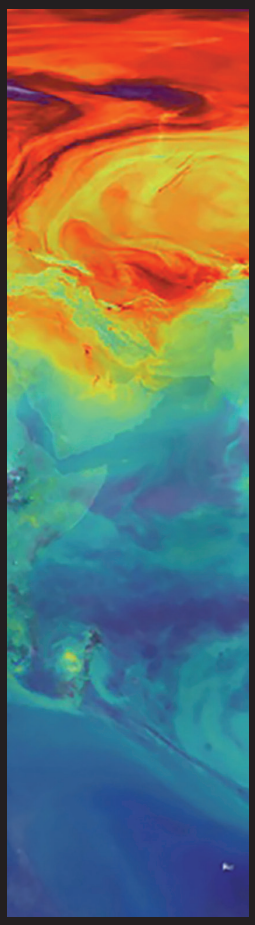
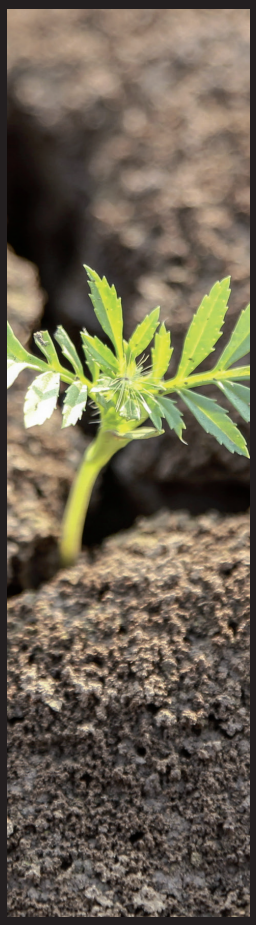
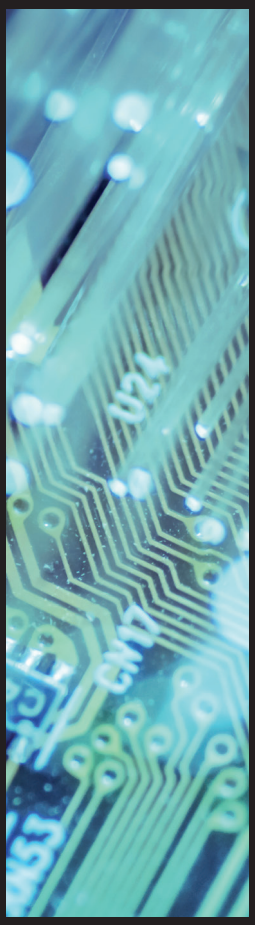
ECMWF

ANNUAL REPORT **2015**

40 YEARS

of advancing global NWP through co-operation



ECMWF

ANNUAL REPORT **2015**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Member States as of January 2016

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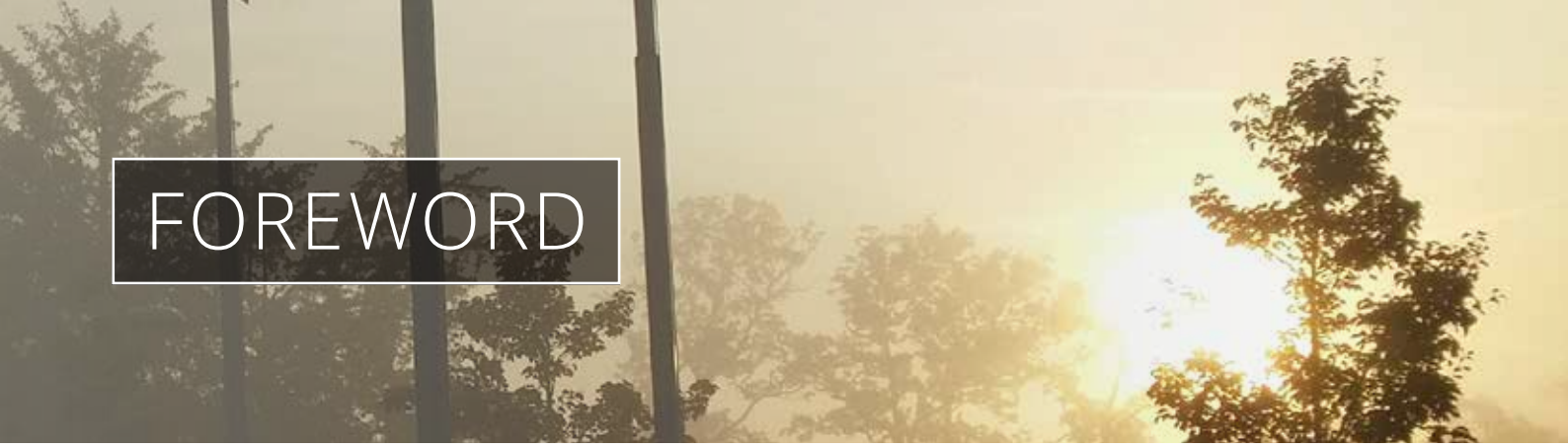


FOREWORD

Challenging and exciting times

Reviewing what ECMWF achieved in 2015 brings back all the excitement and challenges that marked the year. Highlights include witnessing the progress brought by model upgrade 41r1 in our operational output, consistent gains in forecast performance compared to the previous model cycle 40r1, and notably the improvement of forecasts of heavy rainfall. 2015 has also seen ECMWF and its members reap the benefits of years of research as the all-sky assimilation of microwave satellite observations reaches maturity and shows world-leading results; it has also brought the prospect of higher resolution closer as the cubic-octahedral grid, also years in the making, was being finalised.

Today, as I review what this Report lists as some of the many key moments of the year, I have the advantage of having seen the results. I now know that the promise of Cycle 41r2 has materialised, delivering a ground-breaking horizontal resolution of 9 km for the high-resolution forecasts and 18 km for the ensemble forecasts. I can see tangible results coming out of the Scalability Programme, as the projects launched in 2014 and 2015 start to positively impact our ways of developing the whole NWP chain. After all the tests and migrations to the Phase 2 system of our Cray supercomputer, I can see the value in the enormous efforts put into designing and developing this new extension of our supercomputer capability, ensuring that we continue to have the level of technology needed to deliver our mission to our Member and Co-operating States. Seeing the synergies emerge between the Copernicus activities and our research teams gives meaning to the hiring of new staff and setting up and promoting the new services in 2015.

That is the advantage of writing the foreword to an Annual Report: being able to look back and to know that we have done well.

At the end of 2015, our then Director-General, Professor Alan Thorpe, stood down and I was offered the privilege of leading our Centre through the next few years. Many challenges lie ahead, including the need for new accommodation to meet our data centre requirements; the development of an Earth system approach best able to further improve the skill of our ensemble-based predictions; and the development and implementation of a more sustainable and scalable approach to our science. The future promises to be just as exciting as the past.

Dr Florence Rabier
Director-General,
ECMWF.

2015 AT A GLANCE

JANUARY

Serbia becomes a Member State

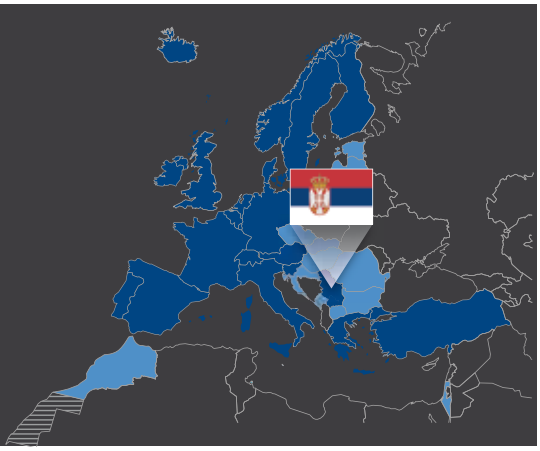
Serbia becomes ECMWF's 21st Member State, having held a co-operation agreement with the Centre since 2003.

Start of meteorological training courses

The 2015 meteorological training programme gets under way with courses on the use and interpretation of ECMWF products, the science underpinning numerical weather prediction, and developments in research. New this year are a collaborative Data Assimilation course with the University of Reading and a three-day blended learning course focused on ensemble products and their use.

MACC-III General Assembly

The EU MACC-III project (Monitoring Atmospheric Composition and Climate) holds its General Assembly at ECMWF. Coordinated by ECMWF, the MACC project has developed pre-operational services for atmospheric composition that will become part of the new Copernicus Atmosphere Monitoring Service.



Strategy engagement with Member States

After several months of engagement with staff, ECMWF is ready to present the first draft of the 2016–2025 Strategy to Member States. In a series of multi-lateral meetings organised with national meteorological services in Member States, we gathered opinions to help guide the strategy developments and enable ECMWF to continue to contribute to the missions of the meteorological services.

FEBRUARY

Start of computing training programme

The first computing training courses of the year get under way, introducing users to ECMWF's software packages and applications for producing and visualising numerical weather predictions. The programme continues in March and April, with courses on ECMWF's computing facilities, the meteorological data archive (MARS), and the use of the new Cray high-performance computing systems.

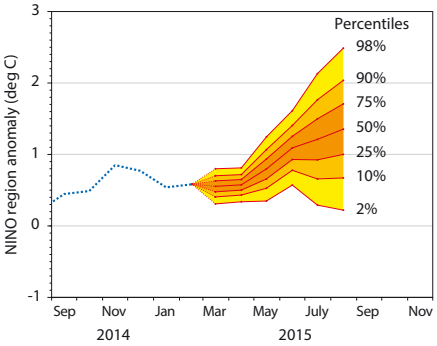
MARCH

Copernicus Climate Change Service (C3S) workshop

ECMWF hosts the first in a series of international workshops to involve the scientific community in defining requirements for the C3S. The focus is on the climate data store, a distributed facility that will provide information about past, present and future climate. Subsequent workshops in April and June focused on 'Climate projections' and 'Climate observation requirements'.

Forecasts signal potentially strong El Niño

The weak El Niño conditions observed since October 2014 continue, with forecasts suggesting sea-surface temperatures (SSTs) in the central Pacific will rise further to become more than 1°C warmer than usual by August, with the possibility of substantially stronger warming. However, there is a great deal of uncertainty beyond June 2015.



New Metview training module

ECMWF launches a redesigned 'Data Analysis and Visualisation using Metview' module that introduces Metview's tools for accessing, processing and visualising meteorological data.

ecCodes software

A beta version of the new ecCodes software package is released for testing. It enables users to decode and encode meteorological data in BUFR or GRIB format using a single, simple interface.

ECMWF/EUMETSAT satellite data assimilation course

The course, sponsored by EUMETSAT, provides a complete overview of the use of meteorological satellite observations in numerical weather prediction.

By the end of 2015, ECMWF employed 304 staff from 31 countries

APRIL

Charity triathlon

Forty-two members of staff take part in a local triathlon event to raise money for Comic Relief, a charity that works to relieve poverty in the UK and around the world.

Ten years of flood forecasting

The European Flood Awareness System (EFAS) holds its 10th anniversary user meeting in Brussels. ECMWF operates the EFAS Computational Centre, which is responsible for running the forecasts.

MAY

New database for sub-seasonal to seasonal forecasts

As part of the WMO's Subseasonal to Seasonal Prediction project (S2S), ECMWF launches a data portal for S2S weather forecasts to help researchers study predictability on timescales of up to 60 days.

New IFS model cycle

The latest model upgrade for the Integrated Forecasting System (IFS), Cycle 41r1, brings improvements in the representation of the current state of the atmosphere and in the forecast skill. Improvements are seen in the modelling of cloud and precipitation, 2-metre temperature and humidity in parts of the northern hemisphere and the tropics, and in the forecasts for tropical cyclones. There are also a number of new output parameters.

JUNE

New Director for ECMWF Copernicus Services

Juan Garces de Marcilla becomes the Director of ECMWF's new Copernicus Services Department.

UEF 2015: 'Quantifying and communicating uncertainty'

Our annual user meeting focuses on quantifying and communicating uncertainty. Topics include the need to tailor probability information and the importance of graphical products in summarising forecast uncertainty. Participants confirm the crucial role of uncertainty when developing NWP models and discuss ways to improve the communication of uncertainty and confidence in the forecasts.

OpenIFS user meeting

Users of ECMWF's OpenIFS model, a version of the IFS for education and research, meet at the Centre for a workshop focusing on uncertainty in numerical weather prediction (NWP).

Eumetcal/ECMWF workshop on education and training in weather prediction

Together with Eumetcal, Europe's virtual meteorological training organisation, ECMWF organises a workshop to explore current and future meteorological training requirements. Participants identify developments in forecasting, in the role of forecasters, and in technology that will affect training requirements.

2015 AT A GLANCE

JULY

Copernicus at Paris climate conference

Ahead of international climate change negotiations later in the year, ECMWF presents how it will implement the EU-funded Copernicus Climate Change and Atmosphere Monitoring Services, at a conference in Paris entitled 'Our Common Future Under Climate Change'.

WMO online book on seamless prediction of the Earth system

The WMO publishes an online book summarising the outcomes of the first ever World Weather Open Science Conference (WWOSC), held in Montreal in August 2014. ECMWF staff contributed to 12 of the 25 collaborative papers contained in the book, entitled *Seamless Prediction of the Earth System: From Minutes to Months*.

AUGUST

Severe heat wave in Europe

Several temperature records are broken around Europe in the summer. ECMWF's ensemble forecasts predicted the onset of the heat wave well from two and a half weeks before the event. For some locations, predicted temperatures were lower than those actually observed.

SEPTEMBER

Annual Seminar on 'Physical processes in present and future large-scale models'

More than 80 scientists from 17 countries meet in Reading for a wide range of presentations on the modelling of physical processes by leading scientists from ECMWF and around the world.

Visualisation in Meteorology week

ECMWF organises its first 'Visualisation in meteorology week', looking at the latest developments in meteorological forecaster workstations and web mapping services. The presentations and demonstrations show the importance of visualisation in meteorology for scientists and operational users.

New office space at University of Reading

To accommodate the growing number of staff, ECMWF opens a second site at the nearby University of Reading, where we already have close scientific ties.

EMS Innovation in meteorology finalists

ECMWF scientists Tim Hewson and Florian Pappenberger are finalists for the Harry Otten Prize for Innovation in Meteorology awarded by the European Meteorological Society. Their entry, 'Flash Flood Prediction using Current-Generation Global Models', proposed an operational system that uses readily available global ensemble output to deliver automated flash flood predictions, to ten days ahead, for anywhere in the world.

Nature article on the quiet revolution of NWP

The science journal *Nature* publishes an article on 'The quiet revolution of numerical weather prediction', co-authored by Peter Bauer and Alan Thorpe from ECMWF and Gilbert Brunet from Environment Canada. It discusses the gradual progress and steady improvements in areas such as physical process representation, model initialisation, and the characterization of analysis/forecast uncertainties through ensembles, as well as supercomputing challenges.

OCTOBER

Scalability projects gather momentum

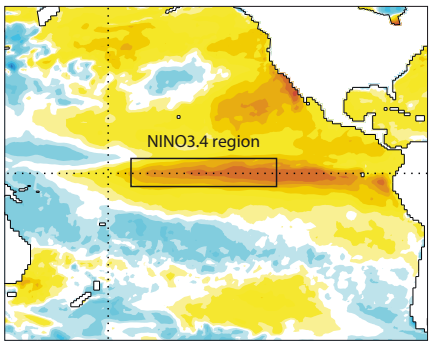
Four EU-funded scalability-related projects in which ECMWF is involved prepare to get under way. ESCAPE (coordinated by ECMWF) was presented to the wider high-performance computing community at a workshop in Rome in September, ahead of its formal kick-off meeting in October. The EarthServer2 project held its second meeting at ECMWF to set out a roadmap for the year ahead,

while NEXTGenIO and ESiWACE started in November and December, respectively.

NOVEMBER

El Niño conditions peak in the central Pacific

Conditions in this year's El Niño event reach their peak, setting new records for sea-surface temperature in the central and western equatorial Pacific. The evolution of the event was well predicted by ECMWF's forecasts throughout the year. At its peak, the NINO3.4 SST anomaly reached 3.0°C, breaking the previous record of 2.8°C set in January 1983. In the NINO4 region, the anomaly reached 1.7°C, a substantial increase of 0.4°C on the previous record, set in 2009.



40 years of the ECMWF Convention

The Convention establishing ECMWF came into force on 1 November 1975. Forty years on, ECMWF has 21 Member States and 13 Co-operating States. ECMWF staff past and present, Council members and invited speakers marked the anniversary in June with a programme of lectures and an evening celebration. Speakers noted the "stunning" advances made in NWP over the last four decades, holding up ECMWF as an example of what can be achieved through international collaboration.

DECEMBER

Redesigned web charts

New and improved versions of all ECMWF web charts and tools become available on ECMWF's website. Updates include forecast charts for tropical cyclones and severe weather demonstration projects, as well as charts for monitoring the quality of observations and for our monthly and seasonal forecasts.

WMO reduced-fee licence

ECMWF announces a new reduced-fee licence for NMHSs that are members of the WMO. The aim is to enable more national weather services, primarily those from developing countries, to benefit from the full range of web-based charts.

JMA to join EUROSIP

A provisional agreement is reached for the Japan Meteorological Agency to join EUROSIP. Seasonal forecasts from the Japanese models will provide valuable input to the EUROSIP multi-model seasonal forecasting system, which currently combines data from ECMWF, the Met Office, Météo-France and the National Centers for Environmental Prediction (NCEP). ECMWF's Council is expected to ratify the agreement in June 2016.

IFS Cycle 41r2 enters the Release Candidate test phase

The full Cycle 41r2 forecast production starts running in parallel with the operational production, with test data being disseminated to the Member States in near-real time. IFS Cycle 41r2 implements an increased horizontal resolution of the high-resolution forecast to around 9 km and ensemble forecast to around 18 km. It also makes use of a new model grid, the octahedral reduced Gaussian grid.

Continued support for Bangladesh forecasting project

ECMWF extends its co-operation agreement with RIMES (Regional Integrated Multi-Hazard Early Warning System) until 2020. Under this agreement, ECMWF provides real-time forecast products free of charge for flood forecasting in Bangladesh, particularly for floods associated with the monsoon. Specific arrangements for Bangladesh will cease once equivalent flood forecasting data and services – open to all interested countries – can be provided globally by Copernicus.

Florence Rabier appointed as Director-General

The ECMWF Council appoints Dr Florence Rabier to succeed Professor Alan Thorpe as Director-General of ECMWF from 1 January 2016. Florence is an internationally recognised expert in NWP and is especially well known in the meteorological community for her key role in implementing a new data assimilation method (4D-Var) in 1997, which was a first worldwide.

ECMWF Director-General Alan Thorpe retires

Professor Alan Thorpe retires as Director-General of ECMWF, having taken up the post in July 2011.

ADVANCING WEATHER SCIENCE

Research and development

ECMWF is both an operational weather prediction centre and a hub for cutting-edge research into all aspects of numerical weather prediction. The advances made by ECMWF's scientists are incorporated into forecasting systems to make sure that predictions are based on the best available science and serve the needs of the Centre's users. Collaboration is a key ingredient in this research effort. ECMWF's scientists work with space agencies, national meteorological services and the research community worldwide to push the boundaries of knowledge.

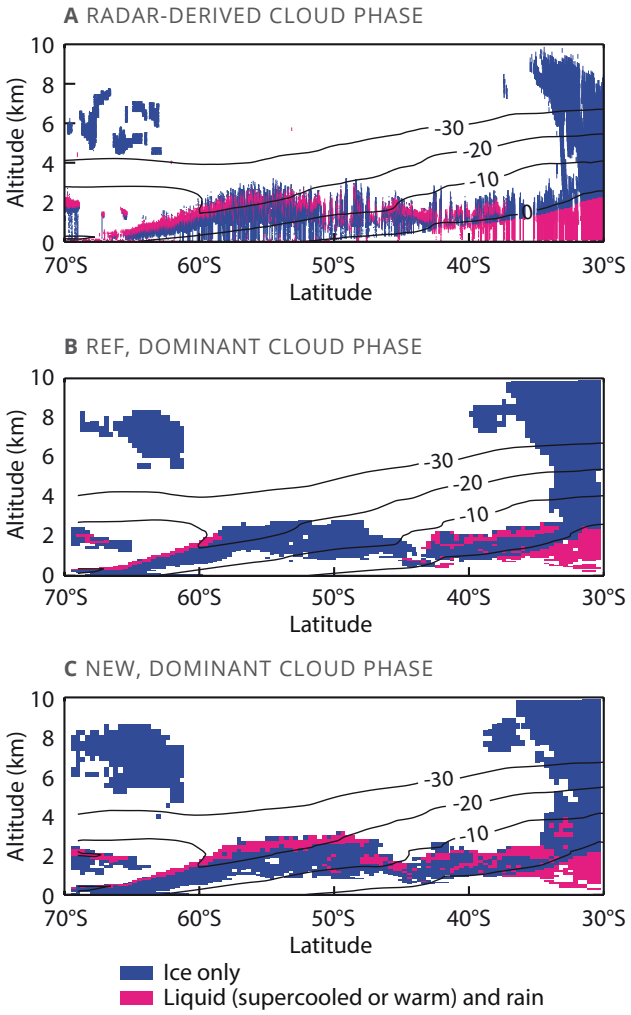
Work carried out in 2015 prepared the ground for the introduction of a new model cycle (41r2) with record-breaking horizontal resolution. At the same time, long-term research into data assimilation methods, Earth system processes, predictability and numerical methods continued apace. The following examples illustrate the progress made.

Cloud physics

Sometimes careful diagnostic work is required to pinpoint the sources of errors in forecasts. An example is the long-standing systematic error in the global shortwave radiation field.

An evaluation of microwave radiance brightness temperature first-guess departures, combined with shortwave radiation and radar/lidar data from satellites, pointed the Centre's scientists to a lack of supercooled liquid water in the modelling of convective cold-air outbreaks as a source of the error.

A solution that increases the detrained supercooled liquid water for convective updraughts with mid-level cloud tops leads to a better fit with cloud phase observations. It also significantly reduces the long-standing shortwave radiation bias over the Southern Ocean, North Atlantic and North Pacific seen at all model resolutions and timescales.



▲ **Ice and liquid water in clouds.** Vertical cross section of dominant cloud phase at about 2230 UTC on 24 August 2013 from latitude 70°S to 30°S close to longitude 120°W through a region of cold-air advection for (a) satellite radar/lidar-derived cloud phase, (b) model-simulated cloud phase from a reference 12-hour forecast (REF), and (c) model-simulated cloud phase with modified convective supercooled liquid water detrainment (NEW). Temperature contours are shown every 10°C from 0° to -30°C.

Pioneering work by ECMWF scientists has enabled the all-sky assimilation of satellite humidity data

All-sky assimilation

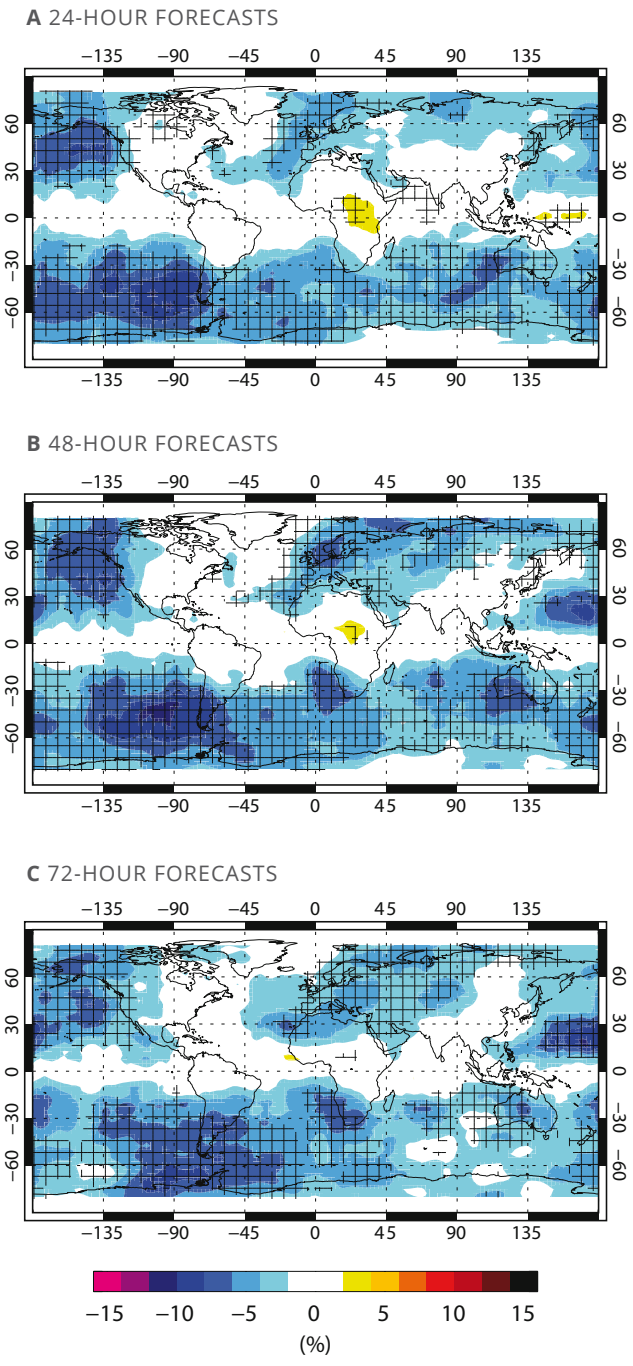
Humidity, cloud and precipitation observations from satellites can be used to infer winds and other dynamical variables in the data assimilation system. This helps to determine the initial state of the atmosphere and leads to improved forecasts.

Based on pioneering work carried out by ECMWF scientists, most data from microwave humidity sounders and imagers can now be assimilated in all-sky conditions over the ocean, land and sea ice. Much of this work was funded by EUMETSAT via Fellowships at ECMWF. The all-sky assimilation of microwave humidity sounder data from four satellites became operational in May 2015.

The assimilation of water vapour, cloud and precipitation data from these satellites, including over snow-covered land, makes it possible to extract dynamical information that benefits medium-range forecasts. For the first time, humidity sounding observations will be able to fill major data gaps over the northern continents during winter and spring.

The result of this research effort is that microwave humidity observations are now having a very significant impact on medium-range forecast scores out to at least day 6.

The next steps will be to apply the all-sky approach to more microwave instruments and to solve the all-sky infrared assimilation problem.



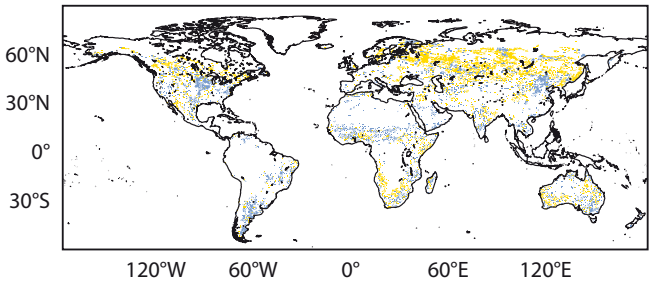
▶ **Reduced error.** Normalised difference in root-mean-square error of 500 hPa geopotential height between forecasts using all-sky assimilation from seven satellites and control forecasts not using these data. Blue areas indicate where all-sky assimilation reduces forecast errors. Cross-hatching indicates statistical significance at the 95% confidence level. The figures are based on six months of experimentation using model cycle 41r1.

ADVANCING WEATHER SCIENCE

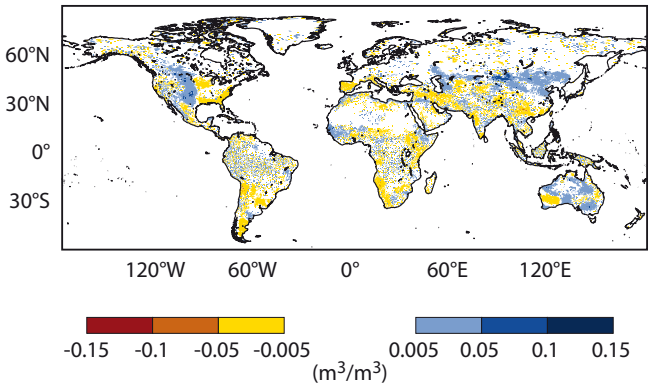
Soil moisture observations

Scientists at the Centre are constantly working to improve near-surface weather parameter forecasts. Following extensive research experiments, they revised the observation error specifications in the land surface analysis and activated soil moisture data assimilation using Advanced Scatterometer (ASCAT) satellite observations.

A ASCAT OBSERVATIONS FROM EUMETSAT METOP SATELLITE



B SYNOP OBSERVATIONS



▲ **Analysis increments.** An analysis of soil moisture can be produced separately for ASCAT observations on the one hand and SYNOP 2-metre temperature and relative humidity observations on the other. The analysis increments – the difference between the analysis and short-range forecasts – are shown left for the surface layer (top 7 cm of soil) accumulated for 1 to 5 April 2015 for (a) ASCAT observations and (b) SYNOP observations. The distribution of increments is different, illustrating that it is useful to combine the two kinds of observations in the soil moisture analysis.

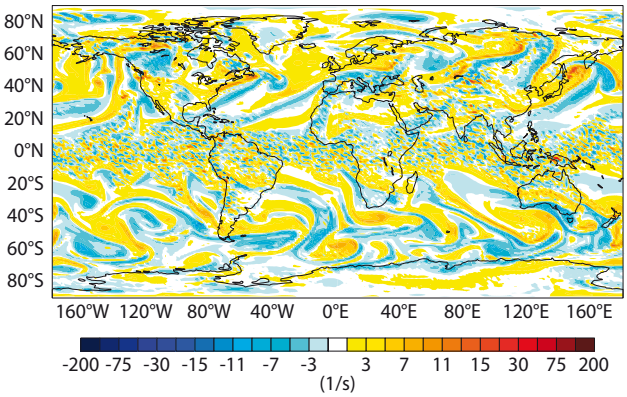
The data assimilation scheme now combines two kinds of observations in the soil moisture analysis: direct ASCAT soil moisture observations on the one hand and SYNOP weather station reports of 2-metre air temperature and humidity on the other.

This work was carried out in collaboration with EUMETSAT. The changes were implemented in May 2015 and contributed to a significant reduction in the near-surface temperature and humidity bias.

Scientists also made progress in their research on Soil Moisture and Ocean Salinity (SMOS) brightness temperature data assimilation by revising the SMOS observation errors and bias correction.

Numerical module

The state-of-the-art spectral transform method used in ECMWF's Integrated Forecasting System (IFS) may become computationally inefficient at very fine resolutions due to the communication overhead associated with global spectral transformations.



▲ **Global circulation.** Simulation of a global circulation using realistic orography, produced using the finite-volume module. The shading shows the vertical component of instantaneous relative vorticity (x 10^6) at about 4 km above the surface, revealing baroclinic eddies in the mid-latitudes of both hemispheres and fine-scale features in the equatorial area and mountainous regions indicative of convection and gravity waves.

A new numerical module and data structure framework have opened up exciting possibilities

Researchers at the Centre have developed a new numerical module which uses the finite-volume method to complement the IFS. This module is compatible with emerging energy-efficient, heterogeneous hardware for high-performance computing, and it is able to represent elements of weather on a large range of scales.

The new finite-volume module is based on a newly developed framework called Atlas. Atlas provides parallel, distributed and flexible data structures for structured and unstructured meshes on a sphere. The new numerical module and Atlas provide a toolbox of new methods. They offer exciting opportunities to combine the strengths of spectral-transform models and grid-point models. Testing of these new tools is now under way.

Photo: Eliza Radzikowska-Białobrzewska/Chancellery of the President of the Republic of Poland.

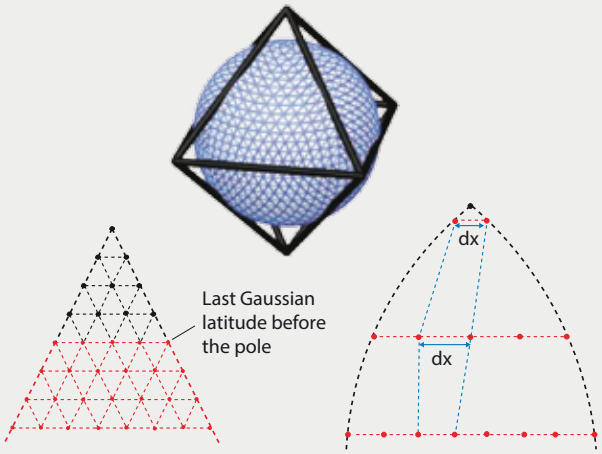
▲ **Award ceremony.** Dr Piotr Smolarkiewicz (right), one of the scientists working on the new numerical module, was granted Poland's highest academic title in February 2015 to become Professor of Physical Sciences. Polish President Bronisław Komorowski handed over the certificate during a ceremony in Warsaw.

CUBIC-OCTAHEDRAL GRID

In preparation for the model upgrade bringing higher- resolution forecasts, ECMWF scientists had to carefully balance the goals of higher resolution and increased forecast accuracy against the need for affordable computational cost. Part of the solution was to develop a new 'cubic-octahedral' grid.

The change from the previous 'linear' grid to a 'cubic' grid is related to the representation of meteorological fields by a sum of wave functions called spherical harmonics. The new grid increases the number of grid points used to represent each wavelength while keeping the number of spherical harmonics constant.

At the same time, scientists used an octahedron-based method to reduce the number of grid points towards the poles. The resulting new 'cubic-octahedral' grid brings significant benefits in terms of computational efficiency and effective resolution.



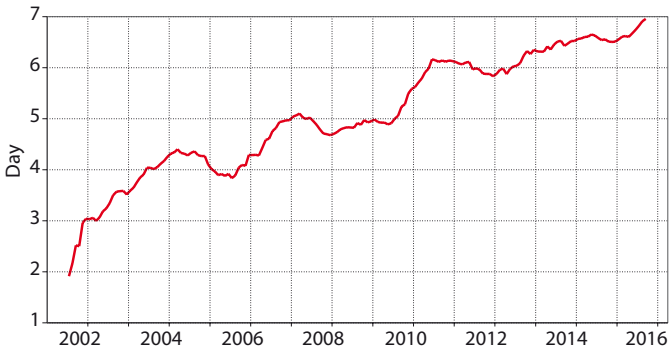
▲ **The octahedral grid.** The grid is built up by dividing each hemisphere of the globe into quarters, with each quarter corresponding to one face of an octahedron (top). Starting with five points per quarter at the Gaussian latitude closest to the pole, one point per quarter is added for each new Gaussian latitude towards the equator (left). Because of the curvature of the Earth, the spacing between the grid points along a latitude circle varies with latitude (right).

IMPROVING GLOBAL PREDICTION

Forecast performance

ECMWF's forecasts help national meteorological services in our Member and Co-operating States to produce weather predictions and early warnings of severe weather for the protection of life and property. They must therefore be of the highest quality.

The quality of our forecasts as measured by a set of headline scores and benchmarks improved markedly in 2015. Forecasts from other global centres also serve as a useful benchmark and show that ECMWF maintained its world-leading position.



▲ **Ensemble forecast performance.** The positive long-term trend continued during 2015 as a result of upgrades to the forecasting system. The curve shows the lead time for which the forecast quality remains above a set threshold, shown here for 24-hour precipitation in the extra-tropical northern hemisphere.

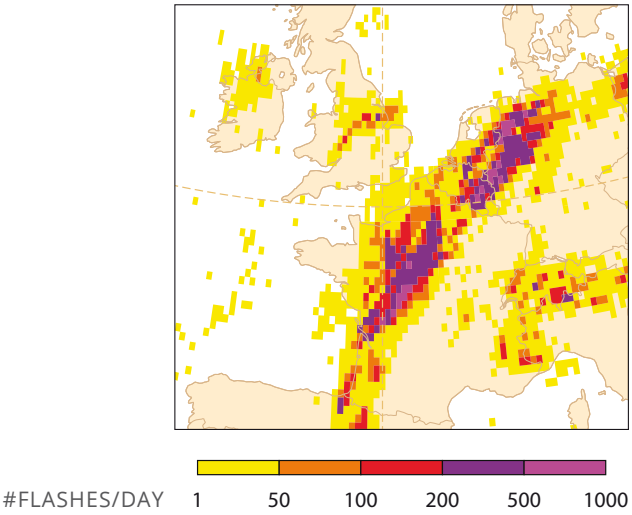
New parameters

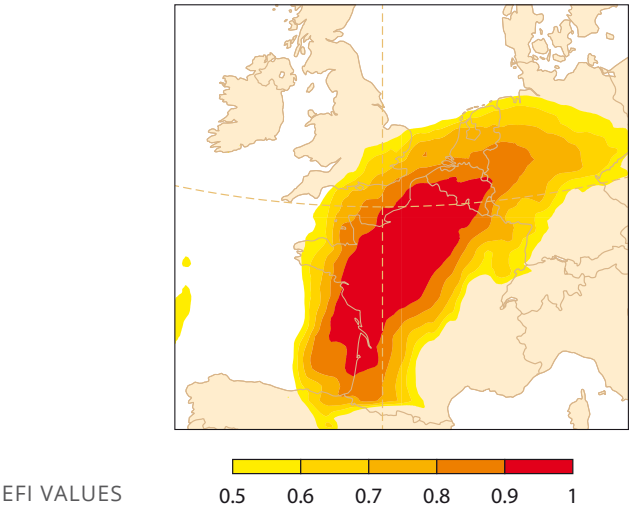
The impacts of weather events involving severe convection can be substantial, so the ability to forecast such events is important. In 2015, two new parameters designed to facilitate this task were added to the Extreme Forecast Index (EFI).

The new parameters are convective available potential energy (CAPE) and a CAPE-SHEAR parameter (CSP), which takes into account the role of vertical wind shear in the development of severe convection.

The new parameters have been shown to discriminate well between severe and non-severe convection in the medium range.

▼ **Severe convection.** On 9 June 2014, an outbreak of severe convection affected a region stretching from southwest France to northwest Germany, as indicated by the lightning activity shown in the top panel. A six-day EFI forecast for that day shows extremely high CAPE-SHEAR parameter values in the area, in excess of 0.9, as shown in the bottom panel.





The quality of our forecasts as measured by a set of headline scores improved markedly in 2015

IMPLEMENTATION OF MODEL CYCLE 41R1

A new model cycle introduced on 12 May brought a range of improvements to ECMWF's Integrated Forecasting System (IFS).

Changes in the ways in which observations are assimilated and atmospheric processes are modelled improved the representation of the current state of the atmosphere as well as the skill of forecasts.

Model cycle 41r1 brought consistent gains in forecast performance at the surface for total cloud cover and precipitation, compared to previous model cycle 40r1.

Improvements in the modelling of cloud and precipitation reduced the excessive occurrence of drizzle in forecasts of rainfall from extensive sheets of cloud, and they increased the amount of precipitation in forecasts of heavy rainfall, leading to a better match with observations.

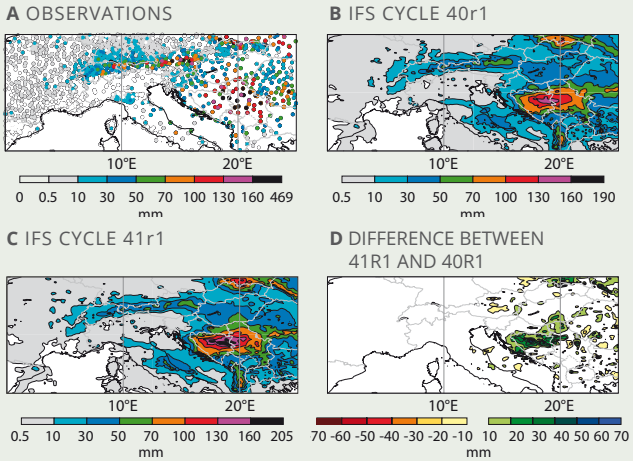
Improvements were also seen for 2-metre temperature and 2-metre humidity in parts of the northern hemisphere and the tropics.

Cycle 41r1 also introduced a number of new output parameters, such as precipitation type, including freezing rain.

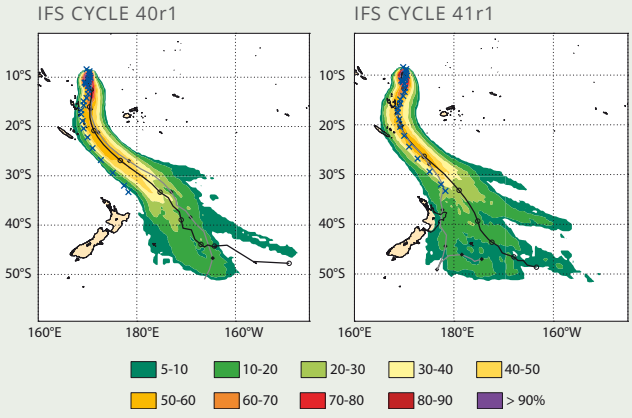
The average position error for tropical cyclones was slightly reduced, and tropical cyclones are now generally forecast to be more intense. IFS Cycle 41r1 performed better than Cycle 40r1 in predicting the track of tropical cyclone Pam, which devastated Vanuatu in the South Pacific in March 2015.

Cycle 41r1 also introduced a lake model, developed by the German national meteorological service, DWD, which improved 2-metre temperature forecasts in the vicinity of small lakes not represented in the previous model version.

A range of additional satellite observations improved the representation of land surface, sea ice and ocean wave parameters. Ocean wave forecasts also benefitted from the extension of the high-resolution wave model from the European and North Atlantic region to the whole of the globe.



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



▲ **Tropical cyclone tracks.** The shaded areas in the two panels show the predicted probability of Pam passing within a 120 km radius over the next 240 hours, starting from its position about 10° South and 170° East on 10 March. The blue crosses show the observed track, the black line represents the ensemble mean and the grey line the high-resolution forecast.

IMPROVING GLOBAL PREDICTION

Better temperature forecasts

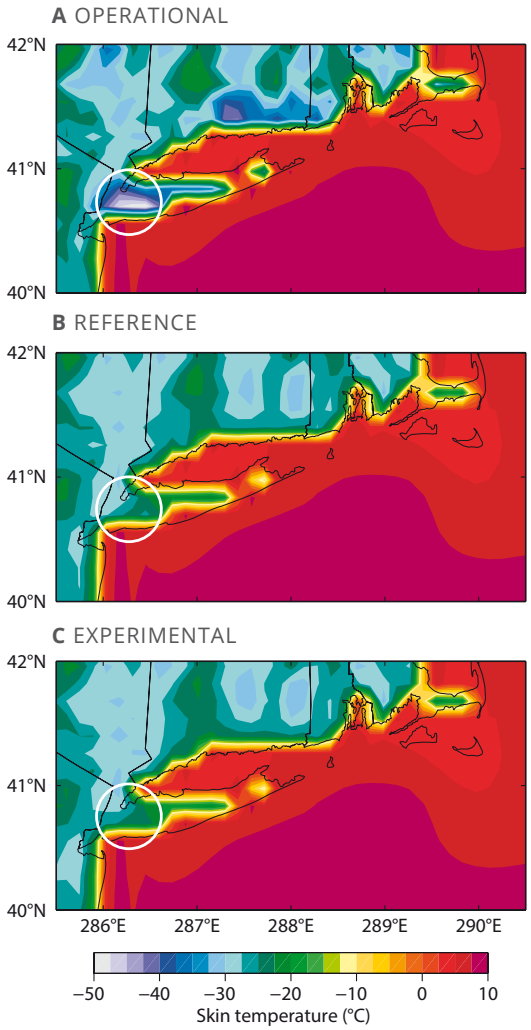
Following reports of temperature forecast errors in coastal areas, for example in Norway, the Centre developed and tested changes in the model in readiness for the next model upgrade. The changes were found to bring significant improvements.

The errors were traced to the way the radiation scheme is used in ECMWF's Integrated Forecasting System (IFS). To limit its high computational cost, the radiation scheme is run on a coarser spatial grid than the rest of the model.

As a result, surface radiative fluxes computed over the ocean in the coarse grid may be used over land in the finer grid. The radiation scheme is also run less frequently than the model time step, which leads to additional errors.

ECMWF scientists developed a solution to these problems in which the surface radiation fluxes are updated at every model time step and grid point according to the local surface temperature and albedo.

The computational cost of this solution is only 2% of the cost of the full radiation scheme, but the gains in forecasting skill are spectacular.



◀ **Long Island forecasts.** Surface temperature at 0700 local time on 4 January 2014 for a region around the coast of Long Island from forecasts initialised 24 hours previously with the radiation scheme run (a) as in operations, (b) on the full model grid at every time step, as a good approximation of the truth, and (c) implementing the experimental solution. The white circle highlights an area of particularly big differences between (a) on the one hand and (b) and (c) on the other.

El Niño

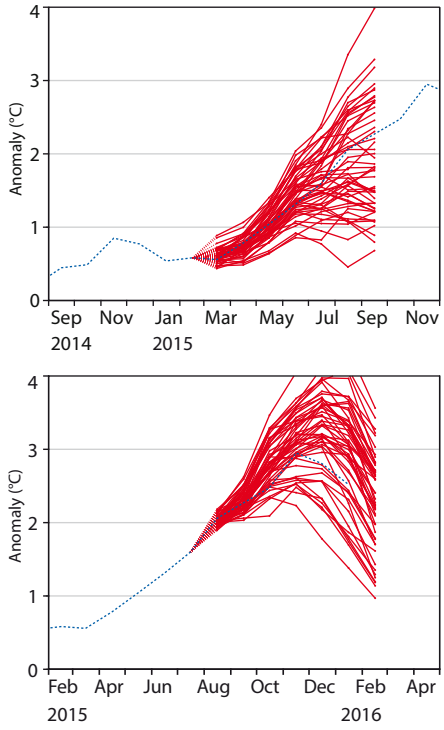
2015 saw a record-breaking El Niño event developing in the tropical Pacific. Its evolution was well predicted by ECMWF's forecasts.

Weak El Niño conditions had been observed since October 2014. By March 2015, forecasts suggested that sea-surface temperatures (SST) in the central Pacific would rise further, from about 0.5°C to more than 1°C warmer than usual by August, with the possibility of substantially stronger warming.

By August, observed SSTs in the region had risen to about 2°C warmer than usual, and forecasts suggested that there would be a very strong and potentially record-breaking event by the end of the year. In the event, the El Niño of 2015/16 set new records in the western and central Pacific.

ECMWF predicted the 2015/16 El Niño event in a series of forecasts produced as part of its seasonal prediction work

▼ **El Niño forecasts.** The charts show ECMWF ensemble forecasts of monthly mean deviations of SSTs from usual, climatological values in the NINO3.4 region in the central Pacific, issued on 1 March (top) and 1 August (bottom). The dotted line shows the observed evolution. The 1 March forecast predicted the observed outcome well although there was growing uncertainty at longer lead times. The 1 August forecast captured the structure of the evolution of SST anomalies fairly well, but many ensemble members predicted too high values.



European heat wave

A heat wave affected large parts of Europe during the summer of 2015. Records included an all-time high for Germany (5 July), an all-time high for Switzerland north of the Alps (7 July), a June record for Madrid (29 June), a July record for the UK (1 July) and an August record for Warsaw (8 August).

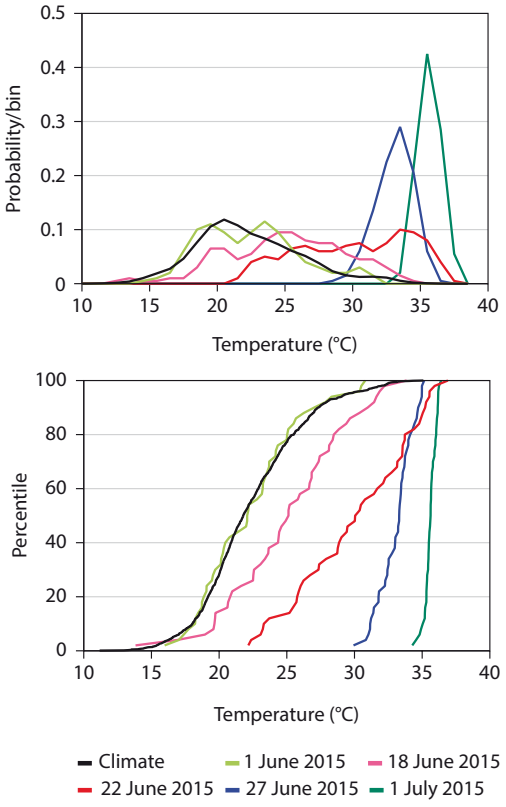
ECMWF's ensemble forecasts predicted the onset of the heat wave well, as illustrated here using the example of Paris.

On 1 July, the observed temperature at 12 UTC was between 35.5°C and 36.8°C among SYNOP stations in Paris, and later that day one station reached 39.7°C, the second warmest temperature on record for the city.

The forecast for Paris from Monday 22 June pointed to a strong possibility of temperatures close to 34˚C, although it did not yet rule out temperatures below 25°C.

Forecasts for Paris changed substantially from around 26 and 27 June: the signal of extreme temperatures was dominant by then and temperatures below 30°C were all but ruled out, although the predicted temperatures were still a little cooler than the observed 36˚C.

▼ **Paris temperature forecasts.** Ensemble forecasts valid at 12 UTC on 1 July in Paris visualised for different lead times by probability density functions (top) and cumulative distribution functions (bottom).



COMPUTING AND SCALABILITY

Supercomputer and data storage

Producing world-leading medium-range weather forecasts and cutting-edge research in numerical weather prediction (NWP) requires one of the most advanced high-performance computing facilities (HPCF) as well as high-volume data storage.

ECMWF's latest HPCF, two Cray XC30s with over 160,000 processor cores in a resilient configuration, has been producing ECMWF's operational forecasts since September 2014.

In 2015, the facility provided a good and reliable service to ECMWF's users. Initial issues with the performance of the Sonexion storage arrays and Lustre file systems were soon resolved.

The archive continued to grow to about 140 petabytes by the end of the year. About 140 terabytes of data were added every day. A working group set up to examine ECMWF's data archive policy made a number of recommendations to control the growth of the archive.

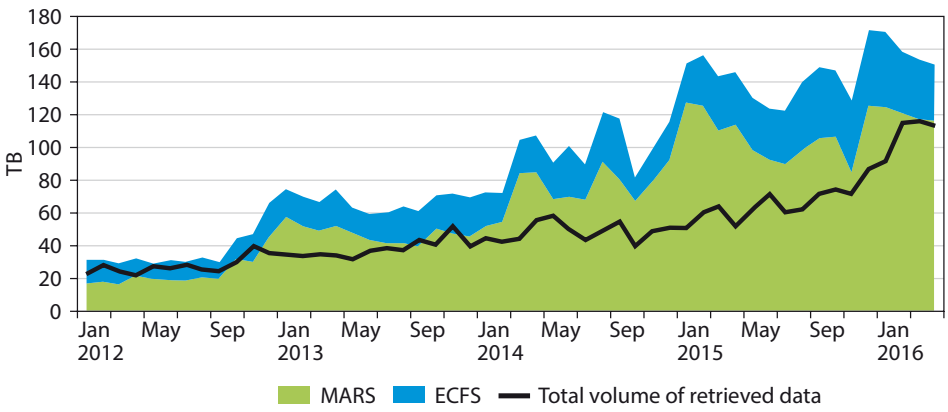
Upgrade plans

ECMWF worked with Cray in 2015 to finalise plans for a significant upgrade of the Cray XC30 supercomputers.

When the upgrade is complete, the HPCF will comprise two Cray XC40s with more than 260,000 cores of the latest Intel Xeon 'Broadwell' processor, 55% more than the current two clusters. It will also have more than double the amount of memory.

▲ Plans to upgrade ECMWF's Cray XC30 system to an XC40 system were finalised in 2015.

AVERAGE VOLUME OF DATA ARCHIVED PER DAY



◀ **High data volume.**
ECMWF's Data Handling System (DHS) comprises a meteorological archive, MARS (Meteorological Archive and Retrieval System), and ECMWF's File Storage system (ECFS), used for files which are not suitable for MARS. In 2015, the total archive grew at a rate of about 140 terabytes a day. A large volume of data, in excess of 80 terabytes per day by the end of the year, was retrieved by users.

The year 2015 saw the launch of four major EU-funded scalability-related programmes in which ECMWF participates

Progressing scalability

As forecasting systems become more complex, with current computing architectures it will soon be impossible to issue forecasts within schedule and at a reasonable cost. Supercomputer energy consumption at ECMWF would have to increase unviably if the more complex forecasting systems of the future were to be run on the current architecture.

A new generation of computing systems with exascale capabilities promise much greater energy efficiency but they will rely on parallel processing at levels to which current NWP codes are not adapted. Changes are needed throughout the entire NWP processing chain if we are to exploit these new opportunities. ECMWF's Scalability Programme, launched at the end of 2013, aims to address these issues. It brings together meteorological modellers, computer scientists and hardware providers from around the world for a coordinated approach to hardware and software development.

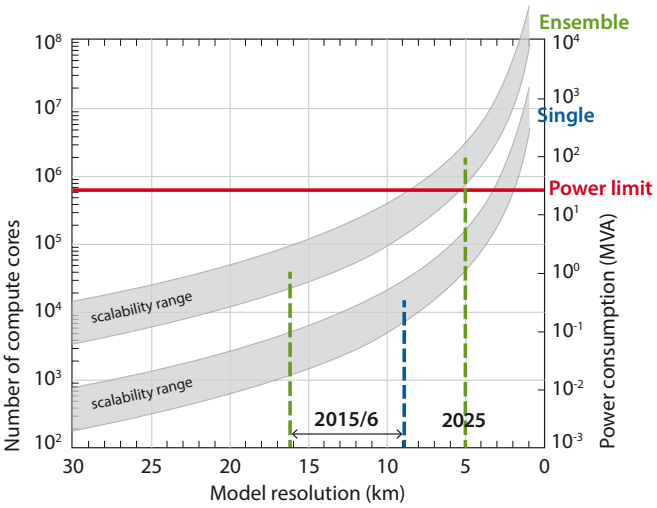
In 2015, ECMWF's Scalability Programme made decisive progress. The European Commission gave the green light to four international scalability-related projects in which the Centre participates and which are funded under the EU's Horizon 2020 Research and Innovation Programme.

The aim of ESCAPE (Energy-efficient Scalable Algorithms for Weather Prediction at Exascale), a 4m-euro project coordinated by ECMWF, is to develop world-class, extreme-scale computing capabilities for European operational NWP. It will do this by defining fundamental algorithm building blocks to run the next generation of NWP on energy-efficient, heterogeneous high-performance computing architectures.

The EarthServer-2 project aims to establish scalable web-based analysis and processing services for multi-dimensional geo-referenced Earth Science data. This will help ECMWF to continue to provide full access to the data it holds as data volumes increase.

The European Commission also approved ESiWACE (Excellence in Simulation of Weather and Climate in Europe), which aims to improve efficiency in computing and storage in the field of weather prediction and climate.

Another Horizon 2020 project which started in 2015, NextGenIO (Next Generation I/O), aims to develop new hardware to accelerate input/output (I/O) processes. The overall objective of the project is to design and prototype a new, scalable, high-performance, energy-efficient computing platform designed to address the challenge of delivering the necessary I/O performance to applications at the exascale.



▲ **Simulation experiments.** The need for greater computing performance is driven by advances in modelling the Earth's physical processes, the use of more observational data and finer model grid resolutions. The graph shows the results of simulations carried out by ECMWF at a range of hypothetical model grid resolutions. They indicate that ECMWF's ability to continue to increase the resolution at which it runs its forecasts, while keeping power consumption within reasonable limits, depends very much on the success of the Scalability Programme. The number of required compute cores, and hence the amount of power consumed, rises rapidly as the resolution of single 'deterministic' forecasts on the one hand and ensemble forecasts on the other increases. Efficiency gains in all parts of the forecasting system are required in order to make a goal such as a 5 km horizontal resolution for ECMWF's ensemble forecasts by 2025 realisable.

IMPROVING USERS' EXPERIENCE

Regular interaction with our Member and Co-operating States helps share experiences and identify user needs. We provide advanced training, tools and documentation to support the use of our forecasts and computing facilities.

Education and knowledge sharing

Interest in ECMWF's training courses is high and has been increasing steadily over the years. In 2015, almost 300 people attended our training courses. The programme includes modules on numerical weather prediction (NWP), the use and interpretation of ECMWF's meteorological products, and ECMWF's computing services, software packages and applications.

New for 2015 were a redesigned module on Metview, ECMWF's meteorological workstation application, and a collaborative Data Assimilation course run with the University of Reading. We introduced a blended course (online and face-to-face) on the 'Use and Interpretation of ECMWF products', which we ran for the first time in October. On the computing side, we supported our Member States by offering a course on the new Cray XC30 high-performance computer to help their migration efforts.

Our training materials are freely available to download and include slidecasts (slides and audio recordings), tutorials and training lectures (presentations in PDF). To reach a wider audience, we have increased our range of online training materials and the number of webinars (online seminars). We also broadcast and recorded lectures from selected seminars and workshops.

We held over 35 workshops and informal seminars during the year, bringing together staff from ECMWF with international experts to discuss the latest research and developments. Topics included subseasonal predictability, OpenIFS, education and training in weather prediction, the requirements for the Copernicus services, tropical cyclone prediction, and the use of satellite data.

The Annual Seminar in September offered 26 lectures on the subject of physical processes in present and future large-scale models. For the first time, we live-streamed the lectures to allow people to attend remotely, and posted the recordings on our website.

Feedback from our Member and Co-operating States is essential to help us improve our products and training. In June our annual user meeting focused on 'Quantifying and communicating uncertainty' and attracted 100 participants. All confirmed the importance of training to enable forecasters to exploit information from ensemble products and the need for appropriate verification methods to help them understand a model's strengths and weaknesses. They cited the Extreme Forecast Index and the use of clusters as good examples for presenting information from ensemble models in condensed form.

▲ Probability information needs to be communicated clearly.

▲ Participants at the Annual Seminar 2015.

We held over 35 workshops in 2015, bringing together international experts to discuss the latest research and developments

We aim to visit each Member and Co-operating State at least once every three years to present an overview of our work and to see how ECMWF products are being used. This two-way communication is essential both for the progress of the scientific work at ECMWF and for product development.

In 2015, we visited 11 countries, discussing the future strategy as well as research and operational plans. On request, we included some training in the form of demonstrations and practical classes. We also introduced many users to ecCharts, our suite of web applications for forecasters. Users can browse, customise and overlay ECMWF forecast products. It also provides a standard web service that enables forecasters to integrate graphical products in their working environment. Increased and diverse use will provide valuable feedback to improve the service.

Support for users in Member and Co-operating States

A major piece of work in 2015 was the migration of Member State time-critical applications and other research applications to the new Cray XC30 HPC system. For many users, this involved switching to a new architecture, operating system, batch scheduler, file systems, and compilers. We followed this up with a user survey about the new service and migration process, with the results presented to ECMWF's Computing Representatives, who represent their organisation in matters relating to the use of ECMWF computing and archiving facilities.

In 2015 we released new datasets on the public data server from the sub-seasonal to seasonal prediction project, the ERA-20C atmospheric reanalysis, and the CAMS Global Fire Assimilation System. There was a large increase in the number of users accessing publicly available datasets. To provide a more reliable service, we introduced a limit on the target file size and number of fields per request.

Our increased use of collaborative software has revolutionised the way we interact with our Member and Co-operating States, for instance to manage software issues and provide documentation. The Forecast User space is a knowledge exchange portal for all users of ECMWF forecast data, and we have created dedicated portals for Computing Representatives and Catalogue Contact Points.

▲ Using ECMWF Forecasts meeting (UEF 2015).

IMPROVING USERS' EXPERIENCE

ecCodes

Most of the data processed at ECMWF are either in BUFR or GRIB format. These are binary data formats developed by the WMO to enable the worldwide exchange of meteorological data through its Global Telecommunication System.

Developing effective software to decode and encode data in these formats is therefore important to facilitate scientific research, build a robust forecasting system and create tools for visualisation and other processing purposes.

In response to requests from users, ECMWF has developed ecCodes, a new software package for decoding and encoding meteorological data in BUFR or GRIB format using a single, simple interface. Users do not need detailed knowledge of binary format. The software hides some of the complexity by giving each descriptor code a key name. The key name syntax is the same in the three programming languages currently available in ecCodes (Python, Fortran 90 and C), making it easier to switch from one language to another.

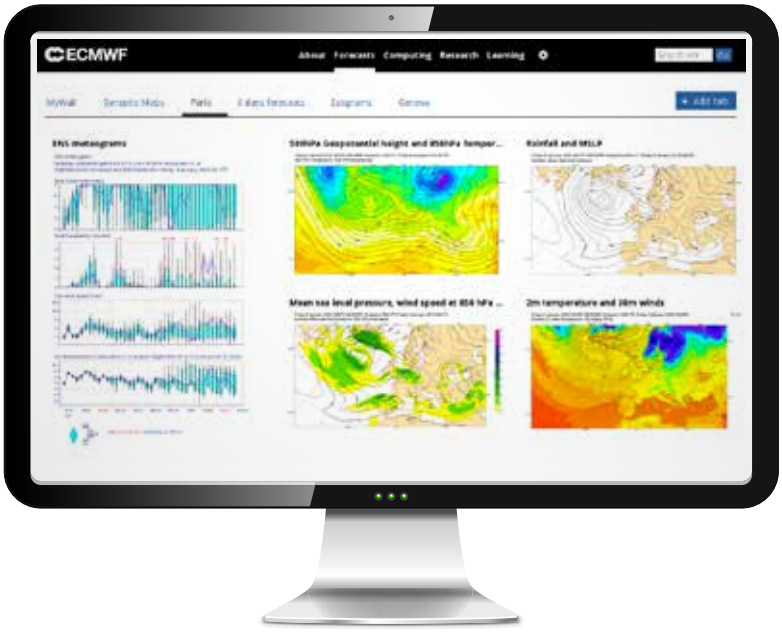
We released beta versions to external users in March and May, with a full release expected in 2016. In December, we provided a training webinar for ecCodes, which 95 people attended. It offered support for using the software and contributed to the preparation of resources for a new training course in 2016.

Web charts

By the end of the year, the 'Charts' section of the website contained the full range of ECMWF charts. They include ensemble meteograms (formerly EPSgrams) and charts for the Extreme Forecast Index, tropical and extra-tropical cyclones, and ocean waves.

Usability remained central to the design process, with some charts featuring wider displays and 'clickable' map interfaces. The Chart dashboard introduced at the end of the year lets users organise charts and diagrams they use regularly in order to compare maps and follow the different forecast steps.

The chart dashboard can also be used to view any product created with ecCharts.



▲ The Chart dashboard

Increased use of collaborative software has revolutionised the way we interact with our Member and Co-operating States

VISUALISATION WEEK

The volume of data involved in numerical weather prediction has grown immensely over the years – by October 2015 we were receiving 300 million observations daily from 130 sources, producing 13 million fields a day (around 8 TB) from our operational models, and disseminating 77 million data products every day. Our Meteorological Archive and Retrieval System (MARS) also passed the 80 PB mark. Users need to be able to capture all of this information quickly and easily, which is where visualisation helps.

In 2015 we held our first 'Visualisation in meteorology week', exploring advances in the visual representation of observations and numerical forecasts. Over 100 external participants attended from national meteorological services, research institutes and commercial organisations around the world. The week combined ECMWF's well-established biennial Workshop on Meteorological Operational Systems (MOS) and the annual meeting of the European Working Group on Operational Meteorological Workstations (EGOWS). The programme also included a Royal Meteorological Society seminar and a 'plug-fest' by the OGC MetOcean Domain Working Group. Innovative uses of 3D and debates on user interaction were among the highlights of the week.

One of the high points was the exhibition of 18 visualisation systems, including all the main forecaster workstation systems developed and used in Europe and South Korea. ECMWF took the opportunity to present the Metview workstation and ecCharts web service for forecasters.

The presentations and demonstrations showed the importance of visualisation in meteorology. It allows scientists to explore and understand new model developments and data sources. Users, especially forecasters and other decision-makers, benefit from easy access to the large amounts of forecast data available to them. Scientists can look forward to much improved and mainstream 3D visualisations to help them understand atmospheric motion, while operational users will start to see benefits from work to make visualisation more interoperable between their systems, through standards such as those from the Open Geospatial Consortium (OGC).

◀ Participants put on special glasses to see the images and animations in the Weather3DeXplorer, developed and operated by the Dutch national weather forecasting service (KNMI). This virtual reality framework for 3D visualisation can be used to explore meteorological data.

ENVIRONMENTAL INFORMATION

The research and facilities needed for numerical weather prediction also contribute to developing the scientific basis for environmental monitoring.

2015 saw the Centre embrace its new role in Europe's initiative to provide comprehensive, global environmental information. After years of monitoring the atmosphere through a succession of EU projects, and the climate through the ECMWF Reanalysis programme, the Centre has risen to the challenge of operating two of the EU's flagship Copernicus Services.

With preoperational atmospheric services to bring into operations, a full architecture to develop for climate change services and products, ECMWF's largest-ever recruitment campaign to run, and additional offices to be rented at the University of Reading, it was an eventful year to say the least.

Atmospheric monitoring

The Copernicus Atmosphere Monitoring Service (CAMS) became operational in the summer. It consolidates many years of preparatory research and development funded by the EU through the Monitoring Atmospheric Climate and Composition (MACC) projects, which ECMWF coordinated. That series drew to a close in 2015, with all CAMS production and validation elements being transferred smoothly from pre-operational status to operations.

CAMS products are freely available on their new website that was launched in July. Examples of global and regional events that were well documented by CAMS products include wildfires in Alaska, the Antarctic ozone hole, Indonesian wildfire emissions and smog events in Europe.

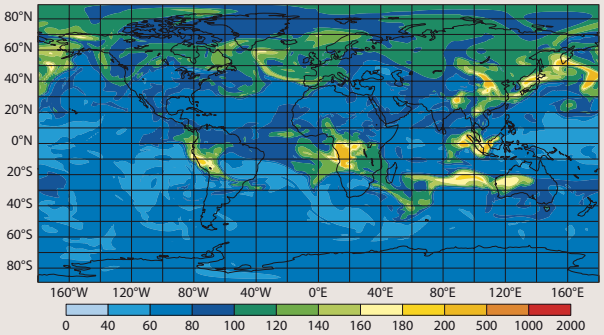
Contracts concluded during the year for outsourced service elements involve over 30 contracting or subcontracting entities from 13 European countries.

SYSTEM UPGRADE

A major upgrade of the CAMS global data assimilation and forecasting system became operational in September after significant testing and validation.

The system combines daily observations with the previous day's forecast to provide the analysis and the forecast for the next five days.

It is based on ECMWF's IFS Cycle 41r1, with additional changes specific to CAMS. The upgrade introduces new satellite data (MODIS Deep Blue and GOME-2 SO2), improvements in the representation of wildfire emissions and improvements to the UV processor that estimates spectral ultraviolet radiation at the Earth's surface.



▲ CAMS forecast from 2 September 2015 at 00 UTC for 500 mb carbon monoxide (ppbv) on 3 September 2015, 12 UTC.

In 2015, all atmospheric composition services were transferred smoothly from pre-operational to operational

Climate monitoring

With the Copernicus Climate Change Service (C3S) still under development, a series of workshops in 2015 helped to define requirements for climate projections, observations, communications, and the climate data store. By the end of the year, a preliminary design had been proposed for the climate data store and an invitation to tender issued for the store and associated toolbox.

Procurement featured heavily during the year, with 17 contracts being signed for procurements totalling 25 million euros. One was for the provision of a global multi-model seasonal forecast product with contributions from ECMWF, the UK Met Office, Météo-France, the Euro-Mediterranean Center on Climate Change (CMCC) and Deutscher Wetterdienst.

Another major achievement was building the team, drawing on expertise from within the Centre as well as new staff.

MONTHLY CLIMATE UPDATES

Although still in the development phase, C3S began publishing monthly climate updates on its website in September. The maps use data from ECMWF's ERA-Interim reanalysis to show the global average surface air temperature.

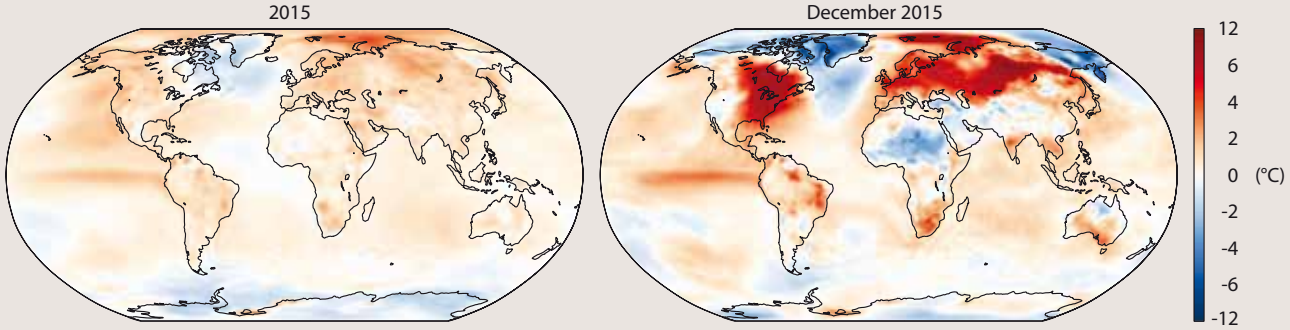
ERA-Interim provides a comprehensive, consistent and up-to-date record of the global climate in the satellite era since 1979.

It combines information from meteorological observations with background information from a forecast model, using the data assimilation approach developed for numerical weather prediction.

When fully operational, C3S will use a new dataset, called ERA5, based on ECMWF's latest forecast model and using reprocessed satellite datasets.

The temperature maps showed 2015 was the warmest year on record, well over 0.4°C warmer than the 1981–2010 average, and almost 0.1°C warmer than the previous warmest year.

At the COP21 climate change conference in Paris, Copernicus presented how its data, including the monthly maps, can be used to address the impact of atmosphere and climate changes.



▲ Surface air temperature anomalies for 2015 as a whole (left) and for December 2015 (right), relative to the period 1981–2010. Source: ERA-Interim.

ENVIRONMENTAL INFORMATION

Flood forecasting

The European Flood Awareness System (EFAS) that ECMWF helped to develop is now a key part of the Copernicus Emergency Management Service. We are responsible for providing daily operational EFAS forecasts and 24/7 support for the technical system.

2015 saw a number of flood events across Europe, one of the most severe being the flooding across the UK and Ireland during December. In the lead up to this event, EFAS was able to deliver warnings up to four days ahead to hydro-meteorological agencies in the UK and Ireland.

Improving the prediction of flash floods

Flash floods are intense events with a rapid onset, often giving little time to issue warnings. In 2015 there were many such events across the continent, some of the most newsworthy being those across southern Europe in January and in Cannes in October.

Predicting flash floods remains a major challenge despite recent notable advances in weather forecasting. In September, EFAS implemented a new flash flooding indicator, called the European Runoff Index based on Climatology (ERIC).

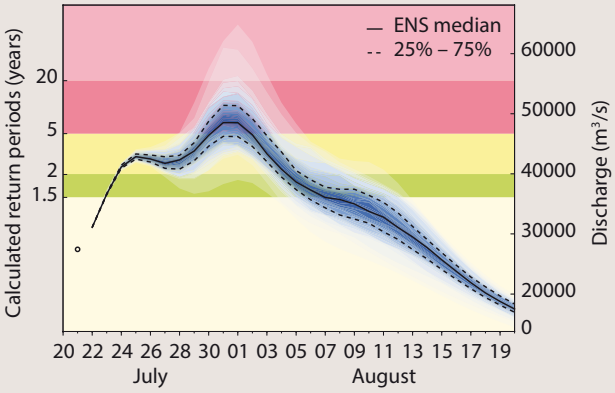
ERIC uses a dynamic and distributed runoff coefficient to weigh each contribution of the upstream precipitation proportionally to the initial soil moisture. This results in a better representation of antecedent catchment conditions that may exacerbate the flash flood severity.

The new ERIC indicator was better able to predict the flash flood events across southern Europe. It led to fewer false alerts and a warning lead time of up to two days. However, capturing events such as that in Cannes remains deeply challenging due to the difficulty of representing localised precipitation extremes. To this end, work is ongoing at ECMWF to improve the forecasting of such events.

GLOBAL FLOOD PREDICTION

ECMWF is also developing the Global Flood Awareness System (GloFAS) in co-operation with the European Commission's Joint Research Centre and the University of Reading. The system uses ensemble forecasts of precipitation and temperature to predict discharge levels and the probabilities of river thresholds being exceeded.

In late July and early August, rainfall and flood forecasts from GloFAS supported the Government and humanitarian agencies in Myanmar/Burma as the country faced the most severe flooding in decades.



▲ **GloFAS** hydrograph for the point on the Irrawaddy River near the river outlet, from the forecast run on 21 July 2015. GloFAS indicated a significant 5- to 10-year return period flood, with some low probability for very severe floods, already 12 to 14 days ahead for the beginning of August at this specific area in Myanmar.

On 31 July, the President of the Union of Myanmar issued a statement declaring natural disaster zones in Chin and Rakhine states and in the Sagaing and Magway regions.

EUROPEAN INVESTMENT IN **ECMWF**

The 34 Member and Co-operating states of ECMWF are the principal source of finance for the Centre, with contributions totalling £42.4 million out of the Centre's £60.0 million* funding. External organisations support both core research and the complementary goals of the centre with funding of £12.8 million, while revenue from sales of data and products provides additional income of almost £4.7 million.

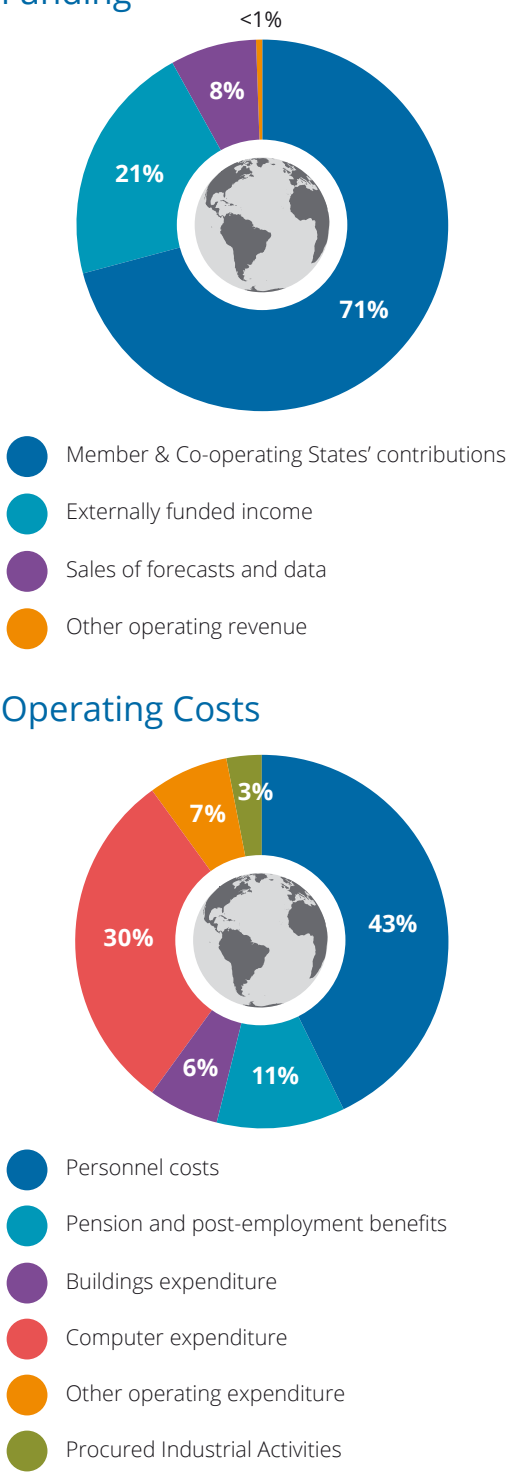
ECMWF continued to invest in its staff, infrastructure and systems to provide the highest quality products to its Member and Co-operating States. The main areas of expenditure are summarised below, and include capital investment of £2.3m, principally for IT and infrastructure.

The main areas of expenditure related to remuneration and related items (£26.3 million net of centre tax), pension schemes (£6.8 million), computer expenses (£18.5 million), buildings (£3.4 million) and other operating expenditure (£4.0 million). Costs associated with Copernicus procured industrial activities amounted to £1.7 million. Net finance costs were £6.4 million.

ECMWF's budget remains on a cash basis and the Financial Statements include a reconciliation of the results under IPSAS and in cash terms. Under cash accounting, the Centre generated a surplus of £0.6 million in 2015, which is available either for future investment or distribution to Member States according to a decision to be made by the Council in 2016.

* Excluding Centre tax

Funding



Operating Costs

WORKING **TOGETHER**

Collaboration, the principle on which ECMWF was founded 40 years ago, has been key to the Centre's success. 2015 was a year for strengthening existing partnerships with our Member and Co-operating States, the WMO, and space agencies. It was also a time for forging new ones, notably through our Fellowship and Scalability programmes.

Forty years of advancing global NWP through co-operation

In order to obtain its objectives, the Centre shall co-operate to the largest extent possible, in accordance with international meteorological traditions, with the Governments and national agencies of the Member States, with States which are not members of the Centre and with governmental or non-governmental international scientific and technical organisations whose activities are related to its objectives. ECMWF Convention, Article 3(1).

The original Convention came into force in 1975 with 18 founding states. By the end of 2015, ECMWF's membership had grown to include 21 Member States and 13 Co-operating States.

ECMWF Fellowship Programme

It was a productive first year for ECMWF's Fellowship Programme, with many opportunities to strengthen links with our Fellows and their research groups.

Professor Tilmann Gneiting and his group at the Heidelberg Institute for Theoretical Studies (HITS) in Germany are working on statistical post-processing techniques that could improve the sharpness of ensemble forecasts to aid decision-making. Some of his recommendations have been implemented in joint work between ECMWF and HITS.

Professor Rupert Klein, professor of mathematics at Freie Universität Berlin, is also keen for more students from his research group to become involved with ECMWF. Their work on numerical methods is relevant for ECMWF's Scalability Programme, and Rupert is an external reviewer for the ESCAPE project.

Professor Tim Palmer from the University of Oxford was one of the organisers of a workshop on 'Stochastic Parametrization' that brought together about 40 participants, mainly from ECMWF, the University of Oxford and the UK Met Office. It was an opportunity to review progress in the simulation of uncertainties in forecasting models and examine the scope for further improvements.

Several students at the University of Oxford are testing their theoretical work with OpenIFS – a version of ECMWF's Integrated Forecasting System for research and education. At the 2015 OpenIFS user meeting, students confirmed the value of learning about operational systems and gaining skills for future employment.

The meetings provide opportunities to meet other international scientists interested in NWP and using the IFS, helping to build a user community that can provide mutual support and encourage international collaboration.

▲ **OpenIFS workshop.** The 2015 meeting was organised by the Department of Physics of the University of Oxford and hosted at ECMWF. The model is used in about 20 research projects and NWP training programmes across the world.

We work closely with our Member and Co-operating States to develop synergies and continue to meet evolving needs

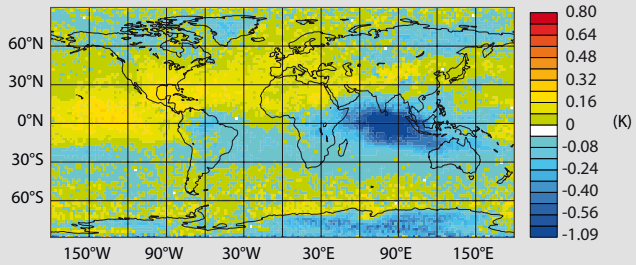
WORKING WITH EUMETSAT

Satellites now provide most of the data used in our models, although more traditional observations are still important. We work with satellite data providers around the world to make the best use of the information available and to provide feedback on the impact of satellite observations on forecast quality.

Our formal collaboration with the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) goes back almost 30 years. It includes joint research and training, as well as initiatives to support the use of satellite data in NWP and enhance collaboration towards maximising the benefit of European satellites to ECMWF's Member and Co-operating States.

At EUMETSAT's meteorological satellite conference in September, scientists from ECMWF updated colleagues from EUMETSAT and other organisations about their research on satellite data, some of which is funded by EUMETSAT's Fellowship Programme. Examples include research into systematic errors in the heights assigned to atmospheric motion vectors (AMVs) obtained from satellite instruments, and work on optimising the use of scatterometer data.

In partnership with EUMETSAT's Satellite Application Facility on NWP (NWP SAF), we run a sophisticated automated monitoring system that checks hundreds of millions of satellite observations every day searching for small anomalies in the data. In September, the system picked up unusually high concentrations of hydrogen cyanide in the atmosphere, which researchers at ECMWF and other organisations identified as coming from wildfires in Indonesia. NWP centres around the world were alerted to this anomaly and removed the affected channels from their data assimilation systems.



▲ In early September, METOP-A satellite data showed an anomaly in infrared observations at the wavenumber 713 cm^{-1} (corresponding to a wavelength of 14 microns) over the Indian Ocean. The chart shows monthly mean values for the period 15 September to 15 October 2015.

In 2015, EUMETSAT and the European Space Agency (ESA) launched new satellites, including Meteosat MSG-4. Once operational, they will provide important information for weather forecasting and environmental and climate monitoring.

ECMWF hugely benefits from the success of such missions. It also contributes to them by taking part in user consultation processes, conducting calibration and validation work, and developing methods for extracting useful information. In addition to European space agencies, ECMWF collaborates with satellite agencies in the US, China and worldwide.

Photo: ESA/CNES/ARIANESPACE-Optique Video du CSG, S. Martin

▲ **MSG-4** was launched from Europe's Spaceport in Kourou, French Guiana, on 15 July.

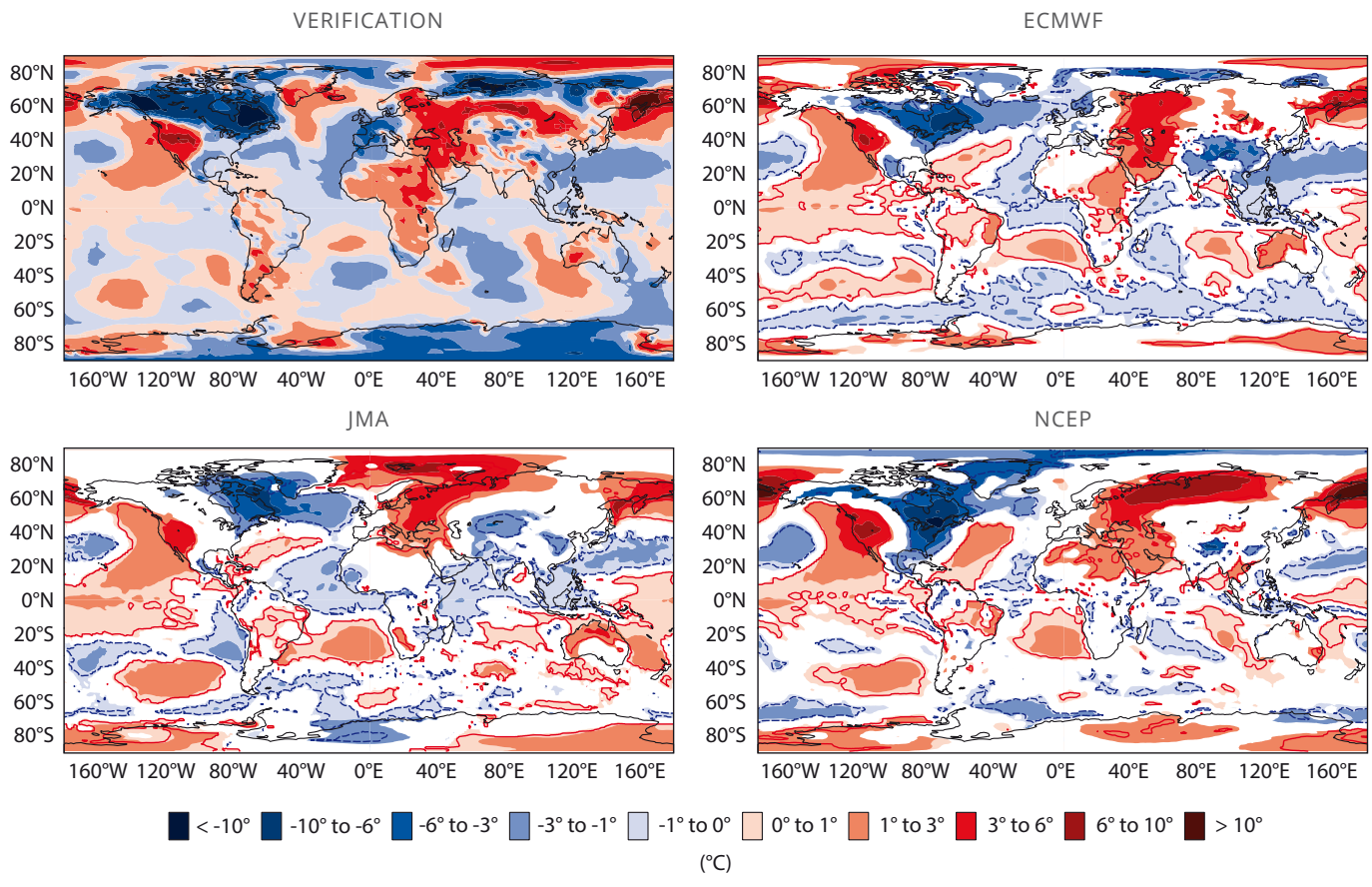
WORKING **TOGETHER**

World Meteorological Organization (WMO)

We work closely with the WMO, contributing to many projects, committees, working groups and expert groups, especially on issues relating to the World Weather Watch. We also support the World Weather Research Programme (WWRP), for instance through work to improve predictability on subseasonal to seasonal timescales (up to 60 days).

In 2015, following extensive consultations with other partners in WMO's Subseasonal to Seasonal Prediction Project (S2S), ECMWF launched a data portal for S2S weather forecasts.

The S2S database contains ensemble forecasts and re-forecasts from 11 operational centres, which are available for scientific research via data archive portals at ECMWF and CMA. It complements the TIGGE (THORPEX Interactive Grand Global Ensemble) archive, which gives access to global forecasts from a range of forecasting centres and has become a focal point for research projects, including on predictability and the prediction of severe weather.



▲ **Multi-model comparisons.** A possible use of the database is to make comparisons between the output of different forecasting centres. The image shows forecasts of 2-metre temperature anomalies from three S2S models and a verification panel based on observations. The forecast starting date is 22 January 2015 and the forecast range is days 12–18.

Collaboration with space agencies is vital to improve the quality of our forecasts

Coupled reanalysis

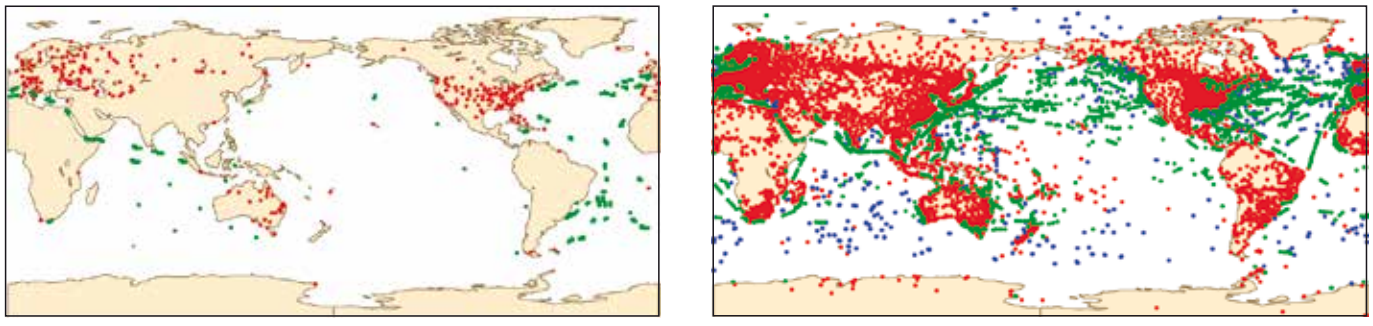
Weather and climate are the outcome of complex interactions between different parts of the Earth system, including the atmosphere, land surface, oceans and sea ice. ECMWF researchers have developed a coupled data assimilation system for climate reanalysis (CERA). In this system, ocean and atmospheric observations are assimilated simultaneously into a coupled atmosphere–ocean model. This achieves a considerable expansion of scope from the atmospheric and land-surface domains to include coupling with other major components of the climate system.

Originally funded by ESA, the work is now part of the ERA-CLIM2 project, funded by the EU under the 7th Framework Programme and coordinated by ECMWF. The project brings together 16 European organisations and involves more than 40 scientists.

A new global 20th century reanalysis, CERA-20C, went into production in 2015 and will reconstruct the Earth's past weather using historical observations. This activity involves significant collaboration between meteorological organisations, satellite agencies and universities to recover and prepare input observations for climate reanalysis.

This includes locating and digitising records from the pre-satellite era (from paper copies, imaged documents and microfilm), as well as extending the usable satellite climate data records. ECMWF's computing facilities and models make it well placed to realise the value of this information and align it with other environmental records. Assessing the quality of reanalysis outputs also relies on collaboration with research institutes involving experts in climate signals and uncertainty evaluation.

Within the ERA-CLIM2 project, national meteorological services, universities and research centres are developing new assimilation techniques that could further improve the CERA system. The CERA system produces a more consistent coupled ocean–atmosphere analysis that improves the use of near-surface measurements and reduces initialisation shocks in coupled forecasts. Originally designed for climate reanalysis, it could pave the way for more advanced data assimilation used in weather forecasting thanks to the contribution of the 16 project partners.



▲ Number of mean sea-level pressure observations per day in 1900 (left) and in 2010 (right) in the ISPDv3.2.6 and ICOADSv2.5 datasets used for the CERA-20C reanalysis.

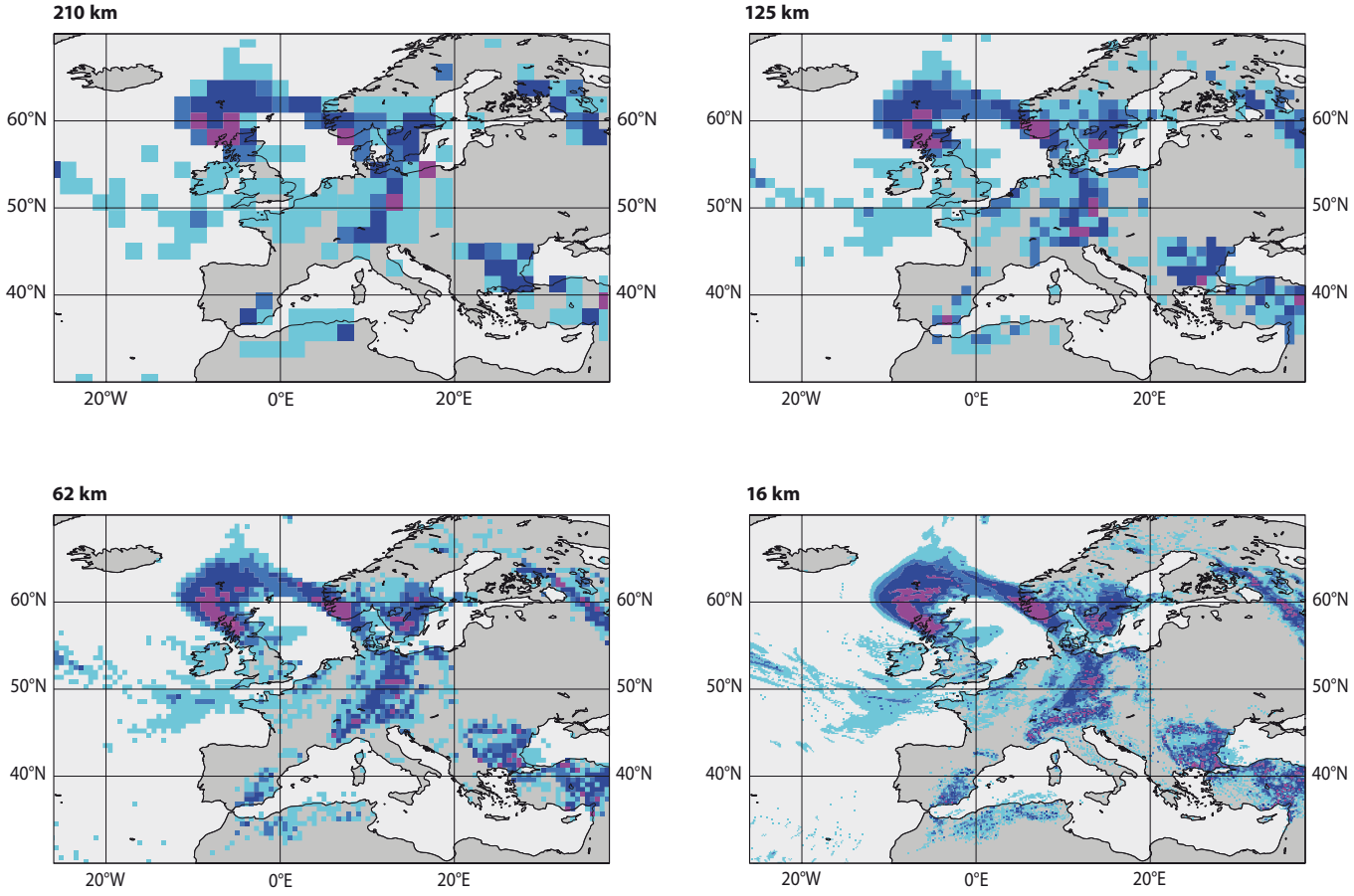
LOOKING TO THE **FUTURE**

40 years of improving forecast skill

2015 is the year when ECMWF turned 40. The past shows us what 40 years of European collaboration has delivered, taking our resolution from 210 km to 16 km, and allowing us to produce today a seven-day forecast as accurately as the three-day forecast was then. The past 40 years have also been marked by the tremendous progress made in the fields of computing and satellites, which have both been key to the advances seen in weather science. With 2016 marking the 30th anniversary of our sister organisation EUMETSAT, we know that the future will bring many more satellite advances, and we are looking forward to exploiting them.

We believe the future of numerical weather prediction lies in pursuing an Earth system modelling approach, which will allow us to improve our knowledge of the initial state of the atmosphere and of how that state develops. We also believe that the ensemble forecast should be at the core of NWP, providing forecasters with a better understanding of the possible scenarios and their likelihood.

All of this will only be possible if all our science, enriched by the best observations and supported by the most advanced computing technology, is developed with scalability at its heart.



HOW WE **WORK**

Organisation of ECMWF as of June 2016

Policy Advisory Committee

Scientific Advisory Committee

Technical Advisory Committee

COUNCIL
22 Member States

Finance Committee

Advisory Committee for Data Policy

Advisory Committee of Co-operating States

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Romania


Slovak Republic

Co-operating States as of January 2016

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