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Improvements in IFS forecasts of heavy precipitation

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Improvements in IFS forecasts of heavy precipitation

Richard Forbes, Thomas Haiden, Linus Magnusson

Good forecast skill for precipitation, and especially for heavy rainfall, is important for many applications. In particular, the accurate prediction of prolonged rainfall events combined with hydrological models can provide early warnings of flooding, which can have significant consequences for peoples' lives and infrastructure. Some of the most extreme precipitation events are associated with orography, where moist air is forced upward, leading to enhanced condensation and precipitation. As the upslope flow can persist over a period of time, considerable precipitation accumulations can occur within the surrounding river catchments, leading to increased levels of river flow and possible flooding both locally and downstream.

Here we evaluate the skill of quantitative precipitation forecasts in the Integrated Forecasting System (IFS) over the last 15 years, with an emphasis on heavy rainfall. The evaluation, which covers both high-resolution forecasts (HRES) and ensemble forecasts (ENS), shows significant improvements in skill over time measured by a number of different metrics and a skill increase equivalent to about one forecast day per decade.

Contributing factors include resolution upgrades and changes in data assimilation, ensemble perturbations, and forecast model numerics and physics, including the representation of cloud and precipitation processes. Recent changes to the cloud and precipitation physics in the latest operational cycle (41r1) have led to further improvements, particularly for high-impact precipitation events associated with orography.

Evolution of precipitation skill over time

ECMWF closely monitors the evolution of HRES and ENS precipitation forecast skill, using a number of different scores. Figure 1a shows the evolution of the headline skill score for precipitation from the HRES over the last 15 years for forecast days 1, 4, 7, and 10. The SEEPS skill score measures the ability of the forecast to distinguish between dry days, light precipitation, and moderate-to-heavy precipitation (Box A).

Figure 1a also shows the SEEPS skill score for forecasts from the ERA-Interim reanalysis over the same time period (dashed lines). Whereas the operational forecasting system has evolved over time, the ERA-Interim system is based on a 2006 release of the IFS. This provides a useful baseline, which removes the effect of year-to-year meteorological variations and changes to the observing system, and gives a more direct assessment of the evolution in skill due to changes to the forecasting system used for operations. Note that the resolution of the ERA-Interim forecasts is lower (TL255) than that of the operational HRES system at the time (TL799) and so the cross-over of skill is earlier than 2006.

The improvement over the last decade relative to the ERA-Interim system, shown in Figure 1b, is equivalent to a gain of about 1 forecast day, similar to the improvement in skill for synoptic-scale forecasts, as represented by the 500 hPa geopotential height. Note that jumps in skill due to the implementation of new model cycles are seen in the Figures as gradual increases over a year due to 12-month running averaging. Significant improvements for the operational HRES are associated with many of the IFS cycle changes over the 15-year period, including the resolution increase from TL399 to TL511 in model Cycle 23r3 (November 2000); data assimilation and cloud scheme changes in Cycle 25r3 (January 2003) and 31r1 (September 2006); and modifications during 2010 to 2013 including the change to prognostic rain and snow variables (*Forbes & Tompkins*, 2011) in Cycle 36r4 (November 2010). The magnitude of the SEEPS skill score change in Figure 1b is largest in the medium range for day 4 and then decreases with lead time.

The improvement of forecast skill specifically for heavy precipitation in the operational HRES is shown in Figures 1c and 1d using the Symmetric Extremal Dependence Index (SEDI) for a 24-hour precipitation accumulation threshold of 20 mm. SEDI is designed to be applicable to rare events and is a function of the hit and false alarm rates of a forecasting system (Box A).

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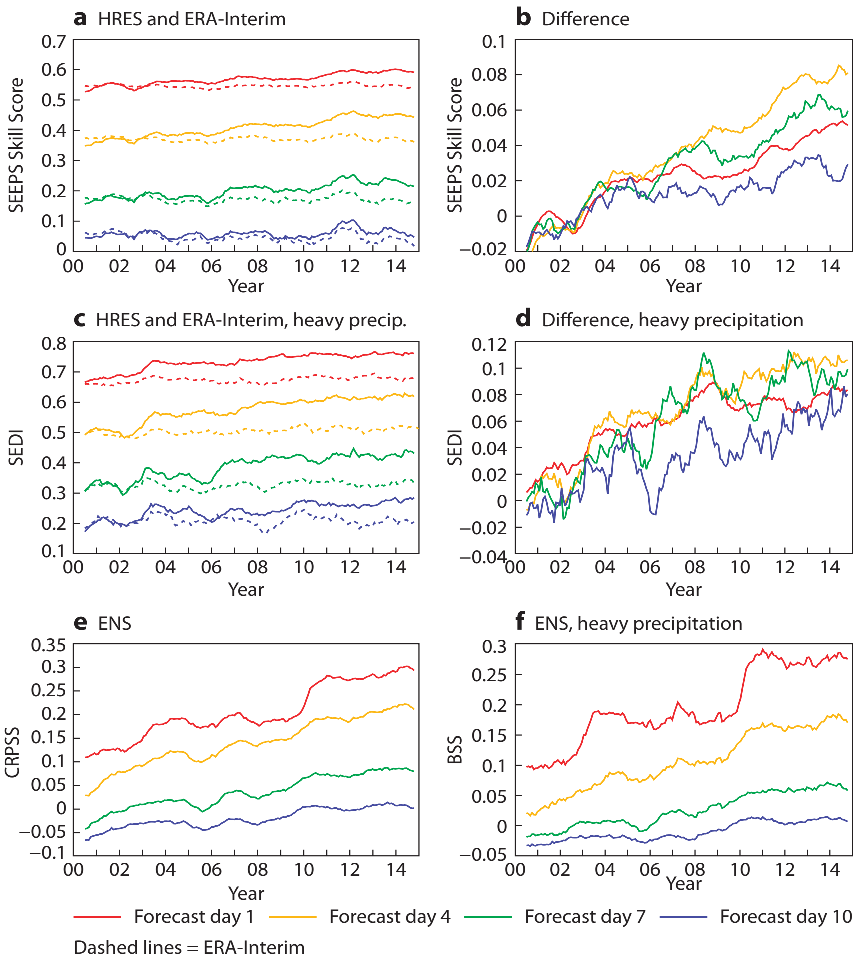

Figure 1 Evolution of extra-tropical 24-hour precipitation skill of the operational IFS over the last15 years for forecast days 1, 4, 7 and 10 showing (a) the headline SEEPS skill score for the HRES (solid) and ERA-Interim (dashed), and (b) their difference; (c) the SEDI for the HRES (solid) and ERA-Interim (dashed) for 24-hour precipitation accumulations greater than 20 mm, and (d) their difference; (e) the CRPSS for ENS, and (f) the BSS for ENS for 24-hour precipitation accumulations greater than 20 mm. All figures show 12-month running averages of the skill scores.

Similar to precipitation in general, the skill of heavy precipitation forecasts has increased substantially over the last decade. In the case of heavy precipitation, it is more difficult to attribute periods of stronger improvement to individual model cycle changes because of inter-annual variations in the number of occurrences and smaller sample size. The ranking of improvements relative to ERA-Interim in Figure 1d is the same as for the SEEPS skill score (forecast days 4, 7, 1, 10) in Figure 1b, but the difference between them is smaller in recent years. The relatively big improvement seen in day-10 forecasts relative to ERA-Interim over the last five years suggests that recent developments in the IFS have been especially beneficial for heavy precipitation forecasts at longer lead times. This is an important result since one of the longer-term goals at ECMWF is to extend the range of useful high-impact weather forecasts.

The evolution of ENS precipitation skill in general is shown in Figure 1e using the Continuous Ranked Probability Skill Score (CRPSS). It measures both the reliability and sharpness of probabilistic forecasts for the whole range of precipitation amounts (Box A). One of the most prominent improvements seen over the last decade can be attributed to the increase in horizontal resolution from TL399 to TL639 in model Cycle 36r1 operational in January 2010. However, in the very short range (day 1) the use of the ensemble of data assimilations (EDA) for initial perturbations, introduced with Cycle 36r2 in June 2010, has also contributed substantially to the increase in skill due to more spread in the initial conditions.

For heavy precipitation, improvements in the ENS are shown in Figure 1f using the Brier Skill Score (BSS) for a 24-hour accumulation threshold of 20 mm. It shows an evolution of skill over time which is similar to the evolution of the CRPSS score for all precipitation accumulations in Figure 1e, but with a substantial increase in the short range related to Cycle 25r3 data assimilation and ensemble changes in January 2003 and the changes in 2010. The overall similarity with the CRPSS is partly due to the fact that the CRPSS is also sensitive to errors in the magnitude of heavy precipitation.

Skill Scores

A

SEEPS

ECMWF developed the Stable Equitable Error in Probability Space (SEEPS) score to monitor the long-term trend in performance for forecasting precipitation (*Rodwell et al.*, 2011). Forecast precipitation accumulated over 24 hours is evaluated against observed precipitation amounts reported from SYNOP stations. At each observation location, the weather is partitioned into three categories: 'dry', 'light precipitation' and 'heavy precipitation'. The boundary between 'light' and 'heavy' is determined by the station climatology so that SEEPS assesses salient features of the local weather and accounts for climate differences between stations. The SEEPS score evaluates the performance of the forecast across all three categories with a value between 0 and 1. As a more accurate forecast gives a lower SEEPS score, it is useful to subtract the score from 1 to give the SEEPS skill score, which has higher values for improved skill.

SEDI

The Symmetric Extremal Dependence Index is a skill score appropriate for extreme events. It provides meaningful results in the case of rare events where the hit rate and false alarm rate decrease towards zero. It is defined for a binary event and thus requires a threshold to be set. Here we use 20 mm, which is a compromise between focussing on the more extreme precipitation events and yet having a large enough sample to reduce the level of noise (due to atmospheric variability) in the resulting scores.

CRPS/CRPSS

The Continuous Ranked Probability Score (CRPS) compares the probability distribution of the quantity forecast by the ensemble forecasting system to the observed value. Both forecasts and observations are expressed by cumulative distribution functions. The Continuous Ranked Probability Skill Score (CRPSS) then compares the CRPS of the forecast to a reference forecast, which in this case is the climatological probability distribution of the quantity.

BSS

The Brier Score (BS) is the most common accuracy measure of probabilistic forecasts of binary events. It is the squared difference between forecast probabilities and corresponding binary observations (0 for non-events, 1 for events). It requires a threshold to be set, and it is converted to a skill score (BSS) by comparing it to a reference forecast, which in this case is the climatological probability of the occurrence of the event.

New cloud and precipitation physics in Cycle 41r1

The latest IFS cycle, 41r1, became operational on 12 May 2015 and contains many modifications to the system, including specific changes to the precipitation physics to reduce the over-prediction of light rain and enhance the heavier rain. New formulations of rain-generation parametrizations were introduced. Changes were also made to the mixed-phase microphysics that increased the growth rate of snow particles falling through supercooled water clouds (Box B).

Precipitation generation is a very non-linear process, and the new physics slows down the initial formation (autoconversion) of rain when the cloud is shallow and liquid water content low, but as the cloud deepens, the amount of rain rapidly grows through the collection of cloud droplets (accretion) (Box B). If the cloud depth extends to temperatures significantly below freezing, ice and mixed-phase processes become important. In this situation, the growth of snow particles through deposition and collection, which subsequently melt before reaching the surface, can significantly enhance rain accumulations.

Evaluation shows improvements in precipitation forecasts due to the cloud physics changes in Cycle 41r1, reducing the occurrence of drizzle from shallow stratiform cloud (*Ahlgrimm & Forbes*, 2014) and increasing the amount of precipitation in forecasts of heavy rainfall (*Haiden et al.*, 2014). Figure 2 shows the SEDI skill score for 24-hour precipitation accumulations greater than thresholds of 20 mm and 50 mm, respectively, calculated over the 7-month period of the 41r1 experimental suite (e-suite) compared to Cycle 40r1, operational at the time. For the 20-mm threshold there is a small increase in skill in the first 5 days of the forecast and an improved frequency bias from 0.88 to 0.91 (a value less than 1.0 means there are fewer occurrences in the forecast than in the observations). For the higher 24-hour accumulation threshold of 50 mm, there is a larger relative increase in the skill further into the forecast, with an improved frequency bias across the forecast range from 0.48 to 0.55.

We expect the frequency of local extreme precipitation totals observed in SYNOP reports to be underestimated by the model due to sub-grid variability, which may for example be linked to unresolved orography. However, accumulations greater than 50 mm are observed at adjacent stations and in radar observations (not shown) across scales larger than the model resolution, which suggests that a large part of the underestimated occurrence of high accumulations is the result of a real model error. The improvement in frequency bias is therefore a step in the right direction to improve forecasts of extreme precipitation events.

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Precipitation physics

B

In the IFS, cloud and precipitation are represented with four separate prognostic variables (cloud liquid, cloud ice, rain and snow) and there are a number of parametrized microphysical processes that lead to precipitation generation and enhancement.

Autoconversion

The autoconversion process represents the collision-coalescence of cloud water droplets within the cloud to create larger droplets that start to fall. This is the process that initiates rain and is parametrized in the model as a rate of conversion from the cloud liquid category to the rain category, dependent only on the amount of cloud liquid water present and the number concentration of cloud droplets (currently a fixed value in the IFS). The more liquid water content there is, the larger the drops and the faster the collision-coalescence process to form rain.

Accretion

The accretion process represents the collection of cloud water droplets by falling rain drops which leads to the enhanced growth of the rain drops. The larger the rain drops, the faster they fall and the more cloud drops they collect, leading to a rapid increase in precipitation, particularly in deeper cloud systems. The parametrization of this process therefore depends on both the cloud liquid water and the rain water content.

Deposition

The deposition process represents the growth of frozen particles from water vapour in ice supersaturated regions. In mixed-phase cloud, the evaporation of supercooled cloud liquid water droplets can keep the air close to water saturation, which therefore maintains ice supersaturation and the continued growth of the ice particles (the Bergeron-Findeisen mechanism). Ice particles are transferred to the snow category as they grow, which can then enhance precipitation at the surface.

Riming

The riming process represents the collection of cloud water droplets by falling snow particles. For temperatures below 0°C, supercooled cloud droplets freeze as they collide with the snow particles, adding to the mass of the falling snow. The parametrized process therefore depends on both the cloud water content and snow water content. If the freezing level is above the surface, then the snow will melt, leading to enhanced rainfall at ground level.

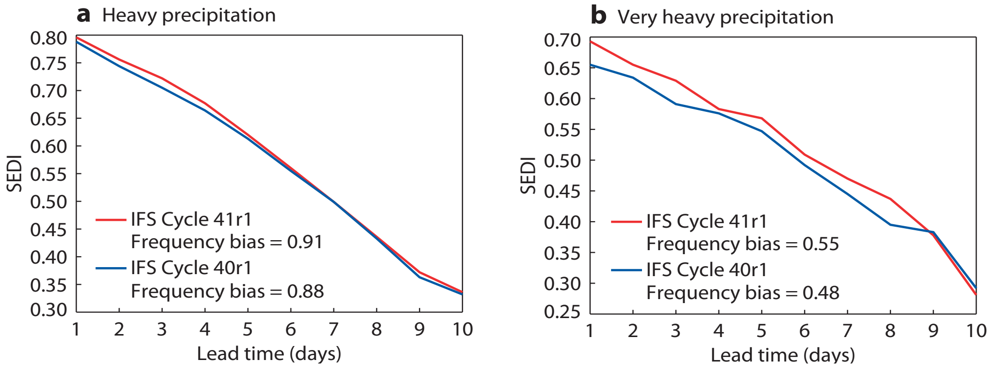


Figure 2 SEDI skill score for 24-hour precipitation accumulations greater than (a) 20 mm and (b) 50 mm for 40r1 (blue) and 41r1 (red) for the extratropics over the 7-month period from October 2014 to April 2015. The frequency bias has been calculated over the whole forecast range.

Impact of Cycle 41r1 on extreme precipitation forecasts

To further investigate the effects of changes in IFS Cycle 41r1 on the more extreme precipitation events, Figure 3 shows the 98th percentile of the 24-hour precipitation accumulation from a 20-year climatology for 40r1 and 41r1 and their difference, for a region of southern Europe centred on the Alps. The precipitation threshold corresponding to a 1-in-50 event in the model climate is based on re-forecast data from days 4 to 7 for the period February to April (for which data is available from the 41r1 e-suite period).

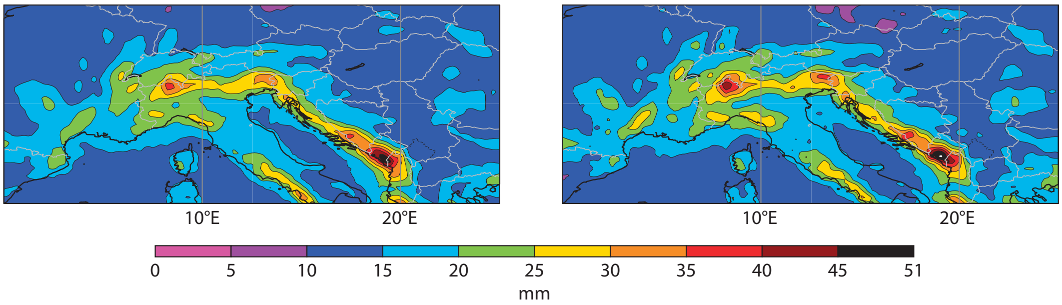
The results show that the predicted magnitude of the heaviest rainfall events has increased (during late winter to early spring) by more than 10% over the southern Alps, along the coast in northern Italy, and over the Balkans, and by over 20% in places. Figure 3d shows the orography for the region to highlight that the areas where the new cycle produces increased precipitation extremes are often associated with steep gradients in orography, where quasi-stationary forcing for deep precipitating cloud systems can lead to large local accumulations.

To illustrate the effect of IFS Cycle 41r1 on forecasts of individual cases, Figures 4 and 5 show two extreme precipitation events in southern Europe. The first case occurred in May 2014 when severe floods affected the Balkans (see *Magnusson et al.*, 2014), and the second case is from November 2014 when flash floods affected southern France and northern Italy over a period of three days. In both cases there were fatalities and widespread damage reported from the flood-affected regions. The figures show the precipitation accumulated over 3 days for forecast hours 6 to 78. Figures 4a and 5a show the observed 72-hour precipitation, 4b and 5b show the 40r1 forecast, 4c and 5c show the 41r1 forecast, and 4d and 5d show the difference between the two forecasts.

In the first case study (Figure 4), there is increased precipitation in 41r1 over the central Balkans, where the observed precipitation accumulations are highest, bringing the model in closer agreement with the observations in this region. The maximum precipitation is on the upslope of the orography, with advection mainly from the east to north-east during the period. In the second case (Figure 5), the flow is from the south and the maximum increase in precipitation is along the upslope of the southern Alps and the north-Italian coast. Again 41r1 increases the forecast accumulations where the precipitation is heaviest, in closer agreement with the observations.

Although neither of these case studies is contained within the reforecast climatology period used for Figure 3, the magnitude of the precipitation increases in 41r1 in the two cases is consistent with the increases in the 1-in-50 event climatology based on re-forecasts.

a IFS Cycle 40r1 **b** IFS Cycle 41r1



c Difference between 41r1 and 40r1 **d** Orography

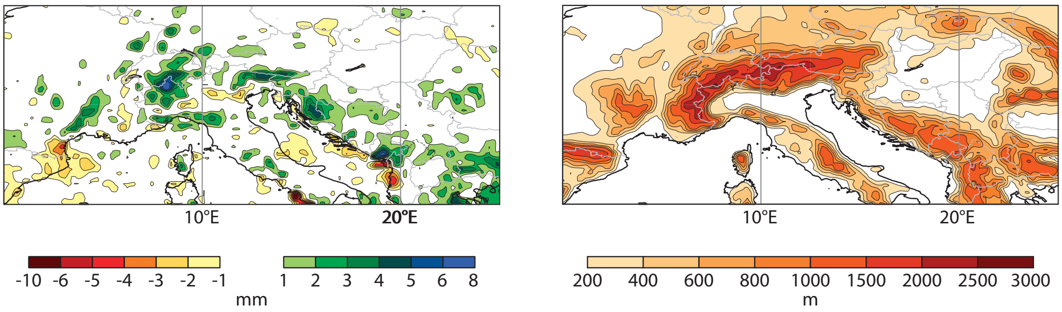


Figure 3 (a) 24-hour accumulated precipitation threshold for a 1-in-50 event (98th percentile) for the IFS Cycle 40r1 climatology over southern Europe, (b) the same as (a) but for the IFS Cycle 41r1 climatology, (c) the difference, Cycle 41r1 minus Cycle 40r1, and (d) the orography. The climatology is based on forecast days 4 to 7 from 4 perturbed ensemble members run once a week for the 3-month period February to April for each year in the past 20 years (4,160 forecasts).

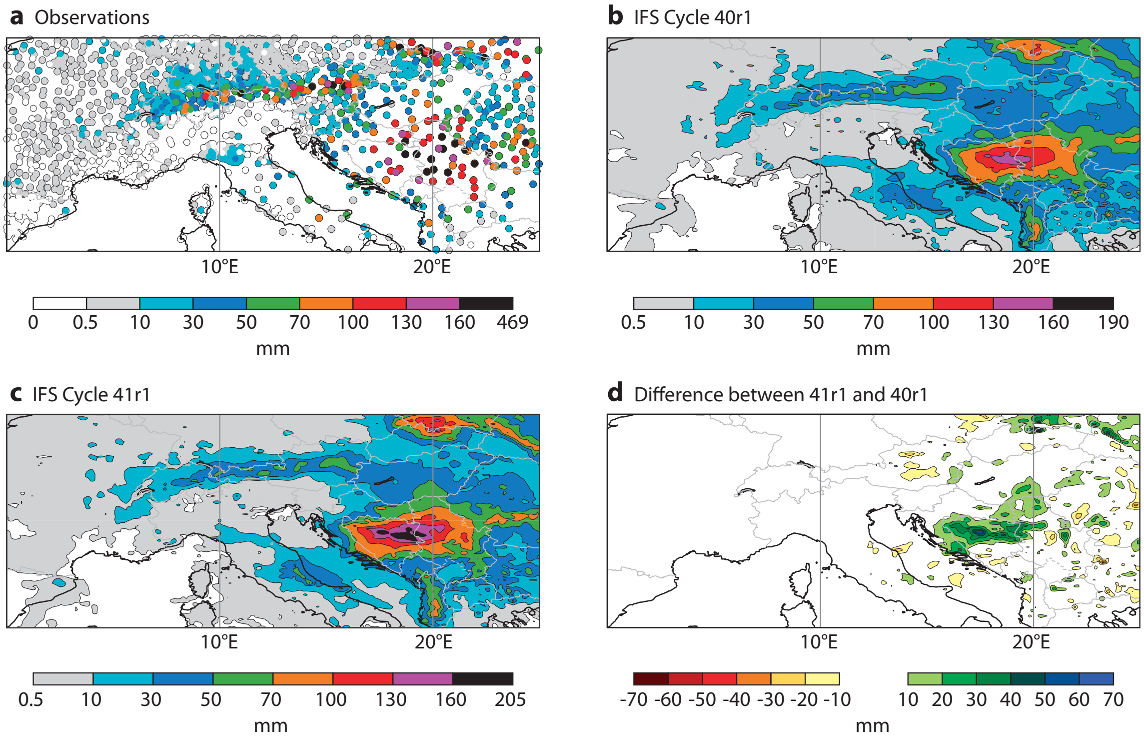


Figure 4 72-hour precipitation accumulation from 0600 UTC on 13 May 2014 according to (a) weather station observations (SYNOP reports), (b) 6 to 78-hour forecast produced by IFS Cycle 40r1 operational at the time, (c) 6 to 78-hour forecast produced by the new operational IFS Cycle 41r1 and (d) the difference, Cycle 41r1 minus Cycle 40r1.

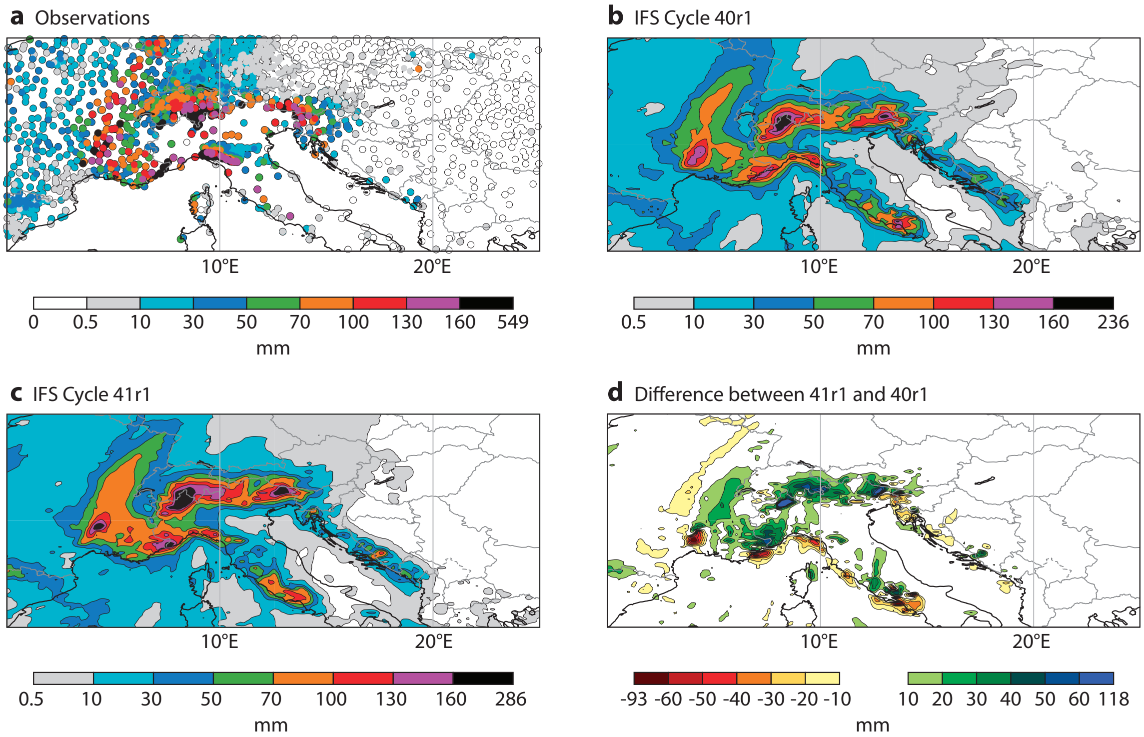


Figure 5 72-hour precipitation accumulation from 0600 UTC on 3 November 2014 according to (a) weather station observations (SYNOP reports), (b) 6–78-hour forecast produced by IFS Cycle 40r1 operational at the time, (c) 6–78-hour forecast produced by the new operational cycle IFS Cy41r1 and (d) the difference, Cycle 41r1 minus Cycle 40r1.

Summary and outlook

Heavy precipitation events can have significant impacts on society and accurate forecasts of the location and magnitude of the precipitation are an important part of severe weather prediction. High-resolution limited-area models provide valuable information on the prediction of more extreme local precipitation from convection and smaller scale orographic features, particularly for the short range. The ECMWF global model plays a complementary role in providing precipitation forecasts for severe events on the larger scale and into the medium-range. Forecasts of precipitation from the IFS, as well as from higher-resolution limited-area models, are used to drive the hydrological model for the operational European Flood Awareness System (EFAS), which produces medium-range probabilistic flood forecasts for Europe. Improving the prediction of heavy precipitation, particularly for extreme events associated with orography, is therefore one of the priorities for improving the reliability of flood forecasting, where early warnings can give additional time for the mitigation of impacts on lives and infrastructure.

In this article, we have looked at the change in the skill of precipitation forecasts in the IFS over the last 15 years. A number of statistical measures all show a significant increase in skill of precipitation accumulations for both HRES and ENS, particularly for the heavier precipitation. The greatest increase in skill for HRES is in the medium range (days 4 to 7), with a rate of skill increase of about 1 day per decade. These increases are a result of improvements in many aspects of the system, including changes to the data assimilation and use of observations, the forecast model, representation of uncertainty and resolution upgrades.

The new physics of warm rain and mixed phase precipitation processes in Cycle 41r1 has decreased the amount of predicted drizzle and increased the amount of predicted heavy precipitation. The biggest impact is in mountainous regions where the increased precipitation in Cycle 41r1 improves the prediction of the more extreme precipitation totals associated with orographic forcing.

Although a lot of progress has been made, work to improve quantitative precipitation forecasting in the IFS is continuing. The skill of precipitation forecasts is very much dependent on the predictive skill of the synoptic-scale forcing as well as the representation of cloud and precipitation physics and the resolution of the model. Further developments in data assimilation and model physics over the coming years should continue to feed into improved forecasts of precipitation.

High precipitation accumulations are usually associated with deep cloud systems extending to low-temperature altitudes. Anticipated improvements in ice and mixed-phase microphysics are expected to lead to further increases in predicted heavy precipitation accumulations, improving the low frequency bias of higher precipitation totals and bringing the model forecasts closer to observations. The grid resolution upgrade to approximately 9 km for HRES and 18 km for ENS planned for early 2016 will lead to an improved representation of the forcing over steep orography, with the potential for positive impacts on the predicted spatial distribution and magnitude of precipitation over complex terrain.

Further reading

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European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading, RG2 9AX, England

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