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DRIHM(2US): an e-Science environment for hydro-meteorological research on high impact weather events

Antonio Parodi[1], Dieter Kranzlmueller[2], Andrea Clematis[3], Emanuele Danovaro[3], Antonella Galizia[3], Luis Garrote[4], Maria Carmen Llasat[5], Olivier Caumont[6], Evelyne Richard[6], Quillon Harpham[7], Franco Siccardi[1], Luca Ferraris[1], Nicola Rebora[1], Fabio Delogu[1], Elisabetta Fiori[1], Luca Molini[1], Efi Foufoula- Georgiou[8], Daniele D'Agostino[3]

[1] CIMA RESEARCH FOUNDATION, Savona, Italy, [2] Ludwig-Maximilians-Universität München, München, Germany, [3] Institute of Applied Mathematics and Information Technologies, National Research Council of Italy, Genoa, Italy, [4] Technical University of Madrid, Madrid, Spain, [5] Department of Department of Applied Physics, Faculty of Physics, University of Barcelona, [6] CNRM-GAME (Météo-France, CNRS) Toulouse, France, [7] HR Wallingford, Howbery Park, Wallingford, Oxfordshire, OX10 8BA, United Kingdom, [8] University of California, Irvine, United States of America

Capsule: DRIHM, or the Distributed Research Infrastructure for Hydro-Meteorology, together with its US facing companion project, DRIHM2US, both funded by the European Union, have developed a prototype research infrastructure for simulating the complete process involved in extreme hydro-meteorological events such as flash flooding. Both projects enabled a step change in how scientists can approach studying high impact weather events.

Corresponding Author: Antonio Parodi, CIMA RESEARCH FOUNDATION, Via Armando Magliotto 2, 17100, Savona, Italy

Abstract

From 1970 to 2012, about 9000 high impact weather events were reported globally causing the loss of 1.94 million lives and damage of US$ 2.4 trillion (United Nations International Strategy for Disaster Reduction, UNISDR report 2014). The scientific community is called to action to improve the predictive ability of such events and communicate forecasts and associated risks both to affected populations and to those making decisions. At the heart of this challenge lies the ability to have easy access to hydrometeorological data and models, and to facilitate the necessary collaboration between meteorologists, hydrologists, and computer science experts to achieve accelerated scientific advances. Two EU funded projects, DRIHM and DRIHM2US, sought to help address this challenge by developing a prototype e-Science environment providing advanced end-to-end services (models, datasets and post-processing tools), with the aim of paving the way to a step change in how scientists can approach studying these events, with a special focus on flood events in complex topography areas. This paper describes the motivation and philosophy behind this prototype e-Science environment together with certain key components, focusing on hydro-meteorological aspects, which are then illustrated through actionable research for a critical flash flood event, which occurred in October 2014 in Liguria, Italy.

1 Introduction

Every year, high impact weather events (HIWE) related to meteorological, hydrological, geological and climate hazards cause significant loss of life. From 1970 to 2012, about 9000 HIWE were reported globally. All together, they caused the loss of 1.94 million lives and economic damage of US$ 2.4 trillion (United Nations International Strategy for Disaster Reduction, UNISDR report 2014). Storms, droughts, floods, extreme temperatures and coastal hazards all figure on the lists of the worst HIWE related disasters. Storms and floods accounted for 79% (44% floods and 35% storms) of the total number of disasters due to weather, water, and climate extremes; caused 54% of lives lost (14% floods and 40% storms) and 84% (33% floods and 51% storms) of economic losses (WMO report 2014). This may hold back economic and social development by years or even decades.

Disaster risk reduction (DRR) is a broad issue, which calls for political commitment and public understanding in order to be properly addressed. The DRR primary aim is to make the public aware of the risks it faces from natural hazards, such as storms and flash floods, and offers reassurances that adequate resources are available to minimize their impacts. A relevant indicator of the reliability and proper functioning of a DRR organization is its ability to inform the public of the procedures it relies upon to rapidly assess and to alert when a disaster is impending. The knowledge that warnings will be issued with clear and sound procedures, with the most advanced tools, also helps to create a consensus towards the authority, which in turn helps it in its risk reduction efforts, such as with the control of land or property limitations.

In summary, sophisticated ”warning scenarios” not only serve immediate needs in a crisis, but also establish the credibility of the organizations, furthering the development of consensus on the required regulations, with a strong focus on risk reduction.

Improving the quality and reliability of such sophisticated ”warning scenarios” requires focused hydrometeorological research (Parodi et al. 2012) to: *(1) understand, explain and predict the physical processes producing HIWEs, (2) understand the possible intensification of such events because of climate change effects, and (3) explore the potential of the increasing computational power provided by High Performance Computing (HPC), High Throughput Computing (HTC) and Cloud Computing - in combination often called e-Infrastructures - to provide deeper understanding of those events through fine-resolution modelling over large domains*.

At the heart of these research challenges lies the ability to have easy access to hydrometeorological data and models, and to facilitate the necessary collaboration between meteorologists, hydrologists, and Earth science experts to achieve accelerated scientific advances in hydrometeorological research (HMR). This can be achieved through stronger collaboration with the Information and Communication Technologies (ICT) community who continually provides new technological solutions (Shapiro et al. 2007 and 2010, Shukla et al. 2009 and 2010).

The EU funded projects DRIHM (Distributed Research Infrastructure for Hydro-Meteorology, www.drihm.eu) and DRIHM2US (Distributed Research Infrastructure for Hydro-Meteorology to US, www.drihm2us.eu), together hereafter denoted as “DRIHM(2US)”, developed a prototype Distributed Computing Infrastructure (DCI) to facilitate this collaboration providing advanced end-to-end HMR services (models, datasets and post-processing tools), with the aim of paving the way to a step change in how scientists can approach studying HIWEs, with special focus on flood and flash-flood events. This paper discusses how DRIHM(2US) services now make it possible to work in a modular environment and enhance the modelling and data processing capabilities of the HMR community through the adaptation, optimization and integration of dedicated HMR services over the associated e-Infrastructure, itself featuring several different computing paradigms (High Performance Computing – HPC, High Throughput Computing – HTC, and cloud-computing).

The paper is organized as follows: Section 2 presents the motivations of the proposed DRIHM(2US) DCI for Hydro-Meteorology. Section 3 discusses the key DRIHM(2US) elements. Section 4 explores in detail the application of the DRIHM(2US) services to the Genoa 2014 flash-flood event. Section 5 provides discussion and conclusions.

2 The Distributed Computing Infrastructure for Hydro-Meteorology: motivations

The quality, quantity and complexity of model engines, post-processing tools and datasets for hydro-meteorology and climate research have dramatically increased over the past 15 years. Some state-of-the-art initiatives can be identified: the Community Earth System Model project (CESM, Hurrell et al. 2013), which provides a fully coupled, global climate-modelling suite; the Community Surface Dynamics Modeling System (CSDMS), using a component-based approach to support geoscience modelling of the Earth’s surface (Peckham et al., 2013); the CUAHSI Hydrologic Information System project (HIS, Horsburg et al. 2009) which provides an internet-based system for sharing hydrologic data, through databases and servers, connected through web services, and client applications, allowing for the publication, discovery and access of data; the Earth System Modelling Framework project (ESMF, Hill et al. 2004) which provides generic tools for building climate, numerical weather prediction, data assimilation, and other Earth science applications; the Water Information Research and Development Alliance initiative (WIRADA, 2008-on going), which is a partnership between the Bureau of Meteorology and The Commonwealth Scientific and Industrial Research Organisation in Australia, covering four broad categories (water information systems, foundation data products, water accounting and assessment, and water forecasting and prediction).

Along these lines, a first analysis of existing gaps between the most advanced HMR communities and the best available ICT tools was conducted within the Distributed Research Infrastructure for Hydro-Meteorology Study (DRIHMS) project in 2011 (Schiffers et al. 2011). The analysis was based on the results of two questionnaires, one for the HMR community and one for the ICT community, augmented by additional expert interviews. Globally, about 300 respondents from 40 countries returned the questionnaire: 82% from European Institutions, while the remaining 18% came from overseas, mainly from the USA. At the European level, the leading countries in terms of number of collected questionnaires were: Italy (20%), Germany (11%), France (9%), Spain (9%) and UK (4%). Most of the HMR respondents were from the fields of Hydro-Meteorology (40%) or Meteorology (43%), with a smaller but still significant contribution from Hydrology (10%). About half of the HMR respondents were from research institutions (47%), with the remainder from institutions with both research and operational responsibilities (38%) or purely operational institutions (15%) A summary of the results did indicate that the ICT challenges for HMR scientists include the ability to exploit significant computational resources for research and operational activities, and the ability to retrieve and access data from different sources.

DRIHM2US represented the natural evolution of the DRIHMS project survey activities. The key element was a set of transatlantic networking activities involving hydro-meteorologists, climate scientists and ICT scientists from both Europe and USA all focused on the challenge to overcome current limitations in the interplay between existing e-Science environments in these two fields. The DRIHM2US consultation (Harpham et al. 2017) focused on identifying the most important features for state-of-the-art numerical models, including eliciting and prioritizing research and development needs, identifying opportunities to answer these needs, and how such a research infrastructure can be maintained, operated and improved over time. Overall, responses were received from about 150 EU and USA specialists from a wide variety of organisations and roles, exhibiting a very high level of experience, ranging from scientific communities and citizen scientists to ICT support staff. Respondents gave a consensus on a number of key factors, which must be taken into account when scoping and specifying any future e-Science infrastructure for HMR. Variations between respondents from Europe and those from the US indicated slightly different experiences with such infrastructures but with a fairly united view overall: it must be very easy to access, very easy to use and accompanied by comprehensive training and support; it must be built on a clear set of standards, particularly for data and model interfacing with the objective of enabling flexible usage, not restricting users; it must not be tied too strongly to any HMR community, should allow interface with other adjacent scientific communities but not become too vast and unwieldy; with regard to data, practitioners from the USA had better experiences of access to open data than their European counterparts.

The DRIHM(2US) initiative has built on these DRIHMS and DRIHM2US findings and has developed a modular environment, the DRIHM(2US) DCI enabling:

- The provision of integrated HMR services (such as meteorological models, hydrological models, stochastic downscaling tools, and hydraulics models) enabled by unified access to and seamless integration of underlying e-Infrastructures;
- The design, development and deployment of user-friendly interfaces aiming to abstract HMR service provision from the underlying e-Infrastructure complexities and specific implementations, thus enabling multidisciplinary and global collaboration between meteorologists, hydrologists and possibly other Earth Scientists;

• The user-driven “composition” of virtual facilities in the form of hydro-meteorological forecasting chains, composed by different HMR resources (models, post-processing tools, and data).

The result is an enhancement of the modelling and data processing capabilities of the HMR community through the adaptation, optimization and integration of dedicated HMR services relying on different computing paradigms and technologies (e.g. High Performance, High Throughput, and Cloud and Grid computing).

3 Key elements of the DRIHM(2US) initiative

The DRIHM(2US) scientific case is built around three experiment modelling suites able to address the interdisciplinary and international challenges of HMR in forecasting flash floods related HIWE. These three different modelling experiment suites (Figure 1) compose the so-called hydro-meteorological forecasting chain, whose end result is a prediction of a hydrological quantity such as river run-off and water level, feasible by feeding the prediction with a large variety of models and data sources..

On a conceptual level, a complete hydro-meteorological forecasting chain consists of 3 consecutive layers:

• *The rainfall layer* pertains to the combination of different numerical weather prediction (NWP) models to form a high-resolution multi-model ensemble together with the possibility to apply a stochastic downscaling algorithms to enable the production of quantitative rainfall predictions for severe rainfall events;

- *The discharge layer* concerns the combination of outputs data from the rainfall layer, such as rainfall, temperature at 2 meters, wind speed and strength, relative humidity predictions, with corresponding observations, which became inputs into multiple hydrological models to enable the production of river discharge predictions;
- *The water level, flow and impact layer* addresses the execution of hydraulic model compositions in different modes to assess the water levels, flow and impact created by the flood events and to compare them against observations through verification metrics.

3.1 Model chaining and model interoperability: the MAP approach

DRIHM(2US) identified an initial set of state-of-the-art model engines for the different modelling experiment suites. In the present version of the platform, 9 are the available models: three meteorological models: WRF (Weather Research and Forecasting)-ARW (Advanced Research WRF, Dudhia et al. 2005), WRF-NMM (Nonhydrostatic Mesoscale Model, Janjic et al. 2005) and Meso-NH (Lafore et al. 1998), together with the option for stochastic downscaling with RainFARM (Rebora et al. 2006). Three hydrological models simulating catchment drainage are available: the semi-distributed rainfall-runoff model DRiFt (Discharge River Forecast, Giannoni et al. 2000), the distributed rainfall-runoff model RIBS (Real-time Interactive Basin Simulator, Garrote and Bras 1995) and the distributed hydrological model HBV (Hydrologiska Byråns Vattenbalansavdelning, Bergström and Singh 1995), together with the option to initialize the models by using rain gauge observations. Two main hydraulic options have been provided for simulating the flood itself: an OpenMI (Gregersen et al. 2007) composition of three models to model lateral exchanges between a river channel and a floodplain: MASCARET, RFSM and Impact Calculator (or Property Damage) or Delft3D (Hydraulics D. 1999). Although other hydrological and hydraulic models could be introduced in the platform, the present configuration allows realizing 3x3x2 (18) different hydro-meteorological chains. Both meteorological and hydrological models have been selected for their specific ability to reproduce mesoscale deep moist convective processes and their hydrological effects in areas where complex topography plays crucial role (Atencia et al. 2011, Fiori et al. 2017).

When considering standards-based DCIs for running numerical models and accessing the supporting data, new numerical models can be written to be directly compliant with the standards incorporated. Conversely, if the infrastructure is to include existing models, then these must be made compliant to the necessary level (e.g. input and output data). The DRIHM(2US) e-Infrastructure is exclusively populated by legacy models, ranging from those common to their scientific domains with long development histories and large user bases to research standard code, which has been iterated many times at universities. To incorporate such a wide variety of models, a simple, gateway concept for numerical model compatibility was derived. Adherence to this would make a model compatible for implementation on the infrastructure and also point toward future, more formal standardization.

Then, DRIHM(2US) abstracted common characteristics from leading integrated modelling technologies and derived a generic framework, characterized as the Model MAP approach (Harpham et al. 2015, Harpham et al. 2016): *M-Metadata, Documentation and Licence* - each model must be supplied with metadata according to a given standard, appropriate documentation, and a licence for users to use it; *A-Adaptors (or bridges)* must be provided, which translate the model inputs and outputs to and from common standards; *P-Portability* - each model must be made portable, that is, not tied strongly to local infrastructure. The Model MAP is a key factor enabling the extensibility of the DRIHM(2US) portal at the model level, by allowing the inclusion of new HMR model engines, and also across new model domains. An example in this sense is provided by the AROME (Application of Research to Operations at Mesoscale) model in Figure 2: the AROME model engine, an instance of which is operational at Météo-France, cannot be shared on the DRIHM DCI because of strict licensing constraints. Still, building on the MAP concepts, its outputs can be used to force subsequent hydrological models, as described in section 4.

DRIHM(2US) makes possible any combination of the abovementioned (and new) models in a chain using two standards-based interfaces (Harpham and Danovaro 2015): the P (or precipitation) interface between the meteorological models and hydrological models is a one-way, file-based interface using the NetCDF file format since the meteorological outputs are grid-series. The second one is the Q (or flow) interface, which allows to use the hydrological variables as inputs for the hydroulic models, applying the

WaterML2 file format for point-series outputs. Interfaces in addition to the P and Q ones can be added to support other topics of potential interest such as ocean dynamics or coastal morphology. Indeed, the P interface has been conceived to offer mainly the precipitation variable for flooding studies, as reference use case of DRIHM(2US) platform, together with others key meteorological parameters such as 10 m wind speed and direction, surface air pressure, 2 m temperature and specific humidity, latent and sensible heat fluxes, and incoming solar radiation, depending on the hydrological models selected for the prescribed chain. Thus, DRIHM(2US) offers the potential to be extended to many other modelling domains with minimal additional effort.

3.2 The underlying e-Infrastructure

From an ICT operational perspective, the major objective of DRIHM(2US) is to support users in enabling the HMR community to setup chains of models on various spatio-temporal scales, to support their integrated configuration, to fetch the data, and to execute the workflow on the most appropriate ICT resources. Such resources are available for the community within the existing European and American e-Infrastructures ecosystem while adhering to constraints imposed by model developers, data owners and resource providers.

In order to overcome these challenges, DRIHM(2US) developed the "Science Bus" concept adapted from Chappell's Enterprise Service Bus approach (Chappell 2004), but extending it to support the required model chaining and the chain execution on Grid resources (e.g., granted by the European Grid Infrastructure (EGI, Kranzlmüller et al. 2010), Cloud resources (e.g., available through EGI's Federated Cloud Initiative), HPC resources (e.g., provided through the Partnership for Advanced Computing in Europe, PRACE, Turunen et al. 2010).

Due to their heterogeneity, the runtime environments for the various models need to be prepared prior to model execution in a "standardized" manner in order to make them executable on arbitrary Grid, Cloud and HPC resources available. These aspects represent the "Adaptor" and "Portability" of the Model MAP. While the software modules required to make the model engines compliant to the adopted P and Q interfaces (i.e. the adapters) could be supplied by the model developers, the "assembly line" management (the process to make a model engine portable) has been provided by DRIHM(2US). This strategy has been proven stable and extensible. It allows for seamlessly integrating new HMR applications with legacy ones and it supports access to the bus through external Web services.

3.3 The DRIHM portal: a science gateway for Hydrometeorology

The DRIHM Portal is the scientific gateway designed to shape the DRIHM(2US) vision (Danovaro et al. 2014). The portal supports users in experiment configuration and execution by providing integrated solutions to manage and exploit the e-Infrastructure's key ingredients: state-of-the-art numerical simulation model engines (Figure 2), a set of powerful distributed ICT resources and an easy-to-use interface. The result is a flexible and extensible environment that guides, for example in the case of the WRF-ARW model, the user in the domain(s) selection (Figure 3, upper panel), parameters selection (Figure 3, middle panel), produces ready to use configuration files or namelists

(Figure 3, lower panel), manages the job submission and result retrieval, and enables results to be analysed and compared in a straightforward way.

The DRIHM(2US) portal is based on the technologies proposed by the SCIentific gateway Based User Support (SCI-BUS, Kacsuk et al. 2013) project, i.e. a customized version for e-Science environments of the generic-purpose gUSE/WS-PGRADE portal family (D'Agostino et al. 2015). The principle is to improve the way the scientist works by decoupling the HMR aspects from the ICT aspects, shielding non-ICT experts from the underlying ICT complexities that specific implementations and computational resources require.

The portal represents a step beyond the state-of-the-art in HMR because models can be freely combined in complex simulation chains. The adoption of standardized interfaces and proper data conversion tools developed in the project results in the possibility to interpret Figure 2 as a direct graph: models are the nodes and arrows are the directed arcs, connecting two models sharing the same interface. Each possible simulation chain is a path on the directed graph; thus, the selection of a single model, or a complex chain (e.g., exploiting WRF-NMM, RainFARM, RIBS, and Delft3D) defines valid chains, supported by the science gateway.

Three user categories exist for the DRIHM portal: citizen scientists, scientists and expert scientists. All generic users have to register[1] to the DRIHM portal and they are automatically classified as citizen scientists. Then HM researchers can apply to be classified as scientists or expert scientists on the basis of their skills and research purposes, which will be assessed by a

[1] https://portal.drihm.eu/liferay-portal-6.1.0/web/guest/home?p_p_id=58&p_p_lifecycle=0&p_p_state=maximized&p_p_mode=view&saveLastPath=0&_58_struts_action=%2Flogin%2Fcreate_account

DRIHM(2US) review committee. Each category corresponds to different rules and regulations to access the available services. For example, the calibration of a basin for executing hydrological simulation has to be inserted by expert hydrologists, who can assure the correctness of data and therefore the scientific validity of simulation results. While scientists are free to define every single parameter of an experiment and to use their own input data, citizen scientists are supplied with pre-defined scenarios targeted to give maximum insight to these non-technical users. All DRIHM(2US) users are offered with a rich set of training information to learn more about available modelling and visualization services. This training information has allowed introducing DRIHM(2US) in some curricula of high degree studies (i.e. European Master on Meteorology, University of Barcelona).

3.4 Key feedbacks and achievements of the DRIHM(2US) 2014 implementation workshop

The DRIHM(2US) platform was thoroughly tested during a hands-on workshop organized in Madrid in September 2014. The workshop gathered 31 participants, coming from many European countries, but also USA, Bolivia, Barbados, Sudan, Thailandia, and Philippines, selected from over 150 applications to receive training on how to build interoperable forecasting chains in DRIHM(2US) and execute them in HPC platforms. After testing the DRIHM(2US) system through the portal, the participants were asked to provide feedback through a questionnaire. Most participants agreed that DRIHM(2US) can fill a crucial gap in hydrometeorology, allowing practitioners to widen the scope of their work by including other types of models that they had not been using so far. Some participants expected to enhance their modelling chains by incorporating some DRIHM(2US) components while others enjoyed the opportunity of simple access to the grid computing infrastructure. DRIHM(2US) was generally perceived as a developing project and participants encouraged further improvement, mainly along two lines: data availability to run models in large geographical areas and flexibility on workflow configuration to customize its application (for instance, to model calibration or data assimilation). Several participants mentioned the possibility of configuring model instances for their own case studies. Overall, the participants expected the platform to grow in the near future, including more models and more critical cases.

4 An example of DRIHM(2US) case study: the Genoa 2014 flash flood

During the project lifetime, the Western-Mediterranean area was affected by a number of very intense flash-flood phenomena, which hit regions with complex topography, lasted less than one day and produced hundreds of millimetres of rainfall in few hours on small watersheds. These kinds of HIWEs are nowadays documented by various studies, both because of their increasing number as well as the improved observational capabilities (Alexander et al., 2006; Coumou and Rahmstorf, 2012; Min et al., 2011; Tramblay et al., 2013).

The post event analysis of one of these events, which occurred on October 2014 event in Genoa (Liguria, Italy), is reported here because its analysis involved all the functionalities associated with DRIHM(2US), allowing the use of different models and the nesting of different runs down to a very fine meteorological grid size of 200 meters.

4.1 The Genoa 2014 event

The Genoa 2014 event, affecting Liguria region in northwestern Italy (Figure 4, panel A), and in particular the torrent-like river, wich crosses the city center, called Bisagno (Figure 4, panel B, 100 km2), was characterized by two distinct phases. Panels on right side of Figure 4 show the first phase during the morning of the day until 12UTC, with rainfall depths between 50 and 130 mm on the Bisagno catchment. After a break in the rainfall phenomena, the second phase in the late evening was characterized by hourly rainfall peaks around 100-130mm between 20UTC and 21UTC reaching rainfall depths between 150 mm and 260 mm. The daily peak rainfall depth was around 400mm and the average rainfall depth over the catchment was 220 mm. As a consequence of these torrential rainfalls the Bisagno river produced a deadly flash-flood in the city centre (around 21UTC) with a discharge peak of 1100 m^3/s.

It is worthy of note that, because of its peculiar spatio-temporal evolution and intrinsic low predictability, the operational hydro-meteorological suite, composed by the MOLOCH (Buzzi et al. 2014) meteorological model at cloud permitting grid spacing (2 km), the RaiFARM model, and the DRiFt model (as used at the hydro-meteorological office of the Liguria Region Environmental Agency (ARPAL)) was not able to predict, with adequate accuracy, 12-24 hours in advance the observed peak discharge (Figure 5) that occurred around 22UTC, at the Passerella Firpo gauging station, near the Genoa city center: the ensemble of DRiFt hydrographs (about 50) falls well below the Q=500 m^3/s (T=10 years) critical discharge. Similar results hold if using the QPF provided by the COSMO 2.8 km (Baldauf et al. 2011) operational model (not shown). For this reason the event resulted in a missed alert.

At the mesoscale, the V-shape back-building MCS observed during the events of October 2010, October and November 2011 over Liguria region (Cassola et al., 2015; Davolio et al., 2015; Rebora et al., 2013), was also a peculiar characteristic of the Genoa 2014 event. Schumacher and Johnson (2005, 2006, 2008, 2009) describe ‘‘back-building’’ mesoscale convective system (MCS) mechanisms, which has been found one of the major patterns which characterizes these severe and persistent phenomena (Fiori et al, 2017). The process is an atmospheric setting where convective cells repeatedly develop upstream of previous ones and pass over the same region: radar signatures of these storms are characterized by a typical V-shape (**Figure 6**). As already done for the 2011 events (Rebora et. al 2013), a map of persistence of rainfall intensity exceeding a threshold of 1mm/h over 24h obtained by the Italian Radar National composite is produced (**Figure 7**): the V-shape MCS structure is apparent. As for the previous HIWEs over the Liguria region, a fundamental meteorological feature for establishing and maintaining the back-building process for the Genoa 2014 HIWE has been the presence of a robust convergence line over the Liguria Sea (Figure 8), as detected by the Advanced Wind Scatterometer (ASCAT) a six-beam spaceborne radar instrument designed to measure wind fields over the oceans (Wilson et al. 2010).

4.2 The Genoa 2014 event hydro-meteorological predictive ability through DRIHM services

Bearing in mind the ARPAL operational results and first considering the cloud permitting grid spacing QPF results, the RIBS model, through the DRIHM portal, has been forced by 34 different members of the AROME ensemble at 2.5 km (Hally et al. 2015), initialized 00UTC on 9 October 2014. Its ouputs have been post-processed in agreement with the MAP procedure and then offered in netcdf-CF format (Harpham and Danovaro 2015) for the chaining with the RIBS model. Only one "AROME member 8" among the 34 members of the ensemble has been able to produce a peak discharge above 500 m3/s even if with a significant error (>12 hours) in terms of the time of the peak with respect to the observed one (Figure 9, lower panel).

Moving towards cloud-resolving grid spacing for QPF results, the RIBS model has then been forced by 10 different members of the MESO-NH ensemble at 500 m grid spacing (Figure 10), generated in agreement with the procedure described in Hally et al. (2015) and initialized 00UTC on 9 October 2014. Almost all the MESO-NH members driving RIBS are enabling discharge predictions above 500 m^3/s, again underestimating the true event and with timing error, but still very relevant to operational logic, while some members are even able to predict the double peak discharge (morning and evening, member 9) in the observed hydrograph.

The MESO-NH results are also confirmed by another hydro-meteorological chain experimented on the DRIHM(2US) platform: WRF-ARW at 1 km and 200 m grid spacing, with the setup defined in Fiori et al. (2014, 2017), feeding into the RIBS model (Figure 11). The results confirm again, even in deterministic mode, the added value provided by the adoption of grid spacing in the cloud resolving range. In particular with the WRF-ARW 1 km as forcing (Figure 11, lower panel, black dashed line), it is possible to predict a discharge peak around 800 m3/s exhibiting, however, a significant timing error. The situation improves when the cloud-resolving simulation is used, because the peak discharge becomes comparable with the observed one and the temporal offset is reduced (Figure 11, lower panel, green dashed line) of about 3 hours.

Similar findings emerge by using the WRF-ARW–DRiFt chain (Figure 12), although it is interesting to notice that despite the same WRF-ARW input (1000 and 200 m) RIBS and DRiFt produce significantly different peak discharges, but still with return period well above 20-30 years, based on regional frequency analysis of annual rainfall and discharge maxima in Liguria region (Boni et al. 2006, Boni et al. 2007).

The comparison between the different hydro-meteorological forecasting chains both in operational and hindcast mode suggest that the adoption of finer grid spacing QPF results (in the cloud-resolving range for WRF-ARW 1 km and 200 m, as well as MESO-NH 500 m) provide better results in terms of peak discharge and its timing than using cloud-permitting QPF results (operational COSMO 2.8 km and MOLOCH 2 km, as well AROME 2.5 km in hindcast mode): Figure 13 confirms this statement, since the finer is the grid spacing (panel e, f, g) the better is approximated the 24 hours QPE radar (panel a) and its localization over the Bisagno catchment.

All together the DRIHM(2US) platform allowed the execution, within a time frame of 4 hours, of 48 hydro-meteorological workflows with 15 of them (30%), predicting a peak discharge above 500 m^3/s, thus justifying, in an operational logic, the issuing of an alert.

5 Conclusions

DRIHM(2US) represents a promising advancement in hydrometeorological research because it allows the researchers/operators to repeat simulations of HIWE critical cases much more rapidly giving more scientific confidence, allowing more simulations and analysis of the results. Where before, HMR chains were often clumsily stitched together and hard-wired to individual models, DRIHM(2US) allows a more interoperable and extensible model chain formulation.

The DRIHM(2US) services now make possible to work in a modular environment with the enhanced modelling and data processing capabilities of the HMR community through the adaptation, optimization and integration of dedicated HMR services over the DRIHM e-Infrastructure. Different computing paradigms have been utilized (HPC, HTC and cloud-computing). By integrating HMR resources, DRIHM allows specialists to enter the e-Science environments more easily and at the same time stimulate use by non-specialists.

In general, the DRIHM(2US) innovations work together to enable a step change in how scientists can approach studying HIWE:

- *DRIHM Distributed Computing Infrastructure*: This allows scientists to execute model chains with each model executed on the most appropriate computing resource. These include High Performance Computing Environments such as PRACE (which provide massively parallel machines), GRID and cloud environments such as those supported by EGI;

- *DRIHM Portal*: Supported by the gUSE technology, the DRIHM portal allows users to execute model chains by selecting from sets of meteorological, hydrological and hydraulic models. Triggering the models and passing data between them is done seamlessly on behalf of the user. Facilities are also included to run ensembles and visualise outputs;
- *Standards*: DRIHM has been built around standards. Many of these relate to environmental numerical models such as those related to cataloguing, coupling and file formats. As well as providing invaluable evidence in how standards are applied, DRIHM(2US) has specified particular implementations of standards such as NetCDF, WaterML and ISO19139;
- *Interoperability Experiments*: Ranging from ICT infrastructures to semantic vocabularies, DRIHM(2US) has tested transatlantic interoperability. European numerical models have been coupled to those from the USA; a European workflow engine has accessed computing resources on XSEDE in the USA; WaterML2 data has been digested directly into an OpenMI composition via web services;
- *Model MAP*: No new numerical models were written; all of the models used were either established research codes at universities, commercial products or community models with large user bases. To handle the functional and technical diversity presented, DRIHM(2US) developed the MAP gateway

concept: Metadata, Adaptors and Portability as a route to model standardisation and interoperability.

The DRIHM(2US) results for the Genoa 2014 critical case demonstrate the great potential, from a research and potentially from an operational standpoint, of the DRIHM services.

In this sense, a dialogue has been initiated with the Liguria Region and the Italian Civil Protection Department authorities, aiming at sharing the key findings and achievements of the project. This culminated in an invitation for the DRIHM(2US) initiative to present their achievements at the Major Risks National Committee meeting held in Rome on 23rd February 2015 and devoted to open a discussion on the improvement of the predictive ability of HIWEs over complex topography areas in Italy. The key recommendations provided by DRIHM(2US) and accepted by the Committee have been in favour of using a multi-model approach in hydro-meteorological forecasting chains; to achieve cloud permitting resolution grid spacing (1 km or so) to model HIWEs in complex topography areas; to recognize the importance of DRIHM(2US)-like platforms to gain a deeper understanding of these extreme hydrometeorological events and finally to recognise the relevance of cloud, grid and high performance computing.

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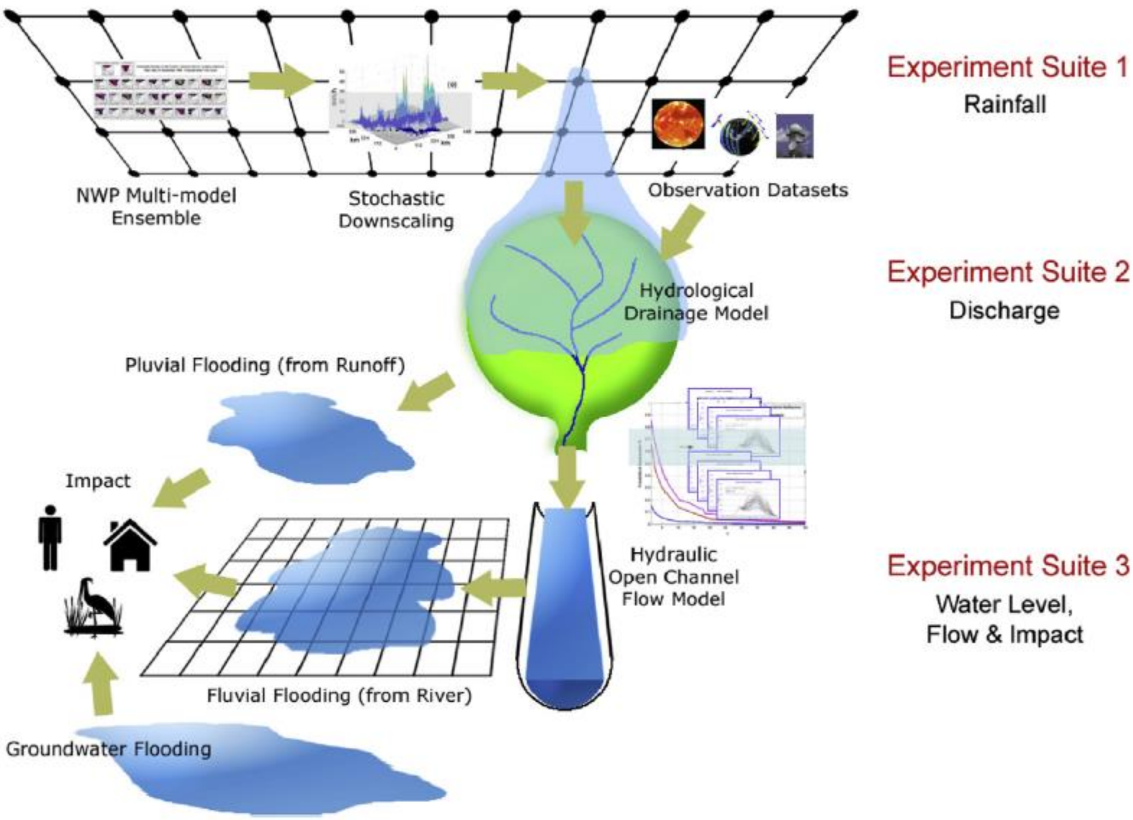

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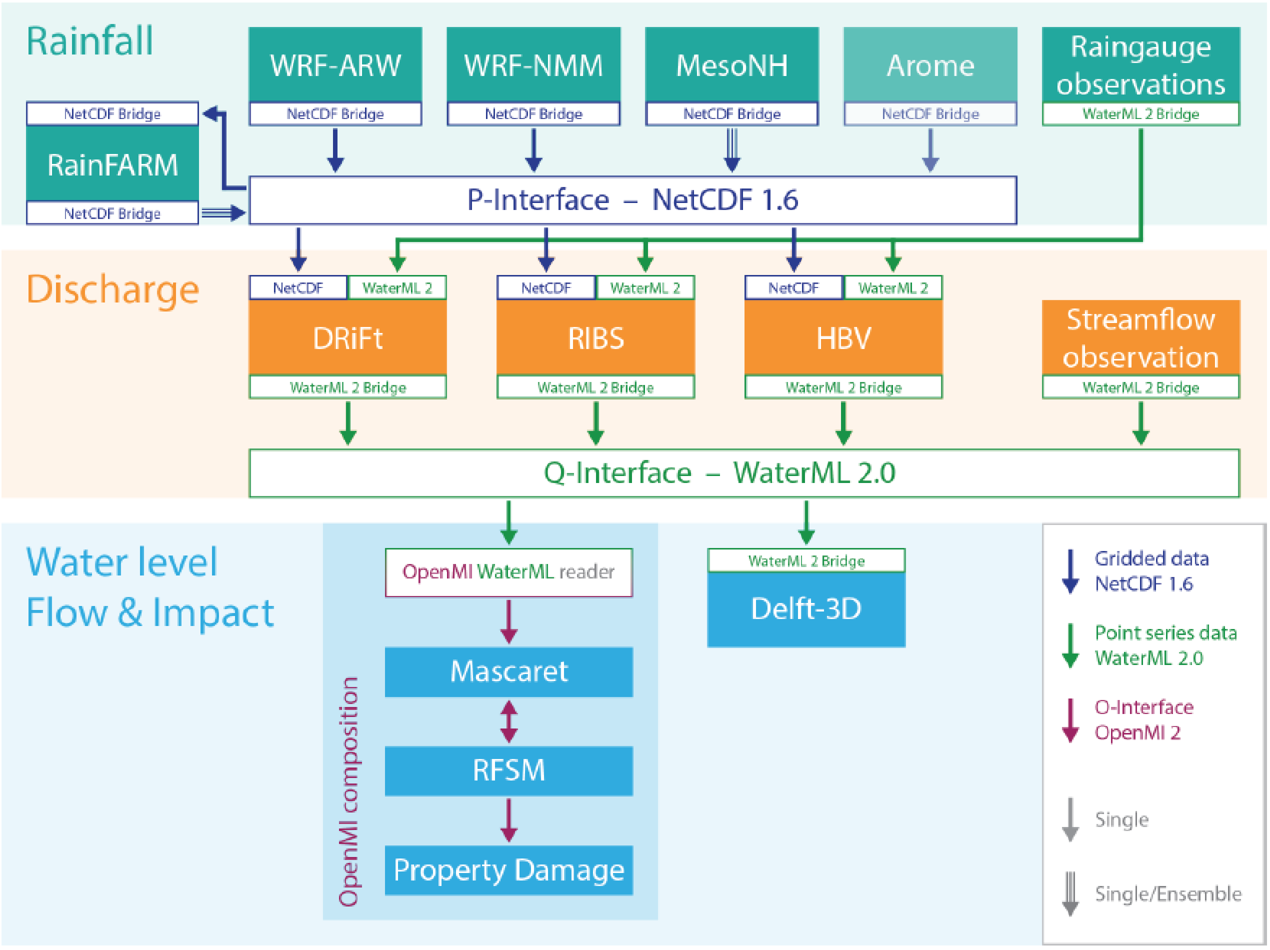

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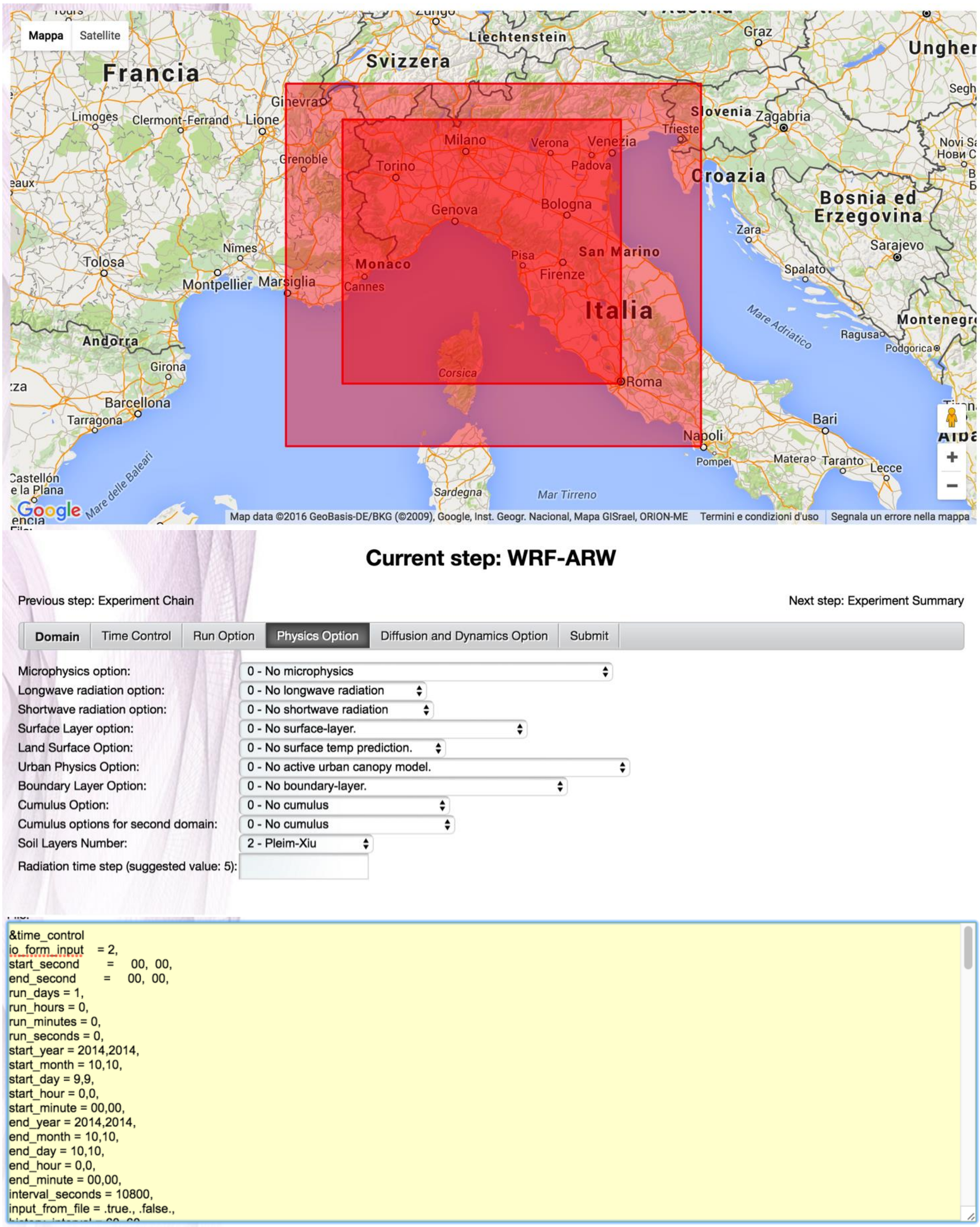

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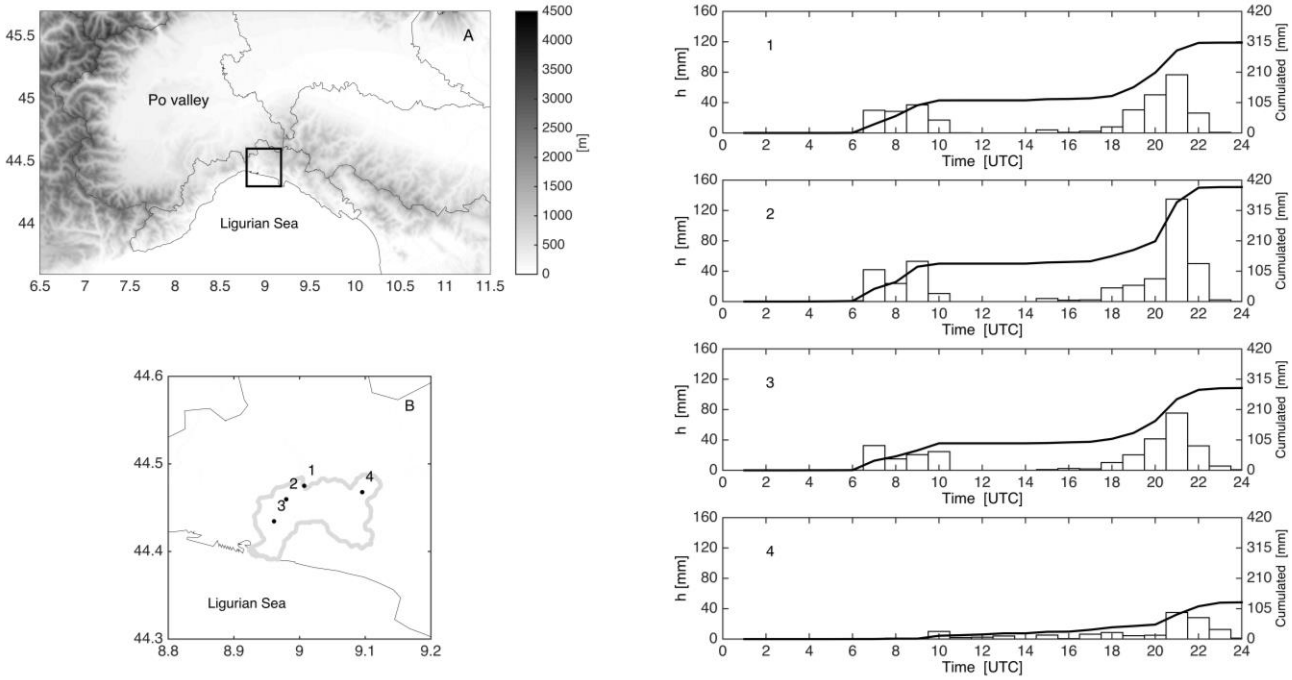

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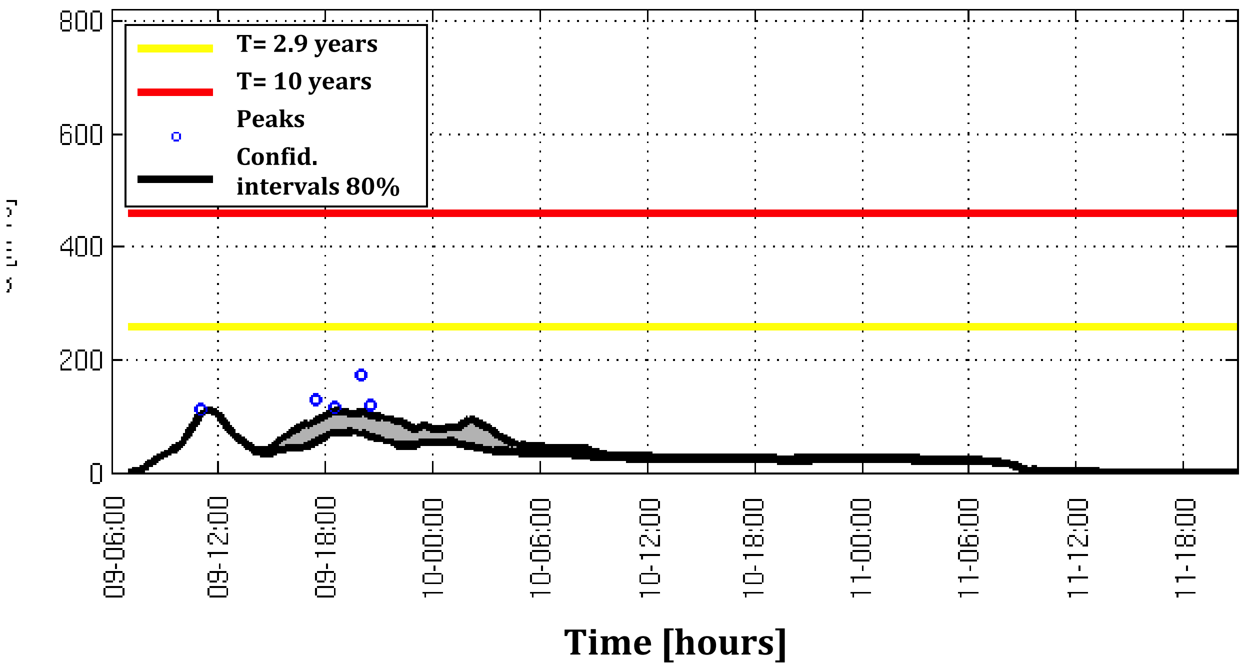

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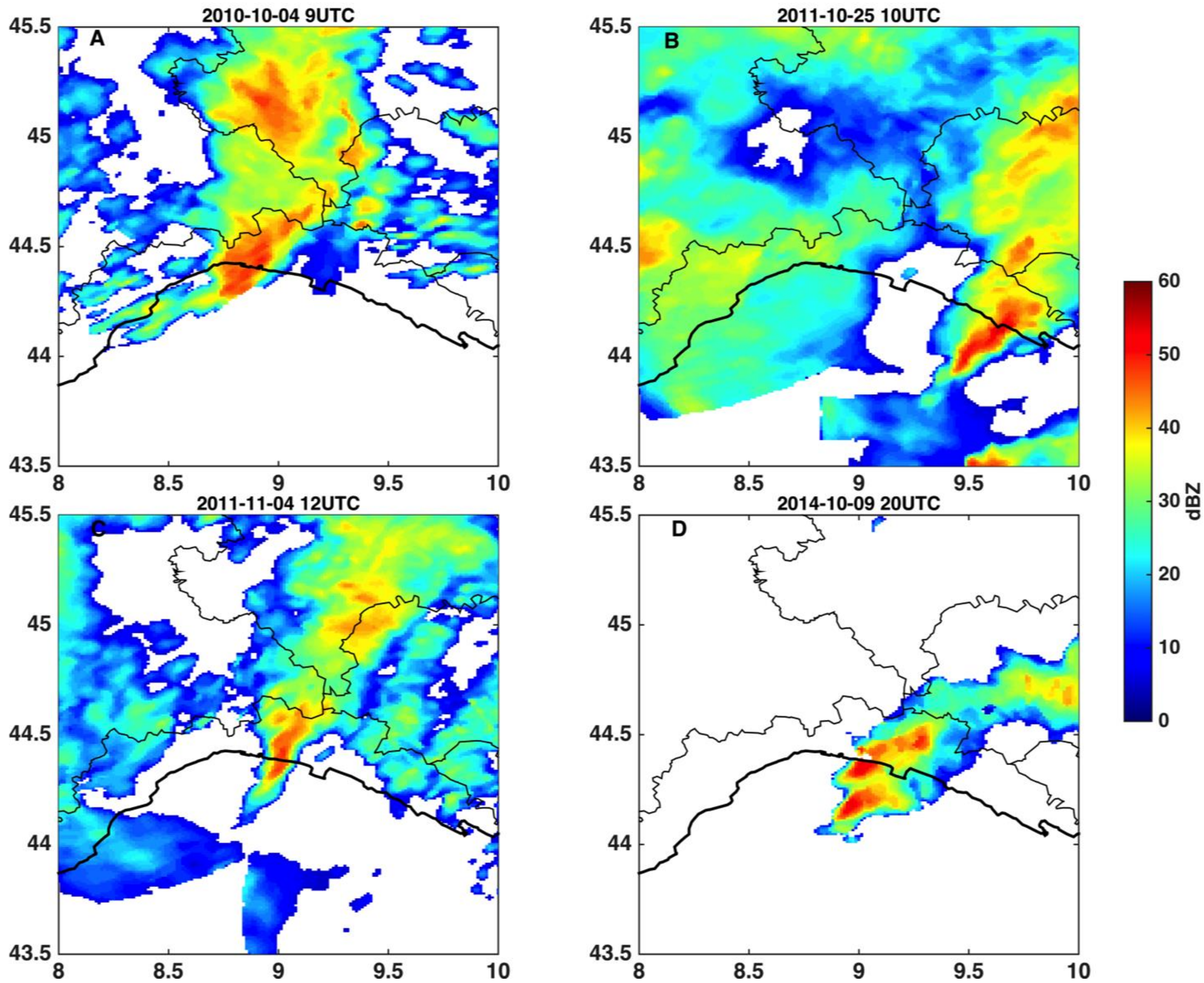

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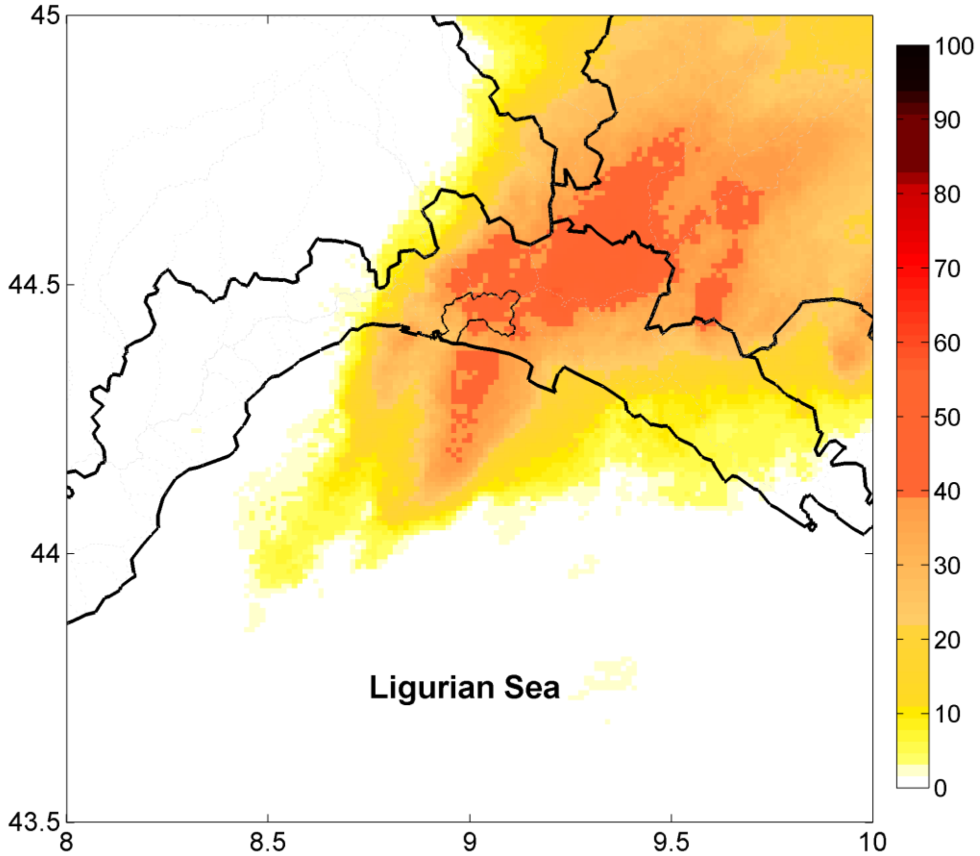

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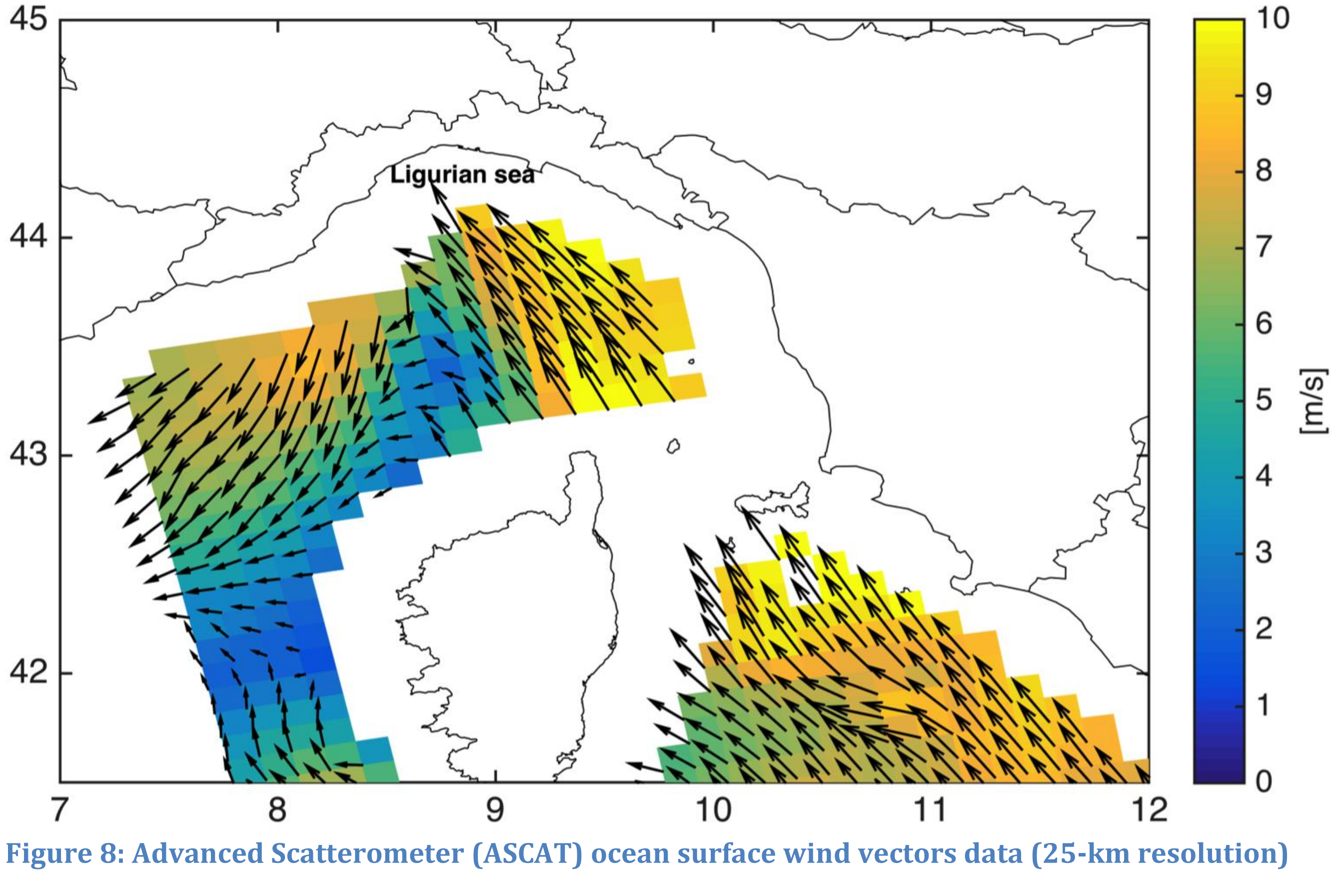

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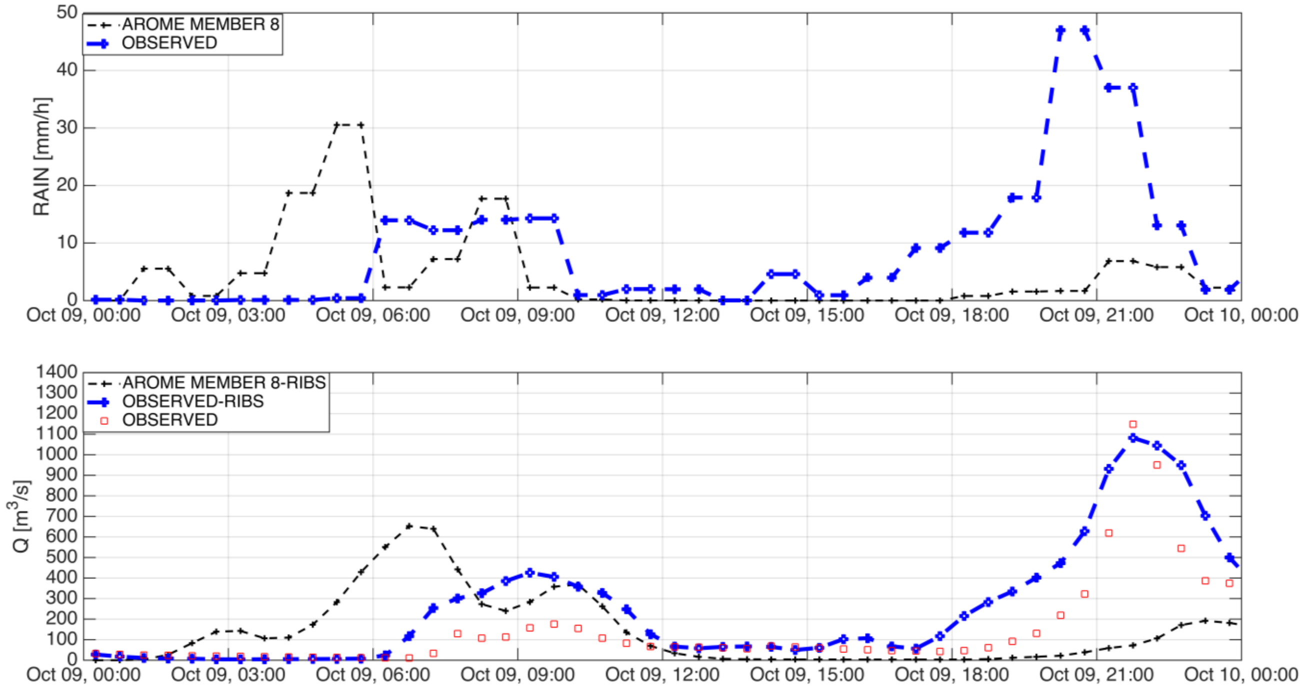

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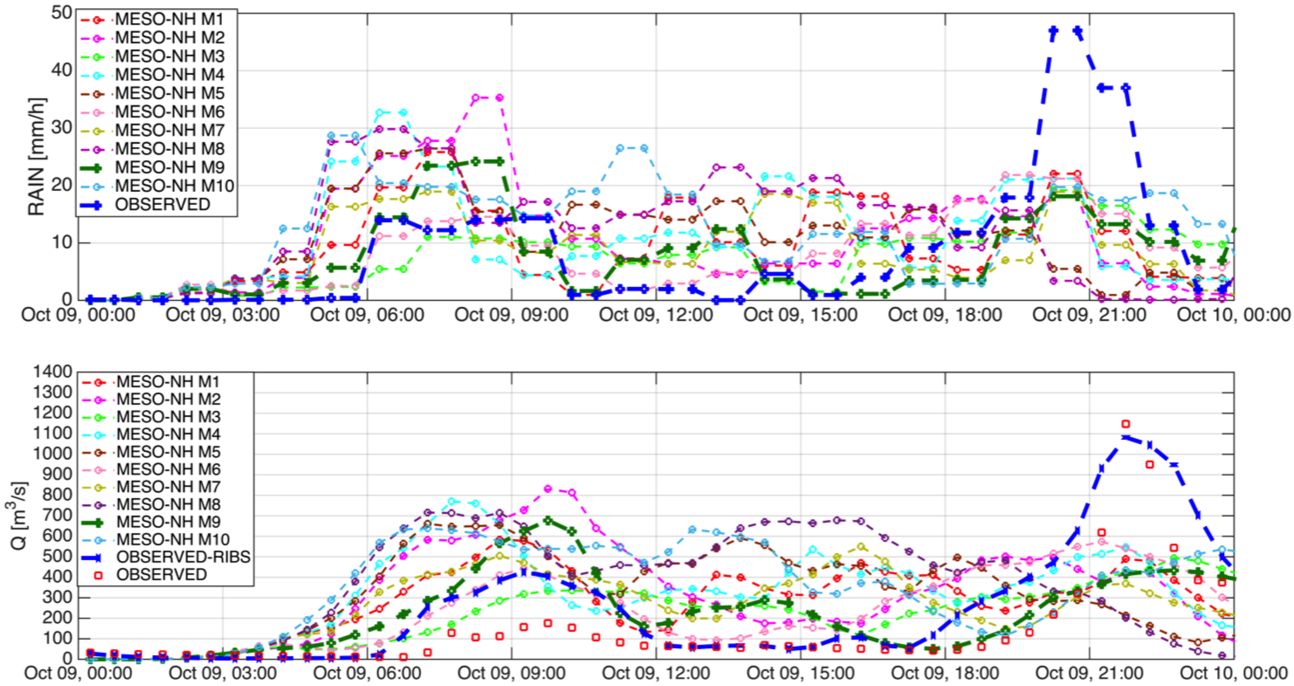

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simulated discharge using the QPF produced by each MESO-NH member (member 9 highligted in heavy dashed green).

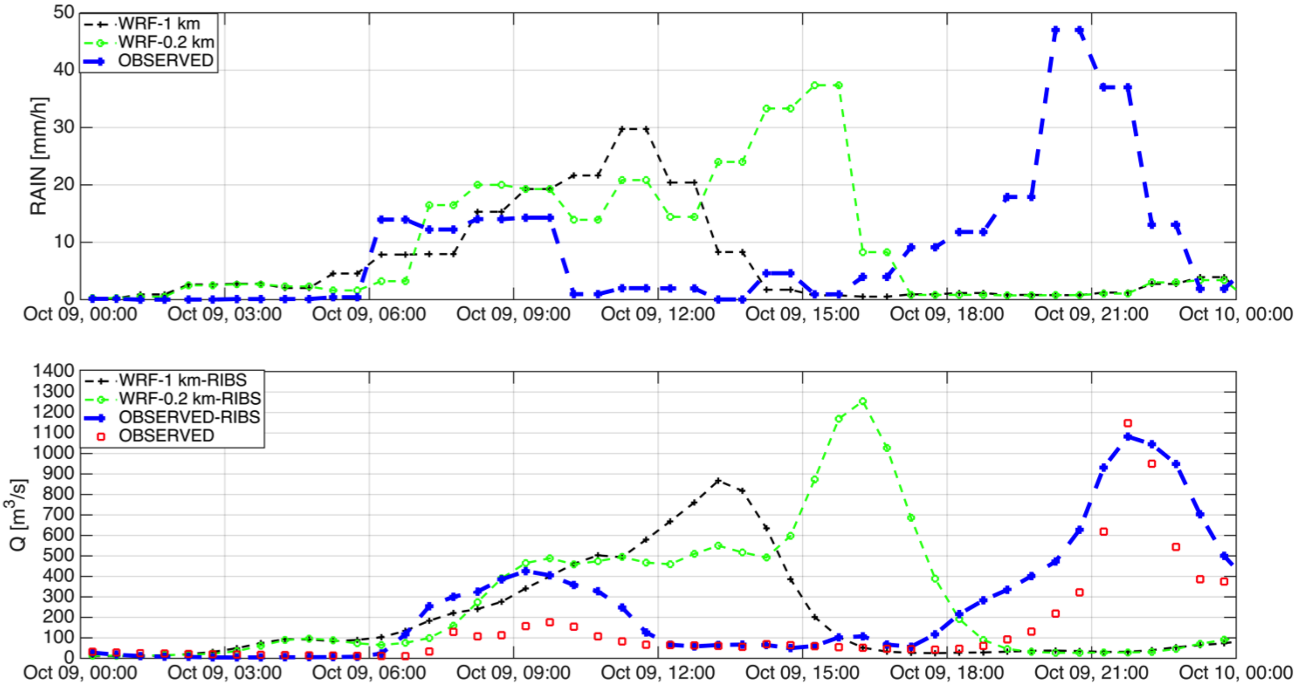

Figure 11: Upper panel - comparison between the mean rainfall over the Bisagno catchment predicted by each WRF-ARW 1 km (black dashed line) and 200 m (green dashed line) and observed (blue heavy dashed line); Lower plot, comparison between the observed discharge at Passerella Firpo (red square), RIBS simulated discharge using observed rainfall depth (blue heavy dashed line), and RIBS simulated discharge using the QPF produced by the WRF-ARW (black dashed line) and 200 m (green dashed line).

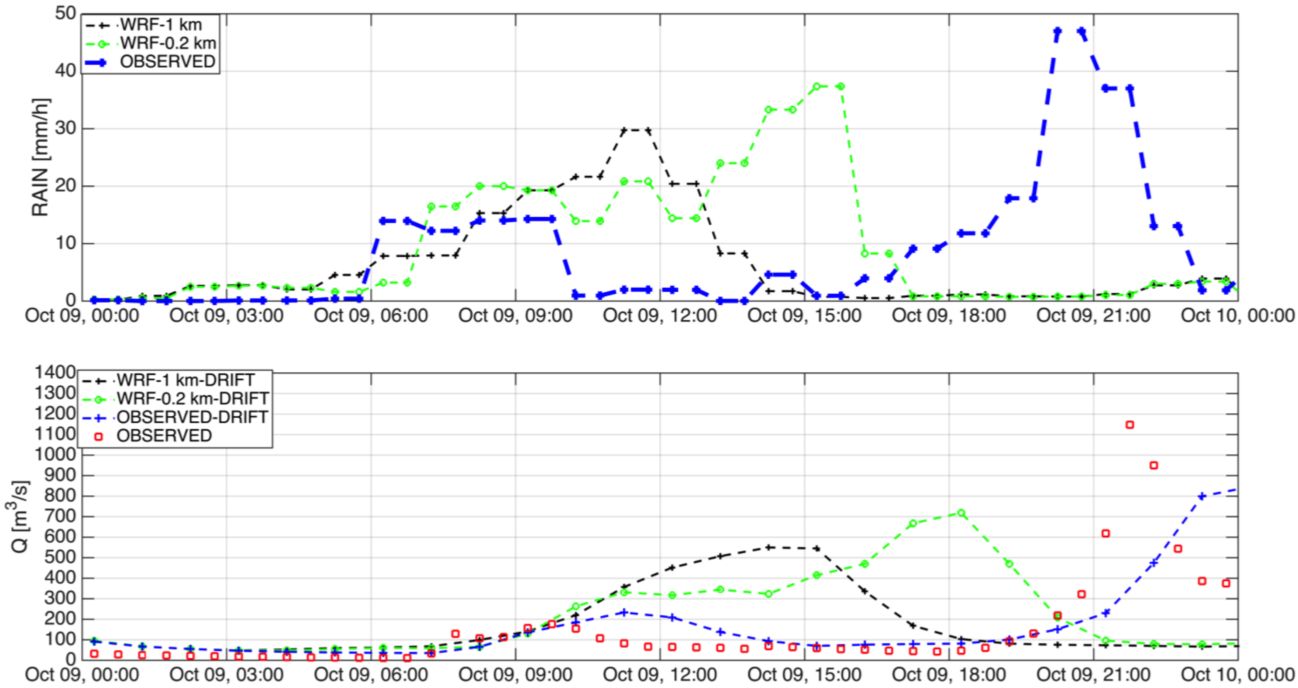

Figure 12: Upper panel - comparison between the mean rainfall over the Bisagno catchment predicted by each WRF-ARW 1 km (black dashed line) and 200 m (green dashed line) and observed (blue heavy dashed line); Lower plot, comparison between the observed discharge at

Passerella Firpo (red square), DRIFT simulated discharge using observed rainfall depth (blue heavy dashed line), and DRIFT simulated discharge using the QPF produced by the WRF-ARW (black dashed line) and 200 m (green dashed line).

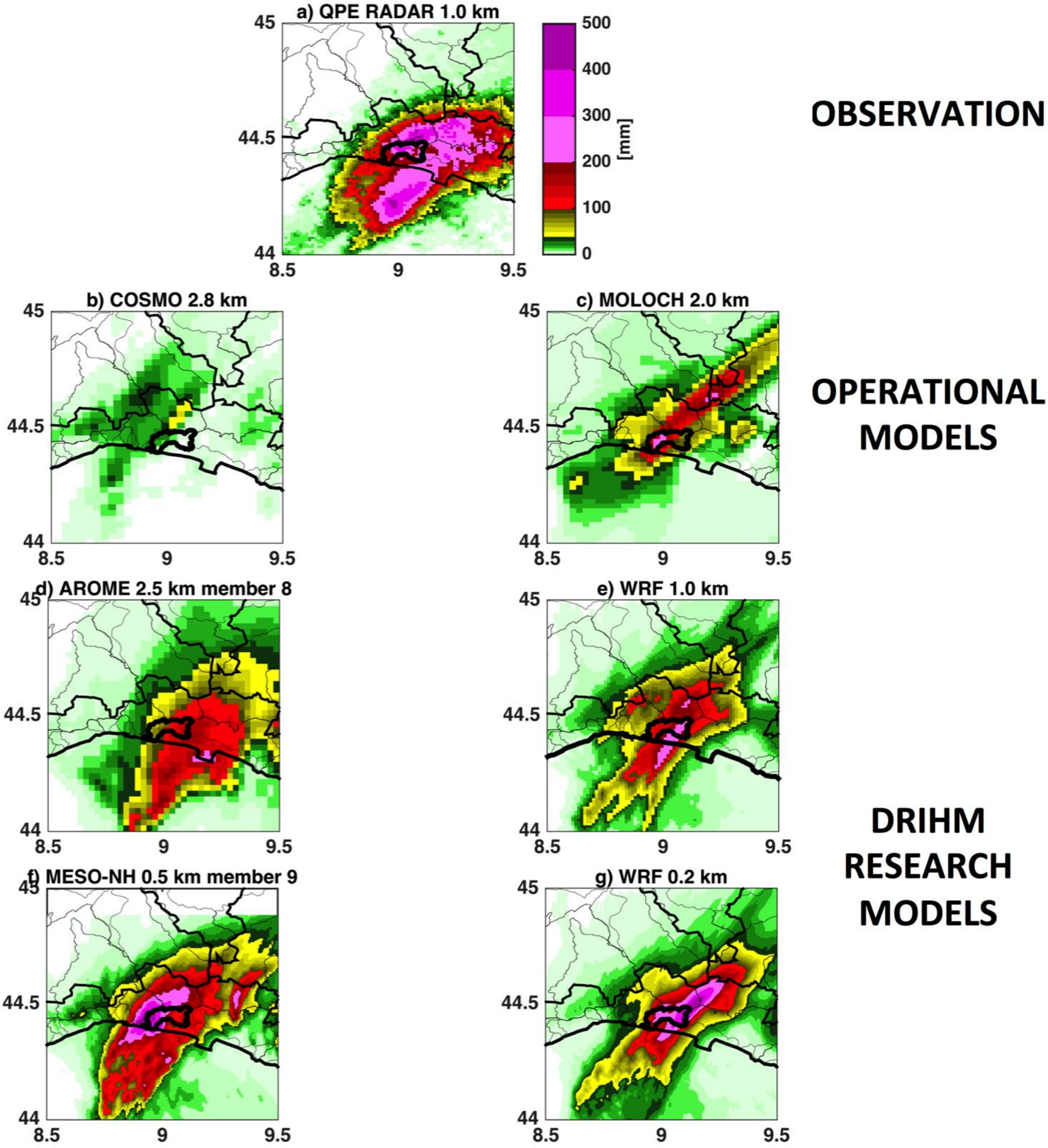

Figure 13: comparison between 24 hours QPE radar (panel a) for 9 October 2014 and 24 hours QPF provided by the cloud-permitting simulations (panel b COSMO 2.8 km, panel c MOLOCH 2 km, panel d AROME 2.5 member 8) and cloud-resolving simulations (panel e WRF 1.0 km, panel f MESO-NH 0.5 km, panel g WRF 0.2 km). The Bisagno catchment (100 km²) is highlighted.