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Discussions

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Towards a new BOLAM-MOLOCH suite for the SIMM forecasting system: implementation of an optimised configuration for the HyMeX Special Observation Periods

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Abstract

In this work, the performance of two versions of the *Sistema Idro-Meteo-Mare* (SIMM) forecasting system, aiming at predicting weather, waves and sea surge in the Mediterranean basin and, in particular, around the Italian coasts, are compared for two high-impact case studies corresponding to the Intense Operation Period (IOP) 16 and 18 of the first monitoring campaign of the HYdrological cycle in Mediterranean EXperiment (HyMeX). The first SIMM version tested – currently operational – is based on the meteorological hydrostatic BOlogna Limited Area Model (BOLAM) one-way nested over two domains, the Mediterranean-embedded Costal WAve Forecasting system (Mc-WAF), and the Shallow water HYdrodynamic Finite Element Model (SHYFEM). The second version tested is the one initially implemented for the HyMeX monitoring campaigns, which is composed by an optimised new configuration of BOLAM defined over a wider, higher-resolution domain, the nonhydrostatic convection permitting model MOLOCH, the Mc-WAF component, and SHYFEM. Both SIMM versions are initialised with data from the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecasting System (IFS).

The accumulated precipitation obtained by applying all the above meteorological model chains at the two case studies is compared with observations. In general, the precipitation forecast quality turns out to improve with increasing resolution, the best result being obtained with the MOLOCH model. Storm surge and tidal forecasts, obtained by forcing SHYFEM with the BOLAM and ECMWF IFS surface wind and atmospheric pressure fields, are compared with observations of tidal elevation measured at the ISPRA “Punta della Salute” tide-gauge, located in the Lagoon of Venice. Results indicate that, for the IOP18, short-term forecasts obtained with BOLAM outperform the ECMWF IFS one, while the opposite seems apparently true for longer-term predictions.

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Towards a new BOLAM-MOLOCH suite for SIMM

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1 Introduction

Since the beginning of the year 2000, the integrated forecasting system named *Sistema Idro-Meteo-Mare* (SIMM) has been operational in Italy to provide hydro-meteorological and marine forecasts over the Mediterranean basin and storm-surge forecasts over the North Adriatic Sea (Speranza et al., 2004, 2007). A co-operation between three Italian national organizations, namely the former Department of National Technical Services of the Italian Cabinet Presidency (DSTN-PMC, now mainly merged into the Institute for Environmental Protection and Research – ISPRA), the National Council of Research (CNR), and the Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), was established in the late nineties with the aim of developing and making operational this integrated system. The SIMM forecasting chain has been realized to simulate and predict the Mediterranean atmospheric and marine phenomena by resolving simultaneously the wide range of scales involved, ranging from synoptic to the meso-gamma scale.

Compared to the initial, original configuration and implementation, the forecasting system has undergone several changes during the last thirteen years. These changes have been introduced to provide SIMM with new forecasting components and to improve the system performance, overcoming some specific weaknesses identified by a continuous and rigorous verification programme (see, Accadia et al., 2005, 2007; Speranza et al., 2007; Mariani et al., 2005, 2014).

The verification activity is mainly devoted to the assessment of the forecast quality of the SIMM meteorological model, namely a parallel version of the BOlogna Limited Area Model (BOLAM, Buzzi et al., 1994; Malguzzi and Tartaglione, 1999) developed by the Institute of Atmospheric Sciences and Climate (ISAC) of CNR. This is motivated by the fact that the BOLAM forecast fields are used to initialise the other SIMM forecasting components. In particular, Mariani et al. (2014) observed a statistically significant increase in the forecast performance after the implementation in 2009 of a fully updated version of the BOLAM code. This stimulated the idea to investigate how to further

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improve the performance of the SIMM forecasting system by modifying the BOLAM model settings. Hence, a massive "reforecast" campaign was carried out by combining and changing in different ways the following model settings: horizontal grid spacing; domain extension; initial and boundary conditions; nesting design; and some aspect of the large scale rain parameterisation of the BOLAM model. In doing so, five reforecast experiments were defined and statistically inter-compared by considering a well-studied six-month time period – the MAP D-PHASE Operations Period (DOP, June to November 2007) – that ensured a high-resolution spatial coverage of rainfall measurements over the Alpine area and Central Western Europe (Casaioli et al., 2013). As a result of this modelling sensitivity study, it was identified an optimised new high-resolution BOLAM configuration (see Sect. 2) that was able to statistically outperform the currently operational BOLAM configuration.

The so-obtained optimised configuration was then deployed, together with the SIMM operational meteorological component and other forecasting chains (see Ducrocq et al., 2014; Ferretti et al., 2013), during the two Special Observation Periods (SOPs, http://sop.hymex.org/) of the WMO-endorsed initiative HYdrological cycle in Mediterranean EXperiment (HyMeX, http://www.hymex.org/) occurred between 2012 and 2013. Besides, a new forecasting suite was set-up by adding in cascade to this optimised BOLAM configuration the non-hydrostatic MOLOCH model (Malguzzi et al., 2006).

In this paper, the new BOLAM-MOLOCH suite is evaluated and compared against the SIMM operational BOLAM over two case studies monitored during two different Intensive Operation Periods (IOPs) of the first HyMeX SOP (5 September–6 November 2012). These events (hereafter IOP16 and IOP18) display some similarity in the ground effects, including heavy precipitation over North-Eastern Italy (NEI), Liguria-Tuscany (LT) Apennines, and Central Italy (CI)[1], and high tide over the Venice Lagoon (*acqua alta*). However, they are rather different from the synoptic point of view, with

[1]NEI, LT and CI are the three Italian hydrometeorological sites monitored during the first HyMeX SOP.

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significant effects on model performance (see following discussion in Sect. 4). Due to the relevance of the events in terms of the *acqua alta* climatology, this study also investigates the performance of the new SIMM storm-surge forecasting component, namely the Shallow water HYdrodynamic Finite Element Model (SHYFEM, Umgiesser et al., 2004), over two high tide events. Although no final conclusion can be achieved by analysing only a couple of case studies, it is important from an operational point of view to assess strengths and weakness of the SIMM new components when dealing with high-impact/severe events. This issue is particularly important in the case of *acqua alta* events due to the national role of ISPRA in monitoring and forecasting hydrological and hydrographic parameters over the Venice Lagoon.

The paper is organized as follows. In Sect. 2, the recent development of the SIMM forecasting system and the new BOLAM-MOLOCH suite is depicted. Section 3 outlines the HyMeX monitoring, modelling and forecasting activities and provides the synoptic description of the IOP16 and IOP18 events. Forecast verification results related to the two selected IOPs are presented in Sect. 4. Conclusions and final remarks are reported in Sect. 5.

2 The updated SIMM and the new BOLAM-MOLOCH suite

Currently, three different forecasting chains coexist within SIMM. The one originally implemented in 2000, and later upgraded in 2009 including a fully updated version of BOLAM (hereinafter *the original SIMM*, Fig. 1), the new one adopting not only the 2009 BOLAM nested one-way over two domains, but also two new components for the marine and storm surge forecasts (hereinafter *the updated SIMM*, Fig. 1), and the newest one, which has been implemented for the HyMeX SOP activities, that includes a higher-resolution BOLAM-MOLOCH suite in place of the 2009 BOLAM (hereinafter *the HyMeX SIMM*). This latter version is not still operational.

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Attention is focused here only on the updated and HyMeX SIMM versions, whilst the reader is referred, for instance, to Speranza et al. (2007) and Mariani et al. (2014) and references therein for a full account of the original SIMM.

At present, SIMM is initialised on daily basis by means of 0.5° analyses and forecasts provided by the 12:00 UTC run from the previous day of the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecasting System (IFS). The set of initial and boundary conditions (IC/BCs) includes for a 96 h forecast range the 3-D geopotential height, temperature, u- and v-wind components, and specific humidity over 15 isobaric levels and the 2-D surface temperature, snow depth, and first-level soil temperature.

The chain deploys two BOLAM runs, nested one-way over two domains (Fig. 2) covering the Mediterranean basin with horizontal spatial size equal to 0.3° (33 km) and to 0.1° (11 km), to provide daily meteorological forecast fields. Every day, the "father" model produces 96 h coarse-resolution forecasts starting from 12:00 UTC of the previous day, whereas the "son" model produces 84 h high-resolution forecasts (http://www.isprambiente.gov.it/pre_meteo/) starting from 00:00 UTC (+12 h to +96 h), with the first 12 h of the father run neglected as a spin-up time period.

The surface wind field produced with the 0.1° BOLAM are post-processed to be used for feeding the Mediterranean-embedded Costal WAve Forecasting system (Mc-WAF, Inghilesi et al., 2012). The Mc-WAF component adopts the 3rd generation WAve Model (WAM, The Wamdi Group, 1988) to analyse the large-scale, deep-sea propagation of surface waves in the Mediterranean Sea, and the Simulating WAves Nearshore (SWAN, Booij, 1999; The SWAN Team, 2013) to simulate waves in several Italian coastal areas (http://www.isprambiente.gov.it/pre_mare/coastal_system/maps/first.html). Regional intermediate-scale WAM grids are also introduced to bridge the gap between the large scale and coastal areas.

Wind and mean sea level pressure forecast fields generated over the Mediterranean Sea with the 0.1° BOLAM run are also used to force the new storm surge forecasting component that models the sea surface elevation in the Mediterranean Sea and,

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in particular, in the Northern Adriatic Sea (http://www.venezia.isprambiente.it/ispra/modellistica/). This component is based on the shallow-water model SHYFEM that has been developed at the Institute of Marine Sciences of CNR as an evolution of the Finite Element Model (FEM, Umgiesser and Bergamasco, 1993), which was implemented only over the Venice Lagoon within the original SIMM, SHYFEM is also forced with the ECMWF IFS wind and mean sea level pressure forecasts, providing this way an cost-effective multi-model forecasting system for the *acqua alta* prediction. Two finite-element grids for the Mediterranean Sea are used in SHYFEM for both the BOLAM and IFS initialisation: a low-resolution grid with 13 180 elements; and a high-resolution grid with 50 409 elements. Recently, a data assimilation module based on the 4-D Physical Space Assimilation System has been developed integrating the sea level measurements from the tide-gauges of the ISPRA observation network located alongside the Italian Northern Adriatic coastline (Bajo et al., 2013). Cordella (2013) and Ferla (2013) showed the impact on forecast performance of the different initialisation (BOLAM vs. IFS) by considering the last year of simulation (October 2012–October 2013) for the Northern Adriatic Sea. Although the performances are, in general, for the two initialisations good and quite similar over the entire period, the BOLAM-initialised SHYFEM overperforms the IFS-initialised SHYFEM when considering high tide events (> 80 cm) and longer lead times.

As premised, ISPRA implemented for and deployed during the HyMeX SOP campaigns a new BOLAM-MOLOCH meteorological suite. The BOLAM configuration adopted within the suite – which was the result of the sensitivity modelling study by Casaioli et al. (2013) – was based on a newer version of the numerical code (dated 2012) and used a wider domain, covering an area from 54° N to 25° N and from 18° W to 43° E (see Fig. 3), with a grid mesh size of 0.07° (7.8 km). In addition, the 0.25° ECMWF analyses and forecasts were directly applied as IC/BCs to BOLAM without using a coarser-resolution father model run. At variance with the operational initialisation set, this higher-resolution IC/BC set contained the 2-D logarithm of surface pressure in place of the 3-D geopotential height. It also included the 3-D temperature, u-

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and v-wind components, specific humidity, and cloud water and ice over 46 (out of the 137 available) hybrid levels, temperature and water content of the first four ECMWF soil levels, and the 2-D skin temperature, land-sea mask, orography, and land use. The forecast range of this initialisation set was 60 h.

Casaioli et al. (2013) tested also the use within this configuration of a coarser-resolution father model run; however they showed that the verification results of this alternative configuration (referred to as EXP-C) were slightly worst than those of the optimised 0.07° BOLAM, although better that those of the operational 0.1° BOLAM (the reference model). As an example, Fig. 4 summarises the difference in forecast skills at three selected medium rainfall thresholds (5, 10 and 20 mm $(24\,h)^{-1}$) between the reference model and the two mentioned alternative configurations by using the categorical performance diagram (Roebber, 2009). The diagram exploits the relationship between four categorical performance measures, namely the probability of detection, the success ratio (the opposite of the false alarm ratio), the frequency bias, and the critical success index (see, e.g., Wilks, 2006 for a fully description of these measures). Given that a perfect, unbiased forecast system has the four plotted scores equal to one, more accurate the forecast is, more concentrated towards the upper right of the diagram the forecast is. From Fig. 4, it is evident the improvement on forecast performance provided by the optimised 0.07° BOLAM.

The MOLOCH model was then nested into the 0.07° BOLAM run to produce higher-resolution forecasts over the domain shown in Fig. 3, with a grid mesh size of 0.0225° (2.5 km), mainly covering Northern and Central Italy. This domain includes five of the eight hydrometeorological sites monitored during the HyMeX SOPs. Both BOLAM and MOLOCH runs started at 12:00 UTC of the previous day (given that the 12:00 UTC ECMWF run was used) and lasted 60 h, but the first 12 h were not provided to the SOP campaigns.

The BOLAM-MOLOCH suite was used in the HyMeX SIMM for initialising the McWAF. A preliminary analysis of the performance of this component afferent to both the updated and the HyMeX versions of the ISPRA forecasting system is illustrated in

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Casaioli et al. (2014). In particular, the comparison during the period from 25 October to 10 November 2012 between the significant wave height forecasts and collected at the "Venice" buoy (located in the Northern Adriatic Sea, and moored at 20 m depth) shows an improvement at regional scale when using the 0.07° BOLAM instead of the 0.1° BOLAM.

Concerning SHYFEM, the initialisation using wind and mean sea level pressure forecast fields generated with the 0.07° BOLAM was also tested, but only a few case studies were at the moment analysed.

3 HyMeX and the IOP16 and IOP18 events

HyMeX is an international collaborative initiative aimed at advancing the scientific knowledge of the water cycle variability in the Mediterranean basin, which involves a large number of technical and scientific experts from the meteorological, hydrological and oceanographic communities (Drobinski et al., 2014). The initiative intends to improve the observation and modelling strategy needed for monitoring and predicting high-impact events, such as high precipitation events (HPEs), flash floods, or dense water formation. The SOP campaigns were then devoted to investigate, in selected target areas, the key physical processes leading to these high-impact events by providing detailed and dedicated (e.g., using instrumented aircrafts) observations (Ducrocq et al., 2013). An ad hoc forecasting activity based on several numerical model products was set up during each SOP to identify in advance the IOPs to be monitored.

Sixteen of the IOPSs declared during the first SOP campaign were dedicated to HPE (see Fig. 5). The nine IOPs affecting the three Italian HyMeX hydrometeorological sites situated in Northern and Central Italy were monitored effectively with the support of the Italian HyMeX Group, which includes experts from regional and national meteo-hydrological services and environmental agencies, research institutes, and universities (Ferretti et al., 2013). Among these IOPs, attention is focused here on IOP16 (25–29 October 2012) and IOP18 (31 October–1 November 2012).

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During the IOP16, a large Atlantic cyclone crossed the Iberian Peninsula on 25–26 October. Then, it moved rapidly eastwards, reaching on 27 October the Genoa Gulf (Fig. 6a), where it was reinforced and made almost stationary by the phenomenon of Alpine cyclogenesis during the next day (Fig. 6b). Finally, it leaved Italy on 29 October.

The event occurred during the IOP18 was due to a Mediterranean low-level cyclone, forming over the Gulf of Lion on 31 October (Fig. 6c), and embedded in the zonal flow connected to an upper-level trough (not shown). Subsequently, the cyclone moved along a similar path of the IOP16 one (Fig. 6d). The difference between the two events was mainly in the time and space scale of the dynamical and physical processes involved. This, in turn, reflected in a different predictability of the two weather systems.

Both events produced intense precipitation over Italy, with some similarity in the rainfall patterns. The precipitation over the Italian HyMeX hydrometeorological sites, and also over Southern Italy, was associated with southerly low level advection of warm and moist air and subsequent frontal passage. Moreover, Scirocco winds over the Adriatic Sea and the mean sea level pressure evolution over NEI were also responsible for the *acqua alta* events in the Lagoon of Venice. At the ISPRA "Punta della Salute" tide-gauge, the sea level exceeded twice the warning level during IOP16 (more than 120 cm), whilst it exceeded once the alarm level during IOP18 (142 cm at 00:00 UTC 1 November). This latter peak represents the 15th maximum tidal level observed in Venice at "Punta della Salute" since 1872. The same meteorological event was responsible in Chioggia Vico of a tide peak of 164 cm, which represents for this station the absolute maximum observed since 1990.

4 Forecast verification and model intercomparison

4.1 Precipitation forecast

During IOP16, intense precipitation over Italy occurred in two phases. On 26 October, warm and moist south-westerly advection towards LT and CI created the

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conditions favourable to the development of pre-frontal convective cells. Particularly intense rainfall occurred over Liguria Region (Fig. 7a), due to orographic triggering ($250\,\mathrm{mm}\,(24\,\mathrm{h})^{-1}$, up to $50\,\mathrm{mm}\,\mathrm{h}^{-1}$). Meanwhile, south-easterly moist advection (Scirocco) on the Adriatic Sea produced convective rain over NEI. On 27 October (not shown), more rainfall affected the Apennines (including Liguria) during the passage of the cold front. At the same time, the Eastern Alps chain triggered intense moist convection on the eastern border of NEI and Western Slovenia.

An overall comparison of the 24 h accumulated precipitation for 26 October predicted by the three models (initialised at 12:00 UTC of 25 October; see Fig. 7b–d) evidences a strong similarity in rain/non-rain patterns, and relevant differences in the details, including in the maximum precipitation amount. In particular, the rainfall peak observed over LT (Fig. 7a) is misplaced by the 0.1° BOLAM (from the updated SIMM, Fig. 7b), while it is underestimated by the 0.07° BOLAM (from the HyMeX SIMM, Fig. 7c). Anyway, the latter model configuration forced the MOLOCH forecast (Fig. 7d) that displays, on the contrary, a very good agreement with the observations. In particular, the two 30 km distant main rainfall peaks – the western one observed during the morning, and the eastern one observed during the afternoon – were resolved and correctly estimated (not shown). Similarly, the 0.1° BOLAM provides over CI a better estimate of the precipitation amount than the 0.07° BOLAM (see Fig. 7a vs. b and Fig. 7a vs. c), but the latter is more accurate in localizing the atmospheric structures. As a consequence, the MOLOCH forecast was able to correctly reproduce the observed multiple rain band pattern (even if with some spatial errors). Finally, the NEI event is hardly visible only in the MOLOCH forecast (see Fig. 7a vs. Fig. 7d).

Similarly, for the second forecast day (27 October, not shown), all three models are able to correctly locate the rainfall patterns over LT, CI, and NEI. In this case, the 0.1° BOLAM tended to overestimate rainfall amounts, whilst the 0.07° BOLAM underestimated the rainfall peaks and the 0.0225° MOLOCH gave the best forecast.

A further discussion on the LT event allows clarifying the differences among the inter-compared model forecasts. The comparison of the forecasts of the convective

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available potential energy (CAPE) field at 15:00 UTC of 26 October (Fig. 8) illustrates the situation leading to heavy precipitation over a very small area in the following hours (westernmost red dots over LT visible in Fig. 7a and d). There, a persistent southerly low-level jet over the Eastern Genoa Gulf advected moist, unstable air on the steep orography, generating a long-lasting stationary convective cell. The unstable low-level jet is evident in Fig. 8 as the high-CAPE area present in all three forecasts. Anyway, a low-CAPE area is present in the HyMeX BOLAM forecast, situated west of Corsica (Fig. 8b), and even more developed in the nested MOLOCH run (Fig. 8c), but it is almost absent in the 0.1° BOLAM forecast (Fig. 8a), possibly due to a lack of details in the initialization fields (which differ from those used in the HyMeX SIMM). The comparatively better performance of MOLOCH does not arise from such differences (actually, it seems more linked, in this case, to the relevant role of the small-scale orographic forcing). However, it should be stressed that a success in positioning the stationary cell requires a correct specification of atmospheric flows, that is, it testifies for a good quality of the 0.07° BOLAM forecast from a dynamical point of view.

During IOP18, rainfall affected the same Italian regions. On 31 October, south-westerly and southerly moist advection induced orographic precipitation over Lazio and Liguria Regions, respectively, with isolated peaks of 120 mm $(24\,h)^{-1}$. Over NEI, convective squall lines developed on 31 October into the Scirocco flow over Northern Adriatic Sea, hitting subsequently the coast and further developing over the mainland. High precipitation over Veneto and Friuli-Venezia Giulia Regions was observed during the evening of 31 October. Finally, a big convective cell developed over Trieste in the first hours of 1 November, associated with the passage of the occluded front.

Also in this case, most of the elements of the complex observed precipitation pattern (Fig. 9a) are caught by the models (initialised at 12:00 UTC of 30 October, Fig. 9b–d). In particular, with respect to the 0.1° BOLAM (Fig. 9b), the 0.07° BOLAM (Fig. 9c) fixes some rainfall underestimate over LT and some overestimate over NEI and Southern Italy, though introducing some underestimate over CI. The details added by the HyMeX MOLOCH forecast (Fig. 9d) seems to be realistic, although their verification

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requires a deeper inspection, as the one performed here for the NEI event (which is related to the severe *acqua alta* event analysed in Sect. 4.2). Concerning this event, it should be noted that a 100 mm precipitation peak over the Veneto Region, not visible in Fig. 9a, was however observed in the official Italian radar composite image and in the gridded analysis operationally provided by the Italian Civil Protection Department (not shown). According to all three models (Fig. 10), a strong, E–W low-level convergence line developed in the last hours of 31 October, deviating the southerly Scirocco moist flow towards the Po Valley, as a combined result of the Alpine range barrier effect and cyclonic vorticity (Silvio Davolio, CNR-ISAC, personal communication, 2014). This forced convection over Veneto Region and the coastline and, later, upwind of the Eastern Alps. The increase in model resolution (from Fig. 10a–c) acts to sharpen the convergence line, but does not affect its evolution, so that the predicted precipitation patterns are rather similar.

On the contrary, it must be noted that the IOP18 forecast seems to depend critically on initial conditions. For instance, if the forecast is initialized one day earlier (12:00 UTC of 29 October), the 24 h accumulated precipitation for 31 October turns out to be largely overestimated and the position of the maximum over NEI different in the two BOLAM (form both the updated and HyMeX SIMM) and in the MOLOCH simulations.

More specifically, this manifestation of chaos affects the evolution of the mesoscale cyclone developing over the Mediterranean Sea, and the associated surface winds (not shown), with relevant implications on the prediction of the storm surge with more than two days in advance. The following Sect. 4.2 illustrates this point in detail.

A basic quantitative approach could be helpful to summarise the above-mentioned results. In Fig. 11, observed and forecast daily precipitation amounts (+12 h to +36 h from the IFS initialisation time) are averaged for the period 25 October–1 November 2012 over three intense rainfall areas selected in LT (Lon: 8.75–11.25° E; Lat: 43.8–44.8° N, Fig. 11a), CI (Lon: 11.7–13.9° E; Lat: 45.3–46.7° N, Fig. 11b), and NEI (Lon: 10.5–13.0° E; Lat: 41.5–43.0° N, Fig. 11c). By averaging the observed and forecast quantities over a not-so-small area, the spatial forecast error that, in general, tends

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to increase when reducing the model horizontal grid step is filtered out by the intercomparison. In the majority of cases, the 0.1° BOLAM from the updated SIMM predicts more rainfall than the 0.07° BOLAM from the HyMeX SIMM, with MOLOCH in an intermediate position. So, among others, the highest observed peaks discussed above (on 26 October over LT and on 31 October over NEI) are best matched by MOLOCH, overestimated by the 0.1° BOLAM and underestimated by the 0.07° BOLAM. Finally, all models at the same extent overestimate the IOP18 rainfall occurred over LT.

4.2 Tide forecast

Sea level forecast verification could add further elements to the evaluation of the SIMM performance during IOP16 and IOP18. The analysis presented in this section deals with the SHYFEM prediction of tidal elevation based on the updated 0.1° BOLAM and the ECMWF IFS model for the two IOPs. The use of the new BOLAM-MOLOCH suite in combination with SHYFEM (i.e., the HyMeX SIMM version) is on course, and it will be the object of a subsequent verification study. On this purpose, the MOLOCH domain should be extended, as the HyMeX-optimised one is too small to allow a correct driving for the surge model.

In both cases, IFS and 0.1° BOLAM wind and surface pressure data are used to force SHYFEM in both the low- and high-resolution operational configurations. Results from the four configurations so obtained (the impact of the data assimilation module will be the object of further studies) were checked against observations taken at the "Punta della Salute" tide-gauge in Venice, for different initial times. For IOP16 (not shown), the IFS-forced runs provide good forecasts, even at long lead times (2–4 days), with small underestimation of tidal elevation. This error is further reduced using the BOLAM input. The effect of SHYFEM resolution is negligible.

The coupled tide forecasting system performance for IOP18 (Fig. 12) is more problematic. Even the question whether the use of BOLAM forcing in place of the IFS one does improve the forecast receives different answers, depending on the forecast initialisation day. For the last useful forecast before the event (Fig. 12a, initialised at

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12:00 UTC of 30 October) this is certainly true, despite a slight overestimation of the main peak by the BOLAM-driven SHYFEM. However, if the two-days-in-advance forecast is considered (Fig. 12b, initialised at 12:00 UTC of 28 October), the BOLAM-based tidal forecast turns out to be affected by larger errors, both in the amplitude and phase of the main event. Oddly, the performance gets even worse when the BOLAM forecast starts one day later, namely at 12:00 UTC of 29 October (not shown). The effect of SHYFEM resolution is negligible also in this case. Whereas IFS-driven tide forecast, although underestimating the peak, is stable with respect to the initial date, the BOLAM-driven tide forecast quality is critically dependent on it. This tends to emphasize the results of the precipitation subjective verification, pointing clearly to predictability issues for the IOP18 cyclone. A more extensive comparison is thus required to assess whether the use of higher resolution atmospheric models can provide better quality results for this event, at least for forecasts longer than two days.

The situation above described for IOP18 is completely different when evaluating the SHYFEM forecasts against the surge levels collected at the CNR “Acqua Alta” oceanographic tower (not shown), located 8 nautical miles off the cost of Venice (see, e.g., Cavaleri, 1999 for details on the oceanographic tower). As pointed out by Bajo et al. (2012), although all four configurations underestimated the maximum surge peak at 01:00 UTC on 1 November, the SHYFEM simulations forced by the BOLAM wind and surface pressure fields provided, in general, a better forecast. Furthermore, Bajo et al. (2012) explained the different behaviour at “Punta della Salute” of the two IFS-forced SHYFEM configurations as due to the sum of two forecast errors: a not correct peak width, and a wrong (greater) astronomic tide value.

5 Conclusions

Evaluating the performance of an integrated meteo-marine modelling system is a demanding task, since forecast has to be verified at any model stage, and the so-obtained results should be inter-related each one in a whole picture. Anyway, the first HyMeX

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SOP experience gave the opportunity to perform verification and intercomparison of different integrated model chains, as presented in this manuscript.

More in detail, a general indicator of the experiment performance is provided by the assessment of the corresponding quantitative precipitation forecasts against the rainfall measurements. Verification of storm surge forecasts over the Venice Lagoon provides further elements to evaluate the performance of the whole modelling chain. Finally, the coupled BOLAM–Mc-WAF suite is the object of another verification study (Casaioli et al., 2014). Anyway, results concerning the updated SIMM chain need to be completed with a more systematic study to allow a first evaluation of the future SIMM performance.

Results from precipitation intercomparison display an objective added value of the MOLOCH forecast, forced by the HyMeX 0.07° BOLAM, in predicting the two most relevant rainfall episodes. Anyway, the ability of the new model chain to improve forecast with respect to the old one varies from case to case. In the IOP16 LT event, a well-described unstable flow over orography makes model resolution the key issue for a good forecast. This is partially true also for the IOP18 NEI event. On the contrary, squall lines developing over sea in the warm sector, as the ones involved in both IOP events occurred over CI, are less able to take benefit from a resolution increase (the forecast rain bands tends to be more realistic, but not necessarily more accurate, when model resolution is increased). Results from the tide forecast verification mostly evidence the different predictability of the two involved weather systems, mainly evidenced by sensitivity to initial conditions. The strongest event, linked to a less predictable weather system, displays to be not only the worse predicted, but also the one whose prediction is most difficult to improve by enhancing model resolution.

These results immediately open the question about their generality and, in the specific case, about the mechanism affecting the performance of forecasts obtained with different model chains initialised at different days. Even if no general conclusion can be drawn from only two cases, results seems to evidence the added value of limited area models (LAMs), and especially, higher-resolution ones, with respect to global NWP in

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driving local tide forecasting systems (e.g., IOP16), except when a less predictable weather system, as IOP18 likely is, is involved. In such a case, the LAM-driven forecast skill is highly unstable, being effective on the short-range and ineffective or even backfiring on longer lead times, but providing anyway additional value for forecasters.

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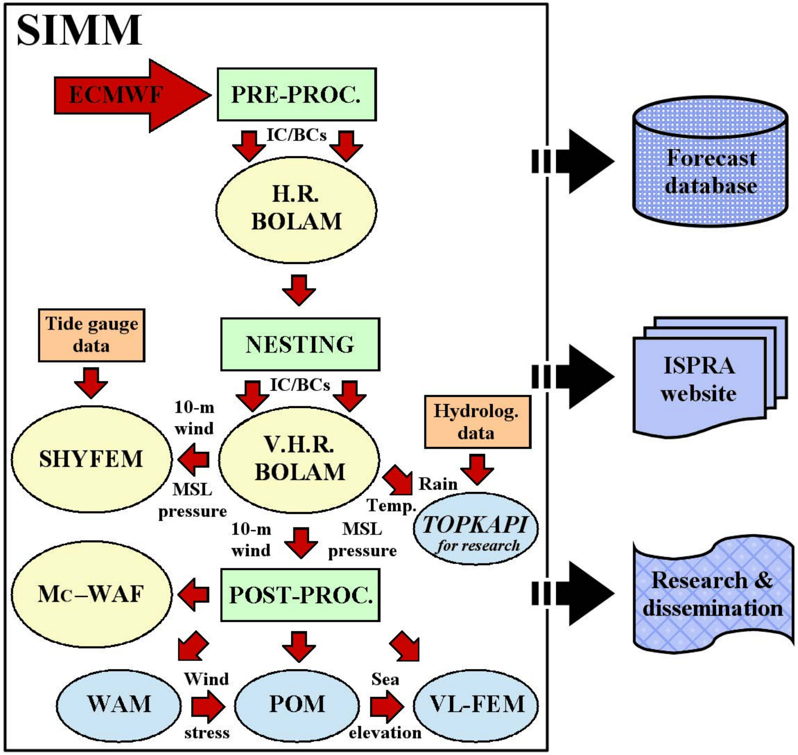

Fig. 1. The SIMM model sequence with the original and the updated forecasting chains, from the ECMWF initialisation to the storage of the weather, marine and coastal products, their publication online at the ISPRA website, their use for research activity, and their dissemination. The original SIMM includes: 0.3° (H.R.) BOLAM, 0.1° (V.H.R.) BOLAM, the hydrologic TOPKAPI model, WAM, Princeton Ocean Model (POM), and FEM. The updated SIMM includes: 0.3° BOLAM, 0.1° BOLAM, Mc-WAF, and SHYFEM.

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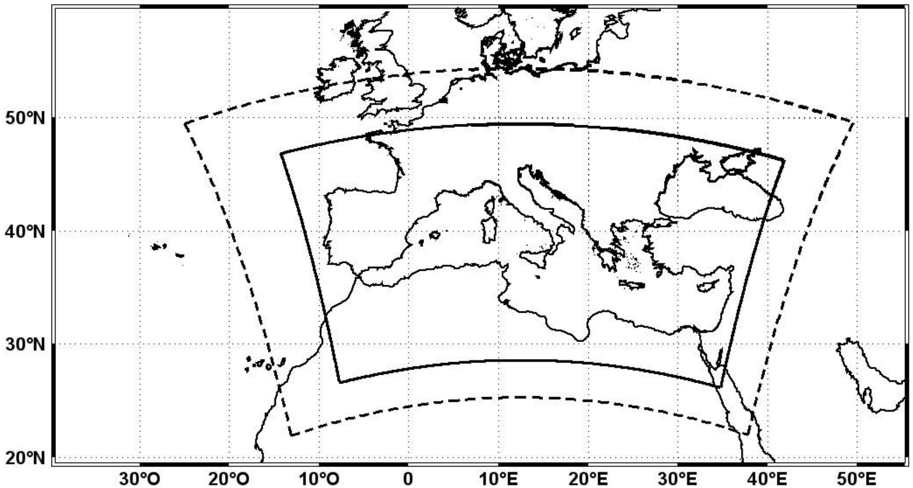

Fig. 2. Computational domains for the current SIMM meteorological component: the 0.3° BOLAM (long-dashed line) and the 0.1° BOLAM (solid line).

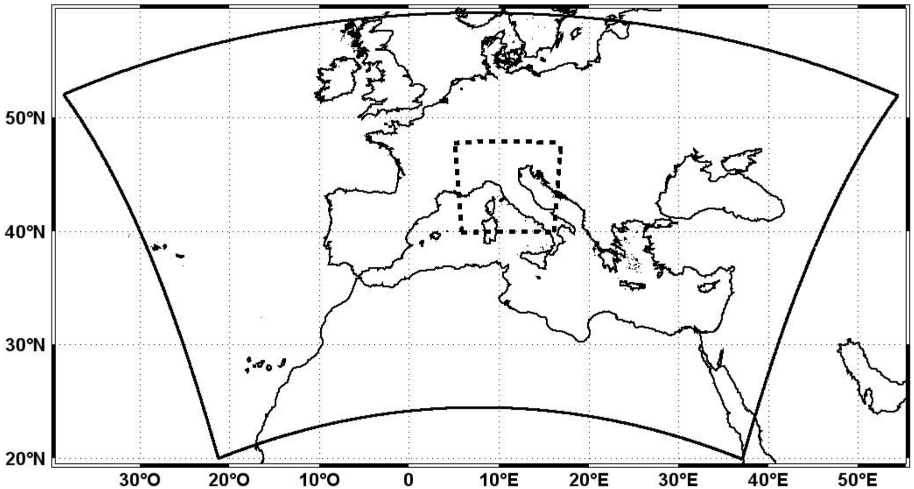

Fig. 3. Computational domains for the HyMeX SIMM meteorological component: the 0.07° BOLAM (solid line) and the 0.0225° MOLOCH (dashed line).

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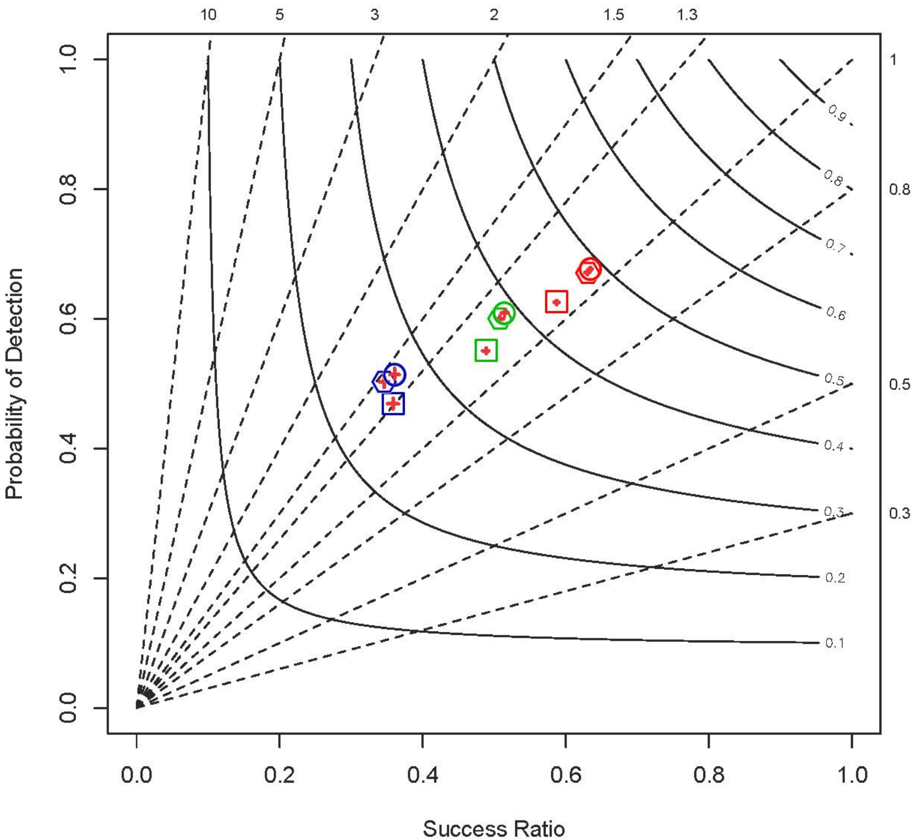

Fig. 4. Categorical performance diagram at 5 (blue), 10 (green) and 20 mm $(24\,h)^{-1}$ (red) for 0.1° BOLAM (open square) vs. EXP-C (open hexagon) and 0.07° BOLAM (open circle).

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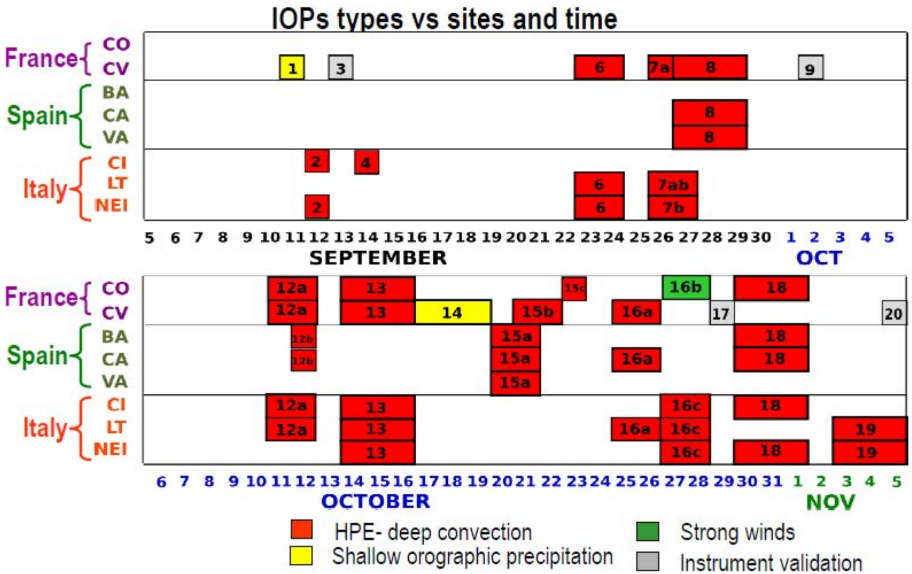

Fig. 5. Overview of the IOPs declared during the first HyMeX SOP campaign, reporting the indication of type (see the below-reported legend), site, and dates. The hydrometeorological sites monitored are in France (Corsica – CO and Cevennes-Vivarais – CV), Spain (Balearic Isles – BA, Catalonia – CA and Valencia – VA) and Italy (Central Italy – CI, Liguria-Tuscany – LT and North-Eastern Italy – NEI). Courtesy of Véronique Ducrocq (Météo-France & CNRS), HyMeX SOPs' debriefing workshop, 15–17 April 2013, Toulouse, France.

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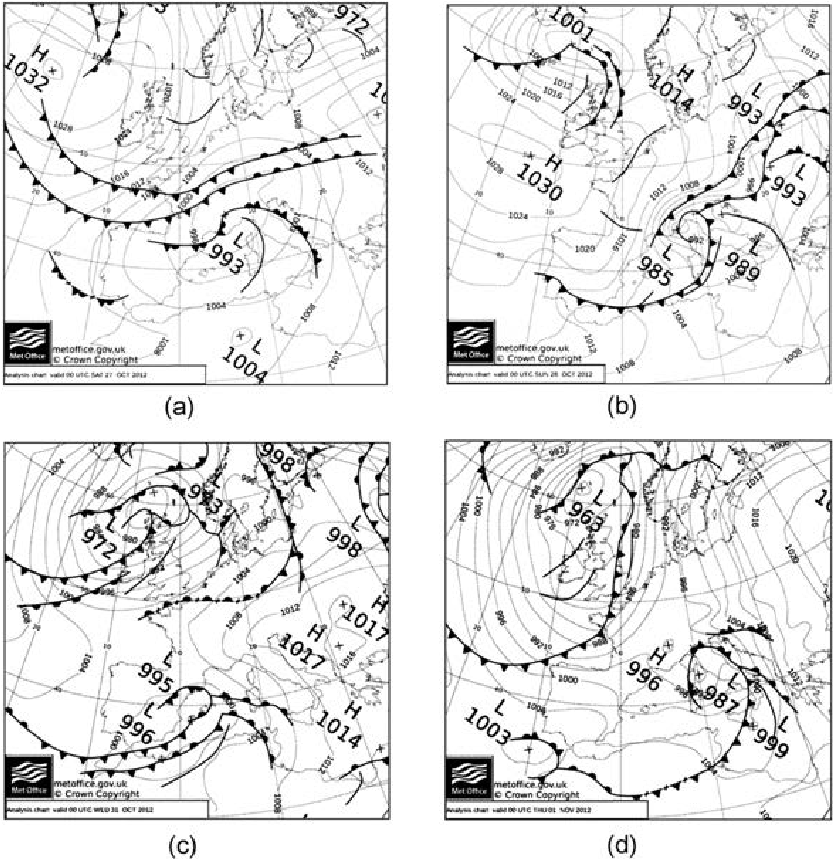

Fig. 6. Upper panels: 00:00 UTC synoptic surface charts for IOP16; **(a)** 27 October 2012; **(b)** 28 October 2012. Lower panels: same for IOP18; **(c)** 31 October 2012; **(d)** 1 November 2012. Courtesy of the UK Met Office.

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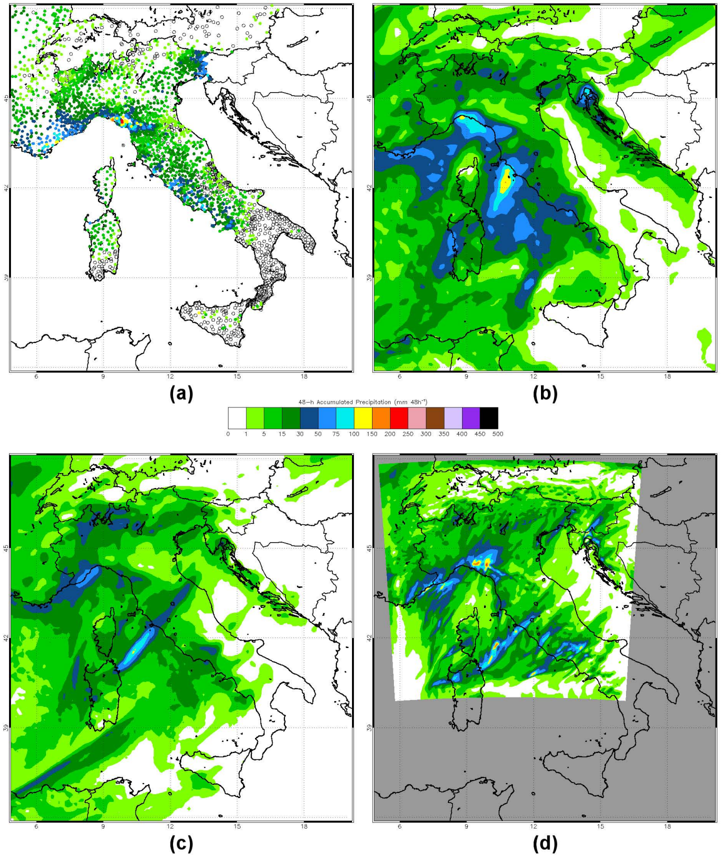

Fig. 7. 24 h accumulated precipitation on 26 October 2012. Focus over Italy: **(a)** rain gauge observations; **(b)** 0.1° BOLAM forecast from the updated SIMM; **(c)** 0.07° BOLAM forecast from the HyMeX SIMM; **(d)** 0.0225° MOLOCH forecast from the HyMeX SIMM (where the area external to the model domain is shaded in grey). The forecasts were initialised at 12:00 UTC of 25 October.

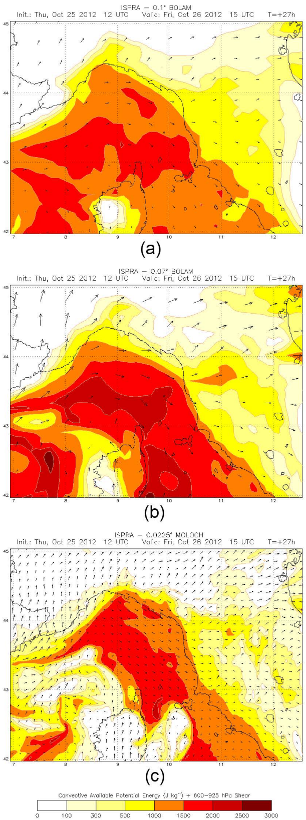

Fig. 8. Contour plot of the CAPE forecast at 15:00 UTC of 26 October 2012 over the LT hydrometeorological site and 600–925 hPa shear for the 0.1° BOLAM from the updated SIMM **(a)**, and the 0.07° BOLAM **(b)** and 0.0225° MOLOCH **(c)** from the HyMeX SIMM. The forecasts were initialised at 12:00 UTC of 25 October.

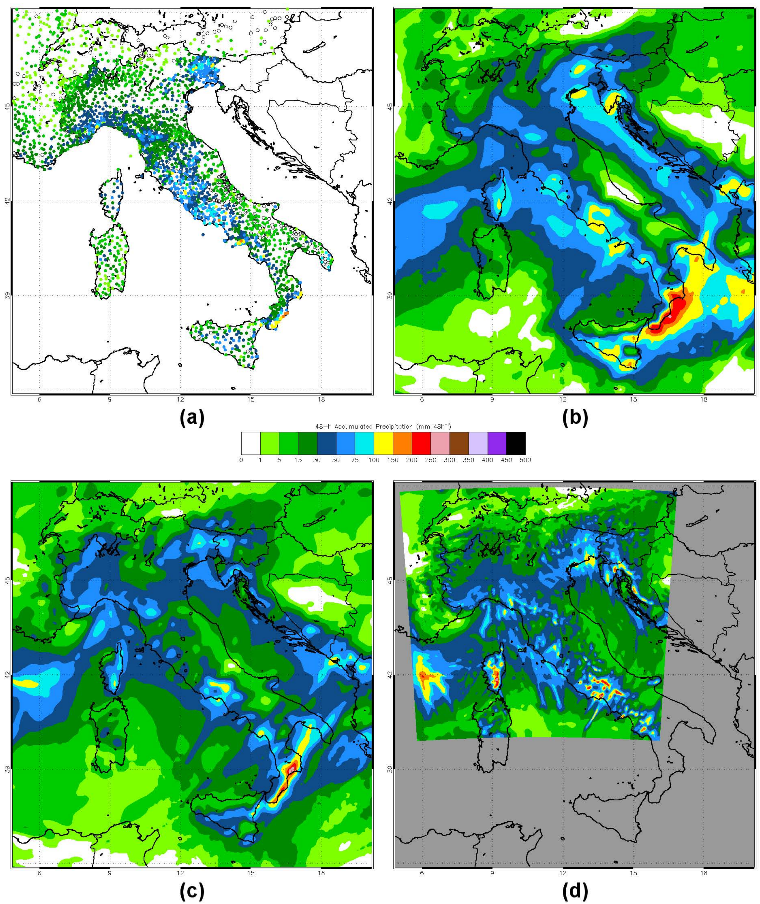

Fig. 9. As in Fig. 7, but for the 48 h accumulated precipitation starting at 00:00 UTC of 31 October 2012. The forecasts were initialised at 12:00 UTC on 30 October.

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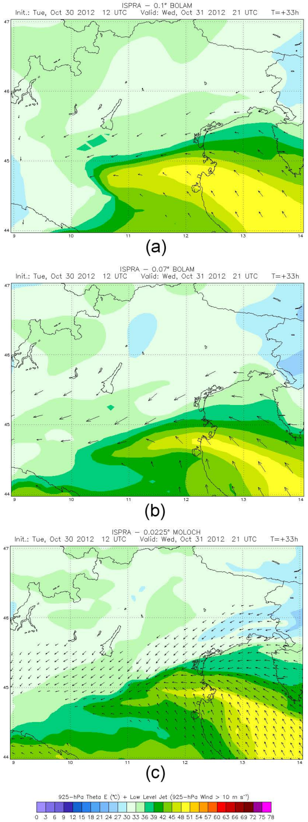

Fig. 10. Contour plot of the 925 hPa Theta E forecast at 21:00 UTC of 31 October 2012 over the NEI hydrometeorological site and the low-level jet forecast for the 0.1° BOLAM from the updated SIMM **(a)**, and the 0.07° BOLAM **(b)** and 0.0225° MOLOCH **(c)** from the HyMeX SIMM. The forecasts were initialised at 12:00 UTC of 30 October.

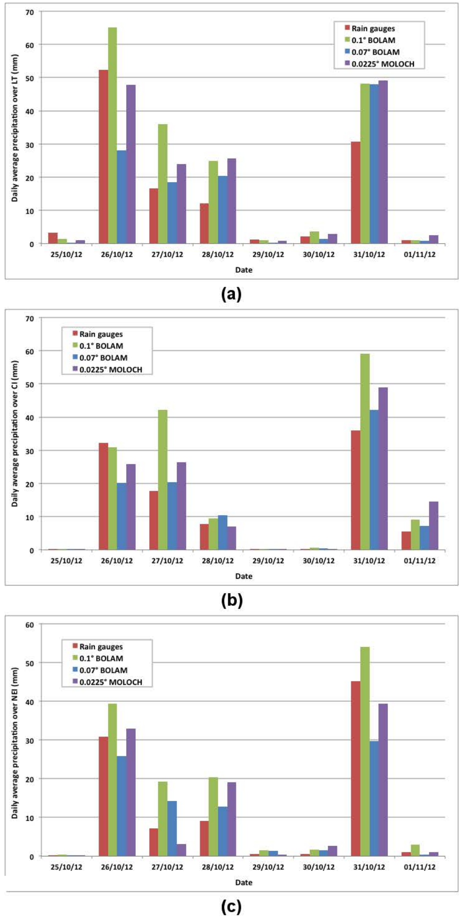

Fig. 11. Comparison between the daily rainfall observations and the daily precipitation fields generated by the tree inter-compared models. The time series are averaged over three selected areas: **(a)** LT; **(b)** CI; and **(c)** NEI.

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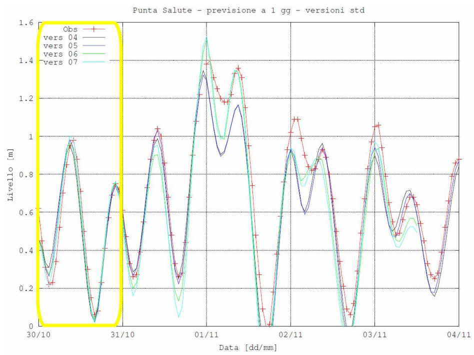
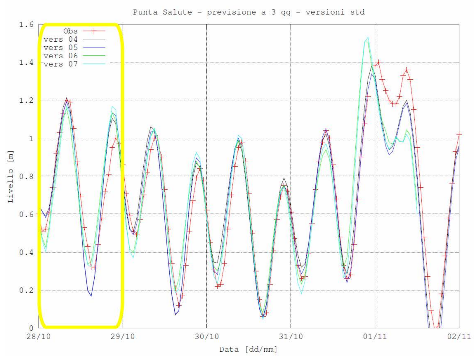


(a)



(b)

Fig. 12. Sea level observation and SHYFEM forecasts for the IOP18 *acqua alta* event on Venice ("Punta della Salute" tide-gauge). **(a)** 30 October run. **(b)** 28 October run. SHYFEM is forced by analysis for the first 24 h (yellow box), then with the NWP forecasts started at 12:00 UTC of the first day. Red crossed line: observations. Black/blue line: low/high resolution SHYFEM forced by the ECMWF IFS forecast. Green/light blue: low/high resolution SHYFEM forced by the 0.1° BOLAM forecast.

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