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‘L’alluvione di Firenze del 1966’: an ensemble-based re-forecasting study

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'L'alluvione di Firenze del 1966': an ensemble-based re-forecasting study

Valerio Capecchi (LaMMA, Italy), Simon Lang, Roberto Buizza (both ECMWF)

During the first few days of November 1966, several Italian regions were hit by a storm that produced intense and persistent precipitation over north-east and central Italy. The exceptionally intense rain on 3–4 November followed weeks of wet conditions and led to disastrous flooding. The historical city of Florence (Firenze) was one of the most severely affected. The Arno River flooded the city, causing huge damage to its cultural and artistic heritage and enormous economic losses. At the same time, Venice experienced the maximum ever recorded storm surge levels. The storm is considered to be one of the most severe weather events to have affected Italy in the last century, with more than 110 fatalities caused by weather-induced conditions.

To mark the 50th anniversary of the Arno River flooding, we have revisited this rainfall event by applying cutting-edge global and regional NWP modelling to it using an ensemble approach. The results show that the ensemble approach provides added value compared to single forecasts by providing objective confidence measures and helping to estimate the probability of high-precipitation values, in this case up to three days in advance. The WRF (Weather and Research Forecasting) limited-area model (LAM) predicts higher probabilities of intense precipitation in the area than the global model, but neither ECMWF's current global model nor the LAM correctly predicts the intensity of the rainfall observed in the Arno catchment area. Part of the explanation may be the limited observations available to initialise the forecasts as well as the relatively coarse resolution of the global model.

Method

We re-forecast the rainfall event on 3 and 4 November 1966 in Italy with ECMWF ensemble forecasts (ENS) using model cycle 41r2, which has been operational since 8 March 2016, at the spectral resolution TCo639, with the newly adopted cubic-octahedral grid with a grid spacing of about 18 km. We also re-forecast the event with a recent version of the WRF model (released in August 2015), with a grid spacing of 3 km and in a convection-permitting configuration. Table 1 summarises the key characteristics of the forecasts used. Both ensembles were initialised using ad hoc analyses, reproduced for the weeks centred around the November 1966 case, and the WRF ensemble forecasts used ENS as boundary conditions.

Our results update and complement those obtained by *Malguzzi et al*. (2006), who simulated the same rainfall event using a single deterministic run of ECMWF's global model (model cycle 23r4) at the spectral resolution TL511L60, with the old linear grid with a spacing of about 40 km. It should be noted that the analyses generated then and now incorporate a very limited number of observational data compared to today, since in 1966 satellite data were not available and only about half the conventional data available today were collected. In other words, the results we have obtained illustrate the forecasting system's capability in a 'data-poor' scenario. This means that our results (as well as the ones obtained by *Malguzzi et al.*) underestimate the full potential of the forecasting systems used. If such a case were to reoccur, ensemble forecasts should be able to provide more accurate information than the forecasts discussed in this work.

	Area	Resolution	Members	Initial conditions	Boundary conditions
ENS	Global	TCo639L91 (18 km, 91 levels, TOA 0.01 hPa)	51	ECMWF TL511L60 (40 km, 60 levels)	N/A
WRF-ENS	Limited area	3 km, 60 levels, TOA 10 hPa	50	ENS	ENS

Table 1 Key characteristics of the forecasts used in this re-forecasting study. TOA indicates the model top of the atmosphere.

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Short-range global forecasts

Figure 1 shows the observed precipitation accumulated on 4 November 1966 and the precipitation predicted 24 hours before the event (i.e. by forecasts initialised at 00 UTC on 4 November). Figure 1a shows the observed one-day accumulation for a set of rain gauges in central Italy. It is worth pointing out that 15 of the 41 reports from the Arno River catchment area registered more than 100 mm in 24 hours, and that many other stations over north-east Italy (not shown) reported more than 400 mm accumulated in two days (3–4 November). Figure 1b shows the precipitation predicted by ECMWF model cycle 23r4 at a spectral resolution of TL511L60, run in 2006 and discussed by *Malguzzi et al*. (2006). Figure 1c–d shows the precipitation predicted by the ENS control (cycle 41r2), run at TCo639L91 spectral resolution with a cubic-octahedral grid (corresponding to 18 km horizontal resolution) initialised at 00 UTC on 4 November 1966, and the precipitation predicted by the WRF control run with a horizontal resolution of 3 km. The latter forecast used the ENS control data as boundary conditions.

At this very short forecast range, all models are able to predict the location of the two precipitation maxima over the north-eastern Alps and along the Tyrrhenian side of central Italy. Nevertheless, the rainfall values are for the most part underestimated in the worst affected part of the inner Arno River catchment area: none of the models predict the accumulations of more than 100 mm observed at several weather stations. More realistic values are predicted for the north-eastern Alps, although even here precipitation maxima are generally underestimated (observed values are not shown). A visual comparison

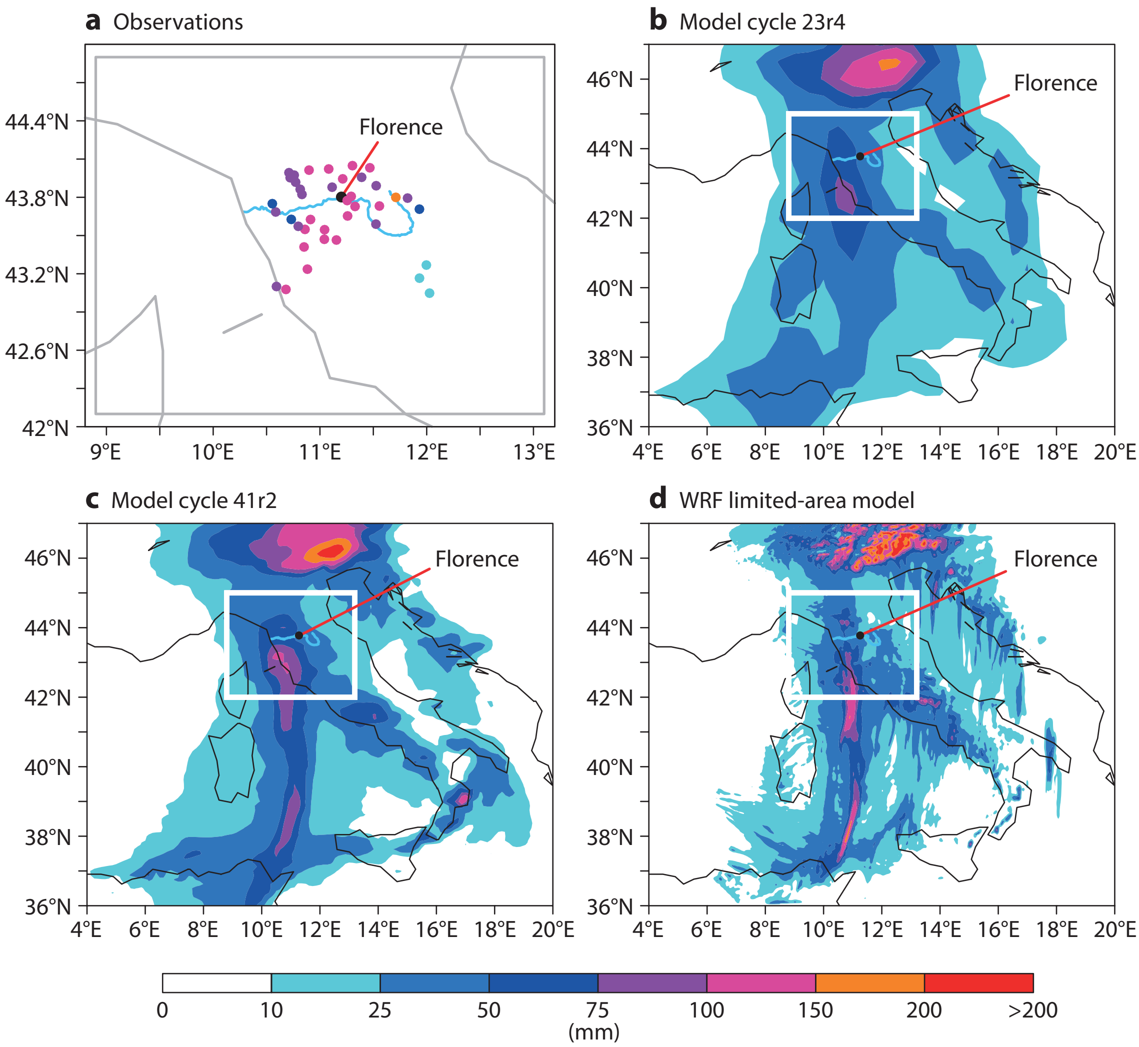

Figure 1 Precipitation charts showing (a) observed precipitation between 00 UTC 4 November and 00 UTC 5 November 1966 from a set of rain gauges in central Italy, (b) 24-hour forecast (model cycle 23r4) for precipitation over the same period as simulated by *Malguzzi et al*. (2006), (c) 24-hour ENS control forecast (model cycle 41r2) for precipitation over the same period and (d) WRF ensemble 24-hour control forecast for precipitation over the same period. The thin blue line in (a) is the Arno River. All forecasts were initialized at 00 UTC on 4 November 1966.

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of Figure 1b and Figure 1c shows some differences in the precipitation patterns predicted by the ECMWF model cycle 23r4 and model cycle 41r2, both in terms of spatial distribution and rainfall amounts, but broadly similar predictions for the Arno catchment area.

Figure 2 shows 24-hour ENS precipitation in excess of 50, 75, 100 and 150 mm/day. These maps indicate that the ensemble gives a probability of 80–100% of at least 75 mm and a 5–20% probability of at least 100 mm over an area in Tuscany centred on the coast, and a probability of 80–100% of at least 150 mm over an area in north-east Italy. To explore further the potential added value of the probabilistic approach, Figure 3 compares the observed precipitation on 4 November (red vertical line) with the ensemble probability distributions (black curves) at four of the rain gauges in Figure 1a. The three vertical black lines in the plots are the minimum, mean and maximum of the ensemble members, while the grey vertical line is the control forecast. Figure 3a,b shows two cases where the control forecast is far from the observed value while the full estimated ENS probability distribution extends all the way to the observed value and beyond, albeit at a low probability density. Figure 3c shows a case where the control prediction is much higher than the observed value, by about 40%, whereas the ENS mean exceeds the observed value by only about 15%. On the other hand, Figure 3d shows an example where both the full ensemble distribution and the control forecast fail to predict even the possibility of the observed exceptionally high amount of rainfall (almost 130 mm in 24 hours) recorded at this particular rain gauge near Florence. Although it is impossible to judge a probabilistic forecasting system by studying a single case (assessments should be based on a large number of cases), these results suggest that the current global ensemble is not able to predict extreme values in all circumstances, possibly partly because of the ensemble's relatively coarse resolution. Higher-resolution forecasts at a convection-permitting scale might enable better predictions in such cases.

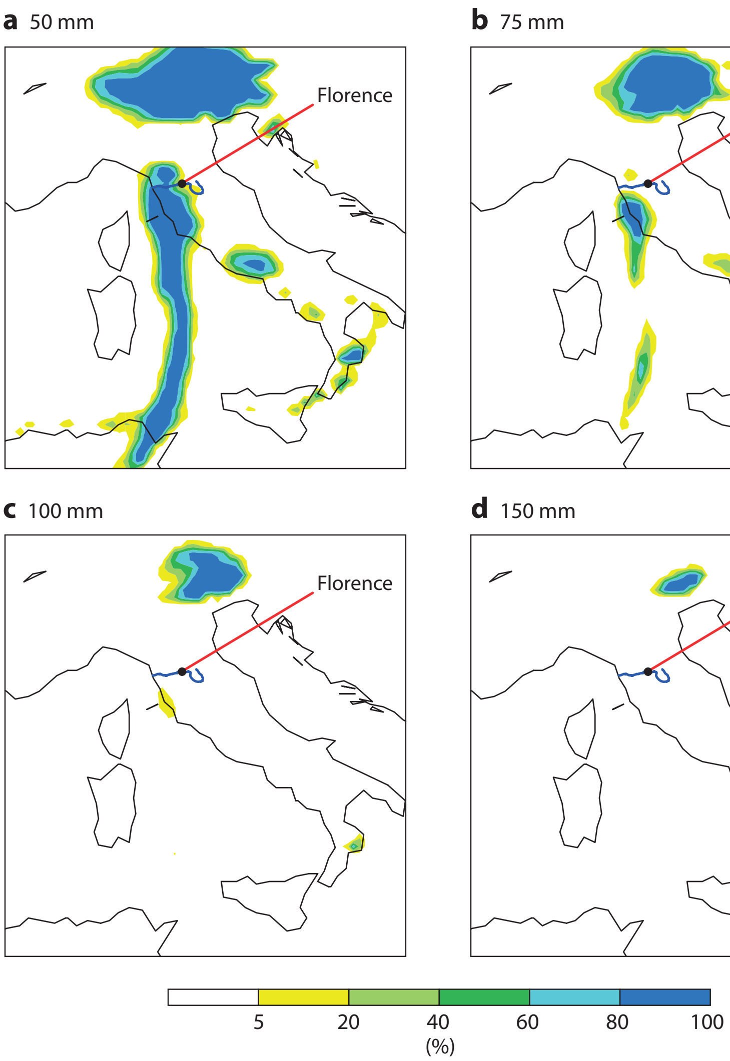

Figure 2 ENS forecasts initialized at 00 UTC on 4 November of the probability that 24-hour precipitation in the period ending at 00 UTC on 5 November 1966 will exceed (a) 50 mm, (b) 75 mm, (c) 100 mm and (d) 150 mm.

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Short-to-medium-range global forecasts

In order to investigate whether the rainfall event was predictable several days in advance, we ran ensemble forecasts using model cycle 41r2 for a longer forecast range. Figure 4 shows the precipitation forecasts from the single ensemble control for four starting dates: 00 UTC 28 October 1966 (192-hour forecast), 00 UTC 30 October 1966 (144-hour forecast), 00 UTC 1 November 1966 (96-hour forecast) and 00 UTC 2 November 1966 (72-hour forecast). In each case, the predicted precipitation in the Arno River valley is low compared to the observations shown in Figure 1a. In fact, although each forecast shows intense precipitation over north-east Italy and in some areas over central Italy, 24-hour precipitation is largely underestimated in the Arno River catchment area. This again confirms the shortcomings of a 'deterministic' approach, in which a prediction is based on a single forecast.

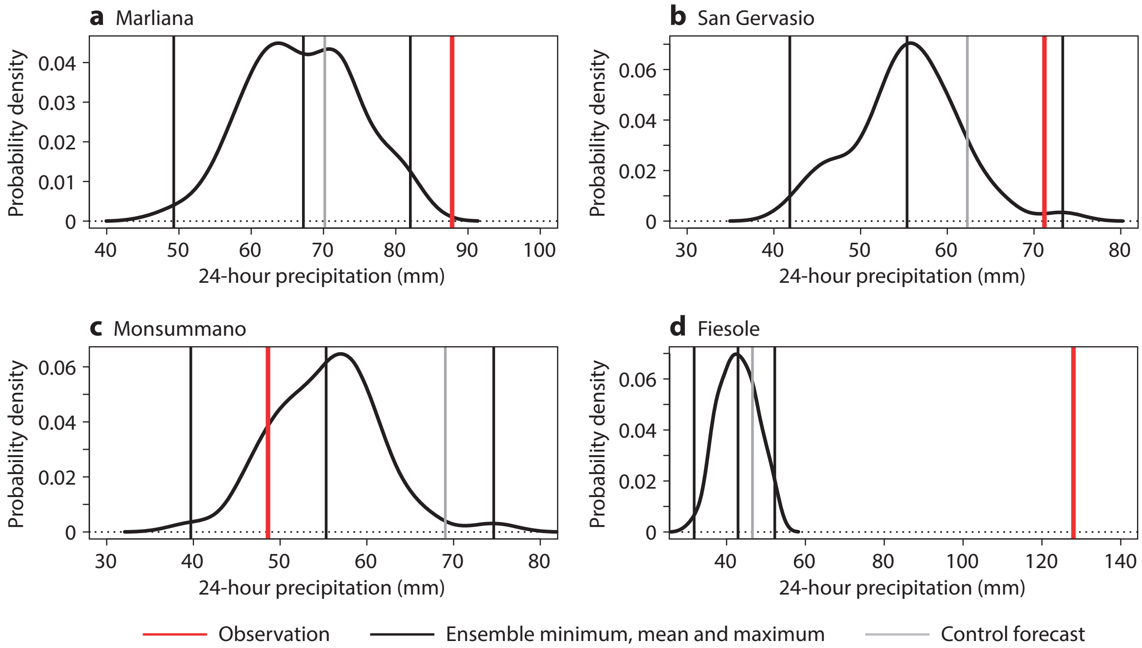

Figure 3 Probability distributions of the ENS precipitation forecasts initialised at 00 UTC on 4 November for accumulated precipitation over the next 24 hours at four rain gauges in the inner Arno River catchment area, located at (a) Marliana, (b) San Gervasio, (c) Monsummano and (d) Fiesole. The red vertical line is the observed value, the three black vertical lines are the minimum, mean and maximum value of the respective ensemble members, and the grey vertical line is the control forecast value. Distributions are estimated by means of the kernel density function.

To estimate the forecast uncertainty and assess the probability that extreme precipitation values might occur, we can look at the ensemble mean and spread (defined by the ensemble standard deviation). A good starting point is to look at the large-scale, synoptic features shown in Figure 5, represented by the geopotential height at isobaric level 500 hPa, for the four starting dates considered in Figure 4. The verification time is 06 UTC on 4 November 1966, which roughly corresponds to the time of maximum rainfall in the Arno River basin. From the analysis, two main synoptic features emerge: an upper-level trough with an axis oriented from France to the North African coast, and a robust ridge over the Balkans and Eastern Europe. As commonly happens during the autumn, a trough in that position favours the advection of warm and moist air northward from the southern Mediterranean Sea, while the ridge acts as a 'block' to the eastward propagation of the storm. The mean forecasts shown in Figure 5 tend to misrepresent the trough as a cut-off low over the Gulf of Lion, south of France, although the spread in this area is relatively high and thus the confidence is relatively low. On the other hand, the ridge over Eastern Europe is well predicted, with a low spread, in all the simulations considered.

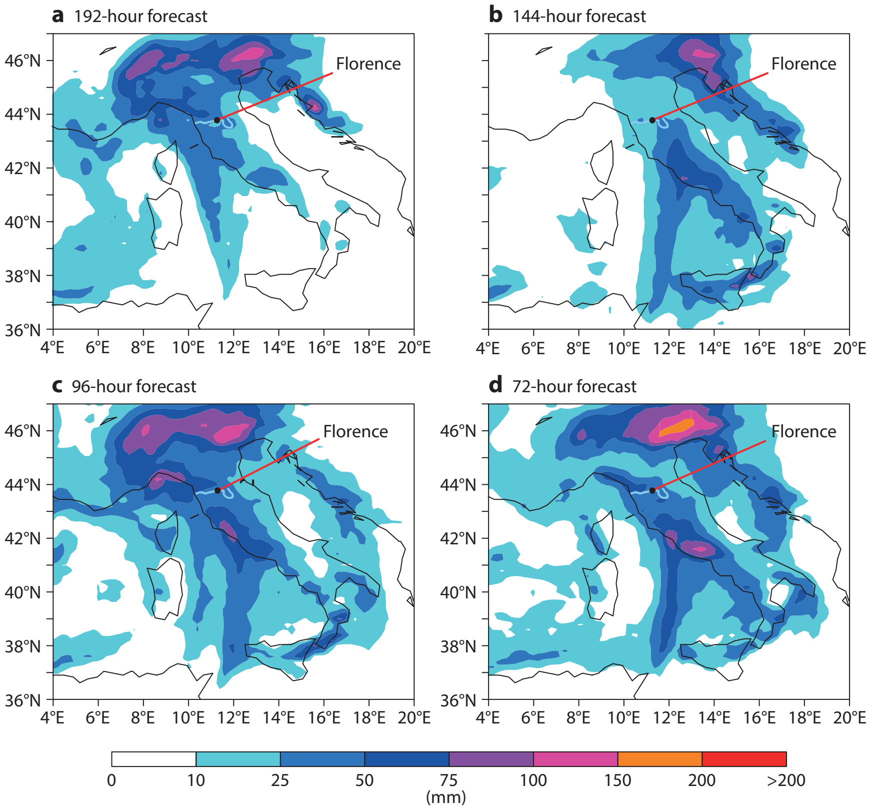

Figure 4 ENS (model cycle 41r2) control forecast of 24-hour accumulated precipitation between 00 UTC on 4 November and 00 UTC on 5 November, showing (a) the t+192h forecast initialized at 00 UTC on 28 October, (b) the t+144h forecast initialized at 00 UTC on 30 October, (c) the t+96h forecast initialized at 00 UTC on 1 November and (d) the t+72h forecast initialized at 00 UTC on 2 November.

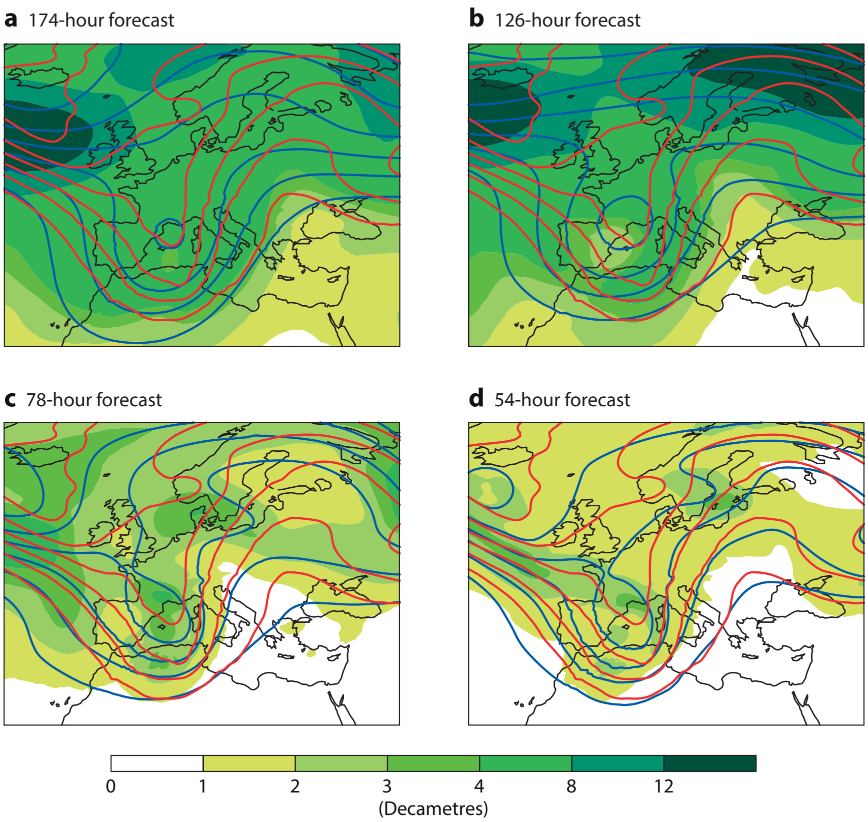

Figure 5 ENS 500 hPa geopotential height mean (blue contours) and standard deviation (shading) verified at 06 UTC 4 November 1966 for (a) the t+174h forecast initialised at 00 UTC on 28 October, (b) the t+126h forecast initialised at 00 UTC on 30 October, (c) the t+78h forecast initialised at 00 UTC on 1 November and (d) the t+54h forecast initialised at 00 UTC on 2 November. The analysis is shown in red contours.

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Precipitation probability forecasts corresponding to those shown in Figure 5, for rainfall amounts exceeding 50 mm in 24 hours (from 00 UTC on 4 November 1966 to 00 UTC on 5 November 1966), are shown in Figure 6. The 192-hour forecast does not show any clear signal of intense precipitation, whereas the 144-hour forecast initialised two days later provides a low to medium probability of intense precipitation over Italy. A day later, the 96-hour forecast shows that high probabilities of precipitation in excess of 50 mm are predicted over the Alps in northern Italy and along the Tyrrhenian coast. The 72-hour forecast initialised on 2 November confirms the earlier prediction, while slightly adjusting the regions most likely to see this level of rainfall to an area in north-east Italy and a larger area on the Tyrrhenian side of central Italy.

Short-range LAM ensemble forecasts

It is interesting to compare the limited-area, higher-resolution WRF ensemble forecasts with the global ENS. Figure 7 shows the predicted probability of precipitation exceeding 50 mm and 100 mm in the 24 hours ending at 00 UTC on 5 November obtained from convection-permitting WRF model simulations initialised at 00 UTC on 2 November. A comparison of the 72-hour forecasts shown in Figures 7a and 6d indicates 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, including the Arno River catchment area.

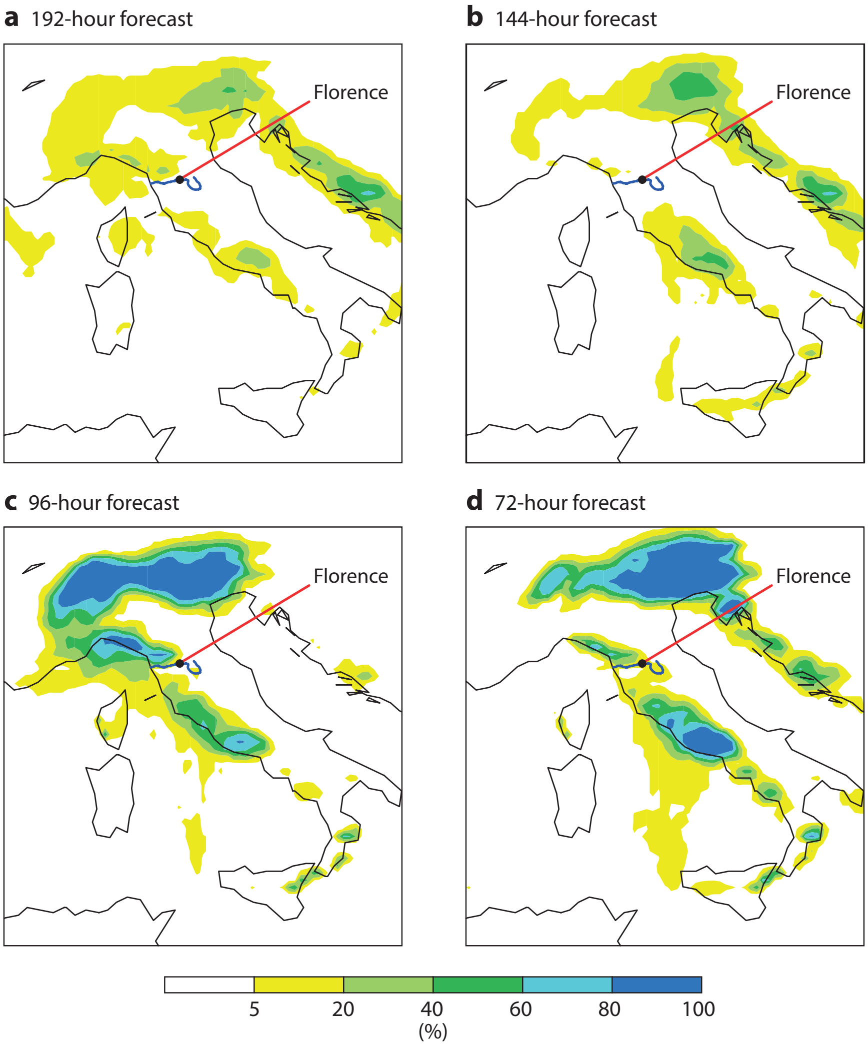

Figure 6 ENS probability of precipitation exceeding 50 mm in 24 hours for the period ending at 00 UTC on 5 November 1966 for (a) the t+192h forecast initialised at 00 UTC on 28 October, (b) the t+144h forecast initialised at 00 UTC on 30 October, (c) the t+96h forecast initialised at 00 UTC on 1 November and (d) the t+72h forecast initialised at 00 UTC on 2 November.

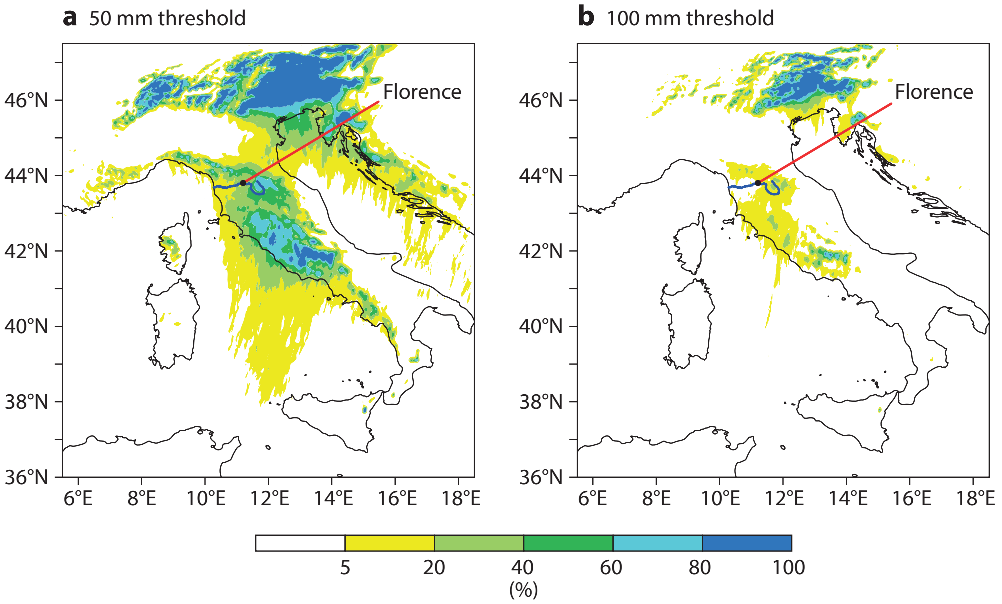

Figure 7 WRF ensemble probability of precipitation exceeding (a) 50 mm and (b) 100 mm in 24 hours for the period ending at 00 UTC on 5 November 1966 for the WRF convection-permitting t+72h forecast initialised at 00 UTC on 2 November 1966.

Conclusions

This brief analysis confirms conclusions published in the literature suggesting that ensemble-based, probabilistic forecasts can provide more valuable information than single forecasts. It also indicates that in the case of ‘L’alluvione di Firenze del 1966’ ensemble forecasts provide additional information on the synoptic conditions associated with the severe weather over Italy up to three days in advance. Results also indicate 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.

Given that we have discussed only a single, extreme event, these results do not enable us to draw any general conclusions on how accurately and how far in advance events of this kind can be predicted. Furthermore, in 1966 there were far fewer observations to estimate the forecast initial conditions than there are today. Thus the results presented here most likely underestimate the potential accuracy of ECMWF ensemble forecasts in predicting this type of extreme event.

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Further reading

Malguzzi, **P.**, **G. Grossi**, **A. Buzzi**, **R. Ranzi** & **R. Buizza**, 2006: The 1966 ‘century’ flood in Italy: A meteorological and hydrological revisitation. *J. Geophys. Res.*, **111**, D24106.

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