SPECIAL PROJECT PROGRESS REPORT

Progress Reports should be 2 to 10 pages in length, depending on importance of the project. All the following mandatory information needs to be provided.

Reporting year	2016
Project Title:	High-impact precipitation events prediction with a convection-permitting model nested in the ECMWF ensemble
Computer Project Account:	SPITCAPE
Principal Investigator(s):	Valerio Capecchi
Affiliation:	LaMMA Consortium - Environmental Modelling and Monitoring Laboratory for Sustainable Development
Name of ECMWF scientist(s) collaborating to the project (if applicable)	Simon Lang
Start date of the project:	6/October/2016 (Late Request)
Expected end date:	31/December/2018

Computer resources allocated/used for the current year and the previous one
(if applicable)
Please answer for all project resources

		Previous year		**Current year**	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	3 000 000 + 3 000 000	~100%	3 000 000	2 135 101 (June 2017)
Data storage capacity	(Gbytes)	25000 GB	10755 GB on EFS	25000 GB	10755 GB on EFS

Summary of project objectives

(10 lines max)

The rationale of the Special Project is to evaluate the accuracy of a cascade of state-of-the-art ensembles, from global-to-local, by re-forecasting past high-impact precipitation events. Starting from the recently implemented ECMWF suite of medium-range ensemble (at Tco639L91 resolution), the aim is to investigate the value of the simple dynamical downscaling approach on high-impact weather events, with a limited-area convection-permitting model directly nested in the new ECMWF global ensemble. The questions addressed in the framework of Special Project are:

1) How many days in advance a high-impact precipitation event can be foreseen by using the global state-of-the-art ensembles?

2) Which is the added value of running a regional convection-permitting high-resolution ensemble in terms of QPF (Quantitative Precipitation Forecast) with respect to global ensembles and with respect to very high-resolution deterministic regional simulation?

Three high-impact precipitation events has been selected on the basis of the pre-existing scientific literature: Cinque Terre, 25 October 2011 (study case analysed in Buzzi et al, 2014), Genoa, 4 November 2011 (study case analysed in Buzzi et al, 2014) and Genoa, 9-10 October 2014 (study case analysed in Silvestro et al, 2015)

Summary of problems encountered (if any)

(20 lines max)

The SBU requested in the SPITCAPE Special Project Request Form (submitted in October 2016) were underestimated. The reasons why additional resources were requested are listed below (see also the Request for additional resources Form forwarded in December 2016):

1. Scientific justification: almost all (~93%) the SBU allocated for this year (2016), were consumed to perform a preliminary test by tuning one parameter that controls the scaling factor of perturbation in the IFS model.

This fine-tuning test was decided in accordance with the Research Department Staff in order to set properly the initial condition perturbation amplitude for the proposed cases. The first case under exam is the Cinque Terre flood (October 2011); it is estimated that the observations available in 2011 were about 60% those available in 2016 (observations routinely assimilated in a single model run were about 45 million in 2011 and were about 70 millions in 2016). Now, since the ensemble spread of the model cycle 41r2 is likely to be under-estimated when assimilating only the observations available in 2011, we modified one parameter (EPSGAMMA) of the singular vector initial perturbation in order to enhance the ensemble spread and have a reliable ensemble (ie ensemble spread as close as possible to the ensemble error)

2. Technical reason: there was an error in the SBU requested in the first Special Project Request Form, namely SBU were under-estimated. The problem has been bypassed by reducing the length of the IFS forecast (forecast length up to 10 days instead of 15 days) and by running on Principal Investigator’s computer facilities part of the WRF simulations initially foreseen on the ECMWF supercomputer.

Summary of results of the current year (from July of previous year to June of current year)

This section should comprise 1 to 8 pages and can be replaced by a short summary plus an existing scientific report on the project

During the first year of the SPITCAPE Special Project (hereafter SPITCAPE-SP), global and limited-area convection-permitting ensemble forecasts (ENS and WRF-ENS respectively) were performed for the Cinque Terre study case.
This severe precipitation event occurred in Italy on 25 October 2011 when about a third of the average annual rainfall was registered by automatic weather stations (hereafter AWS) in less than twelve hours. It is considered as one of the most dramatic rainfall event occurred in Italy in the recent years with thirteen casualties and huge economic losses and damages in the Cinque Terre UNESCO site. It has been analysed in the recent scientific literature, see for example [1], [8] and [11].
Here we briefly report some of the key characteristics of the precipitation event and refer the reader to the above mentioned papers for further reading. The area that was hit most severely is located in the north-western part of Italy and it is shown in Figure 1 with super-imposed 24-hour period rainfall amounts, reported by AWS (data provided by the Italian Department of Civil Protection). This area is known to be prone to severe floods due to its steep orographic and its proximity to

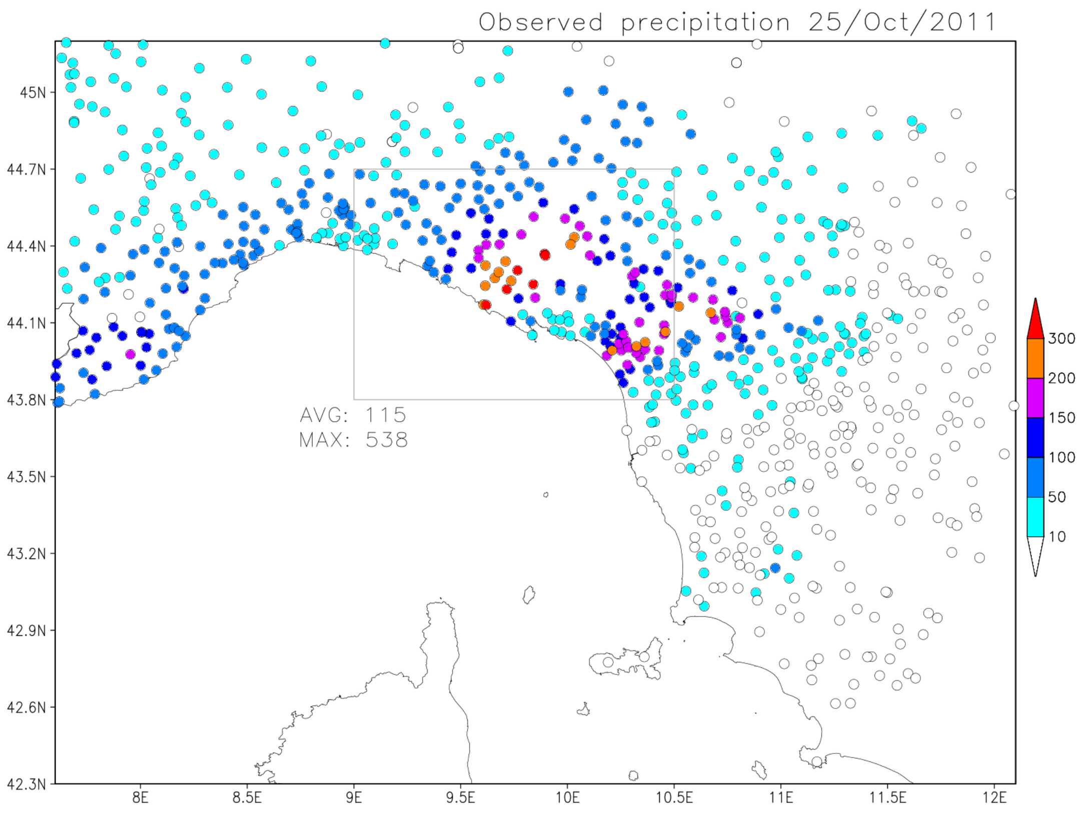


Figure 1: 24-hour observed precipitations on 25/Oct/2011. The average and maximum values in the inset gray rectangle are indicated.

the sea, favoring large sensible and latent fluxes from the sea especially during autumn. Moreover it is well known that large Atlantic disturbances (ie large amplitude trough) are strengthened when entering in the Gulf of Genoa due to orographically induced cyclogenesis (see [13]). As stated in [1] the episode here analysed is the results of both synoptic features (ie large amplitude Atlantic trough entering in the Mediterranean Sea and warm conveyor belt) and meso-α/meso-β scale flows (ie back-building convective cells triggered by orography and surface convergence lines).
Precipitations accumulated in the 24-hour period starting on 00:00 UTC of 25 October 2011 and

recorded by AWS are shown in Figure 1. Maximum precipitation rates registered were (see [11]): 143 mm/1h, 303 mm/3h and 469 mm/6h. Overall, a maximum of almost 500 mm was observed between 08:00 and 16:00 UTC of 25 October 2011 in a rain-gauge (Brugnato-Borghetto) located in the Vara Valley, a small catchment 10 km from the coast over a 500-m hill.
The target area (inset rectangle in Figure 1) where precipitation verification has been carried out, is drawn subjectively considering the following criteria: (i) western bound divides the eastern part of the Ligurian region (characterized by deep moist convection, see [11]) from the western part of the Ligurian region (characterized by widespread stratiform precipitation, see [11]); (ii) eastern bound is drawn to include the Magra valley which registered high precipitation rates in the second part of the event (see [11]); (iii) northern bound is defined by orography that triggered the onset of an organised and self-regenerating mesoscale convective system (MCS) and (iv) the southern bound is drawn to keep the dimension of the target area as close as possible to the extension of the area defined and discussed in [11] (about 50×50 km^2, see also Figure 10 in their article).

Regarding the ENS forecasts, thanks to the help of the Research Department Staff, simulations were performed using the IFS model cycle 41r2 and modifying the parameter EPSGAMMA of the singular vector initial perturbations as motivated in the Request for additional resources Form (December 2016) and as reported above in the “Summary of problems encountered” Section.

Regarding the WRF-ENS forecasts, the WRF (Weather and Research Forecasting, www.wrf-model.org, see also [9]) model was used. The WRF model is the result of the joint efforts of US governmental agencies and the University of Oklahoma. It is a fully compressible, Eulerian, non-hydrostatic mesoscale model, specifically designed to provide accurate numerical weather forecasts both for research activities, with the dynamical core Advanced Research WRF (ARW), and for operations, with the dynamical core Non-hydrostatic Mesoscale Model (NMM).
During the first year of the SPITCAPE-SP, it was possible to successfully build the executables of the WRF-ARW core updated at version 3.8.1 (August 2016). A very concise step-by-step manual on how to build and install the WRF-ARW model on the cca supercomputer was drawn up and forwarded to the ECMWF User Support Staff. Fortran compilers used to build the WRF-ARW sources were GNU, Intel and Cray. Nevertheless due to incompatibilities with some pre/post-processing WRF-ARW utilities, only the executables built with the GNU compiler were used at runtime.
The model dynamics, equations and numerical schemes implemented in the WRF-ARW core are fully described in [10] and [7]. The model physics, including the different options available, is described in [5]. Some of the main characteristics of the numerical settings used and here presented, are listed in Table 1 while the geographical domain of the ensemble simulations is shown in Figure 1 of the SPITCAPE-SP Request Form. This is a standard configuration running daily at Consorzio LaMMA

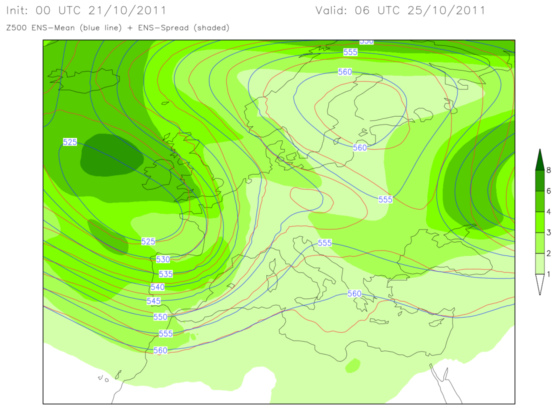
Variable	**Value**
Projection	Lambert
Rows×columns	440×400
Vertical levels	60
Horizontal resolution	3 km
Time step	15 s
Cumulus convection	explicit (no parametrisation)
Micro-physics option	Thompson (2008), see [12]
Boundary-layer option	Yonsei University, see [6]
Land-surface option	Unified Noah model, see [4]

Table 1: Key numerical characteristics and basic physics options chosen for the WRF-ENS numerical simulations.

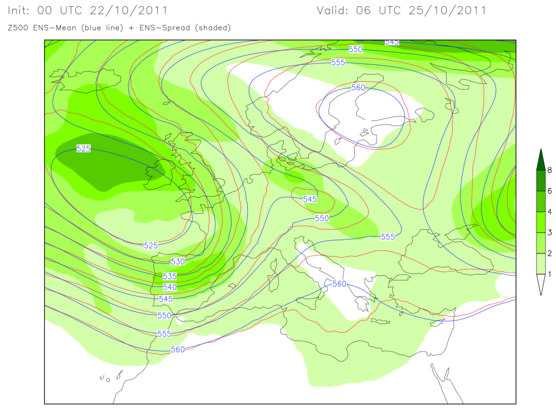
for operative weather forecast service; it has also been used for research purposes, see for example [2] and [3].

To answer to the first question raised in the Scientific Plan of the SPITCAPE-SP Request Form, namely, "How many days in advance a Mediterranean HPE (Heavy Precipitation Event), can be foreseen by using the global state-of-the-art ensembles?", the geopotential height at isobaric level 500 hPa of the ENS forecast has been plotted for different starting dates. As motivated in the Request for additional resources Form (December 2016), due to an under-estimation of the SBU needed to run the ENS forecast, this analysis is limited to forecasts initialised one to ten days prior the rainfall event. Moreover due to the low predictability of the event, only the results regarding forecasts initialised about five to one days prior the rainfall event are shown (see Figure 2 below) and discussed here.

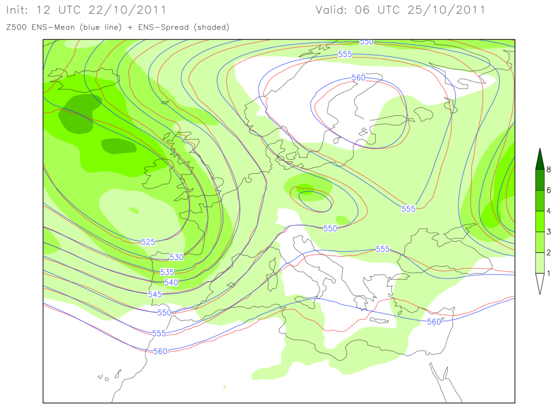
In Figure 2 it is shown the ENS ensemble mean and spread (defined as the ensemble standard deviation) values of the geopotential height at isobaric level 500 hPa for different forecast lengths, namely: t+102 hours, t+78 hours, t+66 hours, t+54 hours, t+42 hours, t+30 hours and t+18 hours. The verification time is 06:00 UTC of 25 October 2011, which roughly corresponds to the beginning of the precipitations in the target area. As expected, the shorter the forecast length, the smaller the green shaded area. High uncertainty (namely large green shaded areas) is found for ENS forecasts with starting dates before 00:00 UTC on 21 October 2011 (results not shown). On the other hand, results seem good enough (visually) for forecast lengths shorter than 42/54 hours (ie for forecast initialised at 12:00/00:00 UTC on 23 October 2011 or later).



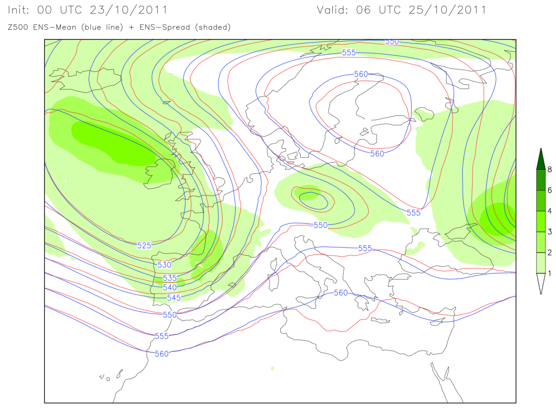
(a) 21/Oct/2011 00:00 UTC + 102 hours



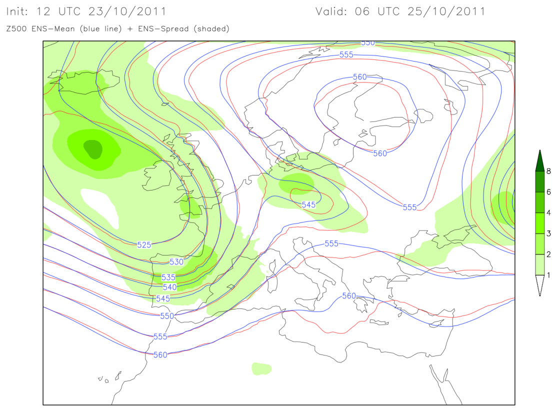
(b) 22/Oct/2011 00:00 UTC + 78 hours



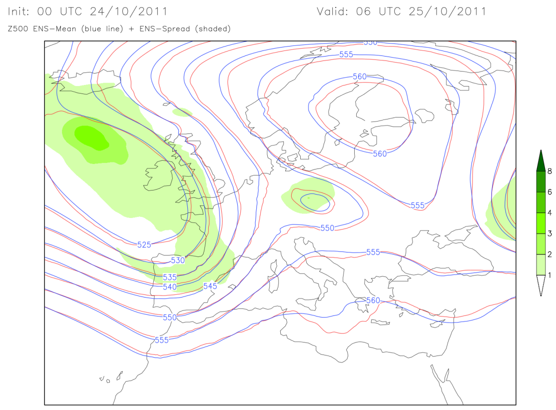
(c) 22/Oct/2011 12:00 UTC + 66 hours



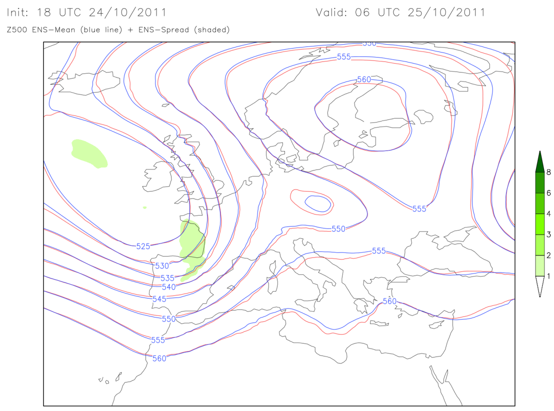
(d) 23/Oct/2011 00:00 UTC + 54 hours



(e) 23/Oct/2011 12:00 UTC + 42 hours



(f) 24/Oct/2011 00:00 UTC + 30 hours



(g) 24/Oct/2011 12:00 UTC + 18 hours

Figure 2: 500 hPa geopotential height ensemble mean (blue contour) and spread (green shades) for different starting dates for ENS data. Verification time is 25/Oct/2011, 06:00 UTC. The analysis (ERA5 data) is plotted with the red contour line.

To further answer to the question raised above, stamp plots were produced with accumulated precipitation predicted by all the members of ENS (plots not shown here). For sake of simplicity, we report in Table 2 the maximum and mean values, averaged among the 50 members of ENS, of the accumulated rainfall predicted in the inset rectangle of Figure 1, as a function of the starting date. These values should be compared with the observed ones reported in the last row of Table 2 (and in Figure 1). Not surprisingly the mean value among the ENS members increases as long as the forecast length reduces. A similar behavior is found for the maximum value.
Moreover the probability of precipitations (hereafter PoP) exceeding the thresholds of 50 mm and 100

Starting Date	**Forecast length**	**Mean/Maximum values** (mm)
18/Oct/2011 at 00:00 UTC	192 hours	10/82
19/Oct/2011 at 00:00 UTC	168 hours	14/99
20/Oct/2011 at 00:00 UTC	144 hours	27/127
21/Oct/2011 at 00:00 UTC	120 hours	30/134
22/Oct/2011 at 00:00 UTC	96 hours	35/152
22/Oct/2011 at 12:00 UTC	84 hours	39/146
23/Oct/2011 at 00:00 UTC	72 hours	42/141
23/Oct/2011 at 12:00 UTC	60 hours	47/143
24/Oct/2011 at 00:00 UTC	48 hours	46/141
24/Oct/2011 at 12:00 UTC	36 hours	55/148
Observed values		**115/538**

Table 2: Mean and maximum values of the 24-hour accumulated rainfall predicted by the ENS members in the inset rectangle of Figure 1, as a function of the starting date. The last row contains the observed values.

mm in 24 hours has been calculated for ENS. Considering the uncertainty found on the geopotential height at isobaric level 500 hPa (see Figure 2), only the forecast initialised on 23/October/2011

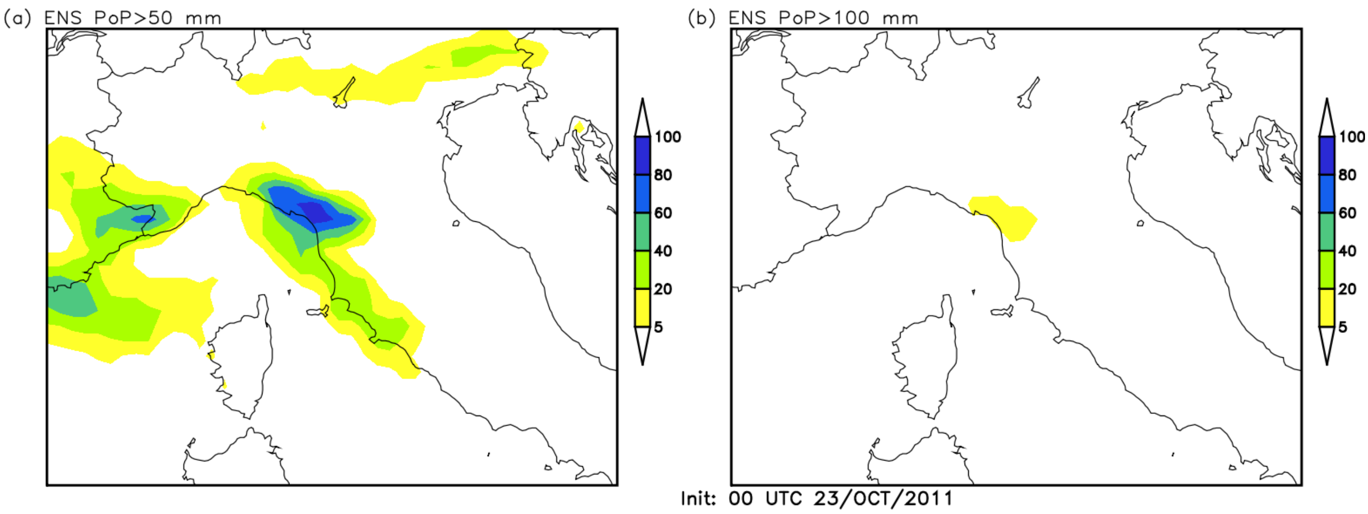


Figure 3: ENS Probability of Precipitation. Starting date is 23/Oct/2011 00:00 UTC

at 00:00 UTC or later are shown (Figures 3-6) and discussed. The ENS PoP exceeding 50 mm in 24 hours provides similar results in all the starting dates considered, even if it refines the areas interested by rainfall as long as the forecast length decreases, suggesting a local event (ie occurring at meso-α/meso-β scale) rather than a large synoptic rainfall event. The ENS PoP exceeding 100 mm in 24 hours is $\simeq 20\%$ for all the starting dates considered. The forecast initialised at 12:00 UTC on 24/October/2011 provides, not surprisingly, the best results both in terms of probability (higher values) and in terms of spatial patterns (larger and darker shaded areas in the target rectangle). Besides the fact that the precipitation predicted is largely under-estimated if compared to the observed

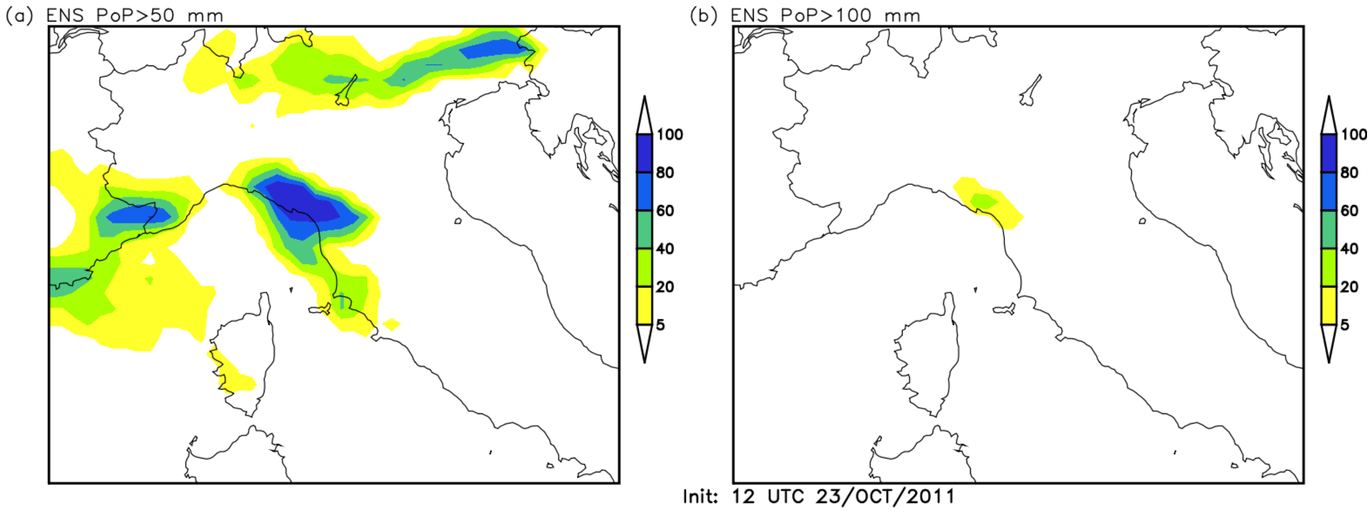


Figure 4: ENS Probability of Precipitation. Starting date is 23/Oct/2011 12:00 UTC

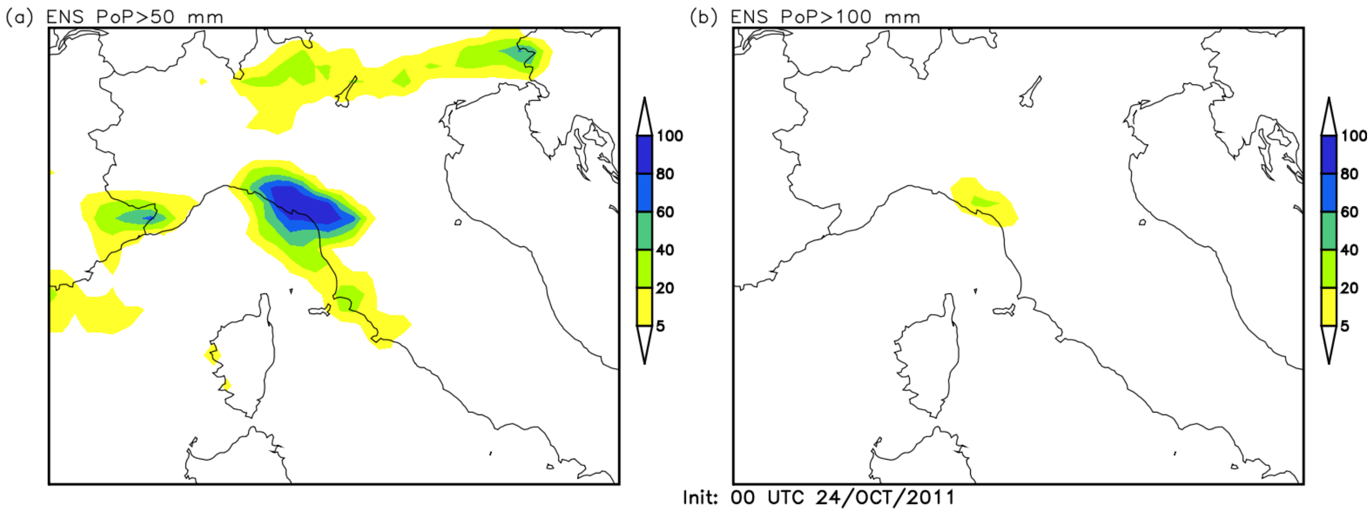


Figure 5: ENS Probability of Precipitation. Starting date is 24/Oct/2011 00:00 UTC

values, the ENS predictions on rainfall seem remarkable. In fact it has to be considered that during the event, the convection is dominant (see [1]) and that the horizontal resolution of the ENS data is relatively coarse (about 18 km).

To answer to the second question raised in the Scientific Plan of the SPITCAPE-SP Request Form, namely "Which is the added value of running a regional convection-permitting high-resolution ensemble in terms of QPF (Quantitative Precipitation Forecast)?", in Figure 7 it is shown the probability distributions of the ENS (black curves) and WRF-ENS (gray curves) precipitation forecasts for accumulated precipitation on 25/October/2011 at some rain-gauges in the target area depicted in Figure 1 (gray rectangle). The red vertical line is the observed value, the black solid (dashed) vertical line is the ENS mean (maximum) value and the gray solid (dashed) vertical line is the WRF-ENS mean (maximum) value. Distributions are estimated by means of a kernel density function. The starting date is 12:00 UTC of 24/October/2011. In the first two Figures (7a and 7b), the ENS forecasts seem to outperform the WRF-ENS forecasts (black curves 'centered' around the red vertical lines). Conversely in Figures 7c and 7d the WRF-ENS predictions seem better than the ENS ones. Finally, in Figures 7e and 7f both predictions seem to largely under-estimate the exceptionally high values observed by the AWS. Besides the fact that we show here few rain-gauges, it seems that the profiles of the WRF-ENS curves are broader than those of the ENS data. This is confirmed by the standard deviations of the members which is, on average, about 15 mm for the ENS forecasts and about 33 mm for the WRF-ENS forecasts.

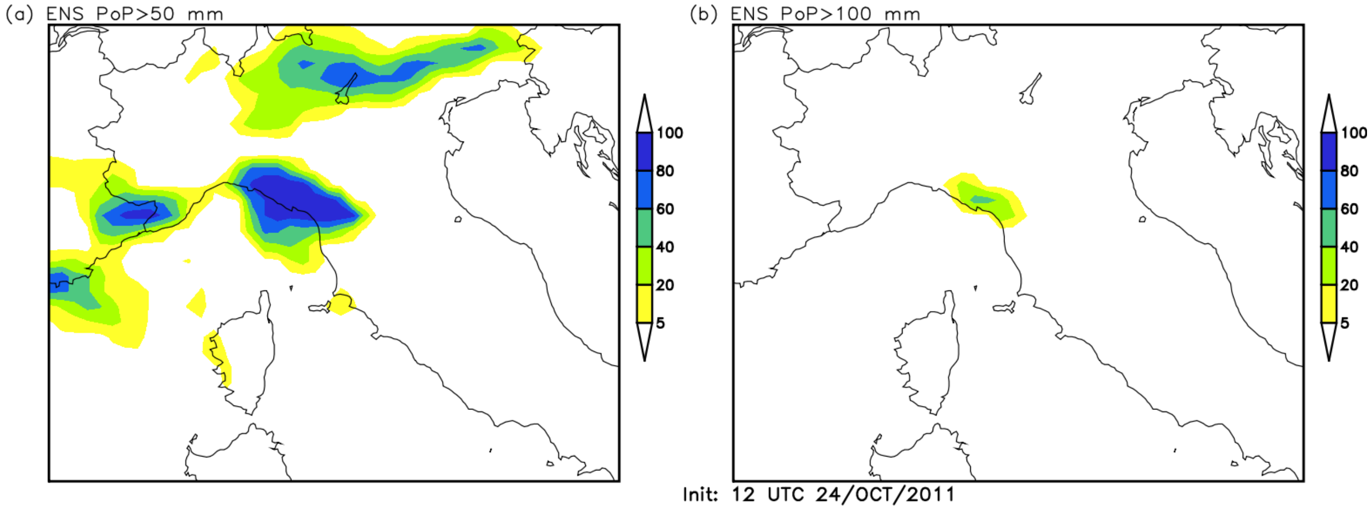
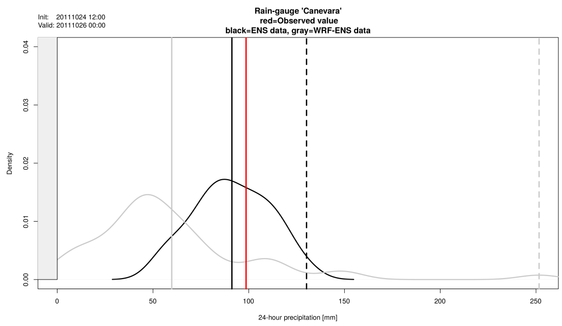
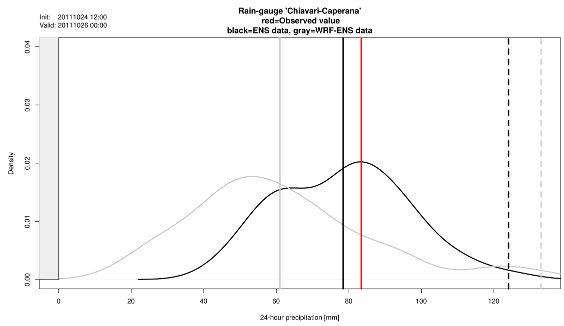


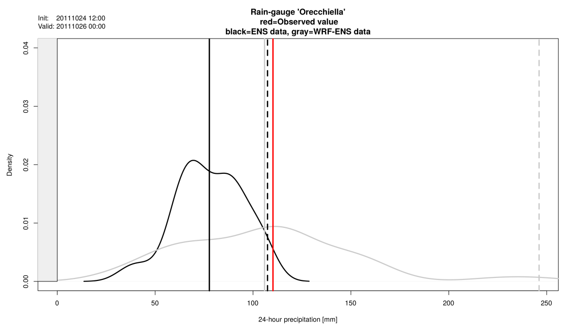
Figure 6: ENS Probability of Precipitation. Starting date is 24/Oct/2011 12:00 UTC



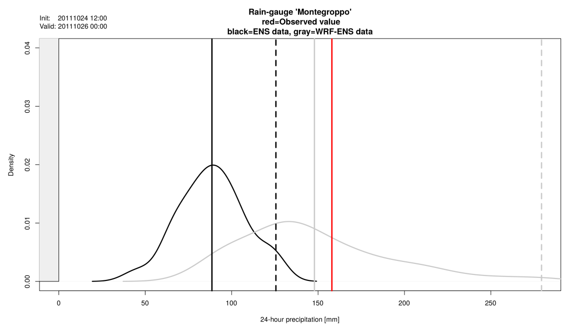
(a) Rain-gauge Canevara



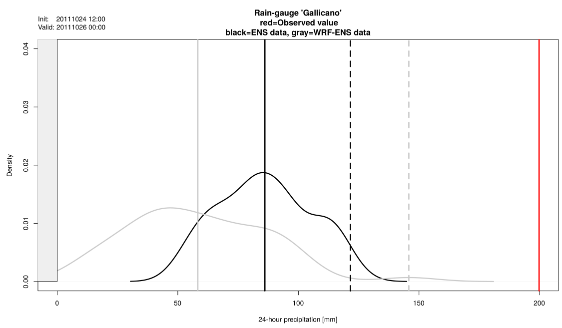
(b) Rain-gauge Chiavari



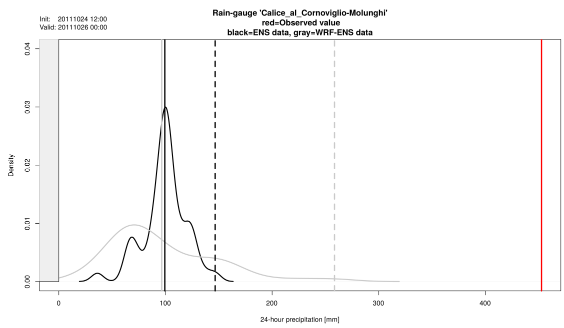
(c) Rain-gauge Orecchiella



(d) Rain-gauge Montegroppo



(e) Rain-gauge Gallicano



(f) Rain-gauge Molunghi

Figure 7: Probability distribution of global ensemble precipitation forecast and observed rainfall amounts (red vertical solid line) at selected rain-gauges in the target area. The black (gray) vertical solid line is the ENS (WRF-ENS) mean value. Dashed vertical lines are the maximum values of ENS (black) and WRF-ENS (gray) forecasts. Starting date is 24/Oct/2011 12:00 UTC.

Taking into account the quantitative skills of the two prediction systems, we report in Table 3 the Root Mean Square Error (RMSE) and the multiplicative BIAS of both ENS and WRF-ENS forecasts for rainfall accumulated in the 24-hour period starting on 00:00 UTC 25/October/2011. The verification has been carried out considering the 171 rain-gauges belonging to the target rectangle area.
Let O_i be the rainfall observed at the *i-th* rain-gauge and let $\overline{F_i}$ and F_i^M be, respectively, the average and maximum accumulated rainfall predicted at the *i-th* rain-gauge among the 50 members of ENS (or WRF-ENS). In formulas:

$$\overline{F_i} = \text{average}\left\{F_{ij}\right\}_{j=1,\ldots,50}$$

and

$$F_i^M = \max\left\{F_{ij}\right\}_{j=1,\ldots,50}$$

In other words, for ENS (WRF-ENS), $\overline{F_i}$ is the black (gray) solid vertical line in Figures 7a-7f, while F_i^M is the black (gray) dashed vertical line. We then consider the RMSE and multiplicative BIAS defined as follows in equations (1)-(4), where N is the total number of rain-gauges taken into account (171 in the Cinque Terre case).

$$\overline{BIAS} = \frac{\frac{1}{N}\sum_{i=1}^{N}\overline{F_i}}{\frac{1}{N}\sum_{i=1}^{N}O_i} \tag{1}$$

$$\overline{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\overline{F_i} - O_i)^2} \tag{2}$$

$$BIAS^M = \frac{\frac{1}{N}\sum_{i=1}^{N}F_i^M}{\frac{1}{N}\sum_{i=1}^{N}O_i} \tag{3}$$

$$RMSE^M = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(F_i^M - O_i)^2} \tag{4}$$

In Table 3 we report the statistical skills as defined above for all the rain-gauges belonging to the

Forecast	$\overline{\textbf{RMSE}}$	$\overline{\textbf{BIAS}}$	$\textbf{RMSE}^\textbf{M}$	$\textbf{BIAS}^\textbf{M}$
ENS	123	0.60	99	0.88
WRF-ENS	125	0.64	90	1.51

Table 3: RMSE and BIAS of the ENS and WRF-ENS considering the average value or the maximum value of each ensemble

Forecast	$\overline{\textbf{RMSE}}$	$\overline{\textbf{BIAS}}$	$\textbf{RMSE}^\textbf{M}$	$\textbf{BIAS}^\textbf{M}$
ENS	116	0.36	96	0.52
WRF-ENS	118	0.37	66	0.86

Table 4: As in Table 3 but only for observed values greater than the 75-*th* percentile

target rectangle area, while in Table 4 we report the statistical skills when considering only those rain-gauges whose value is greater than the 75-*th* percentile (in other words we're considering only those rain-gauges that registered high rainfall amounts). Looking at Table 3, we can deduce that the maximum value of ENS (or WRF-ENS) provides slightly better results than the average value of ENS (or WRF-ENS) (ie $RMSE^M$ is lower than $\overline{RMSE}$ and $BIAS^M$ is closer to 1 than $\overline{BIAS}$ for ENS). $RMSE^M$ for WRF-ENS is slightly lower than $RMSE^M$ for ENS, but WRF-ENS tends to over-estimate precipitations ($BIAS^M$ is $\simeq 1.5$). When considering only rain-gauges whose value is greater than the 75-*th* percentile (see Table 4), taking into account the maximum of WRF-ENS is the best option, since $RMSE^M$ is consistently reduced if compared to ENS (66 mm *vs* 96 mm) and $BIAS^M$ is close to 1.

To further evaluate the added value of running the WRF-ENS convection-permitting ensemble with respect to the ENS ensemble, in Figure 8 we show the PoP plots for the forecast initialised at 12:00 UTC of 24/October/2011. From the visual comparison between Figure 8 and Figure 6 we

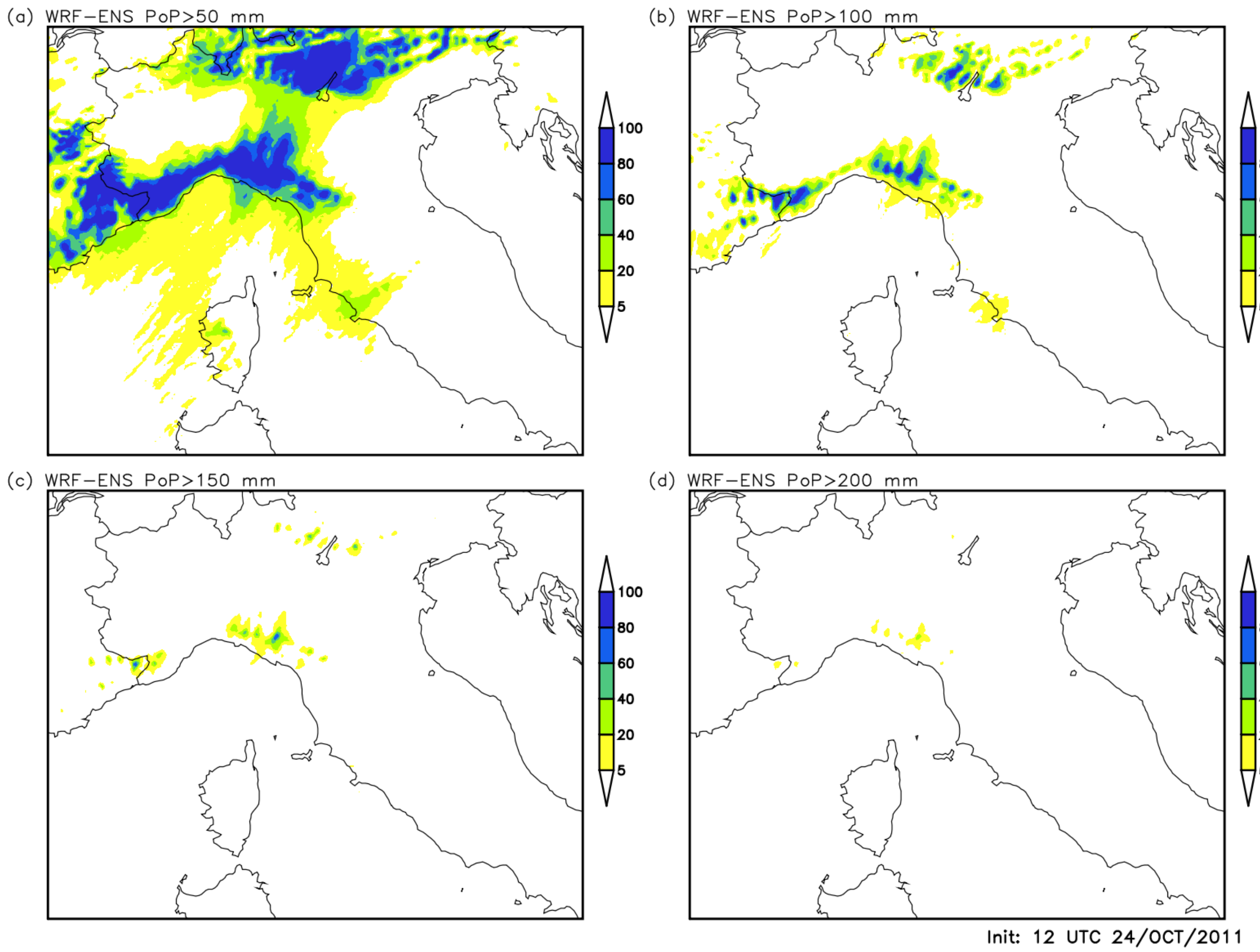


Figure 8: WRF-ENS Probability of Precipitation. Starting date is 24/Oct/2011 12:00 UTC

can argue that nesting a higher-resolution limited-area model into the ENS can provide additional information. The WRF-ENS probability maps highlight larger areas likely to be affected by intense precipitation. Moreover the PoP exceeding the high thresholds 150 mm and 200 mm are greater than 20% and 5% respectively, suggesting that a high-impact event may occur.

In conclusion to partially address the two main questions raised in the SPITCAPE-SP Request Form, namely:

1. How many days in advance a HPE (Cinque Terre here) can be foreseen by using the global state-of-the-art ensembles?

2. Which is the added value of running a regional convection-permitting high-resolution ensemble in terms of QPF (Quantitative Precipitation Forecast)?

we can state that for the Cinque Terre case:

1a. Figure 2 shows that the ENS ensemble spread is relatively low (and thus the confidence is relatively high) for forecast initialised 4/5 days prior the event. Moreover ENS forecasts initialised 2/3 days prior the event provide good results indicating the synoptic ingredients favoring possible high-impact weather events. A high uncertainty in the predictions is found for forecast lengths longer than 5 to 10 days (results not shown), 1b. Table 2 shows that explicit QPF values increase as long as forecast length decreases; this is true both for the ENS mean value and ENS maximum value. Nevertheless QPF values are largely under-estimated if compared to observations also for the short term forecast (ie t+36 hours),

1c. PoP exceeding 50 mm and 100 mm in 24 hours (see Figures 3-6) correctly highlights the areas most likely to be affected by intense rainfall amounts, while slightly adjusting the region as long as the forecast length decreases. This is found for forecast lengths equal or shorter than 72 hours

2a. A point-to-point verification has been carried out for rainfall amounts registered by AWS belonging to the target rectangle (see Figure 7 and Tables 3 and 4). In the short term forecast, the maximum of the WRF-ENS members outperforms ENS forecasts and provides the best results (ie yielding the lowest RMSE). Nevertheless it might over-estimate small rainfall amounts

2b. Results also indicate (see Figure 8) that, in the short forecast range, nesting a higher-resolution ensemble into the global ECMWF ensemble can provide added value in terms of the likely spatial distribution of rainfall as well as the likely amount.

References

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[2] Capecchi, V., Perna, M. and Crisci, A.: *Statistical modelling of rainfall-induced shallow landsliding using static predictors and numerical weather predictions: preliminary results*, Nat. Hazards Earth Syst. Sci., 15, 75-95, 2014

[3] Capecchi, V., Lang, S. and Buizza, R.: *'L'alluvione di Firenze del 1966', an ensemble-based re-forecasting study*, ECMWF Newsletter, Summer Issue, 2016

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List of publications/reports from the project with complete references

None

Summary of plans for the continuation of the project

(10 lines max)

The plan is to simulate the Genoa case (4 November 2011). Results will be analysed and post-processed, as done during the last year for the Cinque Terre case, to be able to draw more statistically sound conclusions.

A new Request for additional resources Form is likely to be forwarded to in the next months to get the SBUs necessary to perform a full numerical experiment with ENS and WRF-ENS ensembles.