ECMWF

European Centre for Medium-Range Weather Forecasts

Annual Report 2018

www.ecmwf.int

Member States as of January 2019

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- Belgium
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- Denmark
- Finland
- France
- Germany
- Greece
- Iceland
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- Italy
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- The Netherlands
- Norway
- Portugal
- Serbia
- Slovenia
- Spain
- Sweden
- Switzerland
- Turkey
- United Kingdom

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A new phase

Florence Rabier
Director-General

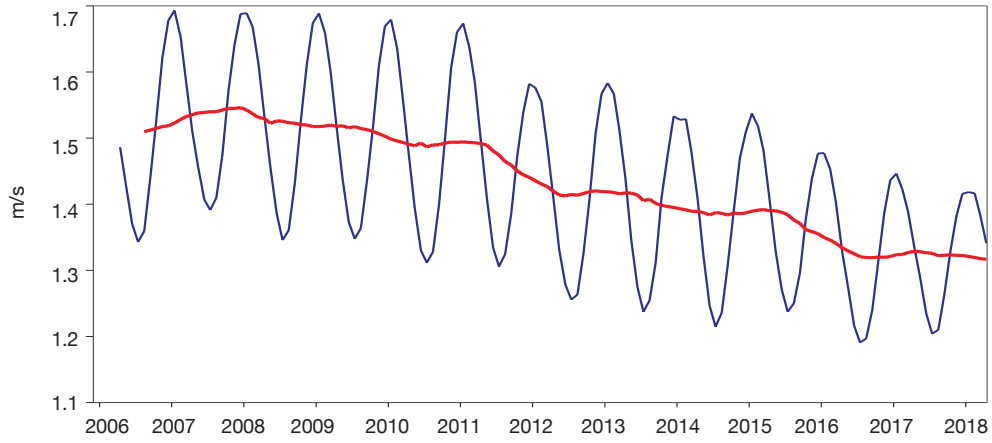
ECMWF has maintained its lead in global modelling, with the ensemble lead time ahead by about one day compared to other global centres in the medium range and by about one week in the extended range.

2018 marked the start of a new phase in ECMWF's life. After the major decision to move our data centre to Bologna was made, the design and implementation plans started in earnest. The year was a bit of a juggling exercise for all, maintaining the scientific and operational standards necessary to continue to best serve our Member States, whilst setting up the framework for a new multi-site operation, defining our high-performance computing (HPC) requirements, and starting to develop plans for our new office accommodation.

The year was marked by noticeable progress towards our Strategy to 2025, with an upgrade of the Integrated Forecasting System in June (IFS Cycle 45r1) bringing seamless coupling to a dynamical 3-dimensional ocean and sea-ice model in all ECMWF forecasts. New continuous data assimilation was developed and tested, allowing the assimilation of observations taken up to one and half hours later than before, as well as an earlier start of the 4D-Var analysis for an identical delivery time. Experimental results for this process, implemented as part of IFS Cycle 46r1 in June 2019, show consistent improvements, translating into a 2 to 3-hour gain in forecast skill. Substantial progress has been made by coupling the complete IFS moist physical parametrizations to the prospective IFS-Finite Volume Module (FVM) dynamical core. The results so far bode well for the future, with the new approach giving us enhanced flexibility to be able to take advantage of evolving HPC architectures. Other areas of progress include a more efficient use of observations, the performance of physical parametrizations linked to the impact of mountains, and the start of a two-year pilot for our European Weather Cloud joint project with EUMETSAT.

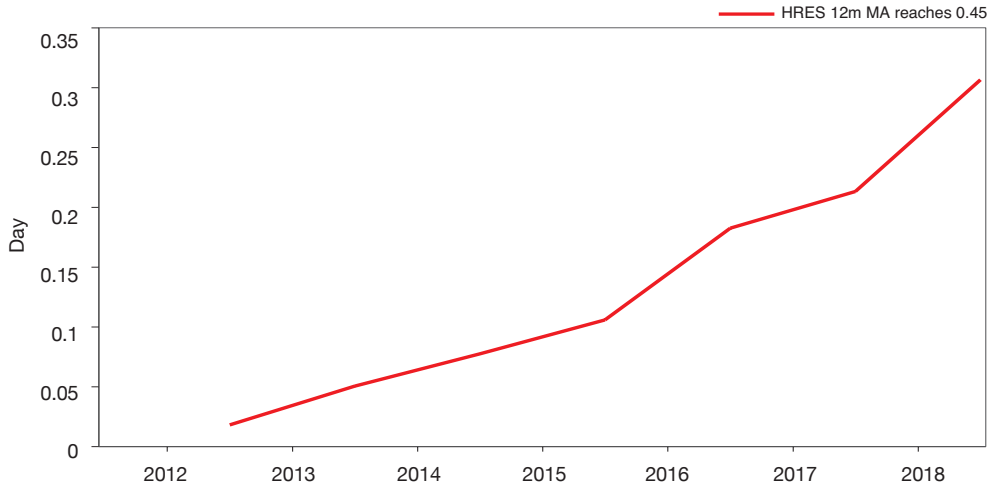
The Scalability Programme continued to fulfil its lynchpin role between science and computing, ensuring that ECMWF and its Member States are best equipped for the architectures of the future.

Our Copernicus activities have been thriving, with reanalyses for climate monitoring (ERA5) and atmospheric composition having been completed, CAMS widely expanding its reach, C3S becoming operational with



Forecast skill – wind

Evolution of forecast skill of ENS 10m wind speed in the northern hemisphere extratropics. The graph shows the CRPS (lower values are better) at day 10. 12-month running averages are shown in red and 3-monthly averages are shown in blue.



Forecast skill – precipitation

ECMWF High Resolution 12 UTC precipitation forecast skill relative to ERA5 has been the highest ever in 2018. Here shown as annual means.

the highly-anticipated release of the Climate Data Store (CDS), as well as the release of our first State of the Climate. GloFAS also became operational and the younger fire and CO2 activities have started to make their mark, including with the first release of operational fire danger forecasts.

It was a year when the staff who make ECMWF showed again not only their talent and skills, but also their resilience in the face of all the changes brought about by the development of the new data centre, and the administrative, reputational and emotional complexities brought about by Brexit.

The older and the younger generations of our scientists deserve credit for meeting, exchanging knowledge, exploring and collaborating with delegates from all our Member and Co-operating States and far beyond to continue to push the boundaries of science. Our gratitude goes to our Fellows, our visiting scientists, our workshop and seminar delegates, our graduate trainees, our Council for supporting and guiding us throughout 2018, and our staff for delivering yet another year of extremely hard and successful work.

June 2019

Bologna

13 November 2018, representatives of ECMWF Member States and the Emilia-Romagna Regione gather at the site of the new data centre in Bologna, Italy to mark the start of the building works.

2018 At a glance

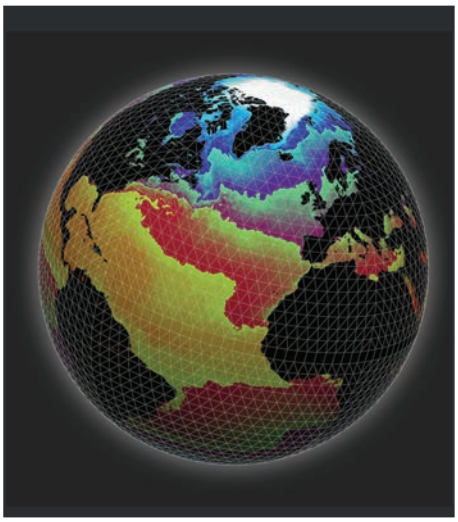
January

Twenty years of 4D-Var at ECMWF

Developing a four-dimensional variational data assimilation system (4D-Var) was one of ECMWF's biggest-ever projects, culminating with its operational implementation in November 1997. A symposium on 26 January reviewed the developments that followed in the 20 years to 2017.

Ocean observations workshop

More than 50 ocean and data assimilation experts met at ECMWF to discuss the way forward for the use of observations of sea-surface temperature (SST) and sea ice in numerical weather prediction (NWP) and climate applications. It was a unique opportunity for ocean, sea-ice and atmosphere experts to exchange information on recent and planned developments in data assimilation, observing systems and observation processing chains.



ECMWF booth at the AMS Annual Meeting

AMS Annual Meeting

ECMWF had a strong presence at the American Meteorological Society Annual Meeting in Austin, Texas, with staff presenting ECMWF's work through 14 talks and 2 poster sessions as well as a booth in the exhibition hall.

First ECMWF Summer of Weather Code

The Centre launched its first Summer of Weather Code (ESoWC) programme, inviting software developers, start-ups, weather professionals and scientists to work with ECMWF to create new and innovative weather-related code. The resulting open-source projects were released in September and will prove useful to ECMWF and its Member and Co-operating States.

February

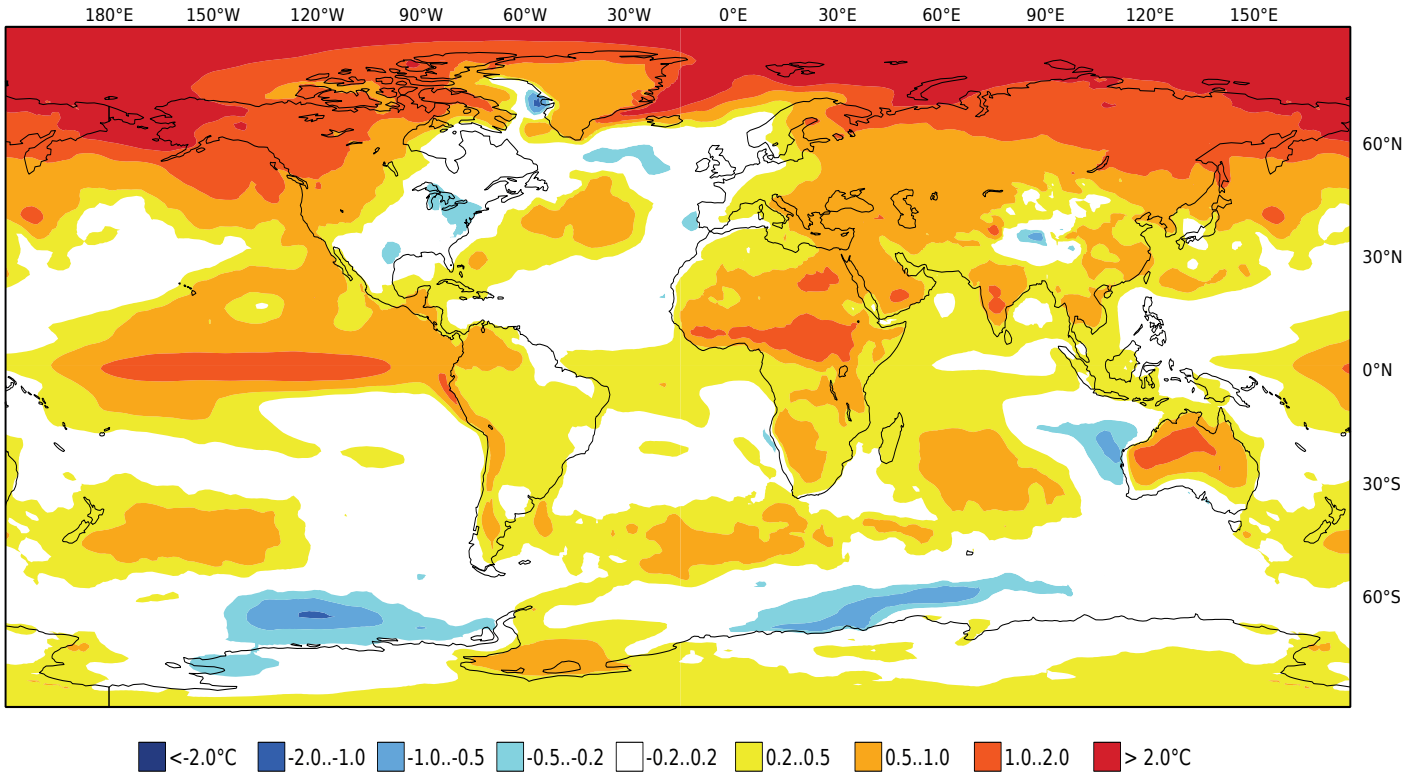
CHE project first General Assembly

ECMWF hosted the first General Assembly of the CO2 Human Emissions project (CHE), which brought together more than 50 experts from Europe and beyond. The EU-funded Horizon 2020 project is coordinated by ECMWF and is working towards an operational capacity to monitor anthropogenic CO2 emissions.

March

Extra radiosonde data from Arctic

Weather data collected by radiosondes in the normally sparsely observed Arctic region were used in ECMWF's data assimilation system. The data were collected as part of the WMO Year of Polar Prediction special observing period. Investigations into their impact on forecasts, conducted at ECMWF for the EU-funded Horizon 2020 APPLICATE project, will help to provide guidance on an optimal observation network for the Arctic.



Example of a C3S multi-system seasonal forecast for mean 2m temperature anomaly

Multi-system seasonal forecasts

The Copernicus Climate Change Service (C3S) multi-system seasonal forecast suite began running fully in operations. The forecasts include data and graphical products for several variables, including air and sea-surface temperature, atmospheric circulation and precipitation up to six months ahead. An upgrade later in the year, in November, saw the number of models increase from 3 to 5, with DWD and CMCC joining Météo-France, the UK Met Office and ECMWF as contributing centres. ECMWF operates the C3S on behalf of the EU.

Atlas software library

ECMWF released the Atlas software library for public use under an open source licence. Atlas is an object-oriented (OO) programming library for the development of efficient numerical weather prediction and climate applications. It is used, for example, in the finite-volume module for ECMWF's IFS and as a foundation for ECMWF's Meteorological Interpolation and Regridding (MIR) interpolation software.

April

European State of the Climate

The EU-funded Copernicus Climate Change Service (C3S) and Copernicus Atmosphere Monitoring Service (CAMS), both implemented by ECMWF, presented the European State of the Climate 2017 at the European Parliament. The report provided an overview of climate indicators for 2017 and the long-term evolution of several key climate variables, such as temperature, greenhouse gases, sea ice, sea level and glaciers.

First operational global flood forecasting system

The Global Flood Awareness System (GloFAS), part of the EU-funded Copernicus Emergency Management Service - Early Warning Systems Floods component (CEMS-EWS Floods), began running in the ECMWF environment, becoming the first operational global flood forecasting system. A major upgrade followed in November. ECMWF is the computational centre for the CEMS-EWS Floods and Fire components.

May

Online Forecast User Guide

The long-awaited, extensively updated edition of ECMWF's user guide was published online at https://software.ecmwf.int/wiki/display/FUG/Forecast+User+Guide. The ECMWF Forecast User Guide helps forecasters and other meteorologists to make the best use of the Centre's forecast products.

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2018 At a glance

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Cycle 45r1 included forecasts of lightning flash density

Using ECMWF's Forecasts meeting

Model upgrade for European flood forecasting system

Continuing a busy period in flood prediction work for the Copernicus Emergency Management Service (CEMS), ECMWF implemented a major upgrade of the operational European Flood Awareness System (EFAS), part of CEMS-EWS Floods. The upgrade included an increase in the geographic coverage of EFAS and improvements in observation processing and hydrological modelling. The new 'Extended Domain' model cycle was co-developed by ECMWF and the European Commission's Joint Research Centre (JRC).

June

IFS Cycle 45r1

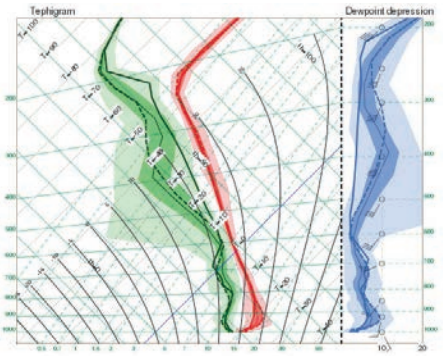
ECMWF's Integrated Forecasting System was upgraded to IFS Cycle 45r1, bringing better global weather forecasts, with particularly consistent gains in the extended range. A key plank of the upgrade was enhanced dynamic coupling between the ocean, sea ice and the atmosphere. It also introduced new products useful in the prediction of severe weather, including forecasts of lightning flash density.

New ensemble vertical profiles

A new product to show the vertical structure of the atmosphere at a point in ensemble forecasts was incorporated into ECMWF's web-based chart-viewing applications. It enables users to examine vertical profiles of the atmosphere anywhere across the globe, at 6-hour intervals, up to a lead time of 120 hours. These can provide considerable assistance with many forecasting challenges, such as predicting cloud layers, layers of instability, precipitation type, wind gust penetration to the surface, and the propensity for supercells to develop.

UEF 2018: 'The only limit is your imagination'

The Using ECMWF's Forecasts meeting (UEF) was attended by a record number of more than 120 participants and focused on imaginative approaches to turning weather data into useful information. A variety of talks showed the use of ECMWF data to support forecasters at national meteorological services in Member and Co-operating States in their duties.



Ensemble vertical profiles of the atmosphere

Climate Data Store and open data hackathon

The Climate Data Store (CDS) was launched by the EU-funded Copernicus Climate Change Service (C3S). It provides access to petabytes of open climate data from the European Commission's Copernicus Programme, including observations, reanalyses, seasonal forecasts and climate projections, and provides policy-makers, businesses, scientists and other users with seamless access to data collections distributed over multiple data suppliers. The CDS and accompanying toolbox were put to the test by over 90 data enthusiasts who attended an open data climate hackathon at the Centre.

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Aeolus in orbit with laser beam

CAMS model upgrade

The global forecasting system of the EU-funded Copernicus Atmosphere Monitoring Service (CAMS) was upgraded to IFS Cycle 45r1. The upgrade introduced observations of NO2 from the GOME-2 instrument onboard the MetOp-A and MetOp-B satellite platforms. Other changes included ozone observations from the Sentinel-5 Precursor satellite in monitoring mode, and several improvements to the aerosol model, resulting in improved sea salt aerosol and an improved representation of secondary organic aerosols.

European fire danger forecasts

ECMWF started the operational phase of the fire danger forecast production. This activity is part of the computational service that ECMWF provides to the EU-funded Copernicus Emergency Management Service – Early Warning Systems Fire (CEMS–EWS Fire). The 10-day forecasts produced feed into the European Forest Fire Information System (EFFIS) and its global extension, the Global Wildfire Information System (GWIS).

July

More data for WMO members

As part of its role as a World Meteorological Centre, ECMWF made available additional data to Members of the World Meteorological Organization (WMO) to help users make better assessments of weather-related risks out to day 10. Additional fields are available from both probabilistic and deterministic forecasts, and all forecasts of weather variables are now provided at 6- or 12-hour time steps instead of 24-hour time steps.

Wildfires in Greece and Scandinavia

The unusually warm and dry summer significantly increased the risk of wildfires, with areas in Greece in particular experiencing devastating wildfire events. The unusual conditions also widely affected the northernmost European regions, with large parts of Scandinavia subject to recurrent fire episodes during the summer. The fire season was widely monitored, with maps from the EU-funded Copernicus Atmosphere Monitoring Service (CAMS) showing the spread of smoke and pollution emitted by wildfires across the

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affected regions. Forecasts from CEMS-EWS Fire, computed by ECMWF, also captured the very high danger of fires 7 days ahead for Sweden and 3 days ahead for Greece.

August

Aeolus satellite launch

The Aeolus satellite was launched successfully by the European Space Agency (ESA). The mission is expected to improve weather forecasts by providing vital information on winds across the globe. ECMWF will process the Aeolus data to provide wind products suitable for use in numerical weather prediction.

2018 At a glance

Director of Research Andy Brown

European heatwave

The late spring and summer of 2018 were among the warmest on record for northern Europe. ECMWF extended-range forecasts predicted warm anomalies weeks in advance. The northerly extent and intraseasonal variability of the heatwave were reflected in forecasts up to two weeks ahead.

September

Typhoon Mangkhut

Super-typhoon Mangkhut hit the Philippines and southern China, causing loss of life, flooding, and extensive damage. Satellite data proved crucial for predicting the landfall on the Philippines. The prediction for the landfall on China was particularly important as it threatened densely populated Hong Kong. ECMWF worked with the Hong Kong Observatory on the evaluation of this event. The difficult elements lay in predicting the re-intensification after passing the Philippines, the interaction with other synoptic features, and the size of the cyclone. The cyclone passed to the south of Hong Kong, but the large radius of the cyclone put the city inside the swathe of extreme winds.

Director of Computing Martin Palkovič

CAMS global atmospheric composition reanalysis

The CAMS Reanalysis dataset for 2003–2016 was released to the public, providing consistent information on aerosols and reactive gases using a fully integrated atmospheric composition modelling system based on ECMWF's IFS.

Annual Seminar on Earth system data assimilation

Nineteen speakers presented progress and challenges in Earth system data assimilation at ECMWF's Annual Seminar, which attracted more than a hundred participants.

HPC Workshop

ECMWF's 18th workshop on high-performance computing (HPC) in meteorology looked especially at scalability and I/O of weather and climate applications on HPC systems. It attracted 113 external participants representing around 60 organisations from ECMWF's Member and Co-operating States as well as from the USA, Canada, China and Japan.

October

New Computing Director

Dr Martin Palkovič joined the Centre to become ECMWF's Director of Computing. He will use previous experience of establishing and managing a supercomputing centre in the Czech Republic and his experience in industry to contribute towards the exciting challenge of moving ECMWF's data centre to Bologna, Italy.

Start of ESCAPE-2 project

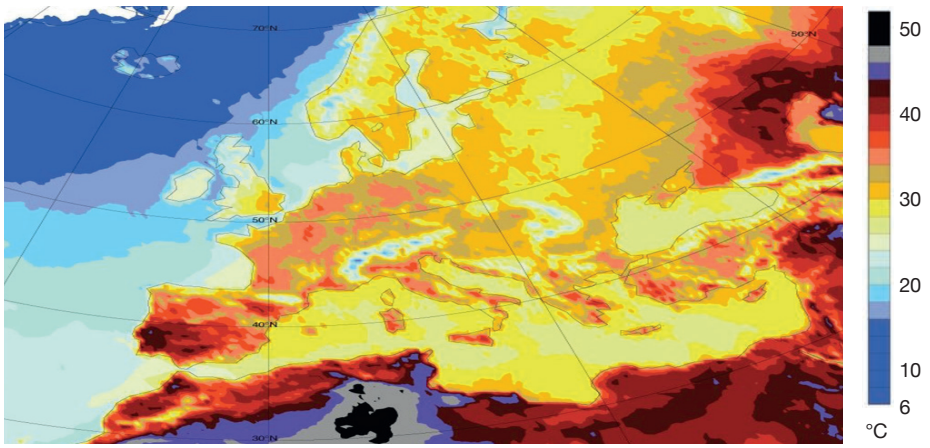
The ESCAPE-2 project on energy-efficient scalable algorithms for weather and climate prediction at exascale was formally launched at ECMWF. The three-year project is coordinated by ECMWF and funded by the European Commission's Horizon 2020 Future and Emerging Technologies for High-Performance Computing (FET-HPC) programme.

Work with WMO on observation monitoring

ECMWF and the World Meteorological Organization (WMO) signed a Memorandum of Understanding to develop the Quality Monitoring Function of the WIGOS Data Quality Monitoring System (WDQMS) to a pre-operational status. The work will benefit the Member States and help to improve the quality of the global observing systems. As part of this, ECMWF will make available an interactive web mapping interface to facilitate the exploration of quality monitoring statistics for conventional observations.

High Frequency Products

Hourly data and 06/18 UTC forecast runs from ECMWF's Boundary Conditions Optional Programme became available to all users holding a real-time licence.



Maximum temperature in Europe, ECMWF analysis between 29 July & 6 August 2018

MIR operational

The Meteorological Interpolation and Regridding package (MIR) was successfully put into operational use after many months of validation.

EFAS output in meteorological archive

The European Flood Awareness System (EFAS), part of CEMS-EWS Floods, started archiving operational hydrological model output in the ECMWF Meteorological Archival and Retrieval System (MARS), making the data more widely accessible to users.

November

HPCF tender and Bologna data centre

An invitation to tender was released for ECMWF's next high-performance computing facility (HPCF), which will be hosted in the new data centre. An event in Bologna on 13 November brought together Member States and representatives from the Emilia-Romagna Region to mark the start in earnest of the building of the new data centre. It incorporated a media briefing, a virtual tour of the facility and architectural plans, and a panel discussion on big data in weather prediction and the Emilia-Romagna region.

Python workshop

In the second workshop of its kind, ECMWF hosted Python experts from around the world to review progress in developing Python frameworks for Earth system sciences. The language is increasingly being used as an interface to interact with ECMWF data and services related to numerical weather prediction and climate science.

Metop-C launch

The Metop-C satellite was launched successfully, completing the EUMETSAT Polar System (EPS) of three polar-orbiting satellites that started with the launch of Metop-A in 2006. The satellite will make a major contribution to the observations available to ECMWF, helping to ensure the continuous supply of crucial data to help initialise numerical weather prediction models.

December

European Weather Cloud

Following preliminary testing, ECMWF's Council approved the development of a two-year pilot run jointly by ECMWF and EUMETSAT. The vision is to set up a federated Cloud Computing infrastructure focused on meteorological data to serve the European Meteorological Infrastructure and its users and customers.

Scientific Advisory Committee members

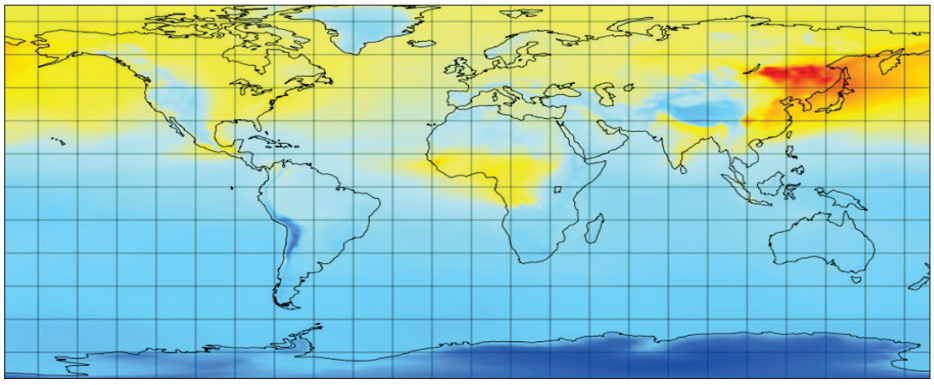
ECMWF's Council re-appointed Prof. Eigil Kaas to the Scientific Advisory Committee for a second term of office and appointed new members Dr Henk Eskes, Prof. Thomas Jung, Dr Chiara Piccolo and Dr Isabel Trigo for a first term of office.

ERA5 climate reanalysis

ECMWF generated datasets for the period 1979–2017 for the ERA5 global atmospheric reanalysis, building up to the official release of ERA5 in 2019 through the EU-funded Copernicus Climate Change Service.

2018 exceptionally warm

Data released by the EU-funded Copernicus Climate Change Service (C3S) showed that 2018 was the fourth in a series of exceptionally warm years. The C3S data show that 2018 surface temperatures were more than 0.4°C higher than the long-term average recorded over the period 1981–2010.



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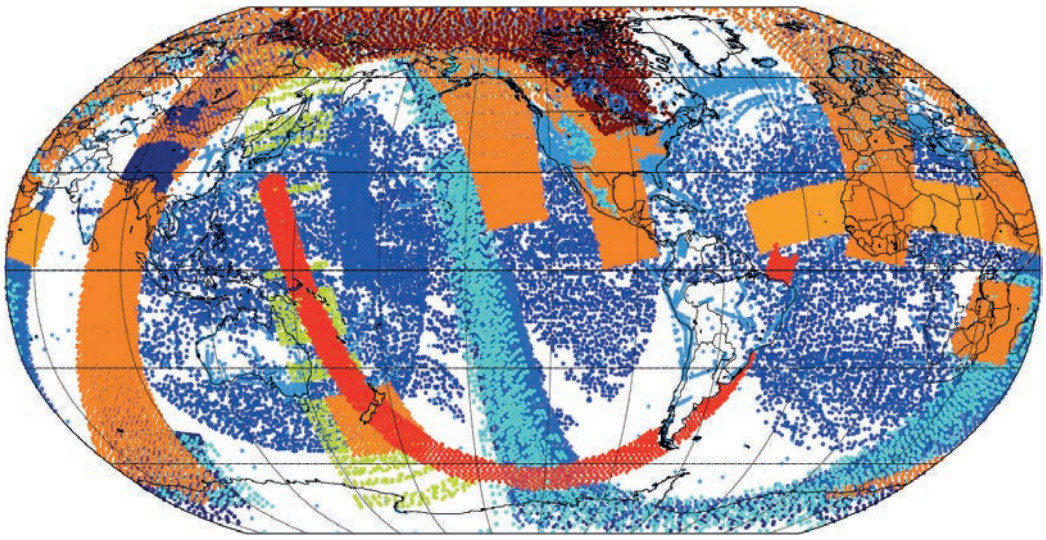
CAMS global reanalysis for carbon monoxide averaged over May 2003.

Advancing weather science



Extra observations

Example of additional observations assimilated in a single continuous data assimilation cycle compared to the current operational setup. They include satellite observations from a large number of instruments as well as in situ measurements.

Continued progress in numerical weather prediction requires sustained, collaborative research in weather observation processing, modelling and computing. Often research efforts in these different areas have to go hand in hand. For example, modelling the atmosphere and other Earth system components at higher resolution requires advances in numerical methods and computing.

ECMWF is well placed to achieve such coordination because its scientists carry out research and development across all areas of numerical weather prediction in close collaboration with partner organisations and fellow scientists across the world.

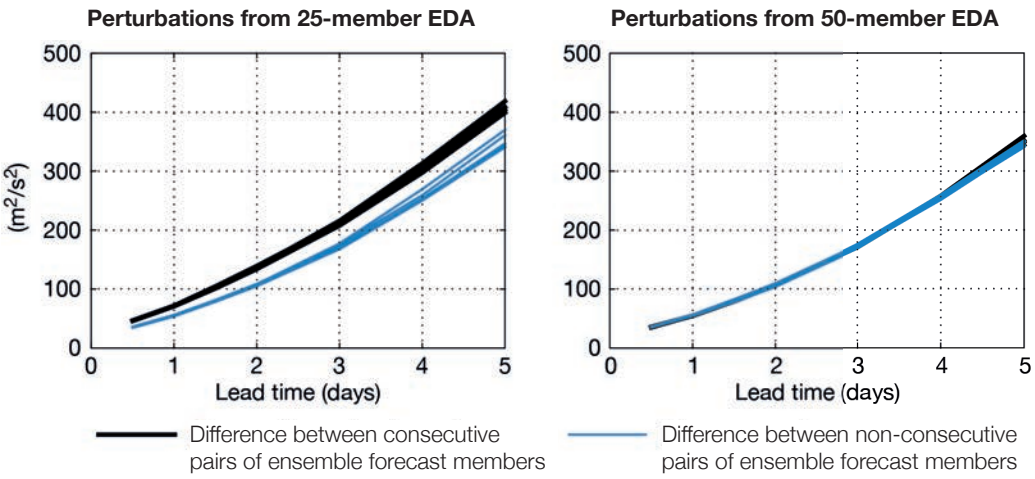
In 2018, several major research projects came to fruition or made decisive progress. Important advances were made in data assimilation and in our understanding of persistent biases in ECMWF's medium-range forecasts of near-surface weather parameters. Progress was also made in ensemble size research, atmospheric composition priorities for numerical weather prediction and work on an alternative dynamical core using the Finite Volume Module.

Continuous data assimilation

Accurate weather predictions rely on an accurate specification of the initial state of the Earth system. Data assimilation combines tens of millions of Earth system observations with model information to arrive at a full set of initial conditions called the analysis. In ECMWF's configuration operational in 2018, by the time the analysis was complete, the most recent observations that had gone into producing it were almost two hours old.

Building on previous work at the Centre and elsewhere, ECMWF scientists developed a revised configuration

> "Accurate weather predictions rely on an accurate specification of the initial state of the Earth system."



◀ Exchangeable ensemble members

The ensemble members produced using the 50-member EDA configuration are exchangeable, as illustrated by these charts of the mean absolute difference of 500 hPa geopotential in the northern extratropics between consecutive pairs of ensemble forecast members and non-consecutive pairs. The plots show the results of an experiment with plus–minus symmetry of the initial perturbations based on a 25-member EDA (left), and of an experiment without such symmetry based on the new 50-member EDA (right). The differences are averaged over a period of 41 days.

of the 4D-Var data assimilation system that enables the analysis to benefit from more recent observations. In the new, more continuous framework, observations taken around one and a half hours later can be assimilated. The change also makes it possible to add another iteration to the data assimilation calculations, thus improving their accuracy.

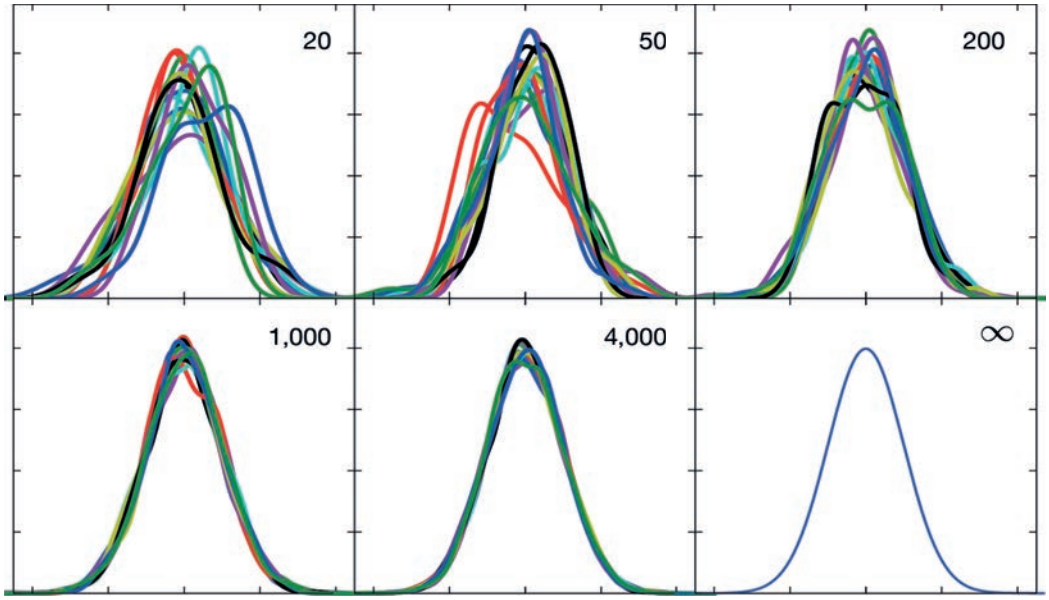
The new data assimilation configuration was found to improve forecast quality significantly. It was scheduled for inclusion in the 2019 upgrade of ECMWF's Integrated Forecasting System to IFS Cycle 46r1.

50-member Ensemble of Data Assimilations

Since 2010, ECMWF has run an Ensemble of Data Assimilations (EDA) to help determine the initial conditions for its forecasts. The EDA is an ensemble of 4D-Var data assimilations that reflects uncertainties in observations, atmospheric boundary conditions and the model physics. It contributes to the high-resolution analysis by providing flow-dependent estimates of the errors in the short-range forecasts used in the data assimilation system. It is also used to determine the perturbed initial conditions for ensemble forecasts: EDA-based perturbations are combined with singular vectors to construct perturbations to the high-resolution analysis.

The year 2018 saw the successful conclusion of work on a new, optimised 50-member EDA configuration that has a comparable computational footprint to the previous 25-member configuration. The increase in ensemble size improves both the high-resolution analysis and the EDA-based perturbations to the initial conditions for the 50-member ensemble forecast. The change also means that ensemble forecast members are exchangeable. Among other things, this will increase the efficiency of research experimentation involving ensemble forecasts. The change was scheduled for inclusion in the 2019 upgrade of ECMWF's Integrated Forecasting System to IFS Cycle 46r1.

Advancing weather science



◀ Probability densities for different ensemble sizes

The probability densities shown here, estimated for ensembles with 20, 50, 200, 1,000 and 4,000 members, illustrate the value of a large ensemble. The underlying true distribution is also shown (bottom right). For each ensemble size, 16 different ensembles were generated from the underlying distribution. The variations among the densities reflect the sampling uncertainty due to the finite ensemble size.

Ensemble size in research

An ensemble forecast is a set of forecasts that represent the range of possible future weather evolutions. The larger the ensemble, the better a probability distribution can be estimated. But research experiments to test new ideas are computationally expensive if the number of ensemble members is high. This can slow down progress: the larger the ensemble, the longer scientists have to wait for the results of their tests.

Work carried out in 2018 showed that some of the most relevant forecast performance scores obtained with a small number of ensemble members can be valid for large ensembles too. This can be achieved by making suitable statistical corrections in the score computation.

An important condition is that ensemble members are exchangeable. In that case, meaningful results for the operational 50-member ensemble can be achieved in tests involving as few as eight ensemble members. These findings can help to speed up progress in numerical weather prediction under the constraint of limited computing resources.

Reducing forecast biases

Investigations carried out in 2018 showed that persistent biases in ECMWF's medium-range forecasts of near-surface weather parameters are closely related to the coupling between the atmosphere and the land surface in the Integrated Forecasting System. They are also related to other processes, such as turbulent mixing, radiation and clouds.

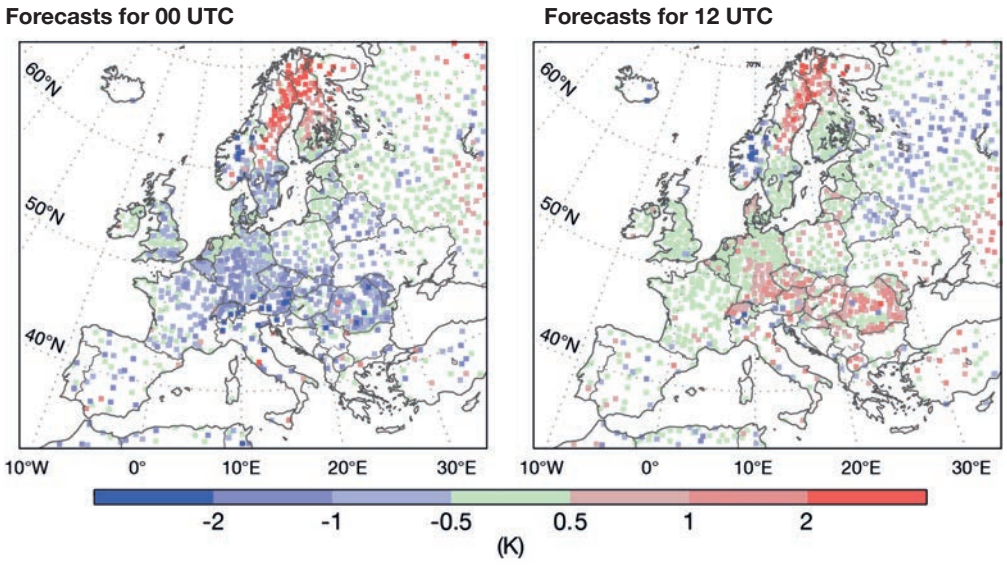
The investigations were part of an ECMWF initiative entitled 'Understanding uncertainties in surface–atmosphere exchange' (USURF), which started in November 2017. Key to making progress was the availability of suitable in situ data from ECMWF's Member and Co-operating States and the development

"Meaningful results for the operational 50-member ensemble can be achieved in tests involving as few as eight ensemble members."

> Key to making progress was the availability of in situ data from ECMWF's Member and Co-operating States and the development of a conditional verification methodology.

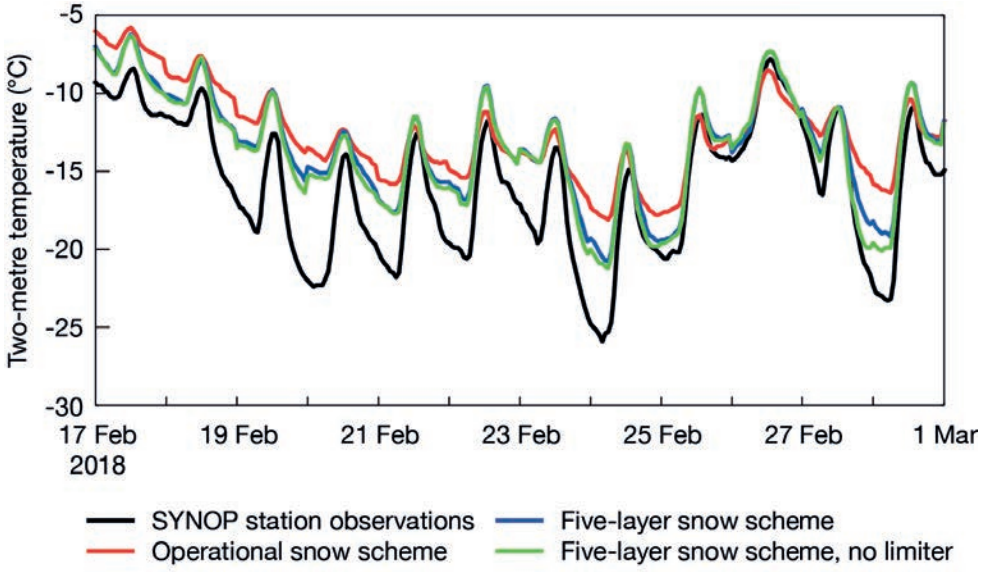
of a conditional verification methodology, which helped to identify specific processes as likely causes of some of the biases. Work in 2018 focused on 2-metre temperature biases in Europe. However, because of the physical links between 2-metre temperature, 2-metre humidity and 10-metre wind speed, investigations have also included some aspects of humidity- and wind-related processes.

The results of the initiative will feed into the operational implementation of a multi-layer snow scheme and an improved land scheme as well as a revised framework for moist processes relying on consistent assumptions and improved coupling between the turbulent diffusion, convection and cloud schemes and the dynamics.



Temperature bias variability

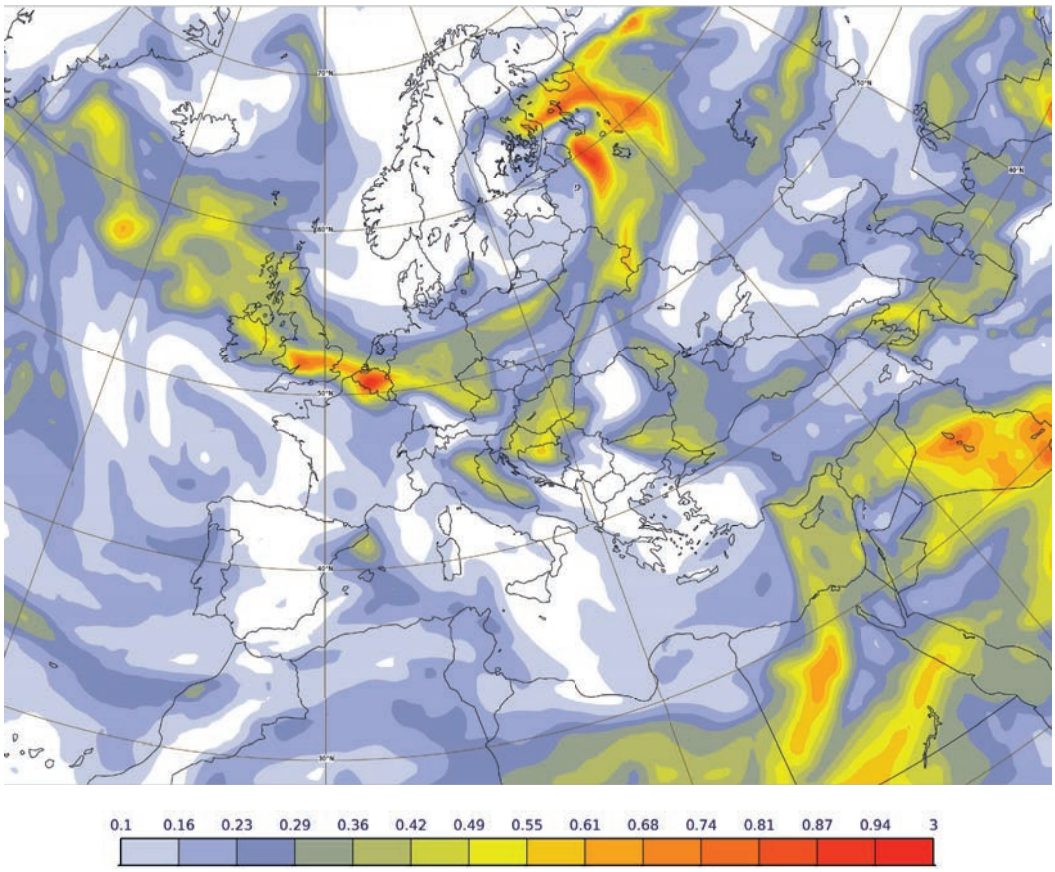
Two-metre temperature biases in the IFS vary according to the time of day as well as by region, as shown in these charts showing the mean error (bias) of the forecast for day 3 in winter 2017/18 (December–January–February) at 00 UTC (left) and 12 UTC (right). Verification was performed against a subset of SYNOP weather station observations.



Experimental snow scheme

Tests showed that a substantial reduction in the 2-metre temperature warm bias in northern Scandinavia can be achieved when using different versions of an experimental multi-layer snow scheme. The tests were carried out for the box 64–70°N, 15–30°E and the period 17 February – 1 March 2018.

Advancing weather science



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Aerosol optical depth

At any one time, the atmosphere contains a mix of aerosols, such as dust, sea salt, biomass burning particles and sulphate, as shown in this example of a CAMS map for aerosol optical depth at 550 nm.

Atmospheric composition priorities

One of ECMWF's strategic goals for 2025 is to develop an integrated global model of the Earth system to produce forecasts with increasing fidelity on time ranges up to a year ahead. This will be achieved through an increased level of complexity of physical and chemical processes as well as of Earth system interactions in the model. Atmospheric composition has the potential to be one of the sources of predictability at different timescales.

A cross-departmental working group on atmospheric composition was set up at ECMWF in spring 2018. It has worked to identify a set of priority developments that have the potential to improve forecasts at all scales, from a few days to seasons ahead.

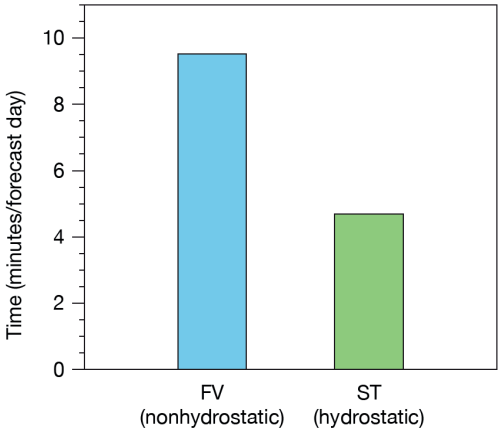
The group made recommendations concerning modelling and data assimilation aspects for ozone, CO2 and aerosols; improving the atmospheric composition numerical infrastructure and code efficiency; and modifying the model performance evaluation process to account for atmospheric composition. In pursuing these objectives, the Centre will be able to leverage some of the capabilities of the Copernicus Atmosphere Monitoring Service (CAMS) implemented by ECMWF on behalf of the EU.

> "Atmospheric composition has the potential to be one of the sources of predictability at different timescales."

Finite Volume Module improvements

Over the next decade, many aspects of ECMWF's Integrated Forecasting System (IFS) may need to change to enable the production of the computationally demanding higher-resolution global forecasts called for by ECMWF's long-term Strategy. The dynamical core lies at the heart of the model infrastructure. It numerically solves the governing equations describing the resolved atmospheric dynamics.

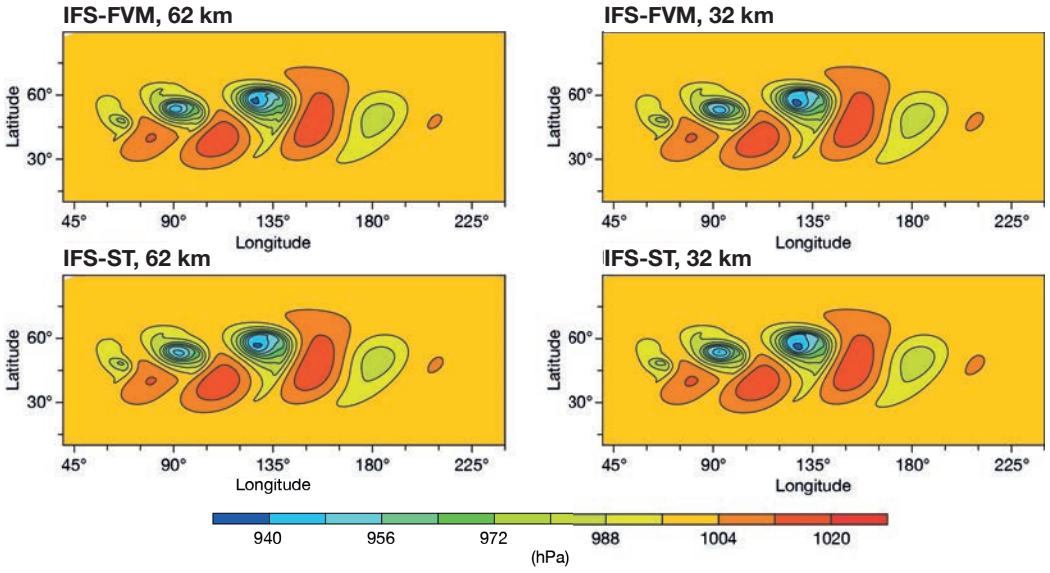
The dynamical core is coupled to parametrizations of small-scale physical atmospheric processes and to models of other Earth system components. The current IFS dynamical core uses the spectral transform method to solve the governing equations. ECMWF is continuing to develop this dynamical core, which also includes a nonhydrostatic option, to make it as computationally efficient as possible.



For added flexibility, it is also developing a new, nonhydrostatic dynamical core which uses the finite-volume method. In 2018, this 'Finite-Volume Module' (FVM) was shown to perform well compared to the current dynamical core in benchmark tests, and its computational cost was reduced substantially. Tests have shown that it holds great promise in terms of computational efficiency for global nonhydrostatic forecasts at high resolution run on future exascale high-performance computing facilities.

◀ Minutes per forecast day comparison

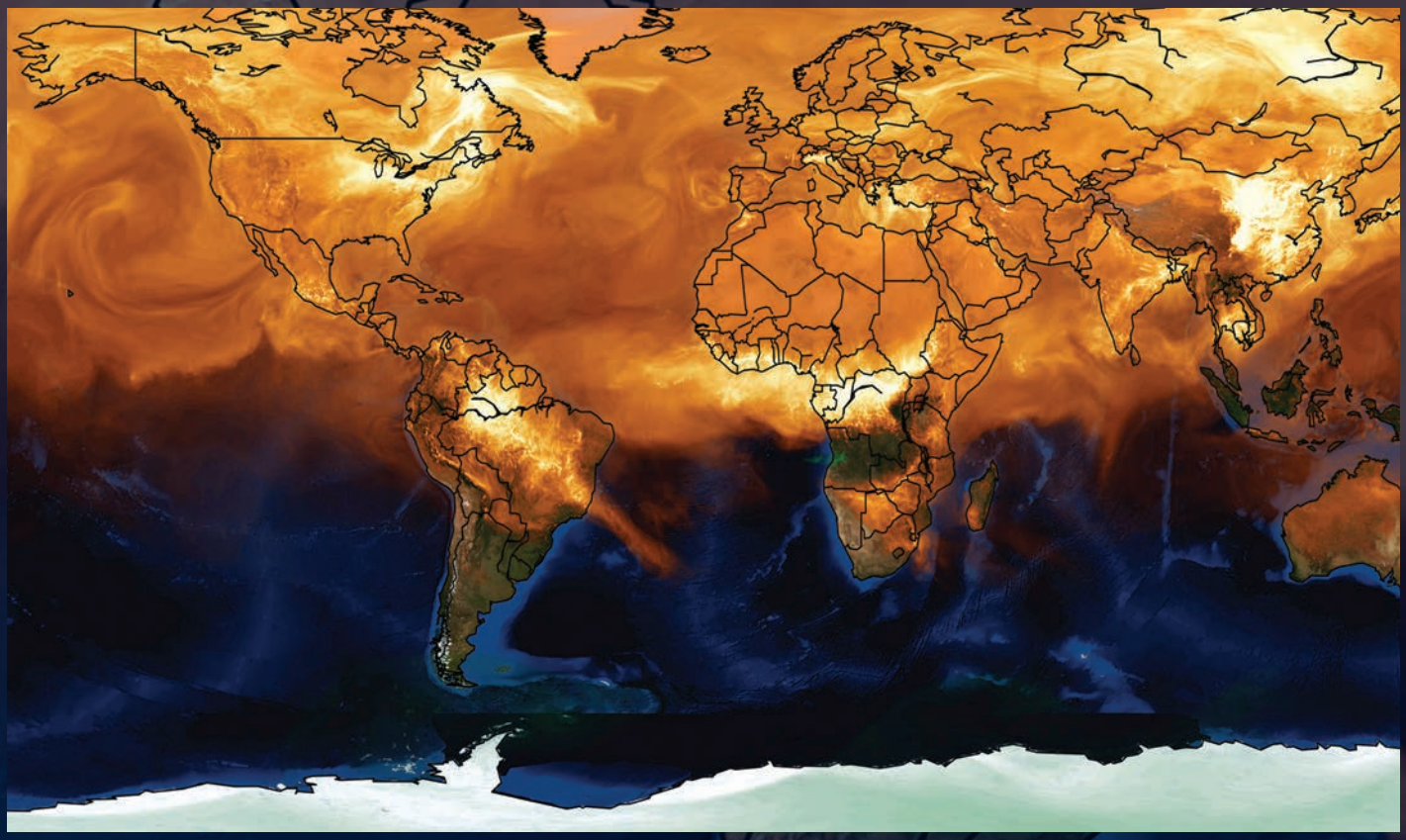
Elapsed time to run one day of the dry baroclinic instability benchmark test similar to the current high-resolution forecast (HRES) configuration using 350 nodes of ECMWF's Cray XC40 supercomputer. Results are for the nonhydrostatic finite-volume (FV) method and the hydrostatic spectral transform (ST) method.



◀ Benchmark tests

One of the tests comparing results obtained using the FVM and the operational spectral transform (ST) method was for baroclinic instability at forecast day 10, showing pressure at the lowest full level for different grid spacings.

CO2 Human Emissions (CHE)



▲ CO2

CO2 concentrations (parts per million) simulated by the CHE project for 12 December 2015, the day the Paris Agreement was adopted. The Paris Agreement aims to strengthen the global response to the threat of climate change and was agreed at COP 21, the 21st Conference of Parties of the United Nations Framework Convention on Climate Change (UNFCCC), held in Paris from 30 November to 12 December 2015.

The ambitious CO2 Human Emissions (CHE) project of the European Commission, coordinated by ECMWF, started in 2017 with the objective to explore the development of a European system to monitor carbon dioxide (CO2) emissions across the world related to human activity. In its second year, the project made noticeable progress towards its key deliverables.

The key requirements that CHE has to meet include isolating emissions related to human activities from other sources of CO2 in the atmosphere; monitoring CO2 emissions from local to global scales; and providing uncertainty estimates. A full prototype for such a system is planned to be available in 2023, with an early version expected in 2021.

The focus of 2018 was on conducting preliminary work towards the development of this prototype, to enable work to start in earnest in early 2019. This included producing global simulations of atmospheric CO2 using the major global sources of fossil fuel emissions along with biosphere CO2 exchanges and their transport.

The project used the capabilities provided by the EU Copernicus Atmosphere Monitoring Service (CAMS) to produce a long "nature run" high-resolution CO2 simulation as well as CO2 ensemble simulations. The ensemble approach was thoroughly tested over the year, with a decision to adopt it being reached at the end of 2018. In that approach, multiple simulations are run with a range of slightly different initial conditions and slightly perturbed surface fluxes and transport. The resulting spread of results gives an indication of the different sensitivities of the observed CO2 variability and the confidence we can have in the data.

At the end of 2018, the project was on track to meet its deliverables, having developed a clear understanding of the basic requirements for the prototype system and in principle knowledge of how to build it, based on climate and environmental reanalysis experiments and enhanced data assimilation adapted to CO2.

About CHE

CHE, as a Coordination and Support Action, brings together expertise from partners in 8 European countries and a consolidated approach to building an operational CO2 emission monitoring capacity. The CHE consortium includes partners from industry, academia, the research sector as well as international organisations. The consortium members are at the forefront of developments in the compilation of emission inventories, the observation of the carbon cycle from ground-based and satellite measurements, the process modelling of the carbon cycle, atmospheric transport modelling, and data assimilation and inversion systems.

The CHE project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no 776186.

Delivering global predictions

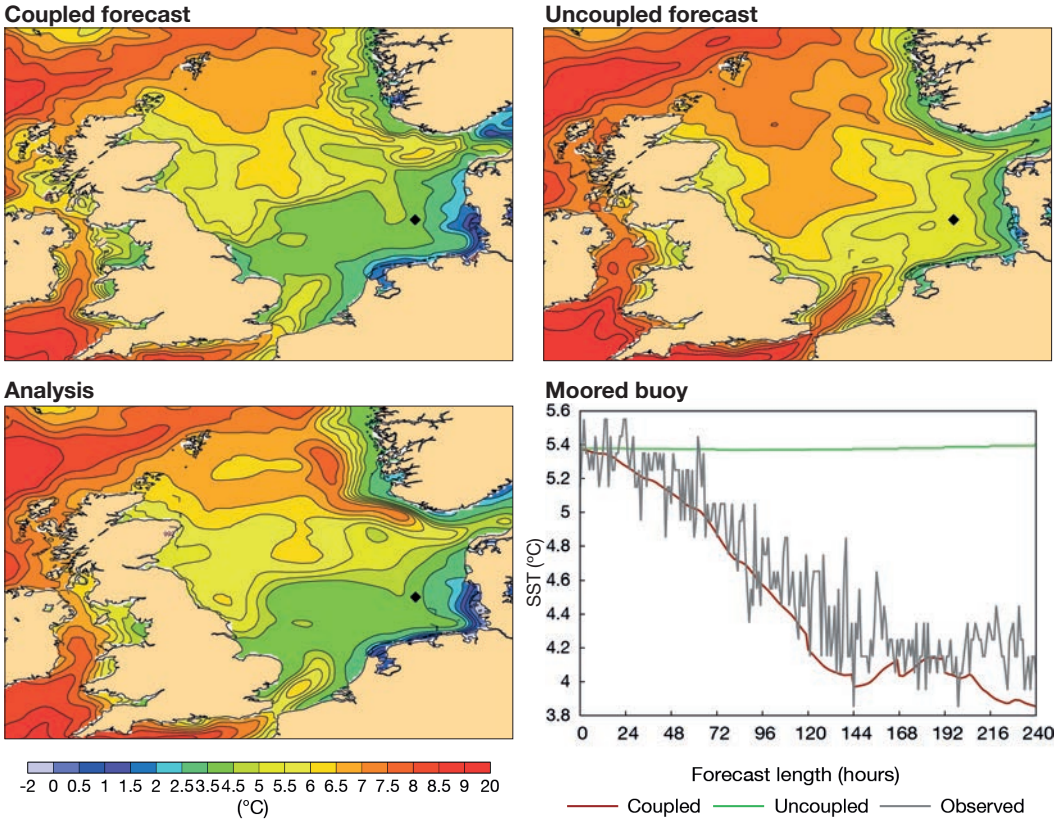
The ultimate test for global weather predictions is their value to society. Several developments in 2018 aimed to maximise the value of ECMWF's forecasts to its Member and Co-operating States and other users.

First among them, ECMWF's high-resolution forecasts followed in the footsteps of its ensemble forecasts by beginning to reflect dynamic interactions between the ocean, sea ice and the atmosphere. The extension of coupling to high-resolution forecasts was introduced as part of an upgrade of ECMWF's Integrated Forecasting System (IFS Cycle 45r1). This and other changes in Cycle 45r1 meant that many aspects of ECMWF's forecasts improved in 2018. Severe weather events, from extreme snow in the Alps to a heatwave affecting much of northern Europe, were predicted well but also highlighted scope for further improvements. New products for lightning and the vertical structure of the atmosphere at a point were made available to support the work of forecasters. Finally, more data were made available to all WMO Members as well as to all users holding a real-time licence.

All forecasts coupled

Including more Earth system components in numerical weather prediction models has the potential to improve weather forecasts because of the interactions of those components with the atmosphere and with each other.

> "Including more Earth system components in numerical weather prediction models has the potential to improve weather forecasts."



North Sea sea-surface temperatures

Predicted sea-surface temperatures for 8-day coupled (top left) and uncoupled (top right) HRES forecasts starting at 00 UTC on 25 February 2018 with the corresponding analysis (bottom left). The bottom-right panel shows the sea-surface temperature evolution of the coupled and uncoupled forecast at the location of a moored buoy, marked with a diamond in the other plots, together with the observed values.

The upgrade of ECMWF's Integrated Forecasting System implemented in June 2018 (IFS Cycle 45r1) brought ocean and sea ice coupling to high-resolution forecasts (HRES) after it had previously been included in lower-resolution ensemble forecasts (ENS).

The change meant that the evolution of ocean and sea ice variables as well as related atmospheric variables in HRES became more realistic. This is for example apparent in the evolution of modelled and observed North Sea sea-surface temperatures during a cold spell in February and March 2018. A coupled high-resolution 8-day forecast was able to predict the observed drop in sea-surface temperatures much better than an uncoupled forecast.

The ocean coupling in HRES also improved predictions of tropical cyclones. For example, the mean absolute intensity error was reduced by about 20% from day 5 onwards. Verification results also showed that using a dynamic sea ice model improves medium-range sea ice predictions, which in turn has repercussions on local 2-metre temperature forecasts.

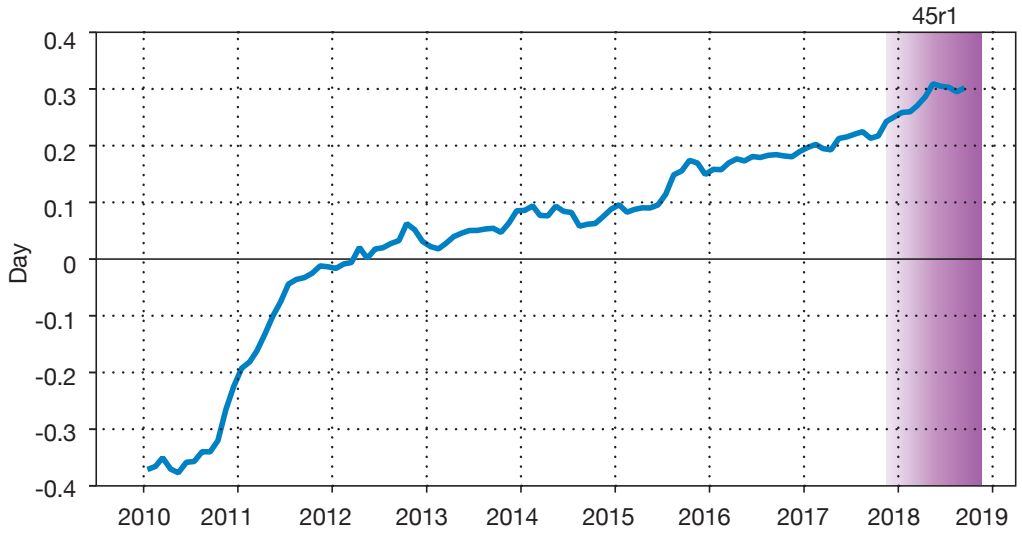
Forecast performance 2018

The skill of ECMWF's ensemble forecasts (ENS) and high-resolution forecasts (HRES) increased in 2018. Part of the increase in skill can be attributed to the upgrade of the Integrated Forecasting System (IFS Cycle 45r1) on 5 June 2018.

In general terms, the upgrade brought improvements in the extratropics for some aspects of the forecast and improvements in the tropics for most parameters. There was an overall improvement in 2-metre temperature in the ENS and HRES, particularly for Europe. Precipitation forecast skill in the HRES increased when compared with a baseline of forecasts based on the ERA5 reanalysis.

Forecasts of tropical cyclones further improved in terms of position, intensity, and speed errors for both the ENS and HRES. The change from La Niña to El Niño conditions in the first half of 2018 was well captured several months in advance. For ocean waves, ECMWF maintained its lead compared to other global wave forecasting systems for forecasts of significant wave height, and its position among the leading systems for peak period.

> "There was an overall improvement in 2-metre temperature forecasts, particularly for Europe."



◀ Lead time gain

The chart shows the difference in lead time, between HRES and ERA5 forecasts, at which the ECMWF SEEPS headline score for 24-hour precipitation in the extratropics drops to 45% (12-month running average values). Above the zero line, HRES skill is better than ERA5 skill. For the years shown, the ERA5 baseline lead time is about four days. The purple shading shows the period during which the influence of IFS Cycle 45r1 on the score grows from 0 to 1.

Delivering global predictions

European heatwave

The late spring and summer of 2018 were among the warmest on record for northern Europe. ECMWF extended-range forecasts predicted warm anomalies weeks in advance. The northern extent and intraseasonal variability of the heatwave were reflected in forecasts up to two weeks ahead. The strongest anomalies occurred in the Baltic Sea region, while the countries around the Mediterranean experienced close to normal temperatures on average.

Looking at composites of weekly anomalies from ECMWF's extended-range forecasts covering the period 7 May to 12 August, the predicted anomalies in week-two forecasts resemble the spatial pattern of the anomalies in the analysis well. Warm anomalies are also present in week-three and week-four forecasts, but they are weaker and the forecasts did not reflect their northern extent.

Further verification shows that week-two forecasts captured intra-seasonal variations reasonably well, while week-three forecasts showed less variation in the predicted anomalies throughout the summer. For example, they failed to give an indication of the warm peak at the end of May or of the break in the warm weather at the end of June, although they gave some indication of the warm period in the second half of July.

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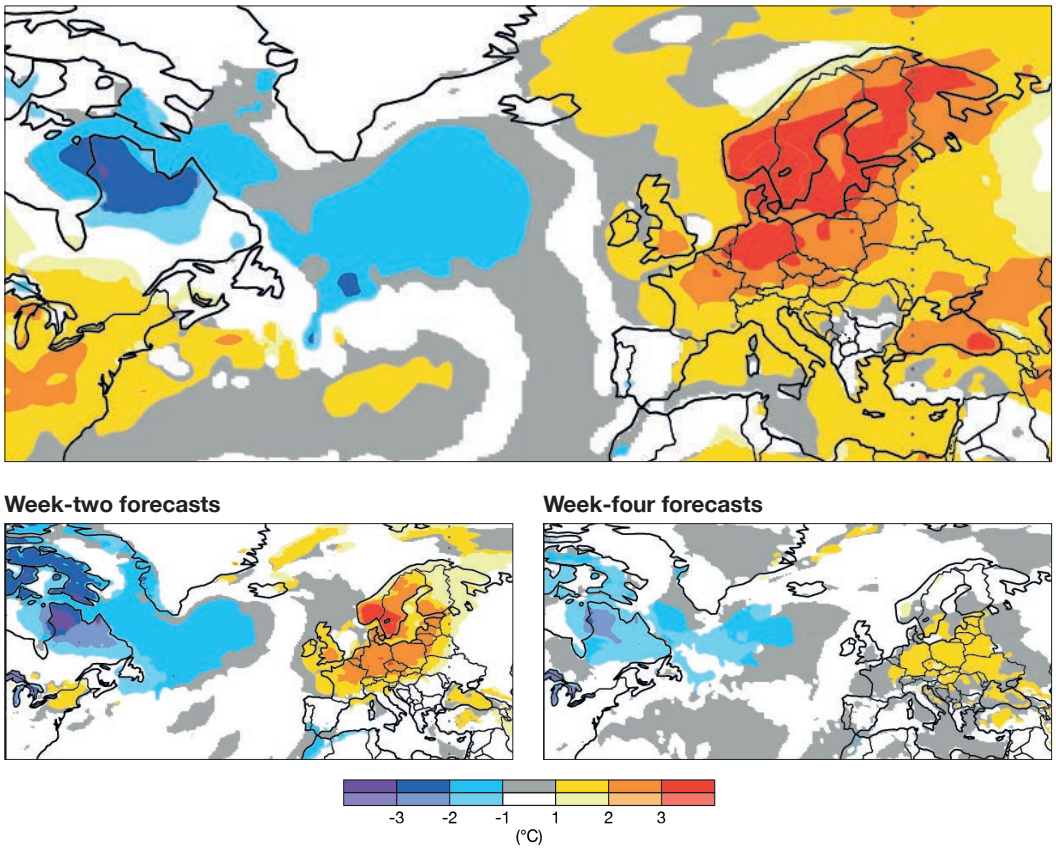
▲ Low river flow

The dry conditions that accompanied the heatwave led to low river levels, such as shown here for the Rhine in August 2018.



◀ Analysis and forecasts of 2-metre temperature anomalies

The plots show ECMWF's analysis of the average 2-metre temperature anomaly 7 May to 12 August 2018 (top) and composites of weekly 2-metre temperature anomalies from extended-range forecasts valid for 7 May to 12 August, based on week-two forecasts and week-four forecasts. Saturated colours indicate significance at the 95% level.

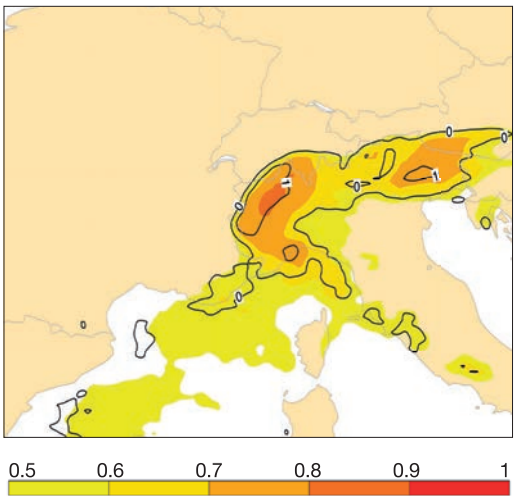
> ECMWF's Extreme Forecast Index for total precipitation showed a signal in the south-western Alps more than a week in advance.

Extreme snow in the Alps

January 2018 saw several episodes of extreme snowfall in the Alps. Up to 3 metres of fresh snow reportedly fell in the south-western part from 7 to 9 January. The ski report for Tignes and Val d'Isère said between 110 and 160 cm of fresh snow had fallen in two days. Road links to several villages were cut by avalanches and tourists were stranded in resorts.

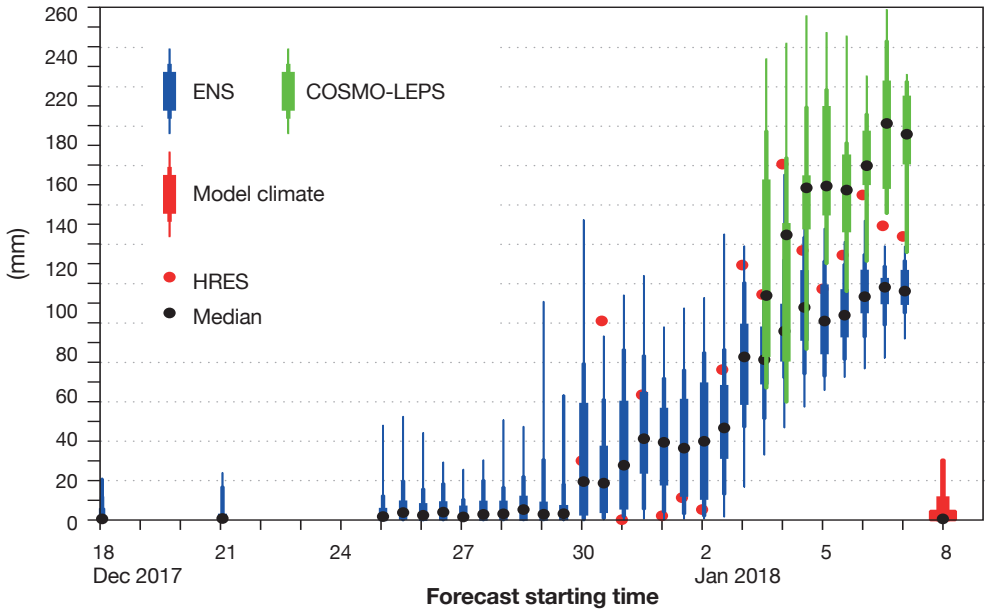
ECMWF's Extreme Forecast Index (EFI) for total precipitation showed a signal in the south-western Alps more than a week in advance. Ensemble forecasts (ENS) starting on 1 January showed a risk of up to 100 mm/48 hours in Val d'Isère for 7–8 January. Between 2 and 3 January, the ensemble forecast became more extreme.

For all forecasts issued from 3 January onwards, the high-resolution forecast (HRES, 9 km grid spacing compared to 18 km for ENS) gave higher two-day precipitation for 7–8 January in Val d'Isère than the ensemble median. Such differences can be expected in steep terrain. The limited-area COSMO-LEPS ensemble with 7 km grid spacing from ARPA-ER SIMC in Italy predicted even higher precipitation accumulations.



Extreme Forecast Index (EFI) and Shift of Tails (SOT)

EFI (shading) and SOT (contours) for three-day total precipitation from 7 to 9 January in the forecast from 1 January.



Ensemble forecasts for Val d'Isère

Total precipitation for Val d'Isère on 7 and 8 January 2018 as predicted by forecasts from different initial times. The box-and-whisker symbols show the 1st, 10th, 25th, 75th, 90th and 99th percentile.

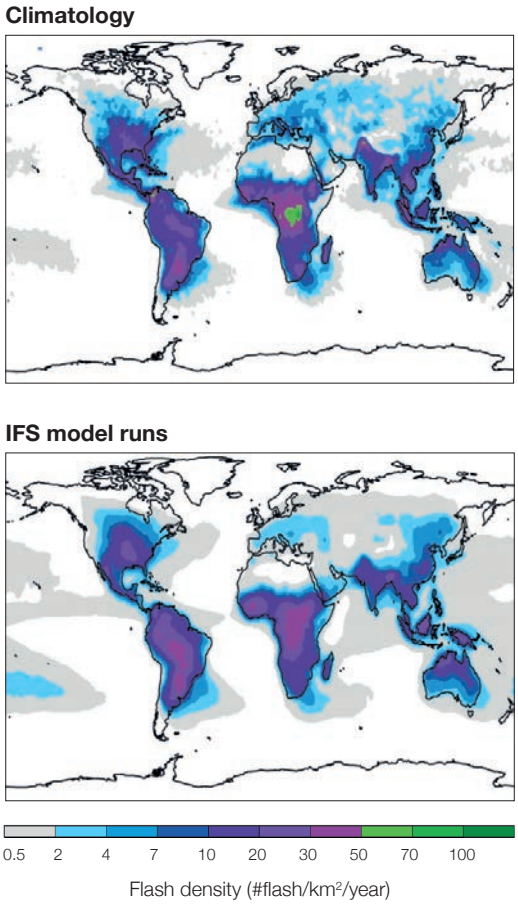
Delivering global predictions

New products

Lightning can trigger wildfires; disrupt air traffic; cause power supply outages or power surges; damage buildings; and even lead to fatalities. In June 2018, a new forecast product for lightning density developed at ECMWF was made available as part of the upgrade to IFS Cycle 45r1. Experiments had shown that ensemble forecasts for lightning can have useful skill to at least day 3. The discrete and random nature of lightning makes it particularly suitable for the probabilistic predictions provided by ensemble forecasts.

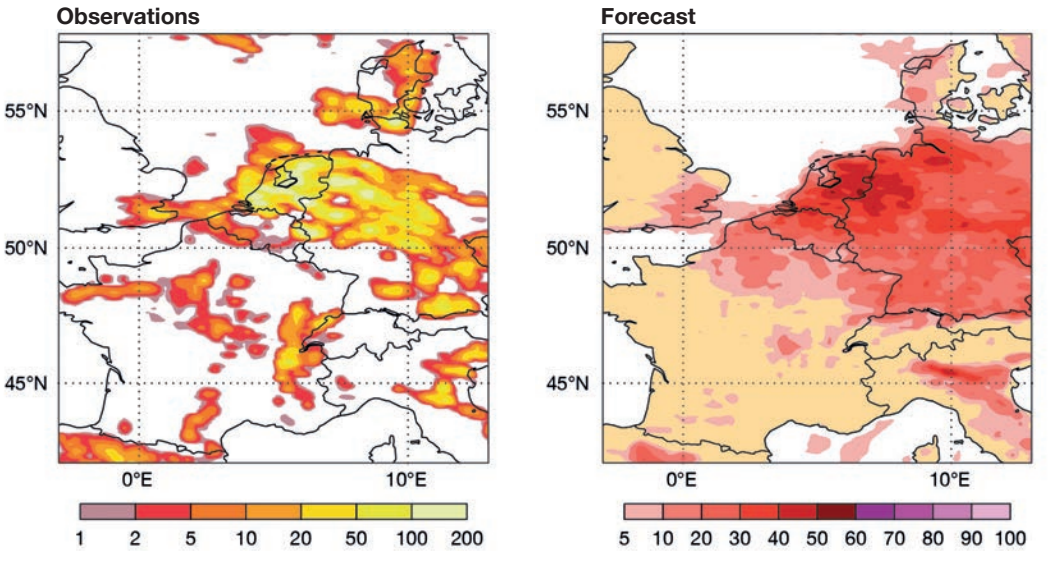
Also in June 2018, a new product to show the vertical structure of the atmosphere at a point in ensemble forecasts (ENS) was incorporated into ECMWF's web-based chart-viewing applications.

Users can now examine vertical profiles of the atmosphere anywhere across the globe, at 6-hour intervals, up to a lead time of 120 hours. Such profiles can support the prediction of cloud layers, layers of instability, precipitation type, wind gust penetration to the surface, and more.



◀ Annual mean lightning flash densities

The lightning parametrization in the IFS has been designed to achieve a good match between a climatological distribution of lightning flash densities based on satellite observations (NASA's LIS/OTD Gridded Lightning Climatology 1995–2010) and ten one-year-long IFS model runs.



◀ Observed and predicted lightning density

The charts show observed lightning density from the UK Met Office ATDnet lightning detection network in flashes per 100 km² per day from 29 May 2018 (left) and the probability of lightning density exceeding 10 flashes per 100 km² per day in ECMWF's forecast from 25 May (right).

> In 2018, ECMWF substantially increased the amount of weather prediction data it makes available to WMO Members.

Wider forecast availability

In July 2018, ECMWF substantially increased the amount of weather prediction data it makes available free of charge to Members of the World Meteorological Organization (WMO). For example, all forecasts of weather variables are now provided at 6- or 12-hour time steps instead of 24-hour time steps. The provision of the data is part of the Centre's obligations as a World Meteorological Centre (WMC). ECMWF became a WMC in June 2017.

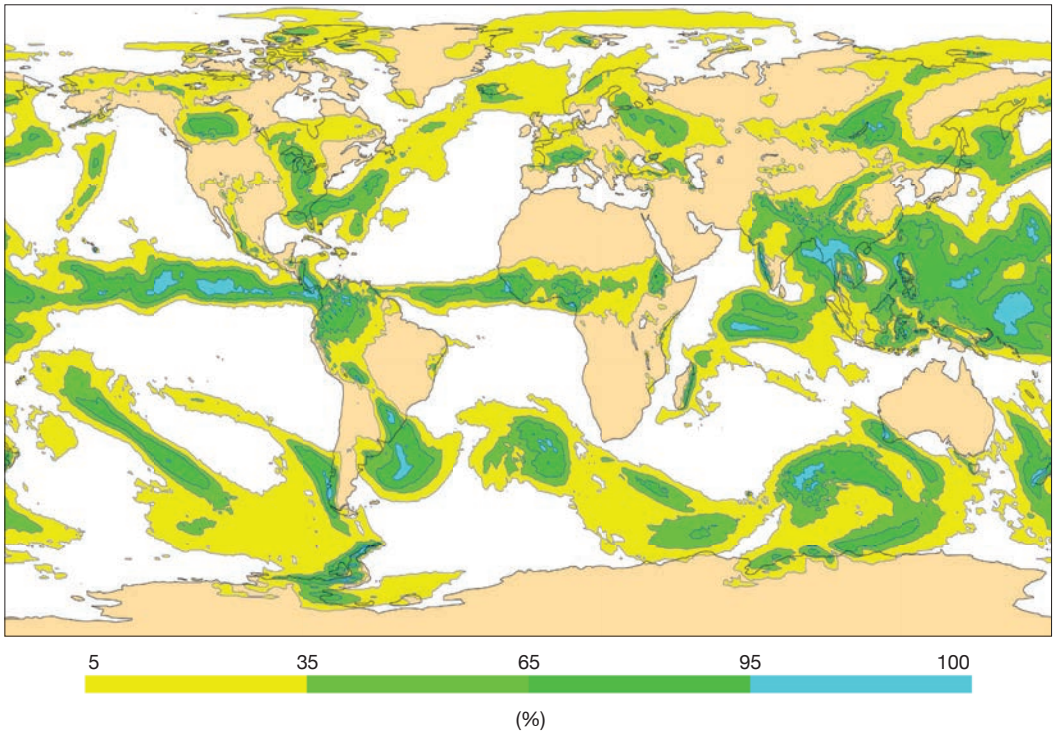
Higher-frequency products

In October 2018, ECMWF made hourly data and 06/18 UTC forecast runs from its Boundary Conditions Optional Programme available to all users holding a real-time licence, upon request. The change applied to both the single high-resolution forecast (HRES) and the ensemble forecast (ENS).

Until then, many users had interpolated the three- and six-hourly data they received from ECMWF to provide hourly weather forecasts. The introduction of hourly time steps and more frequent forecasts reduced the requirement for interpolation and made the hourly forecasts more accurate.

◀ Hourly forecast data

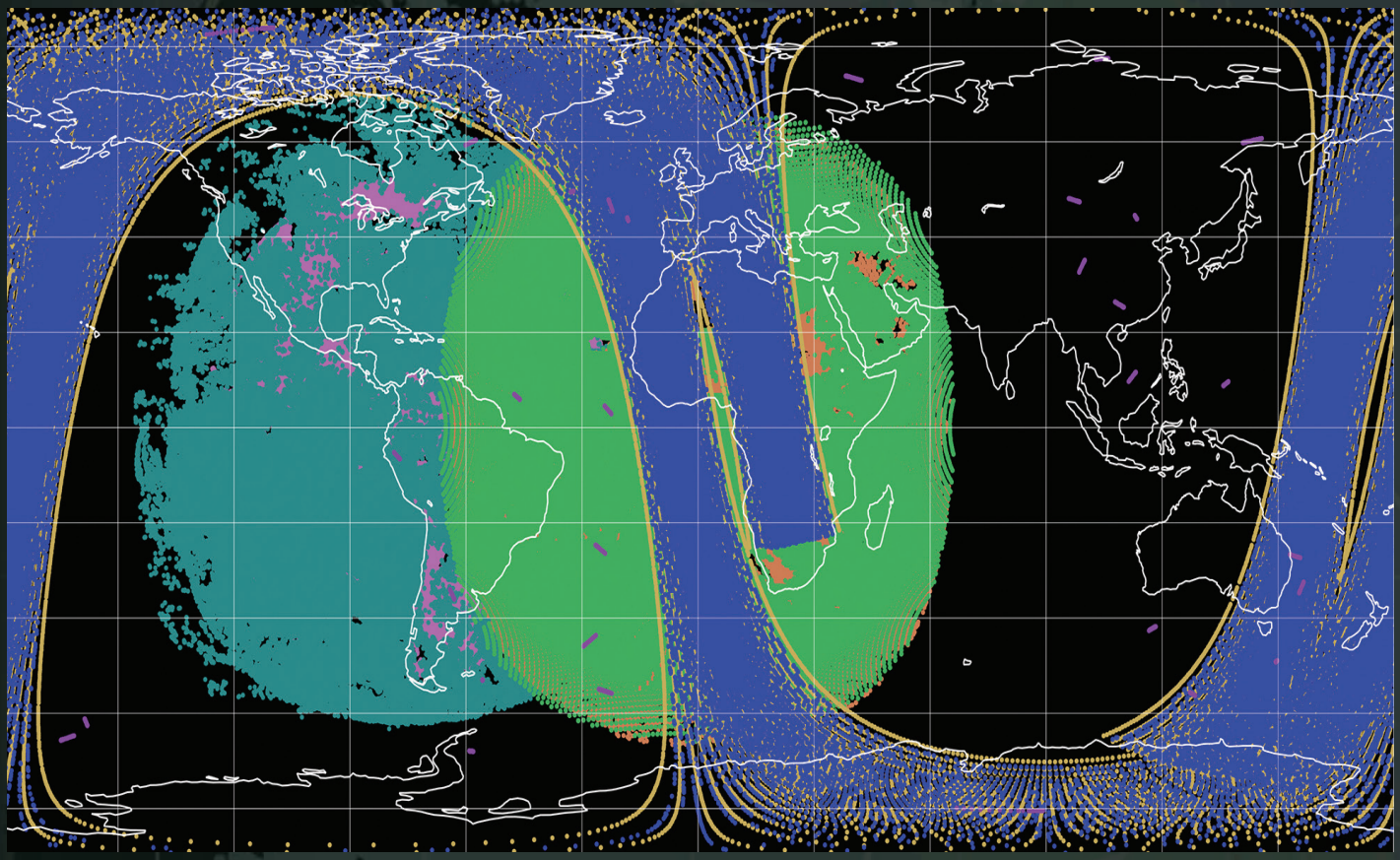
Weather does not change in three- or six-hour time slots. Hourly forecast data thus provide greater accuracy than three- or six-hourly data.



◀ New probability thresholds for WMO Members

The extra data available to WMO Members include forecasts based on new probability thresholds for total precipitation. The chart shows the probability of total precipitation exceeding 5 mm over 24 hours, according to a five-day forecast for 12 UTC on 21 July 2018.

Observations



▲ Observations

Six-hour coverage of additional satellite data activated in 2018. The table right shows new observations activated in the operational ECMWF assimilation system in 2018.

Accurate and timely weather data from across the globe are crucial for numerical weather prediction since they help to determine the initial conditions from which forecasts start.

ECMWF works with the World Meteorological Organization (WMO) and observation providers around the world to investigate all opportunities for new observations and advance efforts to make the best possible use of the data.

2018 was rich in developments to improve the use of existing and new observations. Our forecasting system upgrade enabled the use of more satellite observations over land and sea ice and introduced a scheme to account for the horizontal drift of radiosondes during their ascent. We also saw promising results for the prospects of extracting even more value from radiosondes by using data collected as the radiosonde descends.

In a world first, scientists at the Centre successfully demonstrated the feasibility of assimilating space-borne radar and lidar observations directly into a 4D-Var assimilation system on the global scale, paving the way for the use of data from ESA's future EarthCARE satellite.

New satellites launched in 2018 will make a valuable contribution to the global observing system.

ESA's Aeolus satellite, launched in August, is the first to acquire profiles of the wind on a global scale. ECMWF has been closely involved with the mission right from the design phase. Of particular note in 2018 was ECMWF's direct involvement in the Aeolus ground segment, resulting in the first production of level-2 wind data from Aeolus less than two weeks after launch. The new near-real-time data from this satellite is expected to lead to improvements in determining the state of the atmosphere in the tropics.

A further boost to the observing system came with the launch of EUMETSAT's Metop-C in November. Metop-C will provide information on temperature and humidity, atmospheric composition, the ocean and the land surface which can be used for climate studies and weather prediction.

Additional satellite observations were activated in the operational ECMWF assimilation system in 2018 (see table). Operational use is the result of in-depth research and testing in collaboration with partners.

In partnership with the US National Oceanic and Atmospheric Administration (NOAA), we began assimilating radiance data from GOES-16 in July 2018, before the official product was due to become available. This satellite gives vital information on severe weather events such as storms, hurricanes and wildfires.

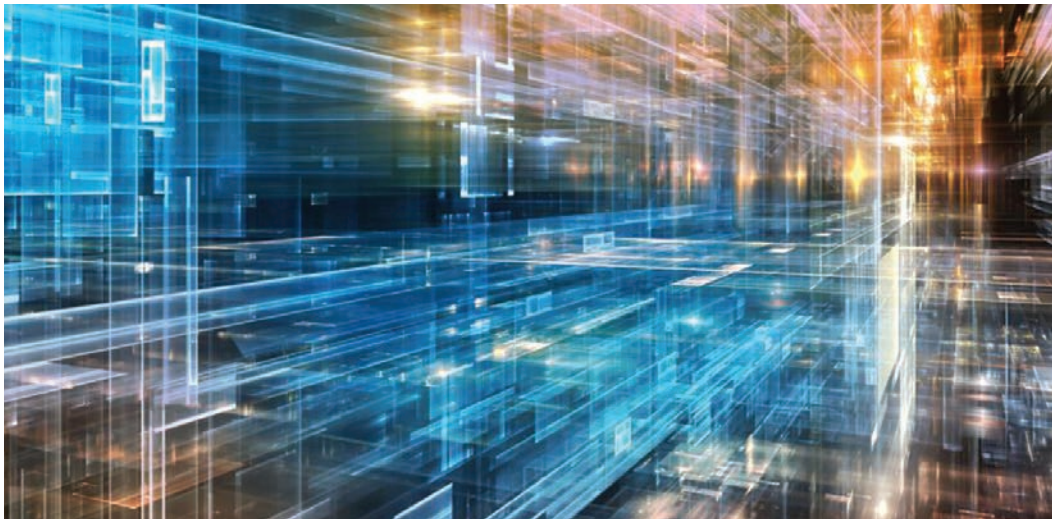
Atmospheric composition data from ESA's Sentinel-5P satellite brought major benefits for the monitoring and prediction capabilities of the Copernicus Atmosphere Monitoring Service (CAMS), implemented by ECMWF on behalf of the EU. The TROPOMI instrument measures radiation at different wavelengths at the top of the atmosphere, providing information on the amount of ozone, carbon monoxide, nitrogen dioxide, sulphur dioxide, formaldehyde and methane in the atmosphere.

Through work with INPE in Brazil, we started to receive radiosonde data from INPE's Antarctic ship campaign and provided support to ensure the data became available to all Member and Co-operating States through the WMO Global Telecommunication System (GTS).

We also contributed to field campaigns such as the 'Atmospheric River Reconnaissance' campaign over the eastern Pacific, which collected information on storm characteristics and provided data that ECMWF could use for diagnostics and to further our understanding of atmospheric predictability.

OBSERVATIONS	MAIN IMPACT
Atmospheric Motion Vectors from Meteosat-11 (replacing Meteosat-10)	Tropospheric wind and humidity
All-Sky Radiances from Meteosat-11 (replacing Meteosat-10)	Tropospheric wind and humidity
Radio occultation bending angles from GNOS on FY-3C	Temperature in upper troposphere/lower stratosphere
Radiances from ATMS on NOAA-20	Temperature, humidity, dynamics
Radiances from CrIS on NOAA-20	Temperature, humidity, ozone, dynamics
Atmospheric Motion Vectors from GOES-16 (replacing GOES-13)	Tropospheric wind
Clear-Sky Radiances from GOES-16 (replacing GOES-13)	Tropospheric humidity and wind
Significant wave height from JASON-3 and Sentinel-3A altimeters (not shown)	Ocean waves

Sustaining high-performance computing



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The Centre's Strategy says that by 2025 ensemble forecasts should use a much smaller grid spacing than the current 18 km. Data assimilation methods will need to follow suit to provide accurate initial conditions at such scales. To make this possible, the Centre's next high-performance computing facility (HPCF) will have to be significantly more powerful than the current one. Much of the groundwork for a new HPCF was laid in 2018. The process started when Council approved the budget for the next generation of supercomputers at its December 2017 session.

The project, known as HPC2020, kicked off with a request for information to vendors as part of the business case aiming to ensure that we will get the most suitable technology and best value for money. We also started to set up a framework contract to purchase the computer storage systems that will support both the headquarters in Reading and the new data centre in Bologna. The invitation to tender for ECMWF's next HPCF was released on 12 November 2018.

The increase in power will have to go hand in hand with efficiency gains resulting from the Scalability Programme. It aims to promote an integrated approach to code development with active participation from ECMWF Member States – through membership in programme and project boards, and direct partnership in internal and externally funded projects. The EU-funded ESCAPE project is part of it and was brought to a successful conclusion in 2018, while other EU-funded scalability-related projects got under way, such as ESCAPE-2, EPiGRAM-HS and MAESTRO.

As part of ESCAPE, 2018 saw demonstrations of efficiency gains for selected model components ('dwarfs') on a range of processor architectures (CPU, GPU, optical processors). It was also possible

to demonstrate efficiency gains for product generation on Intel 3d-xpoint NVRAM technology. After four years of progress, it was time to envisage the next stage for this ambitious programme, and its different strands were brought together under the banner 'ExtremeEarth'. This programme will build upon expertise from its consortium members as well as national and international partners to deliver application-orientated solutions to the environmental extremes affecting the planet today. The aim is to use extreme computing to tackle environmental extremes and their impacts on society.

In the summer, more than 90 data enthusiasts converged on the Centre for a hackathon weekend to develop innovative climate data applications. They tested the capabilities of the Climate Data Store (CDS), a facility that provides free and open access to climate data and information. The CDS has been developed by the EU-funded Copernicus Climate Change Service (C3S) implemented by ECMWF. It was publicly released in June 2018.

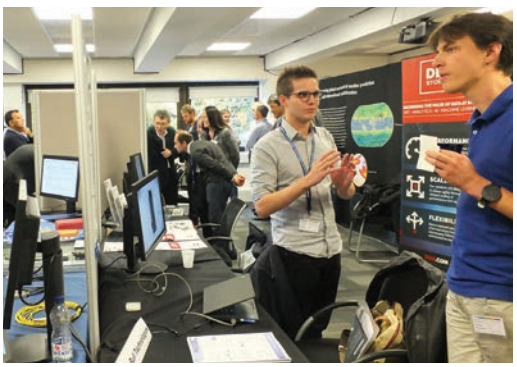
In November 2018, the US Department of Energy's (DOE) Office of Science announced the 62 computational research projects to which it awarded grants as part of its Innovative and Novel Computational Impact on Theory and Experiment (INCITE) program. ECMWF was among the INCITE 2019 award winners, with a project called 'Unprecedented scales with ECMWF's medium-range weather prediction model'.

In 2018, ECMWF reviewed the technologies it uses to archive data. As a result, we successfully ran a competitive tender for the procurement of a new tape library complex, which will provide the foundation for our data archive.

HPC workshop

The 18th workshop on high-performance computing in meteorology took place at ECMWF in September 2018. This workshop looked especially at scalability and I/O of weather and climate applications on HPC systems. Scalability was the key theme because we are approaching the completion of the first milestones of the Scalability Programme and, with the upcoming procurement for our next supercomputer, new technologies offering better ways to achieve scalability become important.

The HPC workshop provided a unique forum to bring together operational centres concerned with running cost-effective forecasting systems on affordable HPC infrastructures; research teams exploring cutting-edge methodologies and novel technologies for future solutions; and HPC industry representatives interested in providing the most suitable technological solutions for an application community with enormous socio-economic impact: weather and climate prediction. The workshop programme included programmatic overview talks; expert presentations; and panel discussions focusing on key topics, such as the European Roadmap towards Exascale and the Convergence of HPC and the Cloud.



Workshop 2018
Vendor exhibition at the ECMWF HPC workshop.

> "In the summer, more than 90 data enthusiasts converged on the Centre for a hackathon weekend to develop innovative climate data applications."

Sustaining high-performance computing

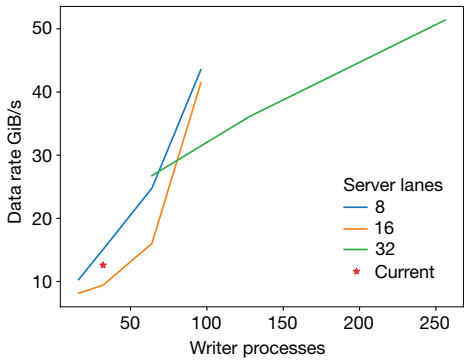
A significant step towards exascale computation: NEXTGenIO

One of the major roadblocks to achieving exascale computing (1000x faster than current petascale systems) is the I/O bottleneck. Current systems are capable of processing data quickly, but speeds are limited by how fast they can read and write data. This represents a significant loss of time and energy. Being able to widen, and ultimately eliminate, this bottleneck would significantly increase the performance and efficiency of HPC systems.

The EU-funded NEXTGenIO project (2015–2019) aims to solve this problem by bridging the gap between memory and storage using Intel® Optane™ Data Center Persistent Memory Modules, which will sit between conventional memory and disk storage. NEXTGenIO has been working on the required hardware and software to exploit this new memory technology. The goal is to build a system with 100x faster I/O than current HPC systems, a significant step towards exascale computing.

In 2018, ECMWF's participation in NEXTGenIO enabled some interesting developments that made it possible to refactor the I/O stack of ECMWF's weather model, making it ready for the future.

ECMWF developed the workflow simulator Kronos Workload Simulator, a key part of the software package for the NEXTGenIO system. Kronos generates and executes workloads representative of the real-life computational workloads of HPC centres in a highly controlled and easily portable way. Furthermore, it aims to generate these workloads automatically, based on analysis of data collected from measured operational workloads. This software was used in 2018 to assess the requirements for the next HPC procurement.



NEXTGenIO
Performance of the FDB5 Weather & Climate distributed object-store running on the Fujitsu built NextGenIO prototype, using Intel's DCPMM NVRAM. Throughput in GiB/s measured with 8, 16 and 32 servers compared with the current software and hardware technology.

2018 also saw the fifth version of the Fields Database (FDB), a software library and internally provided service, used as part of the NWP software stack. FDB5 became part of the processing chain for the Boundary Conditions programme in 2018 and it is expected to be fully implemented in the next IFS cycle upgrade 46r1 in 2019.

> "FDB5 became part of the processing chain for the Boundary Conditions programme in 2018 and it is expected to be fully implemented in the next IFS cycle upgrade 46r1 in 2019."

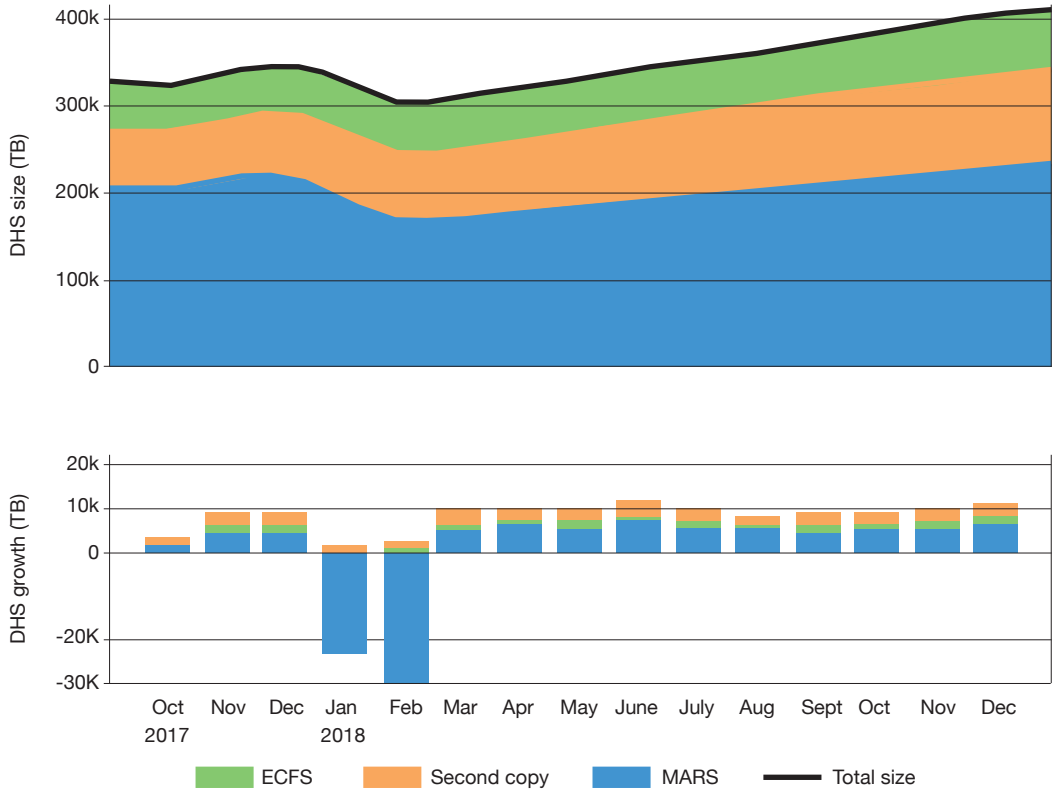
NEXTGenIO has facilitated ECMWF's access to state-of-the-art technology. It enabled ECMWF to participate in the design process and to have access to the first prototype of an HPC system with NVRAM. This was built by Fujitsu and it is currently hosted in Scotland at the Edinburgh Parallel Computing Centre (EPCC). This system has already been successfully tested to produce a six-member ensemble forecast.

The NEXTGenIO project has received funding from the European Union's Horizon 2020 Research and Innovation programme under grant agreement no. 671951.

Data management at ECMWF

ECMWF produces and archives very large volumes of data. Currently the only cost-effective solution available to archive and retrieve such volumes of data is tape. This technology is limited. Therefore, a collaborative effort across ECMWF, coordinated by a Data Steward, led to a reduction in primary data in 2018. By the end of the year, the data stored at ECMWF reached 417 petabytes, while without this effort it would have reached 474 petabytes. Even though the data continued to grow in 2018, we made that growth more manageable. The intention is to keep deleting data which is not useful on a regular basis. At the same time, ECMWF is working closely with scientists to promote best practices with data storage so the whole community can benefit.

We are working closely with users of the archive, to enable them to classify the purpose and examine the usage of their archived data. This allows data which has become redundant to be easily identified for deletion on a regular basis.



◀ DHS size and monthly growth

Data archive growth, showing the impact of the deletion of data (negative values show the volume of deleted data) MARS is our main archive, comprising forecasts, analyses, climate reanalyses, reforecasts and multi-model datasets. ECFS is ECMWF's File Storage system, a file oriented client-server application, providing facilities to archive and retrieve files between local workstation or servers and the Data Handling System (DHS). "Second copy" are backups of important data from both systems.

ESCAPE

▲ Code

Domain-specific languages (DSLs) enable good performance on multiple architectures with a single code.

Image: A. Brookes/ECMWF Copernicus

The scientific advances required to meet the critical need for more accurate forecasts, particularly of extreme weather, call for an increase in supercomputing power of several orders of magnitude (exascale computing), coupled with much greater energy efficiency. To address this challenge, ECMWF embarked in 2013 on a major rethink of its model development, known as the Scalability Programme.

A key idea at the heart of this collaborative programme is to prepare the Centre's model, the Integrated Forecasting System, for new computing architectures towards exascale machines. Consultation and collaboration with Member States and partners from the public and commercial sectors are vital, from workshops to define the programme scope through to development and testing.

The Scalability Programme comprises a series of projects, one of which, the EU-funded ESCAPE project coordinated by ECMWF, came to an end in 2018. ESCAPE stands for Energy-efficient Scalable Algorithms for Weather Prediction at Exascale. The findings presented below are extracted from the end of project report produced by the ESCAPE team.

Exascale computing systems are being developed, but current numerical weather prediction (NWP) models cannot fully exploit them, because the NWP software is not adequately adapted to make the most of the faster and more energy-efficient hardware: the so-called "scalability" challenge. Changes are needed throughout the entire NWP processing chain. It is a huge task, but the ESCAPE project, which ran from 2015 to 2018, has achieved major steps forward.

Key to progress has been dividing the huge volume of code within the ECMWF forecasting model into smaller and more manageable elements known as "dwarfs". Each dwarf performs a particular function within the model, such as modelling cloud micro-physics, and comes with specific computational patterns for accessing processor memory and data communication.

The creation of dwarfs is a prerequisite for any subsequent co-design, optimisation, and adaptation efforts. The dwarfs have enabled high-performance computing centres, research groups and hardware vendors to focus on specific aspects of performance for which code restructuring and adaptation to novel processor architectures is more straightforward.

Teams worked to adapt and optimise the dwarfs for different types of Intel CPU and NVIDIA GPU processors. A new technique was also explored with an optical processor which encodes information into a laser beam by adjusting the magnitude and phase in each point of the beam. It is particularly suited to performing Fourier transformations within the model's dynamics scheme.

Efficiency gains of up to 40% were achieved for spectral transforms (fundamental to the model dynamics scheme) on CPUs. Code optimisation for GPUs delivered speed-up factors of about 10 to 50 on a single node, and by a factor of 2 to 3 when deployed on multiple GPUs with NVSwitch interconnect (used to communicate between GPUs).

Domain-specific languages (DSLs) were also demonstrated as a very promising tool to enable good performance on multiple architectures with a single code. However, designing a user-friendly DSL that is shared by many dwarfs, whilst delivering good performance on each architecture, is a challenge.

ECMWF was successful in securing funding to continue the pioneering work of the ESCAPE project. ESCAPE-2 began in 2018 and will run until 2021. It will extend the work on dwarfs to other models, such as the German national meteorological service's ICON model and the community ocean model NEMO. It will also develop benchmarks that represent the computing and data handling patterns of weather and climate models more realistically, and are thus more suitable for assessing the performance of future HPC systems.

Importantly, ESCAPE-2 will look at re-assembling the dwarfs created in ESCAPE whilst maintaining the efficiency gains obtained so far. Both projects incorporate the expertise of leading European regional forecasting consortia, university research, experienced high-performance computing centres and hardware vendors.

The ESCAPE and ESCAPE-2 projects have received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no 671627 and grant agreement no 800897, respectively.

Supporting ECMWF

To deliver our mission to our Member and Co-operating States, our staff need to work within the right infrastructure. From a welcoming and healthy restaurant to an efficient Human Resources service, supporting ECMWF is about ensuring that staff at individual level work within the best possible environment and that the organisation as a whole is run efficiently and strategically.

2018 was marked by a deliberate and strong focus on the future. With the decision to move ECMWF's data centre to Italy, many ECMWF policies and regulations have needed updating to reflect our new situation as a multi-site organisation. Though this activity was led by necessity, it proved a good opportunity to take a more holistic approach and revisit policies to take account of the Centre's growth, in terms of both staff numbers and range of activities.

One of the major exercises we undertook in 2018 was to implement a new policy for the Protection of Personally Identifiable Information (PIIP), and this was done to align ECMWF regulations with the General Data Protection Regulation (GDPR) applicable in the European Union.

Brexit, and more specifically the uncertainty associated with the impact of the UK planning to withdraw from the European Union, was also a key component of 2018. From handling currency fluctuations to ensuring that ECMWF privileges and immunities would be preserved, reassuring potential candidates as much as existing staff, and trying to envisage the impact on our operational functioning, preparing for Brexit has been a challenging exercise.

Accommodation

Accommodation was at the heart of 2018 with the decision of the ECMWF Council in June to relocate all our Copernicus staff from rented offices at the University of Reading to the Centre's headquarters in Shinfield Park. In parallel, the preparatory work for the transfer of the data centre to Bologna, Italy, kept many teams extremely busy, especially in the field of procurement, where many new processes had to be implemented and managed.

▲ Scientists of the future

To celebrate World Meteorological Day on 23 March, ECMWF opened its doors to 1st Wargrave, a local scout group. The enthusiasm and curiosity expressed by the cubs and beavers during their visit really showed that science can be a fascinating topic, captivating the imagination of boys and girls even at such a young age.

> The ALBINO meeting helped to revitalise the coordination across International Organisations who share similar concerns about the consequences of Brexit.

© MarianVejcik/iStock/Getty Images Plus

Regarding the Centre's headquarters, discussions and negotiations continued with the UK Government following its offer to relocate ECMWF offices and conference facilities to new premises on the University of Reading campus. We appointed experts who worked with us to translate our requirements into an implementation document which will help the project architects to develop detailed plans.

ALBINO 2018

Recognising the specific nature of International Organisations and the importance of their role and presence in the UK, our in-house legal team took the initiative to host the 2018 annual meeting of All London-Based INternational Organisations (ALBINO) on our premises.

ALBINO is a network of International Organisations in the UK, through which lawyers can share experiences and discuss solutions for issues they have in common.

Nearly 30 participants from 14 International Organisations took part, among others the Commonwealth, the European Bank for Reconstruction and Development (EBRD), the European Molecular Biology Laboratory (EMBL), and the International Maritime Organisation (IMO). They were joined by representatives from the UK Foreign and Commonwealth Office (FCO).

A variety of issues were addressed, but the key topic on the agenda was Brexit. In particular, the legal effects and non-effects of Brexit in general, application of visa exemptions after Brexit, settled status for EU staff, future treatment of VAT, data protection and other practicalities related to general Brexit preparedness were discussed.

The meeting helped to revitalise the co-ordination across International Organisations based in the UK who share similar concerns about the consequences of Brexit. Our legal team also took the initiative to motivate other organisations to volunteer hosting ALBINO. As a result, IMO stepped forward and announced that it would host the next ALBINO meeting some time in 2019 in London. The ECMWF legal team will support the organisation of future meetings if need be.

The FCO recognised the importance of keeping International Organisations informed and pledged to keep them abreast of any development related to Brexit implementation.

Supporting ECMWF

> We are proud of our multicultural environment with 364 members of staff from 31 different countries.

ECMWF staff

As an International Organisation, ECMWF is proud of its multicultural environment with 364 members of staff from 31 different countries. Six graduate trainees from the national meteorological services of Austria, Croatia, Hungary, Ireland, Norway and Serbia worked on areas including new flash flood products; real-time hydrological data acquisition; extracting ecCharts information; polar lows in the Norwegian and Barents Seas; investigating near-surface weather forecasts; and a new forecast evaluation tool for OpenIFS users.

Three visiting scientists from China and three from Japan focused on Earth system predictability, model uncertainty, coupled assimilation and physical processes.

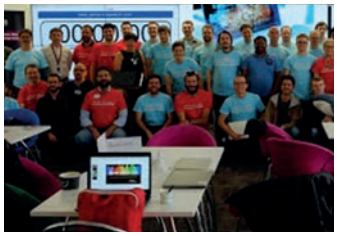
ECMWF funding

The Centre's financial position remained strong, with the sale of ECMWF data and products continuing to increase and generating a surplus of over £1 million in 2018. We continued to work on a new charging and delivery model, a priority in the context of changing technology and political views on open data. Investing in cloud services will play a key role in supporting our future business model for the development of forecasts and the distribution of our data and products.

Life at ECMWF

▲ **Annual summer party**
Staff, families and friends enjoyed an evening together.

◀ **Graduate trainees**
The Graduate training programme is an important part of our scientific cooperation with Member and Co-operating States.



▲ **Hackathon 2018**
Students, software developers and scientists gathered from all over Europe.

◀ **Green Park Triathlon**
Sporting events are a great way to engage with our local communities and support charities. Our 2018 triathletes completed the challenge to raise money for Sport Relief.

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 £43.5 million out of the Centre's £108.3 million funding. External organisations support both core research and the complementary goals of the Centre with funding of £55.5 million, while revenue from sales of data and products provides additional income of over £9.5 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 £1.1 million, principally for IT and infrastructure.

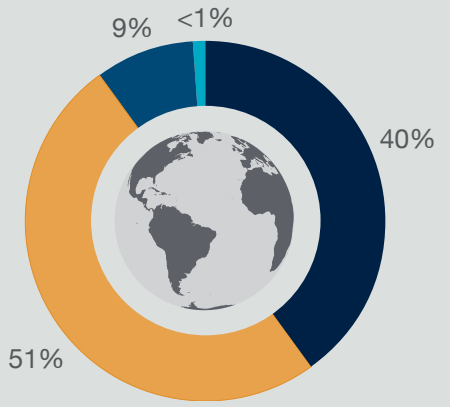
The main areas of expenditure related to remuneration and related items (£25.2 million), pension schemes (£12.8 million), computer expenses (£18.2 million), buildings (£4.7 million) and other operating activities (£4.6 million). Costs associated with externally funded projects amounted to £47.7 million and net finance costs were £7.4 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 £1.856 million in 2018, which is proposed for use in the Data Centre project (subject to Council approval).

Note: all numbers exclude Centre tax.

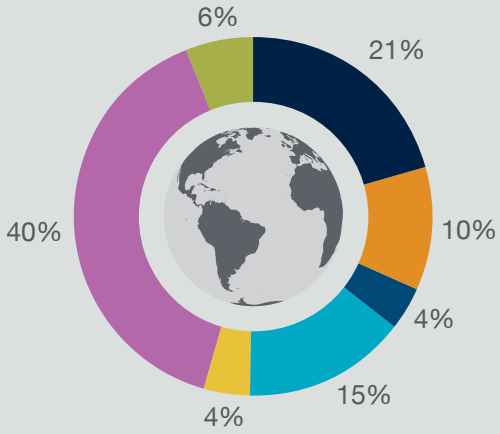
> "ECMWF continues to invest in its staff, infrastructure and systems to provide the highest quality products to its Member and Co-operating States."

Funding



- Member & Co-operating States' contributions
- Externally funded income
- Sales of forecasts and data
- Other operating revenue

Costs



- Personnel costs
- Pension and post-employment benefits
- Buildings expenditure
- Computer expenditure
- Other operating expenditure
- Externally funded expenditure
- Net finance costs

Bologna

December 2017

Hosting agreement ratified by Italian Parliament.

May 2018

Data centre design approved by Emilia-Romagna Region and building tender released.

October 2018

Head of Data Centre Operations appointed, to take up post in April 2019.

Since the decision in June 2017 to locate ECMWF's next data centre in Bologna, Italy, ECMWF has worked closely with the Emilia-Romagna Region and the Italian Government to bring the project to life.

The new data centre will replace the current facility in Reading, UK, and will help the Centre to achieve its strategic goal of producing forecasts with increasing fidelity on time ranges up to one year ahead.

Preparations for the Centre's new data centre progressed apace during 2018, with staff from all departments and external contractors contributing their expertise.

Following months of complex preparatory work, the project entered a new, two-year phase in the autumn that will include building work on the data centre itself, purchasing and installing ECMWF's next supercomputers, and migrating the Centre's computing and data handling operations. The transition to this phase was marked with an event on the site of the new data centre with representatives from ECMWF's Member States, the Emilia-Romagna Region and the Italian Government.

A tender for the new high-performance computing facility that will be installed in Bologna was issued in November.

By the end of the year, the Centre had a high-level conceptual design for the future IT and systems architecture. The design aims to improve the resilience of the information system as well as rationalise the logical and physical infrastructure and day-to-day administration and support of the forecast delivery services.

In designing the solution, the Centre considered how users currently conducted their work, likely future workflows taking into account the merging of the Linux clusters with the HPC facilities, and the anticipated increases in dataset size. All common services necessary to ensure that ECMWF staff and Member State users can connect to services in Bologna with ease and work efficiently are integrated in a common managed layer based on cloud computing concepts. This "service layer" shares common online storage with the HPC and the Data Handling System (DHS), facilitating the sharing of data and products between the services.

A modern server provisioning and configuration infrastructure will be deployed in Bologna, facilitating the roll-out of the data centre. This infrastructure will allow for more frequent updates to bring new features to users quickly and ensure that security patches are rolled out promptly and consistently across whole servers.

November 2018

Invitation to tender issued for ECMWF's next high-performance computing facility (HPCF).

'ECMWF in Bologna 2020' event brought together representatives from ECMWF and its Member States and the Emilia-Romagna Region. The programme incorporated a media briefing, virtual tour and presentation of architectural plans, as well as a panel discussion on the topic of big data.

December 2018

Construction work started in earnest, following the signing of the Bologna data centre contract by the Emilia-Romagna Region.

High-level design of future IT systems architecture completed.

ECMWF registered as an international organisation operating in Italy.

Serving Member and Co-operating States

To support the forecasting activities of users in its Member and Co-operating States, ECMWF continually develops new products, software and computing services and seeks to offer high-quality, relevant training.

We also contribute to Europe's initiatives to provide open and free environmental information.

Making deliverables and expertise available

To support our partners in the use of our products, the User Guide to the ECMWF Integrated Forecasting System was updated and made available online. Improved descriptions for some of the most popular parameters have also made data discovery easier.

A probabilistic point-rainfall product, which can be used to support the prediction of flash floods across the globe, was one of the new products developed this year.

A new interpolation library, Meteorological Interpolation and Regridding (MIR), and a new Python interface to Metview were among the software developments.

In the spirit of homogenising data archiving and the handling of ECMWF forecasting systems, work began during 2018 to make ocean output available in ECMWF's Meteorological Archival and Retrieval System (MARS).

Demand for ECMWF forecasts through commercial and non-commercial licences continued to grow rapidly, along with demands for open data and other pressures, leading the Centre to commission a legal study of ECMWF licensing. A new vision was also developed for future data services based on the provision of ECMWF numerical weather prediction (NWP) products via an on-site cloud (the European Weather Cloud).

Since a decision in December 2017, the European Commission and its Agencies have been able to receive ECMWF products. The DG Joint Research Centres were granted two licences under this agreement in October 2018.

◀ User meeting 2018

A record number of more than 120 participants attended the 2018 user meeting, 'Using ECMWF's Forecasts'.

▲ Events and workshops

In 2018 we held 28 events, attracting just under 1,200 participants in total.

> A variety of partnerships and collaborations help ECMWF to provide improved services and forecasts for Member and Co-operating States.

OpenIFS provides an easy-to-use version of the ECMWF Integrated Forecasting System (IFS) for research and teaching, to encourage academic use and to enhance collaboration. At the end of 2018, the number of institutes licensed to use OpenIFS stood at 73. Training opportunities using OpenIFS prove extremely popular and a number of high-impact scientific papers have been published based on its use.

ECMWF training courses support the professional development of participants within the national meteorological and hydrological services (NMHSs) and research sectors. We strive to make them as efficient as possible through developments such as blended learning; eLearning modules; practical sessions designed around participants' ongoing work; and guest lectures from visiting scientists.

The Centre continues its commitment to support the training partnerships with the World Meteorological Organization (WMO) mandated by the Council. For example, ECMWF is working with the World Bank in Central Asia on a capacity building initiative for the WMO Severe Weather Demonstration Projects.

We continued an active programme of visiting scientists, short-term secondments and graduate trainee placements through 2018.

In December, ECMWF appointed three new Fellows to begin in January 2019, which will take the total number of ECMWF Fellows to eight.

Working with the WMO, ECMWF extended its support to NMHSs by making more forecast products available and continued its role as the archive centre for the WMO TIGGE (medium-range) and S2S (subseasonal) datasets. ECMWF agreed to provide real-time data, until the end of 2019, to the African Centre for Meteorological Applications for Development (ACMAD) for the Satellite and Weather Information for Disaster Resilience in Africa project. ECMWF also continues to work closely with space agencies, with the development of wind products from ESA's Aeolus mission of particular note this year.

With the ECMWF Council's agreement, this year saw the exchange of real-time data, software and support between ECMWF and the US National Oceanic and Atmospheric Administration. Our partnership with INPE (the Brazilian National Institute for Space Research) was formalised at the beginning of the year.

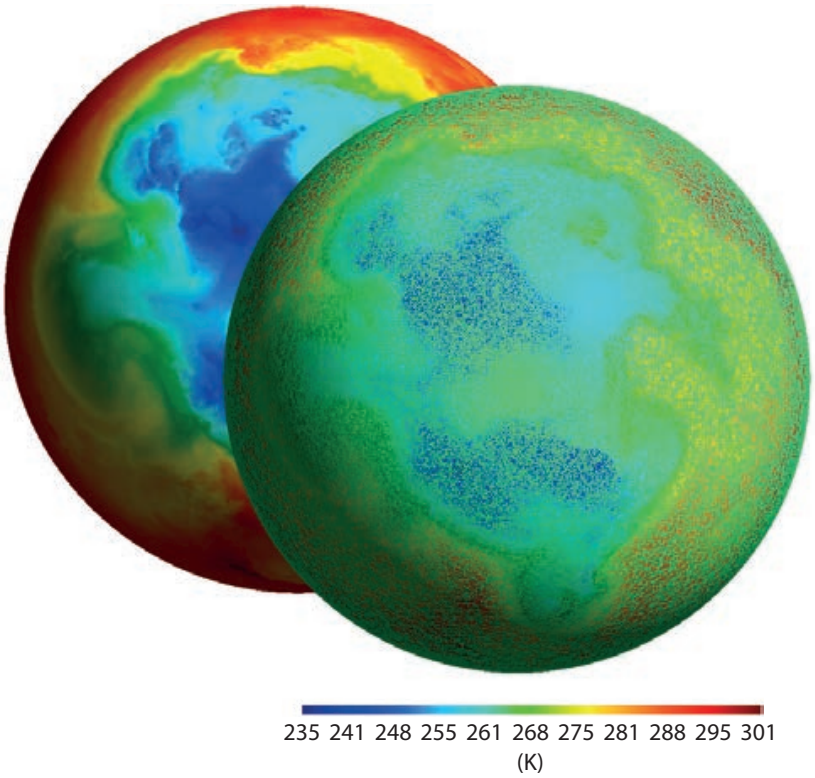
ECMWF workshops and seminars attracted delegates from a wide range of nationalities. The Annual Seminar, this year on Earth System Assimilation, marked the 20th anniversary since the original introduction of the 4D-Var scheme at ECMWF. Scalability and efficiency of computing and data handling for weather and climate applications was the key topic for the five-day workshop on High Performance Computing in Meteorology.

© Irstea

New ECMWF Fellows

From left: Dr Louise Nuijens (TU Delft), Prof. Marc Bocquet (École des Ponts ParisTech) and Dr Maria-Helena Ramos (Irstea).

Serving Member and Co-operating States



◀ Interpolation

Upper atmosphere temperature field in grid space (back) interpolated from a point cloud (an arbitrary set of data points not following a structure) and associated unstructured mesh (front). MIR can perform transformations from one into the other.

Meteorological Interpolation and Regridding software (MIR)

After four years of development and testing, the new MIR software package was introduced in October. Such software is needed for many weather forecasting applications: mapping weather data to different grids and transforming from spectral to grid space, for example.

Improvements in functionality and data handling were noted by users. In general, MIR can produce higher quality and smoother interpolated fields than its ageing predecessor EMOSLIB. The new interpolation package will be an important building block for a new version of the Product Generation software which prepares all data products delivered through ECMWF's real-time dissemination system. Users will use this new interpolation package automatically when retrieving data from the MARS archive.

Python interface to Metview

As a workstation application and tool box that provides powerful data access, processing and visualisation, Metview is a key tool for Member and Co-operating States. A Python interface to Metview has been developed to exploit Python's extensive language features and wide use. Metview's Macro language is effective, but Python is more widely known and connects well to a whole ecosystem of other tools for scientific data processing and has even more language features. The new interface

State of the Climate

The European State of the Climate Report for 2017 was presented by representatives from ECMWF and the European Commission at the EU Parliament.

will mean a shorter learning curve for people who already know the Python language. During 2018, an early version of the interface was used successfully to interact with the Copernicus Climate Data Store. A Python interface to map GRIB files to the NetCDF Common Data Model has also been released as part of this work.

Supercomputing resources for Member State time-critical applications

Members States can request use of their share of ECMWF's high-performance computing facility (HPCF) to run time-critical work. In 2018, both the Republic Hydrometeorological Service of Serbia (RHMSS) and the Hellenic National Meteorological Service (HNMS) began running their operational forecast models at ECMWF using suites developed in ecFlow. Initial data and lateral boundary conditions are taken from ECMWF forecasts, disseminated to the ECMWF HPCF.

Delivering environmental information

The Copernicus Atmosphere Monitoring Service (CAMS) and Copernicus Climate Change Service (C3S), both implemented by ECMWF on behalf of the EU, made excellent progress during 2018 in line with their Implementation Plans as Third-Party Activities.

With the release of the Climate Data Store (CDS) in June 2018, C3S reached a major milestone and moved from proof-of-concept to its operational phase. By the end of the year, more than 5,500 users had registered to use the CDS with its easy access to the portfolio of C3S products. C3S also published the first European State of the Climate Report, covering the climate of 2017 with headline climate indicators to provide a longer-term view of regional and global climate change. The C3S User Learning Services started their activities by delivering a 'train-the-trainer' course in the Netherlands and four blended training events in Serbia, Croatia and Italy.

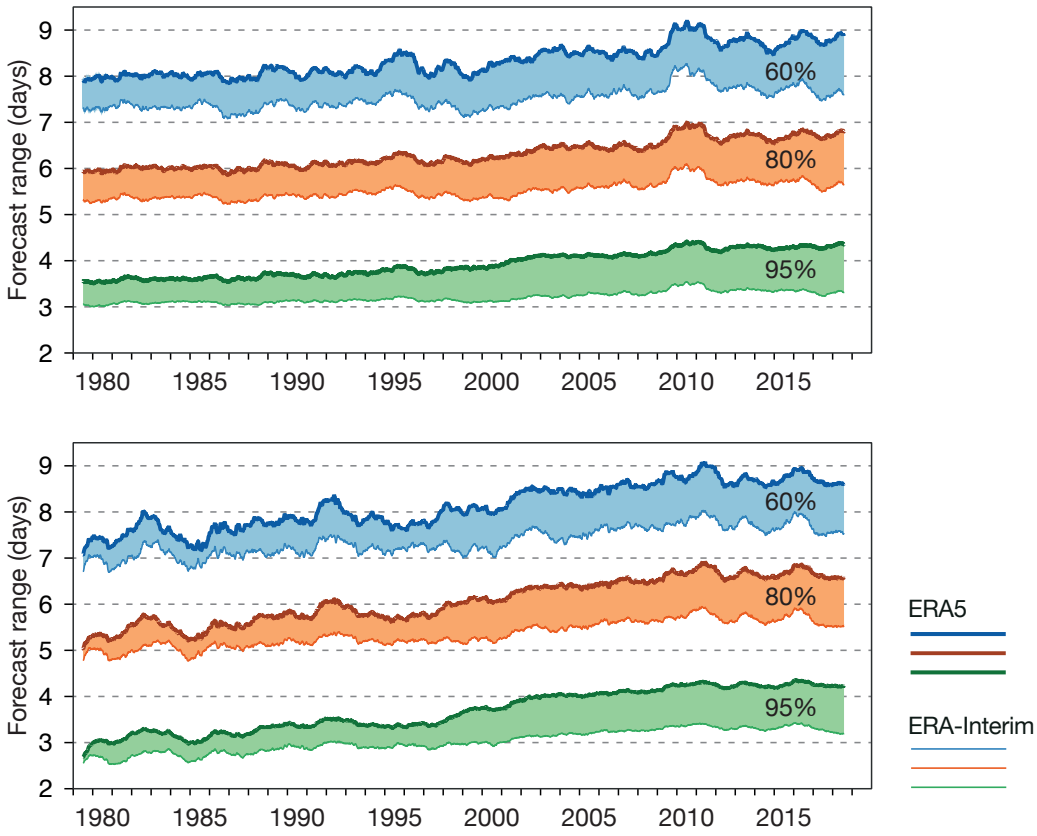
Development of the fully operational CAMS Service continued, with a major modelling upgrade in summer 2018 and the public launch of eight CAMS use cases to support further uptake of its products. The CAMS reanalysis, covering 2003 to 2016, was released to the public in September. Providing consistent information on aerosols and atmospheric gases, the reanalysis is one of the most important ECMWF deliverables to CAMS and it serves a multitude of users from application developers to scientists and policymakers. CAMS provided dedicated information to monitor the Antarctic ozone hole during 2018, and the information was also used by the WMO.

ECMWF is the computational centre for the operational fire and flood services of the Copernicus Emergency Management Service Early Warning Systems (CEMS-EWS). A major upgrade of the CEMS-EWS European Flood Awareness System (EFAS) became operational in May, following a three-year collaboration between ECMWF and the European Commission Joint Research Centre (JRC). Improvements included the expansion of geographic coverage and improved representation of hydrological processes.

Led by ECMWF, the ambitious CO2 Human Emissions (CHE) project, which is exploring a European system to monitor worldwide CO2, published its first strategic research agenda.

> "By October 2018, more than 300 European companies and institutions from 30 EU and ECMWF Member States had been engaged by ECMWF for the provision of CAMS and C3S services."

Serving Member and Co-operating States



◀ Global climate reanalysis

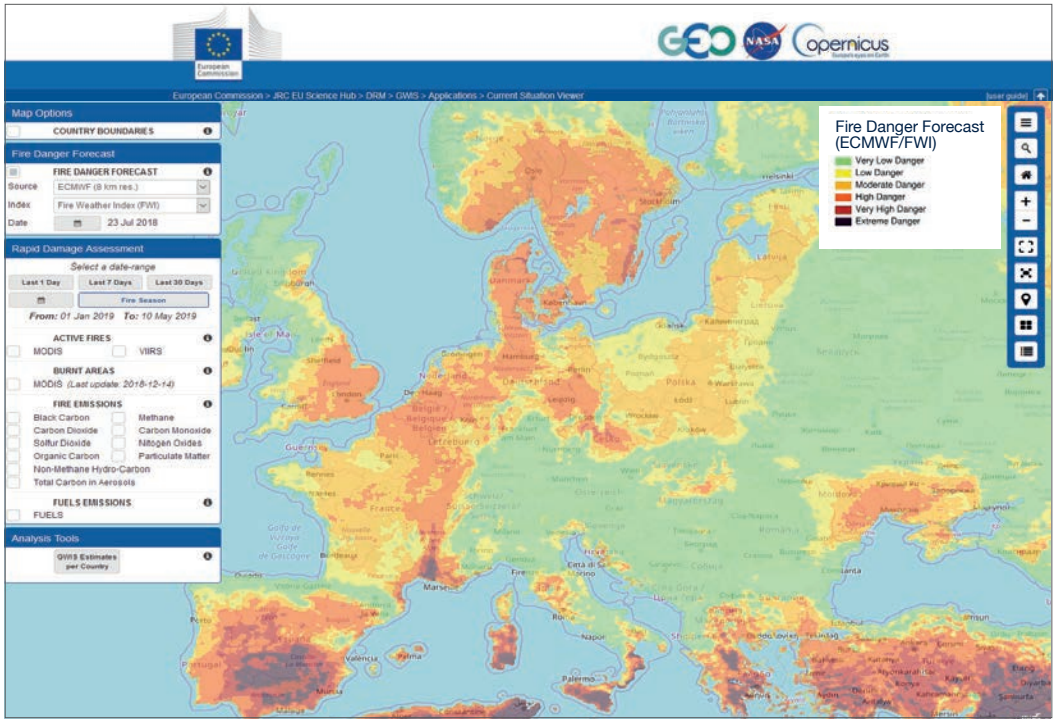
Range (days) at which running 365-day mean anomaly correlations of 500 hPa height forecasts from 00 and 12 UTC reach 95%, 80% and 60%, for the extratropical northern hemisphere (top) and the extratropical southern hemisphere (bottom), from 1979 onwards.

ERA5 global climate reanalysis

ECMWF made major progress this year towards producing the ERA5 global reanalysis for the Copernicus Climate Change Service (C3S). We completed the production of the first phase (covering 1979–2017) and started producing the second phase (covering 1950–1978). Once complete, ERA5 will replace the ERA-Interim reanalysis. It uses a newer model version with higher resolution than ERA-Interim and includes newly reprocessed observational data. Re-forecasts starting from the ERA5 reanalysis show a gain of up to about a day in skilful range with respect to ERA-Interim.

Growing CAMS audience

The number of CAMS users continued to increase steadily, reaching 9,000 by December 2018. The actual audience was much larger, with many successful smartphone applications relying on CAMS data. For example, the “Météo Pollen” app, developed by Weatherforce and Météo-France, had been downloaded by more than 30,000 people by the end of the year. The CAMS daily European air quality bulletins broadcast on Euronews reached an estimated 18.8 million viewers in the second quarter of 2018. A five-week Massive Open Online Course (MOOC) on monitoring atmospheric composition, created in conjunction with EUMETSAT, reached an audience of over 2,500 from all over the world.



◀ Fire danger forecast

The Global Wildfire Information System (GWIS) web interface showing the high-resolution ECMWF forecast from 23 July 2018.

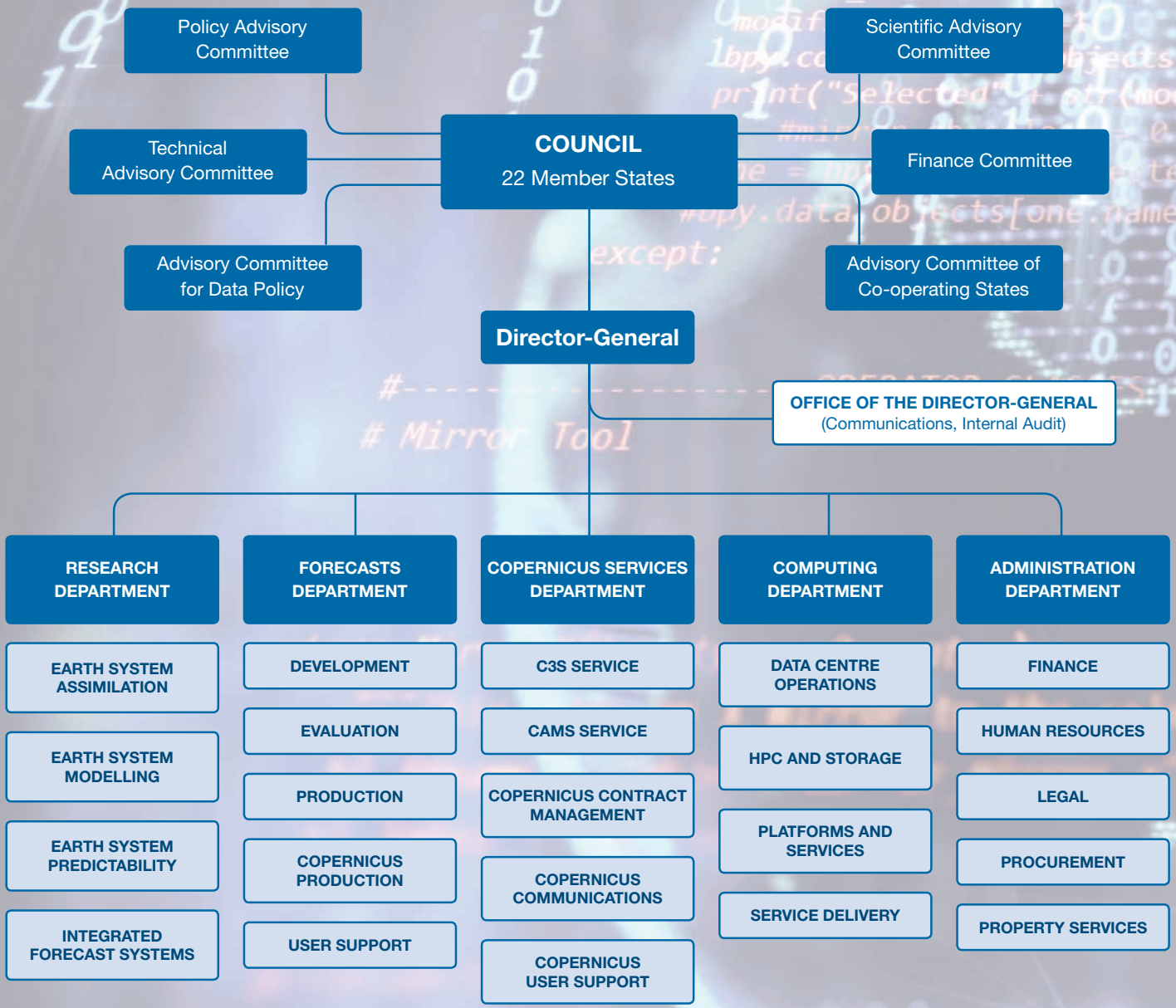
Operational global flood forecasts

In April, the Global Flood Awareness System (GloFAS), part of CEMS-EWS Floods, was migrated from a prototype service to a full operational service, run and managed by ECMWF on behalf of CEMS. Pre-operational since 2011, GloFAS is the first operational global flood forecasting system and now provides a 24/7 service to produce ensemble forecasts of river discharge up to 30 days ahead (GloFAS 30-day) and seasonal hydrological outlooks up to 16 weeks ahead (GloFAS Seasonal).

Operational European fire danger forecasts

After a period of intensive activity to optimise the fire model and production suites, ECMWF started the operational phase of the fire danger forecast production in June 2018, as part of the computational service that ECMWF provides for CEMS-EWS Fire. The 10-day forecasts produced feed into the European Forest Fire Information System (EFFIS) and its global extension, the Global Wildfire Information System (GWIS). These web portals support the services in charge of the protection of forests against fires in the EU countries and provide the European Commission services and the European Parliament with updated and reliable information on wildland fires in Europe and worldwide.

How we work



Organisation of ECMWF at June 2019

Co-operating States as of January 2019

- Bulgaria
- Czech Republic
- Estonia
- Hungary
- Israel
- Latvia
- Lithuania
- Montenegro
- Morocco
- North Macedonia
- Romania
- Slovak Republic

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