degree pan-European domain with ERA-Interim driving the LBCs (see Table 1). This nesting procedure has been performed for each of the modes (WL and CM) separately and exactly for the respective simulation period, leading to different LBCs for CM respectively WL modes. However, teams were also allowed freedom to pursue alternative nesting strategies, which could be used as departure points for investigating the possibility for direct downscaling from e.g., ERA-Interim scales to convection permitting scales and the effects of internal variability developing in the intermediate domain. A few of the CCLM teams chose these different strategies, which clearly impacted the results in interesting ways. One team (CCLM-5-0-9-JLU) directly downscaled from ERA-Interim to ~3km for both simulations. Two others (CCLM-5-0-9-KIT and COSMO-CMCC) first downscaled ERA-Interim to an intermediate pan-European domain (0.22 degrees) for a long-term (> 15 years) and then used output from this for the convection permitting simulations after the fact. These two approaches have the same net effect, which is to impose identical lateral atmospheric boundary forcing for both the WL and CM simulations. This tightly constrains the forcing at the lateral boundaries and should, in principle, limit the development of internal variability.

For each modeling team WL and CM simulations follow the same nesting procedure, however the WL experiments are initialized 24-48 hours before the HP event while the CM ones are initialized one month before the event. The acronyms of the three case studies and the initialization procedures are reported in Table 2 for both the WL and CM cases. This is not meant to be a repetition of similar exercises carried out by the the NWP community (though in this instance the ensemble is much larger than any previously aggregated). It is rather intended as a first check of the ensemble and the individual models (especially new ones) before the consortium launches into the planned long-term climate simulations. It is worth noting that only a preliminary diagnostic analysis of the ensemble model performance is presented here, and a full-fledged, detailed, evaluation of the results is out of the scope, (which is presented in other papers of the special issue). The intention of this paper is primarily to introduce the FPS, and to detail the approach, focusing on challenges and potential.

## Preliminary results

For each of the three test case studies and for both experiment configurations, the analysis focuses here on the total accumulated precipitation for the whole domain during the event as defined in Table 2 and on the time series of hourly and 12 hours accumulated precipitation in the region of maximum precipitation as indicated by observations.

### *Case 1*

The first case (Case 1), referred to as HyMeX-IOP16 (Intense Observation Period 16) in Table 2, is a HP event occurred during the HyMeX measurement campaign in September-November 2012 (Ducrocq et al. 2014). The event is documented in detail by Duffourg et al., (2016) and Martinet et al., (2017), and it consists of slow propagating mesoscale convective systems (MCSs) associated with the evolution of a trough interacting with an upper-level low centered over the Iberian Peninsula which induced warm, moist and unstable southerly flow in the lower troposphere over the western Mediterranean. The interaction of the upper-level forcing with the warm low-level air mass increased instability and induced the deepening of a depression over the Gulf of Lion, favoring in turn the formation of MCSs that affected Southern France and Northern Italy between 25 and 27 Oct, 2012. According to the station observations collected during the field campaign (Ducrocq et al., 2014, http://hoc.sedoo.fr for HyMeX database) three regions were mainly affected by heavy precipitation. Two areas were in Southern France - referred to as CV1 and CV2 and indicating, respectively, the western and eastern parts of the Cévennes-Vivarais (CV) observation site during the HyMeX campaign (see Figure 1 in Ducrocq et al., 2014). The third affected area was Liguria-Tuscany one (LT, Figure 1 in Ducrocq et al., 2014). These three regions are highlighted in Figure 2a with red, green and blue squares; here the observed total accumulated precipitation maxima were, respectively, around 170, 140, and 250 mm. The same figure shows the ensemble average of the WL and CM experiments in panels b and c, respectively, along with all the individual ensemble members (WL/CM in the left/right columns).

As a general comment, we can observe how the locations of the three maxima are generally well captured by the WL ensemble, although the precipitation intensities are lower than observed. For the CM ensemble, the average location of the three events is still well represented but the underestimation is more pronounced. This ensemble behavior is reflected in the individual realizations, where for each CM simulation the intensity of maximum precipitation is lower than the corresponding WL one, although some members of the ensemble still show a maximum precipitation higher than observed.

A more quantitative analysis is reported in Table 3, where for each model and for both modes the spatial correlation of the total accumulated precipitation in the 3 boxes is computed between the observed interpolated field (Figure 2a2) and the model output. If we consider a threshold of 0.5 for a reasonable correlation score, 60% of the WL simulations in the CV1 regions have a correlation higher than 0.5, 30% in CV2 and 20% in LT regions. For the CM simulation the percentages drop to 23% and 14% in the first two regions but increase to 57% in the LT regions.

In Figures 3a,d, and g the spatial correlation of the 12 hourly accumulated precipitation is reported over the duration of the event for each model and for both WL and CM simulations. The value of the observed 12 hourly accumulated precipitation is reported too, as an indication of the time evolution of the event across the 3 regions. For each box the peak model skill is reached during the peak of the event and the percentage of models that are above 0.5 correlation value remains similar to those reported in Table 3 as does the ratio between CM and WL. These indicate that the ability of the models to follow the time evolution of the event is similar in both WL and CM mode.

Concerning the timing and intensity of the events in the 3 subregions, the hourly accumulated precipitation averaged over each box is plotted for each WL and CM ensemble member in Figures 3b,e, and h, along with the observations and the WL and CM ensemble average value in panels c, f and i. For the CV1 and LT regions the WL and CM ensembles behave in the same way, both showing a delay in the onset of the event and an underestimation of the peak intensity. The simulated intensity is higher for the WL than the CM, consistently with what is observed in Figure 2. For the CV2 region, both the WL and CM ensembles exhibit the same time delay and similar peak precipitation underestimations.

*Case 2*

Case 2 (called AUSTRIA hereafter) is a convective orographic precipitation event with weak but persistent large-scale driving factors that was induced by the evolution of a shallow trough over the North Atlantic, from 22-25 June 2009. A cutoff low was isolated over Southern Europe, thus inducing persistent northeasterly flow over Austria, associated with unstable warm-moist air, impinging on the Alps. This caused extreme rainfall along the northern flanks of the Alps due to orographic lifting. On June 24, however, the position of the rainfall maximum moved further to the east and south (Burgenland and South-Eastern Styria) because of strong embedded deep-convective cells (Haiden, 2009). On June 25, the regionally extended event ended and became more localised and scattered. The overall largest 6-day (22-27June) rainfall sum was recorded at station Steinholz (lower Austria, located in the northern foothills of the Eastern Alps) with 354 mm and a return period of more than 100 years (Godina and Müller, 2009).

In Figure 4 the same analysis as Figure 2 is reported but for Case 2 precipitation. The observed precipitation (Figure 4a) shows a hook-shaped spatial pattern with the highest maxima following the terrain elevation peaks and a secondary maximum in the southeastern part of the domain. The WL ensemble (Figure 4b1) shows a less pronounced hook shape precipitation, with the first maximum well located but with lower intensity than observed and with the secondary maximum definitely underestimated. These translate in a percentage of 90% of the models that have a spatial correlation pattern of the total accumulated precipitation higher than 0.5 (see Table 4).  The CM ensemble (Figure 4b2) reduces even more this signal up to a 60% underestimation of the maximum value. In contrast to the previous case study, the CM ensemble value is the result of a few CM members capturing the event and even overestimating it, a few showing different spatial pattern distributions from observed and half of the ensemble members not capturing or severely underestimating it as it is confirmed from the drop of the percentage of models with good correlation score to only 42% (see Table 4). Also in this case the skill in following the time evolution of the events is maximum during the pick of the precipitation and the evolution in time of the skill for both WL and CM mode (Figure 5a) and is consistent with Table 4.

This large uncertainty is well depicted in Figure 5b, where the hourly accumulated precipitation averaged over the rectangular box in Figure 4a is reported as a function of time. The individual CM ensemble members go from nearly zero mm to over 1.5 times the observed accumulation, while the WL ensemble members are more narrowly grouped around the observed accumulation line. The difference in behaviour between the two ensembles is evident in Figure 5c where the CM ensemble shows an underestimation around the 60% of the correspondent observed curve and in accordance with Figure 4.

*Case 3*

Case 3 (called FOEHN hereafter) is a Foehn event that occurred on November 2014 Kramer et al., 2017). In this case the slow eastward evolution of a deep trough, associated with a mid-latitude cyclone over the North Atlantic induced persistent southerly flow over the Alps. Steady orographic precipitation occurred on the windward side of the Alps, with a consequent release of latent heat and drying of the air, that induced a Foehn effect on the leeward side of the mountains. The slow eastward evolution of the trough caused persistent precipitation over the Alps with daily precipitation locally exceeding several hundreds of mm and reaching maxima around 500 mm. From Figure 6a-b we can see that both the WL and CM ensembles agree well with observations. All the single members of the WL and CM have a similar behavior, the spatial correlation of the total accumulated precipitation is above 70% in both cases (see Table 5), the time evolution of the models skill is similar among the WL and CM and is always very high (above 0.5 for most of the event) as it is shown in Figure 7a, the maximum intensity is reproduced and the hourly evolution of the event is well captured (Figure 7a). The model spread is symmetric around the observations and the ensemble average WL and CM precipitation amounts are in good agreement with the observations both in terms of timing and magnitude.

## Discussion

In this manuscript we have introduced an ambitious, first-of-its-kind project that aims to design, produce and analyze multi-model ensembles of CP simulations. The project is organized under the WCRP-sponsored CORDEX - Flagship Pilot Studies mechanism. As such, the project mobilizes participants from Euro-CORDEX, Med-CORDEX and CORDEX-ESD (Empirical Statistical Downscaling). The project has also engaged actors from outside the CORDEX community in order to bring in fresh perspectives and additional expertise. This diverse consortium is able to leverage years of expertise in NWP, climate modeling and downscaling, statistical modeling and downscaling. The overarching scientific aim of the project is to produce long-term simulations under present and future conditions at CP resolutions, with focus on increasing our understanding of convection, convective processes and their impacts in a global warming context. Given the challenges and costs involved in running dynamical models at CP-RCM scales, test cases were designed to provide a zero-order assessment of the ensemble and its characteristics. In this manuscript we have presented a preliminary and illustrative analysis of these case studies.

These preliminary results of the three case studies illustrate both the challenges and potential in CP-RCMs. They also provide a clear argument for the advantages of the ensemble-based approach. Case 1 is a fall HP event driven by the development of MCS over the western Mediterranean basin advecting moist air over three topographically complex regions in the southern coast of France and the Liguria-Tuscany regions. The three precipitation maxima are well located by both WL and CM ensembles. However, the intensity of the peaks is generally underestimated, especially  in the CM experiments. Case 2 is an orographic precipitation event that shows the effects of internal variability more strongly in CM than the other cases. From the ensemble point of view the event is captured in both WL and CM mode, with the latter one showing much more damped signals. The Foehn case (Case 3) is characterized by persistent orographic precipitation driven by a slow eastward moving through and it was the best captured by the models. Both the WL and CM ensembles were in very good agreement with observations, representing well both the timing and intensity of the HP event.

There are interesting and subtle differences between the case studies themselves and the ways in which the individual models represent them. Even within an individual test case there are differences in dominant processes that are then reflected by the ensemble. The general increase in spread (both spatially and temporally) between the WL and CM can be expected and points toward the strong effect of internally generated variability in the models.

Case 1 shows a larger spread over regions in which the precipitation is most affected by complex topography. Unsurprisingly, the individual WL and CM ensemble members exhibit a broader range of behaviors over these areas (the red and blue boxes in Figure 2), which results in different ensemble mean responses . Conversely, the model behaviour is more consistent between WL and CM over the CV2 region (green box), resulting in very similar ensemble mean responses and correlation skill score of the individual models (Table 3 and Figure 3d). The heavy precipitation event over this area was the result of an organized MCS forming over the sea, weakly supported by the orographic forcing. In this case the WL simulations are closer to the CM behaviour on average (low predictability problem), with some members showing results as uncertain as in CM.

Case 2 is in many ways the most interesting, with a wide range of model behaviours in the CM simulations. Some simulations completely miss the event while others exhibit a considerably damped response. Only 9 of the 21 CM simulations have the spatial pattern of the total accumulated rainfall that has a correlation with the observations higher than 0.5 (Table 4). While one should not expect exact reproduction of events in terms of timing, location and intensity in CM, it is reasonable to expect credible representation of the events given the experiment design. Therefore we provide some discussion on why some models reproduced the salient characteristics of the event over Austria whereas some missed it entirely. A detailed investigation is beyond the scope of this paper, but we speculate that at least three factors may be responsible for this result. The first is that the event is close to the domain boundaries, which can be problematic, and model teams used varying sponge layer depths and nesting strategies. This last point is illustrated by the fact that the simulations that missed the event in its entirety all had an freely evolving (i.e. not nudged) intermediate nest, which allows internal variability to develop. Interestingly, the differences in nesting strategy did not have such a strong effect on the other test cases. Another factor is that this event occurred in a relatively weak background synoptic state, which would decrease the large scale forcing compared to the local forcing, and thus increase diversity across models. Lastly, though the spread is large, the ensemble mean pattern captures the event, and the location of each simulations' maximum rainfall is roughly in the correct region (i.e. along the Northern foothills of the Austrian Alps, not shown). This can be considered as a good starting point for a future analysis where a more in depth investigation will be needed to fully understand the driver of the HP event and the reason some of the models do not capture it.

Case 3 showed the best model performance in both the WL and CM ensembles. In this experiment, both the ensemble mean and all individual members reproduce the results, in terms of precipitation, of a strong Foehn event. The reason for this could be that this event is driven by a well-defined, slowly-evolving large-scale circulation which forced long-lasting orographic precipitation over the Alps. It is worth mentioning that this case presents the typical synoptic conditions conducive to heavy Alpine rainfall, which are easier to predict than average conditions (Grazzini, 2007). Therefore, models which are able to capture the large scale organization of the precipitating system can provide a quite surprising reproduction of the event, provided that convective precipitation, embedded in the stratiform rainfall, is represented.

The preliminary results presented here have important implications for the longer term simulations the project aims to undertake, and more generally for the use of CP-RCM in a climate context; one is that results can be highly model and event dependent. They suggest that we can expect varying ranges of responses for different types of convective events (e.g. strongly steered by synoptic conditions vs. weakly steered, local scale interactions with complex topography vs. stronger ocean influence, etc.), which would affect uncertainties in future projections. As Grell et al. (2000) noted, precipitation over complex terrain is not likely to converge toward one solution at CP-RCM scales and, more importantly, the precipitation moves with the local upper level flow unlike in coarser RCM simulations where the precipitation remains locked to the mountain tops. For test cases, however, it is difficult to disentangle the extent to which model differences are due to internal noise (which will lead to differences in the timing, positioning and evolution of specific event, particularly if not strongly forced by the large-scale conditions) or due to differences in model physics. Multiyear climatological statistics will be less influenced by internal noise and hence the intercomparison of results from the upcoming ERA-Interim (and scenario) simulation across models will allow a more in depth understanding of model performance and uncertainty. For more insight on some of the issues raised here, the authors would like to point the reader to the other papers in the special collection convection permitting modeling.

The CORDEX-FPS on convection over Europe and the Mediterranean is an ambitious and challenging undertaking. It has a tremendous potential and is a logical next step to bring together the Euro-CORDEX, Med-CORDEX and the nascent scientific communities forming around the use of CP-RCM on climate scales. The findings from the project will enhance our understanding of convective processes and their response to climate warming, which may bring some surprises with respect to the findings from coarse resolution models (e.g. Giorgi et al. 2016). Further, as recent single model, longer-term climate change CP-RCM experiments indicate, previously unresolved but highly destructive features such as intense mesoscale convective systems increase substantially in a warming climate (Prein et al. 2017). The project will, therefore, also provide critical added value to decision makers as ensemble-based and combined dynamical-statistical approaches will help improve confidence even under conditions of high uncertainty. The initiative is open to all interested scientists and potential collaborators are encouraged to contact the project leaders if they wish to participate.

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Figure

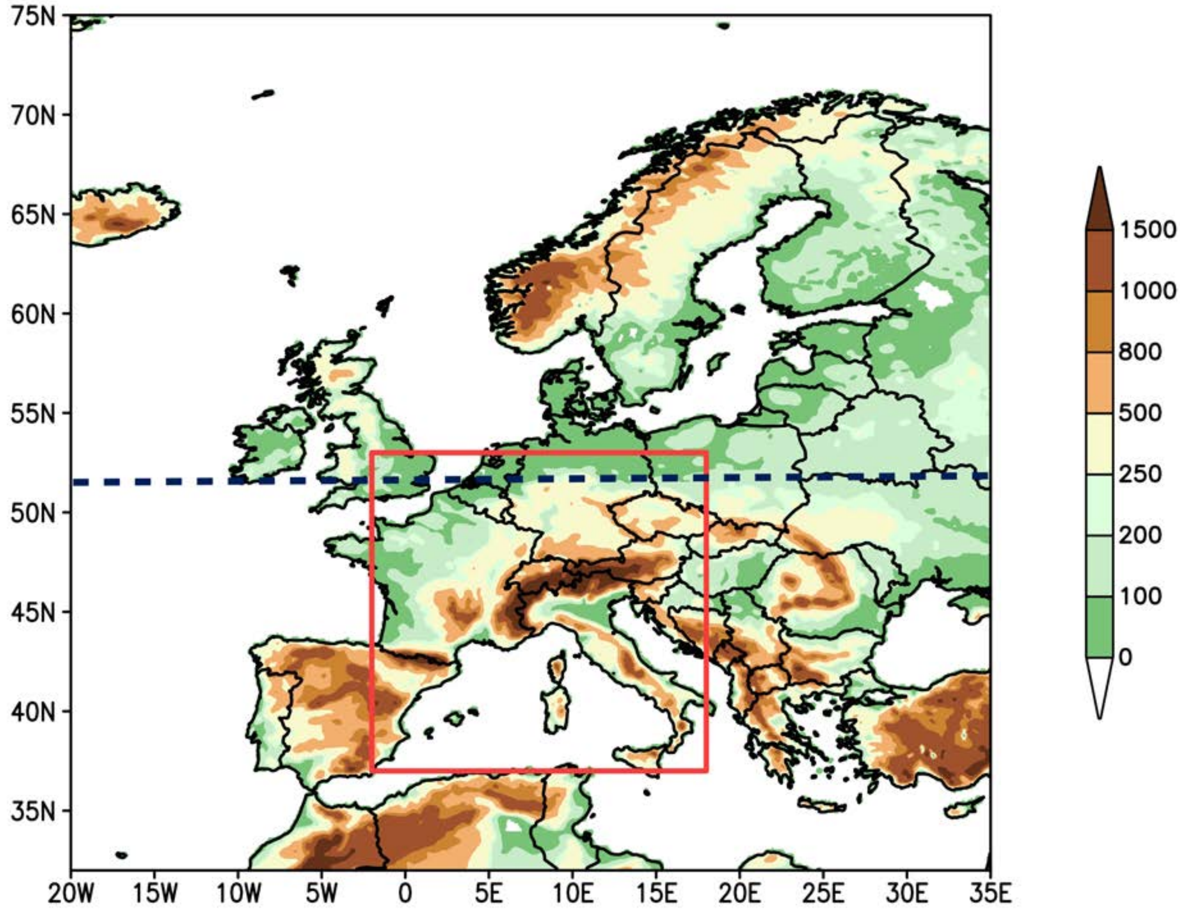


**Figure 1:** Euro-CORDEX domain at 0.11 degrees resolution with highlighted red box for FPS mandatory domain. The blue dashed line represents the Northern boundary of the Med-CORDEX domain.

| Total accumulated precipitation during the event (mm) | | |
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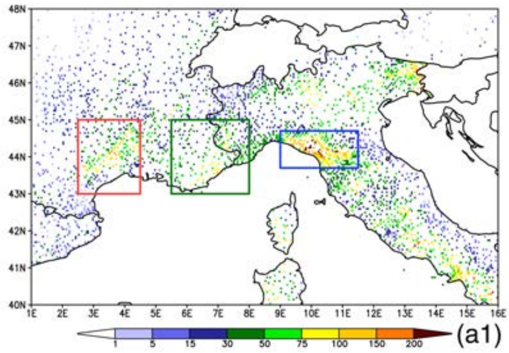
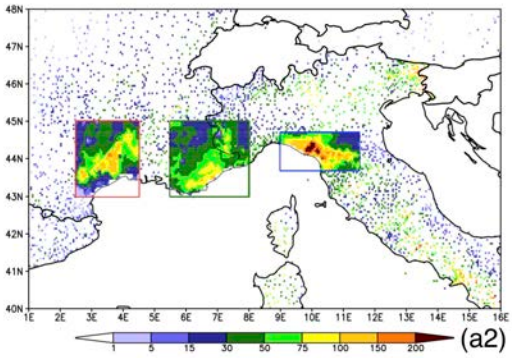
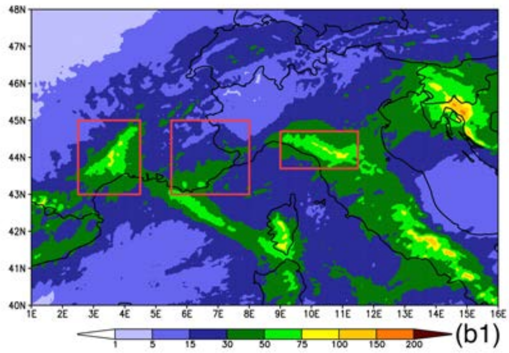
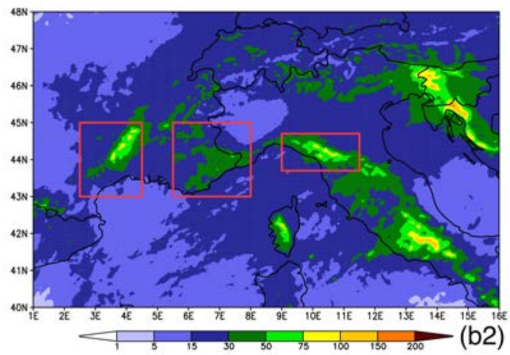
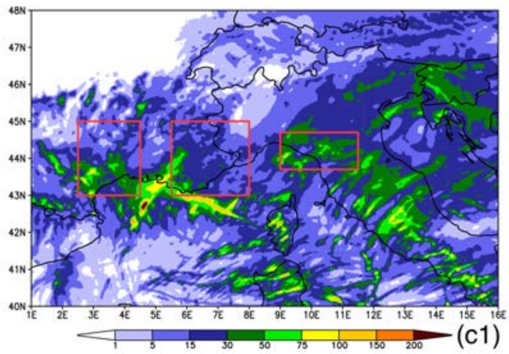
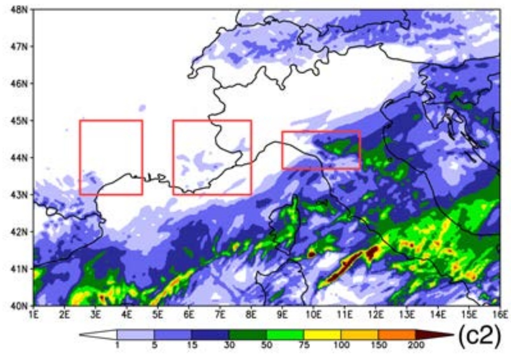
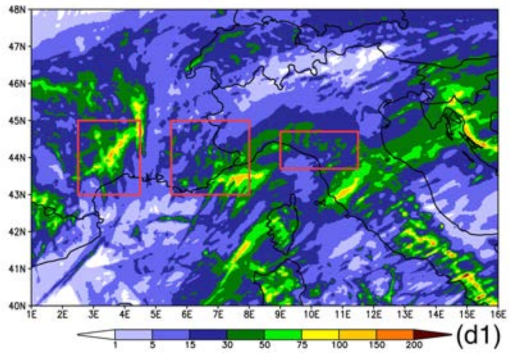
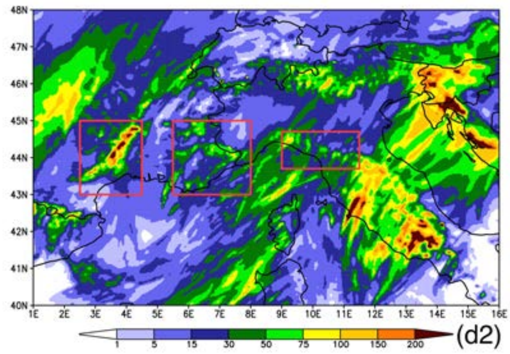
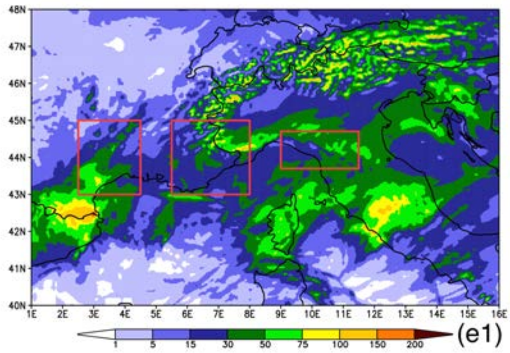
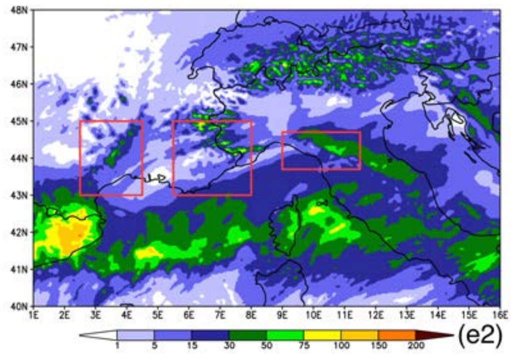
| OBS |  |  |
| ENSEMBLE |  |  |
| RegCM4-ICTP |  |  |
| RegCM4-DHMZ |  |  |
| RegCM4-CUNI |  |  |

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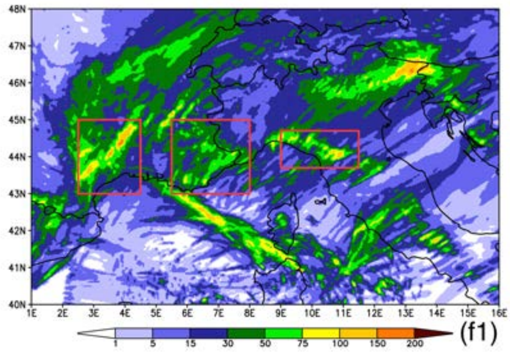
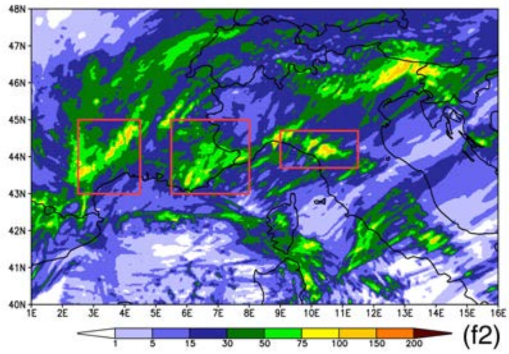
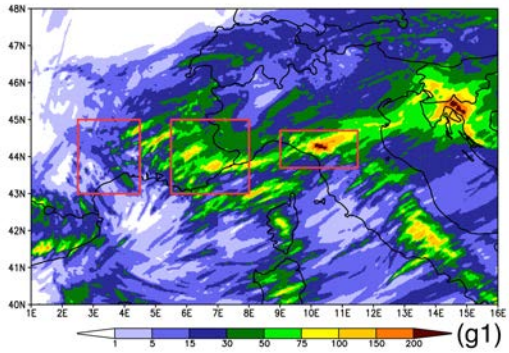
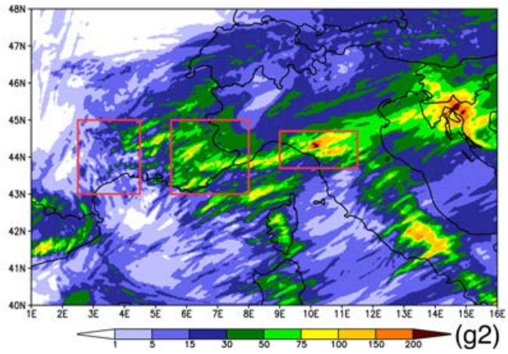
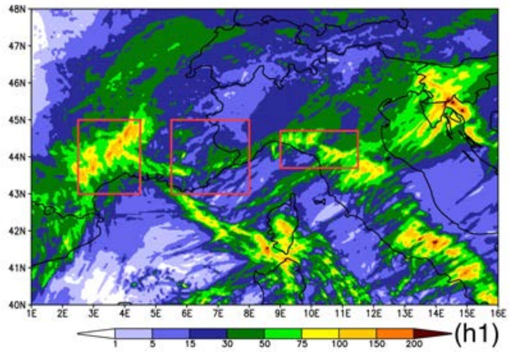
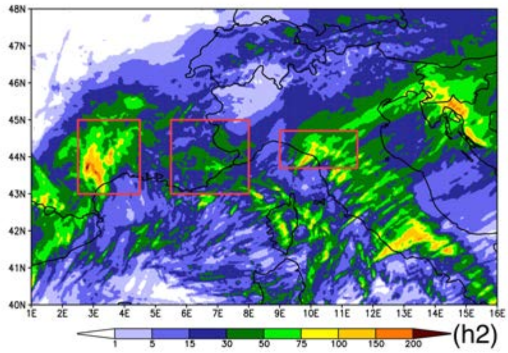
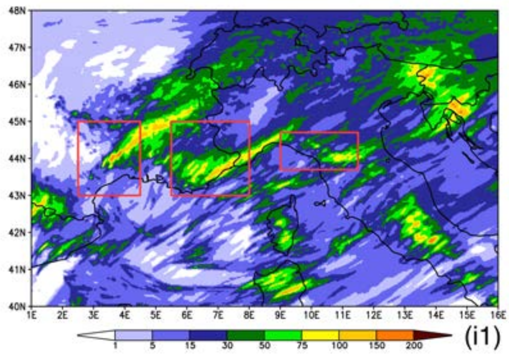
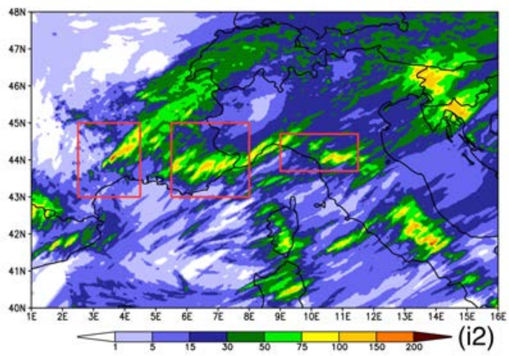
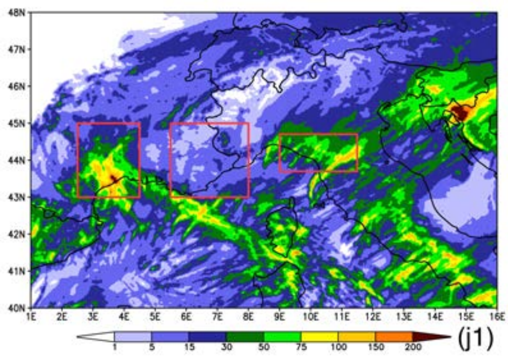
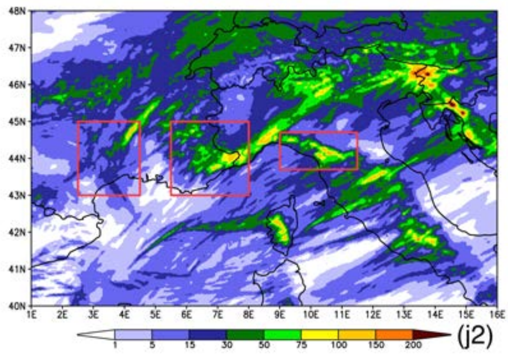
| CCLM-0-9-JLU |  |  |
| CCLM-0-9-KIT |  |  |
| COSMO-KIT |  |  |
| COSMO-CMCC |  |  |
| WRF-UHOH |  |  |

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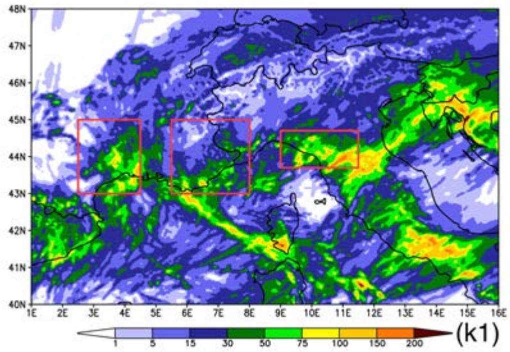
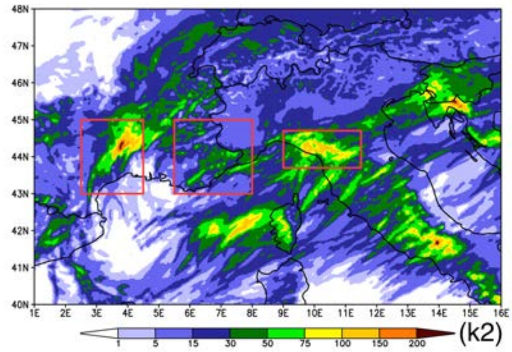
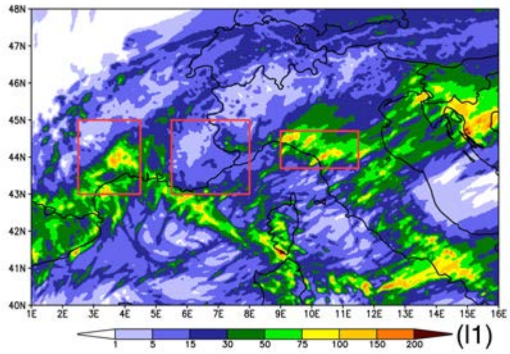
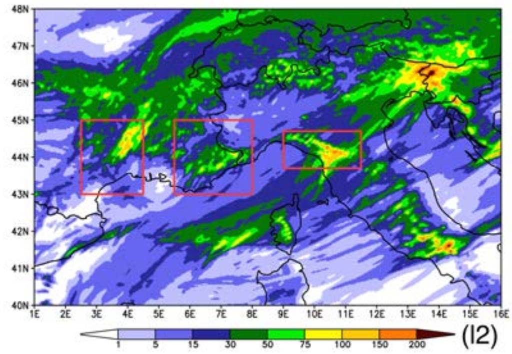
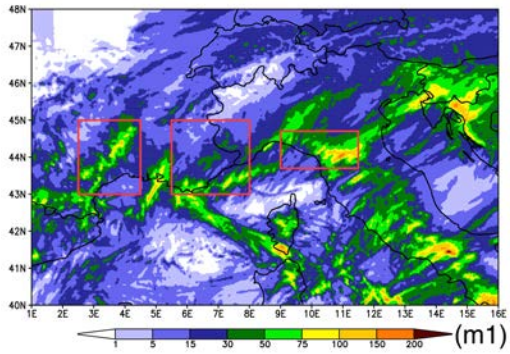
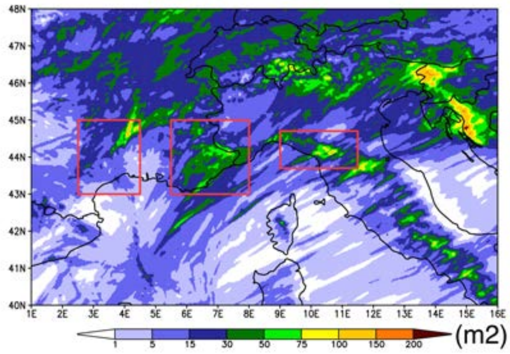
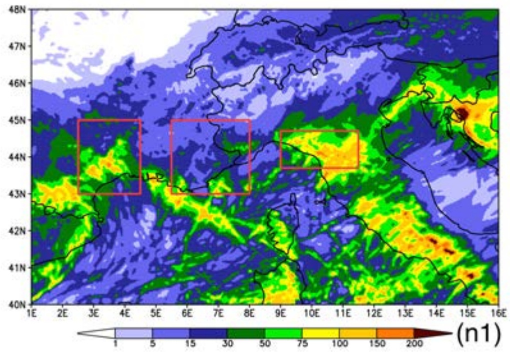
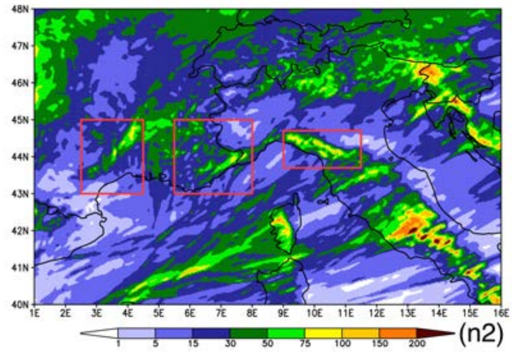
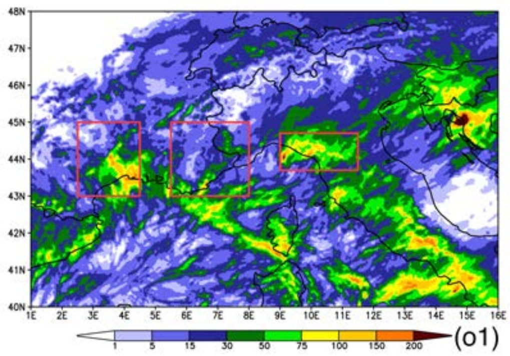
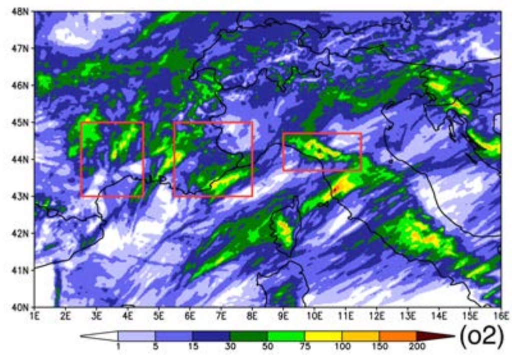
| WRF-AUTH-MC |   |   |
| WRF-FZJ-IBG3 |   |   |
| WRF-IPSL |   |   |
| WRF-BCCR |   |   |
| WRF-UNICAN |   |   |

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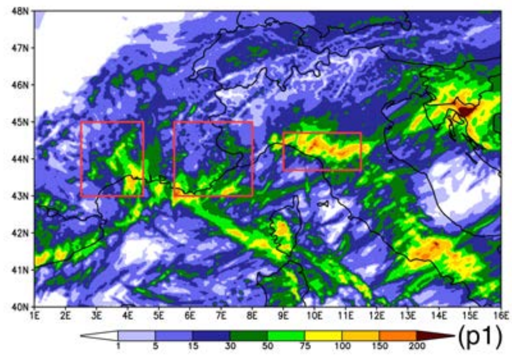
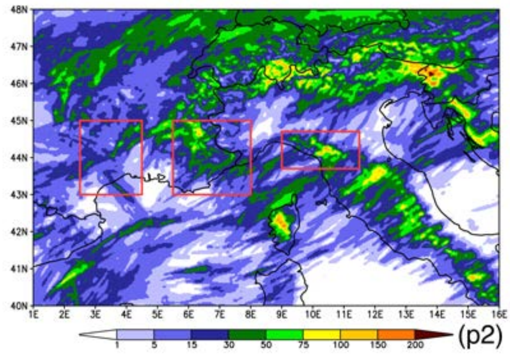
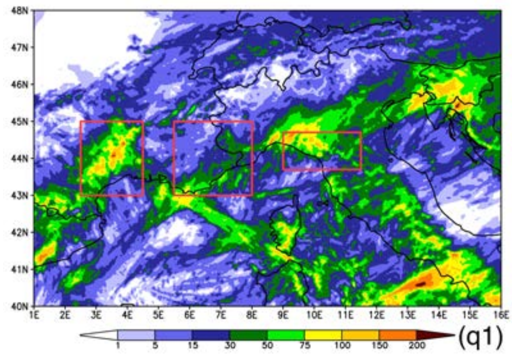
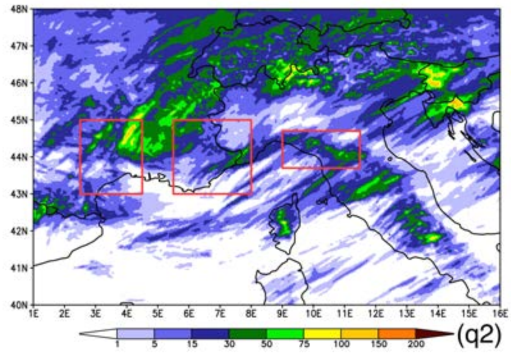
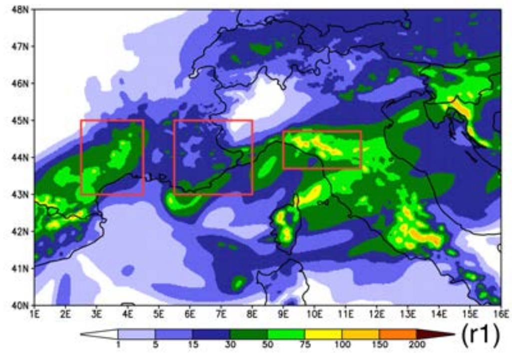
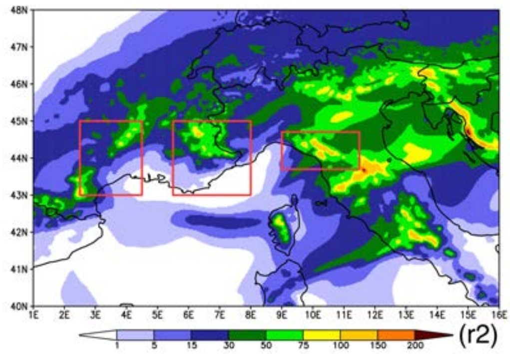
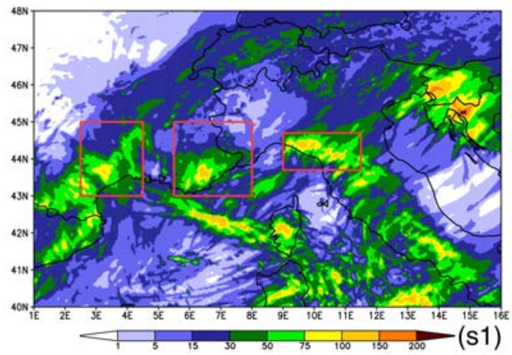
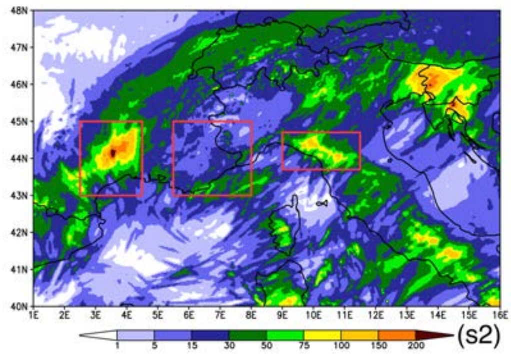
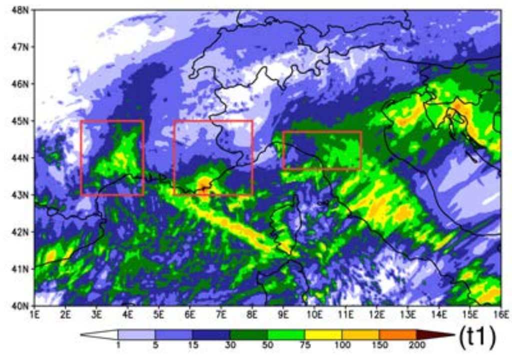
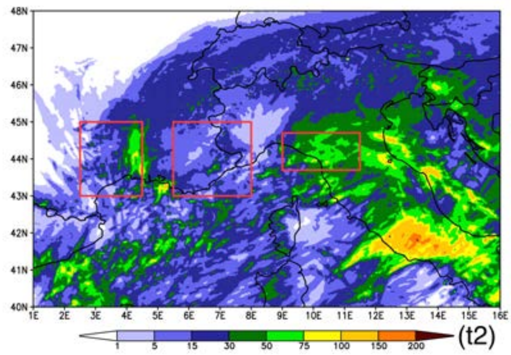
| WRF-IDL |  |  |
| WRF-CICERO |  |  |
| REMO-GERICS |  |  |
| HCLIM-KNMI |  |  |
| HCLIM-METNo |  |  |

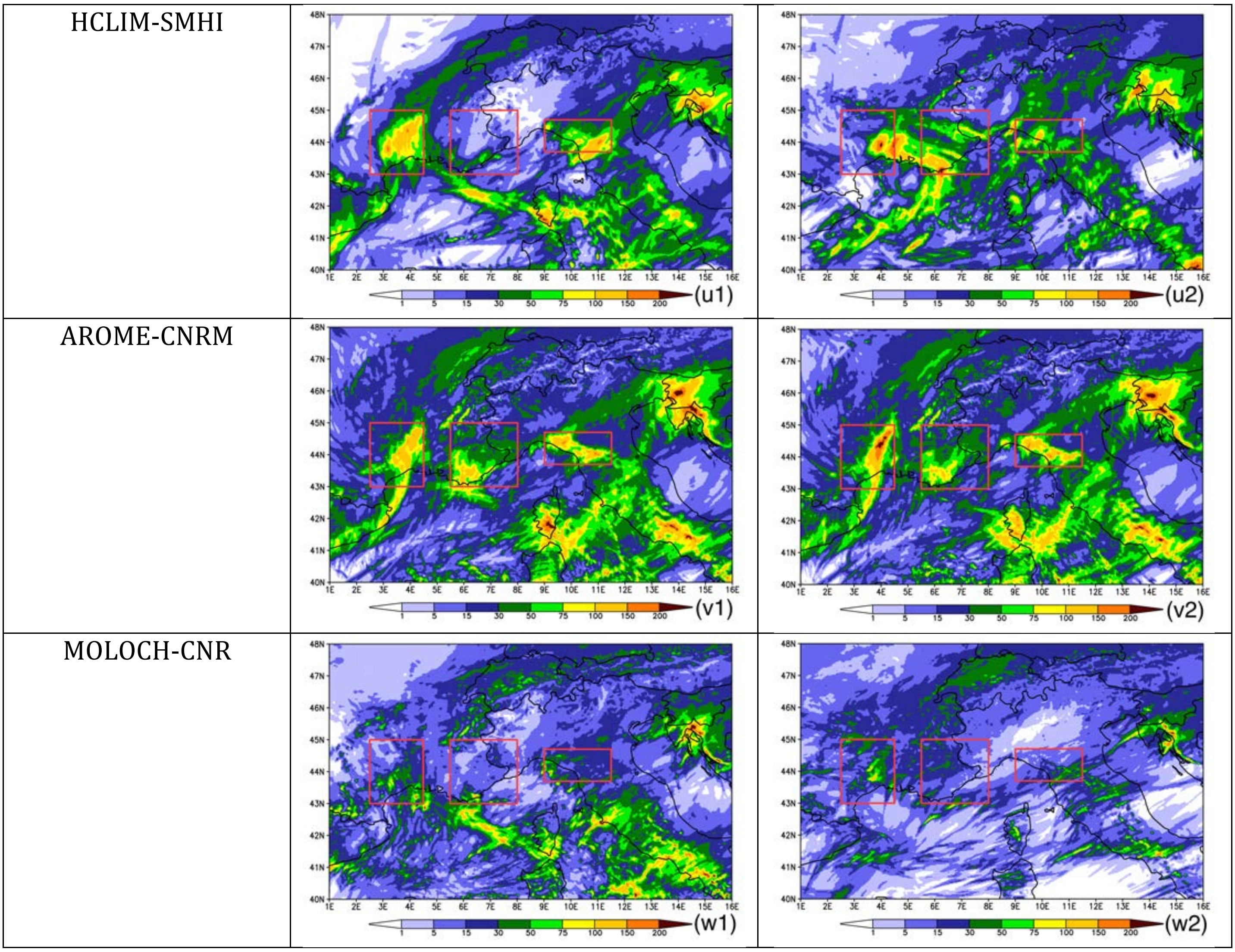



**Figure 2:** CASE 1 - HyMeX-IOP16. Total accumulated precipitation (mm) for observations, multi-model ensemble mean (MMEM) and each ensemble member. Results are shown for the models run in WL mode (left) and in CM (right). Red, green and blue boxes on panels (a1) and (a2) indicate specific areas of interest. Panel (a2) shows an interpolation of the observed precipitation field.

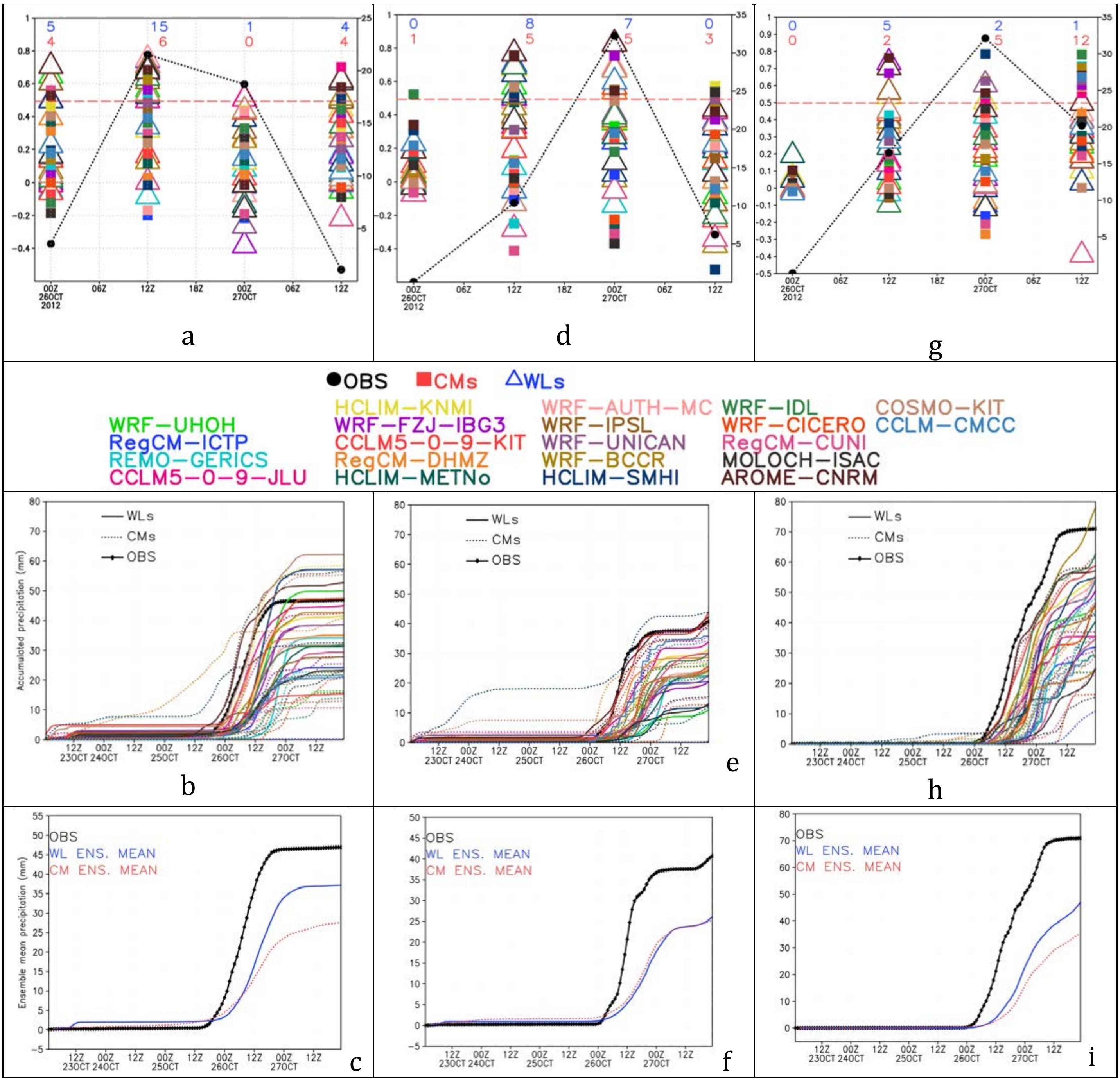
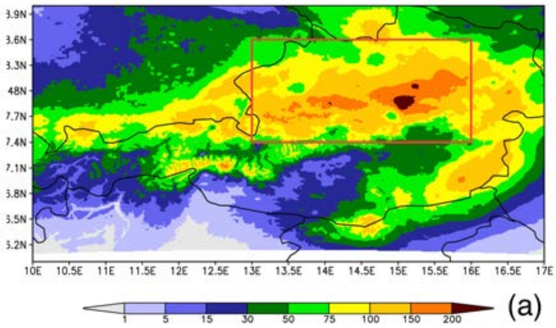
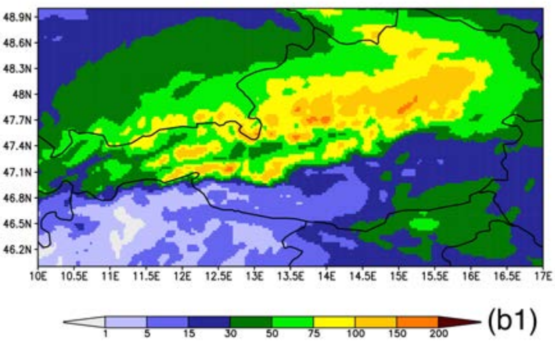
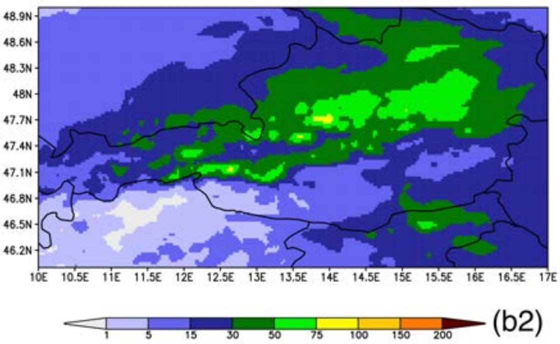
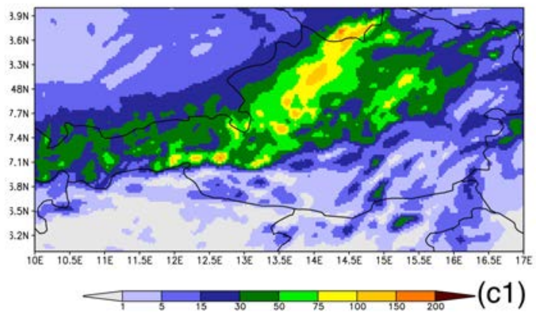
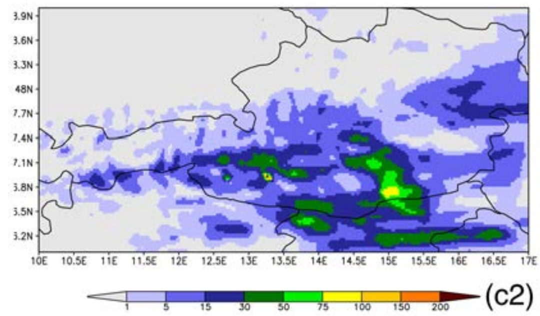
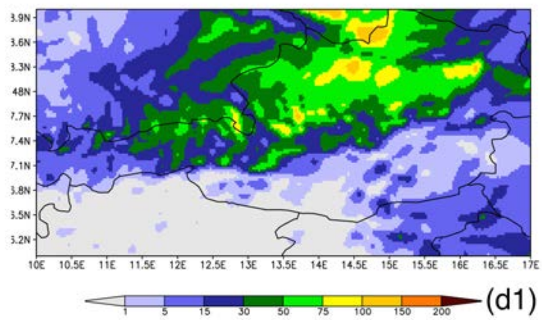
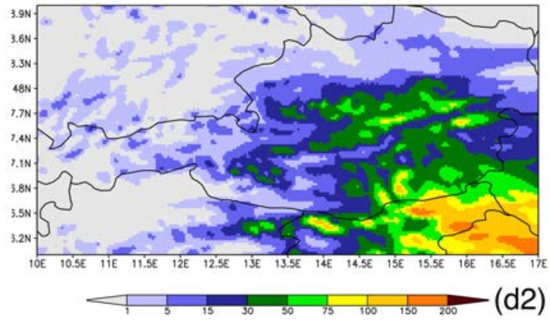
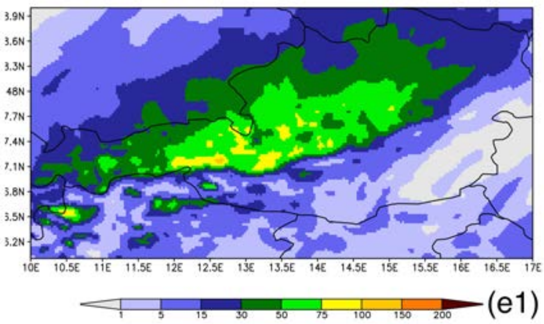
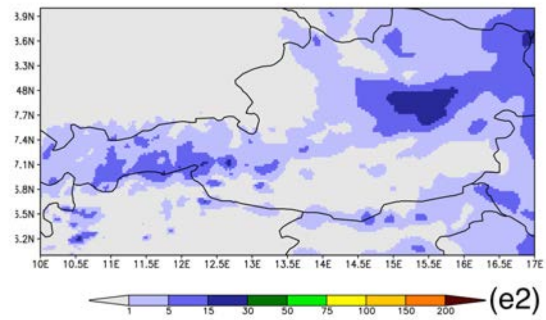


**Figure 3:** Time series of the 12 hours accumulated precipitation (in mm on the y-axis) during the event and temporal evolution of the spatial correlation between simulations and interpolated observation of the 12 hours accumulated precipitation, over CV1, CV2 and LT boxes (panels (a,d,g)). Left hand side y-axes refer to correlation (colored symbols); right hand side y-axes refer to the accumulated precipitation (black line). Numbers of models with a correlation greater than 0.5 for WL simulation (in blue) and CM simulation (in red) are reported on the top of each plots. Time series of the hourly accumulated precipitation averaged over the red, green and blue boxes (Fig. 1a) for each model and observations (panels b,e and h ). Time series of hourly accumulated precipitation ensemble mean (WL and CM respectively in blue and red) and observations (black) for the three areas of interest (panels c,f and i).

| Total accumulated precipitation during the event (mm) | | |
|---|---|---|
| | CASE 2 - AUSTRIA (WL) | CASE 2 - AUSTRIA (CM) |
| OBS |  | |
| ENSEMBLE |  |  |
| RegCM4-ICTP |  |  |
| RegCM4-DHMZ |  |  |
| RegCM4-CUNI |  |  |

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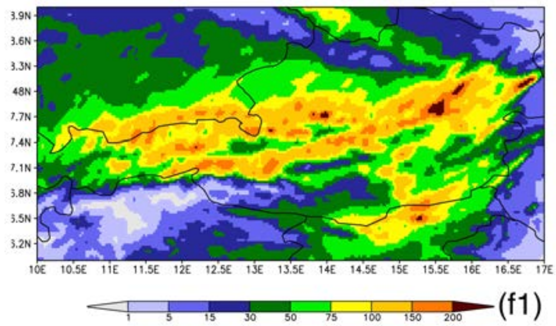
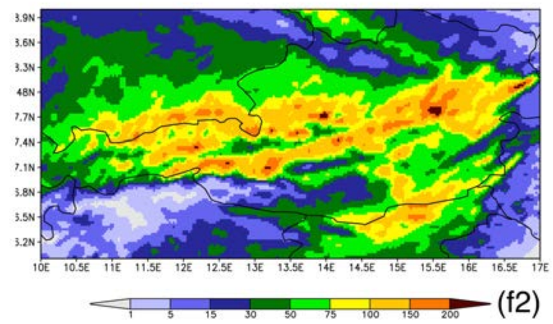
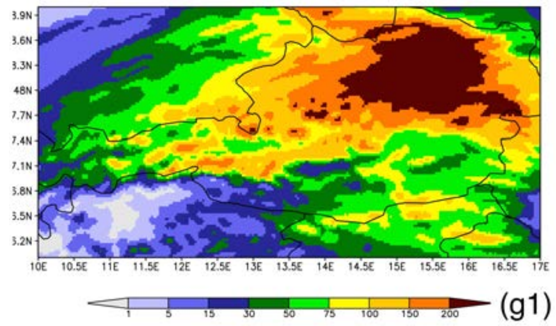
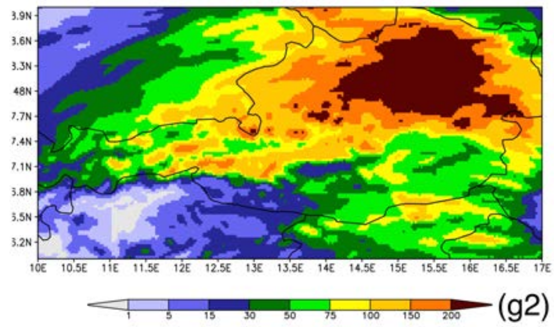
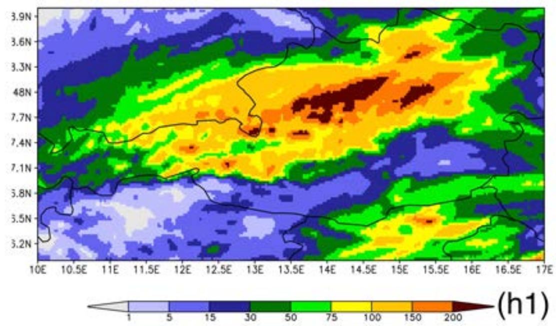
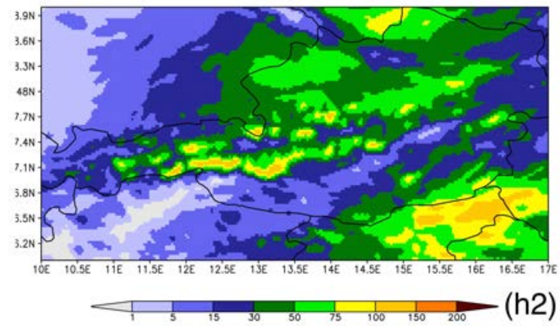
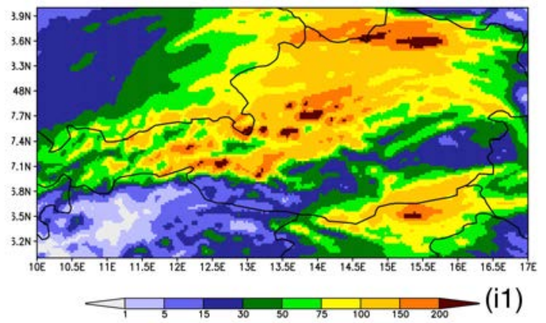
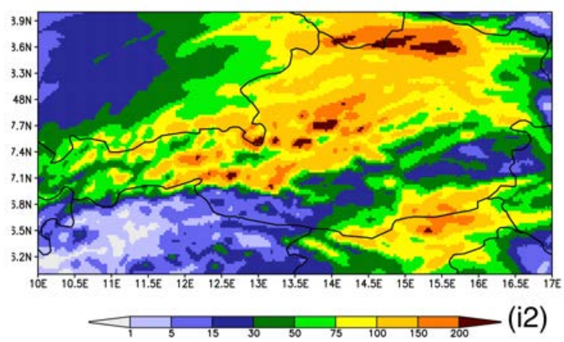
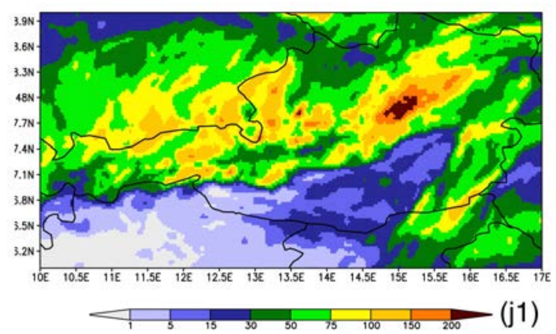
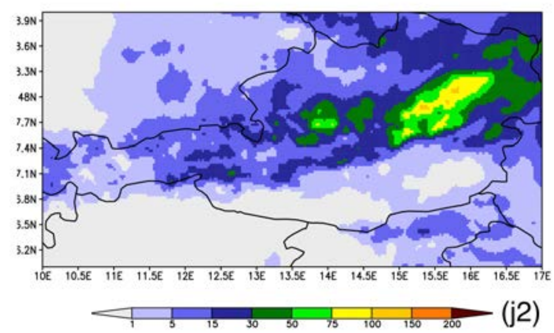
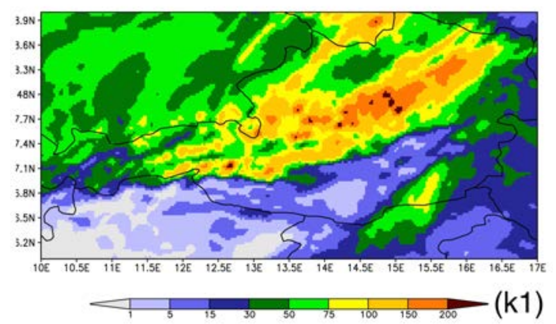
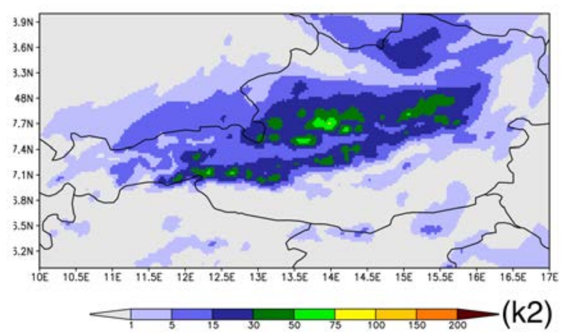
| CCLM5-0-9-JLU |   |   |
| CCLM-0-9-KIT |   |   |
| CCLM-WEGC |   |   |
| COSMO-CMCC |   |   |
| WRF-UHOH |   |   |
| WRF-WEGC |   |   |

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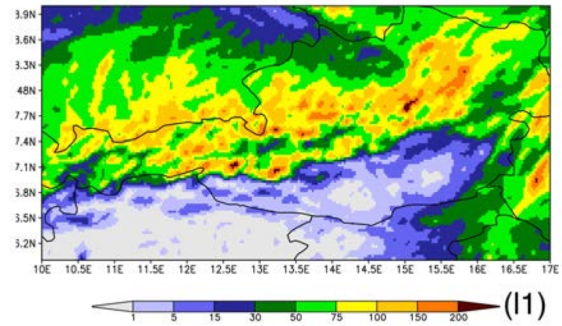


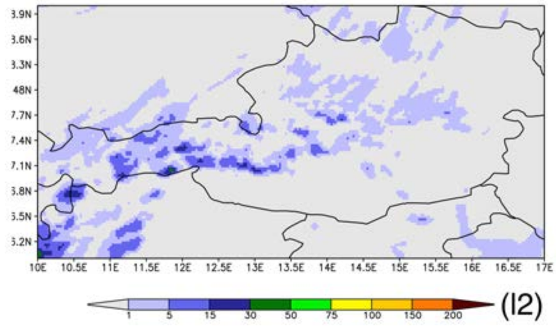


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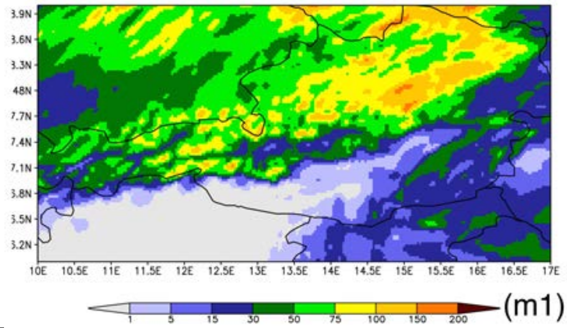


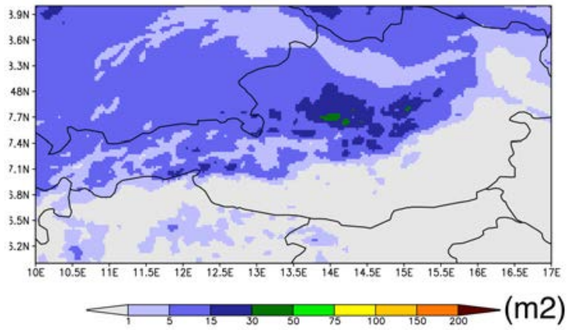


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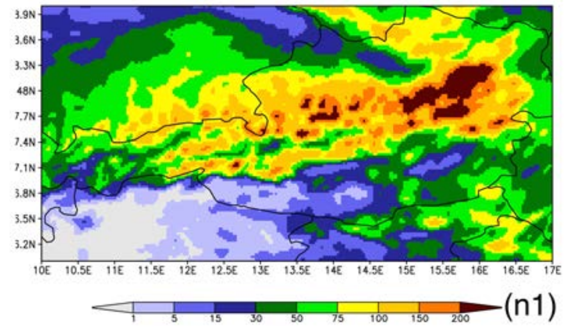


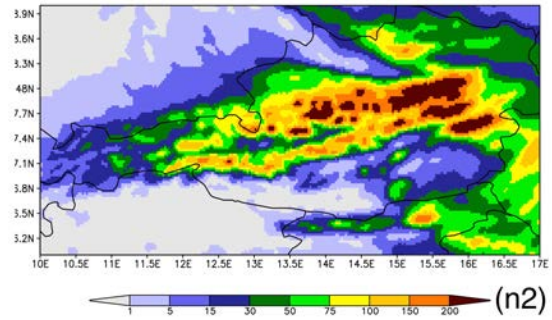


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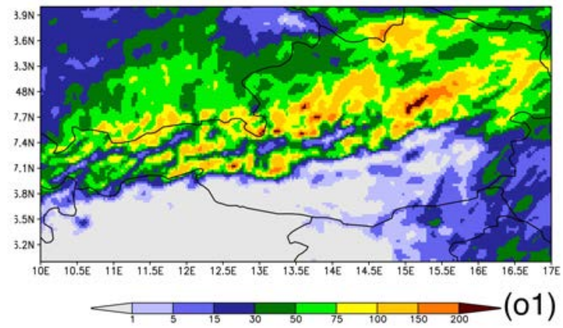


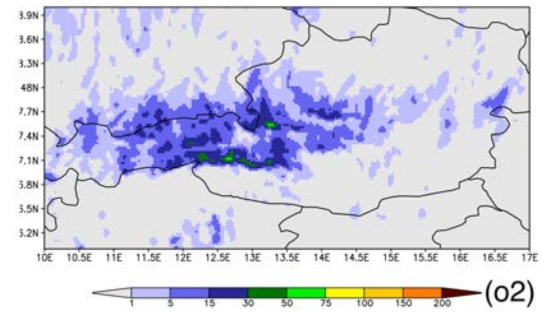


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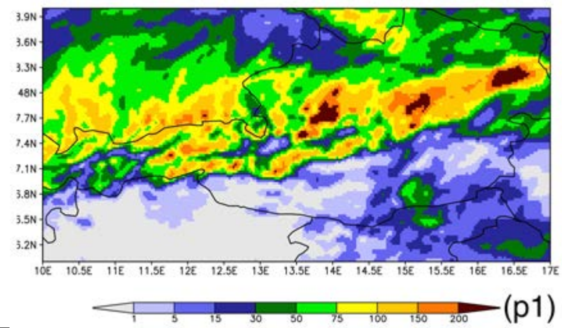


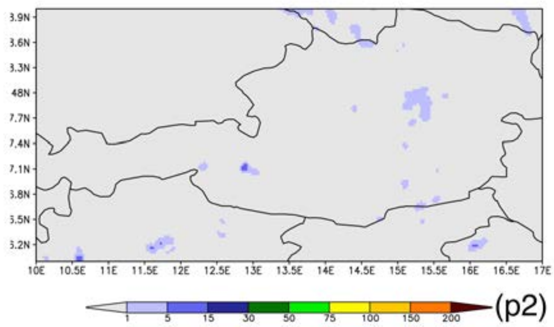


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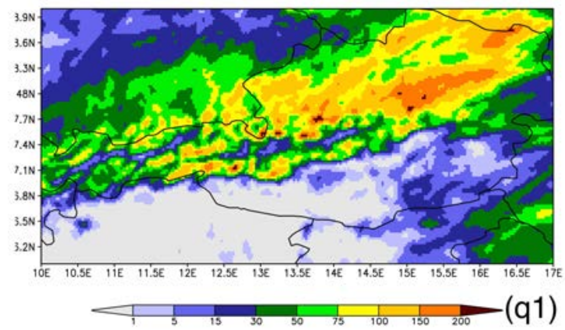


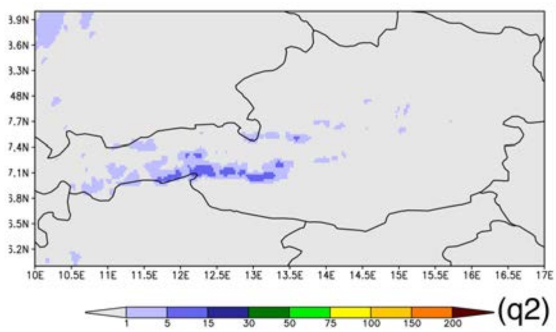

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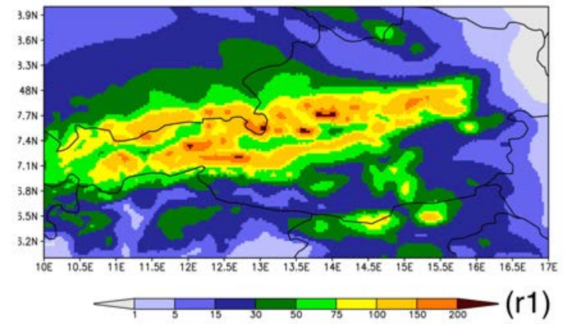
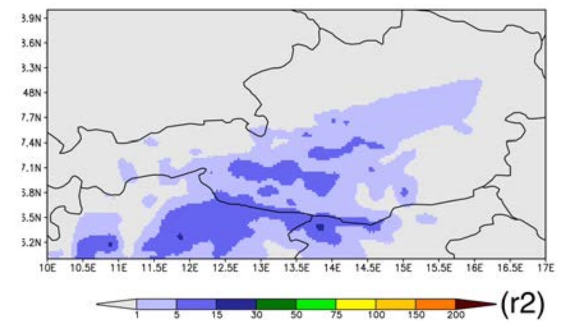
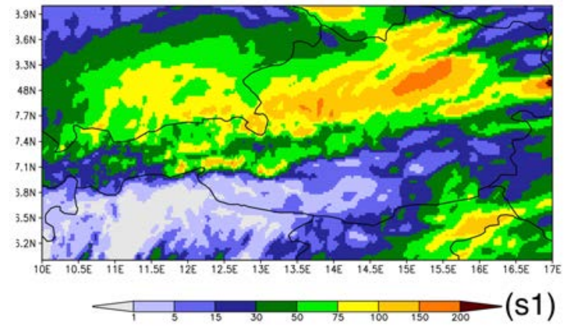
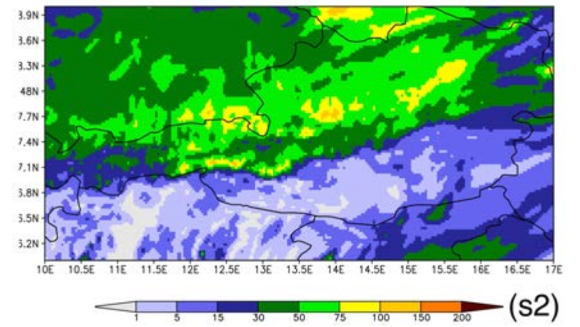
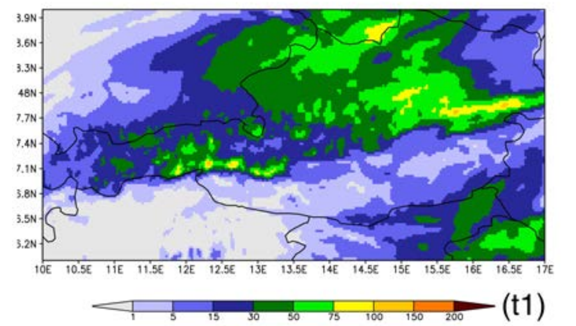
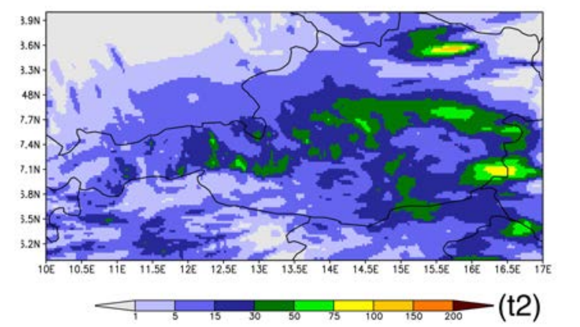
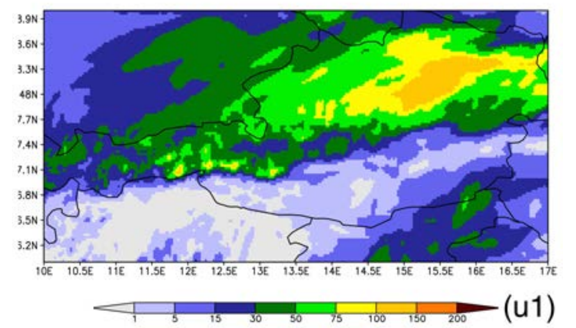
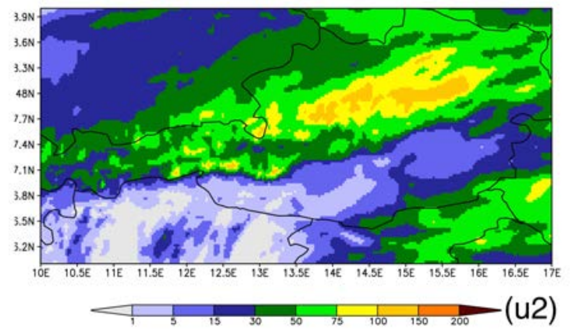
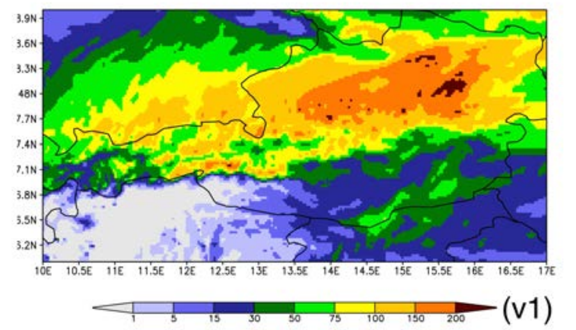
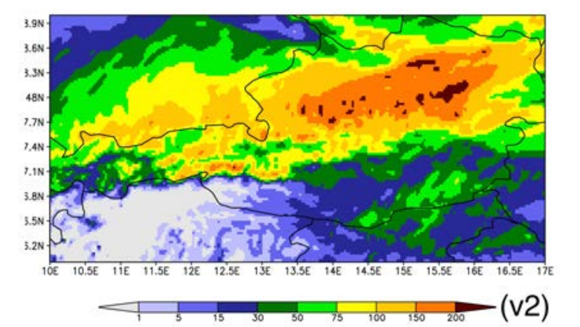
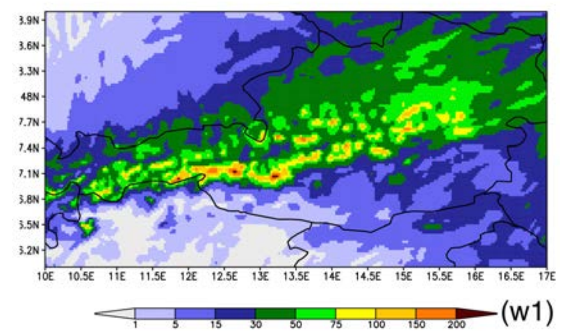
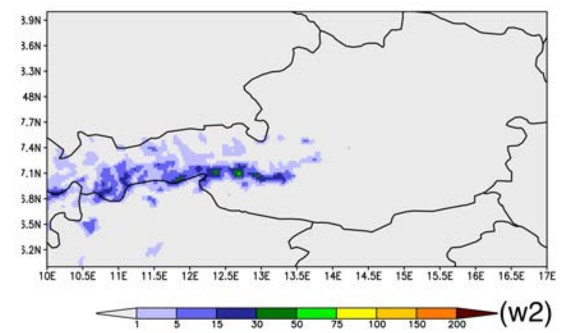
| REMO-GERICS |  |  |
| HCLIM-KNMI |  |  |
| HCLIM-METNo |  |  |
| HCLIM-SMHI |  |  |
| AROME-CNRM |  |  |
| MOLOCH-CNR |  |  |

**Figure 4:** CASE 2 - AUSTRIA. Total accumulated precipitation (mm) for observations, multi-model ensemble mean and each ensemble member. Results are shown for the models run in WL mode (left) and in CM (right). Red box on panel (a) indicates specific area of interest.

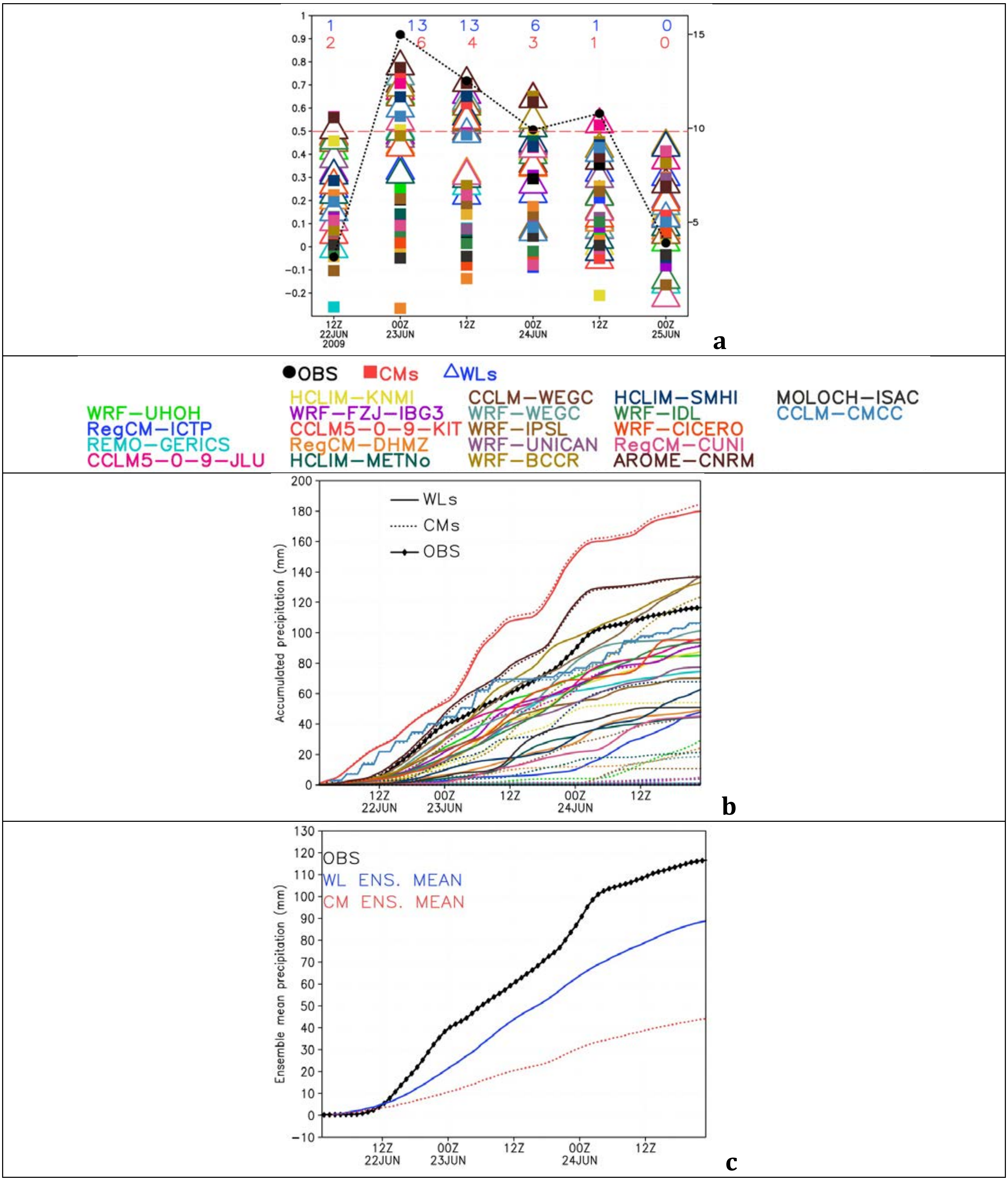
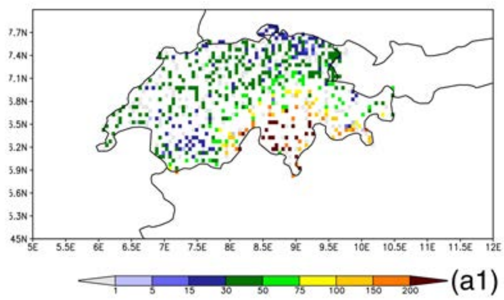
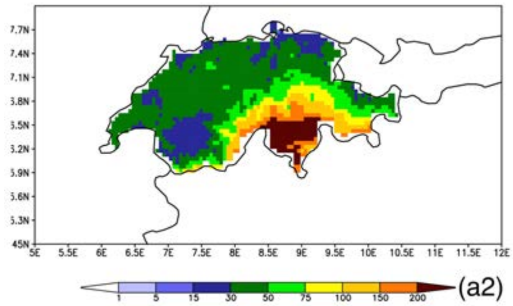
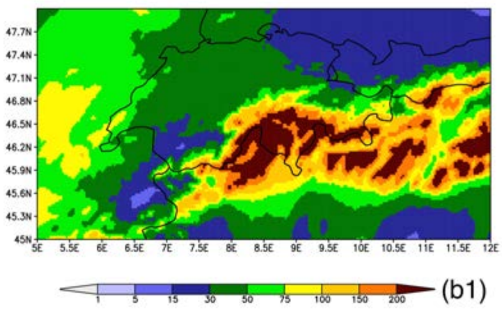
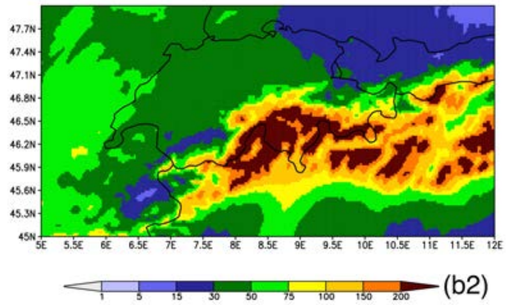
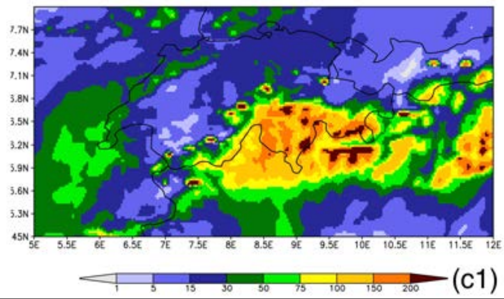
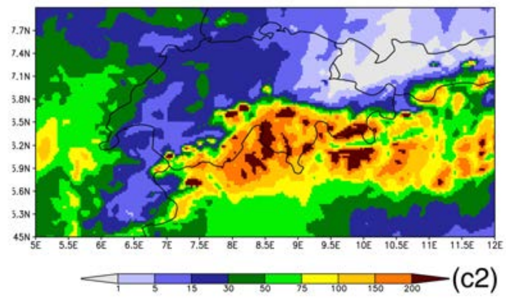
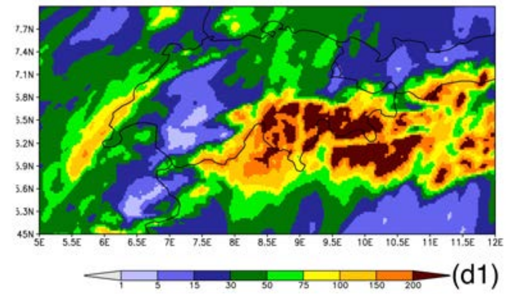
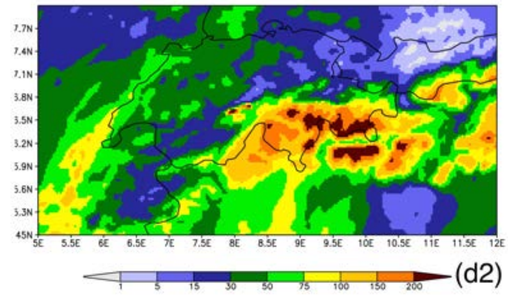
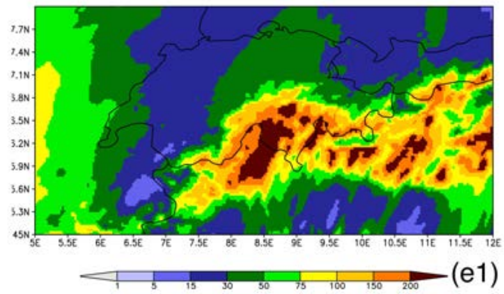
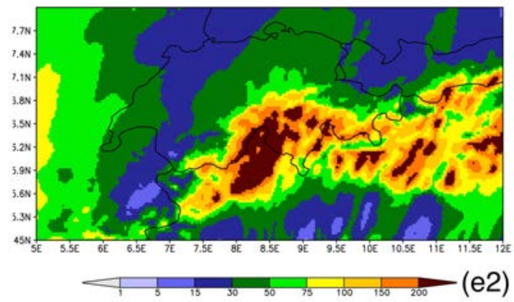
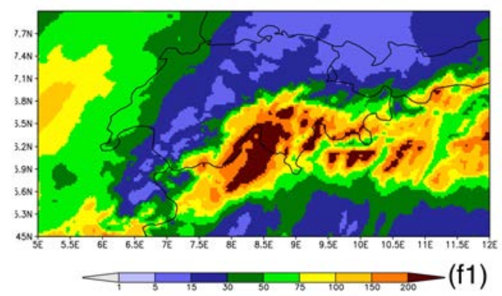
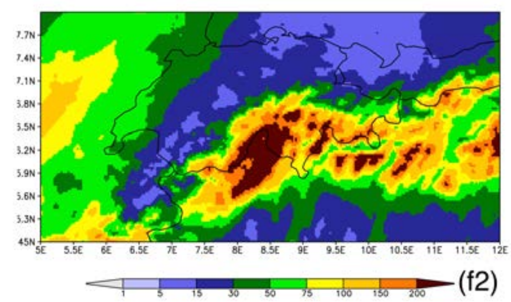



**Figure 5:** Time series of the 12 hours accumulated precipitation (in mm on the y-axis) during the event and temporal evolution of the spatial correlation of the accumulated 12 hours precipitation between the simulations and observation (panel a). Left hand side y-axes refer to correlation (colored symbols); right hand side y-axes refer to the accumulated precipitation (black line). Numbers of models with a correlation greater than 0.5 for WL simulation (in blue) and CM simulation (in red). Time series of the precipitation averaged over the red area (Fig. 3a) for each model and observations (panel b). Time series of hourly accumulated precipitation ensemble mean(WL and CM respectively in blue and red) and observations (black) over the area of interest (panel c).

| Total accumulated precipitation during the event (mm) | | |
|---|---|---|
| | CASE 3 - FOEHN (WL) | CASE 3 - FOEHN (CM) |
| OBS |   |   |
| ENSEMBLE |   |   |
| RegCM4-ICTP |   |   |
| RegCM4-DHMZ |   |   |
| CCLM5-0-9-JLU |   |   |
| CCLM-0-9-KIT |   |   |

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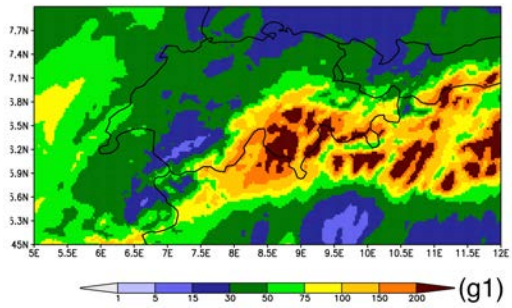
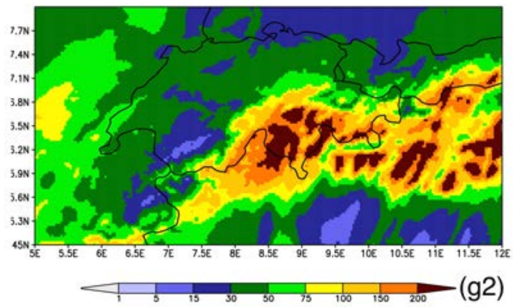
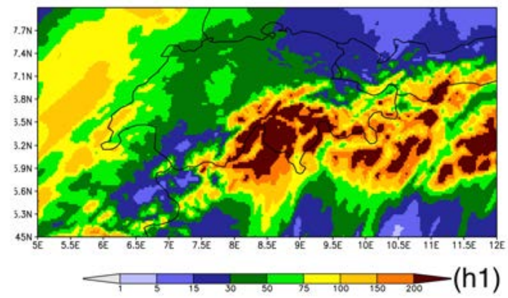
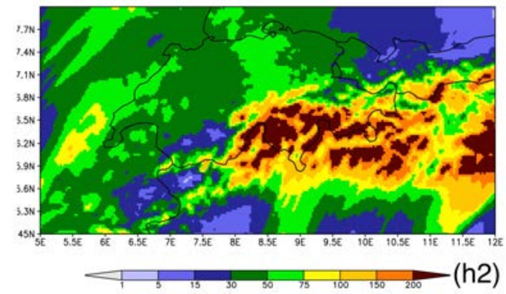
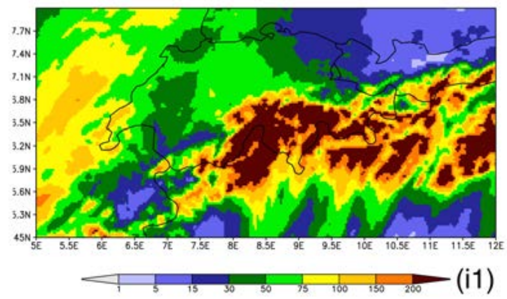
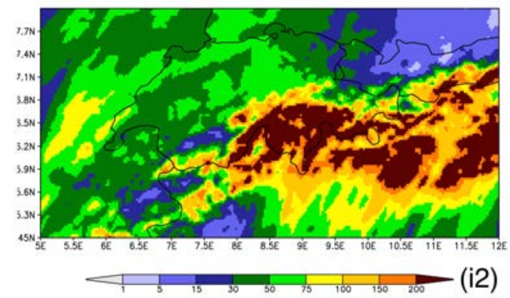
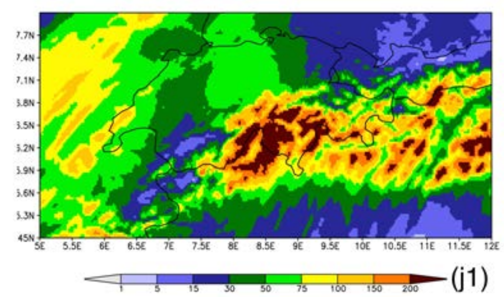
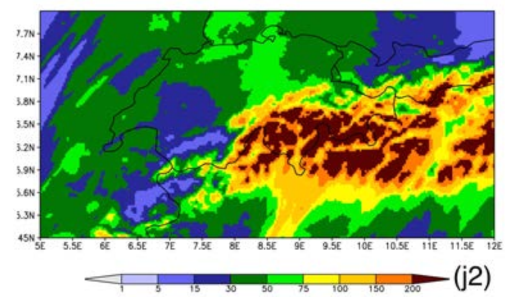
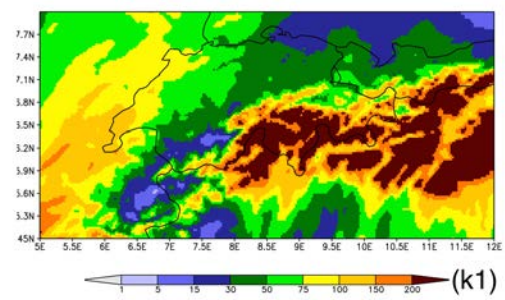
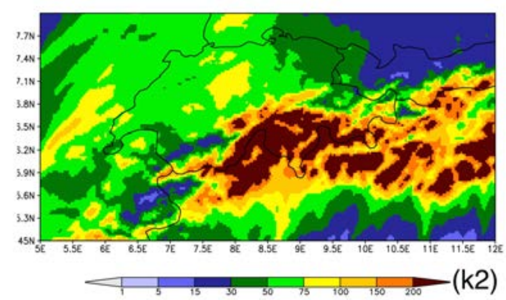
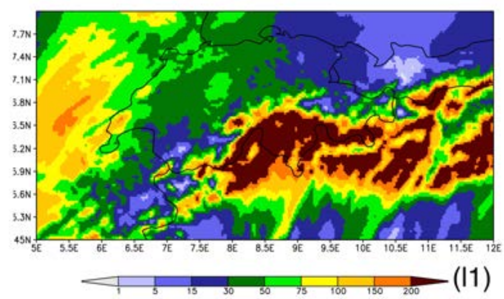
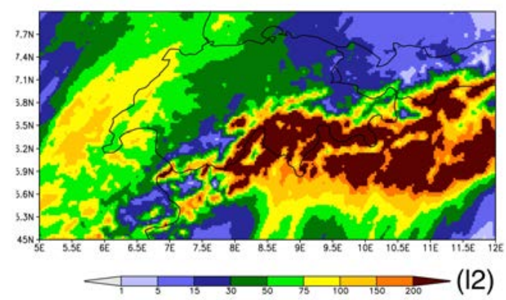
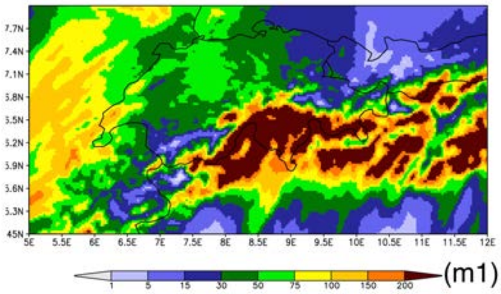
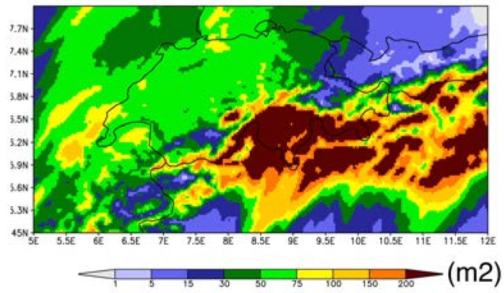
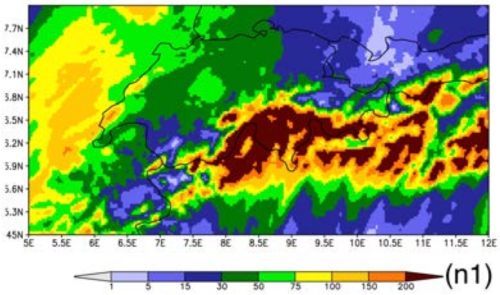
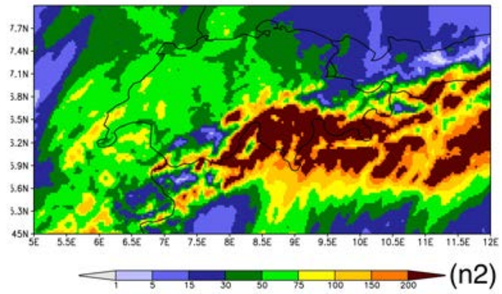
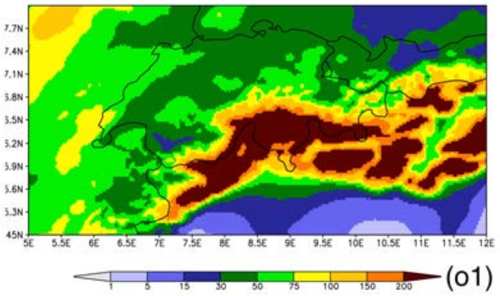
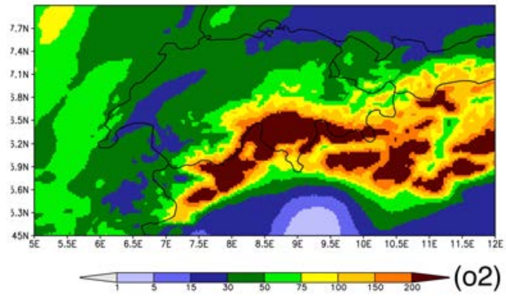
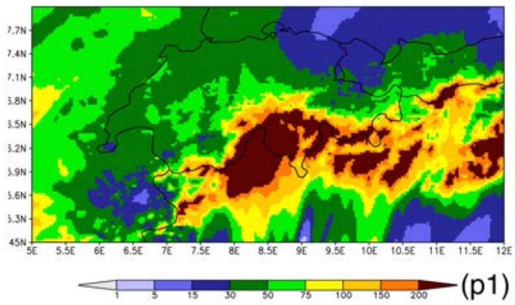
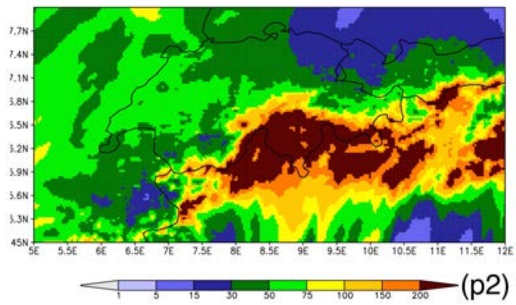
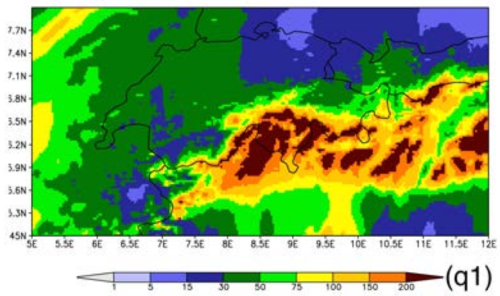
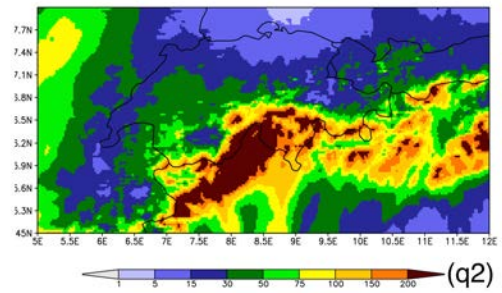
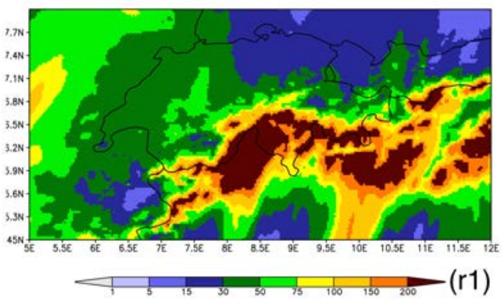
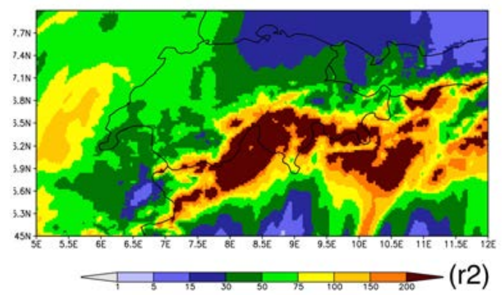
|---|---|---|
| COSMO-CMCC |  |  |
| WRF381 - UHOH |  |  |
| WRF- FZJ-IBG3 |  |  |
| WRF381-IPSL |  |  |
| WRF381-BCCR |  |  |
| WRF381-UNICAN |  |  |

| | | |
|---|---|---|
| WRF381-IDL |  |  |
| WRF381-CICERO |  |  |
| REMO-GERICS |  |  |
| HCLIM-KNMI |  |  |
| HCLIM- METNo |  |  |
| HCLIM-SMHI |  |  |

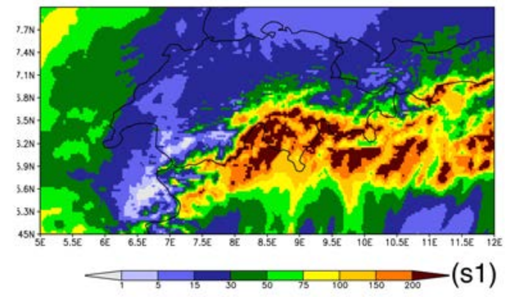
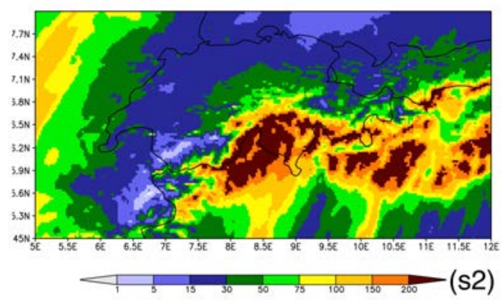
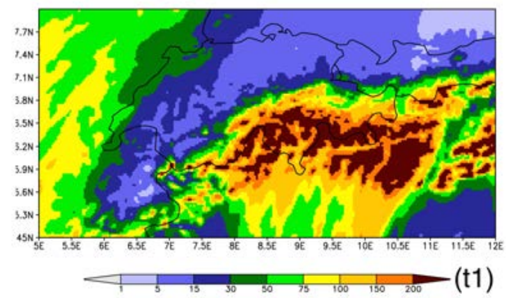
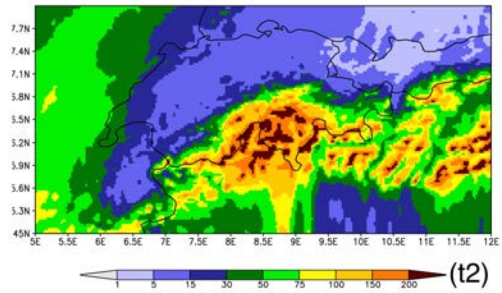
| | | |
|---|---|---|
| AROME-CNRM |  |  |
| MOLOCH-CNR |  |  |

**Figure 6:** CASE 3 - FOEHN. Total accumulated precipitation (mm) for observations, multi-model ensemble mean and each ensemble member. Results are shown for the models run in WL mode (left) and in CM (right). Panel (a2) shows an interpolation of the observed precipitation field.

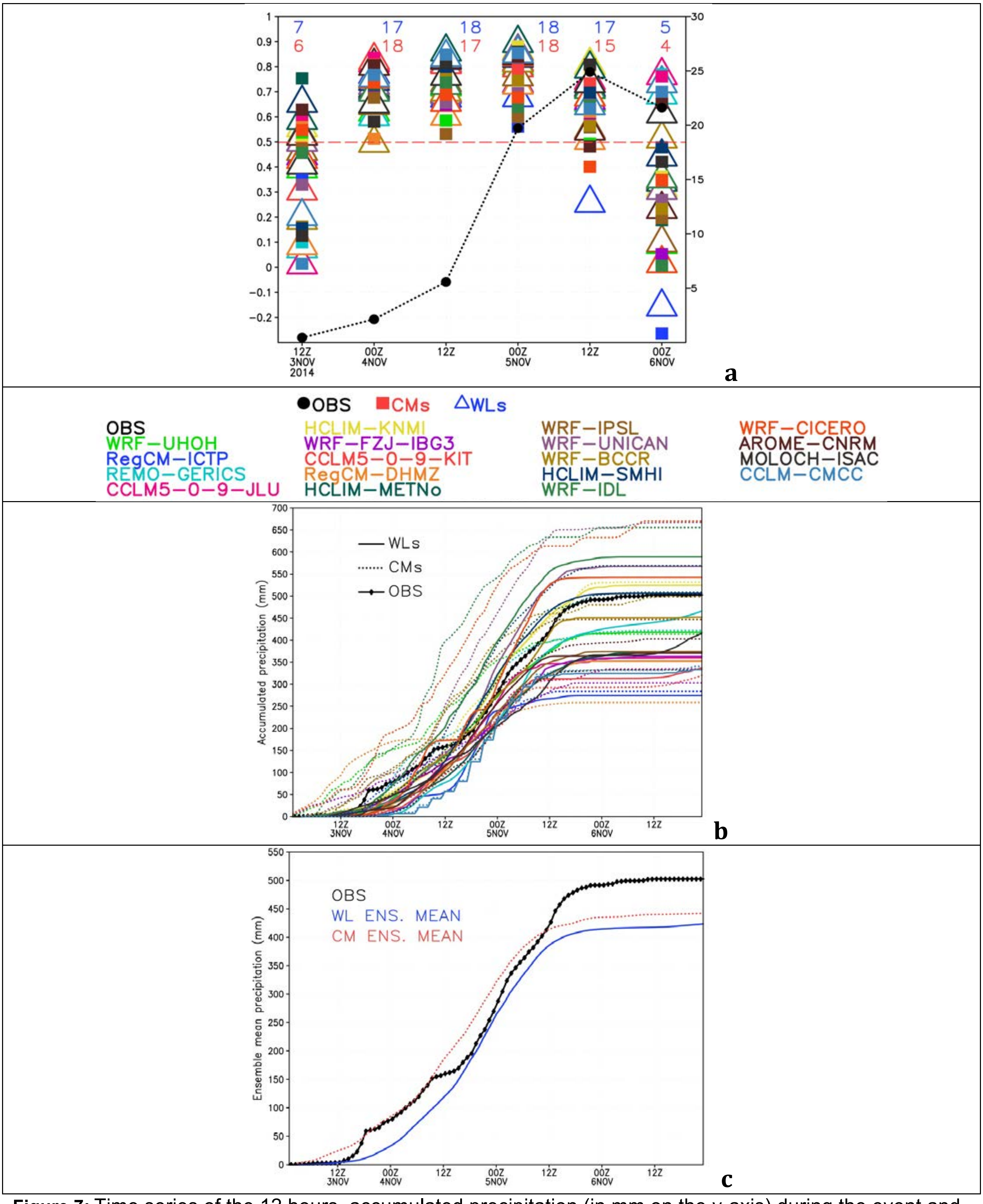



**Figure 7:** Time series of the 12 hours accumulated precipitation (in mm on the y-axis) during the event and temporal evolution of the spatial correlation of the accumulated 12 hours precipitation between the simulations and observation (panel a). Left hand side y-axes refer to correlation (colored symbols); right hand side y-axes refer to the accumulated precipitation (black line). Numbers of models with a correlation greater than 0.5 for WL simulation (in blue) and CM simulation (in red). Time series of the precipitation averaged over the region covered by the observations (Fig. 6a) for each model and observations (panel b). Time series of hourly accumulated precipitation ensemble mean(WL and CM respectively in blue and red) and observations (black) over the observation area (panel c).

Table

**Table 1:** List of contributors.

| | Contributor's ID | Contact Person | Model | Institute | Testcases | Climate Scenario Simulation | Nudging (Yes/No) | Resolution of the feeding domain |
|---|---|---|---|---|---|---|---|---|
| 1 | RegCM4-ICTP | Erika Coppola | RegCM4 | Abdus Salam Internatinal Centre for Theoretical Physics - Earth System Physics | √ | √ | No | 0.11 EURO-CORDEX |
| 2 | RegCM4-DHMZ | Ivan Guettler | RegCM4 | Meteorological and Hydrological Service of Croatia | √ | √ | No | 0.11 EURO-CORDEX |
| 3 | RegCM4-CUNI | Michal Belda | RegCM4 | Univerzita Karlova, Matematicko-fyzikální fakulta, Praha | √ | √ | No | |
| 4 | CCLM-JLU | Merja Toelle | CCLM5-0-9 | Justus-Liebig University of Giessen, Department of Geography, Climatology, Climate Dynamics and Climate Change | √ | √ | No | 0.75 ERAINT |
| 5 | CCLM-KIT | Hans-Juergen Panitz | CCLM5-0-9 | Karlsruhe Institute of Technology | √ | √ | No | 0.22 EURO-CORDEX |
| 6 | CCLM-WEGC | Marie Piazza | CCLM5-0-9 | Wegener Center for Climate and Global Change, University of Graz | √ | √ | No | 0.11 EURO-CORDEX |
| 7 | COSMO-KIT | Samiro Khodayar | CCLM5-0-9 | Karlsruhe Institute of Technology | √ | | No | 0.11 EURO-CORDEX |
| 8 | COSMO-CMCC | Mario Raffa | CCLM5-0-9 | Euro-Mediterranean Center on Climate Change | √ | √ | No | 0.22 EURO-CORDEX |
| 9 | CCLM-GUF | Bodo Ahrens | CCLM | Goethe University Frankfurt am Main | | √ | No | 0.11 EURO-CORDEX |
| 10 | CCLM-ETH | Nikolina Ban | CCLM | Institut für Atmosphäre und Klima, ETH Zürich | | √ | No | |
| 11 | WRF-UHOH | Josipa Milovac | WRF | University of Hohenheim, Germany | √ | √ | No | 0.11 EURO-CORDEX |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 12 | WRF-WEGC | Heimo Truhetz | WRF | Wegener Center for Climate and Global Change, University of Graz | √ | √ | No | 0.11 (WL)<br>15km (CM) |
| 13 | WRF-AUTH-MC | Eleni Katragkou | WRF | Aristotle University of Thessaloniki, Department of Meteorology & Climatology | √ | √ | No | 0.11 EURO-CORDEX |
| 14 | WRF- FZJ-IBG3 | Klaus Goergen | WRF | Research Centre Jülich, Institute of Bio- and Geosciences (Agrosphere, IBG-3) | √ | √ | No | 0.11 EURO-CORDEX |
| 15 | WRF-IPSL | Lluís Fita Borrell | WRF | The Institute Pierre Simon Laplace, Paris | √ | √ | No | 0.11 EURO-CORDEX |
| 16 | WRF-BCCR | Stefan Sobolowski | WRF | Bjerknes Centre for Climate Research | √ | √ | No | 0.11 EURO-CORDEX |
| 17 | WRF-UNICAN | Jesus Fernandez | WRF | Santander Meteorology Group, Universidad de Cantabria, Dept. Applied Mathematics and Comp. Sci. | √ | √ | No | 0.11 EURO-CORDEX |
| 18 | WRF-IDL | Rita Margarida Cardoso | WRF | Instituto Dom Luiz, Faculdade de Ciências da Universidade de Lisboa | √ | √ | No | 0.11 EURO-CORDEX |
| 19 | WRF-CICERO | Louis Marelle | WRF | Center for International Climate and Environmental Research - Oslo | √ | √ | No | 0.11 EURO-CORDEX |
| 20 | WRF-L-IPSL | Robert Vautard | WRF | The Institute Pierre Simon Laplace, Paris | | √ | No | 0.11 EURO-CORDEX |
| 21 | WRF-GIUB | Andrey Martynov | WRF | Institute of Geography and Oeschger Centre University of Bern Bern, Switzerland | | √ | No | |
| 22 | REMO-GERICS | Kevin Sieck | REMO2017 | Climate Service Center | √ | √ | No | 0.11 EURO-CORDEX |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Germany | | | | |
| 23 | HCLIM-KNMI | Hylke de Vries | HCLIM38-AROME | The Royal Netherlands Meteorological Institute | √ | √ | No | 0.11 EURO-CORDEX |
| 24 | HCLIM-METNo | Andreas Dobler | HCLIM38-AROME | The Norwegian Meteorological Institute | √ | √ | No | 0.11 EURO-CORDEX |
| 25 | HCLIM-SMHI | Danijel Belusic | HCLIM38-AROME | Swedish Meteorological and Hydrological Institute | √ | √ | No | 0.11 EURO-CORDEX |
| 26 | AROME-CNRM | Samuel Somot | AROME41t1 | CNRM-MeteoFrance | √ | √ | No | 0.11 EURO-CORDEX |
| 27 | MOLOCH-CNR | Silvio Davolio | MOLOCH | Institute of Atmospheric Sciences and Climate, ISAC-CNR | √ | | No | 0.11 EURO-CORDEX |
| 28 | UM10.1-MOHC | Lizzie Kendon | UM10.1 | Met Office Hadley Centre | | √ | No | |

**Table 2:** List of acronyms of the three test cases and initialization procedure.

| CASE | ACRONYM | Initialization Procedure | Analyzed Time Window |
|---|---|---|---|
| 1 | HymexIOP16 | Starting DATE (WL): 2012-10-23<br>Ending DATE (WL): 2012-10-28<br>Starting DATE (CM): 2012-10-01<br>Ending DATE(CM): 2012-11-01 | 23 Oct 2012 00:00<br>-<br>28 Oct 2012 00:00 |
| 2 | AUSTRIA | Starting DATE (WL): 2009-06-20<br>Ending DATE (WL): 2009-06-27<br>Starting DATE (CM): 2009-06-01<br>Ending DATE(CM): 2009-07-01 | 22 Jun 2009 00:00<br>-<br>25 Jun 2009 00:00 |
| 3 | FOEHN | Starting DATE (WL): 2014-11-02<br>Ending DATE (WL): 2014-11-07<br>Starting DATE (CM): 2014-10-01<br>Ending DATE(CM): 2014-11-07 | 3 Nov 2014 00:00<br>-<br>7 Nov 2014 00:00 |

**Table 3:** Spatial correlation of the total accumulated precipitation between simulations and interpolated observation for each of the boxes identified in the Case 1.

| Models | CASE 1 - IOP16 Red box (WL) | CASE 1 - IOP16 Red box (CM) | CASE 1 - IOP16 Green box (WL) | CASE 1 - IOP16 Green box (CM) | CASE 1 - IOP16 Blue box (WL) | CASE 1 - IOP16 Blue box (CM) |
|---|---|---|---|---|---|---|
| ENSEMBLE | **0.74** | **0.65** | **0.67** | 0.45 | **0.60** | **0.77** |
| RegCM4-ICTP | 0.30 | -0.11 | 0.20 | 0.28 | -0.02 | -0.19 |
| RegCM4-DHMZ | **0.62** | **0.64** | 0.43 | 0.15 | -0.05 | 0.22 |
| RegCM4-CUNI | 0.07 | **0.53** | -0.03 | -0.14 | -0.53 | -0.24 |
| CCLM-JLU | **0.50** | **0.50** | 0.41 | **0.52** | 0.48 | **0.57** |
| CCLM-KIT | 0.29 | 0.22 | 0.24 | 0.28 | 0.27 | 0.36 |
| WRF-UHOH | 0.38 | 0.23 | 0.35 | 0.11 | 0.20 | **0.61** |
| WRF-AUTH-MC | **0.57** | 0.48 | **0.58** | 0.33 | 0.31 | **0.75** |
| WRF-FZJ-IBG3 | 0.44 | 0.37 | 0.49 | **0.50** | 0.32 | **0.71** |
| WRF-IPSL | **0.56** | 0.15 | 0.45 | 0.38 | 0.18 | 0.45 |
| WRF-BCCR | **0.50** | **0.54** | 0.21 | 0.24 | 0.34 | **0.68** |
| WRF-UNICAN | 0.45 | 0.15 | 0.49 | 0.23 | **0.66** | **0.68** |
| WRF-IDL | **0.52** | 0.29 | **0.52** | -0.14 | 0.46 | **0.60** |
| WRF-CICERO | **0.61** | 0.15 | **0.51** | -0.06 | 0.27 | **0.52** |
| REMO-GERICS | **0.54** | 0.06 | 0.37 | -0.36 | **0.50** | **0.64** |
| HCLIM-KNMI | 0.33 | **0.64** | **0.65** | 0.39 | **0.54** | **0.75** |
| HCLIM-METNo | **0.56** | 0.26 | **0.51** | 0.45 | -0.25 | 0.29 |
| HCLIM-SMHI | **0.66** | 0.18 | **0.51** | 0.37 | 0.25 | **0.69** |
| AROME-CNRM | **0.71** | **0.58** | 0.49 | **0.56** | **0.65** | **0.71** |
| MOLOCH-CNR | 0.44 | 0.48 | 0.23 | -0.20 | 0.09 | 0.17 |
| COSMO-KIT | **0.57** | 0.38 | 0.33 | 0.49 | 0.30 | 0.45 |
| COSMO-CMCC | **0.51** | **0.50** | **0.54** | 0.39 | 0.18 | 0.33 |

**Table 4:** Same as Table 3 but for the Case 2.

| Models | CASE 2 -AUSTRIA (WL) | CASE 2 - AUSTRIA (CM) |
|---|---|---|
| ENSEMBLE | **0.82** | **0.81** |
| RegCM4-ICTP | **0.62** | -0.01 |
| RegCM4-DHMZ | **0.63** | 0.02 |
| RegCM4-CUNI | 0.49 | 0.37 |
| CCLM-JLU | **0.63** | **0.62** |
| CCLM-KIT | **0.77** | **0.77** |
| CCLM-WEGC | **0.75** | 0.39 |
| WRF-UHOH | **0.69** | **0.60** |
| WRF-WEGC | **0.68** | **0.61** |
| WRF-FZJ-IBG3 | **0.62** | 0.05 |
| WRF-IPSL | **0.54** | 0.47 |
| WRF-BCCR | **0.77** | **0.64** |
| WRF-UNICAN | **0.69** | 0.27 |
| WRF-IDL | **0.64** | 0.10 |
| WRF-CICERO | **0.67** | 0.05 |
| REMO-GERICS | 0.44 | 0.23 |
| HCLIM-KNMI | **0.67** | **0.60** |
| HCLIM-METNo | **0.62** | 0.41 |
| HCLIM-SMHI | **0.72** | **0.71** |
| AROME-CNRM | **0.83** | **0.82** |
| MOLOCH-CNR | **0.58** | -0.001 |
| COSMO-CMCC | **0.62** | **0.63** |

**Table 5:** Same as Table 3 but for the Case 3.

| Models | CASE 3 -FOEHN (WL) | CASE 3 - FOEHN (CM) |
|---|---|---|
| ENSEMBLE | **0.91** | **0.90** |
| RegCM4-ICTP | **0.78** | **0.73** |
| RegCM4-DHMZ | **0.78** | **0.77** |
| CCLM-JLU | **0.92** | **0.89** |
| CCLM-KIT | **0.87** | **0.86** |
| WRF-UHOH | **0.86** | **0.84** |
| WRF-FZJ-IBG3 | **0.78** | **0.81** |
| WRF-IPSL | **0.84** | **0.81** |
| WRF-BCCR | **0.82** | **0.85** |
| WRF-UNICAN | **0.86** | **0.82** |
| WRF-IDL | **0.84** | **0.84** |
| WRF-CICERO | **0.85** | **0.82** |
| REMO-GERICS | **0.91** | **0.90** |
| HCLIM-KNMI | **0.89** | **0.90** |
| HCLIM-METNo | **0.90** | **0.83** |
| HCLIM-SMHI | **0.87** | **0.87** |
| AROME-CNRM | **0.89** | **0.91** |
| MOLOCH-CNR | **0.86** | **0.89** |
| COSMO-CMCC | **0.90** | **0.90** |