ECMWF

ANNUAL REPORT 2016

 Austria

 Belgium

 Croatia

 Denmark

 Finland

 France

 Germany

 Greece

 Iceland

 Ireland

 Italy

 Luxembourg

 The Netherlands

 Norway

 Portugal

 Serbia

 Slovenia

 Spain

 Sweden

 Switzerland

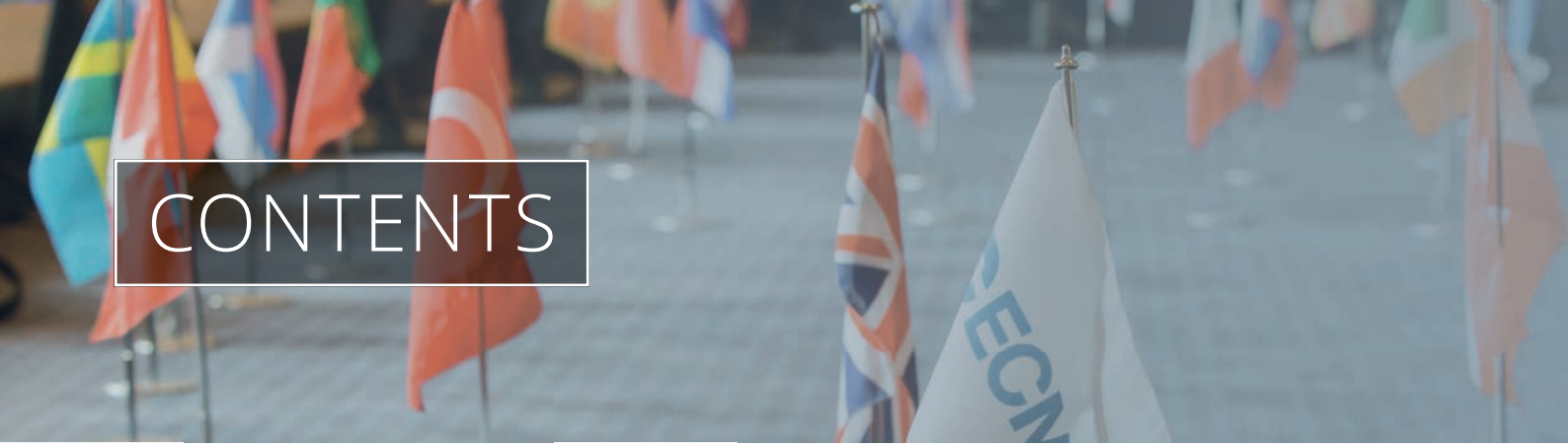
 Turkey

 United Kingdom

Member States as of January 2017

ECMWF

ANNUAL REPORT **2016**



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FOREWORD

The year that was … the strength of a common goal

A reason to remember 2016 is of course that ECMWF's Strategy to 2025 eventually came to fruition, after what was a long and extensive development process. It was also a process which made it entirely deserving of its ambitious title, 'The Strength of a Common Goal'. And this close working relationship with our Member and Co-operating States is possibly one of the defining aspects I will take away from 2016. The development process took a large part of two years and culminated in Council's decision at its June session to endorse the text. This led to what is today our Strategy to 2025, relying on a scalable Earth system approach to develop a high-resolution ensemble.

The Strategy was only one part though. 2016 saw the implementation of our octahedral grid, enabling the ground-breaking resolution upgrade which took our high-resolution forecast from 16 km to 9 km, and the ensemble from 36 km to 18 km up to day 15, and 36 km thereafter. But that was not all for the Integrated Forecasting System, truly and appropriately the star of 2016, as the second upgrade of the year saw the introduction of dynamic sea ice and finer resolution in the ocean. All these advances were made possible thanks to substantial progress achieved by our Scalability Programme, and of course the upgrade of our Cray computers. 2016 also allowed us to further develop the new ECMWF Fellowship programme, extending our collaboration with more of the best brains in the world.

A key moment for the many who mainly know ECMWF through its reanalysis programme was the release of a new and complete reanalysis of the 20th century. It is the first to use a coupled atmosphere–ocean data assimilation. Unlike its predecessors, this reanalysis also offers vital information about the uncertainties in the resulting output. Whilst the ECMWF-run Copernicus Atmosphere Monitoring Service became fully operational, the contract for our contribution to the Copernicus Emergency Management Service was renewed.

Our links with the WMO were stronger than ever. A new programme saw the arrival of a forecaster from Vietnam's National Centre for Hydro-Meteorological Forecasting join our teams for a 12-month period. This placement, part of the WMO's ambition to enhance forecasting capability in developing countries, will enable the Fellow to provide support and guidance when back in his home country. As we see the damage from severe weather too regularly affecting the poorest countries in the world, I can only salute this initiative from the WMO and take pride that ECMWF has been able to support it.

Of course, it is a fact of life that a year would not be complete if it were not declared the hottest on record. 2016 was no exception, and the data provided by our Copernicus Climate Change Service provided evidence that most regions around the world had experienced above-average temperatures during the year.

Enjoy reliving 2016, and be prepared that the year that was may be nothing yet compared to the year that will be.

© Stephen Shepherd

Florence Rabier
Director-General

2016 AT A GLANCE

JANUARY

New ECMWF Director-General

Dr Florence Rabier takes up the role of Director-General of ECMWF on 1 January, succeeding Professor Alan Thorpe.

Croatia becomes 22nd Member State

Croatia officially joins ECMWF on 1 January, moving to full membership from a co-operation agreement in place since 1995.

Collaboration with Chinese weather service

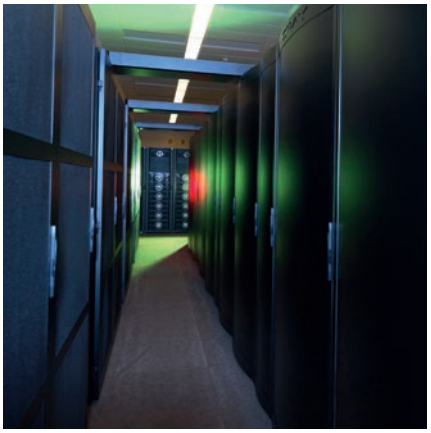
A successful co-operation agreement between ECMWF and the China Meteorological Administration (CMA) broadens beyond its initial focus on satellite data to include other areas, such as dust storms, which can affect air quality in Chinese cities.

Floodhack to help flood prediction work

ECMWF hosts a hackathon for developing tools to save lives worldwide by improving the Global Flood Awareness System, which provides global forecasts of extreme flood events. ECMWF is working with the European Commission's Joint Research Centre and the University of Reading to develop GloFAS, which gives early warning of flood risk up to 30 days ahead.

Supercomputer deal boosts prediction capabilities

ECMWF signs a contract with Cray Inc. to significantly upgrade its supercomputing power and allow the Centre to improve the quality of service provided to Member and Co-operating States. The new Cray XC40 systems were installed in the first half of the year, with the first operational forecast produced on 6 June.



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FEBRUARY

Train-the-trainer course

Twenty-one meteorologists from ECMWF's Member States attend a new course to help them train others in the use of ECMWF products. The course includes new sessions on assessing training needs and learning outcomes as well as sessions on ECMWF's ensemble products.

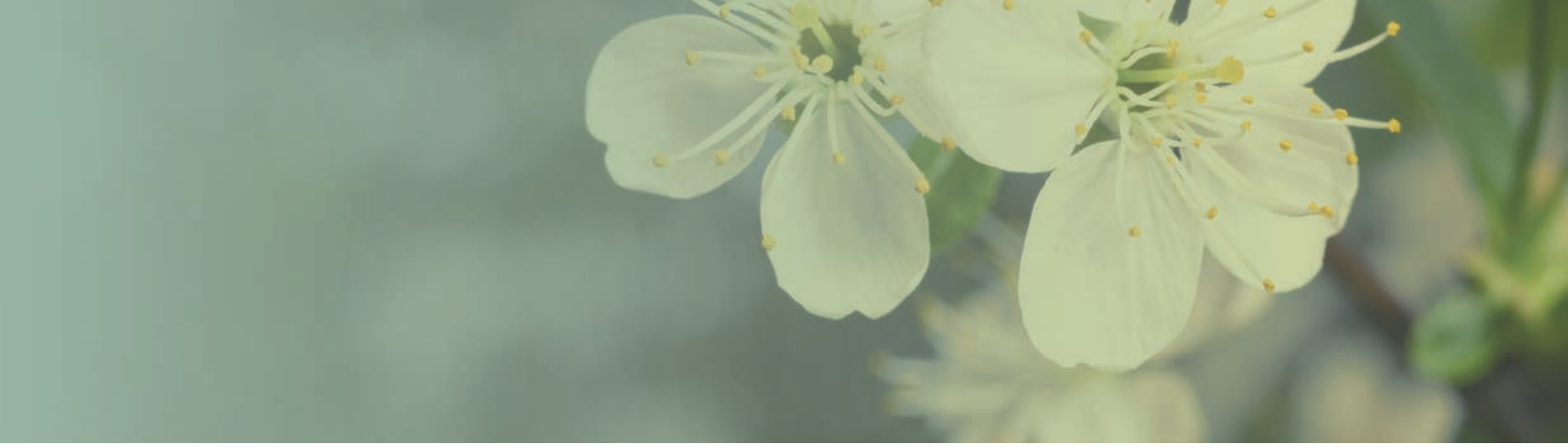
MARCH

International Women's Day

Staff at ECMWF gather for an informal discussion to mark International Women's Day and raise awareness of the gender gap in science. Women comprise only a third of the global workforce at national meteorological/hydrological services, and only 19% of senior staff. At ECMWF the proportion of female staff has grown from 14% in 1979 to 26% in 2016.

Model upgrade brings highest-ever resolution

ECMWF launches a new, higher-resolution modelling system bringing improved weather forecasts. These changes give the finest resolution to date: 9 km in the Centre's highest-resolution model. The developments in Cycle 41r2 provide national meteorological services with more accurate and timely information which can then be used to improve weather warnings for emergency response services, policymakers, and others.



Simulated satellite data product

A new forecast product is launched which provides a unique satellite's 'eye view' of cloud and other weather features up to ten days into the future. The new visualisation product uses information from the high-resolution forecast to produce 'simulated' satellite images of predicted future conditions. Weather forecasters are familiar with using satellite observations, of upper-level clouds for example, to infer current weather conditions on the ground. The new simulated product will allow forecasters to use the same skills to infer future weather conditions.

APRIL

ECMWF/World Weather Research Programme workshop on model uncertainty

Almost 80 scientists from 15 countries meet at ECMWF to improve the way uncertainty is dealt with in weather forecasting. Improving the reliability of forecasts hinges on understanding uncertainty better, and the meeting highlights many promising new approaches.

MAY

Two new ECMWF Fellows

Professor Daniel Jacob from Harvard University and Professor Heini Wernli from ETH Zurich join the growing group of ECMWF Fellows. The Fellowship Scheme began in 2014 to foster collaboration and help the Centre in improving forecast skill in the medium and extended range. Professor Jacob brings expertise in atmospheric chemistry as well as links with NASA, while Professor Wernli works on mid-latitude weather systems and transport processes in the atmosphere.

Cray User Group meeting

Hosted by ECMWF, a diverse group of over 200 Cray supercomputer users convene in London to share ideas about how to meet the need for ever-greater computer power.

New aircraft weather data used for forecasts

ECMWF starts to use newly available aircraft observations of humidity, temperature and wind to help initialise its forecasts. The data come from the Aircraft Meteorological Data Relay (AMDAR) programme of the World Meteorological Organization (WMO) and help to fill data gaps over Africa, the Caribbean and the ocean. Such gaps in observations are one source of uncertainty in weather forecasts.

Annual user meeting

This year's annual Using ECMWF's Forecasts (UEF) event focusses on evaluating forecasts of high-impact weather. The meeting brings together ECMWF data users from the private and public sectors and provides the Centre with important feedback.

JUNE

OpenIFS workshop for Météo-France students

At a workshop in Toulouse, France, students from the Ecole Nationale de la Météorologie, run by Météo-France, explore ensemble forecasts using ECMWF's Open Integrated Forecasting System (OpenIFS). Students looked back at September 2012, when Hurricane Nadine in the Atlantic contributed to ensemble forecasts suggesting two quite different rainfall forecasts for southern France. Students gained valuable experience in the difficult situation of decision making given two possible outcomes.

ECMWF statement on the UK voting to leave the EU

ECMWF is an intergovernmental organisation which includes EU and non-EU member countries. Its collaborative mode of operation will continue notwithstanding the UK's decision to leave the EU.

JULY

New Director of Forecasts

Professor Florian Pappenberger is appointed the new Director of Forecasts at ECMWF, having worked as a Principal Scientist in the Forecast Department since 2006.

2016 AT A GLANCE

AUGUST

20th century climate reanalysis

ECMWF completes a new, innovative 'reanalysis' of 20th century climate known as CERA-20C. In reanalysis, observations are blended with fields produced from weather forecasting. The new reanalysis uses an Earth system model for the first time which includes interactions between the atmosphere, ocean, land surface and other components. It is also produced within ECMWF's ensemble system which provides vital information about uncertainties in the data. Scientists will now study the data to see what new insights it brings. CERA-20C is an outcome of ERA-CLIM2, an international research project in which 16 organisations have participated.

Seasonal outlook for river levels

A new seasonal outlook developed by ECMWF that extends the forecast horizon for river levels from two weeks to two months enters a test phase within the Copernicus European Flood Awareness System (EFAS). The outlook is produced by using the ECMWF seasonal ensemble forecasts as input to a hydrological model of Europe's rivers.

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SEPTEMBER

Flash floods in Greece

Extreme rainfall affects parts of Greece on 6 and 7 September. Flash floods cause four fatalities and damage properties and infrastructure. Ensemble forecasts three to five days ahead correctly highlighted both Thessaloniki in the north and Kalamata in the south as being at risk, though the performance of the high-resolution forecast was geographically uneven. The Extreme Forecast Index (EFI) for precipitation was high in both locations, suggesting that very large rainfall totals were likely, whilst the Shift of Tails (SOT) was also high, suggesting that a truly exceptional event was possible.

ECMWF Strategy for 2016–2025

ECMWF launches its ambitious Strategy for 2016–2025 at the annual meeting of the European Meteorological Society (EMS) in Trieste, Italy. The Strategy sets challenging targets for improving medium- and long-range numerical weather prediction, including the ability to make skilful ensemble predictions of high-impact weather up to two weeks ahead.

Annual Seminar on Earth system modelling

Delegates at ECMWF's flagship Annual Seminar debate the issue of Earth system modelling and atmospheric predictability. An Earth system approach, which couples together atmosphere, ocean, land and other processes, can enable better forecasts and a wider range of environmental products. However, delegates at the seminar stress that fundamental processes, such as clouds, must also be improved in models.

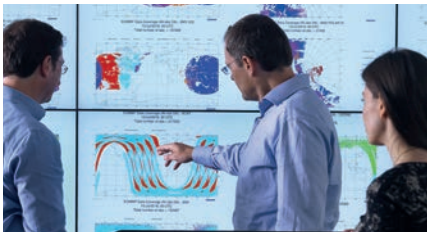
Preparations for Year of Polar Prediction

International invitees from operational centres, research institutes, universities, and initiatives convene at the Centre to prepare for the Year of Polar Prediction (YOPP), an initiative of the WMO. The Chief of the WMO's World Weather Research Division says the YOPP will help to develop a new observational network in the polar regions to enable better weather predictions.

OCTOBER

WMO Fellow from Vietnam

A forecaster from Vietnam's National Centre for Hydro-Meteorological Forecasting begins a 12-month placement at ECMWF, sponsored by the WMO as part of a programme to develop forecasting capacity in developing countries. The placement will enable the Fellow to provide guidance in Vietnam on how to use ECMWF's ensemble forecasts to predict the track and intensity of tropical cyclones.



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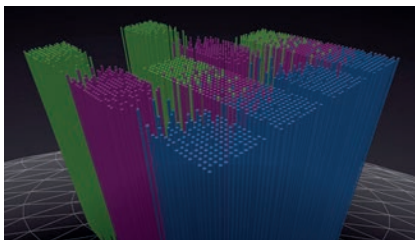
HPC in meteorology workshop

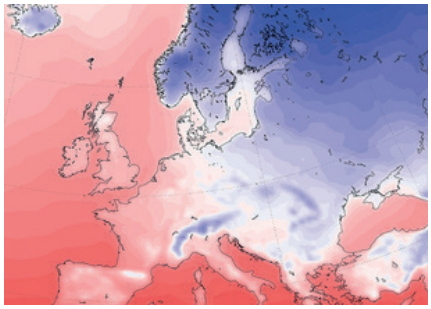
ECMWF's workshop on High-Performance Computing in Meteorology, held every two years, highlights the need for supercomputer architectures which can handle tomorrow's weather prediction models and the need to adapt models so that they run efficiently on those architectures.



NOVEMBER

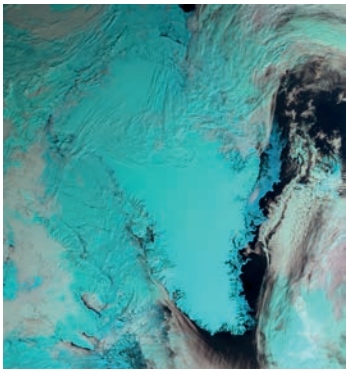
Global climate monitoring tool

One year after the Paris Agreement on climate change, ECMWF releases test data from its most powerful global climate monitoring tool to date, ERA5. The ERA5 climate reanalysis, which combines model data with observations, is produced by C3S. It brings finer spatial resolution, hourly data and estimates of data uncertainties, among other developments. The free and open-access ERA5 data will cover 1979 to present and provide unprecedented opportunities for exploring climate for users in research, education, and the private sector.



Sea-ice coupling and higher ocean resolution

ECMWF implements a new version of its forecasting system, which introduces dynamic sea ice and finer resolution in the ocean. These and other changes significantly improve the Centre's weather predictions. In the new system, Cycle 43r1, sea ice can change 'dynamically' within the model in response to changing temperature and wind for example. Other changes have brought improvements in forecasts of extreme weather.



New satellite wind data

At a joint ECMWF/ESA workshop on tropical modelling, observations and assimilation, there is general agreement that the most needed observations in the tropics are wind profiles. The two organisations are working closely to prepare a new satellite mission that will provide wind profiles from the ground up to a height of 30 km. New wind information from the Aeolus satellite is expected to contribute to improved tropical analyses and therefore improved medium-range forecasts, including in the mid-latitudes. ECMWF will be involved in monitoring and processing the data provided by Aeolus, set for launch early 2018.

ISO certification for quality management

ECMWF's quality management system is certified to ISO 9001:2015.

DECEMBER

New Director of Research appointed

Dr Andrew Brown, Director of Science at the UK Met Office, is appointed to become ECMWF's next Director of Research after Professor Erland Källén steps down in July 2017.

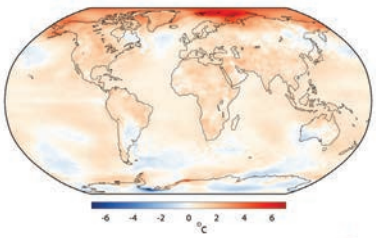
New appointments in ECMWF governance

ECMWF's Council elects Professor Jorge Miguel Alberto de Miranda (Portugal) as its President and Professor Juhani Damski (Finland) as its Vice-President, both for a first term of office of one year. It also appoints five new members to the Centre's Scientific Advisory Committee.

2016 warmest calendar year on record

C3S data shows that most regions around the world experienced above-average temperatures during 2016. The largest differences in regional average temperatures were found in the Arctic but conditions were also extreme over southern Africa early in the year, over southern and south-eastern Asia prior to the summer monsoon, over the Middle East later in summer, and over parts of North America in summer and autumn.

AVERAGE SURFACE AIR TEMPERATURE FOR 2016



ADVANCING **WEATHER SCIENCE**

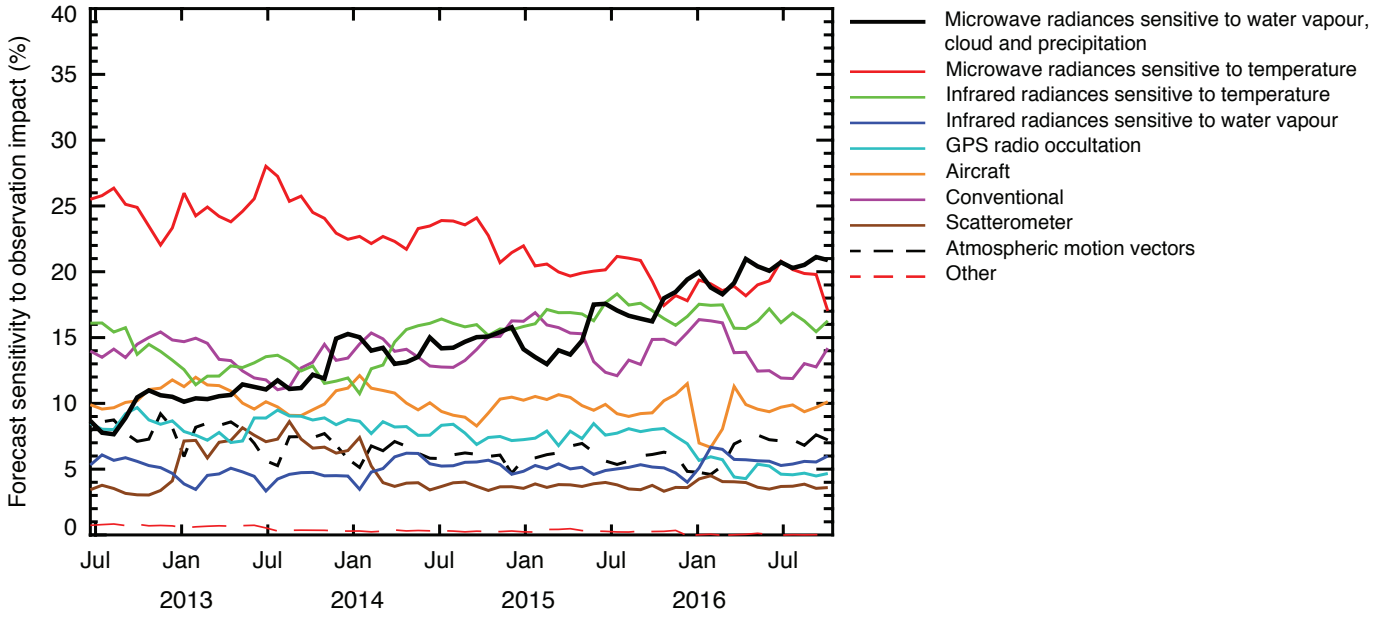
To ensure continuing improvements in our forecasts, ECMWF carries out world-leading research into all aspects of numerical weather prediction. The results of this research are incorporated into operations for the benefit of forecast users. Collaboration with space agencies, national meteorological services and the research community worldwide is a key ingredient in this research effort. The year 2016 saw decisive progress in a number of areas.

Examples include advances in the all-sky assimilation of microwave satellite data; the development of a coupled atmosphere–ocean data assimilation system (CERA), enabling the production of a new global climate reanalysis of the 20th century (CERA-20C); research on lightning parametrization, which brought the possibility of new lightning forecast products; radiation code work, which resulted in greater accuracy and improved computational performance; and research on reducing computational precision to increase efficiency, which showed promising results.

All-sky assimilation

Advances in the all-sky assimilation of microwave satellite data led to noticeable operational improvements. As shown in the chart, in 2016 microwave radiances sensitive to water vapour, cloud and precipitation made one of the most significant contributions to weather forecasts compared to other parts of the observing system.

All-sky assimilation has roughly doubled the impact of microwave radiances on forecast performance compared to clear-sky assimilation. For example, the clear-sky assimilation of microwave humidity sounding observations extends the skilful range of forecasts in the southern hemisphere by about three quarters of an hour, while all-sky assimilation extends it by about one and a half hours. Much of the pioneering 'all-sky' work carried out by ECMWF scientists was funded by EUMETSAT via Fellowships at ECMWF.



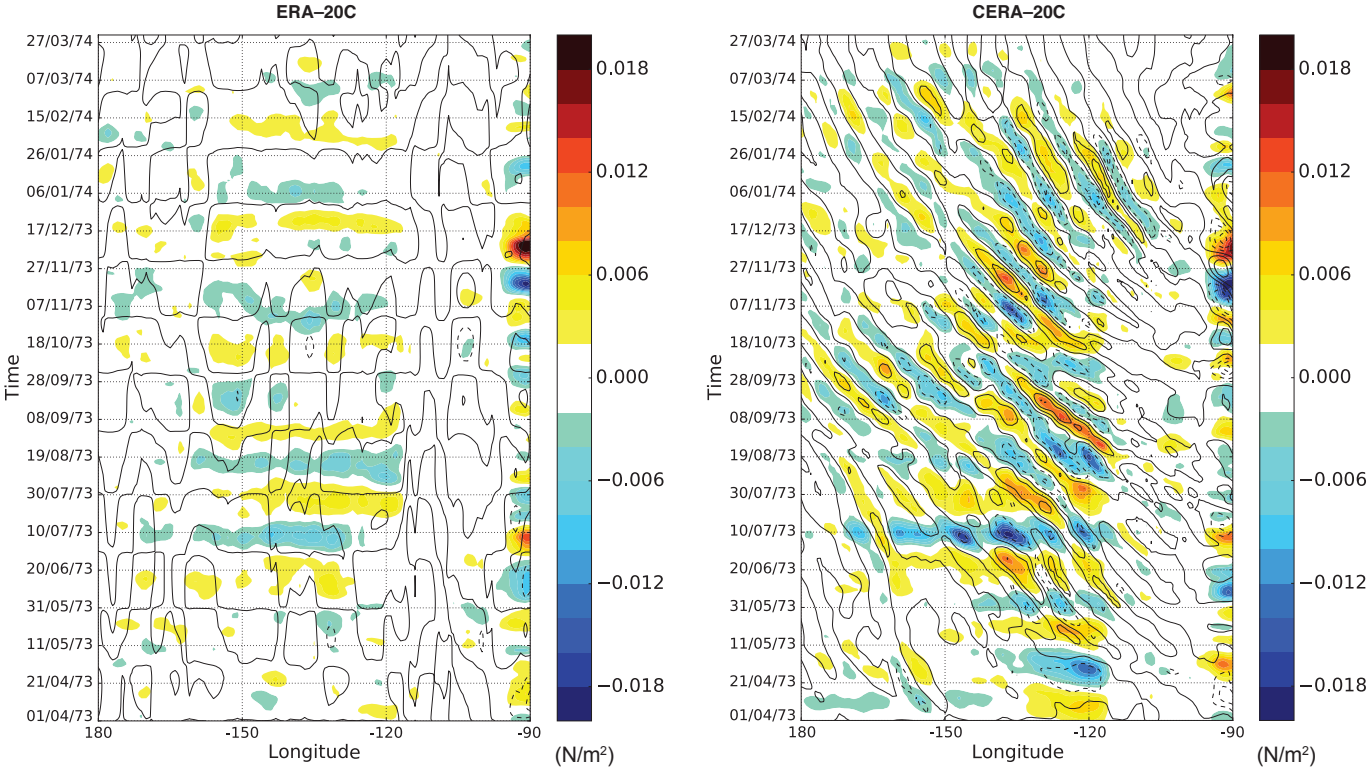
▲ **Impact on forecasts.** The impact of microwave radiances sensitive to water vapour, cloud and precipitation on ECMWF forecasts has grown steadily over the years relative to that of other parts of the observing system. This is shown here in terms of forecast sensitivity to observation impact (FSOI) in the ECMWF operational system from June 2012 to October 2016, averaged in 25-day bins and normalised so that the total impact is 100%.

Coupled data assimilation

ECMWF continued to develop its coupled atmosphere–ocean data assimilation system (CERA). CERA was used to produce a new global 20th-century reanalysis (CERA-20C), which aims to reconstruct the past weather and climate of the Earth system. CERA-20C is part of the EU-funded ERA-CLIM2 project and extends the atmospheric reanalysis capability developed in ERA-20C to the ocean and to sea ice.

In CERA-20C, atmospheric and ocean observations are assimilated simultaneously. Ocean observations can have a direct impact on the atmospheric analysis and, conversely, atmospheric observations can have an immediate impact on the analysed state of the ocean. Only surface pressure, marine wind observations and ocean temperature and salinity profiles are assimilated.

CERA-20C is the first climate reanalysis for all parameters and levels over the 20th century to provide a ten-member ensemble of reanalyses. Ensemble generation is based on the Ensemble of Data Assimilations (EDA) system developed at ECMWF, which explicitly accounts for errors in the observational record and in the forecast model. The ensemble approach aims to provide an indication of the confidence users can have in the resulting output.



▲ **Tropical Instability Waves.** Spatially high-pass filtered wind stress anomalies (shading) and sea-surface temperature anomalies (contours, ranging from -1 to 1°C in 0.25°C increments) for ERA-20C (left) and CERA-20C (right) over the period from 1 April 1973 to 27 March 1974. CERA-20C is able to represent Tropical Instability Waves (TIWs) thanks to the ocean dynamics, and the atmosphere is responding accordingly with the surface wind stress sensitive to the ocean TIWs. In ERA-20C, there are no TIWs or wind stress signals.

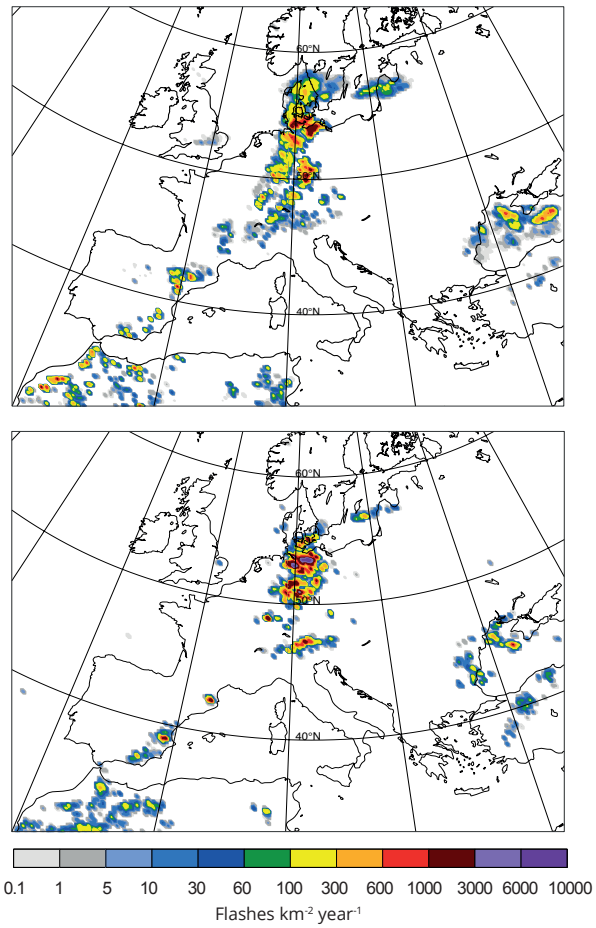
ADVANCING **WEATHER SCIENCE**

Lightning

ECMWF scientists developed a new experimental method to predict lightning flash densities. Possible applications include high-resolution (HRES) and ensemble (ENS) lightning forecasts in the IFS. The current version diagnoses total lightning flash densities, with no distinction between cloud-to-ground and intra-cloud discharges.

The new method was calibrated and validated using a satellite lightning climatology. An example of the level of agreement between a 9 km resolution total lightning forecast and ATDnet ground-based observations is shown in the figure.

Work is continuing on the development of an additional method that focuses on the cloud-to-ground component of lightning. Ultimately lightning observations should be assimilated from networks of ground-based sensors and from the next generation of geostationary satellites. Such assimilation is expected to bring benefits in convective regions in the tropics all year round and in the extratropics in summer.



▶ **Lightning forecast.** Eighteen-hour forecast of total lightning flash densities on 28 August 2016 (top) and ATDnet ground-based observations over Europe (bottom; UK Met Office data). Flash densities are expressed in flashes per square kilometre per year. ATDnet sensors only detect about 80% of cloud-to-ground flashes and a much smaller fraction of intra-cloud flashes.

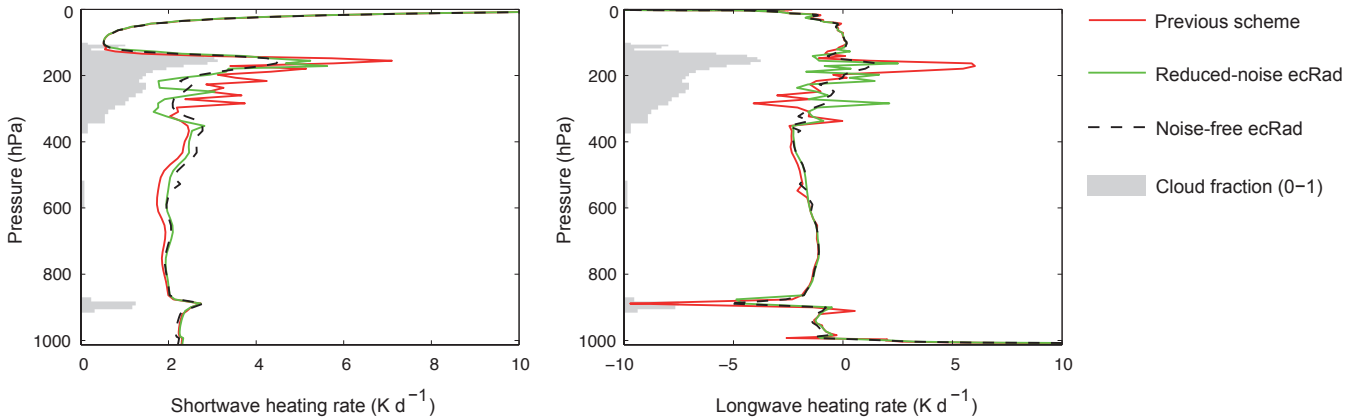
Radiation

The flows of solar and thermal-infrared radiation through the atmosphere provide the heating and cooling that drive large-scale weather patterns. An accurate treatment of these flows is important not only for medium-range surface temperature forecasts, but also for pushing the boundaries of predictability at longer timescales.

ECMWF scientists have developed a new radiation scheme called ecRad. It is 31% faster than the previous scheme, offering the possibility to improve forecast skill by calling the radiation scheme more frequently for the same overall computational cost. In addition, an improved stochastic cloud generator produces less noise in atmospheric heating rates. This leads to a small but significant reduction in root-mean-square temperature errors. A better treatment of thermal-infrared radiative transfer reduces both the cold bias at the tropopause and the warm bias at the stratopause.

The scheme's modular design makes it possible to modify the different components of the scheme independently of each other. This facilitates the development and testing of new features, such as a new algorithm which allows the flows of radiation through cloud sides to be represented for the first time in a global model.

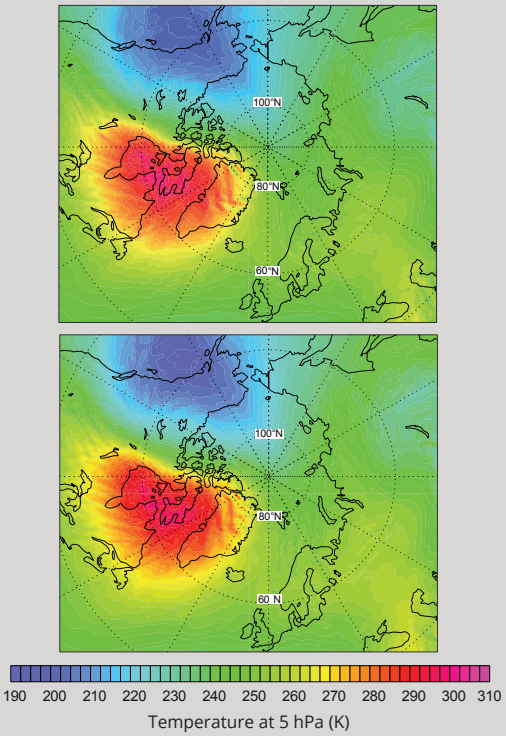
▼ **Less noise in atmospheric heating rates.** Solar heating-rate profiles (left) and thermal-infrared heating-rate profiles (right) for a single column of the atmosphere, comparing the previous scheme (with noise of up to 5 K per day), the reduced-noise ecRad scheme, and a computationally more expensive noise-free ecRad option. The grey shading indicates the location of clouds.



PRECISION WORK

As the precision in computations is reduced, the data volume shrinks and performance increases. This can make it possible to improve the overall accuracy of the model by carrying out more complex simulations at higher resolution. ECMWF scientists therefore investigated the use of single precision (32 bits) within the IFS instead of the traditional double precision (64 bits).

Many technical difficulties had to be addressed before single precision forecast simulations could be run successfully. Some parts of the code had to be kept at high precision. With all required adjustments made, it was shown that, at low resolution, single-precision forecasts are about 40% more efficient to produce while forecast quality is comparable to double precision. First tests at higher resolution showed promising results but revealed an increase in mass conservation error that needs to be investigated further.



▶ **Single vs double precision.** The charts show a single-precision 7-day forecast (top) and a double-precision 7-day forecast (bottom) of a sudden stratospheric warming event at high resolution, valid at 10 January 2013 00 UTC. These events are challenging for weather models as they involve very small vertical velocities that are sensitive to noise.

DELIVERING **GLOBAL PREDICTIONS**

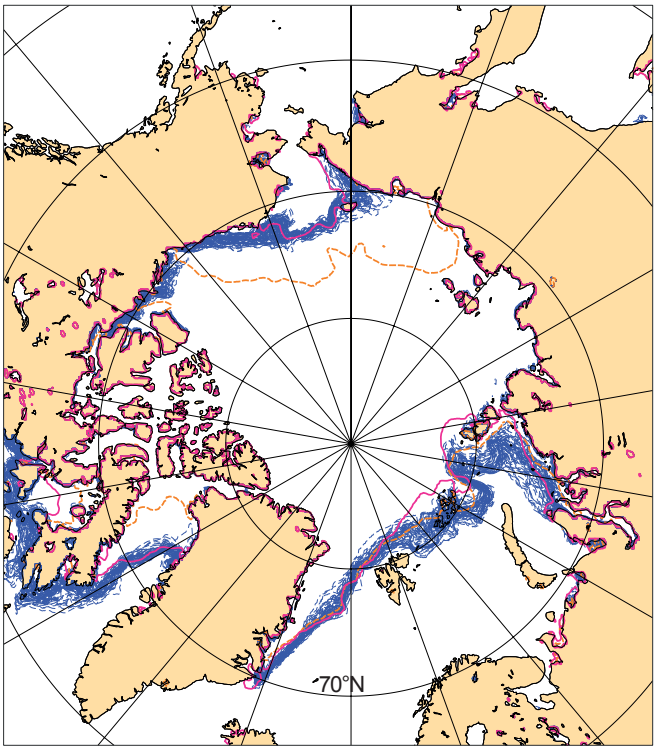
ECMWF implemented two major upgrades of its Integrated Forecasting System (IFS) in 2016. The first, IFS Cycle 41r2, brought record-breaking resolution in global forecasts, with three times as many prediction points as before. The second, IFS Cycle 43r1, introduced an interactive sea-ice model in the medium-range and monthly ensemble forecast and a four times finer horizontal resolution in the ocean model. The resulting improvements in forecast quality helped national meteorological services in our Member and Co-operating States to produce predictions and early warnings of severe weather for the benefit of society. ECMWF's new 2016–2025 Strategy sets a demanding target of up to four weeks for the skilful prediction of weather regime transitions. An assessment of the Centre's ability to predict such transitions in 2016 showed useful skill up to 15 days ahead.

The way in which ECMWF's forecasts can help in the protection of life and property is illustrated by flash floods in Greece in September 2016 after extreme rainfall. ECMWF's ensemble forecasts indicated the risk of such rainfall in the main areas affected. Ensemble forecasts describe the range of possible weather scenarios and the likelihood of their occurrence. They have a central place in the new Strategy.

Sea-ice coupling

IFS Cycle 43r1 was implemented on 22 November 2016. For the first time the IFS now includes an interactive sea-ice model for medium-range and monthly ensemble forecasts. The interactive sea-ice model LIM2, the Louvain-la-Neuve Sea Ice Model developed at the Belgian Université catholique de Louvain, allows sea-ice cover to respond to changes in the atmosphere and oceans. This enables a more accurate sea-ice, sea and air interaction. In the previous model version, sea-ice cover was left static up to forecast day 15. Bringing additional Earth system components into the model and developing ECMWF's ensemble forecast capabilities are important elements of the Centre's new Strategy.

Other key changes include a significant increase in resolution in the ocean model. The horizontal resolution was increased from 1 degree to 0.25 degrees and the vertical resolution went up from 42 to 75 layers, with a particular large change from 5 to 18 layers in the first 50 metres. The upgrade also introduced a new, higher-resolution ocean ensemble of analyses and reanalyses, ORAS5.

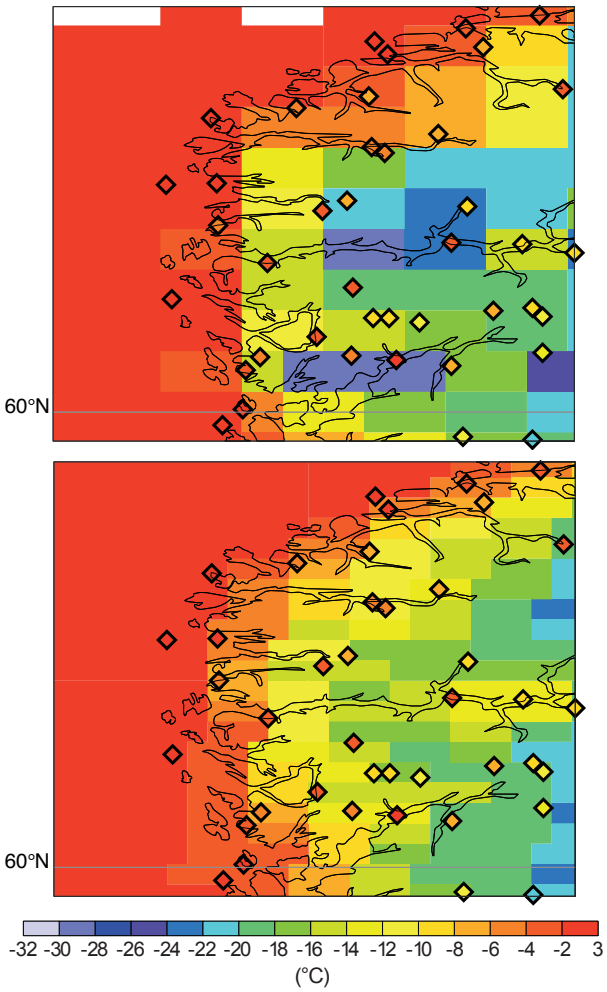


▲ **Dynamic sea-ice cover.** Dynamic predictions of sea-ice cover produce very different results from the assumption of static sea-ice cover. This is illustrated by this two-week ensemble forecast from 2 November 2016 (blue lines), which shows a significant evolution from the initial conditions (dashed orange line). Subsequent verification (pink line) shows that the dynamic forecast is much closer to observations than the static sea-ice cover. The spread of the blue lines gives an indication of the range of likely scenarios given inevitable uncertainties in the evolution of atmospheric and ocean conditions.

Record-breaking resolution

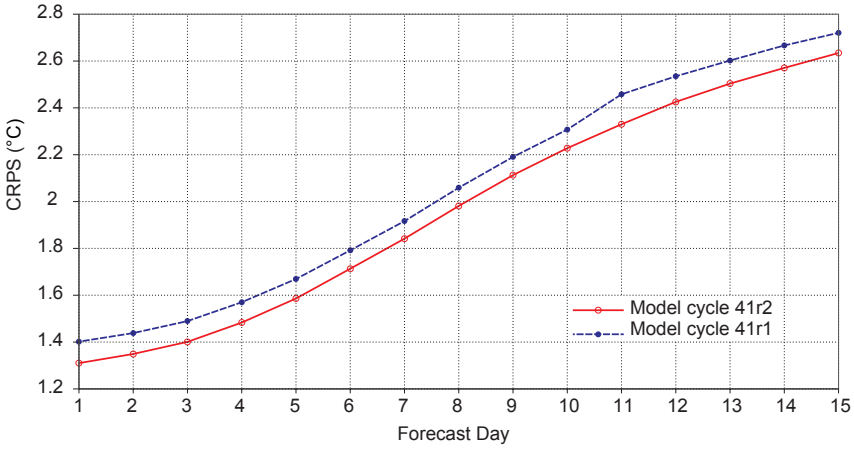
IFS Cycle 41r2 was implemented on 8 March 2016. It introduced a new grid on which forecasts are run, comprising up to 904 million prediction points. For high-resolution forecasts (HRES) and ensemble forecasts (ENS) the grid-point resolution was doubled to 9 km and 18 km, respectively, while for the Ensemble of Data Assimilations (EDA) it was tripled to 18 km.

The new 'cubic octahedral' grid used in Cycle 41r2 brought increased realism at smaller scales and allows for the future implementation of a hybrid spectral/grid-point model. In combination with several other scientific and technical changes, the upgrade led to a significant increase in forecast accuracy and computational efficiency.



▶ **Coastal areas.** The charts show 12-hour ensemble control forecasts of 2-metre temperature for a coastal area in Norway valid at 12 UTC on 7 January 2016. The forecasts were produced using the previous model cycle (41r1 – top) and the new model cycle (41r2 – bottom). The diamonds show observed temperatures. The charts show that spurious cold areas have disappeared in the 41r2 forecast thanks to the higher resolution as well as improved radiation physics in the new model cycle.

The consistency in medium-range ensemble forecasts was improved by lowering the resolution only on day 15 rather than day 10. This is illustrated by the disappearance of the kink in temperature forecast skill that could be seen in the previous IFS cycle.



▶ **Temperature forecasts in Europe.** The chart shows the Continuous Ranked Probability Score (CRPS – a measure of skill) for ensemble forecasts of 2-metre temperature in Europe averaged over 12 UTC forecasts from 10 August 2015 to 25 February 2016. Forecasts produced using the new model cycle (41r2) have consistently better CRPS values than those produced using the previous cycle (41r1), and the forecast range at the same level of skill is larger for the new model cycle by 12 hours or more across the range shown.

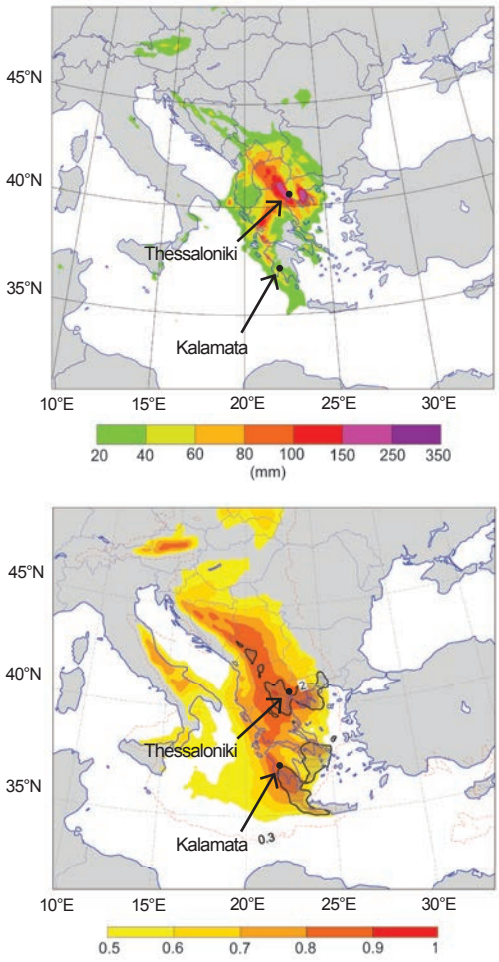
DELIVERING **GLOBAL PREDICTIONS**

Flash floods in Greece

Between about midday on 6 September and midday on 7 September 2016, extreme rainfall affected parts of Greece. The resulting flash floods caused four fatalities, invaded properties, closed roads, and caused cars to be piled up and locally swept out to sea.

The performance of the high-resolution forecast was geographically uneven. Ensemble forecasts three to five days ahead, on the other hand, correctly highlighted both Thessaloniki in the north and Kalamata in the south as being at risk. The Extreme Forecast Index (EFI) for precipitation was high in both locations, suggesting that very large rainfall totals were likely, whilst the Shift of Tails (SOT) was also high, suggesting that a truly exceptional event was possible.

The case illustrates that, in the medium range at least, ensemble forecasts are the main tool to use by forecasters when it comes to identifying areas at risk.



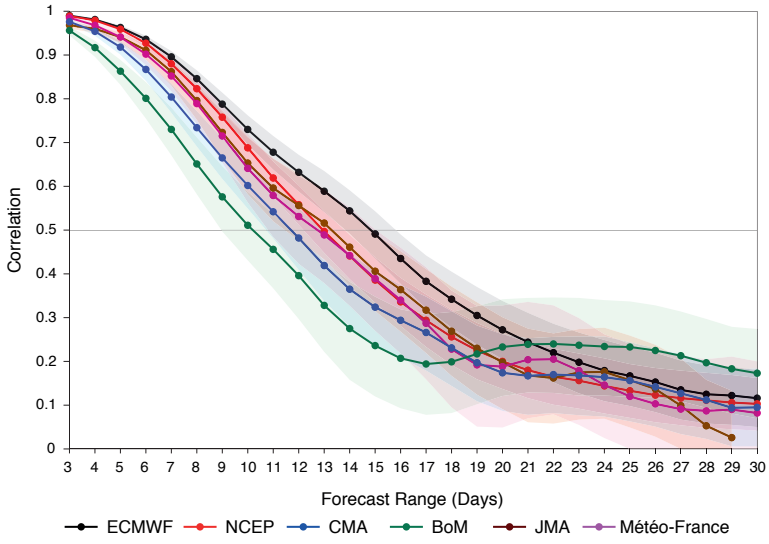
▶ **Rainfall forecast.** The top chart shows the high-resolution forecast of 72-hour rainfall total initialised at 00 UTC on 3 September 2016, valid from 00 UTC on 5 September to 00 UTC on 8 September. The bottom chart shows the EFI (shading) and SOT (hatching for SOT>2) for 72-hour rainfall initialised and valid at the same times.

Regime transitions

One of the goals set in ECMWF's new Strategy is the skilful prediction of weather regime transitions up to four weeks ahead. In 2016, work was carried out to assess the Centre's current skill in predicting such transitions. At timescales of several weeks, forecasts cannot be expected to make skilful predictions of day-to-day variability of the weather. What can be predicted, however, is large-scale circulation patterns lasting more than a week. In Europe, these may be associated with high-impact temperature anomalies. For examples, high pressure over Scandinavia may bring cold winter temperatures to parts of Europe.

The assessment of the Centre's skill in predicting such transitions used data from the Sub-seasonal to Seasonal Prediction project (S2S), which brings together forecasts from several models. S2S is a joint research initiative launched in 2013 by the World Weather Research Programme (WWRP) and the World Climate Research Programme (WCRP). Tests showed that there is a wide range of skill among the S2S models. In some cases the skill dropped below a useful level after 10 to 13 days, while ECMWF forecasts retained useful skill up to day 15.

▶ **Regime transition forecast skill.** The chart shows the skill of ensemble forecasts in predicting transitions between four wintertime Euro-Atlantic weather regimes: the positive and the negative phase of the North Atlantic Oscillation, Scandinavian blocking and the Atlantic ridge. The skill is shown as a correlation depending on forecast lead time, with a 5-day running mean applied to the forecasts and verifying data. The shaded areas represent 95% confidence levels. A correlation of 0.5 or more can be regarded as indicating a useful level of skill. Results are shown for ECMWF, the US National Centers for Environmental Prediction (NCEP), the China Meteorological Administration (CMA), the Australian Bureau of Meteorology (BoM), the Japan Meteorological Agency (JMA), and Météo-France.



FORECAST QUALITY

The quality of ECMWF forecasts as measured by various skill scores continued to improve in 2016. The Centre consolidated its lead compared to other forecasting centres in the skill of 500 hPa geopotential height forecasts for the northern hemisphere extratropics. Similar improvements are found for the southern hemisphere and for other upper-air skill metrics. The skill in predicting surface variables increased for 2-metre temperature and humidity, 10-metre wind speed, precipitation, and total cloud cover, with error reductions in the order of 1–2% in the early medium range.

▲ **Headline score.** The chart shows the skill of ensemble forecasts as measured by ECMWF's primary probabilistic headline score. Results for temperature at 850 hPa in the northern hemisphere extratropics show that in the year 2016 the medium-range probabilistic forecast skill reached its highest level so far. The chart shows 12-month running average values of the forecast range at which the continuous ranked probability skill score (CRPSS) drops below 25%.

SUSTAINING **HPC**

Following a complex supercomputer upgrade in the first half of the year, ECMWF's high-performance computing facility (HPCF) now comprises two Cray XC40s with 260,000 processor cores and more than 900 terabytes of memory. It is one of the most powerful supercomputing facilities in Europe.

The increased computer power will allow ECMWF to improve the quality of service provided to Member and Co-operating States, including better prediction of severe weather such as storms and floods.

The third year of ECMWF's Scalability Programme has brought substantial progress towards improving the efficiency and scalability of computer code. The upgraded computing facilities provide a space to implement and test current science as well as new architectures for ECMWF and its partners to test code on future hardware systems.

Cray Phase 2 upgrade

In January ECMWF extended its contract with Cray Inc. until 30 September 2020, providing for a more powerful Phase 2 upgrade than originally planned and the addition of a novel architecture platform to explore new accelerator technologies.

During the first half of 2016, Cray converted the two XC30 clusters to XC40s by upgrading all the compute blades and adding an extra cabinet with 128 nodes to each machine. The upgraded system has 50% more processor cores, double the memory and an extra five petabytes of high-performance storage for only a four percent increase in electricity consumption.

A three-stage approach allowed ECMWF to access the new technology for large-scale code testing while retaining operational resilience. The first operational forecast with the new systems was produced on 6 June.

The data handling system was enhanced with extra servers and disk cache to support the growing volume of data, which passed 200 petabytes at the end of 2016.

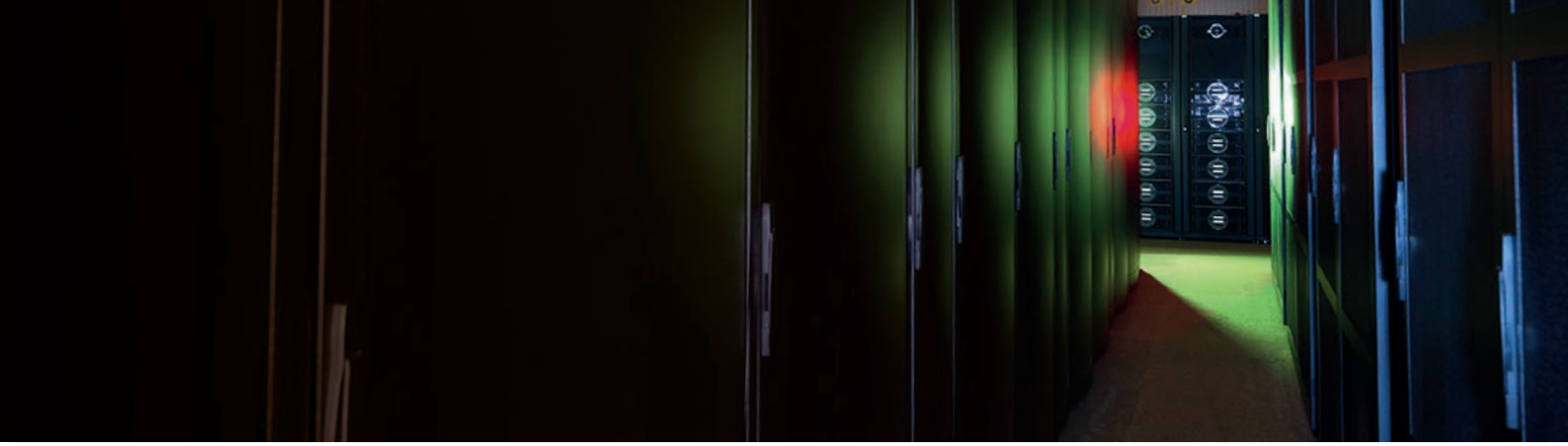
Scalability

Exploiting the potential of new HPC architectures is one of the challenges for the Scalability Programme. In September, the deployment of Phase 2 was completed with the installation of a 32-node cluster using Intel Xeon Phi 'Knights Landing' processors to complement the 34-node NVIDIA graphics processing unit (GPU) cluster installed earlier in the year. The two clusters provide access to the current leading novel architectures and are of a size that allows researchers to run components of the Integrated Forecasting System (IFS) at operational scales. Both systems are available to Member State researchers.

The Programme's success hinges on collaboration across ECMWF and with partners from academia and industry. The Centre's first 'scalability day' in May brought staff together from individual projects within the Programme to share results and plans. Partnerships with Member States, HPC centres and hardware vendors through four EU-funded projects are bearing fruit: ESCAPE, ESiWACE, NEXTGenIO and EarthServer-2 have all passed their first reviews. In 2017, ECMWF will join 15 organisations in a new consortium, EuroExa, using dwarfs from ESCAPE as representative applications.

The Atlas library being developed at ECMWF advanced greatly this year and plays an important role in enabling developments in other projects.

◀ **Inside one of ECMWF's large tape libraries.** All the data in ECMWF's data handling system (DHS) archive resides on tape. The latest tapes can each contain 8.5 terabytes of uncompressed data. The Centre has four main tape libraries, each of which can hold about 10,000 tapes and 64 high-performance tape-drives.



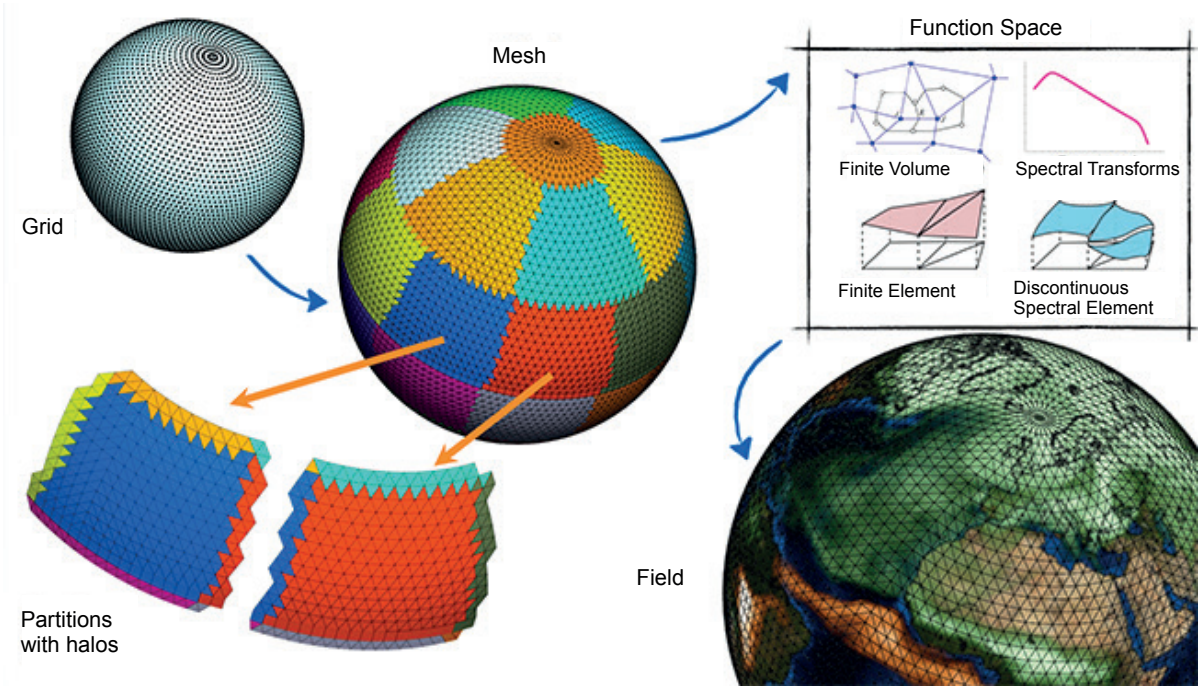
ATLAS—RESPONDING TO EVOLVING HARDWARE

Emerging diverse and complex hardware solutions have a large impact on the programming models traditionally used in NWP software. Furthermore, NWP models are becoming increasingly complex as more Earth system components are introduced, possibly each with different numerical algorithms that could be based on structured or unstructured grids.

In response, ECMWF is developing Atlas, an object-oriented (OO) programming library for developing flexible next-generation NWP models on existing and emerging hardware, such as GPUs.

Atlas provides mesh generation capabilities from a wide catalogue of grids. Through an OO design, the memory layout and parallelisation of fields defined on meshes can be abstracted to accommodate specific numerical methods and hardware implementations.

Atlas is being used in the development of a finite-volume numerical module for ECMWF's IFS, and as a foundation for ECMWF's Meteorological Interpolation and Regridding (MIR) interpolation software. Atlas will be crucial in longer-term IFS developments, exemplified by the ESCAPE project, where it serves as a collaborative framework to develop next-generation building blocks (NWP and climate dwarfs) for NWP and climate models.



▲ One of the ways to keep computational cost down is to find clever ways to arrange the model's grid points. The grid used at ECMWF is shown here for illustrative purposes at a much lower resolution than the operational one. It is designed to work well with numerical methods which may be used in the IFS in the future. The mesh constructed from the grid is partitioned into areas between which information can be exchanged efficiently via 'halos'. Mesh information is combined in alternative 'function spaces' to evolve the physical fields in time.

SUPPORTING **ECMWF**

Accommodation

2016 saw the start of a major project to find suitable long-term accommodation for the Centre, as staff, data and IT requirements outgrow the current facilities in Reading, UK.

In mid-2016, it was decided to hold an open international competition for bids to host the data centre. Proposals were to be compared alongside the solution being considered within the UK. A decision regarding staff accommodation will be taken later and in the meantime, a survey of the current site in Reading is being carried out to assess the work required for continued occupation of that site.

Staff from the ECMWF Copernicus Climate Change Service and Atmosphere Monitoring Service took up occupation of dedicated office space at the University of Reading in spring 2016 and are now well established. The University of Reading site provides a medium-term solution to accommodation needs. Efforts are being made to ensure effective communication and cohesion between staff based at the two sites.

Staff and funding

Complications and uncertainties surrounding the departure of the UK from the EU, including the volatility of exchange rates, are being carefully monitored. In particular, concerns have been raised about the potential impact on the ability to recruit non-UK staff and to procure IT equipment priced in US dollars.

Despite these uncertainties, ECMWF staff have continued to be recognised internationally for their achievements.

▼ **Awards and recognition.** The team in charge of ECMWF's Meteorological Archival and Retrieval System (MARS) received the EMS Technology Achievement Award 2016 (top photo). The MARS system, which began operating in 1987, stores meteorological data and makes them available to the Centre's Member States. Several staff were awarded certificates from the World Meteorological Organization (WMO) for their leadership of and contribution to WMO's work (bottom). This included an award for outstanding work in observing systems for numerical weather prediction. Staff were also awarded prizes from WMO's World Climate/Weather Watch Research Programmes. Last but not least, Irina Sandu was awarded the prestigious WCRP/WWRP International Prize (centre).

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 £43.3 million out of the Centre's £78.5 million funding. External organisations support both core research and the complementary goals of the centre with funding of £29.0 million, while revenue from sales of data and products provide additional income of almost £6.1 million.

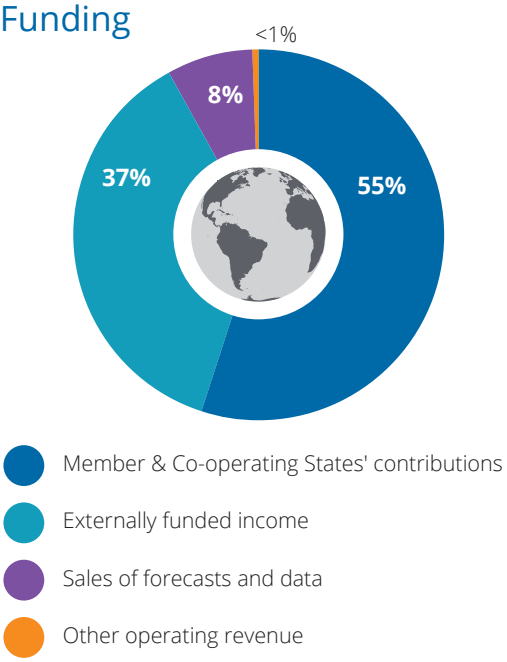
ECMWF continued to invest in its staff, infrastructure and systems to provide the highest quality products to its Member and Co-operating States. The main areas of expenditure are summarised below, and include capital investment of £2.1 million, principally for IT and infrastructure.

The main areas of expenditure related to remuneration and related items (£21.5 million), pension schemes (£7.2 million), computer expenses (£19.0 million) and buildings (£3.7 million). Costs associated with externally funded projects amounted to £22.0 million and net finance costs were £2.5 million.

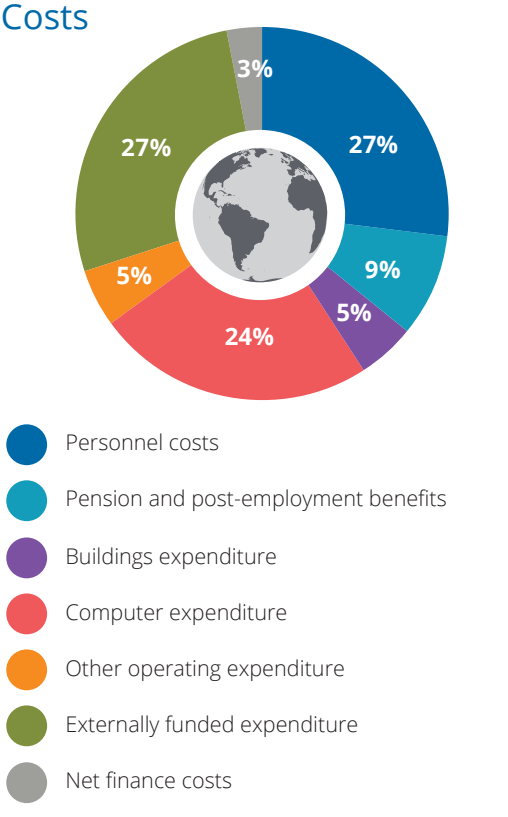
ECMWF's budget remains on a cash basis and the Financial Statements include a reconciliation of the results under IPSAS and in cash terms. Under cash accounting, the Centre generated a surplus of £3.8 million in 2016, which Council subsequently approved for use in the Data Centre project.

Note: all numbers exclude Centre tax.

Funding



Costs



SERVING **MEMBER AND CO-OPERATING STATES**

2016 was another year of ECMWF serving its community by providing world-leading weather forecasts, specialist software, and the largest meteorological data archive in the world. Workshops, seminars and training courses continued to facilitate scientific collaboration and exploration, whilst equipping users with the latest tools.

ECMWF is also serving its community through its contribution to the EU Copernicus flagship programme, which continued to successfully progress. The ECMWF-run Atmosphere Monitoring Service (CAMS) became fully operational, whilst its big sister on Climate Change (C3S) continued its proof of concept with some notable results. ECMWF's contribution to the Emergency Management Service (CEMS), through running the computational centre of the European Flood Awareness System (EFAS) was renewed, allowing the Centre to continue to support Europe's efforts in flood management.

Making deliverables and expertise available

Croatia becoming ECMWF's 22nd Member State in January gave a very positive start to a year marked by intense interaction with the community. Eleven liaison visits to Member and Co-operating States, 13 training courses, 7 ECMWF workshops, 7 hosted events, a hackathon, and our Annual Seminar were some of the platforms providing opportunities for the community to share expertise.

Over 300 people attended both regular and new training courses in 2016, which included modules on meteorology, ECMWF's computing services, and software packages and applications. Our first train-the-trainer version of the 'Use and interpretation of ECMWF products' course covered many of the course's regular topics and was designed to help participants spread knowledge by using their organisations' own channels of training.

Plans for an eLearning programme were finalised, with the first modules to be available in 2017. The initial phase will focus on topics that are most requested by users and used in multiple training settings.

Workshops covered topics including Earth system model design, tropical modelling, and the Earth radiation budget. One highlight was the 'Workshop on High-Performance Computing in Meteorology', attracting over 100 participants and dedicated this year again to scalability. The workshop looked at issues relating to the scalability of NWP codes and the steps required to enable us to use future large-scale heterogeneous computer systems.

CRAY USER GROUP

ECMWF hosted this year's Cray User Group (CUG) conference in London. With 230 people attending, hosting the conference was an opportunity for ECMWF to engage with experts from industry, users of Cray computers and Cray representatives. Delegates shared ideas on how best to use high-performance computing systems and discussed the importance of improving scalability in the area of numerical weather prediction, which will be critical to the success of ECMWF's Scalability Programme.

▼ WMO Secretary-General Petteri Taalas (left) and the President and CEO of Cray, Peter Ungaro, at the CUG 2016.

◀ International experts at the joint ECMWF/WWRP workshop on model uncertainty discussed the latest developments in diagnosing and characterising model error, and building schemes for simulating model uncertainty in assimilation and prediction systems.

▲ The drag processes workshop attracted about 50 participants from the main numerical weather prediction and climate centres in Canada, France, Germany, Japan, the Netherlands, the UK and the US as well as from several universities.

High-impact weather is of particular interest to forecast users, and was the theme of our annual user meeting, 'Using ECMWF Forecasts' (UEF). UEF2016 focussed on verification aspects with some emphasis on measuring the quality of a forecast in a manner that is relevant to users.

'Earth system modelling for seamless prediction' was the topic of the Annual Seminar. Discussions on the processes and the level of complexity required took place against the backdrop of ECMWF's new Strategy, which sees Earth system modelling and assimilation as the way to further improve skill in the 1-day to 1-year forecast range covered by ECMWF forecasts.

New for 2016 was a workshop on 'Drag processes and their links to the large-scale circulation', organised jointly by ECMWF, the World Climate Research Programme (WCRP) and the World Weather Research Programme (WWRP). Participants aimed to assess the current state of our understanding of drag processes and their impact on the large-scale circulation on timescales ranging from numerical weather prediction to climate.

We also strengthened our ties with leading academics and their research groups through our growing Fellowship programme, and welcomed our first WMO Fellow from Vietnam.

Ensuring that data is efficiently accessible to users is a priority, and initiatives are always ongoing to meet this objective. One such example is the RMDCN computer network infrastructure. The system, managed by ECMWF for some of the WMO communities, saw the Basic Package bandwidth for ECMWF Member States doubled to 8 Mbps, at no extra cost.

A new data governance group was created at ECMWF to work closely with Member States and WMO expert teams to minimise the time and effort of introducing new data and to facilitate data format compatibility between ECMWF and international partners. This in turn helps enable cross-cutting collaboration.

ECMWF's Meteorological Archival and Retrieval System (MARS) is the world's largest archive of meteorological data. In March we organised a workshop for MARS administrators, providing Member and Co-operating States with comprehensive information about developments in the MARS software.

ECMWF continues to support the WWRP and the WCRP Sub-seasonal to seasonal prediction project (S2S), most especially through the development and maintenance of the S2S database launched in 2015. The database contains near-real-time forecasts and re-forecasts up to day 60. In 2016, the number of ensembles available increased to 11, and the total volume of archived data reached 35 terabytes. Work is ongoing to add additional ocean variables. The number of users is increasing steadily, with about 740 users from 79 countries registered by the end of 2016. There were up to 80 active users per month, who in 2016 downloaded about 97 terabytes of data.

The S2S database complements the TIGGE database of medium-range ensemble forecasts that ECMWF maintains on behalf of WWRP. The TIGGE archive started collecting data in 2006 and now holds ten years of multi-model ensemble data comprising 1.5 PB, from ten global models, totalling by the end of 2016 more than 5.4 billion fields that are available to the community.

SERVING **MEMBER AND CO-OPERATING STATES**

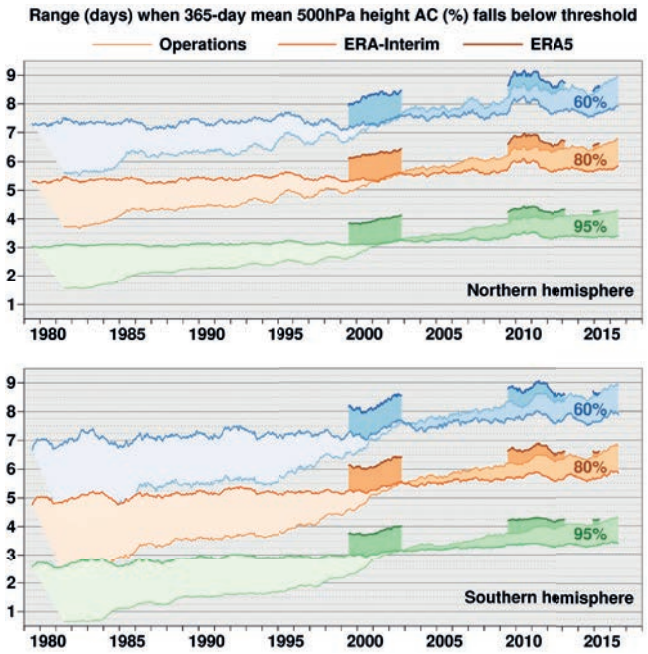
Delivering environmental information

Climate Change Service

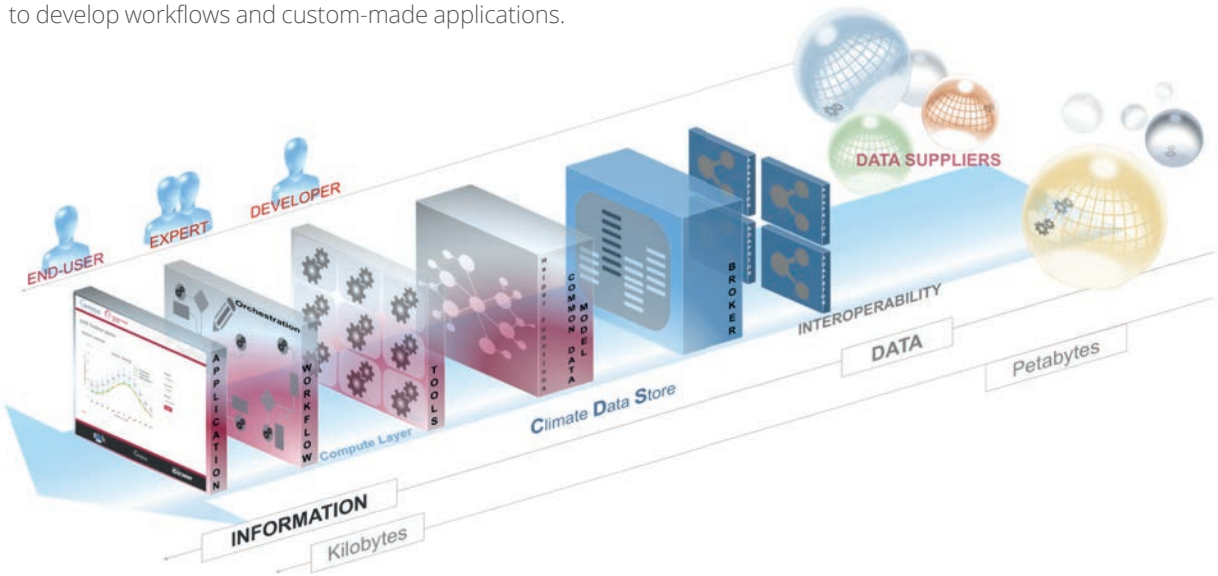
A major development for the ECMWF Copernicus Climate Change Service (C3S) was the launch of a new climate reanalysis, ERA5. By the end of 2016, four separate ERA5 reanalysis production streams were in progress, with approximately 12 years of reanalysis completed. Two months of hourly test data were released to the public in November, highlighting the higher resolution and its information about uncertainties.

C3S launched a new multi-system seasonal forecast service in December. This first operational release of the service provides graphical products based on seasonal forecast data provided by ECMWF, the Met Office and Météo-France. Updated products are published on the C3S website on the 15th of each month.

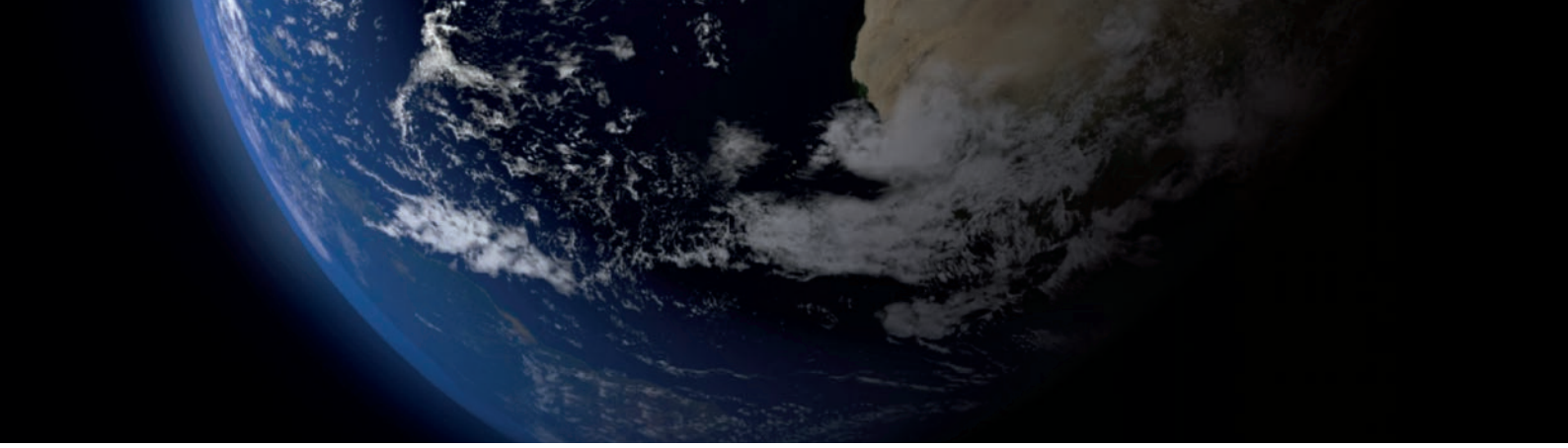
Development of the C3S Climate Data Store (CDS) accelerated in 2016. The CDS is at the heart of the C3S infrastructure, providing information about the past, present and future climate in terms of Essential Climate Variables (ECVs) and derived climate indicators. It is designed as a unified web interface to high-quality climate datasets hosted at various data centres.



▲ **ERA5 production status at the end of 2016.** Skill of forecasts started from ERA5 reanalysis fields compared to those initiated from the ERA-Interim reanalysis and the ECMWF operational system. Note that operational forecasts can only use observations available close to real time, while reanalyses benefit from additional observations collected up to 6 hours after initialisation of the forecast.



▼ **The Climate Data Store (CDS)** will provide access to observations, historical climate data records, Earth-observation-based ECV datasets, global and regional climate reanalyses, global and regional climate projections and seasonal forecasts. It will also provide tools for users to develop workflows and custom-made applications.



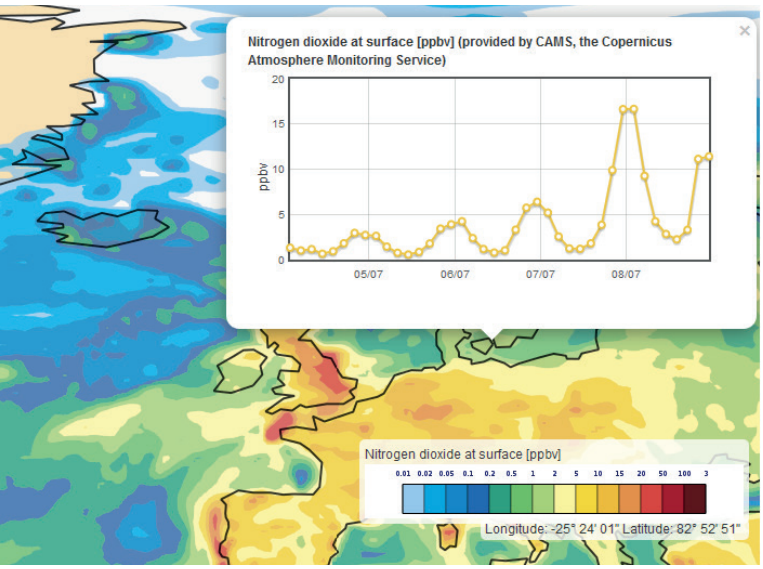
Monitoring the atmosphere

The CAMS global production system, which generates daily analyses and forecasts out to five days, ran continuously throughout 2016. A delayed-mode system also runs a few days behind real time with pre-operational status to generate analyses and forecasts of greenhouse gases. In June, a major upgrade of the IFS configuration used for the CAMS global production became operational. This included a spatial resolution increase from 80 km to 40 km, the introduction of two 5-day forecasts per day, and an improvement in the timeliness of the output data by 12 hours. The system was also fully integrated into the operational environment at ECMWF to benefit from the close monitoring and use of the highly reliable computer infrastructure.

Access to data by users is a priority and the CAMS website has been significantly enhanced, with a new intuitive search engine to help navigate the portfolio of products and the release of 'live maps'. Over 2016, the number of visits to the CAMS website more than doubled.

The CAMS reanalysis system was configured and tested. It started running in the second half of 2016. It will provide a consistent analysis of atmospheric composition over the period 2003 to the present, using a fixed configuration of the data assimilation system. Production of this first CAMS reanalysis is expected to be concluded at the end of 2017 or early 2018. The previous corresponding dataset produced during the MACC and MACC-II precursor projects attracted over 2,700 users worldwide.

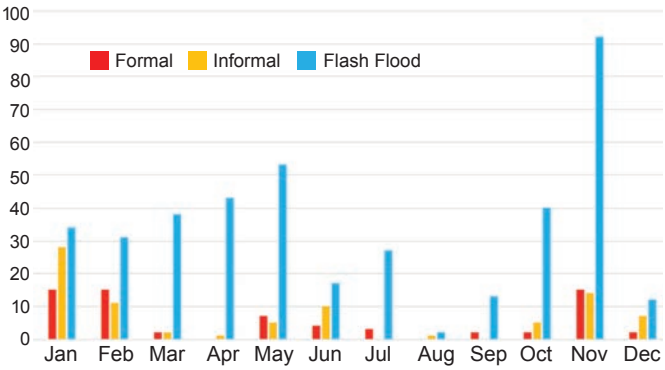
▼ **Interactive maps for main CAMS global products.** This example shows nitrogen dioxide at surface (ppbv) for the Copenhagen area.



Flood forecasting

An exciting and rewarding moment in 2016 was the renewal of the now long-standing partnership between the EU and ECMWF on the European Flood Awareness System (EFAS).

As part of this service, EFAS issues notifications for Europe's emergency agencies and services.



▲ **EFAS notifications in 2016.** 2016 was an active year for flash flood events, with more than 25 flash flood alerts per month in 8 months of the year; November was clearly the most active month with 92 flash flood notifications issued. January, February and November saw the most formal flood notifications issued, while the early spring and late summer were very quiet in terms of flood notifications. In total, 67 formal, 84 informal and 402 flash flood notifications were issued during 2016.

ECMWF also worked closely with the EU and the University of Reading on the Global Flood Awareness System (GloFAS), applying the EFAS concept at a global scale. One highlight this year was the testing of global flash flood warnings. Training was also provided for hydrologists and meteorologists in countries across South East Asia in the use of this global system for transboundary flood forecasting.

HOW WE **WORK**

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

Director-General

OFFICE OF THE DIRECTOR-GENERAL
(Communications, Internal Audit)

RESEARCH DEPARTMENT	FORECASTS DEPARTMENT	COPERNICUS SERVICES DEPARTMENT	COMPUTING DEPARTMENT	ADMINISTRATION DEPARTMENT
EARTH SYSTEM ASSIMILATION	DEVELOPMENT	C3S SERVICE	HIGH PERFORMANCE COMPUTING	FINANCE
EARTH SYSTEM MODELLING	EVALUATION	CAMS SERVICE	NETWORKS	HUMAN RESOURCES
EARTH SYSTEM PREDICTABILITY	PRODUCTION	COPERNICUS CONTRACT MANAGEMENT	OPERATIONS	LEGAL
INTEGRATED FORECAST SYSTEMS	COPERNICUS PRODUCTION	COPERNICUS COMMUNICATIONS	SERVERS AND DESKTOPS	PROCUREMENT
	USER SUPPORT	COPERNICUS USER SUPPORT		PROPERTY SERVICES


Bulgaria


Czech Republic


Estonia


Former Yugoslav Republic of Macedonia


Hungary


Israel


Latvia


Lithuania


Montenegro


Morocco


Romania


Slovak Republic

Co-operating States as of January 2017

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