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PUBLICATION POLICY

The *ECMWF Newsletter* is published quarterly. Its purpose is to make users of ECMWF products, collaborators with ECMWF and the wider meteorological community aware of new developments at ECMWF and the use that can be made of ECMWF products. Most articles are prepared by staff at ECMWF, but articles are also welcome from people working elsewhere, especially those from Member States and Co-operating States. The *ECMWF Newsletter* is not peer-reviewed.

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New Strategy

After some eighteen months in the making, ECMWF's Strategy 2016–2025 has now been finalised. This ambitious plan, which sets ECMWF's direction of travel for the years to come, was developed with our Member and Co-operating States and partners and was unanimously approved by our Council on 30 June. Most of the process of drawing it up took place in 2015 as the Centre marked its 40th anniversary, and this provided a fitting background, helping us to shape our future through the scientific advances we have achieved in the past.

Today, as we acknowledge how tremendous the progress of the past 40 years has been, we recognise that much more can be done. More progress in research and computing techniques is needed in order to make an even bigger contribution to society. Our new Strategy rests on three pillars: an Earth system approach to modelling; the primacy of an ensemble approach to forecasting, providing forecasters with a range of likely scenarios; and scalable computations to meet the new technological challenges. The goals it sets include making skilful ensemble predictions of high-impact weather up to two weeks ahead. We also aim to predict large-scale patterns and regime transitions up to four weeks ahead and global-scale anomalies up to a year ahead.

The Strategy fundamentally relies on more collaboration with the wider scientific community in order to achieve our ambitious goals. We believe that with the support and cooperation provided by the community of European national meteorological services, the World Meteorological Organization, EUMETSAT and other space agencies, academia and all our partners across the world, we will continue to advance global numerical weather prediction at a pace that meets increasing societal demands.

As we wait for the full implications of the UK's EU referendum to unfold, we know that the spirit of collaboration, which is the essence of ECMWF, will remain, notwithstanding the fact that the UK has voted to leave the EU.

Over the 40 years of its existence, ECMWF has been living proof of what cooperation between EU and non-EU members can deliver in the scientific field, and we trust it will remain that way.

Florence Rabier
Director-General

New Strategy is "ambitious but not unrealistic"

On 30 June, ECMWF's Council approved the Centre's new 10-year Strategy, which covers the period up to 2025. In an interview with the Newsletter, ECMWF's Director of Research Erland Källén explains how the Strategy was drawn up, why collaboration lies at its heart, and what needs to happen to turn the "ambitious" goals it sets into reality.

What is the purpose of ECMWF's Strategy?

The purpose is to set our direction of travel for the next ten years. I think it is extremely important for an organisation like ECMWF to have a clear goal in mind that everybody understands. An important reason for our success in the past has been that all members of staff as well as our key stakeholders, the national meteorological services, are clear about this goal. Having such a focus is extremely motivating.

This is a ten-year Strategy, yet a new one is drawn up every five years. Why?

This is because we want to take into account things that are happening around us. In ten years a lot of things can happen. There may be significant scientific or technological developments, such as new supercomputer architectures which require highly scalable computer code. Therefore we have to be able to adjust the Strategy in shorter intervals than ten years. On the other hand, you need the ten years to set a broad direction of travel.

How was the Strategy drawn up?

It started with an internal consultation process within ECMWF. We have a lot of in-house expertise to tap into, and we have a scientific vision of where we want to go. In order to remain in a leading position, I think it is important for the impetus for our goals to come from inside.

But of course it is equally important for our Member and Co-operating States to be involved in the whole process to make sure that what we do meets their requirements. So the second step was to have intense consultations with all our Member and Co-operating States. The Directors of ECMWF travelled to most of our Member States and presented the results of the internal consultation to their national meteorological services to get their opinion.

After that we drew up a first draft version of the Strategy, which we then also submitted to our Committees. The Committees represent both our Member States' meteorological services and scientific specialists in relevant areas of science. So this consultation mechanism was also very important.

Finally, the input of space agencies was very important, especially of EUMETSAT, our main strategic partner in the area of space observations, and they were also involved in the consultation process.

"A very ambitious goal is to say that we will be able to predict high-impact weather events up to two weeks ahead."

Can you give an example of how the consultations influenced the outcome?

The emphasis on ensemble prediction is a good example. It was our intention to focus our attention on the ensemble method, on probabilistic forecasting, to produce and present forecasts. When we travelled to our Member States, we found that this approach resonated very well with them: everybody was on board.

This was by no means clear before the consultation process because many users still regard the high-resolution or deterministic forecast as ECMWF's prime product. We also show the Council our results in terms of deterministic forecast scores. But during the consultation process it became very clear to us that we should focus on the ensemble and that our scores and other follow-up mechanisms should reflect that better than today.

What are the main goals set by the Strategy?

A very ambitious goal is to say that we will be able to predict high-impact weather events up to two weeks ahead. I don't think anyone else has dared to state this as clearly as we have done in our Strategy. Of course, going out into the future as far as possible has always been the objective, but I think what is new is to say that we will be able to do this in the probabilistic sense up to two weeks ahead.

Another goal is to predict large-scale patterns and regime transitions up to four weeks ahead, and global-scale anomalies up to a year ahead. The meteorological community is putting more and more emphasis on the monthly timescale, and we believe we can meet that challenge and make much better probabilistic predictions on this timescale.

In terms of resolution upgrades, the Strategy specifies the target of a 5 km ensemble by 2025. That is ambitious, too. It is at the limit both in terms of what we can do scientifically and in terms of the computing capacity we envisage having in 2025.

These goals are ambitious but not unrealistic.

"We cannot do all the necessary research ourselves, it has to be supported and embraced by the scientific community in our Member States as well as worldwide."

How can they be achieved?

An important element is collaboration with our Member and Co-operating States. In the Strategy we have very much stressed the collaborative effort that is needed to reach these goals. We cannot do all the necessary research ourselves, it has to be supported and embraced by the scientific community in our Member States as well as worldwide.

The other collaborative aspect concerns weather observations, which we rely on but don't do ourselves. The Strategy says that we will continue to rely on the space programmes being planned with EUMETSAT, which is a very important partner organisation for us.

"New information from satellite data will be important for achieving our strategic goals."

The collaboration with ESA is also important, and then of course we also want to influence the American, Japanese and Chinese satellite programmes to make sure that the satellite data we get in the future will be useful to us.

Today more than 95% of all the observations we get come from satellites. New information from satellite data will be important for achieving our strategic goals.

What will have to happen in research and development?

In the area of research, there are three main goals. One is the fact that we want to use and further develop the ensemble method in all aspects of the forecasting system. This is necessary to achieve the goal of predicting severe weather up to two weeks ahead.

A second goal is improved Earth system modelling. We need to consider more parts of the Earth system, and the ones that we have included need to be better described. The description of clouds and radiation will have to be improved, and we believe that a better description of atmospheric composition will also lead to better weather forecasts.

A third main area is scalability, in other words adapting the forecasting system to the changing architectures of high-performance computers. Higher resolution is essential to improve the accuracy of the initial state and of our forecasts, but we need greater computing power to achieve it. That means we also need to develop our software to be able to use that kind of computing power. If we fail to deliver on scalability, we will not be able to increase the resolution at the required pace. So scalability is an absolutely essential part of our research programme.

What needs to change in the area of Earth system modelling?

If you look at weather prediction in historical perspective, it started out 60 years ago with scientists only looking at the mean flow in the atmosphere at a height of five kilometres, disregarding all the sub-grid scale physics, things such as radiation and clouds. When clouds and radiation began to be taken into account, this was still with a very primitive description of the Earth's surface.

Today we have a better description of the thermodynamics and dynamics of the atmosphere and we have a better coupling with the land surface. But there are still a lot of things we need to develop in sub-grid scale physics. One example is clouds and radiation, another is the exchange of moisture between the surface and the atmosphere.

Ocean coupling will also have to improve. In the past, we have regarded the oceans on the timescales relevant to medium-range prediction as completely static, which they are not. They are part of the dynamics of the whole system. And we have to get better at including the oceans in the data assimilation and at representing atmosphere–ocean couplings, including sea ice, at all time ranges. We have come to realise that, even just a couple of days ahead, the interaction between the atmosphere and the ocean in the tropics makes a big difference, and we have to get better at including that.

"We need to consider more parts of the Earth system, and the ones that we have included need to be better described."

In addition to scalability, what are the plans for high-performance computing?

The Strategy says that we want to be a centre for high-performance computing in meteorology. We want to continue to make it possible for Member States to use computing capacity on our machines, including for the optional provision of boundary conditions for limited-area modelling.

For future high-performance computing, the Strategy makes it clear that environmental sustainability is an important goal. Using computers in an environmentally sustainable manner means both making them more energy-efficient and making sure that the energy is generated in an environmentally sustainable way.

What role does environmental prediction play in the Strategy?

The EU-funded Copernicus Earth observation programme is now a large part of our organisation, in the form of the Atmosphere Monitoring Service and the Climate Change Service. We also contribute to the Emergency Management Service through flood computations and there might be scope for further development, taking on third-party activities that complement what we do.

Importantly, these activities should be in line with our core goals, with the Centre's Convention. I have already mentioned the link between atmospheric composition and weather forecasting. Climate reanalysis is also extremely important to weather prediction, for example as a source of verification, initialisation and calibration.

Outside ECMWF, scientists use reanalysis as a dataset to improve our knowledge of atmospheric processes. We can in turn use the insights gained to improve our forecasting system.

How important will training and education be?

In accordance with our Convention, we should continue to be a centre for advanced training and education in NWP. We want to continue to do that by providing courses and software, such as the OpenIFS. A new element in the Strategy is that we want to deepen training collaboration with our Member States.

This is important because ECMWF has unique collective expertise in NWP. We should take advantage of that by providing appropriate training and education. We also want to be able to recruit people in the future who can continue to develop our models, and scientists and others in the Member States are our recruitment base.

What does the Strategy say about funding?

There will continue to be a diverse set of funding sources to support ECMWF. The Member States and their contributions will continue to provide the core of our funding, but we also have to look for other types of funding, such as research funding from the European Commission, funding by satellite agencies, and other types of third-party funding.

Forecasts showed Paris flood risk well in advance

LINUS MAGNUSSON,
FREDRIK WETTERHALL,
FLORIAN PAPPENBERGER

At the end of May 2016, large parts of Europe were affected by severe convective precipitation. Flash floods in several places in southern Germany led to fatalities. Further to the west, the River Seine burst its banks. The peak flow in Paris, which was reached in the early hours of 4 June, was the highest since 1982.

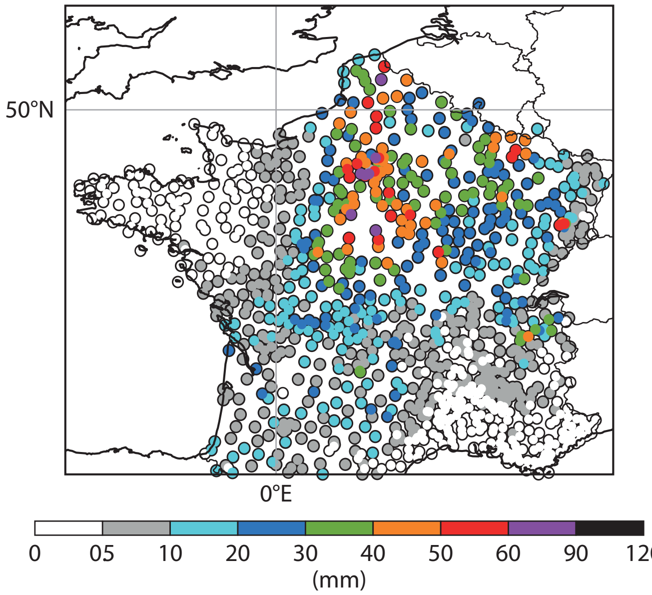
ECMWF's forecast index for extreme weather showed the risk of extreme precipitation in the affected regions several days in advance. The Centre's precipitation and temperature forecasts feed into flood forecasts issued by the EU's Copernicus Emergency Management Service (EMS). These indicated the possibility of an event with a 20-year return period in Paris as early as 25 May.

Record precipitation

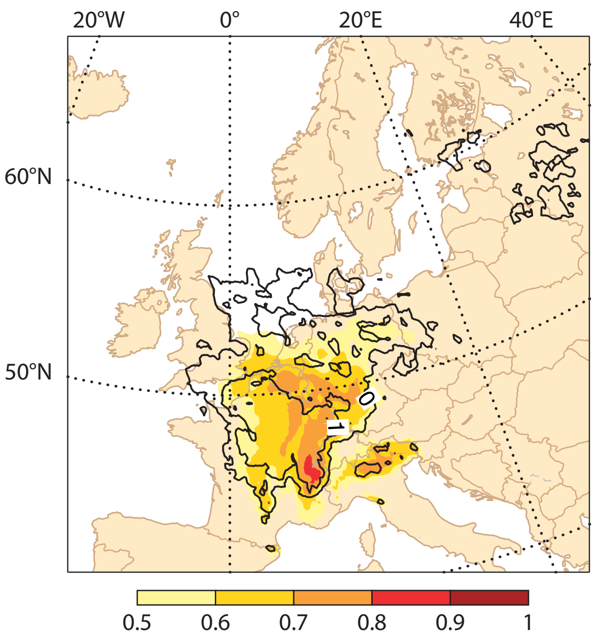
According to the French national meteorological service, Météo-France, May 2016 was the wettest since 1960 in the Île-de-France region. At the Paris-Montsouris weather station, the monthly total reached 179 mm, about three times as much as the climatological average, beating the previous record of 133 mm reached in May 1992. In the catchment area for the Seine, the soil was wet even before the most intense rainfall, which occurred around 30 May. As part of the ongoing project to collect high-density observations from national networks for verification purposes, ECMWF receives precipitation data from about 1,100 weather stations in France, a much higher number than the 190 SYNOP stations from which data is received through the Global Telecommunication System. These data enable ECMWF to better understand the spatial structure of precipitation events such as this. For 30 May 06 UTC to 31 May 06 UTC, almost all stations in northern-central France reported more than 20 mm accumulated precipitation, with a number of stations reaching 40 mm and a few more than 60 mm, which is equivalent to about a month's worth of rain. The precipitation was caused by an upper-level cut-off low that had a destabilising effect on the atmosphere and brought warm air northwards on its eastern side.

Extreme Forecast Index

ECMWF produces the Extreme Forecast Index (EFI) and the Shift of Tails (SOT) to help identify areas at risk of extreme weather. Both products compare the probability distribution function (PDF) derived from the ensemble forecast with the climatological PDF derived from a reforecast dataset. While the EFI measures the integrated shift of the PDF in the forecast, the SOT focuses on the extreme tail of the distribution. The forecast from 25 May 12 UTC indicated an increased risk of extreme precipitation for the 3-day period 29–31 May. High SOT values indicate



High-density network. Observed precipitation between 30 May 06 UTC and 31 May 06 UTC from high-density observations received from France.



Risk of extreme precipitation. Extreme Forecast Index (EFI) (shading) and Shift of Tails (SOT) (contours) for precipitation accumulated between 29 May 00 UTC and 1 June 00 UTC in the forecast from 25 May 12 UTC.

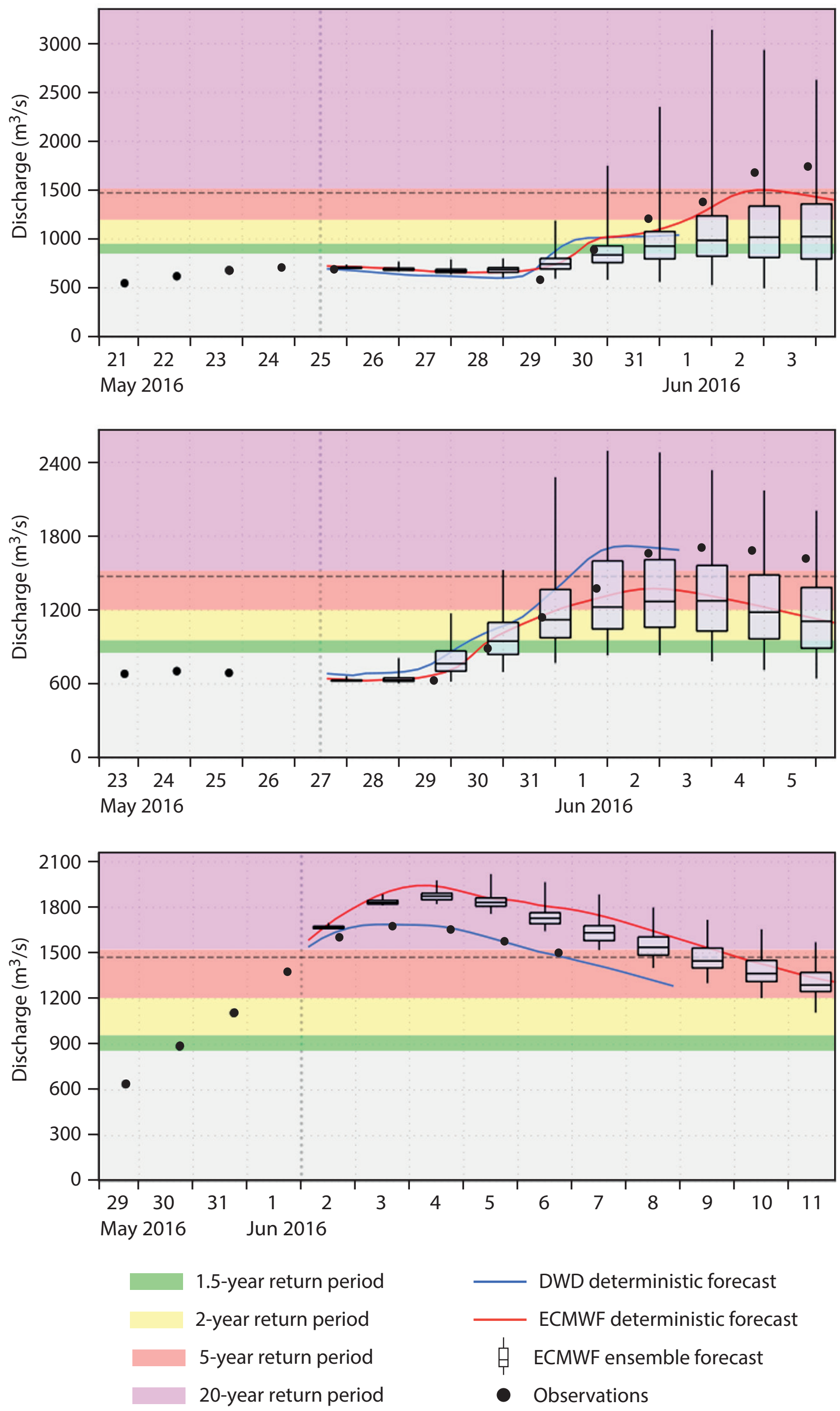
that a few ensemble members predict extreme precipitation. The early detection of the risk of extreme precipitation was due to the large-scale forcing. Although the forecasting system is not able to correctly predict individual convective cells, the increased probability of such cells is predictable.

Flood forecasts

The European Flood Awareness System (EFAS) uses precipitation and temperature forecasts from ECMWF, the German national meteorological service (DWD) and the COSMO consortium (COSMO Limited-Area Ensemble Prediction System forecasts) as forcings for its flood forecasts (https://www.efas.eu/user-information.html). EFAS produces medium-range probabilistic flood forecasts across Europe as part of the Copernicus Emergency Management Service – Early Warning Systems. In the figures presented here, the ECMWF ensemble forecast and high-resolution (deterministic) forecast are presented together with the DWD's deterministic forecast. COSMO-LEPS short-range forecasts were similar to ECMWF's predictions in this case.

The EFAS forecast system indicated the possibility of river discharge levels with a return period of more than 20 years as early as 25 May. By 26 May, a flood notification for a 1-in-20 year event was issued by EFAS for the Loing River (a tributary of the Seine). On 28 May, the warning was extended to the Seine in Paris.

As the event drew nearer, the magnitude of the predicted river discharge fluctuated between 30 May and 31 May depending on the expected rainfall for the event, but the timing was very stable, with the peak flow centred on Friday 3 June. Overall, the DWD deterministic forecast showed a more stable performance. Forecasts closer to the peak flow, for example from 2 June, showed a much smaller spread in the ensemble forecasts. This was mainly due to the fact that the major precipitation event occurred on 30 May, and the hydrological model propagated the flood wave down the Seine. The 2 June ensemble forecast generally slightly overpredicted discharge levels for the following few days. This was true for all ensemble members, indicating that the forecasts were not diverse enough to capture the observed intensity of the event. Although the ensemble spread cannot be assessed on the basis of a single case, we expect the ensemble to be over-confident as the EFAS system does not yet represent initial and model uncertainties in the hydrological model.



EFAS forecasts. The charts show EFAS forecasts issued on 25 May 12 UTC (top), 27 May 12 UTC (middle) and 2 June 00 UTC (bottom) for the Seine in Paris. The box-and-whisker plot represents the ECMWF ensemble forecast and shows the median (horizontal line), the 25th and 75th percentiles (box), and the minimum and maximum values (vertical lines).

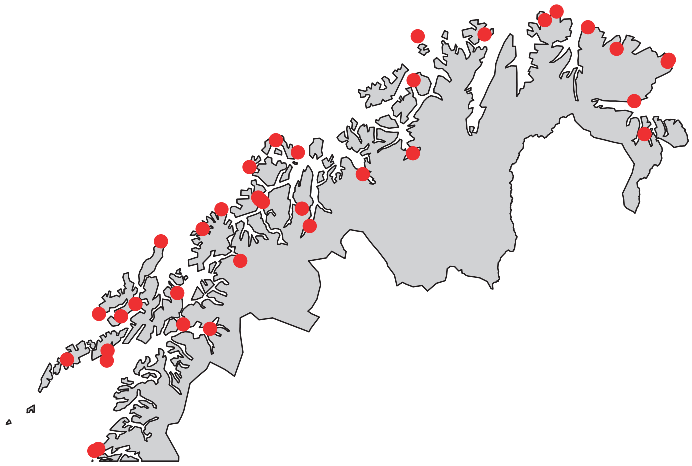
Better temperature forecasts along the Norwegian coast

IVAR SEIERSTAD,
JØRN KRISTIANSEN,
THOMAS NIPEN
(all MET Norway)

Surface temperatures from the ensemble forecasts (ENS) produced by ECMWF's Integrated Forecasting System (IFS) have often had large winter-time cold biases along the coast in northern Norway. Errors of 10–15°C have not been uncommon in the Lofoten and Tromsø areas. For instance, in Tromsø this winter we saw forecasts below -30°C even though the current minimum record is -18°C.

On 8 March 2016, ECMWF increased the horizontal resolution of its high-resolution (HRES) and ensemble (ENS) forecasts as part of the model upgrade to IFS Cycle 41r2. At the same time an important change was introduced to the radiation scheme. In the new version, the radiative heating and cooling at the surface is improved by approximate updates on the full grid and at every time step (ECMWF Newsletter No. 145, pp. 30–34). In the previous model cycle, 41r1, the radiation scheme was run on a much coarser grid, which contributed to large cold biases at several coastal land points. These model changes were therefore keenly anticipated by MET Norway after reporting back to ECMWF on this issue.

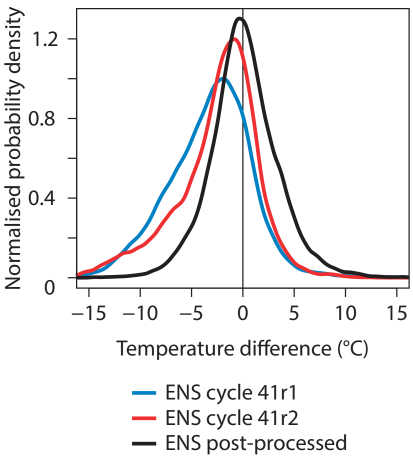
To evaluate the impact of the improved model, we have compared ENS temperature forecasts produced using the two model cycles this winter at 37 coastal weather stations. Probability density functions of the errors for the new and old model cycle show that the old cycle is skewed heavily towards negative values and has a substantial tail of large negative errors. The new cycle is clearly better, with fewer cases of too cold temperature forecasts. Out of 37 stations, 20 have a cold bias exceeding 2°C for the old cycle. This is reduced to 11 for the new cycle. However, some challenges remain: there are still some cases with unrealistic low temperatures. This is particularly true in areas with complex topography near the coast.



Coastal weather stations. The 37 weather stations along the coast in northern Norway that were used to evaluate the ECMWF ENS forecasts.

How has the impact of the cold bias on forecasts been reduced for users? Medium-range forecasts (3–10 days) are provided as location-specific forecasts on the weather website Yr (www.yr.no). Both consensus and probabilistic forecasts are produced using the ENS 51-member ensemble. Forecast users expect a smooth transition from the short-range forecast, which is based on a 2.5 km convection-permitting model (Arome-MetCoOp in collaboration with the Swedish national meteorological service, SMHI), to the medium-range forecast. To achieve this, ECMWF ensemble re-forecasts are an invaluable tool. The re-forecasts are reruns of the current operational ENS and provide a model climatology. The re-forecasts are particularly important when there are major model upgrades, such as this spring, as they quickly provide a large training dataset suitable for statistical post-processing.

The 2 m temperature ENS forecasts are bias-corrected for Norway using quantile mapping between the re-forecasts and a 2-metre climatology based on a high-resolution model and observations. The probability density function for these reprocessed forecasts shows that this method removes most of the cold bias for the 37 coastal weather stations in northern Norway. The probability density curve is no longer skewed towards negative values. The combination of improved model and statistical post-processing therefore makes us confident that MET Norway can provide its users with good medium-range temperature forecasts, including along the Norwegian coast in winter.



Reduced errors. Probability density functions (normalised to maximum value) of the difference between 3–5 day forecasts and observations at 37 coastal weather stations in northern Norway. Negative values mean that the forecasts are too cold. The evaluation period is 10 December 2015 to 1 February 2016. The post-processed forecast was produced using IFS Cycle 41r1.

Atmospheric composition forecasts move to higher resolution

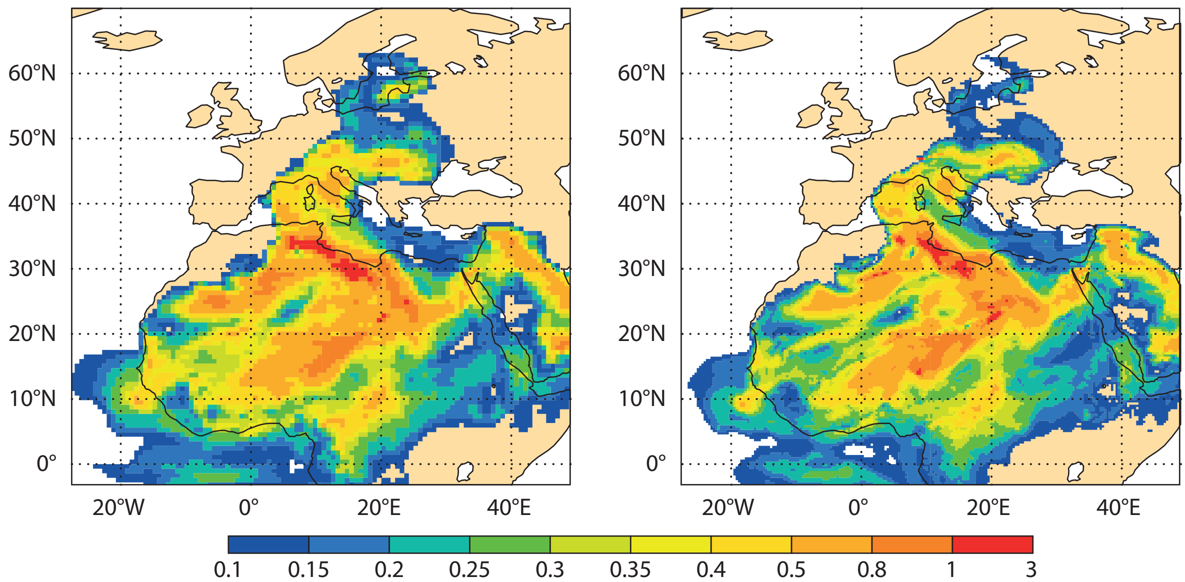
RICHARD ENGELEN

On 21 June, a new version of the global forecasting system run by the Copernicus Atmosphere Monitoring Service (CAMS) was made operational. This upgrade increases the spatial resolution of the forecast model from 80 km to 40 km. The improved system also produces two 5-day atmospheric composition forecasts per day instead of one. In addition to the forecast initialised at 00 UTC, there is now also a forecast initialised at 12 UTC, which is available before 22 UTC. The two changes mean that forecasts now provide more geographical details and are delivered to CAMS users in a timelier manner.

CAMS, which is operated by ECMWF as part of the EU's Copernicus Earth observation programme, is subject to quality control and validation. The improved forecasting system ran in test mode for several months before it was made operational. The CAMS validation team, which comprises many European actors and is led by the Dutch national weather forecasting service KNMI, carefully assessed the output to ensure the quality of the daily analyses and forecasts. Their report, which is available on the CAMS website (http://atmosphere.copernicus.eu/), was published at the end of April and formed the basis for the decision to go ahead with the implementation of this improved production system.

While the impact of the resolution increase on forecast quality is mostly neutral, in some cases significant improvements are seen close to the surface. This is due to better-resolved orography as well as a better use of the high-resolution emission datasets that form an input into the CAMS analyses and forecasts.

CAMS forecasts are available directly from the ECMWF MARS archive, through the CAMS web data server, or through operationally supported FTP access as described on the CAMS website. For any questions, please contact our User Support team at copernicus-support@ecmwf.int.



Forecasts at different resolutions. The charts show 21-hour forecasts of dust aerosol optical depth at 550 nm for 21 UTC on 5 April 2016 at the previous resolution (left) and at the new resolution (right).

OBE for Alan Thorpe

Professor Alan J Thorpe, ECMWF's previous Director-General, has been made an Officer of the Order of the British Empire (OBE) for services to environmental science and research.

During his time as Director-General (July 2011 to December 2015), Alan oversaw the restructuring of ECMWF and negotiations for the Centre to implement two of the EU's Copernicus services. He was instrumental in setting up the Scalability Programme and was an advocate of Earth system modelling. His previous positions include chief executive of the Natural Environment Research Council (NERC), director of the Hadley Centre for Climate Prediction and Research, and head of the Department of Meteorology at the University of Reading.

New satellite data reduce forecast errors

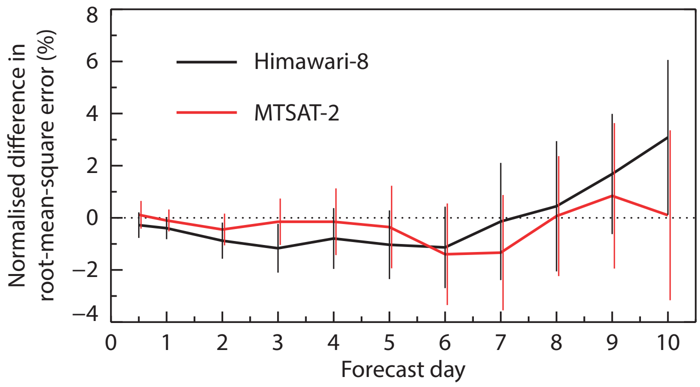
HEATHER LAWRENCE, JULIE LETERTRE-DANCZAK, KATIE LEAN, KIRSTI SALONEN, NIELS BORMANN

The first four months of this year saw a number of new satellite observations being assimilated operationally at ECMWF for the first time. These include observations from the geostationary satellite Himawari-8 over the Western Pacific region, winds derived from the AVHRR instrument on board the Metop polar-orbiting satellites, and new microwave radiances from the Chinese FY-3C polar-orbiting satellite. These additions include the first-ever use of some observational capabilities that have never before been available from space, and they reflect the constantly evolving satellite observing system.

Experiments show that the new data lead to a range of error reductions. These include reductions of about 1% in forecast errors of vector wind and geopotential height for some lead times and geographic locations. While such reductions may seem small, they have a significant cumulative effect, leading to an extension of the range of predictive skill.

Himawari-8

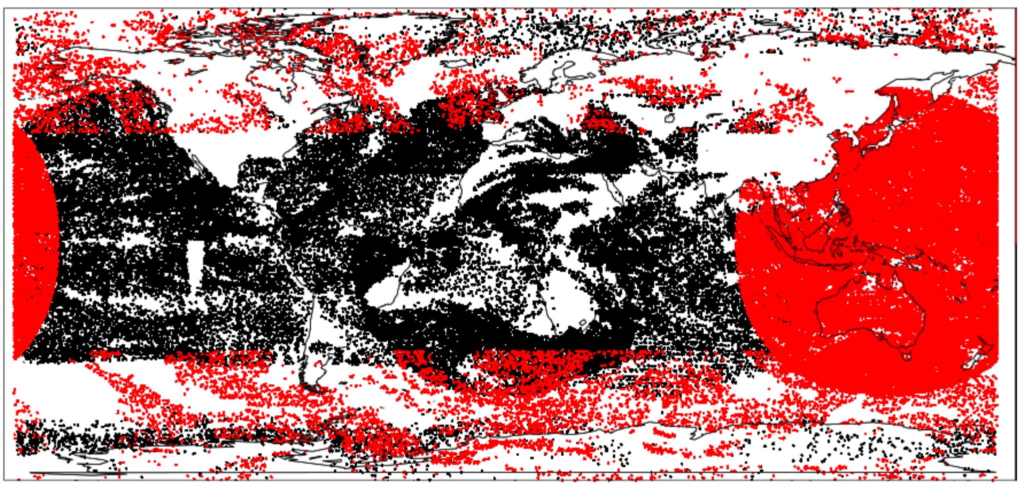
Himawari-8, which is operated by the Japan Meteorological Agency (JMA), is the successor of MTSAT-2. It carries the Advanced Himawari Imager (AHI), the most advanced imager currently in geostationary orbit. Compared to its predecessor, it provides up to two times higher spatial resolution; it is able to produce full-disk images over two times faster; and it has 16 rather than 5 channels. Himawari-8 data are assimilated at ECMWF in the form of Clear Sky Radiances (CSRs) from water vapour channels and Atmospheric Motion Vectors (AMVs) derived by tracking cloud structures in consecutive images. The data were activated on 12 January and 15 March 2016, respectively.



Impact of assimilating Himawari-8 CSRs. The chart shows the relative change in the root-mean-square error of 500 hPa geopotential height forecasts over the southern hemisphere (–90° to –20°) as a function of forecast range for the assimilation of three water vapour channels from Himawari-8 (black line) and of one water vapour channel from MTSAT-2 (red line). The vertical bars are uncertainty bars. Negative values indicate reduced errors compared to not assimilating data from the respective water vapour channels.

The Himawari-8 CSR assimilation benefits from the fact that for the first time three water vapour channels are available from geostationary orbit (compared to one for MTSAT-2), resulting in better discrimination of humidity structures in the vertical. This also facilitates the extraction of dynamical information through the tracing effect in ECMWF’s 4DVAR data assimilation system. In addition, the improved spatial resolution enables the use of a better cloud and aerosol mask. Tests show that assimilating Himawari-8 CSRs reduces forecast errors more than assimilating MTSAT-2 CSRs does.

The assessment of the Himawari-8 AMVs shows improved data quality

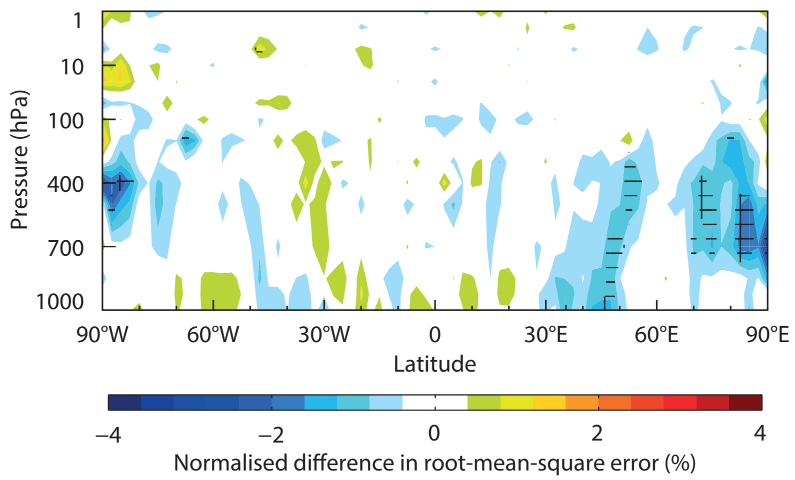


Better AMV coverage. The map shows the positions of assimilated AMV observations for a 12-hour assimilation cycle, with the recently activated AMVs shown in red and the old coverage shown in black. Himawari-8 is positioned over the Western Pacific, whereas the dual/single Metop AMVs cover the higher latitudes.

compared to MTSAT-2, resulting from a combination of the new instrument capabilities and a completely revised derivation algorithm developed by JMA. There is a substantial increase in the number of available AMVs, including from some of the additional channels available. Early experiments tried to exploit the data available from the new channels, but mixed results led to choosing a selection that is similar to the previous MTSAT-2 configuration. This nevertheless leads to a very significant increase in the number of assimilated wind data, with some positive impact on wind forecasts. A second iteration which aims to further optimise and expand the data selection is under way.

Metop satellites

The introduction of the EUMETSAT-processed single and dual Metop AMVs on 4 February 2016 greatly increased the global AMV coverage, closing the gap that has traditionally existed between geostationary and polar AMVs (around 55–70°N/S). This has been made possible by deriving AMVs from the combination of the two AVHRR instruments available on the two Metop satellites that are flying in tandem, resulting in global coverage for the dual Metop product. In addition, EUMETSAT has introduced several changes to their polar AMV processing in recent years, and the long-term monitoring statistics indicate significant improvements in data quality. At high latitudes, the single and dual Metop AMVs now have characteristics similar to other AMVs, and the assimilation of the data poleward of 40°N/S has a positive impact on short-range and a neutral impact on longer-range forecasts. Enhancing the use of polar wind data in general is desirable, as some of the old polar AMVs have recently been lost.

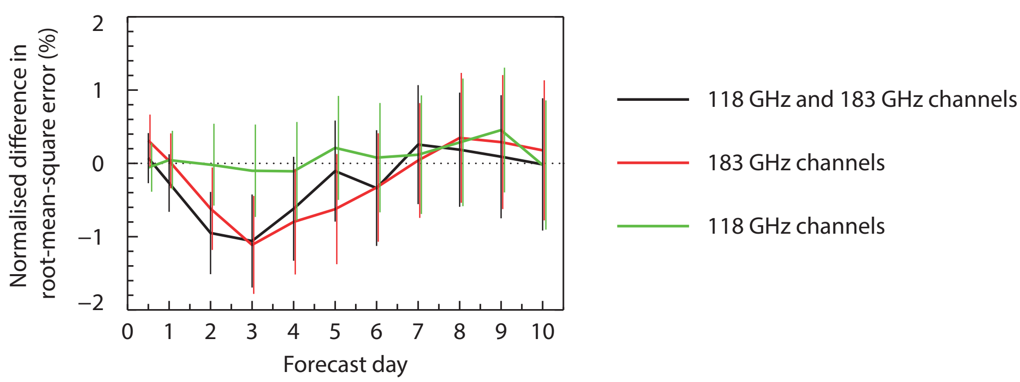


Impact of assimilating Metop AMVs. The chart shows the relative change in the root-mean-square error of day 2 wind forecasts resulting from the assimilation of the combination of single and dual Metop AMVs, shown by latitude and pressure level. Reductions in the forecast error (blue shading) can notably be seen at high latitudes. Cross-hatching indicates statistical significance.

FY-3C

Finally, the MicroWave Humidity Sounder-2 (MWHS-2) instrument carried by the Chinese polar-orbiting FY-3C satellite was activated in operations on 4 April 2016. This instrument combines traditional microwave humidity sounding capabilities at 183 GHz with new channels at 118 GHz, which have never before been available from space. The 118 GHz channels provide new information on temperature, humidity and cloud. We use the data in ECMWF's all-sky system, continuing the pioneering work on the use of cloud-affected microwave radiances.

Trials show that assimilating 118 GHz channels improves short-range forecasts for low-level humidity and cloud in the southern hemisphere. The 183 GHz channels were also found to improve short-range humidity forecasts globally and vector wind day 3 forecast scores. The operational assimilation of MWHS-2 is another successful outcome of ECMWF's fruitful collaboration with the Chinese Meteorological Administration (CMA) regarding the evaluation and assimilation of new Chinese satellite data. MWHS-2 is the second Chinese instrument to be activated at ECMWF, following on from the activation of the FY-3B MWHS humidity sounder in 2014.



Impact of assimilating different MWHS-2 channels. Relative change in the root-mean-square error of wind forecasts at 850 hPa in the southern hemisphere (–90° to –20°) as a function of forecast range for three different sets of assimilated channels. The figure shows a 1% reduction in the forecast error at day 3 resulting from assimilating MWHS-2 data from the 183 GHz channels and from assimilating MWHS-2 data from both the 183 GHz and the 118 GHz channels.

ECMWF steps up assimilation of aircraft weather data

BRUCE INGLEBY, LARS ISAKSEN, MOHAMED DAHOUI

On 8 March 2016, ECMWF started the operational assimilation of humidity data from commercial aircraft reporting via the AMDAR programme. This was one of the changes included in model cycle 41r2, which was made operational that day. About 11% of AMDAR reports include a usable humidity value, mainly from the US AMDAR programme but also from its European equivalent. The aircraft involved have a diode laser instrument installed to measure atmospheric water vapour.

EUMETNET, a grouping of 31 European national meteorological services that cooperate in activities including observing systems, is considering whether to install further humidity sensors. EUMETNET funded ECMWF to perform a study of the usefulness of aircraft humidity data, including a trial covering the period from April to June 2014.

Over North America, the quality of AMDAR humidity data was similar to or slightly better than that of radiosondes when compared with short-range forecasts. In the same region, the assimilation of AMDAR humidity data slightly improved short-range precipitation forecasts verified against radar/surface composite fields.

The impact on standard verification scores was small, in part because the extra data are in already well-observed regions. Early in 2016, the European AMDAR humidity sensors were upgraded, and monitoring in ECMWF's Integrated Forecasting System (IFS) helped in the early diagnosis of problems. The sensors now provide high-quality data.

New routes

Over the last few years, there has been a significant increase in the number of AMDAR reports. This has come primarily from US-based aircraft, but Europe and other regions are also contributing. Earlier this year, work by the WMO, EUMETNET-AMDAR and Météo-France resulted in 70 Air France and 60 British Airways Boeing 777 aircraft providing AMDAR data. In part these are replacing older aircraft, but there are also new routes over several data-sparse areas of the globe. These reports include wind and temperature but not humidity information. To minimise the communication costs involved, these aircraft do not report over Europe, which is already densely observed, but they do report over Africa, the Carribean and ocean areas.

Bias correction

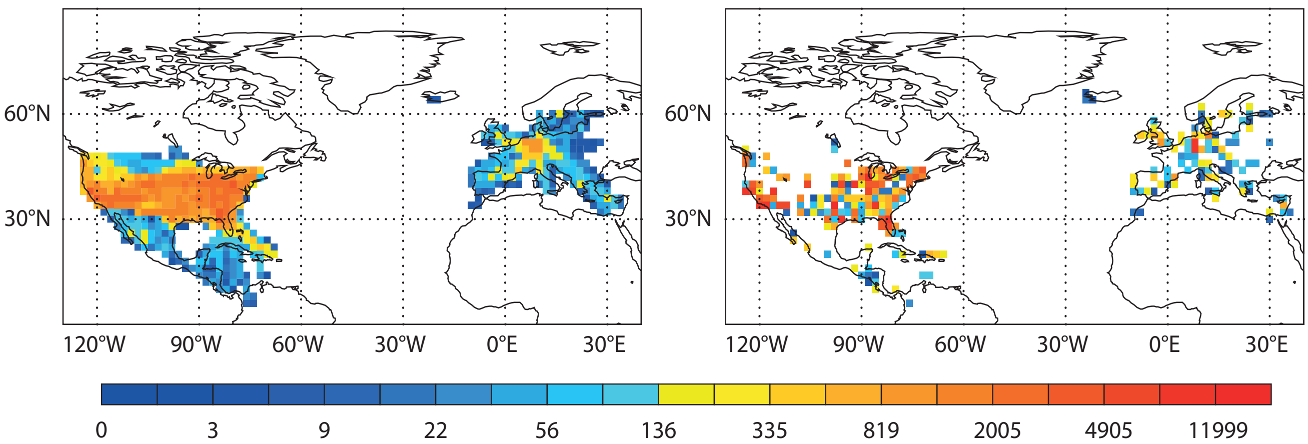
In the IFS, aircraft data are currently the most important in situ data in terms of improving forecasts. This is despite the fact that, for reasons that are not fully understood, aircraft temperature reports are often biased towards higher values (typically by 0.2 to 0.5 degrees). The size of the bias depends on various factors. An improvement to the bias correction used at ECMWF is being prepared for future implementation.

The AMDAR programme

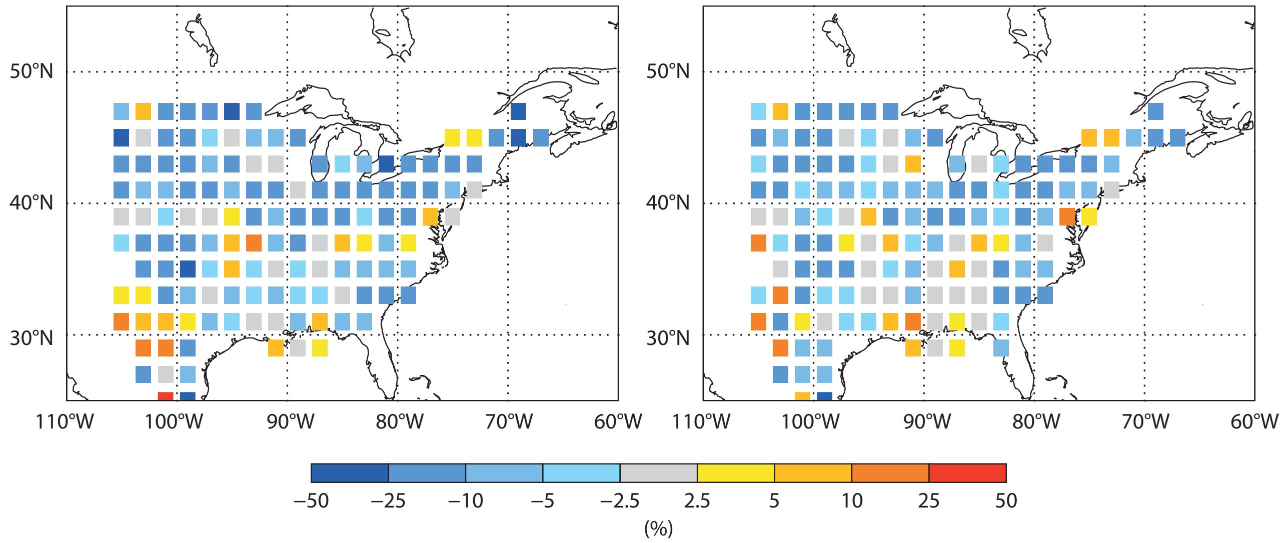
The Aircraft Meteorological Data Relay (AMDAR) programme is coordinated by the World Meteorological Organization (WMO) and is part of the Global Observing System. It uses predominantly existing aircraft on-board sensors and communication systems to collect, process and format meteorological data and to transmit them to ground stations.

The global AMDAR system produces about 700,000 observations per day of air temperature and wind speed and direction as well as an increasing number of humidity and turbulence measurements.

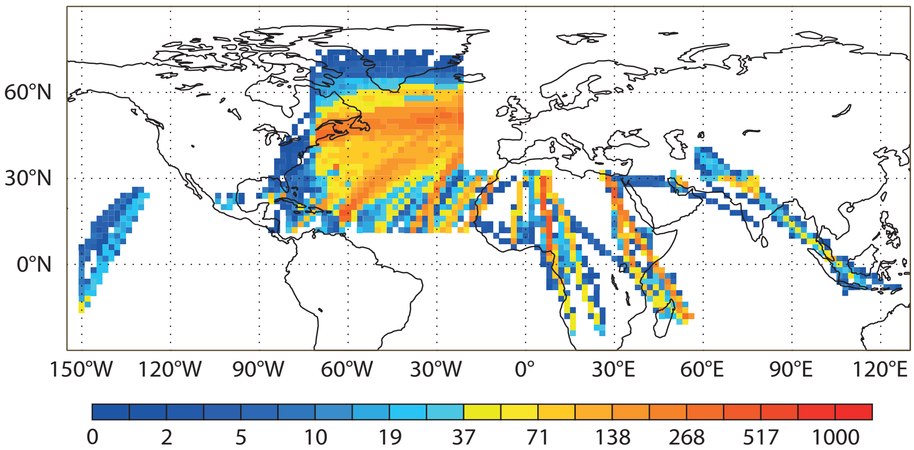
EUMETNET runs the E-AMDAR service to provide measurements of high-quality upper-air meteorological parameters from aircraft.



Number of humidity observations. The maps show the number of AMDAR aircraft humidity observations per 2°x2° square used at ECMWF in April 2016 for the upper troposphere (above 400 hPa) (left) and for the lower troposphere (below 700 hPa) (right). One flight route in Southeast Asia with a small number of observations is not shown.



Improvement in forecasts. The charts shows the normalised percentage difference between radar/weather station (SYNOP) observations and 6-hour accumulated precipitation forecasts without using aircraft humidity observations (left) and using such observations (right), in an experiment covering the period 1 April to 30 June 2014. More grey squares or less intense colours indicate improvements (smaller biases).



Number of wind observations. The map shows the number of AMDAR aircraft wind observations in the upper troposphere (above 400 hPa) per 2°x2° square recently made available from Air France and British Airways Boeing 777 aircraft and used at ECMWF between 9 March and 25 April 2016.

GloFAS meeting supports integrated flood forecasting

REBECCA EMERTON (University of Reading & ECMWF), HANNAH CLOKE & LIZ STEPHENS (University of Reading)

From 4 to 6 May, the University of Reading held the first Global Flood Awareness System (GloFAS) community workshop, aimed at supporting the integration of GloFAS forecasts into existing national and local forecasting capabilities. The workshop, led by Professor Hannah Cloke and Dr Liz Stephens (University of Reading), included seminars, practical activities and discussion sessions.

Workshop participants came from ECMWF and the University of Reading, alongside the Servicio Nacional de Meteorología e Hydrología del Perú (SENAMHI), the Red Cross/Red Crescent Climate Centre (RCCC), the Mozambique Red Cross, the Belize Hydromet Service, the Xiamen Weather Service Centre and the European Commission Joint Research Centre (JRC).

Open event

The event began with an afternoon of seminars followed by a poster session, attended by 80 delegates from across the globe, including forecasters, policy makers, academics and decision makers, all interested in

Keynote presentation. ECMWF Director-General Florence Rabier gave a keynote talk at the GloFAS community workshop.

Interactive session. Ervin Zsoter (ECMWF) led a session on post-processing of GloFAS forecasts.

learning about GloFAS and the use of global forecasts. Florence Rabier, the Director-General of ECMWF, gave the first keynote presentation, providing an insight into the role of ECMWF and its forecasts, and how GloFAS came to be. In a second keynote talk, Dr Nicola Ranger of the Department for International Development (DFID) discussed how DFID make use of a range of forecasts, both directly and indirectly. Further presentations were given by Erin Coughlan de Perez from the RCCC, Professor Ros Cornforth, the director of the Walker Institute, and Dr Peter Salamon, the GloFAS project manager at the JRC.

Interactive sessions

The following two days focused on the use and integration of GloFAS forecasts. They included training sessions provided by Hannah Cloke and Liz Stephens on ensemble forecasting, hydrological modelling and decision-making with probabilistic forecasts, and by Peter Salamon on the GloFAS interface and forecasts. The workshop also involved several interactive sessions. The first of these, led by Liz Stephens, provided training for participants on how to access and interpret the output of GloFAS forecasts. This involved accessing and plotting the forecast data using different visualisations and discussing the pros and cons of each in the context of decision-making. A second session, run by PhD students Louise Arnal and Rebecca Emerton (University of Reading and ECMWF), focused on evaluating the forecasts using different verification metrics and skill scores. Ervin Zsoter and Paul Smith (ECMWF) designed a further session, led by Ervin, on post-processing of GloFAS forecasts, where participants were able to apply two bias correction techniques in an attempt to improve the forecasts in different river basins using available river flow observations.

GloFAS community

The workshop provided an excellent opportunity for forecasters and decision makers to receive training from GloFAS model developers at ECMWF and the JRC through tailored courses and interactive sessions. It also provided a platform for discussion of the experiences of forecast users in implementing GloFAS forecasts at the local scale and using these for decision-making. Everyone came away from the event having learnt something valuable about the forecasting system and its use in decision-making for flood events.

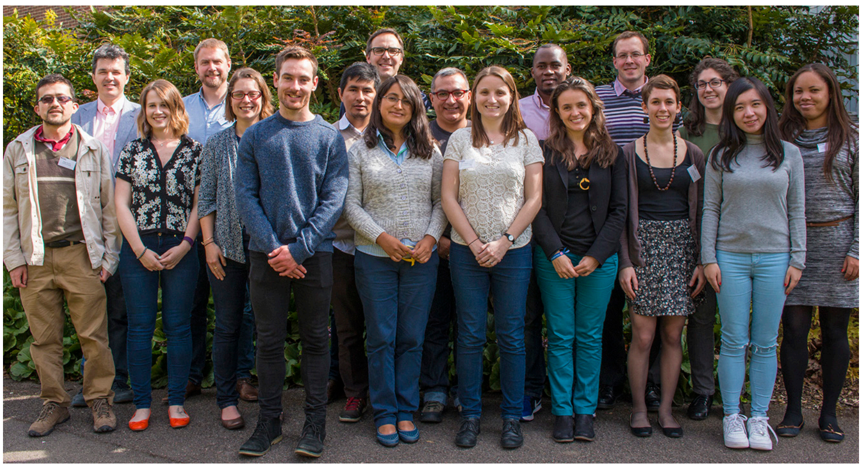
Workshop organisers. The workshop was led by Liz Stephens (left) and Hannah Cloke from the University of Reading.

A big thank you to the workshop organisers at both the University of Reading and ECMWF, and to the speakers and participants, who helped make the event such a success.

This workshop was funded by the GFDRR/DFID Challenge Fund and a research impact award made by NERC to Professor Hannah Cloke, with further support from the University of Reading and the Walker Institute.

ECMWF and GloFAS

ECMWF is developing the Global Flood Awareness System (GloFAS) in cooperation with the European Commission Joint Research Centre (JRC) and the University of Reading. GloFAS combines the Centre's medium-range weather forecasts with a hydrological model to provide global forecasts of flood events. GloFAS users include national and regional water authorities, water resource managers, hydropower companies, civil protection and first line responders, and international humanitarian aid organisations.



Workshop participants. The full three days of the event were attended by delegates from ECMWF, the University of Reading, SENAMHI, the Red Cross/Red Crescent Climate Centre, the Mozambique Red Cross, the Belize Hydromet Service, the Xiamen Weather Service Centre and the JRC.

First Scalability Day charts way forward

PETER BAUER

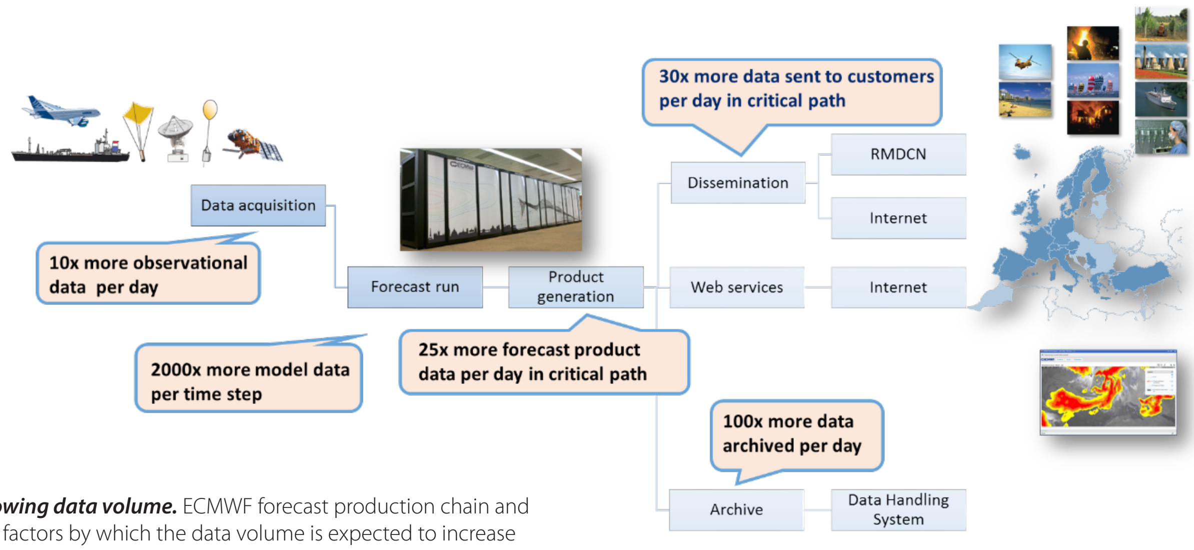
The first ECMWF Scalability Day was held on 24 May 2016. It served to chart the way forward for the Scalability Programme, which aims to prepare the Centre for the exascale era of supercomputing. The event provided a forum for staff directly involved in the programme to explain their work, and it gave all staff an opportunity to get an update on the challenges and potential solutions across data handling, data assimilation, modelling, the software stack and hardware. It was the first in a series of similar events intended to foster discussions on how best to manage different tasks across ECMWF.

The 23 presentations that were given demonstrated that, two years after it was established, the Scalability Programme has already achieved a lot, in particular:

- The provision of a workflow for observational data pre-processing that optimises data handling for both operational suites and research experiments. The framework relies heavily on the Observational Database (ODB), whose efficiency has recently been substantially increased, producing much better scalability of 4DVar.
- The maturing of the object-oriented data assimilation framework, which will introduce a more flexible and scalable approach to producing initial conditions. This project has received significant resources over the past two years and we expect its first demonstration in 2016.
- The introduction of a grid-point module complementing the spectral dynamical model core based on the same octahedral cubic grid. In addition, an efficient way of representing and managing data structures supporting algorithmic flexibility and the parallelised handling of model fields has been developed. This will also benefit data assimilation and post-processing.
- The revision of model output data handling to reduce data movement and introduce flexible interfaces to distribute workloads on demand to potentially heterogeneous computer architectures.
- Significant progress on code optimisation, employing a variety of programming models and investigating possible benefits of new processor types. This is supported by the on-site availability of a new GPU cluster and the inclusion of accelerators in the Cray Phase 2 upgrade.
- The complementary support of ECMWF projects by external funding (through the European Commission's Horizon 2020 framework) and bilateral projects with hardware vendors, but also with the strong involvement of ECMWF Member States across the Scalability Programme.

The success of the Scalability Programme hinges on ECMWF-wide collaboration. It requires the realisation that all aspects of the forecasting system need to be included and that obtaining efficiency gains will require some scientific rethinking. ECMWF's new ten-year Strategy defines ambitious goals and – given limited high-performance computing resources – relies on achieving substantial efficiency gains across the forecast generation and product dissemination chain. A roadmap for obtaining such efficiency gains in the forecasting system is being drawn up. The Scalability Programme will contribute to this roadmap as its outcomes take shape. The Scalability Days will help to coordinate shorter-term and longer-term activities and to facilitate cross-departmental collaboration.

All Scalability Day presentations are available under 'Projects' on the Scalability Programme page: https://software.ecmwf.int/wiki/display/SCA/



Growing data volume. ECMWF forecast production chain and the factors by which the data volume is expected to increase over the next ten years.

Evaluating forecasts tops agenda at 2016 user meeting

ANNA GHELLI

More than 100 users of ECMWF forecasts met at the Centre from 6 to 9 June 2016 to discuss new approaches to the evaluation of weather predictions. Using ECMWF's Forecasts (UEF) is an annual event which attracts participants from ECMWF's Member and Co-operating States, primarily from national meteorological services (NMSs), as well as from commercial weather companies and academia across the world. The idea of the meeting is to provide a forum where ECMWF data users can network and learn from each other. ECMWF is also keen to receive feedback from all its users on how they use its products and what they think of them.

This year's topic, 'Shaping future approaches to evaluating high-impact weather forecasts', focused on verification aspects, with an emphasis on measuring the quality of forecasts in a manner that is relevant to users and for different time ranges.

Three key themes

High-impact weather is of particular interest to forecast users, and its prediction with a seamless ensemble analysis/forecast system is at the heart of ECMWF's new ten-year Strategy. Weather can have a big impact by virtue of its extreme amplitude (e.g. tropical cyclones), its duration (e.g. heat waves) or its societal impacts on specific user communities. All these aspects present a particular challenge for forecasting systems and demand considerable development of diagnostic and verification capabilities. ECMWF is working with its Member and Co-operating States to review and develop its current set of metrics, including for the evaluation of forecast skill for high-impact weather at lead times of two to four weeks. UEF 2016 offered an opportunity to hear from ECMWF data users what verification metrics they use and how ECMWF data can provide added value.

UEF 2016 teased out ideas in three thematic areas:

Registration time. UEF events provide opportunities for a diverse set of forecast users to exchange information and network.

- Assessing long-term improvements - Forecasting high-impact weather is central to the work of NMSs. The knowledge of the quality of model data and relevant ensemble-based products is essential to deliver high-value information.
- User-oriented verification - Measures of model performance need to be relevant for user communities in order to identify the extent to which the forecast is useful as a basis for decision-making in weather-sensitive activities.
- Seamless verification across different timescales - NWP models provide forecasts for various timescales. From the verification viewpoint, this poses a challenge as the skill at different timescales will need to be compared even though verification questions may be different.

Session highlights

The meeting offered a mix of activities aimed at giving information, networking and providing feedback. In a session on 'Assessing the long-term improvement of high-impact weather forecasts', Petra Friederichs from the University of Bonn, Germany, reminded the audience that "there is no unique definition of extremes, but extremes are generally associated with rare or severe events. Mathematically, extremes are defined

Break-out sessions. A lot of the discussions took place in small break-out sessions devoted to particular topics.

as block maxima or exceedances above high thresholds." She added that appropriate metrics are the first step towards improving the prediction of extremes using post-processing.

ECMWF's model climate was highlighted in a number of contributions as an invaluable dataset that can be used to define extreme events without using location-specific thresholds. Speaking in a session on 'User-oriented verification', Cristina Primo Ramos from the German national weather service (DWD) stressed the importance of using proper scores and appropriate verification methods to correctly answer the different questions that users may have about forecast quality. Therefore, verification needs to be done by experts for optimal results and to reach appropriate conclusions.

Nicole Girardot (Météo-France) introduced the audience to new scoring methods for 'sensible weather' (weather we can observe using our senses, such as rain, wind, sun and cloud cover). She explained that those methods aim to take into account the user perception of the weather and of forecast error. Grant Elliott from Woodside Energy Ltd mentioned that from the private sector viewpoint there are a number of challenges: "For example, procedures are designed to minimise the risks to which the workforce is exposed. Therefore we need robust verification methods for rare events that allow us to demonstrate the compliance of procedures."

Talks given at a session on 'Seamless verification across timescales' explored the ability of forecasts to predict heat waves, cold spells, droughts and precipitation anomalies. Tressa Fowler from the US National Center for Atmospheric Research explained how verification methods must follow numerical models into seamless temporal space. She mentioned that users require a fair comparison of forecasts at all timescales although their questions may not be identical. Matthew Wheeler from Australia's Bureau of Meteorology showed the audience an innovative way to verify forecasts across timescales by averaging them over intervals comparable to their lead times. He demonstrated that, when the prediction skills of these averages are plotted as a function of the logarithmic scale of time, a fair comparison of skill can be made across a large range of scales.

User-oriented visualisation

Visualising the uncertainty of a forecast is of primary importance. ECMWF has developed the Ensemble Meteogram (ENS Meteogram), which is primarily a probabilistic representation, for a given location, of forecasts from an ensemble forecasting system. ECMWF is seeking ways to improve this very popular product. To this end, the UEF 2016 event saw the launch of a competition ('The Challenge') for innovative ideas. If you are interested in participating in The Challenge or you have a colleague who may want to submit a project, please visit:

http://www.ecmwf.int/en/learning/workshops/challenge-uef2016

I would like to thank ECMWF staff who helped during the meeting in various ways. I would also like to extend my thanks to all the participants, who contributed actively to the activities and gave us constructive feedback.

Group photo. More than 100 forecast users participated in the event.

First Women in Science Lunch held at ECMWF

JULIA WAGEMANN,
ANNA GHELLI

ECMWF's first Women in Science Lunch took place during the Using ECMWF's Forecasts (UEF) meeting from 6 to 9 June 2016. The networking lunch brought together around 30 women and men from around the world to analyse the challenges women in science and technology currently face. The participants discussed the role that international bodies and individuals can play in addressing these challenges.

Googling 'famous meteorologists'

Professor Liz Bentley, Chief Executive of the UK's Royal Meteorological Society, gave a keynote talk on 'Inspiring women in meteorology' and presented the biographies of four outstanding scientists: Professor Dame Julia Slingo (Chief Scientist, UK Met Office), Dr Florence Rabier (Director-General, ECMWF), Professor Jo Haigh (Professor of Atmospheric Physics at Imperial College London) and Marianne Thyrring (Director of the Danish Meteorological Institute). She showed how searching for 'famous meteorologists' in Google produces a list of 100 men and not a single woman. On refining the search to 'famous female meteorologists', the top story was an article about why so many female weather forecasters wear the same 23-dollar dress. According to Liz, the Google search results illustrate the misconceptions women in science have to contend with. Liz suggested that women do not tend to advertise their successes. She said one way to increase public awareness of their achievements in meteorology is to nominate outstanding women for awards, such as the ones granted by the Royal Meteorological Society (www.rmets.org/our-activities/awards/details-our-awards).

Problems and progress

Julia Wagemann produced a summary of the key findings of the SheFigures 2015 report by the European Commission. The report highlights that:

- Less than a quarter of researchers in STEM (Science, Technology, Engineering and Mathematics) disciplines are women
- Women researchers earn on average 18% less than their male counterparts. This gender pay gap widens with age and amounts to almost a quarter in the older age groups (45 years and older)
- Women become increasingly under-represented when progressing through academic career paths.

Despite all these inequalities, the report underlines that noticeable change has occurred. Between 2005 and 2012, the proportion of women researchers increased in some European countries, e.g. to around 40% in the United Kingdom and the Netherlands. Figures also show that the highest proportion of women in top positions (e.g. professor level) can be found in the youngest age group (<35 years). This suggests that the situation is improving for a younger generation of women researchers.

Leading by example

In smaller groups, participants discussed what individuals and international bodies can do to help address the challenges faced by women in science. The key outcomes of the discussion were that:

- Gender equality can only be achieved in cooperation with men.
- International organisations (including ECMWF) have to lead by example. Key responsibilities include raising public awareness of gender inequalities, fostering women's talents in their organisations and supporting outreach activities to showcase outstanding female researchers in STEM disciplines.
- A joint initiative across national meteorological services and ECMWF would be welcome, to coincide with next year's International Women's Day on 8 March 2017.

Women in Science lunch. Around 30 UEF 2016 participants took part in ECMWF's first Women in Science lunch.

New Director of Forecasts appointed

Professor Florian Pappenberger has been appointed Director of Forecasts at ECMWF. He took up the position on 1 July after ECMWF's Council approved the appointment.

Professor Pappenberger joined the Centre in 2006. He is the author of over 150 publications and has won multiple awards. At ECMWF, he was responsible for the Operational Centre of the European Flood Awareness System (EFAS) and he led the Applications team. The post of Director of Forecasts became vacant when Dr Florence Rabier was appointed as ECMWF's Director-General in January 2016.

Croatian flag raised at ECMWF

Representatives from all of ECMWF's Member States used the occasion of the first Council meeting of 2016 to raise the flag of ECMWF's newest member, Croatia.

Opening the ceremony on 30 June, Council President Gerhard Adrian reminded those present of the importance of collaboration between national meteorological services. Dr Nataša Strelec Mahović, the Director of Croatia's Meteorological and Hydrological Service, stressed the "vital importance" of full membership for the country. Croatia became a Member State on 1 January 2016, having had a formal co-operation agreement with the Centre since December 1995.

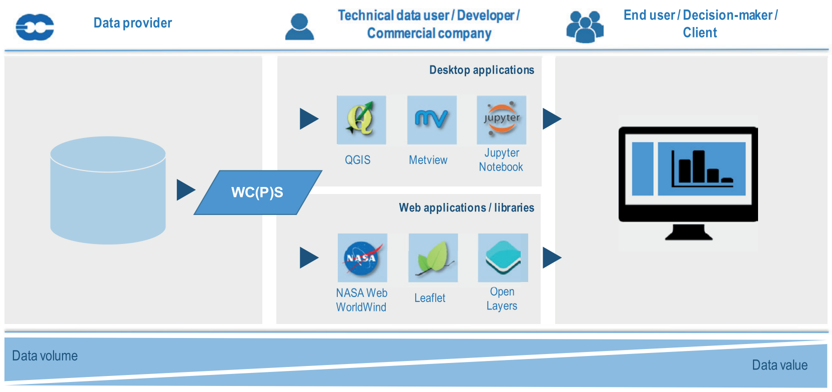
Web standards for easy access to big data

JULIA WAGEMANN, STEPHAN SIEMEN

Since May 2015, ECMWF has been part of the EU-funded Horizon 2020 EarthServer-2 project. Our goal as a project partner is to explore standardised web services on top of ECMWF's MARS archive for efficient access to large data volumes. The project explores two standard data-access protocols defined by the Open Geospatial Consortium (OGC), designed to offer web-based access to multi-dimensional geospatial datasets: (i) Web Coverage Service (WCS) and (ii) Web Coverage Processing Service (WCPS).

The experience of the first project year shows that WC(P)S can be of great value, especially for developers or scientists who build applications and want to have access to large data volumes but do not want to store all the data on their local discs. WCS and WCPS are machine-to-machine interfaces and therefore aimed at technical data users or developers rather than end users. By facilitating the spatial and temporal subsetting of gridded meteorological data, time-consuming data download and processing is shortened, enabling a greater focus on the interpretation of data.

Multi-dimensional gridded data fields (called coverages) can be accessed and processed in an interoperable way. Technical data users, for example, can integrate a WCS request into their processing routine and further process the data. Commercial companies can easily build customised web-applications with data provided via a WCS. This approach is also strongly promoted by the EU's Copernicus Earth observation programme, which generates climate and environmental data as part of an operational service. Commercial companies can use the data to build value-added climate services for decision-makers or clients. Web-based data access with the help of a WCS can make ECMWF data more accessible to researchers, technical data users and commercial companies, within the MetOcean community and beyond.



Data-processing chain. Example of how a WCS can be integrated into the standard web-based data processing chain.

Test users welcome

Two outreach events within the past year showed that there is growing interest in ECMWF data being accessible via web services. In January 2016, ECMWF hosted a hackathon that aimed to improve the Global Flood Awareness System (GloFAS). Part of the 3.5 TB of data that had been prepared for the event was served with the Web Coverage Service that is being set up at ECMWF as part of the EarthServer-2 project. Additionally, raw datasets were offered for download via an FTP server. Four out of five teams took advantage of the facilitated data access and integrated the WCS data retrieval into their applications. By exploiting the WCS, the teams were able to devote most of their time to building functional applications rather than wasting it on data download and pre-processing.

In April 2016, the EarthServer-2 project hosted a splinter meeting at the General Assembly of the European Geosciences Union (EGU) in Vienna. For this event, all EarthServer-2 service partners built a custom web-client that visualises global data fields with NASA WebWorldWind, a three-dimensional virtual globe API, and allows the on-demand retrieval of time series information of individual geographical points. The demonstration at the meeting showed that it is simple to build customised web-applications on top of a WCS. Participants in the meeting were keen to use ECMWF's WCS service to gain access to climate reanalysis data.

We are planning to grant access to the WCS to selected test users. If you are interested in using the WCS service, please send an email to earthserver@lists.ecmwf.int and we will get in touch with you.

What is OGC WCS?

The Web Coverage Service (WCS) is described by the Open Geospatial Consortium (OGC) (2012) as follows:

"The OGC WCS supports electronic retrieval of geospatial data as 'coverages' – that is, digital geospatial information representing space/time-varying phenomena".

Therefore, WCS is a standard data-access protocol that defines and enables the web-based retrieval of multi-dimensional geospatial datasets.

Unlike Web Mapping Service (WMS), another widely-used OGC standard, which returns spatial data as an image, WCS returns data in its raw form, with its original semantics. This allows for further web-based data processing and analysis or the building of web applications.

Useful web links

EarthServer-2 project: www.earthserver.eu.

ECMWF's role within EarthServer-2: www.ecmwf.int/en/research/projects/earthserver-2 and http://earthserver.ecmwf.int.

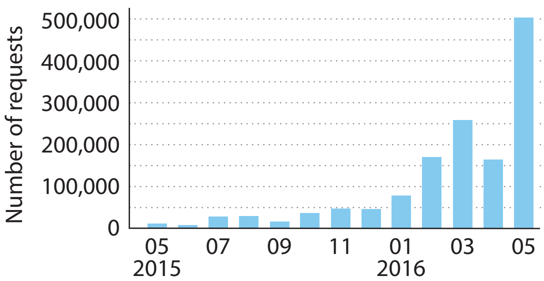
WCS protocol: http://www.opengeospatial.org/standards/wcs.

Joint work with CMA leads to second S2S database

FRÉDÉRIC VITART, MANUEL FUENTES, RICHARD MLADEK, AXEL BONET, IOANNIS MALLAS, MATTHEW MANOUSSAKIS, CHAOYANG SUN (CMA), SÉBASTIEN VILLAUME, CRISTIAN CODOREAN, ENRICO FUCILE, SHAHRAM NAJM

The multi-model Sub-seasonal to Seasonal (S2S) prediction database operated at ECMWF since May 2015 has successfully been synchronised with a second S2S database run by the China Meteorological Administration (CMA).

To achieve the timely synchronisation of the two databases, Dr Chaoyang Sun from CMA spent one year at ECMWF as a visiting analyst to design and implement an appropriate synchronisation system. Chaoyang participated in all decisions related to the development and operation of the S2S datasets. He developed a system to transmit to CMA not only routinely acquired near-real-time data or on-the-fly re-forecasts, but also the re-forecasts from fixed configurations which were ingested at ECMWF before the database was opened. A mechanism was also built in to enable the retransmission of old cycles. If there were any outage in routine transmission, it would thus be possible to resend the data at a later time. CMA is using ECMWF's MARS system to support its S2S database, and Chaoyang's stay at ECMWF helped to configure CMA's MARS instance. Chaoyang returned to CMA at the end of June 2016. He will continue to be involved in the operation of the S2S database at CMA.



Rising number of requests. The total number of requests executed at the ECMWF S2S database per month has gone up significantly since the database was launched in May 2015.

Facts and figures (June 2016)

- *Total size of the database today: 40 terabytes, 1 billion meteorological fields*
  - *Real-time forecasts: 6 terabytes*
  - *Re-forecasts: 34 terabytes*
- *Real-time forecasts currently grow by about 750 gigabytes/month, while re-forecasts grow by about 1.5 terabytes/month.*
- *Number of users: 498 from 68 countries.*

The database works by transferring data from each data provider using ECMWF's data acquisition system. The data is then pushed to CMA via ECMWF's Product Delivery System (ECPDS). ECMWF's contribution is handled like that of any other data provider, so the synchronisation of ECMWF's contribution to CMA happens automatically.

The S2S database is part of the S2S project, a joint research initiative launched in 2013 by the World Weather Research Program (WWRP) and World Climate Research Program (WCRP). The project's main goal is to improve forecast skill and the understanding of the sub-seasonal to seasonal timescale, and to promote its uptake by operational centres and its exploitation by the application communities. The database currently includes ten models. A further model, that of the Korean Meteorological Administration (KMA), is due to be ingested upon the completion of tests.

Access to ECMWF's S2S database

The S2S database can be accessed using two methods:

- A web interface (http://apps.ecmwf.int/datasets/data/s2s/), where users can navigate through the S2S dataset in a dynamic and user-friendly way. After each selection, the web page is updated automatically in order to reflect the availability of data. The purpose of this interface is to help users navigate the content of the database, get familiar with it, extract sample data interactively and/or obtain the script to download data in batch. An additional tool, the S2S history page (http://apps.ecmwf.int/datasets/history/s2s-prod/), shows a summary of available dates by data provider and cycle.
- A batch interface using the ECMWF Web API (https://software.ecmwf.int/wiki/display/WEBAPI/What+is+ECMWF+WebAPI), the preferred way for data download via scripting languages such as Python.

One of the main challenges of the S2S database is to provide easy access to re-forecast data. With the different configurations of the various models, it can be quite difficult for users to grasp what is available, let alone write the extraction scripts to retrieve the data in an efficient way. To facilitate this, documentation is available at https://software.ecmwf.int/wiki/display/WEBAPI/S2S+reforecasts+retrieval+efficiency. This shows users how to access re-forecasts efficiently from the archive. Note that this page and related S2S pages can be 'watched'. This is an extremely useful feature if users want to be notified of changes. Suggested areas to watch are the 'News' section (https://software.ecmwf.int/wiki/display/S2S/News) and the section on 'Issues with data' (https://software.ecmwf.int/wiki/display/S2S/Issues+with+data).

Web links

S2S Project website: http://www.s2sprediction.net/

S2S at ECMWF: http://s2s.ecmwf.int

S2S at CMA: http://s2s.cma.cn

S2S model descriptions: https://software.ecmwf.int/wiki/display/S2S/Models

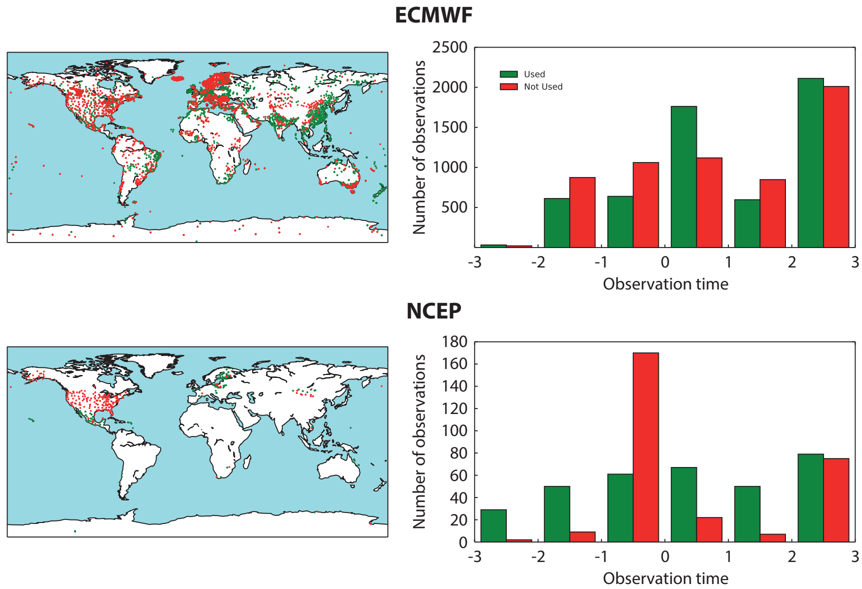
ECMWF takes part in WMO data monitoring project

CRISTINA PRATES, DAVID RICHARDSON

ECMWF is participating in a major effort by the World Meteorological Organization (WMO) to review and modernise the monitoring of the conventional components of the Global Observing System (GOS). At the moment, WMO monitoring of conventional observations is based on monthly reports produced by leading Centres. The aim is to move towards a near-real-time (e.g. daily) monitoring of the GOS in terms of data availability and data quality. This would help the WMO to report back to data providers quickly so that problems can be fixed in a timely manner.

Pilot project

Two WIGOS (WMO Integrated GOS) workshops on Quality Monitoring and Incident Management, held in December 2014 and December 2015, developed plans for a WIGOS Data Quality Monitoring System (WDQMS) comprising three components: Quality Monitoring, Quality Evaluation and Incident Management. ECMWF, the US National Centers for Environmental Prediction (NCEP) and the Japan Meteorological Agency (JMA) have agreed to participate in a Data Quality Monitoring pilot project and to provide quality information based on feedback from their data assimilation systems daily. It was decided to start with surface (SYNOP) observations and to extend the project to other observation types later. These quality monitoring reports will provide the input for the Evaluation function. This function will combine information from the quality monitoring reports with metadata about the observing stations from the WMO Observing System Capability Analysis and Review Tool (OSCAR) to generate routine performance reports. It will then be down to the WIGOS Incident Management function to assess the issues considered by the Evaluation function and to take the necessary action.



Comparison of data use. The maps and charts show the location and number of surface pressure observations from SYNOP reports not shared in ECMWF's and NCEP's data assimilation (DA) systems within the 6-hourly interval centred on12 UTC on 12 June 2016. The discrepancies in the overall numbers are partly a result of the fact that NCEP shows only the data that pass a quality control step prior to DA.

The second workshop led to the creation of a Task Team on the WIGOS Data Quality Monitoring System (TT-WDQMS) in order to test and consolidate the concept of the WDQMS. It consolidated plans for a Demonstration Project to be implemented in WMO Region I to test the end-to-end functionality and outputs of each of the three components. The Demonstration Project will run for eight months from the beginning of July 2016.

Inter-centre comparisons

This initiative represents not only a major step forward in the WMO monitoring of the GOS, it also opens new doors to exchanging information on NWP observational data quality and usage. Comparisons of the availability and use of SYNOP observations in the data assimilation (DA) systems of the three participating NWP centres are already possible in near real-time. They suggest that, when the same data is available to different centres, the statistics of 'used' and 'not used' are similar, with only a small proportion of discarded observations. For observations which are not shared between different centres, the proportion of 'used' data is much lower and there is a big difference in the amount of data seen by the two centres (totals of 11,688 and 621 for ECMWF and NCEP, respectively, in the example shown in the figure). In fact, this is a consequence of the different characteristics of the two DA systems. NCEP shows only the data that pass a quality control step prior to DA, therefore part of the data available that is deemed to be of poor quality or duplicate is filtered out and is not available to the DA, whereas ECMWF shows even the data that is deemed to be of poor quality and is rejected and/or blacklisted. This example shows that the procedures used at the different NWP centres must be taken into account in such comparisons.

More details on the pilot project are available here: https://software.ecmwf.int/wiki/display/WIGOS/WIGOS+pilot+project+on+data+quality+monitoring.

Single-precision IFS

FILIP VÁŇA, GLENN CARVER, SIMON LANG, MARTIN LEUTBECHER, DEBORAH SALMOND (all ECMWF)
PETER DÜBEN, TIM PALMER (both University of Oxford)

Since the early days of numerical weather prediction (NWP), the issue of appropriate numerical precision has been the subject of considerable interest. Indeed, ECMWF's second Technical Report, published in 1976 by *Baede at al.*, was devoted to 'The effect of arithmetic precision on some meteorological integrations'. Some precision-sensitive operations, such as matrix inversion, often require at least so-called double-precision arithmetic (i.e. a 64-bit representation of real numbers) to deliver acceptable results. With the growth of computer power and especially the availability of 64-bit processors, double precision came to be commonly used for all floating-point computations in numerical modelling, including in NWP.

However, such precision may be wasteful since it uses up precious computing resources while not necessarily making much difference to forecast quality. Building on work carried out at the University of Oxford, we have made single-precision arithmetic (a 32-bit representation of real numbers) available for ensemble forecasts in ECMWF's Integrated Forecasting System (IFS). Experiments show that, at a horizontal resolution of 50 km, single precision brings significant savings in computational cost without degrading forecast quality.

Computing challenges

Numerical weather prediction relies on powerful supercomputers to carry out the complex calculations on which forecasts are based. Limitations in the available computing power represent a significant obstacle to increasing the accuracy of such forecasts. In current architectures, the limiting factor is not so much peak processor performance but the speed of memory access.

As a result, there is growing interest in reducing the data volume being processed to the minimum information necessary to deliver high-quality forecasts. Intuitively, evaluating temperature to 16 valid digits might seem excessive given that in current NWP systems even the third digit is subject to significant error. Thus the important practical question is how much information needs to be included when weather or climate models are run on supercomputers. Assuming that only a fraction of the information contained in double-precision data is relevant, the key question is how this can be exploited in running the model: how can the redundant overhead be eliminated in order to profit computationally while still producing forecasts of equal skill? This question needs to be addressed and answered before possibly adapting the code to future computer hardware that offers a choice of floating-point precision or even variable levels of precision (see *Düben et al.*, 2015).

Considering possible future high-performance computing (HPC) architectures, there is also an exciting area of research into the development of approximate and stochastic computing hardware that allows a trade-off between precision and energy consumption. With this in mind, it is important to better understand the minimum computational precision requirements essential for successful weather forecasts.

Adapting the code

As a part of their involvement in the design of a future probabilistic Earth system model for climate prediction, a research group at the University of Oxford led by ECMWF Fellow Professor Tim Palmer has adapted the OpenIFS model to use single-precision arithmetic. The OpenIFS model is a version of the IFS which is available to universities under licence and in which the data assimilation code has been removed. It is ideally suited to this kind of proof-of-concept study because it offers a portable and much-reduced code whilst retaining all the forecast capability and code of the operational IFS. This pioneering exercise delivered very sensible forecasts while requiring only a few scientific code modifications.

The encouraging results have prompted ECMWF to make this option available in the IFS for ensemble forecasts. Since the IFS code is used in different configurations, implementing the single-precision option requires making both levels of precision available within the same source code. Single precision has been available as an alternative to the default double-precision arithmetic in IFS forecasts from model cycle 41r2, the current operational cycle at ECMWF. This article summarises the main results obtained with the single-precision IFS code.

Technical implementation

The key element defining model precision is the setting of the Fortran KIND parameter of all real variables in the IFS code. This means the precision is determined at the compilation stage and cannot be changed during the execution. Additional code changes were required to allow both single and double-precision functionality within the same code, mostly related to hard-coded numerical thresholds introduced to suit exclusively double precision; extending code interfaces with raw (i.e. binary) data; the MPI (Message Passing Interface) library interface; system functions; and mathematical libraries. Systematic experimentation with single-precision arithmetic revealed some poorly conditioned code, for which a more robust but scientifically equivalent formulation was sought to deliver equal performance for both precisions. Such changes were very beneficial to the overall code robustness regardless of the precision used.

Finally, a few areas of the code that were sensitive to precision had to continue to run strictly using double-precision arithmetic. As well as some specific double-precision computations in surface-scheme and shallowconvection physics, double precision must mainly be used in the setup part of the Galerkin methods used in the IFS: calculations of the roots and the associated polynomials for Legendre transformation, and the evaluation of integral operators for the vertical finite element (VFE) discretisation scheme. In both cases, double precision is only required for the (once-only) initial pre-computation of operators. The results are then truncated to the chosen precision used consistently for all other computations. These changes have been found to deliver equally skilled forecasts in both precisions up to TL399, which corresponds to about 50 km horizontal resolution, the highest resolution tested to date.

Forecast skill

To evaluate the skill of the single-precision IFS, two sets of experiments were performed: a long-range integration to test the model's ability to deliver a reasonable climate, and the production of medium-range ensemble forecasts (ENS) to compare the skill of single-precision ENS with that of reference double-precision ENS.

Long-term simulations

In order to assess the model climate and compare it against observations, a four-member ensemble was integrated for 13 months at TL399 resolution with 137 vertical levels. All integrations were run in uncoupled mode, with prescribed sea-surface temperatures, although coupling to the operational wave model was included. The first month of the integrations was discarded. The start of each member of the ensemble was shifted by 1 day and 6 hours in order to properly sample the diurnal cycle. The 12-month integration covering the period of September 2000 to August 2001 was compared with various datasets, including the ERA-Interim 60-level climatology. The model was configured in exactly the same way as the operational forecast model, the only difference being the activation of the pressure mass fixer to ensure mass conservation, which is necessary for long-term integrations.

The differences between the single-precision experiment and the double-precision reference run were generally small relative to the magnitude of systematic forecast errors. The main differences were observed in the mid-latitudes and the polar areas, typically over continental land masses. This can be attributed to the high flow variability and associated uncertainty of long-term integrations in these parts of the globe. The maximum difference of annual zonal averages between the two sets of climate simulations is less than 2% in relative humidity, 0.5 K in temperature and 1 m/s in wind speed. Compared to observations, the experiments performed equally well. This is illustrated by Figure 1, which shows the difference in top-of-atmosphere shortwave radiation flux between the annual climatology computed by each of the model versions on the one hand and data from the CERES EBAF satellite product on the other.

Medium-range ensemble forecasts

To investigate the single-precision IFS capability for ensemble forecasting, 46 single-precision and double-precision ensemble forecasts with 50 members each were run evenly distributed over an entire year, between 4 December 2013 and 29 November 2014. The resolution used was again TL399, this time with 91 vertical levels, as used for operational ensemble forecasts. The forecast range for each ensemble was 15 days.

In the extra-tropics, the results of the single and double-precision experiments are very similar for the first 12 days of the forecasts. After day 12, there are some small differences between the two experiments, e.g. for geopotential at 500 hPa (not shown). This could be an effect of the limited sample size. For temperature at 850 hPa, the results are very similar throughout the forecast period.

In the tropics, a more striking difference between the experiments is observed for geopotential at 500 hPa: the single-precision forecasts systematically outperform the double-precision reference forecasts (Figure 2a). This difference stems from the non-conservation of mass in the IFS. The slight gain or loss of mass contributes to a warm or cold temperature bias in the tropics. It appears that the slightly less conservative single-precision version, for

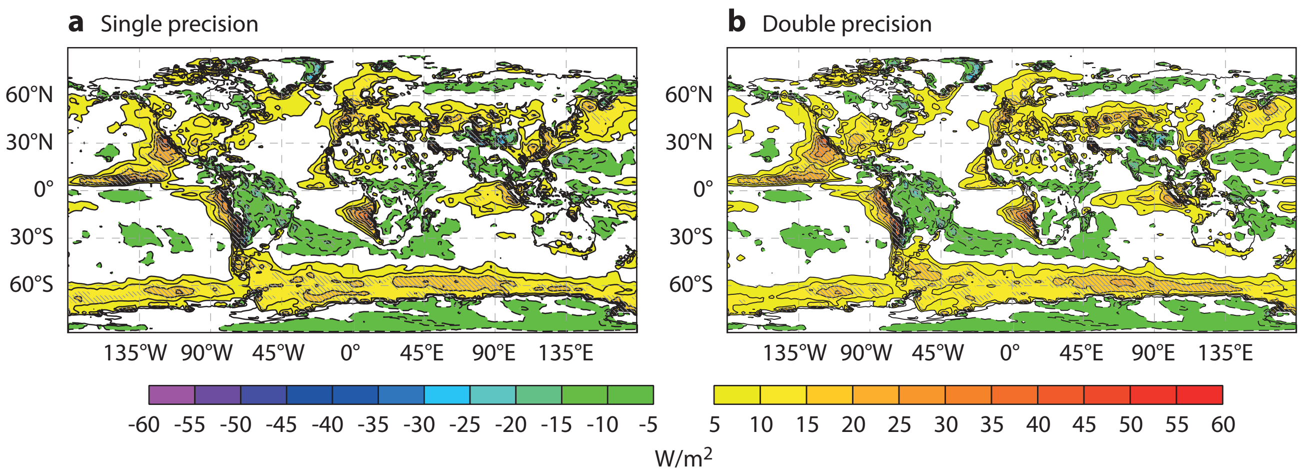


Figure 1 Difference between the mean top-of-atmosphere shortwave radiation flux in a 1-year IFS simulation at the resolution TL399 and in the CERES EBAF satellite data product for (a) the single-precision IFS and (b) the double-precision IFS. Hatching indicates statistically significant differences at the 95% confidence level.

this particular combination of time step and resolution, compensates better for the existing model bias. When the mass fixer is activated for both experiments, the results are indistinguishable in the tropics too (Figure 2b–c).

Despite being slightly less conservative, the single-precision IFS delivered ensemble forecasts of equivalent skill compared to the double-precision reference forecasts.

Computational cost

To evaluate the gain in computing performance brought by the single-precision IFS, the computational cost of the two sets of ensemble forecasts described in the previous section was compared on ECMWF's Cray XC30 HPC facility. All experiments were submitted with the same topology: 96 MPI tasks and eight OpenMP threads.

The reduction in computational cost per standard model time step when using the single-precision version was found to be 37%. When the difference in cache utilisation between the two versions is compensated for by doubling the length of the inner 'DO-loops' in the model (by adjusting the tunable namelist parameter NPROMA), this gain increased to 40.7%.

Figure 3 shows a breakdown of computational cost by model component. The results obtained for single and double precision with the same NPROMA parameter are surprisingly similar. This implies that all parts of the model benefit from single precision. However, the gain in the Fast Fourier Transformation code (FFT) is only 20%, which is significantly less than the overall gain of 37%. This probably confirms that the FFT code is already very efficient and that it is hard to speed it up any more. Another notable result is the 62% performance gain in grid-point dynamics using single precision. This shows that the current value of the NPROMA parameter (NPROMA = 16), which has been optimised for the model as a whole, is too big for this particular part of the IFS. The reduction in data size with single precision and the reduced memory access also result in better cache utilisation for this code part. Significant differences in relative computational cost can also be seen in the model components labelled 'Other' in Figure 3, which, among other things, include input/output (I/O) and setup. Here some parts have to be computed exclusively using double precision, and the precision of I/O is prescribed by GRIB packing. As a result, the relative cost of the 'Other' category increases in the single-precision IFS.

When doubling the NPROMA parameter in the single-precision run (to return to roughly the original cache utilisation), the breakdown diagram looks different (Figure 3c). Not surprisingly, the grid-point dynamics reverts to the original, less optimised performance. But this is the only component for which the absolute cost has increased compared to running the single version with NPROMA = 16. The other model parts are all improved, but their absolute performance gain is proportional to the ratio between computation and data manipulation. Notably the IFS physics, which involves a lot of computation with a relatively limited amount of data manipulation, benefits least from this final optimisation step.

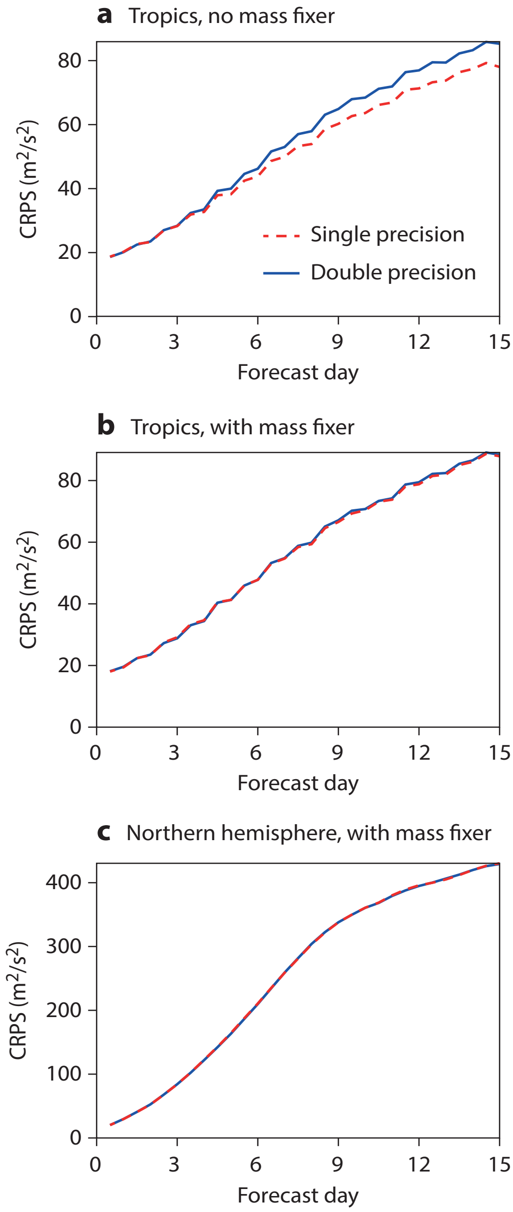


Figure 2 Continuous Ranked Probability Score (CRPS) for 15-day ensemble forecasts of geopotential at 500 hPa (a) in the tropics without mass fixer, (b) in the tropics with mass fixer and (c) in the northern hemisphere with mass fixer.

Discussion and outlook

A study using ECMWF's OpenIFS model demonstrated the potential computational benefits of using reduced numerical precision in the production of ensemble forecasts. The single-precision arithmetic has now been successfully implemented in the IFS. According to first tests with ensemble forecasts at a horizontal resolution of 50 km, it offers almost indistinguishable forecast quality at about 40% greater computational efficiency. The savings in computational cost come from reduced memory access on ECMWF's Cray XC30 high-performance computing facility. To achieve this, it was necessary to review the entire IFS code and to ensure that all components of the model are

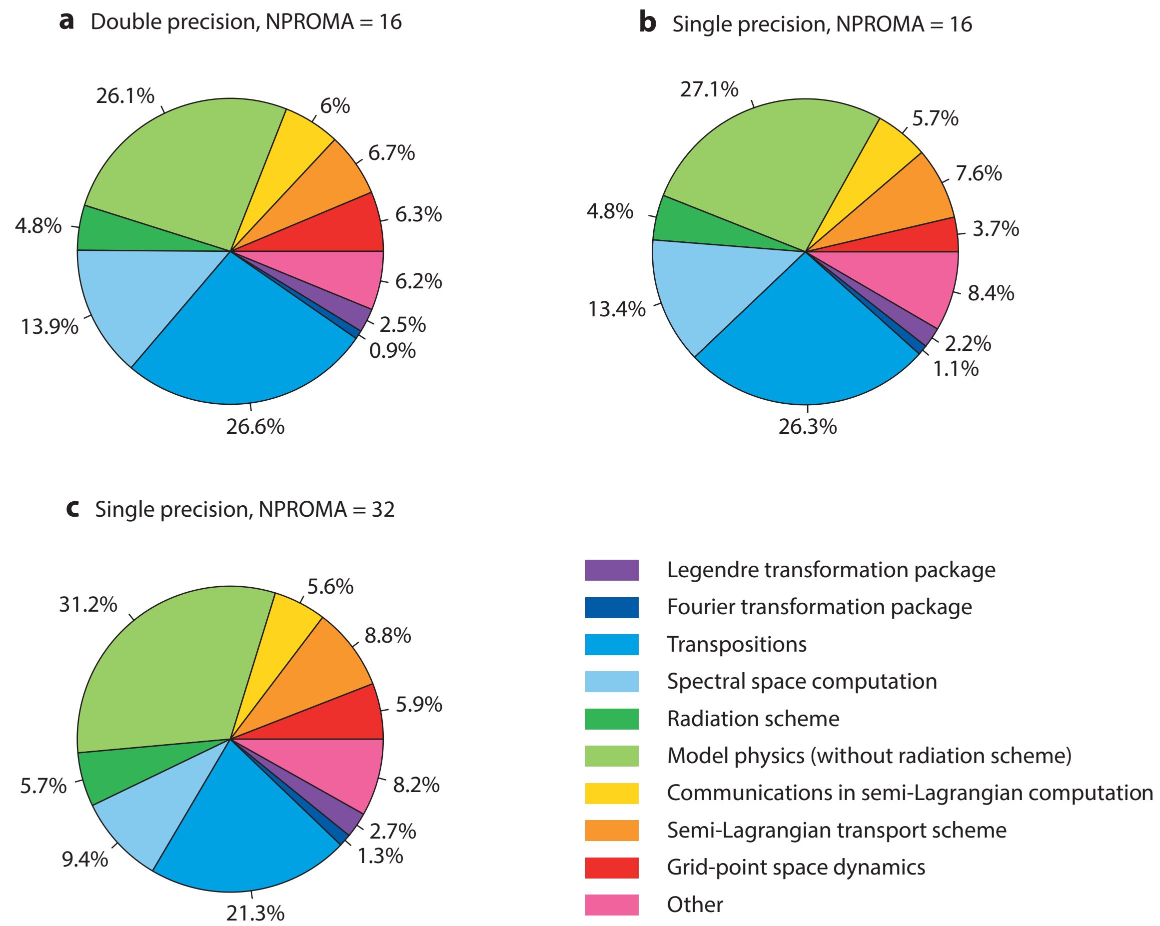


Figure 3 Breakdown of computational cost by model component shown for (a) the double-precision IFS with the default setting NPROMA = 16, (b) the single-precision IFS with NPROMA = 16 and (c) the single-precision IFS with NPROMA = 32. The results were obtained at the resolution TL399 with 91 vertical levels.

still delivering expected results at this precision. Overall, the results of the experiments demonstrate that there is a great potential to reduce power consumption and save computational time by investing in more sophisticated code that can handle reduced-precision arithmetic.

In addition to the reduced computational cost, the process of testing single precision using the IFS code has helped to detect and fix badly conditioned code. In the future, we would like to review more configurations with the single-precision alternative (such as the tangent-linear code) to reveal potentially problematic code.

The relatively straightforward success of applying single-precision arithmetic indicates that there is further potential for improved efficiency with future computing architectures. The work described here can serve as the starting point for further research into the use of reduced precision beyond single precision, and in particular into a flexible reduction of numerical precision depending on spatial scale, as proposed by *Düben et al.* (2014) and *Düben et al.* (2015). Future work at ECMWF will focus on exploring the impact of reduced precision at higher resolutions. As operational ensemble forecasts are produced in coupled mode with the NEMO ocean model, it is also desirable to extend the reduced-precision option from the atmospheric component to the whole coupled system. The single-precision option could also be explored for different configurations of the IFS, such as those used in data assimilation, observation processing and atmospheric composition. Finally, the ability to run the IFS in single precision will increase flexibility for ECMWF's Scalability Programme, which aims to prepare forecasting systems for the exascale era of supercomputing, for example when running the IFS on alternative hardware (such as GPUs) and architectures requiring parallelism far beyond current levels.

FURTHER READING

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Düben, **P.D.**, **H. McNamara**, & **T.N. Palmer**, 2014: The use of imprecise processing to improve accuracy in weather & climate prediction. *J. Comput. Phys.*, **271**, 2–18.

Düben, **P.D.**, **F.P. Russell**, **X. Niu**, **W. Luk**, & **T.N. Palmer**, 2015: On the use of programmable hardware and reduced numerical precision in earth-system modeling. *J. Adv. Model. Earth Syst.*, **7**, 1393–1408.

Hungary's use of ECMWF ensemble boundary conditions

MIHÁLY SZŰCS, PANNA SEPSI, ANDRÉ SIMON (all OMSZ)

Forecasters at the Hungarian Meteorological Service (OMSZ) make extensive use of ECMWF's high-resolution (HRES) and ensemble forecasts (ENS) in their daily work. In addition, like most other European national meteorological services, OMSZ also runs limited-area models (LAM) to provide improved forecast information at even higher resolution. OMSZ, which is part of the ALADIN consortium, uses the ALADIN and AROME models. Running these LAMs requires not only initial conditions (ICs) but also lateral boundary conditions (LBCs). Their availability has been ensured through ECMWF's Optional Boundary Condition (BC) Programme.

OMSZ's limited-area ensemble activity started almost a decade ago. Météo-France's global ensemble system (Prévision d'Ensemble ARPEGE, or PEARP) has been used to produce boundary conditions since our first system became operational in 2008. OMSZ has also been interested in ECMWF's ENS boundary conditions (ENS-BCs) from the beginning. While tests confirmed this interest, some technical issues have in the past imposed severe limitations on the operational use of ENS-BCs. The extension of ECMWF's Optional BC Project in July 2015 made ENS-BCs available in a similar way to HRES-BCs.

In recent experiments, the current ENS-coupled version of our limited-area ensemble system (ALEPS-ENS) produced forecasts that were significantly different from those produced by the operational version (ALEPS-PEARP). Single members were more accurate for most variables, so the root-mean-square error (RMSE) of the ensemble mean was lower. At the same time, the system was less dispersive. Neither ALEPS-ENS nor ALEPS-PEARP outperformed ECMWF ensemble forecasts in terms of standard scores, but they provided crucial added value when an extreme weather event occurred over Hungary.

Operational LAM ensemble

In OMSZ's operational system (ALEPS-PEARP), we integrate 11 ensemble members using boundary conditions derived by simple dynamical downscaling of the first 11 members of PEARP (*Descamps et. al.*, 2014). Model runs start at 18 UTC every day and cover the next 60 hours.

For the integrations we use the ALADIN model in hydrostatic mode with 8 km horizontal resolution and 49 model levels. Our domain covers most of continental Europe (Figure 1). Parametrized processes are described by the ALARO physics package. OMSZ's long-term plans include the development of a convection-permitting ensemble prediction system (EPS) based on the AROME model with 2.5 km horizontal resolution (*Szintai et. al.*, 2015).

Atmospheric perturbations are derived from interpolated global ICs and LBCs while surface fields are identical for all ensemble members at the beginning of the model runs. Coupling is realised every six hours based on the outputs of the 18 UTC PEARP run. In order to use local observations and improve the representation of initial condition uncertainty, we have investigated using the Ensemble of Data Assimilations (EDA) method in both the ALEPS and the AROME-EPS frameworks (*Horányi et. al.*, 2011, *Szintai et. al.*, 2015). For model error representation we have tested the Stochastically Perturbed Parametrized Tendencies (SPPT) scheme (*Szintai et. al.*, 2015).

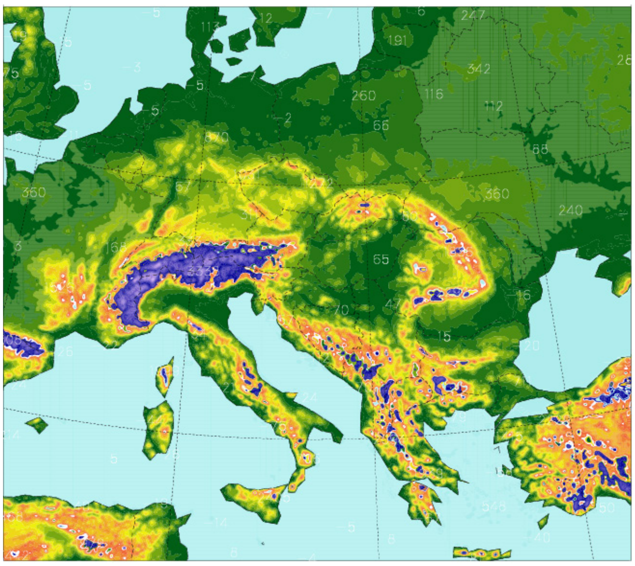

Figure 1 The ALADIN domain of ALEPS forecasts at 8 km horizontal resolution.

ENS-coupled LAM ensemble

The downscaling of an ECMWF global forecast to obtain the ALADIN model BCs consists of three major steps. The first is the file retrieval from the MARS database, separated into atmospheric spherical and grid-point fields and surface grid-point fields. The second step is the file conversion between the GRIB and FA data formats (ALADIN 901 configuration). Finally, global fields are interpolated to limited-area ones (ALADIN e927 configuration) with 15 km resolution.

In the case of HRES-BCs, this process has been run by ECMWF for many years as part of the Optional BC Programme. In the case of ENS-BCs, ECMWF Member States may run a similar process or even a whole ensemble prediction system (*Weidle et al.*, 2015) on ECMWF's supercomputer using a national quota of system billing units (SBU). While Hungary is a Co-operating State without its own SBU, this option became available after the extension of the BC Programme in the summer of 2015. OMSZ then prepared related tasks on ECMWF's supercomputer, which were implemented in ECMWF's operational suite in November 2015 with the assistance of ECMWF.

Once this had been done, OMSZ began to routinely download ENS-BCs via ECMWF's dissemination system to OMSZ's supercomputer. Following a second interpolation step to 8 km horizontal resolution, we run an ensemble of forecasts (ALEPS-ENS). Like the operational ensemble system, ALEPS-ENS comprises 11 members, the first of which is coupled to the ENS control and the others to the first 10 of the 50 perturbed members. Model runs start at 18 UTC every day and cover the next 60 hours. The coupling frequency was improved to 3 hours compared to 6 hours in the operational system. In addition, we get ENS-BCs for 12-hour periods from the other three ENS production times (00, 06 and 12 UTC). These can support our future plans for maintaining an ensemble of data assimilation cycles.

The surface processes in ECMWF's Integrated Forecasting System (IFS) are quite different from those in the ARPEGE and ALADIN models, where the ISBA parametrization scheme is used. As a result, it is not feasible to initialise surface fields directly from the IFS at the beginning of an ALADIN run. Since there is no surface data assimilation in OMSZ's ALEPS, the issue can simply be resolved by obtaining surface fields from an interpolated ARPEGE file. However, if such a procedure were to be used for all members, it would lead to the elimination of the surface field perturbations in ENS. Since we would like to preserve such perturbations, we decided to add them to the surface fields obtained from the PEARP control member. This step and the whole process are visualised in Figure 2.

Verification results

We have examined the impact of ENS-BCs on forecasts up to 60 hours ahead produced during a 52-day winter

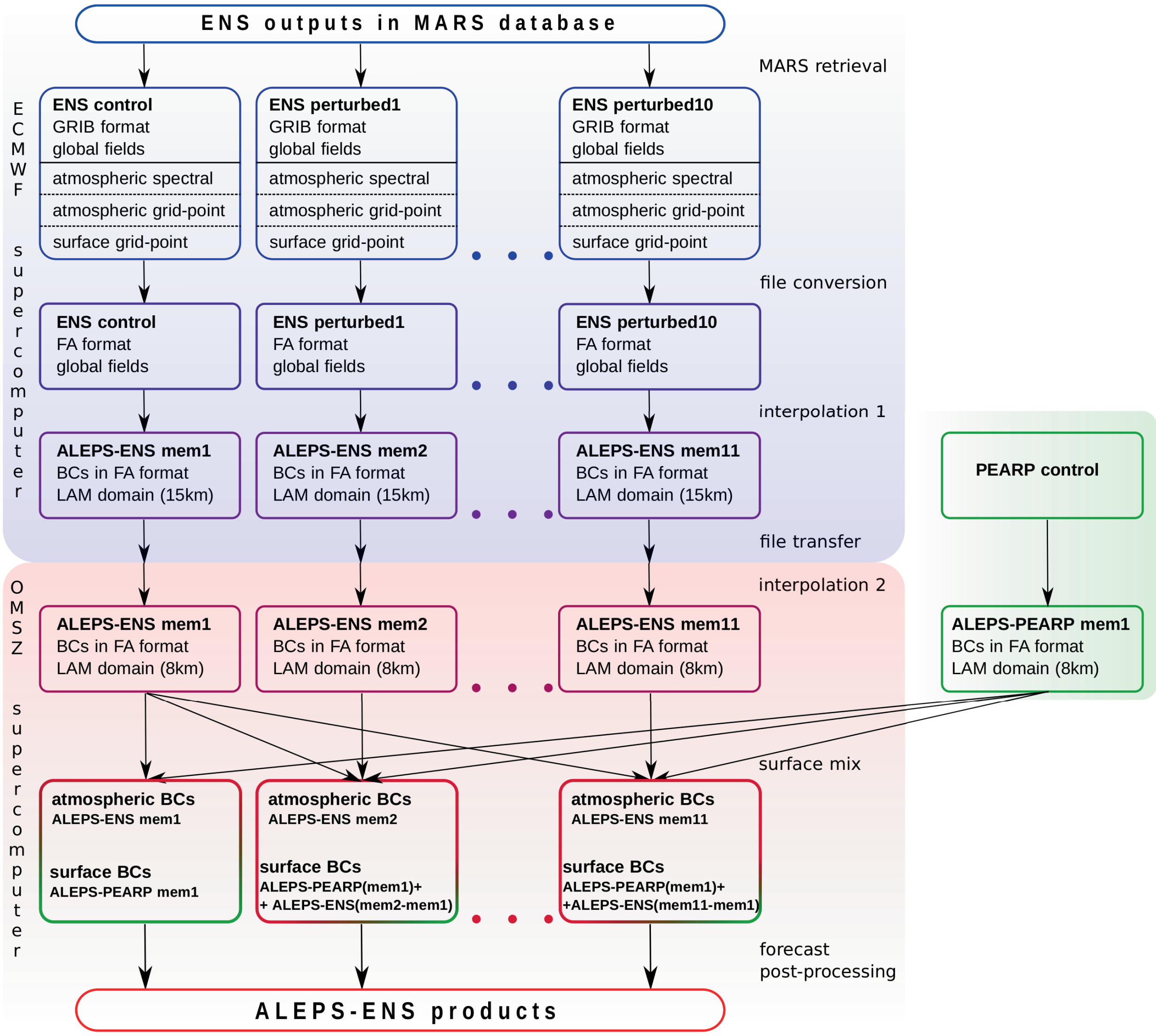

Figure 2 Chart of dataflow for ALEPS-ENS dynamical downscaling. Eight-km-resolution BCs are generated on OMSZ's supercomputer from the 15-km-resolution BCs generated on ECMWF's supercomputer. As a final step before the model integration, surface fields are taken from the ALEPS-PEARP control because of the inconsistency of the surface schemes used in ECMWF's global model on the one hand and in the ALADIN model on the other. To preserve surface perturbations, we simply add the difference between the downscaled ENS perturbed members and the ENS control member to the ALEPS-PEARP control surface fields.

period, between 11 December 2015 and 31 January 2016. ALEPS-ENS ran every day at 18 UTC during this period. The results were compared with the operational system (ALEPS-PEARP) and also with the ENS. To avoid any effects stemming from inconsistencies in the number of ensemble members, in this comparison we verified only the first 10 perturbed members and the control member of the ENS.

We verified upper-air variables against radiosonde measurements over the whole model domain (on average 37 measurements at 00 UTC and 43 measurements at 12 UTC). We found the RMSE of the ensemble mean to be generally smaller for ALEPS-ENS compared to ALEPS-PEARP. At the same time, the spread of ALEPS-ENS forecasts was also smaller than that of ALEPS-PEARP forecasts. ECMWF ENS had preferable features in terms of RMSE and the spread–error relationship compared to the ALEPS forecasts (Figure 3).

We calculated the RMSE and the spread for near-surface parameters against 30 SYNOP stations located in Hungary (Figure 4). For the two versions of ALEPS, the results are similar to those obtained for upper-air parameters. The quality of the ensemble mean is slightly better in ALEPS-ENS, except for 10-metre wind speed, but at the same time the system is less dispersive than ALEPS-PEARP. ALEPS-ENS was able to outperform ECMWF ENS only for 2-metre relative humidity.

Winter case study

On 6 and 7 January 2016, a high amount of precipitation occurred in Hungary in various forms (rain, freezing rain, wet snow, snow). This weather event caused a lot of damage to power transmission lines, especially in southern and central parts of the country, where mixed-phase precipitation occurred.

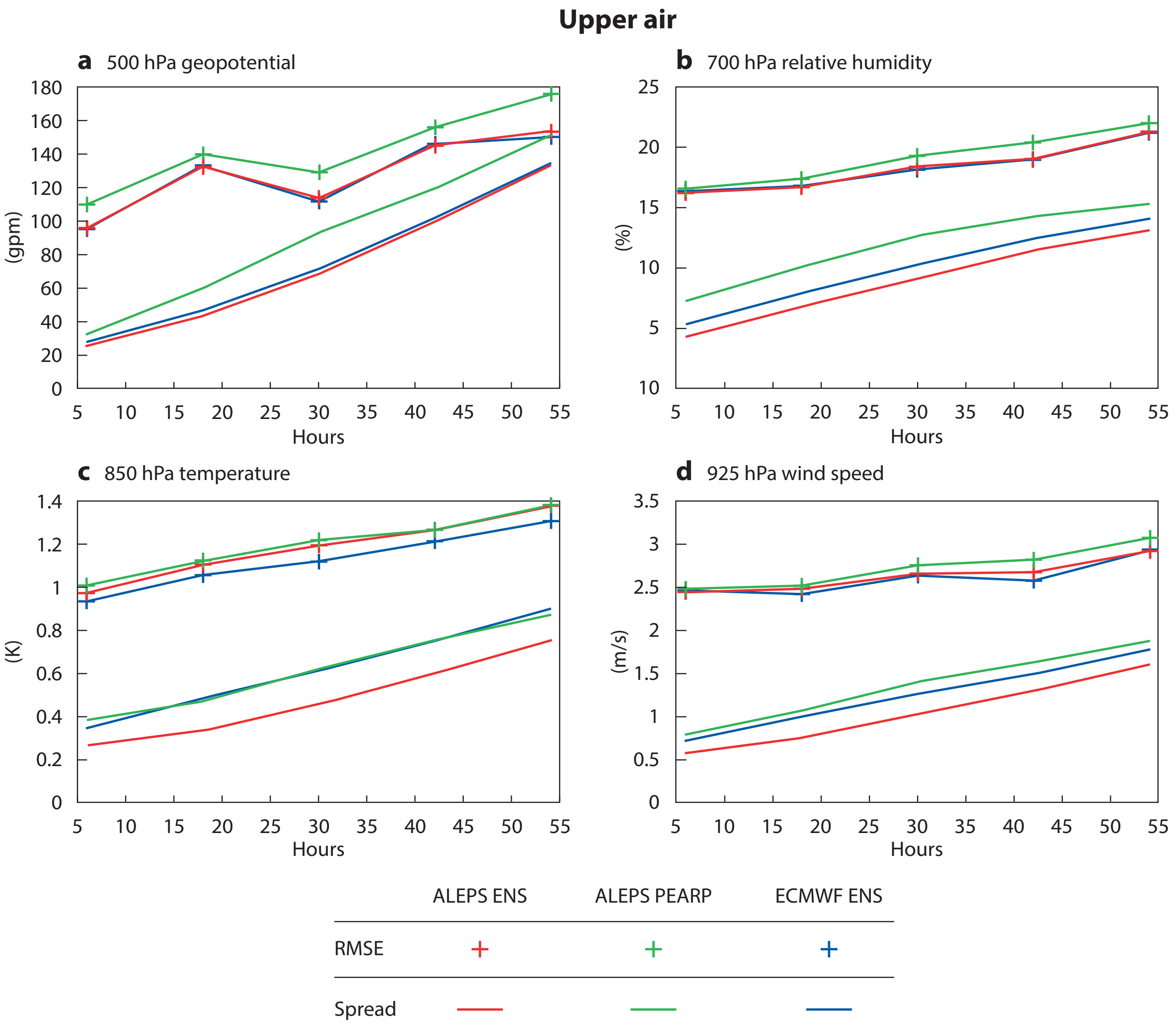

Figure 3 RMSE of the ensemble mean and spread around the ensemble mean of forecasts up to 60 hours ahead run at 18 UTC every day between 11 December 2015 and 31 January 2016 for (a) 500 hPa geopotential, (b) 700 hPa relative humidity, (c) 850 hPa temperature, and (d) 925 hPa wind speed.

The probability of high amounts of precipitation was much lower in the ENS than in the limited-area ensembles run by OMSZ. Due to their higher resolution, ALEPS forecasts seem to capture high-impact weather better than global model runs. In addition, ALEPS-ENS provided good probabilistic guidance for mixed-phase precipitation in the form of freezing rain and wet snow.

Synoptic description

On 6 January, a cyclone developed over the Adriatic Sea and propagated toward the Balkan Peninsula and the Black Sea (Figure 5). At upper tropospheric levels (500 hPa), a trough started to deepen over Central Europe and moved eastward. Consequently, the region of Hungary was at the northern flank of a well-defined baroclinic zone accompanied by significant horizontal and vertical wind shear. In the afternoon and evening of 6 January, there was mostly a northerly-northeasterly flow of cold air at the surface, while at 925 and 850 hPa levels the wind turned to an easterly, southeasterly direction, bringing back warmer air (Figure 6). Hence, there was a potential for falling precipitation to pass the 0°C isotherm several times, causing snowflakes to melt and refreeze in some places.

Precipitation

Although in such winter cases large-scale motions dominate over local effects, there is a strong sensitivity to lower atmospheric features, which can be the main source of forecast uncertainty. It can be important to estimate this uncertainty with a high-resolution ensemble system whose members are able to capture the bigger precipitation events. To see how well ALEPS-PEARP, ALEPS-ENS and the ENS were able to do this, we compared their probability maps. We note that in this case study we used

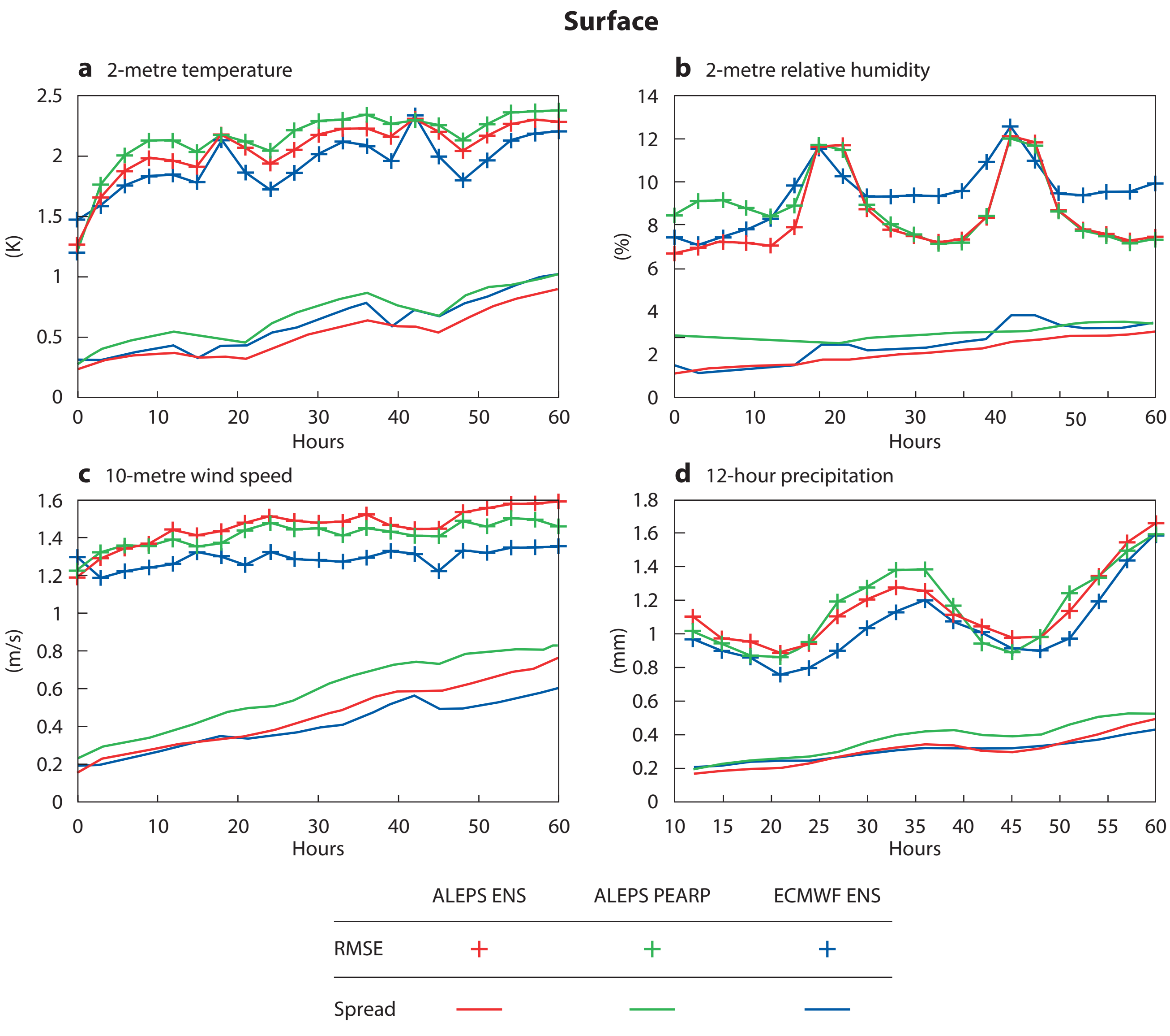

Figure 4 RMSE of the ensemble mean and spread around the ensemble mean of forecasts up to 60 hours ahead run at 18 UTC every day between 11 December 2015 and 31 January 2016 for (a) 2-metre temperature, (b) 2-metre relative humidity, (c) 10-metre wind speed, and (d) 12-hour precipitation.

all the 50 perturbed and the control member of ENS. The probability maps show that all three ensembles gave a similar likelihood for 24-hour precipitation to be over 10 mm in the southern and the middle part of Hungary (Figure 7c–e). There are differences in structure, with the ENS looking much smoother than the ALEPS versions. This is not surprising because of the difference in horizontal resolution and the number of members. If we focus on the 20 mm threshold, the outcome is quite different (Figure 7f–h). Limited-area ensembles predicted much higher probabilities for such a level of precipitation. The areas of the highest probabilities were in relatively good accordance with the area of the observed occurrence of the event. In the Hungarian weather alarm system, 20 mm is the first warning level for rain and approximately the second warning level for snow.

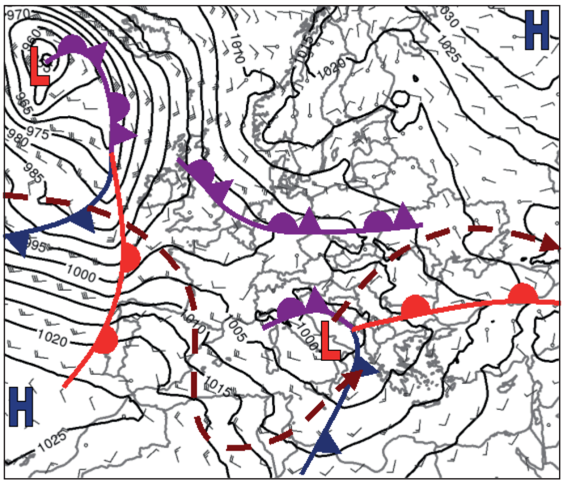

Figure 5 Synoptic chart based on the HRES analysis of mean sea level pressure (contours, in hPa) and 10-metre wind (barbs) valid at 12 UTC on 6 January 2016. The dashed line marks the position of the 300 hPa wind speed maximum (nearly the axis of the upper tropospheric jet).

Freezing rain and wet snow

As mentioned above, mixed-phase precipitation caused the greatest damage during the high-impact weather event on 6 and 7 January 2016. We have used quite simple methods to visualise the probability of severe weather such as freezing rain and wet snow in the ALEPS-ENS. We assumed that snow will be wet during snowfall in temperatures between 0 and 3°C. We note that the sticking efficiency further depends on the liquid water content, which is mostly between 5 and 40%, and wind speed, but the exact determination of these factors is currently rather problematic (*Somfalvi et al.*, 2015). In the case of freezing rain, we simply added up the amount of rain if the temperature was below 0°C.

We then produced probability maps for 36-hour accumulated freezing rain (Figure 8). We examined 1 mm and 5 mm thresholds, which correspond to the second and third warning level in the Hungarian alert system, respectively. ALEPS-ENS provided good guidance on which areas of the country were at risk and highlighted the most threatened counties.

A similar probability map was produced for wet snow with a 5 mm threshold (Figure 9a). Although there is no specific warning level for wet snow, large amounts can cause serious damage, especially to the electricity grid. According to reports by Hungarian disaster management

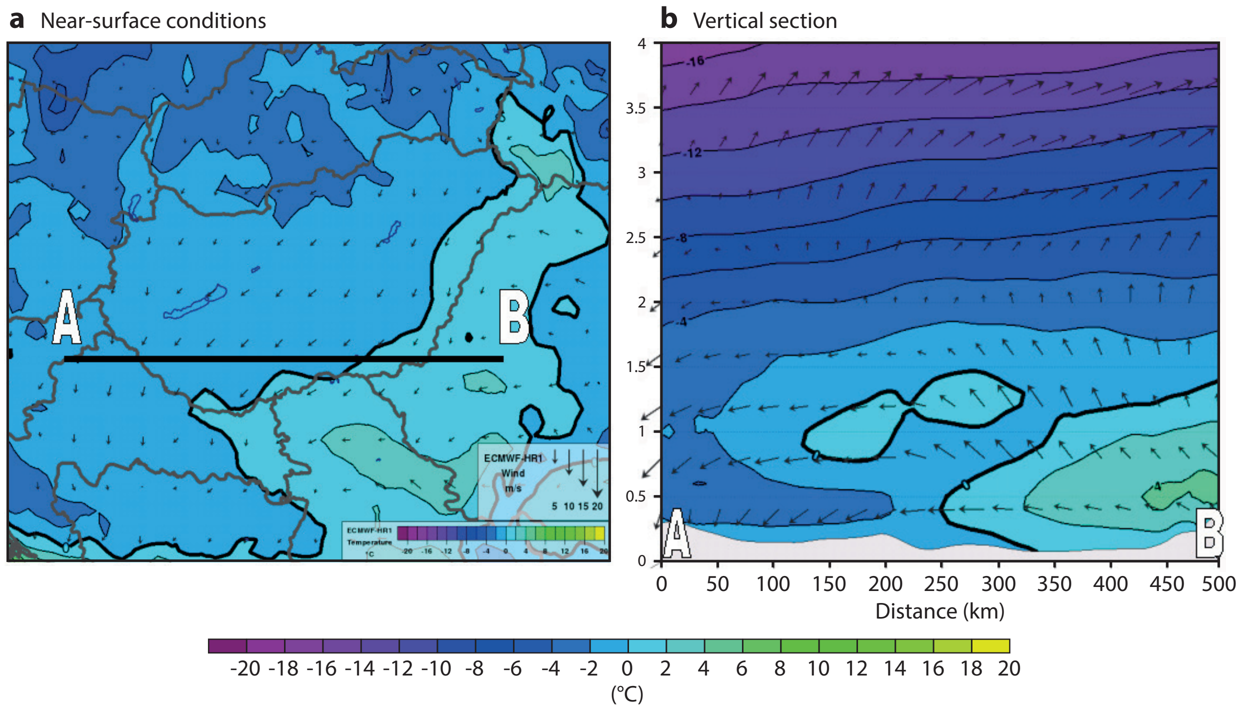

Figure 6 Three-hour HRES forecast of (a) 2-metre temperature (shading) and 10-metre wind (arrows) valid at 15 UTC on 6 January 2016, and (b) the same as (a) but in vertical cross section along the line AB up to a height of 4 km. The 0°C isotherm is depicted by a thicker line.

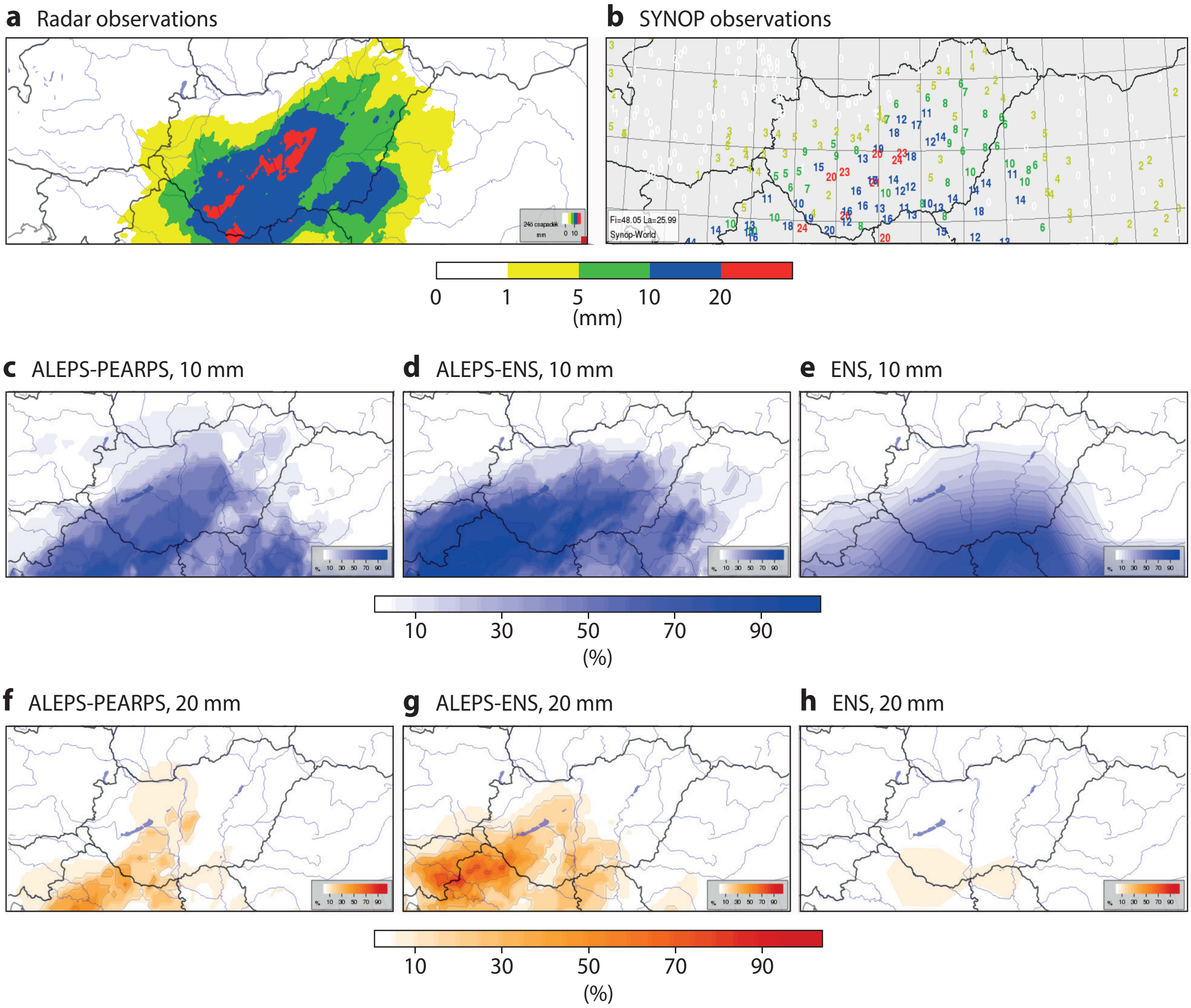

Figure 7 Precipitation in the 24 hours ending at 06 UTC on 7 January 2016 according to (a) estimates based on radar measurements, (b) SYNOP observations, (c)–(e) 36-hour forecasts of the probability of reaching 10 mm, produced by ALEPS-PEARPS, ALEPS-ENS and ENS, respectively, and (f)–(h) 36-hour forecasts of the probability of reaching 20 mm, produced by ALEPS-PEARPS, ALEPS-ENS and ENS, respectively.

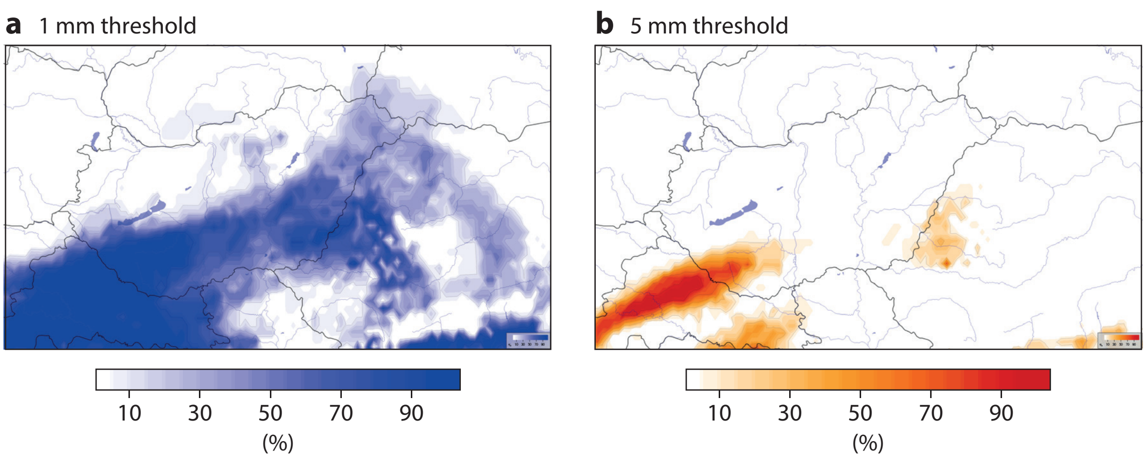

Figure 8 ALEPS-ENS forecast valid at 06 UTC on 7 January 2016 of the probability of 36-hour accumulated freezing rain to be (a) over 1 mm and (b) over 5 mm.

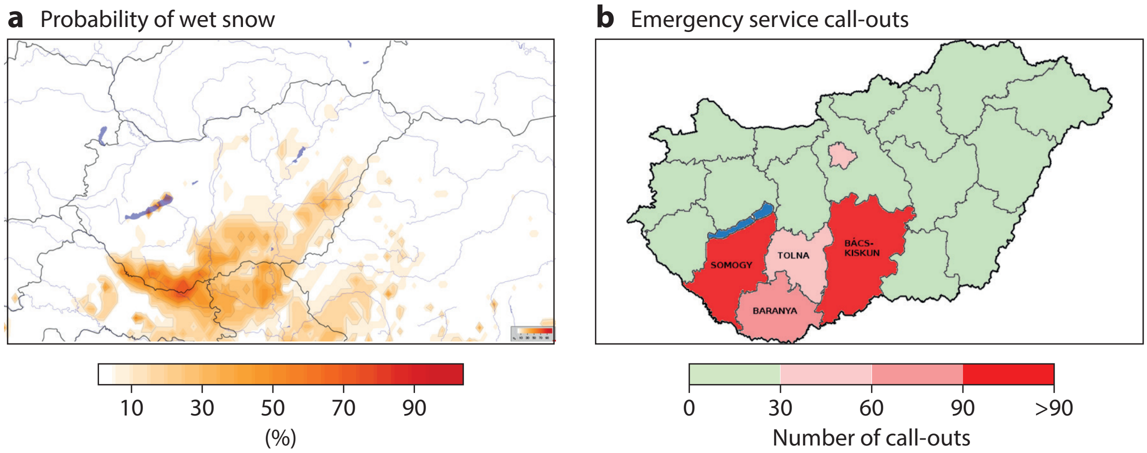

Figure 9 The charts show (a) the probability of 36-hour accumulated wet snow to be over 5 mm from the ALEPS-ENS forecast valid at 06 UTC on 7 January 2016 and (b) the number of call-outs reported by Hungarian disaster management bodies on 6 and 7 January 2016.

bodies, there were temporary power cuts in approximately 40,000 households in Somogy, Bács-Kiskun and Baranya counties. On 6 and 7 January, fire brigades were alerted about three times more often than on average days and most call-outs were in the above-mentioned southern areas (Figure 9b). These statistics correspond well to the ALEPS-ENS predictions, which identified those same counties as the ones most at risk.

Summary and outlook

After the ensemble forecasting extension of the Optional BC Programme, OMSZ was able to run extended tests with an ENS-coupled limited-area ensemble. This system has different characteristics than the operational one: broadly speaking, ALEPS-ENS members are more accurate but the system is less dispersive. Although limited-area ensembles can usually not beat the ENS in scores, they add great value when it comes to forecasting high-impact weather events.

Finally, we would like to underline that ENS-BCs can support our plans to run a local EDA. First, BCs are available with higher frequency and from more production times (four times per day) than in the currently operational version. Second, this setup of LBC generation can ensure that the members of a possible EDA system would be identical with the ones coupled to HRES. It makes the technical maintenance easier and the EDA can correctly describe the uncertainty of our deterministic run as well.

These considerations have led us to prepare further tests with an ENS-coupled EDA system. The results of these experiments will eventually determine the precise role of ENS-BCs in our operational system.

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

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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.

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

	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.

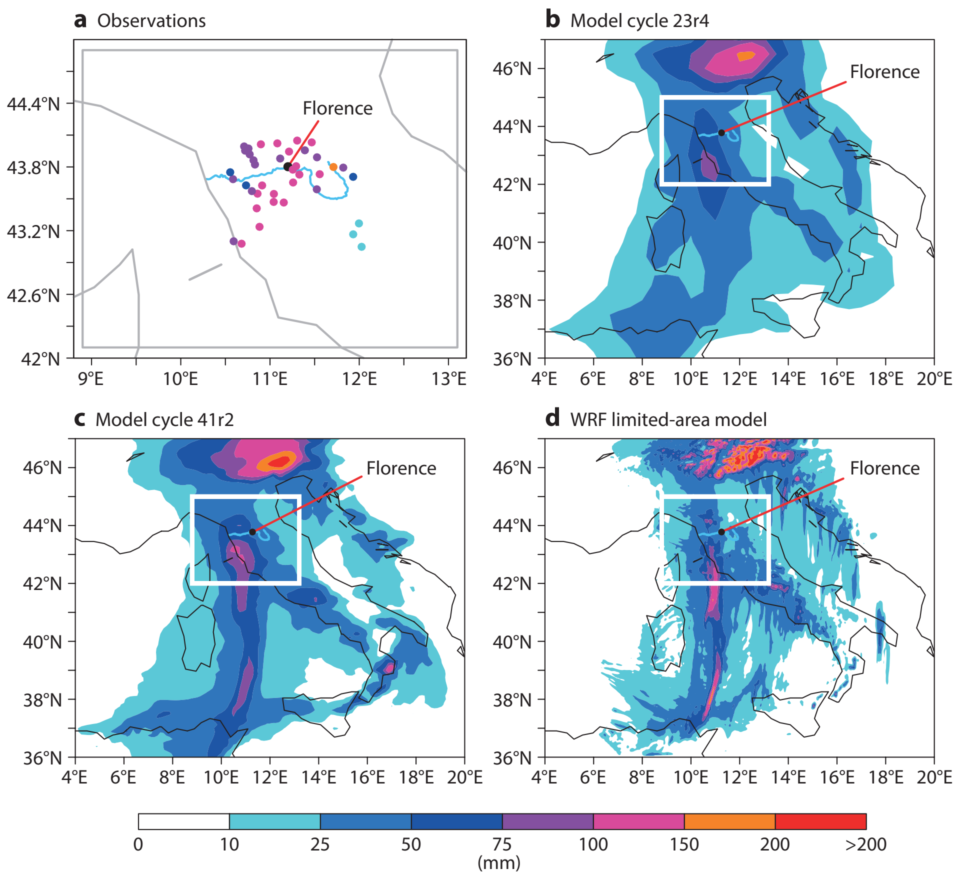

Figure 1 Precipitation charts showing (a) observed precipitation between 00 UTC 4 November and 00 UTC 5 November 1966 from a set of rain gauges in central Italy, (b) 24-hour forecast (model cycle 23r4) for precipitation over the same period as simulated by *Malguzzi et al.* (2006), (c) 24-hour ENS control 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.

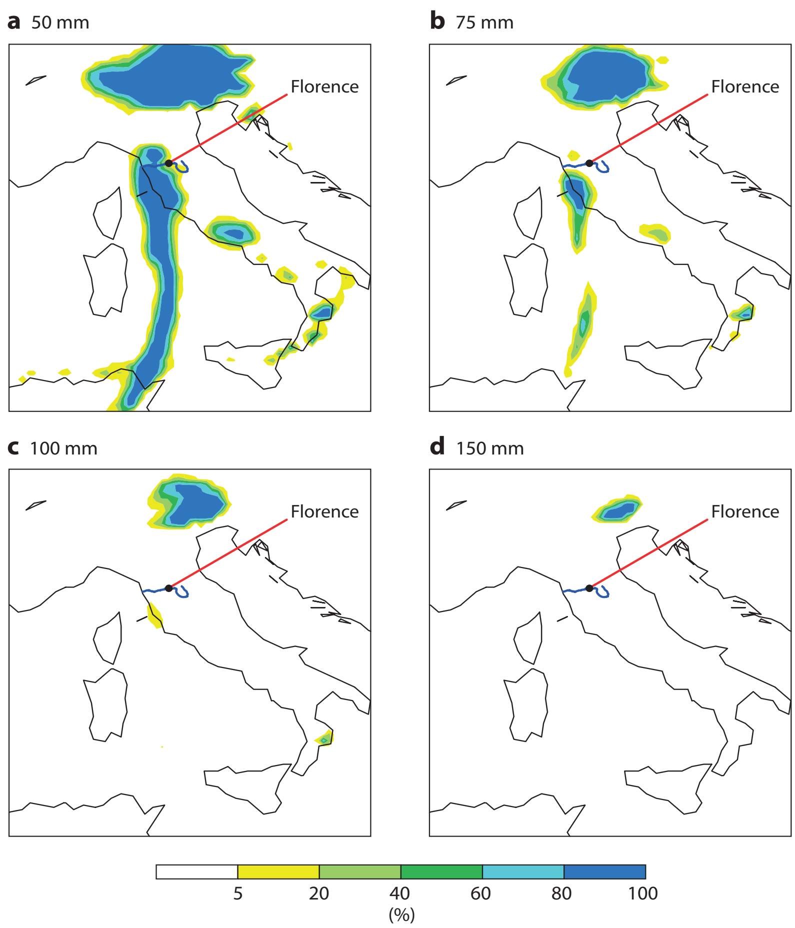

Figure 2 ENS forecasts initialized at 00 UTC on 4 November of the probability that 24-hour precipitation in the period ending at 00 UTC on 5 November 1966 will exceed (a) 50 mm, (b) 75 mm, (c) 100 mm and (d) 150 mm.

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 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.

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

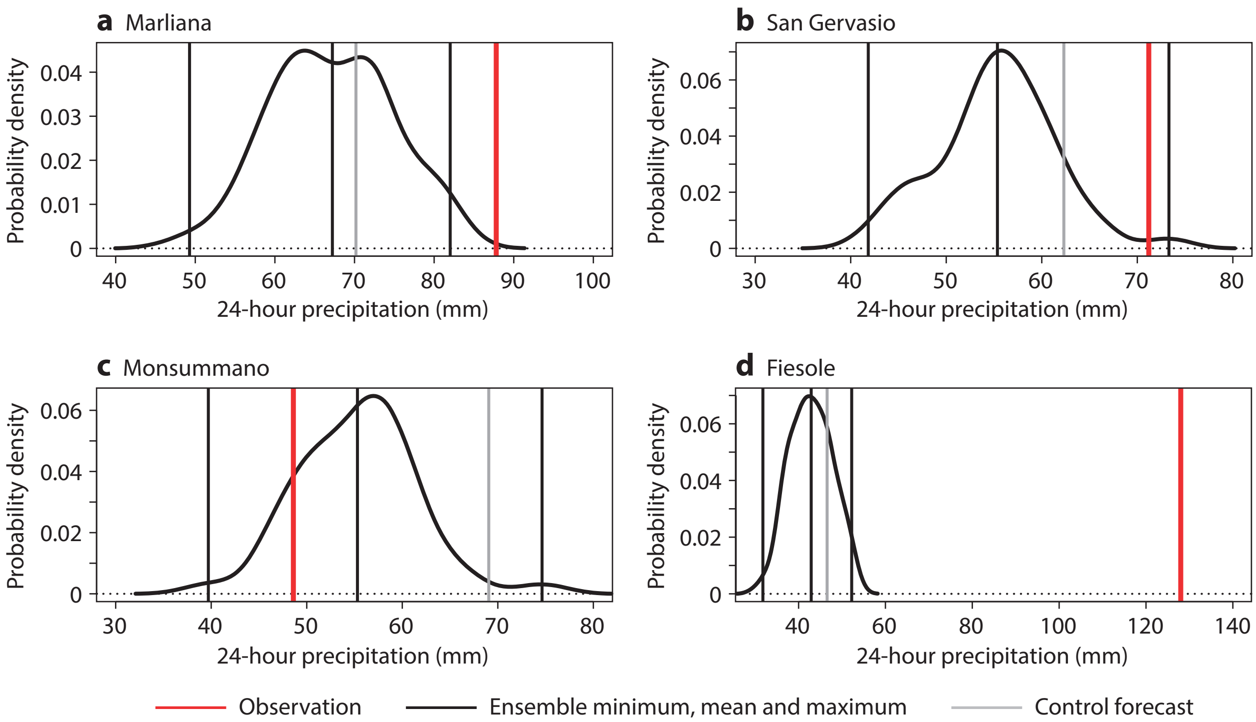

Figure 3 Probability distributions of the ENS precipitation forecasts initialised at 00 UTC on 4 November for accumulated precipitation over the next 24 hours at four rain gauges in the inner Arno River catchment area, located at (a) Marliana, (b) San Gervasio, (c) Monsummano and (d) Fiesole. The red 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.

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.

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.

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-

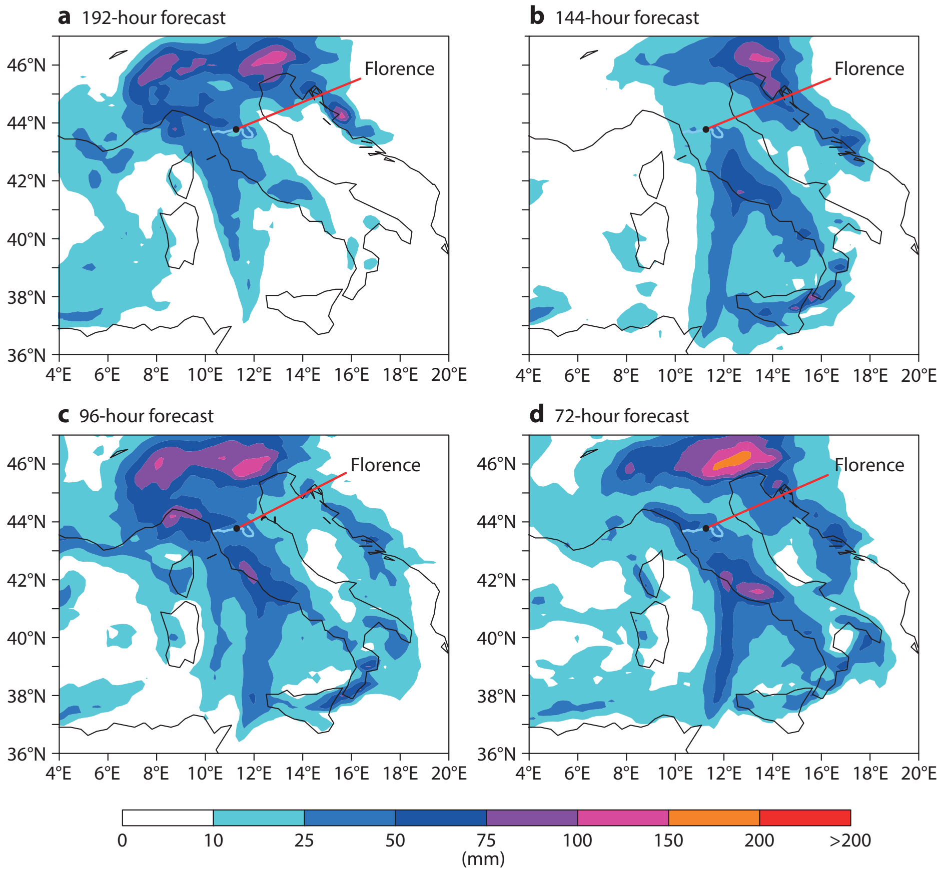

Figure 4 ENS (model cycle 41r2) control forecast of 24-hour accumulated precipitation between 00 UTC on 4 November and 00 UTC on 5 November, showing (a) the t+192h forecast initialized at 00 UTC on 28 October, (b) the t+144h forecast initialized at 00 UTC on 30 October, (c) the t+96h forecast initialized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

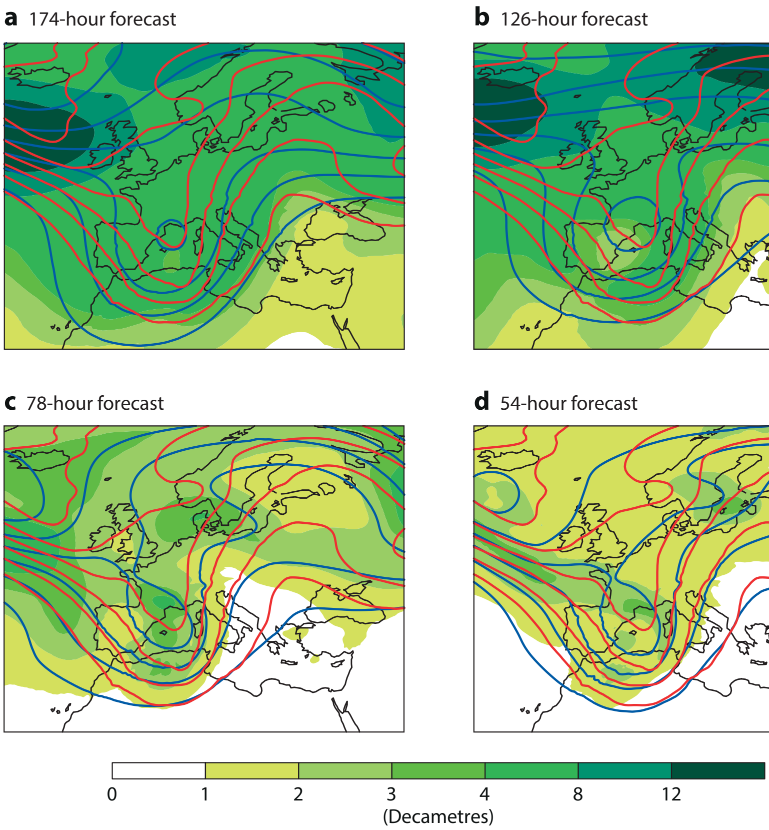

Figure 5 ENS 500 hPa geopotential height mean (blue contours) and standard deviation (shading) verified at 06 UTC 4 November 1966 for (a) the t+174h forecast initialised at 00 UTC on 28 October, (b) the t+126h forecast initialised at 00 UTC on 30 October, (c) the t+78h forecast initialised at 00 UTC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

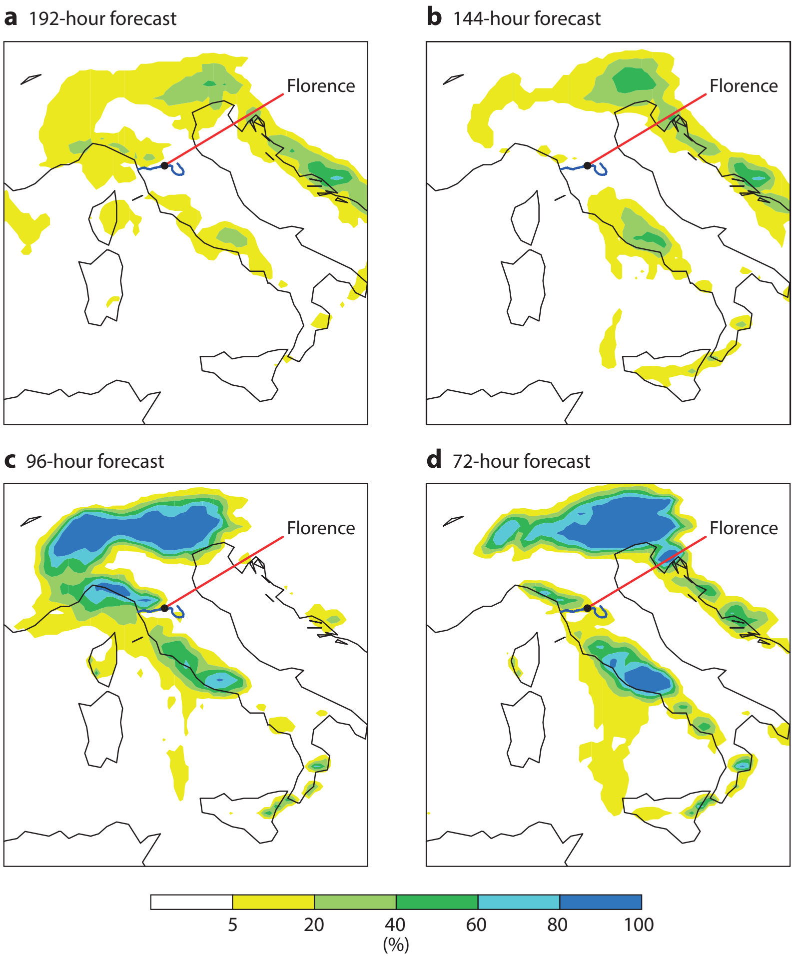

Figure 6 ENS probability of precipitation exceeding 50 mm in 24 hours for the period ending at 00 UTC on 5 November 1966 for (a) the t+192h forecast initialised at 00 UTC on 28 October, (b) the t+144h forecast initialised at 00 UTC on 30 October, (c) the t+96h forecast initialised at 00 UTC on 1 November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

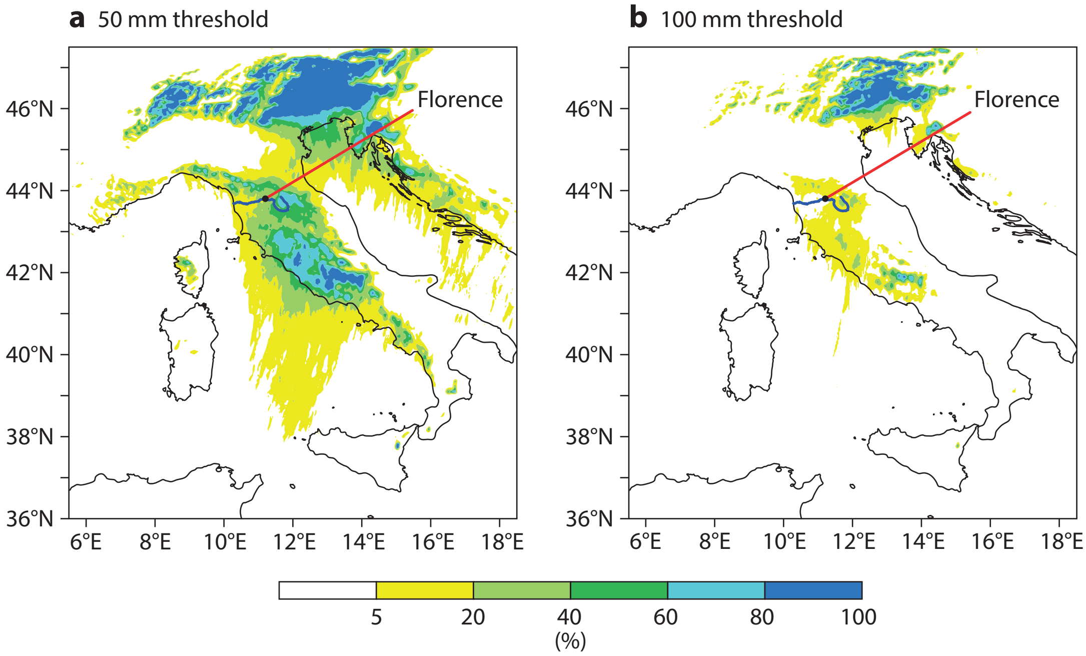

Figure 7 WRF ensemble probability of precipitation exceeding (a) 50 mm and (b) 100 mm in 24 hours for the period ending at 00 UTC on 5 November 1966 for the WRF convection-permitting t+72h forecast initialised at 00 UTC on 2 November 1966.

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.

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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What conditions led to the Draupner freak wave?

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On 1 January 1995 at 15 UTC, the most famous freak wave to be detected by a measuring instrument was recorded by a downward-looking laser at the North Sea Draupner gas platform. The wave was 25.6 m high, with an 18.5 m crest height (Box A). The significant wave height in the area is estimated to have been almost 12 m. The measurement confirmed the existence of giant rogue waves, which had previously been reported anecdotally by sailors. It prompted a number of studies which aimed to determine the meteorological and wave situation at the time and to provide a physical explanation of the event.

High-resolution retrospective forecasts (hindcasts) recently produced at ECMWF show the evolution of wind, pressure and wave fields on 1 January 1995 in unprecedented detail and shed fresh light on how the Draupner wave event may have come about. They suggest that waves driven by a southward-moving polar low interacted with a substantial local wind-generated wave system to produce the conditions conducive to the observed large rogue wave.

New tools

An overview of studies into the origin of the Draupner wave is given by *Cavaleri et al*. (2016a). A detailed analysis was reported by *Sunde* (1995) and summarised by *Haver* (2004). It is often reported that a depression located over Sweden generated a vigorous north-westerly flow leading to substantial south-east propagating waves covering the whole North Sea. *Adcock et al*. (2011) made use of a dedicated reanalysis based on ERA-Interim reanalysis data. The ERA-Interim system, which uses model cycle 31r2 of ECMWF's Integrated Forecasting System (IFS), was run at an increased resolution (TL799, corresponding to a horizontal grid spacing of about 25 km) to produce a new investigation of the situation. However, the resolution of *Adcock et al.*'s simulation was still too coarse to capture the fine details of the event. A new, highly detailed description of the overall situation not previously available is reported here. It was obtained by hindcasting the meteorological and wave conditions using the current resolution of high-resolution forecasts, TCo1279, corresponding to a horizontal grid spacing of about 9 km (*Hólm et al*., 2016), with IFS Cycle 41r1 rather than 41r2, which has now been used for the operational introduction of TCo1279.

The Draupner storm was modelled as a series of forecasts starting from initial conditions provided by the dedicated TL799 reanalysis. The model version used in the simulation benefits from all model upgrades between IFS Cycle 31r2, used for ERA-Interim, and IFS Cycle 41r1.

New results

All results reported here have been obtained starting from the analysis valid at 1 January 1995 00 UTC. Figure 1 provides a sequential view of the meteorological conditions on 1 January. A low-pressure system is centred over Sweden. At 00 UTC (Figure 1a), a polar low is clearly visible off the coast of Norway. It brings with it an energetic increased flux of cold air from the north. At Draupner (represented by the black triangle near the centre of each panel), the wind direction is about 315° (i.e. from the northwest). Over the next 12 hours (Figure 1b–c), the polar low moves rapidly southward, with increased wind speeds on its western flank. It reaches the Draupner latitude at about 15 UTC (Figure 1d). In the area of the platform, the 10-metre wind speed at that time exceeds 20 m/s, and the direction is turning more northerly. In the following hours the low keeps moving south and southeast, reaching the Dutch coast close to the German border at about midnight.

As shown in Figure 2, an extensive area of southward-propagating waves follows the polar low. A detailed analysis of the 2D wave energy spectra indicates the presence of partly crossing-sea conditions at the platform at the time of the freak wave event. The small number of in-situ wave height observations obtained at the time by ECMWF are also shown. At Draupner, the maximum modelled significant wave height is close to 11 m, about 1 m lower than the reported height. An interesting detail emerges when analysing the motion of the polar low.

Some wave-related terminology

A

2D wave energy spectrum: The distribution of wave energy both in frequency and direction. This quantity is the prognostic variable of any modern wave model.

1D wave energy spectrum: The 2D wave energy spectrum integrated over all directions.

Crest height: The height between the top of the wave and the undisturbed water surface.

Crossing sea: Sea state with two wave systems travelling at oblique angles.

Significant wave height: Four times the square root of the integral of the wave spectrum. It closely corresponds to the average height of the highest one third of waves.

Swell: A wave system originating from a distant storm and not affected by local winds.

Wave peak period: The reciprocal of the frequency corresponding to the highest value of the 1D wave energy spectrum.

Wind sea: A wind wave system directly generated and affected by local winds.

From the model output, it is straightforward to estimate that the speed at which the low was moving was about 15 m/s. This is too fast for dynamical wave generation to occur, i.e. for a wave system to move at the same speed as the low and to continuously receive energy from it. For a wave group speed of 15 m/s, the corresponding wave peak period is around 19 s, which is much larger than typically found in studies of the Draupner storm.

However, given the prevailing meteorological conditions, it can be assumed that there was wave energy in this frequency range or just below it. These wave components were moving with the storm, while at the same time receiving energy from nonlinear interactions with the bulk of the wind-sea frequency spectrum (and not directly from the wind as their phase speed was higher than the wind speed). As a result, the area of the highest waves followed the trajectory of the low. *Cavaleri et al.* (2016a) interpret this as a 'dynamically locked' low-frequency part of the spectrum, which is fed by non-linear interactions with the wind-sea part of the spectrum and moves with and at the same speed as the storm. It is only at 15 UTC, when the centre of the low passed near the Draupner area, that the 'locked' low-frequency wave components are present together with a substantial local wind-generated system.

Resolution and observations

It is clear that the high horizontal resolution is an essential element in the success of this latest simulation. As shown by *Cavaleri et al.* (2016a), running the same experiment

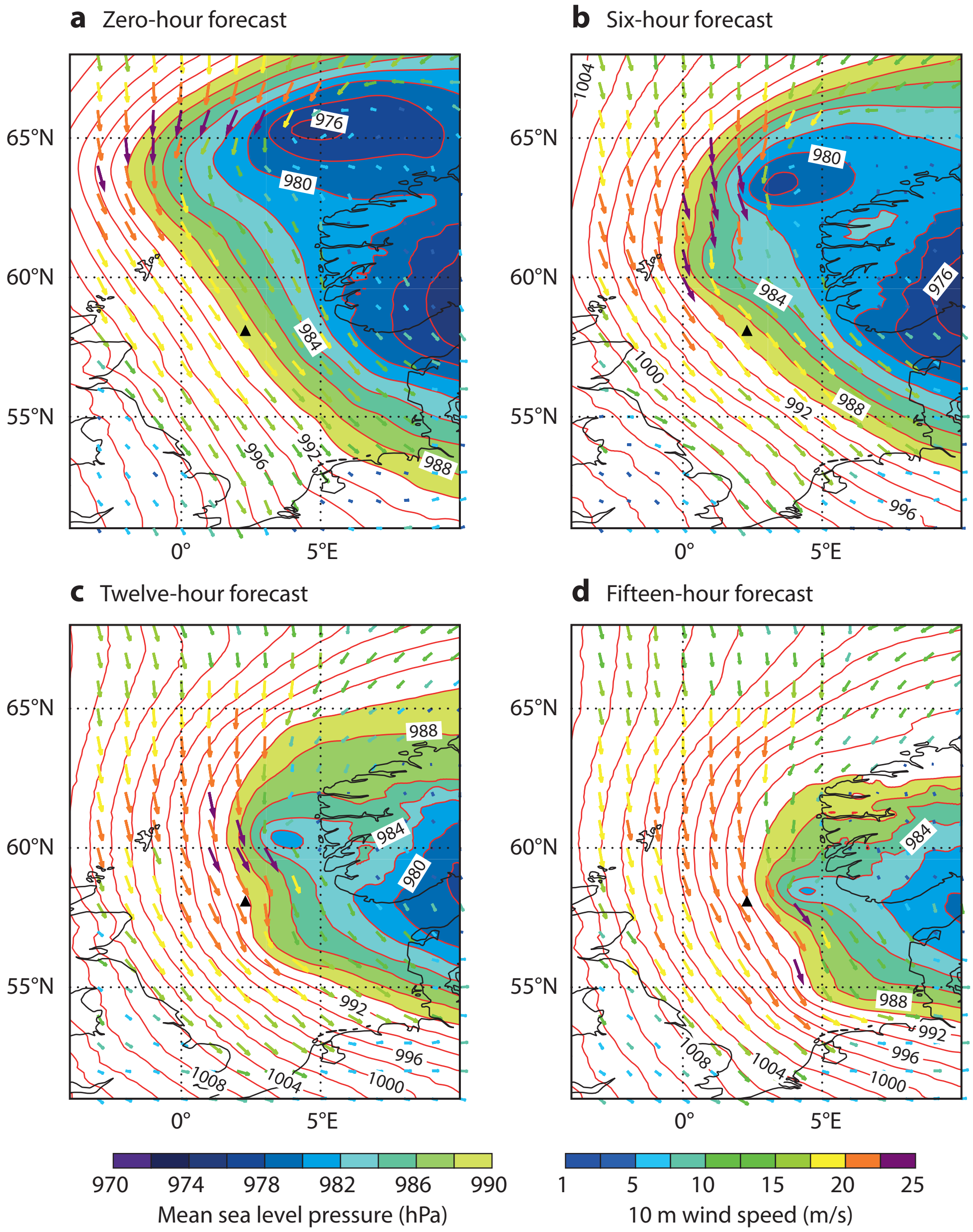

Figure 1 High-resolution forecasts of 10-metre wind (arrows) and mean sea level pressure (contours, shading) in the North and Norwegian Seas on 1 January 1995, showing (a) a 0-hour forecast, (b) a 6-hour forecast, (c) a 12-hour forecast, and (d) a 15-hour forecast, all starting from 00 UTC. The black triangle shows the position of the Draupner platform.

at TL799 does not produce a well-defined polar low but rather an area with slightly more intense winds embedded in the large-scale circulation caused by the depression over Sweden. Similarly, by comparing this TL799 run with the corresponding forecast from the dedicated reanalysis, it was shown that model improvements since ERA-Interim were also a contributing factor, since with the old model the area with intense wind was much more confined.

As for the predictability of the event, longer-range forecasts were not very good at anticipating the evolution of the polar low. There might be several reasons why earlier analyses did not have the relevant information, resolution being one of them. The polar low was only noticeable in the analysis map when it was already on its way south. Its whole trajectory from the far north (about 66° N), where it was identified, to the Dutch coast took less than 24 hours. There was no clue of its existence, and hence no possible prediction based on it, before 1 January 00 UTC. This points to a lack of observations, which is today possibly being alleviated as a result of a strong interest in the Arctic. For example, EUMETNET have deployed additional marine buoys in the area, which measure surface pressure with high accuracy.

Demystifying the Draupner wave

Based on the simulations described above, *Cavaleri et al.* (2016b) have analysed the Draupner wave, drawing on

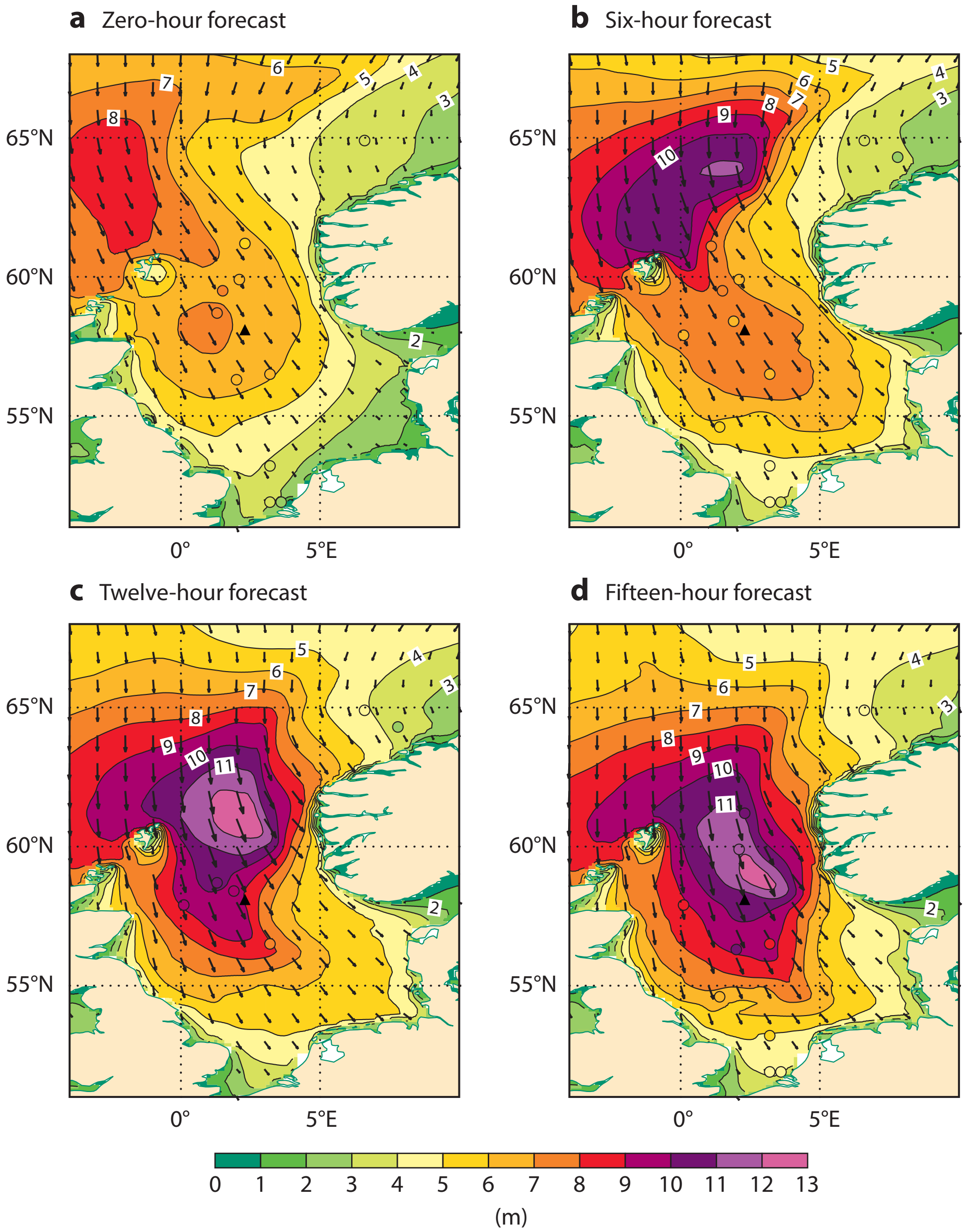

Figure 2 High-resolution forecasts of significant wave height distribution (shading) and mean wave direction (arrows) in the North and Norwegian Seas on 1 January 1995, showing (a) a 0-hour forecast (b) a 6-hour forecast, (c) a 12-hour forecast and (d) a 15-hour forecast, all starting from 00 UTC. The black triangle shows the position of the Draupner platform. Coloured circles denote corresponding wave height observations (same colour scale as for the forecasts) as archived at ECMWF.

recent work on the distribution of extreme waves and crest heights. From this vantage point, the Draupner event, like probably most of the large waves reported in the literature, loses much of the mystery surrounding it: such waves are a regular part of large storms and coming across them is just a matter of probability depending on the spatial and temporal scales considered.

In the case of the Draupner, the wave conditions, both in terms of height and spectral shape, made encountering a particularly high wave and crest particularly likely. The probability of such an event may have been enhanced by the presence of two crossing low-frequency wave systems that could only be properly modelled because of recent improvements in the IFS and the use of increased resolution. *Cavaleri et al.* (2016b) have introduced the concept of 'dynamical swell' to identify the part of the wave spectrum which moves with the storm without receiving energy from the wind because of its higher phase speed, but which is made more energetic via nonlinear interactions from the active part of the wind-sea spectrum. This condition may be more common than had been thought, particularly in the case of fast-moving storms.

FURTHER READING

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Oct 24	Advisory Committee of Co-operating States, Bratislava
Oct 24–28	Workshop on High-Performance Computing in Meteorology
Nov 7–11	Workshop on Tropical Modelling and Assimilation
Nov 15–17	EUMETSAT Satellite Application Facility on Climate Monitoring (CM SAF) Workshop
Nov 21–25	UERRA General Assembly
Nov 29–30	ECOMET General Assembly and EUMETNET Assembly
Dec 1–2	Council

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