ECMWF

European Centre for Medium-Range Weather Forecasts

Annual Report 2019

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Building up resilience

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Florence Rabier
Director-General

Another very busy year during which the forecast performance has been consistently high with the highest ever skill for the Extreme Forecast Index (EFI) for 10-metre wind speed.

2019 was rich in developments and achievements. One highlight worth singling out has been watching our new data centre in Bologna take shape, with considerable progress both on site and in the processing of tenders to procure equipment and services.

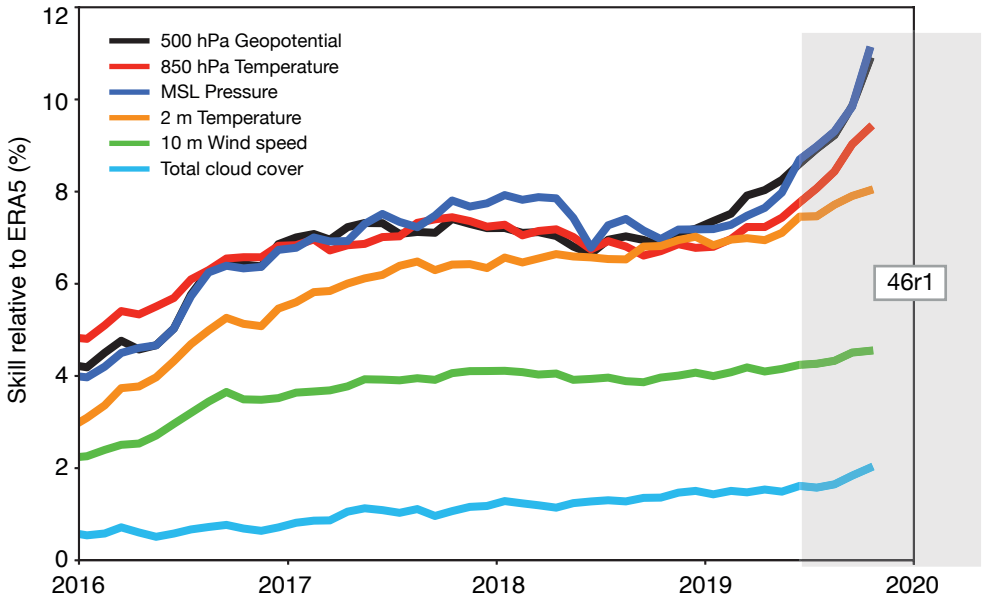
Another was the opportunity to look back over 40 years since ECMWF's first operational forecast was disseminated to the Member States. The international cooperation behind that remarkable achievement continues to underpin the scientific advances presented in this Report. Examples include the European Weather Cloud pilot, which was launched in partnership with EUMETSAT; a new short-term secondment scheme developed with Member States; and the opportunity to welcome three new ECMWF Fellows to work with us in the coming years. We made more data available to WMO Members, and the Subseasonal-to-Seasonal (S2S) real-time pilot was launched, another great illustration of our close collaboration with the WMO.

A major milestone for the EU-funded Copernicus Climate Change Service (C3S) implemented by ECMWF was reached at the beginning of 2019 with the availability of 40 years of the latest ECMWF reanalysis dataset (ERA5) being made available in the Copernicus Climate Data Store (CDS).

We were allocated time on the world's biggest computer via a US Department of Energy award, enabling us to explore the competitiveness of the spectral-transform based Integrated Forecasting System (IFS).

The year ended on a high note, with our Council authorising the Centre to enter into contractual arrangements with Atos for the supply of a BullSequana XH2000 high-performance computing facility (HPCF), illustrating the continuous support and trust of the Member States in ECMWF.

Putting together this Annual Report has been a very different experience this year. As we live through the impacts of the COVID-19 pandemic felt around the world, 2019 is taking a different dimension. The achievements of the past few years, and more specifically those of the past year that we are reviewing here, challenge us to ask ourselves how they prepared us for what was to come in 2020.



High-resolution forecast skill relative to ERA5

Changes to ECMWF's Integrated Forecasting System (IFS) introduced with IFS Cycle 46r1 in June 2019 had a large positive impact compared to the ERA5 reanalysis for all weather parameters. The graph shows the skill of the high-resolution forecast (HRES) for forecast day 5 relative to ERA5 for the northern hemisphere extratropics. Skill based on the standard deviation of the forecast error.

The work of the Computing Department on our Virtual Desktop Infrastructure (VDI), allowing staff to access their work setup from anywhere in the world, was instrumental in enabling the teleworking pilot which successfully ended at the end of 2019. Though our VDI and teleworking schemes were never designed to cope with the whole organisation using them at the same time, the experience of the past couple of months has demonstrated the extreme resilience of the system. The investment we made in 2019 to upgrade our live-streaming equipment, as well as the experience gained over the year, allowed the smooth transformation of all training courses and workshops into virtual events when circumstances required us to close our premises.

A programme that we launched in 2019 to enable Member and Co-operating States to install ECMWF's Scalable Acquisition and Pre-Processing System (SAPP) in their own operational processing environments is now proving helpful for coordinating with our partners upcoming changes to the observing system due to the pandemic. The fantastic achievements of ESA with the Aeolus satellite and our close partnership with the teams involved (the German Aerospace Center, DLR; Météo-France; the Dutch national meteorological service, KNMI; and the software company DoRIT) allowed Aeolus to be ready for implementation for data assimilation at ECMWF at the end of 2019. Implementing continuous data assimilation in operations as part of the 46r1 cycle upgrade, with the purpose of gaining more benefits from the global observing system, made us much more resilient. The same applies to accelerating the implementation of the EUMETSAT Metop-C sensors in operations and to the observation monitoring and alarm system becoming completely automated, giving us up-to-the-minute alarms when observations are missing, or indeed not being reported correctly.

These are just a few examples, and I invite you to read the highlights of 2019 through the lens of this year's challenges. It is an inspiring experience.

2019 was a year in which the work of our staff and our friends and partners around the Member States and beyond proved instrumental in preparing us for the challenges of 2020.

June 2020

ECMWF Council

In December 2019, Member States authorised the Centre to enter into contractual arrangements with Atos for the supply of a BullSequana XH2000 high-performance computing facility (HPCF).

2019 At a glance

January

ECMWF contributes to AMS Annual Meeting

Fifteen ECMWF scientists including Director-General Florence Rabier attended the American Meteorological Society (AMS) Annual Meeting in Phoenix, Arizona, giving a total of 32 talks and poster presentations and meeting visitors at the joint ECMWF and Copernicus-ECMWF stand.

European Weather Cloud pilot launched

The European Weather Cloud pilot got under way with the first monthly co-ordination meeting between ECMWF and EUMETSAT. The project aims to provide data-related services via cloud technology to service the European Meteorological Infrastructure and its users.

New Director of Administration takes up post

Luiz de Castro Neves formally took up the role of ECMWF Director of Administration, succeeding Nyall Farrell. Luiz joined the Centre in June 2017 as Deputy Director of Administration.

Director of Administration Luiz Neves.

ECMWF staff at the AMS Annual Meeting.

ECMWF allocated time on world's biggest computer

The US Department of Energy's (DOE) Office of Science announced ECMWF as an award winner in the 2019 Innovative and Novel Computational Impact on Theory and Experiment (INCITE) programme. The project 'Unprecedented scales with ECMWF's medium-range weather prediction model' provided a computing resource allocation of 102K Summit node-hours for ECMWF to explore the competitiveness of the spectral-transform based Integrated Forecasting System (IFS) on Summit, the biggest computer in the world.

ERA5 dataset extended back to 1979

ECMWF released a further 21 years of its global atmospheric reanalysis ERA5, extending the dataset back to 1979. The data is available from the Copernicus Climate Change Service (C3S) implemented by ECMWF on behalf of the European Union. ERA5 contains estimates of atmospheric variables such as air temperature, pressure and wind at different altitudes, as well as surface variables such as rainfall, soil moisture content and ocean wave height.

Three new ECMWF Fellows welcomed

Dr Louise Nuijens (TU Delft), Prof. Marc Bocquet (École des Ponts ParisTech) and Dr Maria-Helena Ramos (Irstea) began three-year ECMWF Fellowship terms on 1 January.

SAPP Optional Programme launched

ECMWF opened a new Optional Programme to enable Member and Co-operating States to install the Scalable Acquisition and Pre-Processing System (SAPP) in their own operational processing environments. SAPP is ECMWF's operational acquisition and pre-processing system for observations and other input data.

APPLICATE partners meet at ECMWF

The EU-funded APPLICATE project, in which ECMWF is a partner, held its General Assembly at ECMWF, followed by an early career event. APPLICATE aims to enhance weather and climate prediction capabilities in polar regions and to understand the impact of Arctic climate change on the northern hemisphere mid-latitudes.

February

Training to improve use of ECMWF products in Central Asia

With the support of the World Bank, ECMWF delivered a training course to five national meteorological and hydrological services in Central Asia.

March

CHE-VERIFY General Assembly

The EU-funded projects CHE (CO_2 Human Emissions) and VERIFY (Verifying greenhouse gas emissions) held a joint General Assembly at ECMWF with over 110 scientists and stakeholders. Coordinated by ECMWF, CHE is developing a prototype system for anthropogenic CO_2 emission monitoring and, in so doing, delivering highly beneficial developments for ECMWF's Integrated Forecasting System (IFS).

April

ECMWF represented at European Geosciences Union meeting

More than 20 ECMWF scientists presented their findings on Earth system processes related to weather, climate and atmospheric composition at the European Geosciences Union (EGU) General Assembly in Vienna, Austria. The two Copernicus services implemented by ECMWF on behalf of the EU were strongly represented.

European State of the Climate 2018 unveiled

The EU-funded Copernicus Climate Change Service (C3S), implemented by ECMWF presented the European State of the Climate 2018 report. One of the most significant events in 2018 was the exceptionally warm and dry spring and summer in central and northern Europe.

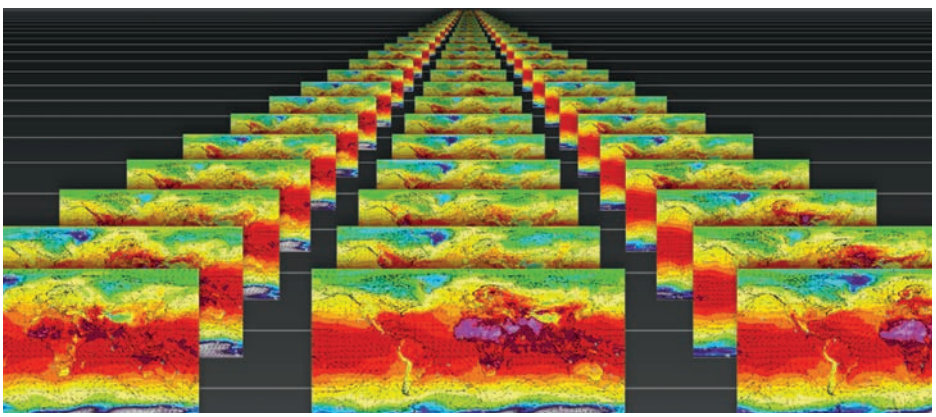
Workshop explores forecast databases for weather research

One hundred international scientists met at ECMWF to discuss predictability, dynamics and applications research using the TIGGE and S2S ensemble forecast databases. The TIGGE database was set up by the World Weather Research Programme and comprises operational global medium-range ensemble forecasts from ten weather forecasting centres. S2S is a similar database for forecasts up to 60 days ahead from 11 forecasting centres. It is one of the outcomes of the WMO Subseasonal-to-Seasonal (S2S) Prediction Project launched in 2013.

May

European flood data available in Climate Data Store

Two European Flood Awareness System (EFAS) datasets were made available to users through the Copernicus Climate Data Store. The datasets are EFAS forecasts, which are available with a month's delay, and a simulation forced with observations over a 30-year period. EFAS is part of the Copernicus Emergency Management Service (CEMS) Early Warning Systems.



TIGGE/S2S workshop graphic.

2019 At a glance

Data Handling System upgraded

The High-Performance Storage System (HPSS) was upgraded and the core of its environment transferred from an old AIX-based system to a much more powerful Linux-based machine. The HPSS provides the backbone of ECMWF's Data Handling System, allowing the storage of about 300 PB of data and over 370 million files in a very large hierarchical storage environment of disk and tape storage.

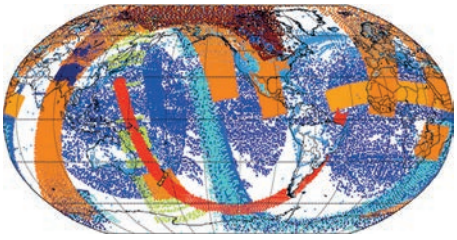
Online training week launched

ECMWF's first online training week sparked great interest among Member and Co-operating States, with 160 participants taking part. The four webinars given in 2019 covered visualisation of ECMWF data; post-processing of ECMWF data; the Meteorological Archival and Retrieval System (MARS); and compiling programs on ECMWF computers. Recordings are available on ECMWF's website.

June

IFS upgraded to Cycle 46r1

ECMWF upgraded its Integrated Forecasting System (IFS) to Cycle 46r1. Notable changes included more continuous data assimilation; the introduction of a 50-member Ensemble of Data Assimilations; the use of weakly coupled data assimilation for sea-surface temperature in the tropics; and improvements in the wave model, the convection scheme, the radiation scheme and the use of observations.



Example of extra observations assimilated in a single data assimilation cycle in IFS Cycle 46r1.

Observational campaigns workshop

Seventy weather observation specialists and modelling experts met at ECMWF from 10 to 13 June to discuss how to maximise the benefits of observational campaigns for weather forecasting and vice versa.

Ensemble forecasting centre stage at user meeting

The Centre's annual user meeting focused on ensemble forecasting, with about 100 participants considering aspects such as processing model outputs, visualisation, verification and diagnostics, and applications and impact forecasting.

New temperature records set in western Europe

In late June, large parts of western Europe experienced a severe heatwave in which many June temperature records were broken. France set an all-time national record with 46.0°C in Vérargues on 28 June. ECMWF forecasts predicted the heatwave well from 19 June. Another heatwave at the end of July saw new national temperature records being set in the Netherlands, Germany, Belgium, Luxembourg and the United Kingdom.

CAMS monitors unusual Arctic wildfires

Scientists from the EU-funded Copernicus Atmosphere Monitoring Service (CAMS) implemented by ECMWF tracked intense and long-lived wildfires in the Arctic Circle. In June alone, the fires emitted 50 megatonnes of carbon dioxide into the atmosphere.

Observational campaigns workshop.

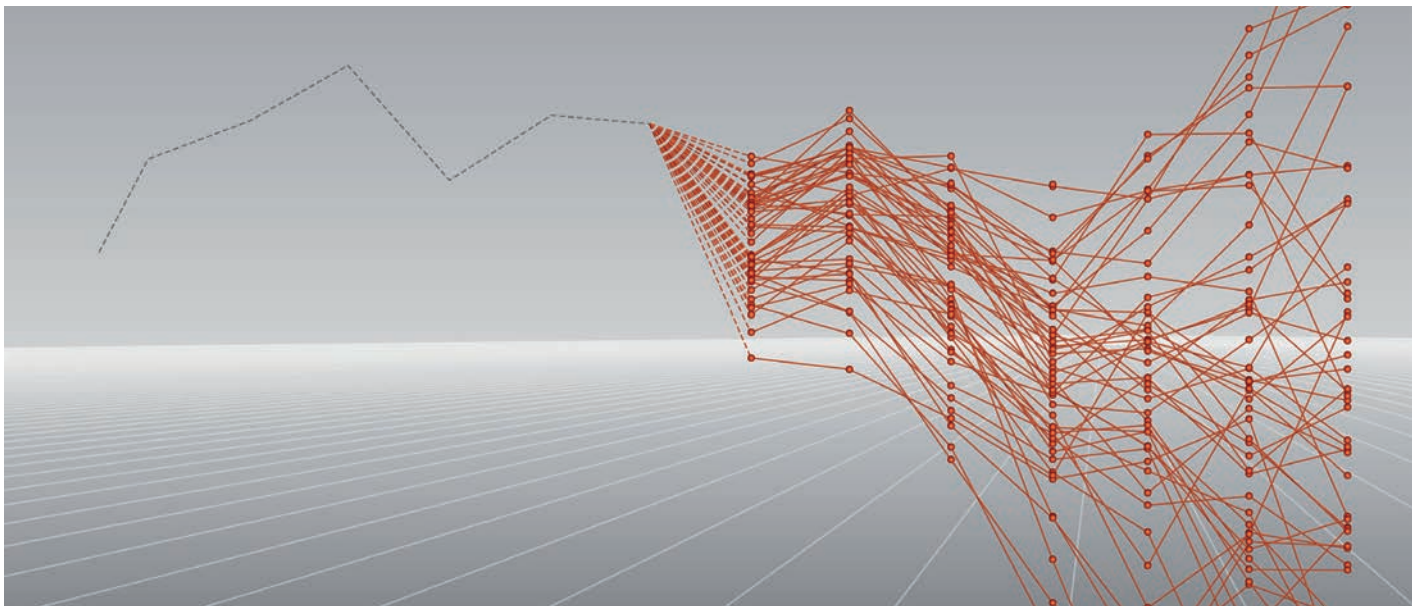
July

More data available to WMO Members

Following decisions by ECMWF's Council, the Centre introduced changes to give WMO Members access to a much wider range of ECMWF products. These included making all the static web charts and the ensemble meteograms on the ECMWF website available free of charge to all WMO Members and the introduction of lower-cost licences for web products and other data.

CAMS global forecasting system upgraded

Building on ECMWF's June IFS upgrade, the global forecasting system of the EU-funded Copernicus Atmosphere Monitoring Service (CAMS) was successfully upgraded, making air quality forecasts more accurate and robust.



Annual Seminar graphic.

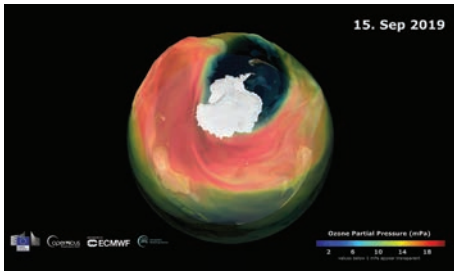
New automatic observation quality alarm system introduced

A new automatic observation alarm system came into use, offering many more options than the previous system and making it easier to add features, checks and data types, and more importantly, covering almost all observations.

August

Copernicus service monitors unusually small ozone hole

Through August and September, the EU-funded Copernicus Atmosphere Monitoring Service (CAMS) monitored the ozone hole, which forms annually over Antarctica during southern spring. In 2019, the development of the hole was stalled by a sudden stratospheric warming (SSW) over the Antarctic, which led to a less stable and warmer polar vortex than usual, resulting in reduced ozone depletion. The 2019 ozone hole was one of the smallest since the mid-1980s and the ozone hole season was unusually short.



Ozone hole.

ECMWF marks 40 years of operational forecasting

ECMWF recalled the events of 1 August 1979, the day on which ECMWF disseminated its first operational medium-range forecast to Member States.

September

Annual Seminar focuses on sub-seasonal and seasonal forecasting

ECMWF's Annual Seminar reviewed advances in the understanding of predictability at sub-seasonal time scales. It presented current forecasting capabilities and summarised recent but consolidated findings from numerical experimentation and the exploitation of public databases.

Ensemble data disseminated earlier

ECMWF brought forward the dissemination time for ensemble forecast (ENS) and wave ensemble forecast (ENS-WAM) daily products by 20 minutes. The dissemination schedule time of the ENS Extended products, both real-time forecast and re-forecast, was also brought forward by 120 minutes. The changes were part of ECMWF's strategic effort to facilitate swifter access to products and to promote the use of ensemble-based forecast products.

Austin Woods, Adrian Simmons and Florence Rabier marking 40 years of operational forecasting.

Summer coding projects showcased

Participants and mentors in ECMWF's 2019 Summer of Weather Code presented the outcomes of their projects at the Centre. In total, seven weather-related software developments were released, related to machine learning, data visualisation, software development, Jupyter notebooks and functionalities of open-source geographic information systems.

CDS team receives Technology Achievement Award

The ECMWF team who developed the EU-funded Copernicus C3S Climate Data Store (CDS) received the European Meteorological Society (EMS) Technology Achievement Award 2019. By December, the CDS had about 30,000 users, provided access to 45 datasets and delivered an average of 50 TB of data per day.

2019 At a glance

Hurricane Dorian hits Bahamas

Hurricane Dorian formed on 24 August in the central Atlantic and caused severe damage on the Bahamas on 1 and 2 September. It later affected the US east coast and Canada. ECMWF forecasts captured the probability for slow propagation over the Bahamas and the northward turn before Florida. However, they missed the rapid intensification starting on 31 August.

Copernicus Sentinel-3 image of Hurricane Dorian as it pummels the Bahamas on 2 September 2019. © contains modified Copernicus Sentinel data (2019), processed by ESA.

October

New leadership for ECMWF Copernicus Services

Jean-Noël Thépaut took up the role of ECMWF's Director of Copernicus Services, succeeding Juan Garces de Marcilla. Jean-Noël was previously Director of the Copernicus Climate Change Service (C3S) and was succeeded in that role by Carlo Buontempo.

Director of ECMWF Copernicus Services Jean-Noël Thépaut.

November

S2S pilot launched

1 November saw the launch of the Subseasonal-to-Seasonal (S2S) real-time pilot, an initiative from the World Weather Research Programme (WWRP)/World Climate Research Programme (WCRP) S2S project in collaboration with the WWRP working group on Societal and Economic Research Applications (SERA). The initiative will provide real-time access to the forecasts archived in the S2S database, currently available with a three-week delay, for 16 application projects. ECMWF is a data provider in the project and the main S2S data archiving centre.

Data exchange to improve early warnings

ECMWF joined Directors of national meteorological and hydrological services in south-east Europe in signing a policy on the exchange of hydrological and meteorological data, information, forecasts and advisories under the umbrella of the WMO project South-East European Multi-Hazard Early Warning Advisory System (SEE-MHEWS-A). The project is funded by the World Bank and aims to strengthen the existing early warning capacity in the region.

Global Flood Awareness System upgraded

ECMWF and the EU-funded Copernicus Emergency Management Service (CEMS) launched a new release of the Global Flood Awareness System, GloFAS 2.1, in collaboration with the European Commission's Joint Research Centre (JRC). It includes an upgraded river discharge reanalysis based on officially released ERA5 data; a new set of flood and seasonal re-forecasts; upgraded flood thresholds; new global flood risk assessment and mapping products; and additional web layers.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Wildfire and river flow reanalyses released through CDS

The first river discharge and fire danger reanalyses to be updated in near real time were released through the Copernicus Climate Data Store (CDS). The datasets, produced by ECMWF for the EU-funded Copernicus Emergency Management Service (CEMS), provide daily information over the whole of the globe stretching back almost 40 years.

Quality management certification renewed

ECMWF's quality management certification to the ISO9001:2015 standard was renewed for a further three years.

December

Pre-operational data quality monitoring webtool released

ECMWF became the official provider of the WIGOS Data Quality Monitoring System (WDQMS) webtool, which was released on ECMWF kubernetes infrastructure in pre-operational mode. The tool monitors the availability and quality of observational data based on monitoring information from the Monitoring Centres of the WMO Integrated Global Observing System (WIGOS).

Prof. Juhani Damski, Director-General of the Finnish Meteorological Institute.

Council appoints President and Vice-President

The ECMWF Council elected Juhani Damski (Finland) as its President and Silvio Cau (Italy) as its Vice-President, both for a first term of office for one year. Dr Christina Koepken-Watts from Germany was elected as a new member of the Scientific Advisory Committee (SAC).

ECMWF represented at American Geophysical Union meeting

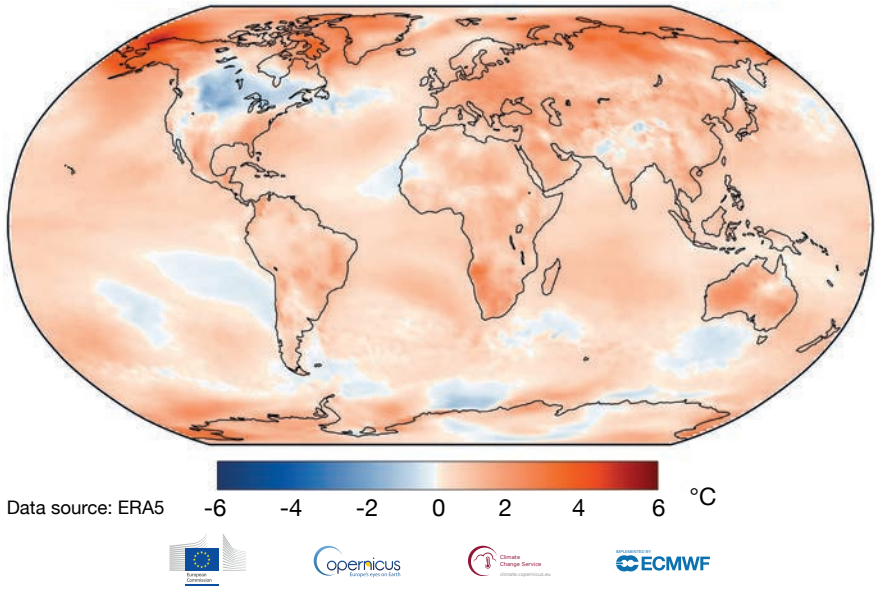
ECMWF was well represented at the American Geophysical Union (AGU) meeting in San Francisco, USA. In addition to staff giving talks and presenting posters, ECMWF had two exhibition booths showcasing the activities of core ECMWF and Copernicus. Staff also took part in the World Climate Research Programme (WCRP) Climate Science Week that celebrated 40 years of international climate science.

Green light for new supercomputer contract

ECMWF's Council authorised the Director-General to enter into contractual arrangements with Atos for the supply of a BullSequana XH2000 high-performance computing facility, to be hosted in the new ECMWF data centre being developed in Bologna, Italy.

2019 second warmest year on record

Data from the EU-funded Copernicus Climate Change Service (C3S) showed that 2019 was the fifth in a series of exceptionally warm years and the second warmest year globally ever recorded.



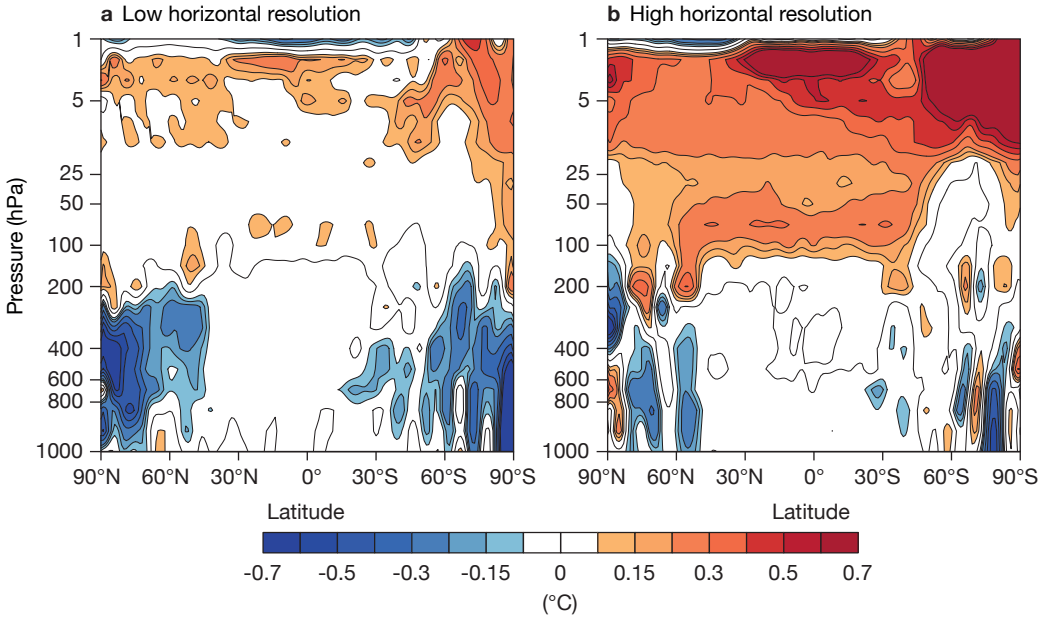
Temperature difference between 2019 and 1981–2010.

Advancing weather science

ECMWF scientists constantly work to refine and develop all aspects the Integrated Forecasting System (IFS) to push the quality of our weather predictions to the limit. They do so in collaboration with experts across our Member and Co-operating States and beyond. A good example is the close collaboration of ECMWF scientists with the European Space Agency and other organisations on new wind observations from the ground-breaking Aeolus satellite. This work and its impact on our forecasts are described separately in this Report.

In 2019, ECMWF also developed quintic vertical interpolation to address temperature biases in forecasts for the stratosphere; a new version of weak-constraint 4D-Var to improve the handling of model bias in data assimilation; and continuous long-window data assimilation to make the best possible use of observations, all in readiness for the next IFS upgrade. ECMWF scientists prepared the IFS for the operational use of cloud radar and lidar satellite data, and they made progress in coupled ocean–atmosphere data assimilation.

The new ERA5 reanalysis began to be used to initialise re-forecasts, and ECMWF scientists picked up on work carried out in our Member States on a new vertical numerical scheme, which was adapted for use in the IFS. ECMWF also introduced modifications to its wave physics package to improve the prediction of ocean waves. The wave physics changes had previously been implemented by Météo-France, and ECMWF scientists adapted and optimised them for use in the IFS.



◀ A warmer stratosphere in forecasts

Differences in zonally (latitudinally) averaged temperature between quintic and cubic vertical interpolation forecasts for (a) a grid spacing of about 79 km and (b) a grid spacing of about 9 km. Mean values over 31 forecasts starting in July 2017 and valid at day 10 are shown. The plots show that quintic vertical interpolation warms the stratosphere more at high horizontal resolution.

Quintic vertical interpolation

ECMWF has over the years repeatedly increased the horizontal resolution of its forecasts to today's grid spacing of 9 km in high-resolution forecasts (HRES) and 18 km in ensemble forecasts (ENS). The resolution increases greatly improved forecast quality in most parts of the atmosphere but led to unphysical cooling in the lower to mid-stratosphere. Investigations showed that this was a result of numerical errors accumulating due to insufficient vertical resolution in the stratosphere.

Accurately representing the stratosphere is important because variability in the winter- and spring-time stratosphere can influence tropospheric weather patterns, and because accurate model information in the stratosphere aids the use of satellite data to obtain the best possible estimate of the state of the Earth system at the start of forecasts.

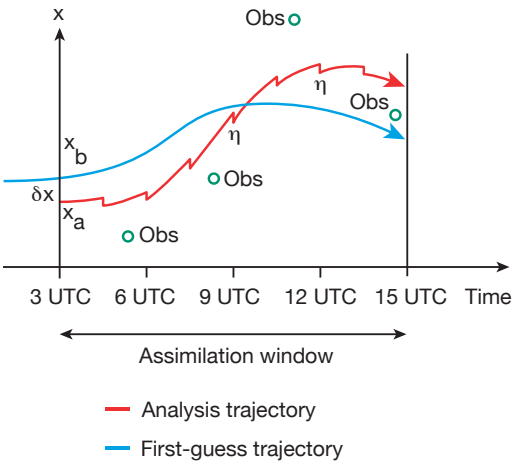
In 2019, ECMWF scientists worked on a method to address stratospheric temperature biases without introducing a computationally costly increase in vertical resolution. They showed that, in ECMWF's Integrated Forecasting System (IFS), fifth-order (quintic) vertical interpolation leads to more physical model behaviour, reduced sensitivity to horizontal resolution, and better forecast skill in the lower to mid-stratosphere. Quintic vertical interpolation was therefore scheduled to be implemented in the IFS upgrade planned for 2020.

Handling model bias in data assimilation

Data assimilation combines a short-range forecast (the first guess) with the most recent observations to estimate the state of the Earth system at the start of forecasts (the analysis). A high-quality analysis is hugely important for successful forecasts. For the atmosphere, ECMWF uses the 4D-Var data assimilation method. In the standard formulation, known as strong-constraint 4D-Var, the model is assumed to be perfect and any systematic model errors (biases) which gradually accumulate in the short-range forecasts are not taken into account.

When it turned out that there are significant model errors that develop during the data assimilation cycle for temperature in the stratosphere, ECMWF scientists worked on relaxing the assumption of a perfect model. They did that by introducing a forcing term η into the model to correct for the model bias which builds up in the model trajectory.

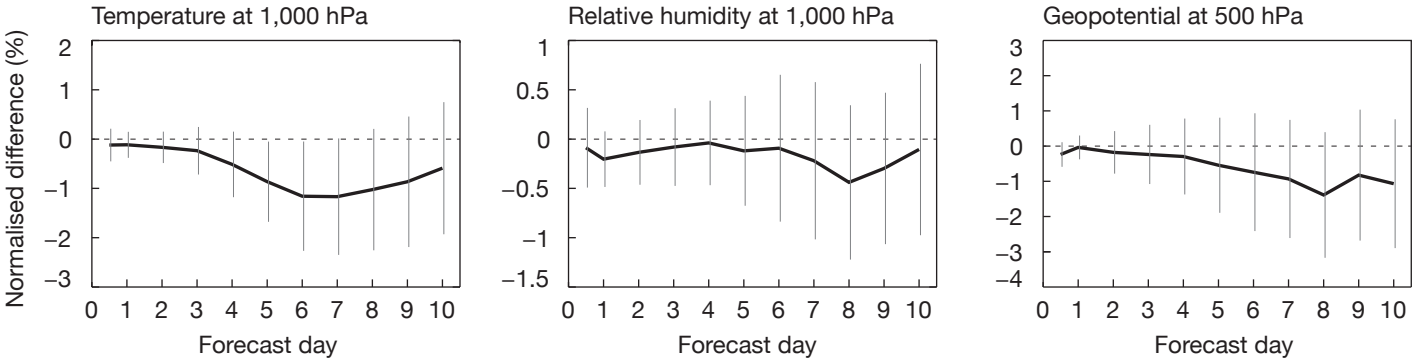
The resulting version of 4D-Var, known as weak-constraint 4D-Var, was found to reduce temperature biases in the analysis of the stratosphere by up to 50%. The improvement was achieved by correctly handling large-scale systematic errors as model deficiencies. In view of these results, the revised version of 4D-Var was due to be implemented in the next upgrade of the Integrated Forecasting System planned for 2020.



◀ Weak-constraint 4D-Var

In the case illustrated here, for a single parameter x (e.g. temperature), the forcing term η cools the trajectory at every time step to correct for the temperature warm bias in the model. In this formulation of 4D-Var, the error statistics of the model bias need to be calculated offline. They then enter into the calculations through which the data assimilation system determines the optimal combination of initial state and forcing term adjustments.

Advancing weather science



Assimilating cloud radar and lidar data

Successful weather forecasts start from accurate estimates of the current state of the Earth system. Such estimates are obtained by combining short-range forecasts with the latest Earth system observations in a process called data assimilation. Work carried out at ECMWF in 2019 demonstrated for the first time that assimilating cloud observations from satellite radar and lidar instruments into a global, operational forecasting system using a 4D-Var data assimilation system is feasible and improves weather forecasts.

The assimilation experiments used the full range of regularly assimilated observations at ECMWF to test the impact of adding the radar and lidar data on ten-day forecasts. They showed improvements in forecast quality across a range of key variables and altitudes. For example, as shown in the figure, between forecast days 4 to 8 the error in predictions of temperature at 1,000 hPa was reduced by about 1%. There are improvements for other variables too, but not yet at the same level of confidence.

Historical CloudSat radar reflectivity and CALIPSO lidar backscatter data were used to carry out the assimilation experiments. In the next few years, new satellite missions with cloud radar and lidar are planned, such as EarthCARE from the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA).

Coupled data assimilation

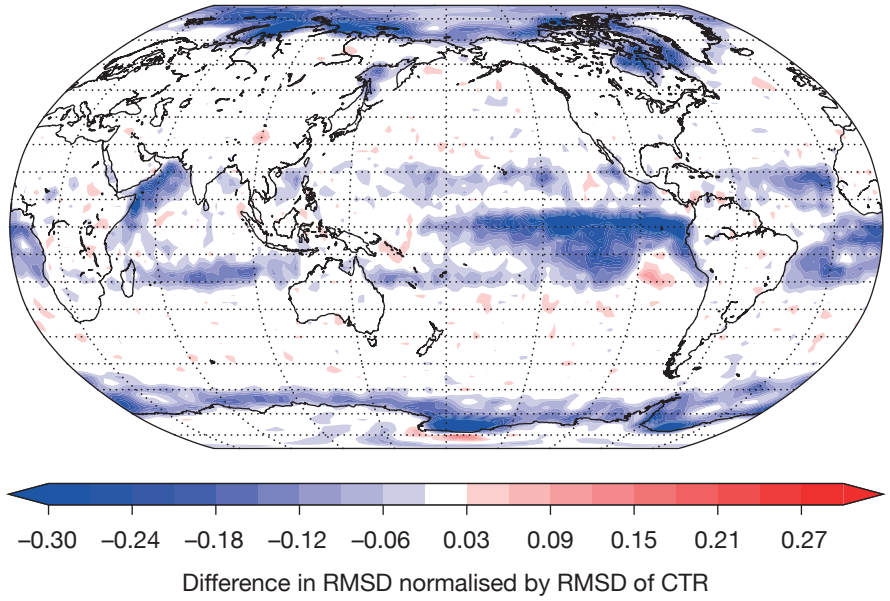
ECMWF's Integrated Forecasting System (IFS) uses separate data assimilation systems for the atmosphere, the ocean, ocean waves, the land surface and sea ice. This may produce an internally inconsistent analysis if the data assimilation systems are independent from each other. Coupled data assimilation aims to ensure that the analysis of different Earth system components is consistent.

In 2019, research resulted in the implementation of 'weakly coupled' data assimilation for the atmosphere and sea-surface temperature in the IFS. In weakly coupled data assimilation, the observations of one Earth system component influence the analysis in other components with a certain delay. Previously, weakly coupled data assimilation had been implemented for the atmosphere and sea ice.

Weakly coupled data assimilation of the atmosphere with the sea-surface temperature of the ocean was implemented in the tropics and not the extratropics. This is because the ocean model used has greater effective

▲ Reduced errors

The charts show the impact from assimilating space-borne cloud radar and lidar observations on forecast errors (root-mean-square error) for a range of variables computed against ECMWF's own analysis, up to 10 days ahead. The zero line represents errors without the assimilation of cloud radar and lidar observations, so that negative values indicate reduced errors. Bars indicate 95% confidence intervals. All scores are for the whole globe over the period of August to October 2007.



Better analyses

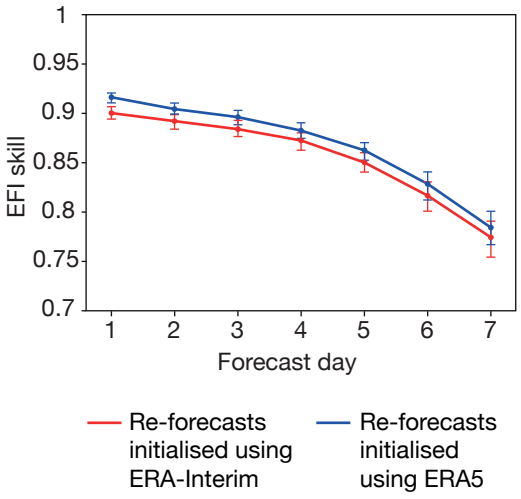
Normalised difference in root-mean-square deviation (RMSD) of forecasts from the experiment's own analysis with and without weakly coupled data assimilation (EXP minus CTR) for forecasts of temperature at 1,000 hPa 24 hours ahead, for the period 9 June 2017 to 21 May 2018. Blue shades mean that the differences between forecasts and the analysis are smaller when weakly coupled data assimilation is used.

resolution in the tropics than in the extratropics, where it is unable to resolve eddies. Experiments confirmed that the adoption of coupled atmosphere/sea-surface temperature/sea-ice data assimilation significantly improves the analysis of atmospheric variables such as temperature and humidity in the tropics and the polar regions.

Use of ERA5 to initialise re-forecasts

Reanalysis, in other words the combination of observations with model information to reconstruct past weather and climate, plays an important role in numerical weather prediction. An example of this is the use of reanalysis to initialise re-forecasts. Re-forecasts are forecasts produced at the current time but starting from some point in the past. They are used to estimate a forecast model climate, which is needed to calibrate forecast products. Re-forecasts also serve to assess extended-range forecast skill and the evolution of forecast skill from year to year.

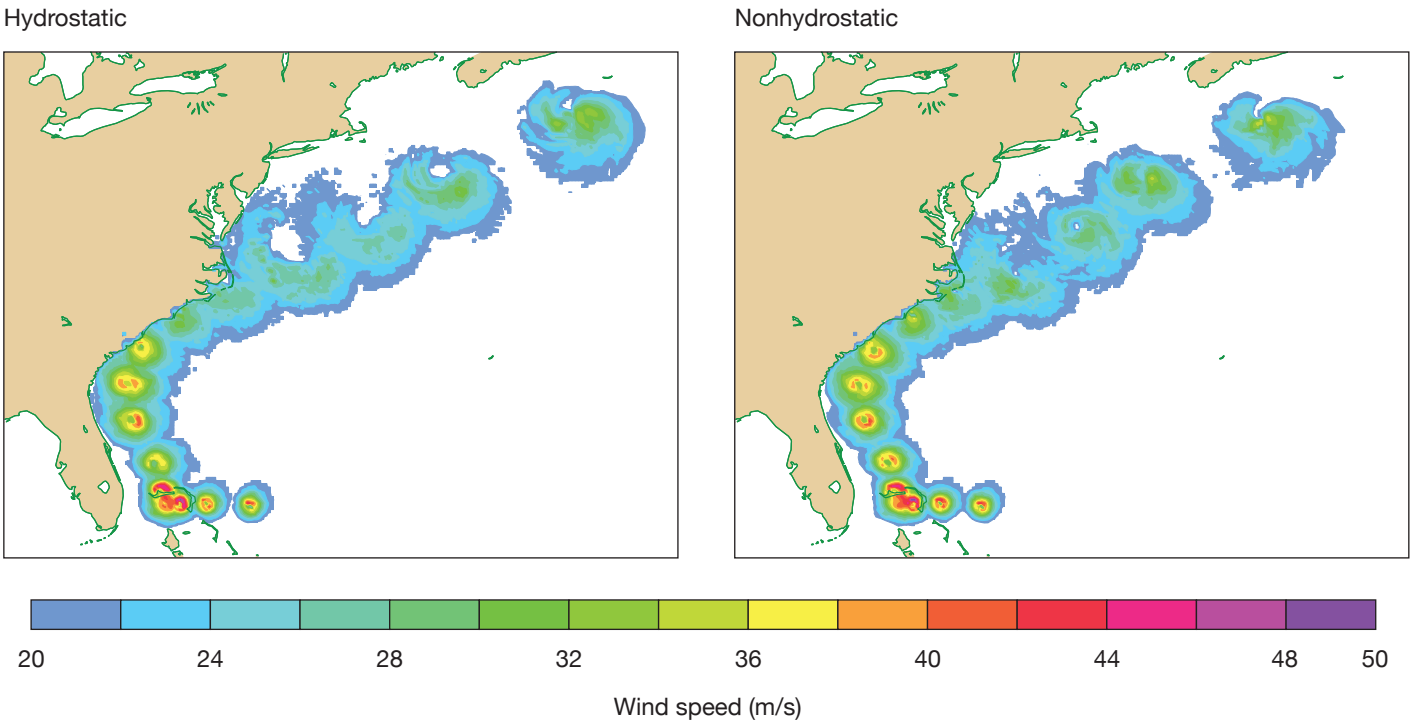
Like all forecasts, re-forecasts require a set of initial conditions, which reanalysis can readily supply. In 2019, ECMWF's new ERA5 reanalysis replaced the older ERA-Interim to initialise re-forecasts. Tests showed that this resulted in better re-forecasts, better Extreme Forecast Index (EFI) skill scores, and improvements in the prediction of extended-range anomalies.



Better EFI skill scores

The chart shows how using re-forecasts initialised using ERA5 instead of ERA-Interim improves EFI skill for global 2-metre temperature during the summer of 2018. Skill is here measured by a ROC area score (2 x ROC area – 1) so that '1' corresponds to a perfect forecast and '0' to 'no skill'. The vertical bars show 95% confidence intervals.

Advancing weather science



New numerical scheme

ECMWF has worked with experts in its Member and Co-operating States to test a new numerical scheme for calculations over the vertical grid used in its Integrated Forecasting System (IFS). The results are very encouraging. The IFS employs a spectral method to solve the equations describing atmospheric dynamics in the horizontal and a finite element method to solve them in the vertical. A team led by Jozef Vivoda from the Slovak Hydrometeorological Institute (SHMI) and Petra Smolíková from the Czech Hydrometeorological Institute (CHMI) has developed a new vertical finite element (VFE) scheme.

In 2019, the new scheme was adapted to the IFS and was shown to meet three key requirements: the need to enhance flexibility in the chosen accuracy in the vertical; robustness with reduced precision, which is computationally more efficient; and the need to prepare the IFS for higher resolutions, including the ability to run a nonhydrostatic version of the model that is compatible with the current hydrostatic one.

As the figure illustrates, a 10-day forecast at a grid spacing of 5 km with the new nonhydrostatic scheme for Hurricane Dorian is remarkably similar to the equivalent hydrostatic forecast using the new scheme. The forecasts also agree very well with the observed hurricane track.

▲ Forecasts using the new vertical finite element scheme

The charts show maximum 10 m wind speed for a 10-day forecast of Hurricane Dorian, starting from 12 UTC on 31 August 2019, at a grid spacing of 5 km, for every 12 hours starting 12 hours into the forecast. The left-hand panel shows the forecast using the hydrostatic IFS with the new VFE and the right-hand panel the forecast using the NH-IFS with the new VFE. Both forecasts were run in single precision, using the same time step of 240 s and, where applicable, identical settings for model dynamics.

Ocean wave upgrade

Ocean waves are an important part of the Earth system: they depend on conditions in the atmosphere and the ocean, and in turn they influence those conditions, for example by slowing down winds. As part of ECMWF's Earth system approach, the wave model component of the Integrated Forecasting System (IFS) is coupled to both the atmosphere and the ocean modelling subsystems.

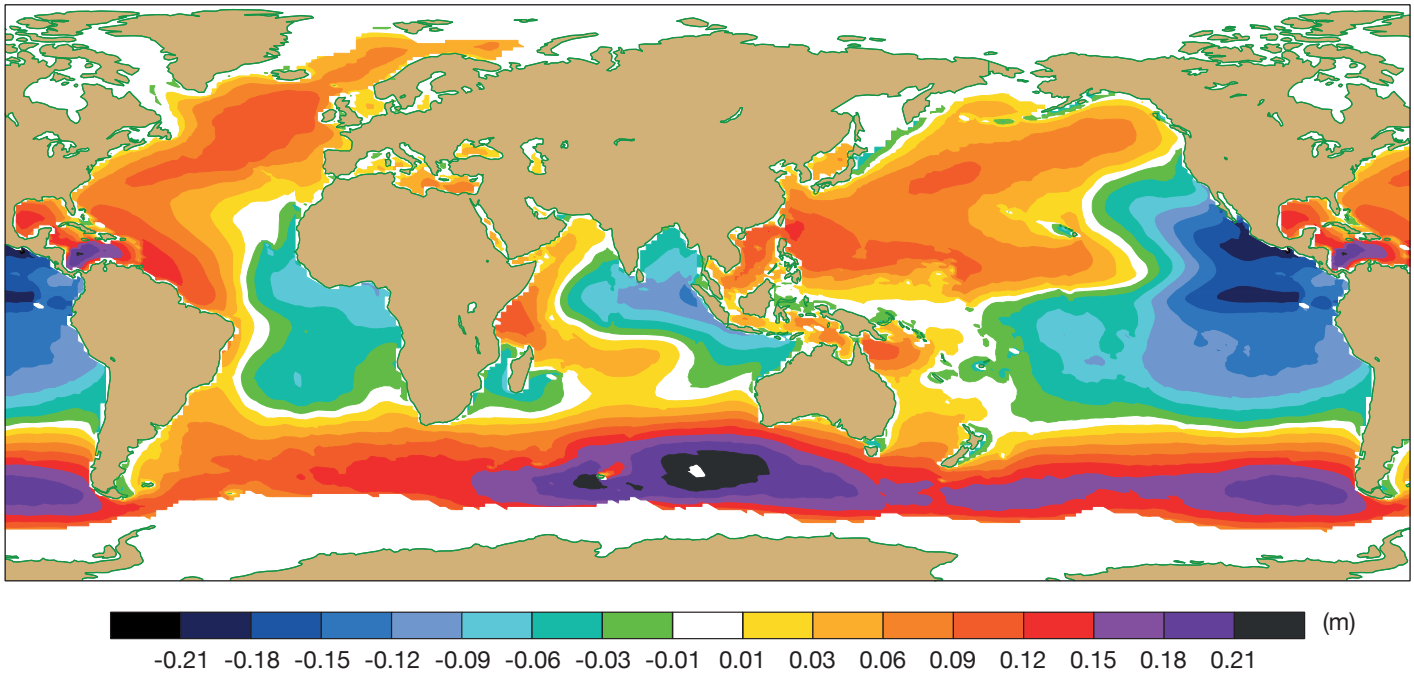
In 2019, ECMWF introduced modifications to its wave physics package to improve the prediction of ocean waves. The wave physics package models how the wind generates waves, how different waves interact with each other, and how wave energy gradually dissipates.

The changes in the physics package included new parametrizations for wind input and deep-water dissipation of waves as previously implemented by Météo-France, based on work by Fabrice Ardhuin (Ifremer, France) and collaborators. ECMWF scientists adapted and optimised the changes so that they would run efficiently in the IFS. They ensured that the new parametrizations return a similar level of feedback from the modelled sea state to the atmosphere model, and they assessed the impact of ocean waves as modelled by the new package on the modelled ocean circulation.

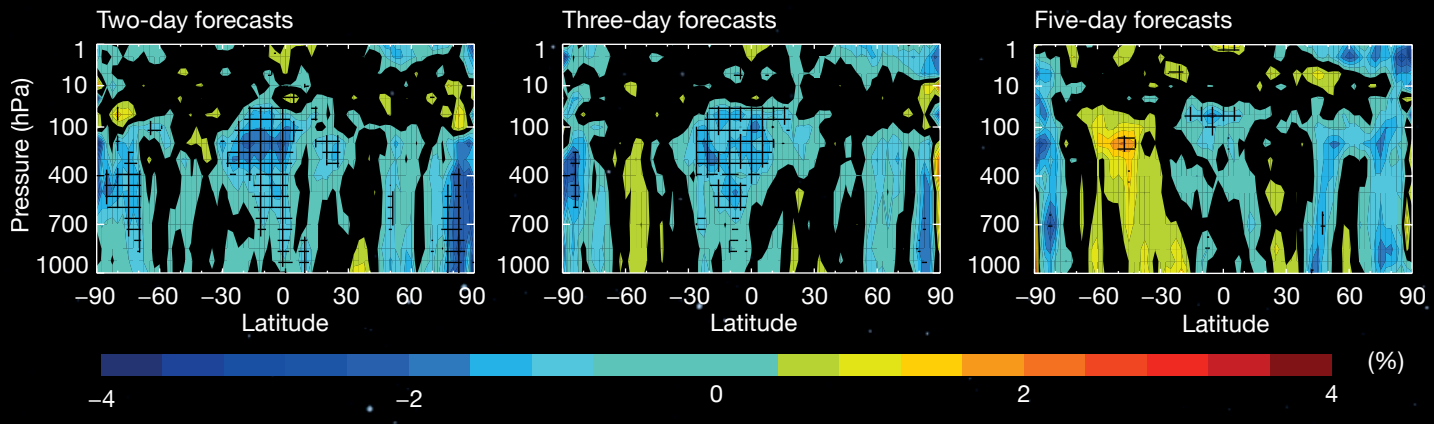
The main impact of the changes was increased accuracy and realism of ocean wave parameters, such as significant wave height (roughly the average height of the highest one third of waves). The new formulation reduced the overprediction of long period swell energy and the small wave height underestimation in the storm tracks. Forecasts were generally improved up to 10 days ahead.

▼ Differences between the new and the old wave physics

The chart shows the annual mean difference in significant wave height between the new and old wave physics (new minus old). The data are from standalone wave model runs with atmospheric and ocean variables provided by the ERA5 reanalysis.



Aeolus



▲ Impact on forecasts

Example of the impact of assimilating Aeolus wind data on 2-, 3- and 5-day forecasts for the period 2 August to 31 December 2019. The figure shows the relative change in root-mean-square (RMS) error of the vector wind forecast with the assimilation of Aeolus data compared to without it, verified against operational analyses. Hatching shows statistical significance at the 95% confidence level. Blue colours indicate forecast improvement due to Aeolus.

In 2019, ECMWF made decisive progress towards the operational use of wind data from the European Space Agency's ground-breaking Aeolus satellite. ECMWF scientists worked with others to resolve data quality issues, improve data processing and correct biases. By the end of the year, they had shown that assimilating Aeolus data improves forecasts.

After more than two decades of development, ESA's polar-orbiting Aeolus satellite was launched in August 2018. It carries just one large instrument – a Doppler wind lidar called ALADIN - which is the world's first functioning lidar to provide profiles of horizontal line of sight winds from space. Observations from Aeolus help to fill a significant gap in the global observing system, as many parts of the globe, such as the tropics, oceans and upper troposphere, lack wind profile measurements.

ECMWF has been closely involved with the mission right from the design phase. In 2019, the Centre made major strides in testing Aeolus data within the Integrated Forecasting System (IFS) to:

- understand data quality and biases and develop corrections,
- prepare the data and analysis system for operational assimilation to improve estimates of the initial state of the Earth system at the start of forecasts,
- investigate the effect of assimilating the data on medium-range weather forecasts.

ECMWF worked within the Aeolus DISC (Data Innovation and Science Cluster) closely with ESA, the German Aerospace Center (DLR), Météo-France, the Dutch national meteorological service (KNMI) and the software company DoRIT to identify and resolve any data quality issues and to contribute to improved data processing. The main problem from a data assimilation point of view was that the Aeolus data had biases that were larger and more complex to understand than was expected before launch.

Systematically comparing Aeolus winds with short-range ECMWF forecasts provided a very valuable method to assess the Aeolus wind biases. The method was also used to compute day-by-day bias corrections depending on the satellite's position in orbit. Tests showed that applying such bias corrections improves the impact of the Aeolus data on forecasts.

Further work showed that biases in Aeolus wind data were closely correlated with tiny temperature variations across the 1.5 m diameter mirror which forms an important part of the Aeolus instrument. A 0.1°C change in temperature difference was found to lead to a change in wind bias of around 5 m/s.

These results enabled Aeolus engineers and scientists to start investigating why such temperature differences cause large wind biases and if the mirror temperatures can be controlled better. This led to the development of an improved bias correction method. A better understanding will be very valuable when designing and building a potential follow-on Aeolus instrument.

The impact of assimilating Aeolus data compared to other Earth system observations was also tested. The overall impact of Aeolus data on short-term forecasts in the southern hemisphere and the tropics was found to be comparable to that of data from some other major components of the global observing system, such as Atmospheric Motion Vectors, satellite-to-satellite radio occultation data, and satellite data from infrared sensors.

Crucially, inclusion of Aeolus data was found to bring clear improvements in medium-range weather forecasts. The improvements are most marked in the tropics and near the poles.

The positive results meant that by the end of 2019 ECMWF was testing the assimilation of Aeolus data in e-suite mode in preparation for operational implementation in January 2020.

"As early as 15 months after launch, ECMWF and several other numerical weather prediction centres have shown very large improvements in weather forecasts when Aeolus data is assimilated in test experiments. This is a success story of close collaboration between ESA, ECMWF, other weather prediction centres and all scientists involved."

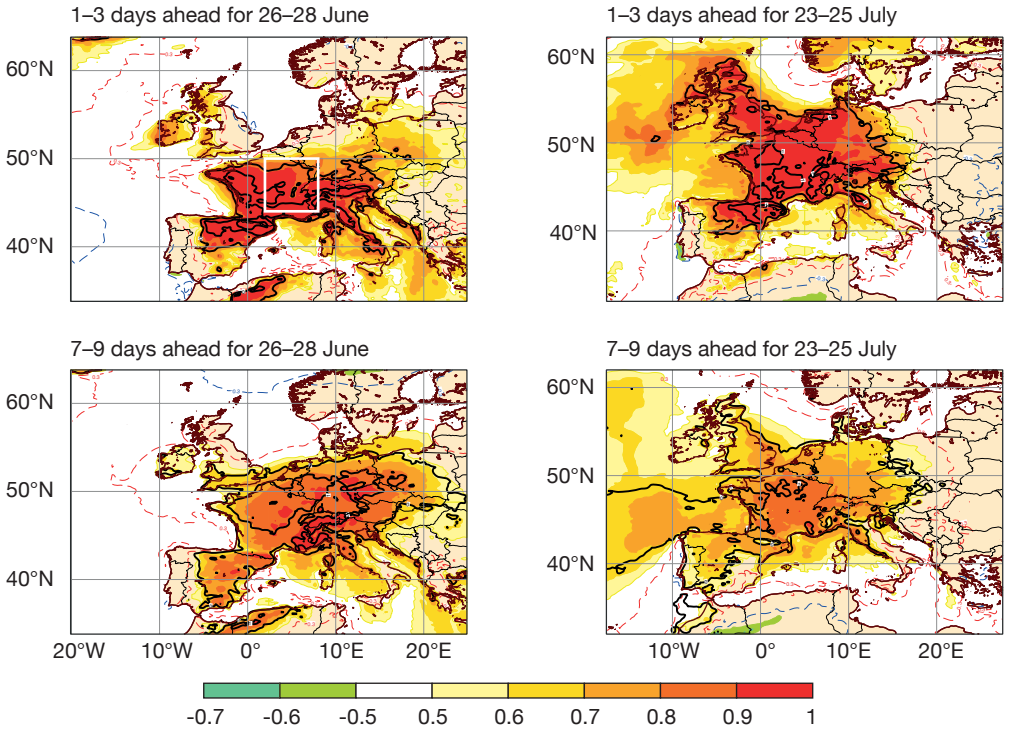
Tommaso Parrinello, Aeolus Mission Manager at ESA

Delivering global predictions

In 2019, ECMWF continued to provide high-quality weather predictions to its Member and Co-operating States and other users of its data and products across the globe. Severe weather events that were well predicted by ECMWF forecasts include freezing rain early in the year in Romania, two short heatwaves that brought record-breaking temperatures to many parts of Europe, and tropical cyclones that hit the Azores and Mozambique.

An upgrade of the Integrated Forecasting System (IFS) in June improved the skill of forecasts substantially across most variables and regions. Amongst many other improvements, IFS Cycle 46r1 introduced more continuous data assimilation to improve ECMWF's estimate of the state of the Earth system at the start of forecasts. It also included new ocean wave physics and new output parameters in the extended range to provide better advance information on the probability of severe weather.

Among many improvements in forecast scores, ECMWF recorded its highest ever skill for Extreme Forecast Index wind predictions. ECMWF also widened access to its products by making Ocean5 reanalysis charts freely accessible, and more products were made available to Members of the World Meteorological Organization (WMO). Experimental products to predict cold spells in Europe were made available to registered users, and a new product generation package was rolled out.



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

The charts show the EFI (shading) and SOT (contours) for maximum temperature in forecasts from 00 UTC on 26 June for 26–28 June (top left); from 00 UTC on 23 July for 23–25 July (top right); from 00 UTC on 20 June for 26–28 June (bottom left); and from 00 UTC on 17 July for 23–25 July (bottom right). The white square in the top left panel shows the area of 44°N–50°N and 2°E–8°E referred to in the text.

Two European heatwaves

In 2019, national all-time maximum temperature records tumbled in Belgium, France, Germany, Luxembourg, the Netherlands and the UK. The records were broken during two relatively short but extreme episodes of heat that hit western Europe at the end of June and the end of July 2019. The geographical extent of the heatwaves was well captured a week in advance, as illustrated in the panels showing Extreme Forecast Index predictions 7–9 days ahead.

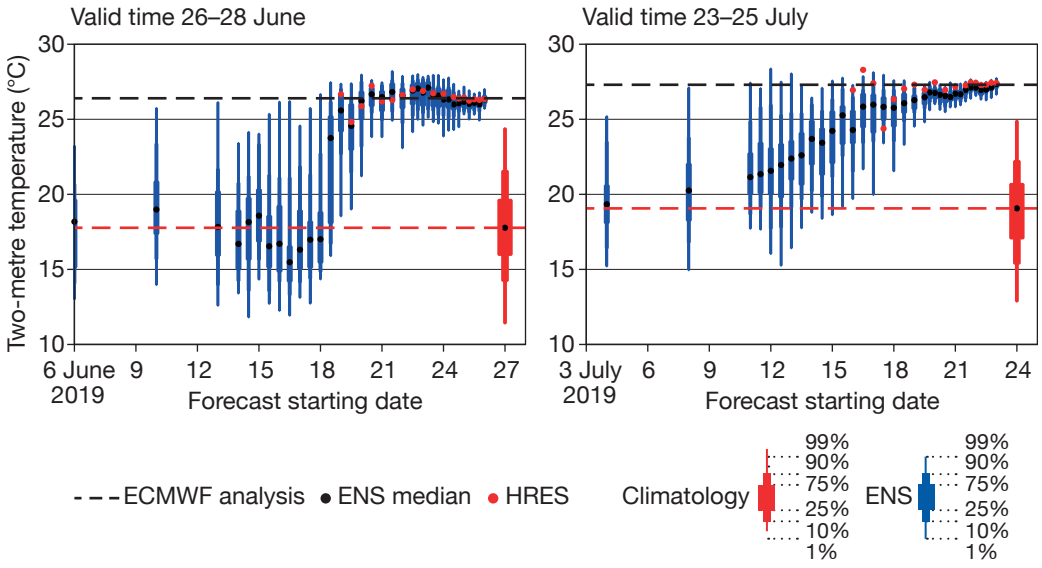
In the medium range, the ensemble forecast for the area shown as a white square in the EFI plots was more confident about the extreme heat for the June episode. This can be seen in the two plots below, where the blue symbols indicate the range of possible outcomes predicted at different times ranges ahead of the event.

However, between 9 and 11 days before the June event, most ensemble members actually predicted a cold anomaly. For the July episode, a warm anomaly was present in forecasts issued as early as two weeks in advance. Later on, the ensemble distribution continued to smoothly shift to more and more extreme temperatures, but with a large ensemble spread.

Response to tropical cyclone Idai

The tropical cyclone season of 2019 in the southern Indian Ocean was one of the most active on record, with 15 tropical storms. On 15 March, tropical cyclone Idai made landfall in Mozambique, causing around a thousand fatalities. This made Idai the deadliest cyclone in the southern Indian Ocean for more than 100 years.

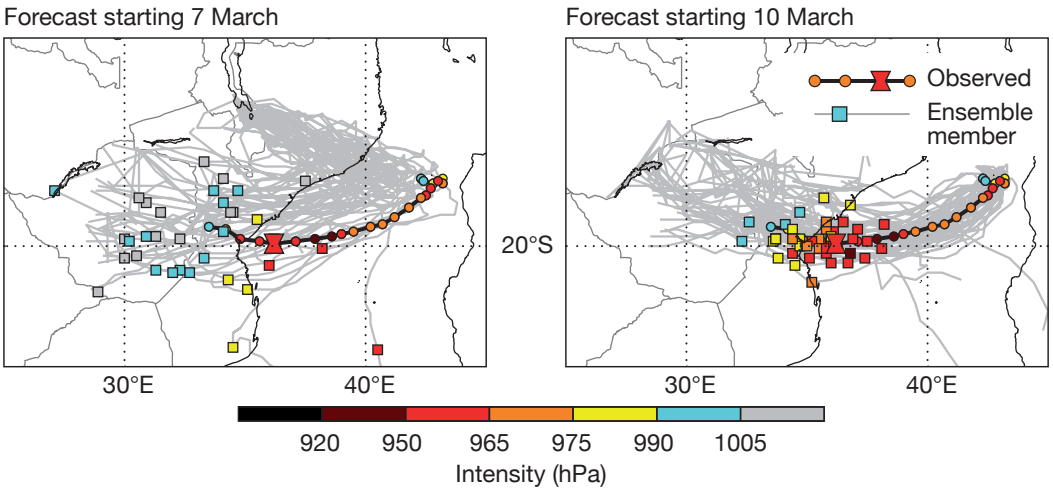
ECMWF's tropical cyclone track forecasts are available as free and open data. Our forecasts predicted the landfall location and extreme precipitation and winds with high confidence about 5 days ahead of landfall. At the same time range, flood forecasts based on ECMWF's precipitation forecasts indicated a moderate risk of severe flooding, rising to a very high risk after landfall.



◀ Ensemble temperature forecasts

The charts show the evolution of forecasts for 3-day average 2-metre temperature in western-central Europe (the white square in the EFI plots) valid on 26–28 June (left) and 23-25 July (right). The blue box-and-whisker symbols show ensemble forecasts for different starting dates. The red dots indicate ECMWF's deterministic high-resolution forecasts (HRES).

Delivering global predictions



◀ ECMWF's track, position and intensity forecasts for Idai

The plots show forecasts starting at 00 UTC on 7 March 2019 (left) and 00 UTC on 10 March 2019 (right). The squares indicate position and intensity forecasts for 12 UTC on 14 March. The black line shows the observed track ('Best Track' estimate), while the observed position and intensity at 12 UTC on 14 March is indicated by the hourglass symbol.

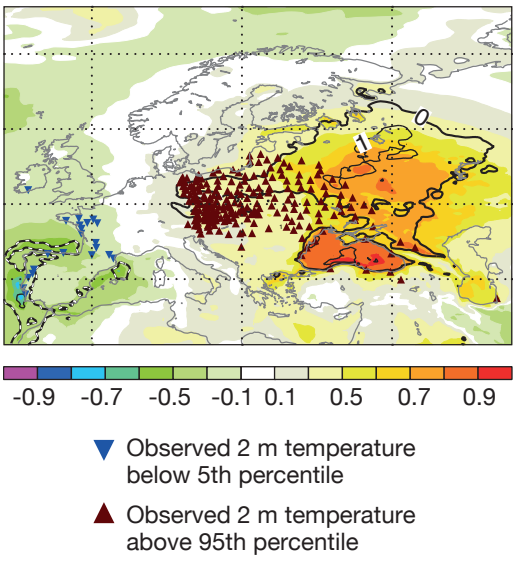
ECMWF worked with partners at the Universities of Reading and Bristol and the UK Government to support the humanitarian response to the disaster.

It did so by helping to provide scientific information on flood hazard and population exposure. Forecasts from the Copernicus Emergency Management Service's Global Flood Awareness System (GloFAS), for which ECMWF is the computational centre, played a key role. They were used in combination with satellite imagery and flood extent maps to identify where, when and for how long flooding may occur, as well as where people may be impacted.

New forecast outputs

The upgrade of ECMWF's Integrated Forecasting System to IFS Cycle 46r1 in June 2019 introduced an Extreme Forecast Index (EFI) for water vapour flux as well as new EFI and Shift of Tails (SOT) products to highlight potential extremes in the extended range. The new extended-range EFI and SOT were for 2-metre temperature and total precipitation. An example is shown in the figure.

Also as part of 46r1, probabilities for 850 hPa temperature anomalies in terms of standard deviations from the model climate average, as well as additional probability thresholds for precipitation and near-surface (10 m) wind, were added to support the activities of World Meteorological Organization Members. Ocean fields, including sub-surface data such as the depth of the 20°C isotherm and the average salinity and potential temperature in the upper 300 m, were also made available.



◀ Extended-range Extreme Forecast Index (EFI) & Shift of Tails (SOT)

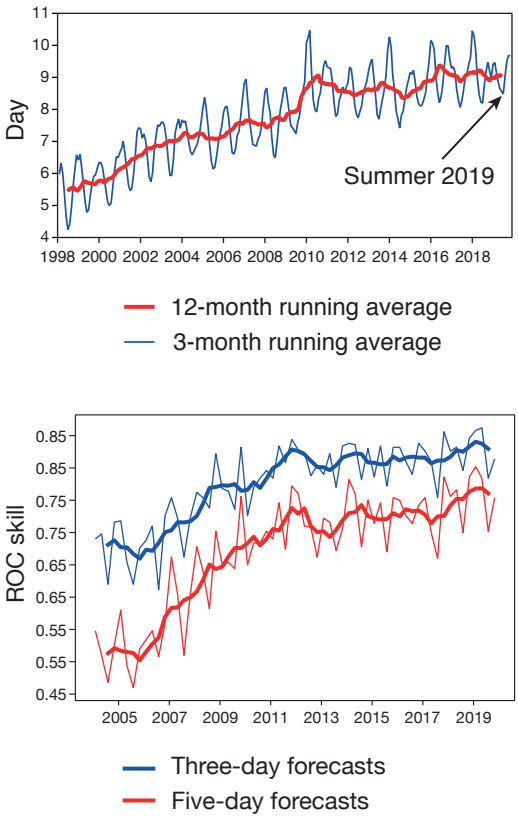
The chart shows the EFI (shading) and SOT (contours) for 2-metre temperature from 00 UTC on 3 June 2019 for the week from 10 to 17 June together with the locations where the observed 2-metre temperature in that week was below the 5th percentile or above the 95th percentile of the observed 20 year climatology. The forecast gave an indication of the anomalously cold conditions in the west and the unusually hot conditions in eastern Europe.

Forecast performance

On 11 June 2019, ECMWF implemented a substantial upgrade of its Integrated Forecasting System (IFS). IFS Cycle 46r1 included changes in the model and in the data assimilation procedure used to generate the initial conditions for forecasts. For example, the more continuous data assimilation introduced by 46r1 enabled the use of additional and more recent observations. The upgrade had a very positive impact on the skill of medium-range and extended-range ensemble forecasts (ENS) and medium-range high-resolution deterministic forecasts (HRES). Improvements could be seen across a range of parameters and atmospheric levels, including surface weather parameters.

Upper-air performance of the ensemble forecast (ENS) is monitored through the continuous ranked probability score (CRPS) for temperature at 850 hPa over the northern hemisphere extratropics. As the first chart shows, forecast skill during summer 2019 was higher than in previous summer seasons, and comparison with re-forecast skill based on the ERA5 reanalysis shows that this is partly due to the IFS upgrade.

The second score shown here monitors forecast skill for strong winds in terms of the Extreme Forecast Index. This score reached its highest ever value in 2019. There was also a slight increase in forecast skill for 2-metre temperature, and a gain in precipitation forecast skill. In addition, ocean wave parameters in the HRES were improved in Cycle 46r1 by up to 10% due to a major upgrade in the ocean wave model.



More products for WMO Members

In July 2019, ECMWF substantially increased the amount of weather prediction products it makes available free of charge to Members of the World Meteorological Organization (WMO). All the static web charts and the Ensemble Meteogram on the ECMWF website were made available to all WMO Members.

The additional products enabled a much more comprehensive view than before of atmospheric conditions as predicted by ECMWF, including near-surface weather conditions. The products included both probabilistic and deterministic forecasts.

◀ Skill of the ENS as measured by ECMWF's primary headline score

Evolution of 850 hPa temperature ensemble forecast performance in the northern hemisphere extratropics, verified against the corresponding analysis. The chart shows 12-month and 3-month running average values of the forecast range at which the continuous ranked probability skill score (CPRSS) falls below 25%.

◀ ENS headline score for strong winds

Evolution of the skill of the Extreme Forecast Index (EFI) for 10-metre wind speed in Europe at day 3 and day 5, verified against SYNOP weather station observations. The chart shows 12-month running average values (bold) and seasonal values.

Delivering global predictions

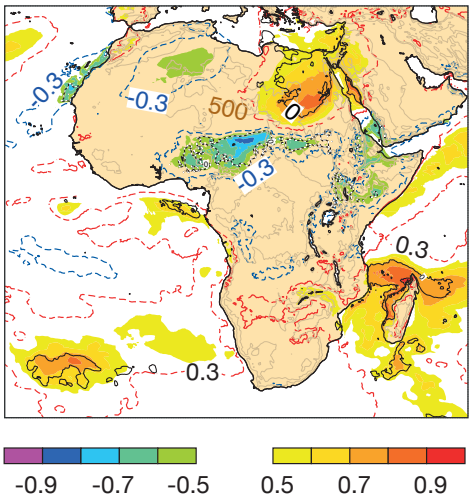
The changes helped to provide forecasters in the national meteorological and hydrological services (NMHSs) of WMO Members with the information they need to carry out their operational activities.

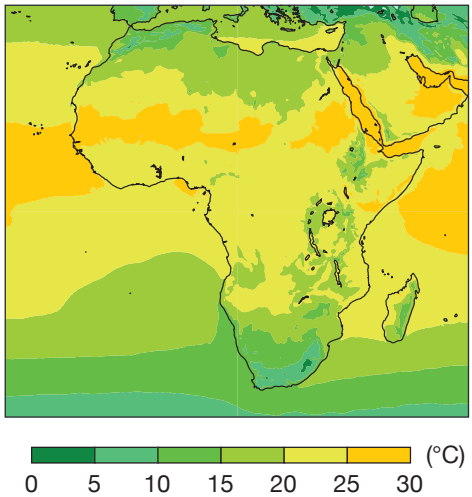
ECMWF also reduced the cost of the NMHS web non-commercial licence, which gives access to the ecCharts service, and it introduced a cheaper 'standard' licence which provides access to a fixed dataset of the licensee's specification for a reduced fee. The changes were approved by the ECMWF Council at its June 2019 session and are part of the Centre's efforts to serve WMO Members.

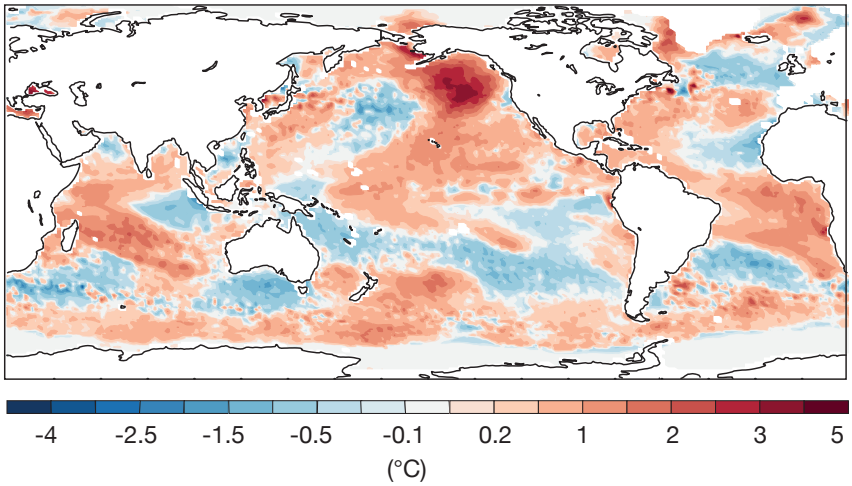
Ocean5 charts made available online

Ocean5 is ECMWF's current ocean and sea-ice analysis system. It provides initial conditions for the ocean and sea-ice component of ECMWF's Earth system forecasting system. Ocean5 runs both a behind-real-time stream that produces the Ocean Re-Analysis System 5 (ORAS5) and a near-real-time (NRT) stream. ORAS5 is used for climate monitoring while Ocean5 NRT provides initial conditions for the Centre's forecasting activities.

In November 2019, charts for each stream were made freely accessible to both internal and external users on the ECMWF website. At the time, the daily sea-surface temperature (SST) maps showed a persistent anomalously warm water mass off the west coast of North America and Alaska. This is illustrated in the figure for 26 November 2019. This 'marine heatwave' looked similar to a long-lasting marine heatwave in the same area from 2014 to 2016, baptised 'the Blob' by the community.







◀ New products for WMO Members

The new products include static charts such as the Extreme Forecast Index (EFI) for 2 m temperature. The top panel shows the EFI (shading and dashed contours) and the Shift of Tails (SOT) (solid contours) from 00 UTC on 2 October 2019 for 72-hour 2 m mean temperature valid from 8 to 11 October 2019. The bottom panel shows the 99th percentile of the corresponding model climate for those days.

▼ Sea-surface temperature (SST) anomaly November 2019

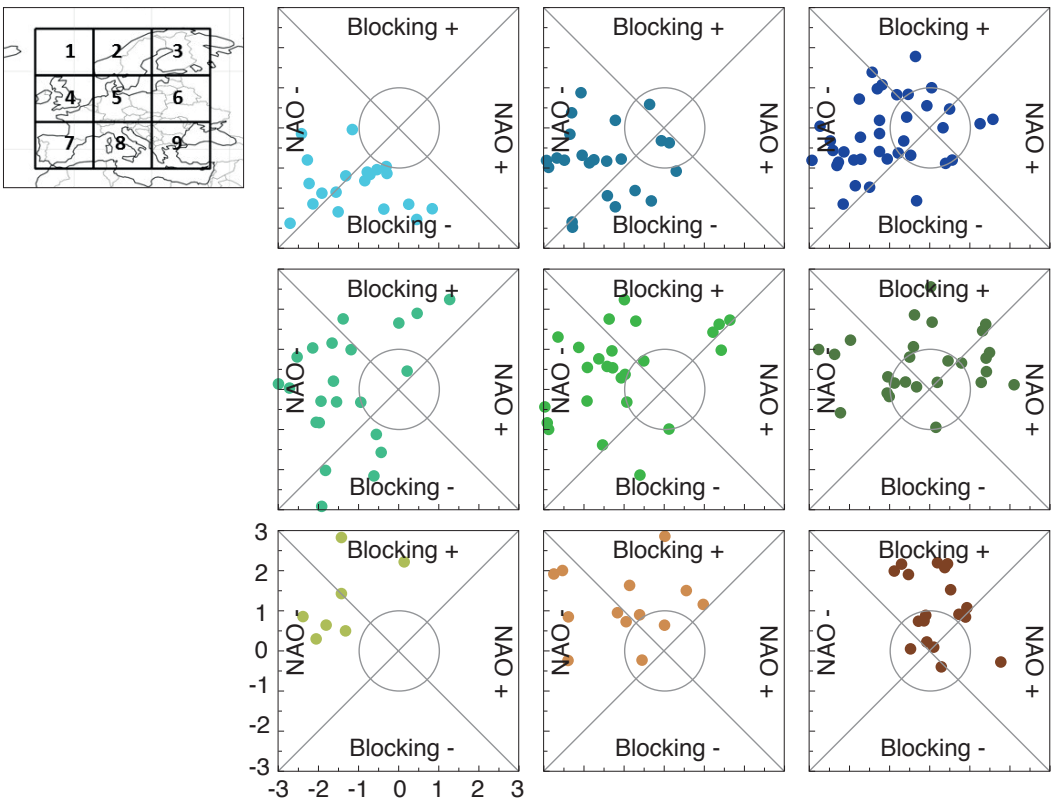
This Ocean5 NRT chart shows the SST anomaly on 26 November 2019 computed with respect to the 1993–2016 climate from ORAS5. This kind of chart and many more are freely available to view and download on the ORAS5 and Ocean5 NRT pages on ECMWF's website.

Testing new extended-range products

A particular concern at the sub-seasonal forecast range (up to 60 days ahead) is the ability to predict high-impact, large-scale and long-lived weather events, such as cold spells or heatwaves. ECMWF's Strategy to 2025 calls for skilful predictions of regime transitions up to four weeks ahead. In 2019, experimental products to predict cold spells in Europe were made available to registered users. Tests had shown that the products had useful skill up to two and a half weeks ahead.

The products exploit the fact that cold spells in different parts of Europe are closely linked with the occurrence of particular weather regimes. These include a blocking high over Scandinavia ('Blocking' in the Figure below), and anomalously high pressure over Greenland combined with low pressure over the Azores (a pattern known as the negative phase of the North Atlantic Oscillation, 'NAO-').

ECMWF ensemble forecasts were found to provide reliable probabilities of cold conditions associated with the establishment of the NAO- pattern beyond the medium range. The predictability of such events is enhanced by tropical–extratropical teleconnections. On the other hand, predicting the occurrence of cold events associated with a transition to blocking was found to present a bigger challenge.



◀ Predicting cold spells in the extended forecast range

The occurrence of cold spells in Europe is closely linked to large-scale atmospheric circulation patterns, such as Blocking and the negative phase of the North Atlantic Oscillation (NAO-). In the figure, this is illustrated for nine different regions in Europe. For each region, the diagrams show the dominant circulation patterns associated with severe cold events (indicated by the dots) that occurred from 1980 to 2015.

Spectrum and Earth observations

> This is the first time we've seen a threat to what I'd call the crown jewels of our frequencies – the ones that we absolutely must defend come what may.

Stephen English, Head of Earth System Assimilation Section at ECMWF

The radio frequency bands used for many Earth observation satellites and other systems are now facing interference from the growing demands of non-meteorological applications.

Numerical weather prediction (NWP) relies on data from satellites, radiosondes, aircraft, radar and other observing systems as inputs. In turn, these observing systems rely on the allocation of radio frequency bands both for directly observing the Earth system and for exchanging observations through telecommunication networks. Many non-meteorological technologies, such as wifi, mobile phones and radios, also rely on radio frequencies, and many new applications are emerging.

It is vital to ensure continued allocation of the frequencies required for Earth observation, as well as protecting these frequencies from out-of-band emissions from neighbouring frequency bands. NWP users are already seeing evidence of radio frequency interference.

The allocation of radio frequency bands is agreed internationally at the annual International Telecommunication Union (ITU) World Radiocommunication Conference (WRC), held every four years. In the WRC, the demands of different application areas need to be weighed up, taking into account economic and societal benefits. The aim is not to hamper new technologies, but to make sure that their implementation does not interfere with life-saving applications, such as weather prediction.

The World Meteorological Organization (WMO), with strong support from space agencies such as EUMETSAT and ESA, as well as EUMETFREQ (a EUMETNET programme), coordinates the response of the international meteorological community and represents the community at WRC. For the meteorological case to be fairly heard, the best and most up-to-date information is required on the value of radio frequency bands to meteorology, in terms that can be compared to other application areas. ECMWF has been proactive in providing information and coordinating inputs from the wider meteorological community to support the WMO and the space agencies.

Many satellite observations for NWP use passive sensing techniques in radio frequency bands.

Passive sensing makes it possible to gain information on the current state of the Earth system by exploiting the absorption characteristics of the atmosphere. Such passive measurements are made by very sensitive instruments that measure the very low-power microwave radiances naturally emitted from the atmosphere and the Earth's surface. Such passive microwave sensors are used to provide information on atmospheric temperature, moisture, clouds, precipitation and surface properties. These passive techniques are vulnerable to interference from new users of radio frequencies.

Furthermore, assessments of the impact of weather observations have found that microwave observations are presently the most important satellite observing system for global NWP, typically contributing around 30–40% of the overall improvement in forecast skill arising from the use of observations.

New applications outside the field of meteorology (e.g. 5G) are interested in the microwave frequency bands adjacent to 24 GHz and 50 GHz, which are crucial for obtaining accurate estimates of water vapour and temperature.

The use of radio frequencies in meteorology is not limited to these passive microwave observations. Systems such as weather radar also suffer from radio frequency interference. Radiosondes rely on a specific allocation for tracking and telecommunication. Command and download of data from all satellites needs specific frequency allocations.

ITU's World Radiocommunication Conference in 2019 (WRC-19) in Sharm el-Sheikh, Egypt, agreed that 5G could operate at a number of frequency bands, including 24.25 to 27.5 GHz. To reduce interference with satellite observations, it was also agreed that 5G equipment would limit the strength of signals within the 24.25–27.5 GHz band. However, the agreement reached in Egypt falls far short of ensuring 5G applications do not interfere with weather observations. ECMWF continues to discuss with Member States and regulatory authorities to bring forward an agreement to strengthen protection before the main 5G rollout at 24.25–27.5 GHz.

Sustaining high-performance computing

In December 2019, ECMWF's Council of Member States gave ECMWF authorisation to sign a contract with Atos for the supply of the BullSequana XH2000 supercomputer.

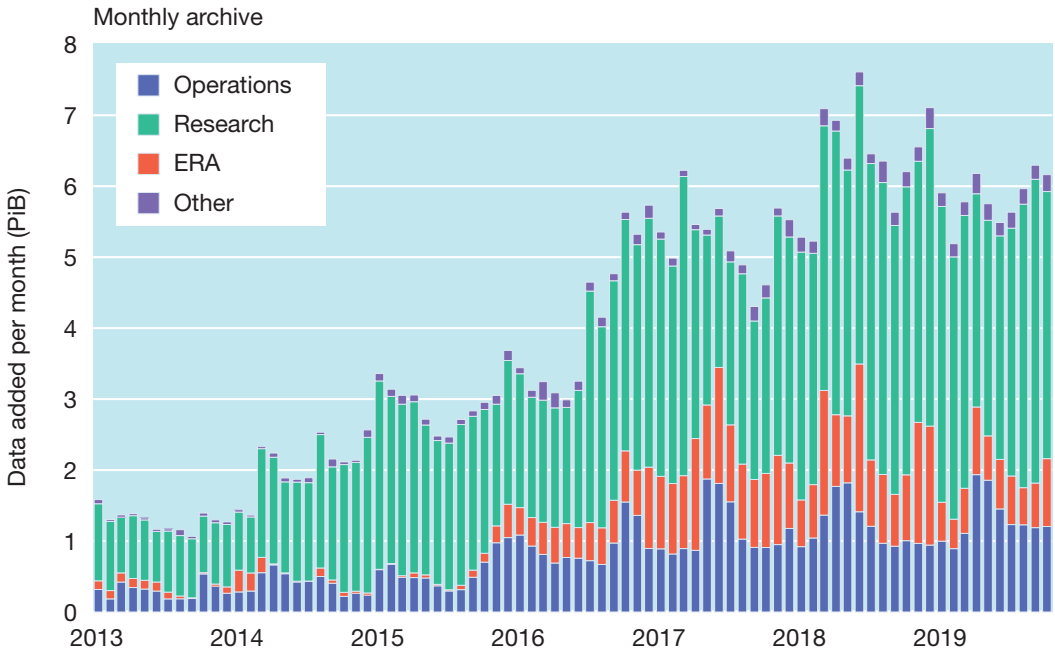
The supercomputer will be hosted in the new ECMWF data centre currently being developed by the Italian Government and the Regione Emilia-Romagna in Bologna, Italy. It is expected to be fitted in 2020 and to become fully operational at the end of 2021.

The Cray XC40 HPCF

ECMWF's current Cray XC40 high-performance computing facility (HPCF) continued to provide a good and stable service, processing more than half a million jobs per day on average. At the end of 2019, the data archive held 310 petabytes of primary data and a further 123 petabytes of backups. On average around 290 terabytes of new data is added to the archive daily, and 220 terabytes retrieved. Despite the amount of data added to the archive daily, the overall size of the primary archive was little changed over the year, showing the benefit of data stewardship efforts.

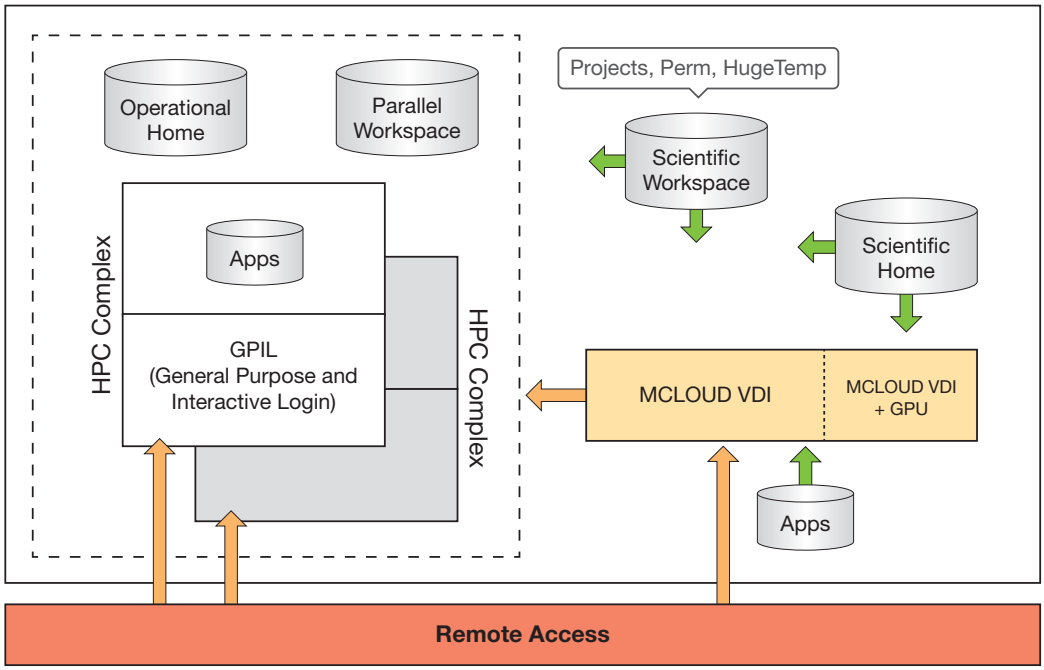
New IBM tape libraries were installed at Shinfield Park and put into operational use. Old, but still needed, data held in the Oracle

> "The high-performance computing facility processes more than half a million jobs per day on average."



◀ Monthly data archive growth

The increase in the growth of ECMWF's data archive has been driven by three areas: research, the ERA-Interim and ERA5 weather and climate reanalyses, and operations.



New operating model for end-user compute

The operating model developed by the Centre's Technical Design Authority is being used to validate user workflows and ensure all service components are migrated to or created for the Bologna environment.

tape libraries is being migrated to the new libraries in a process that will take several years to complete.

The High-Performance Storage System (HPSS), which provides the backbone of ECMWF's Data Handling System, was upgraded in May 2019, in turn allowing the core platform to be moved from an AIX-based system to a more powerful Linux-based machine. This will help support the load increase anticipated from the new supercomputer and is a prerequisite for supporting the new tape libraries and drives and migration to Bologna.

In addition to running the existing data centre and managing the network, considerable work went into designing the ICT service for the new data centre and for the European Weather Cloud pilot phase. Member States have a new web-based tool for managing user access to ECMWF services, the network infrastructure at Shinfield Park has been prepared for the site-to-site connection to Bologna, and many web services have moved to a new Single Sign-On platform. A major effort to wind down legacy infrastructure and services got under way with a view to simplifying the migration to Bologna.

Work also went into building and testing new systems for data centre infrastructure management, service configuration management, and server and application deployment automation.

Sustaining high-performance computing

New supercomputer contract

A comprehensive tender process was launched in 2018 for the new ECMWF HPCF. The tenders submitted were assessed against criteria including committed performance, implementation plan, flexibility and risks, quality of technical solution, environmental impact, quality of service provision and support, and price.

At its December session, ECMWF's Council authorised the Director-General to sign a contract with the successful tenderer, Atos UK Ltd. The new facility will be provided under a four-year service agreement and will deliver a performance increase of about five over the current system, based on the time-critical capability and capacity benchmarks. It will be hosted in the new data centre in Bologna and initially will run in parallel with the existing Cray HPCF.

The high-performance computing facility serves not only to produce forecasts but also to run research experiments designed to push the boundaries of predictability, including ground-breaking work on the assimilation of cloud observations from satellite radar and lidar into ECMWF's Integrated Forecasting System (IFS), and progress towards assimilating satellite radiances in the visible part of the spectrum.

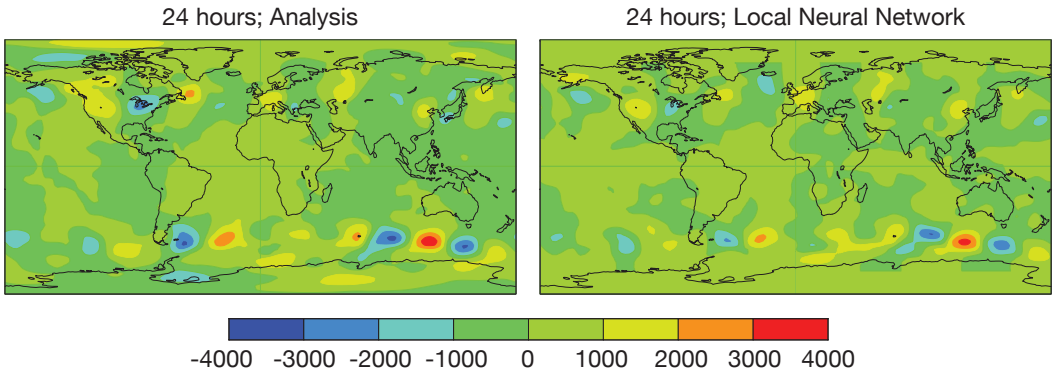
Of the available computing resources, 25% is allocated for workload from ECMWF Member States.

> "The new facility will deliver a performance increase of about five over the current system."

	Cray XC40	Atos Sequana XH2000
Clusters	2	4
Processor type	Intel Broadwell	AMD Epyc Rome
Cores	18 cores/socket, 36 cores/node	64 cores/socket, 128 cores/node
Base frequency	2.10 GHz	2.25 GHz (compute) 2.5 GHz (GPIL)
Memory/node	128 GiB (compute)	256 GiB (compute) 512 GiB (GPIL)
Total number of compute nodes	7,020	7,488
General purpose 'GPIL' nodes	208	448
Total memory	0.9 PiB	2.19 PiB
Total number of cores	260,208	1,038,848
Water-cooled racks	40	80
Air-cooled racks	0	10

◀ System specifications

The Cray XC40 system and the new Atos Sequana XH2000 system.



◀ Neural network experiments

Geopotential at 500 hPa (in m^2/s^2) between 00 UTC on 1 March and 00 UTC on 2 March 2017 according to the analysis (left) and according to a 24-hour neural network forecast starting from the analysis at 00 UTC on 1 March (right).

Scalability Programme

The first phase of ECMWF's Scalability Programme, a major programme to prepare all ECMWF's systems for future supercomputer architectures, is complete. The second, implementation phase (2020–2024) will bring the results into operation.

The cutting-edge research of the first phase was achieved through close work with ECMWF's Member States, participation in several European research projects funded by the European Commission, and the support of actors in public–private partnership ETP4HPC and PRACE. This participation provides key contributions to European infrastructure investments and to the planning of funding programmes.

Examples include the EU-funded NEXTGenIO and ESCAPE-2 projects. ECMWF was one of 8 partners in NEXTGenIO, which ended in October following a final workshop and hackathon hosted by ECMWF. The project designed and built a prototype hardware platform that promises massive gains in input/output (I/O) capabilities in supercomputing. Some of the developments have been implemented at ECMWF: FDB5 (Fields Database 5) and MultIO are used in ECMWF's time-critical operational workflows.

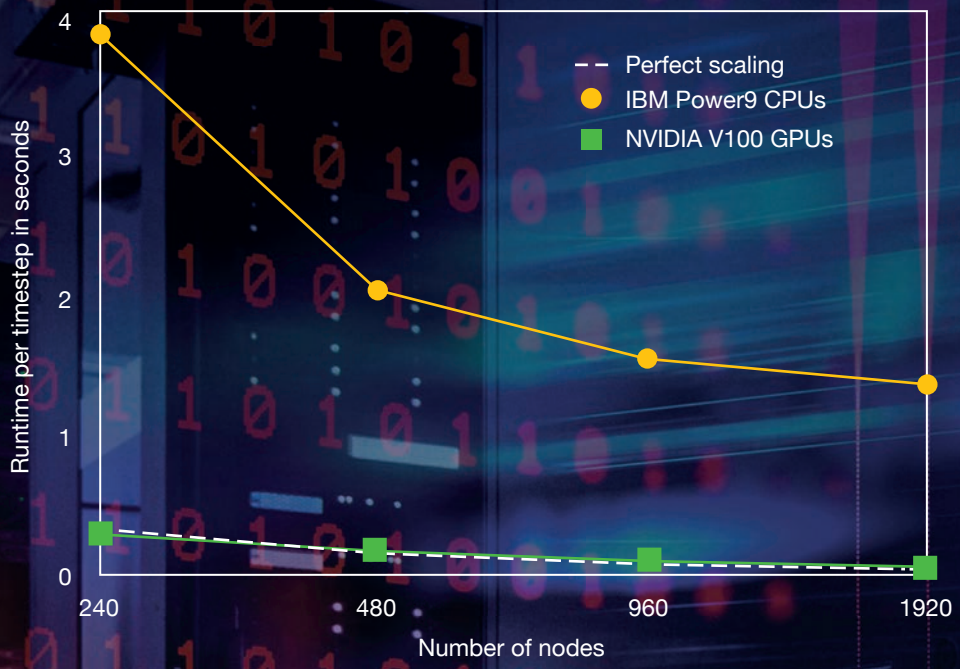
ESCAPE-2, led by ECMWF, is preparing components of leading European Earth system models for heterogeneous processor architectures through advanced numerical method and novel programming approaches.

Such individual developments are being tested and disseminated through the EU-funded ESiWACE centre of excellence, which aims to coordinate research and its transfer to operations across weather and climate prediction centres in Europe, and for which ECMWF coordinates the weather prediction efforts.

With machine learning and artificial intelligence expected to play an important role in ECMWF's long-term Strategy, in 2019 the Centre appointed a Coordinator of machine learning and artificial intelligence (AI) activities at ECMWF.

Potential areas of use for AI techniques include data quality control; bias correction in data assimilation; emulating model components; and quantifying uncertainty. For example, experiments carried out at ECMWF illustrate that properly trained neural networks can already make short-range predictions of surprising accuracy.

Scalability



▲ Spherical harmonics

Scaling of spherical harmonics dwarf across multiple Summit nodes, using a hybrid Open-MP/OpenACC/MPI configuration, using GPUdirect for MPI_alltoallv and Cuda DGEMM/FFT libraries across multiple nodes. Each node uses 6 MPI tasks and each MPI task uses one V100 GPU.

The largest simulation therefore corresponds to 11,520 GPUs. Each Summit node contains two IBM POWER9 processors and six NVIDIA Volta V100 accelerators. Each physical core supports up to four hardware threads.

ECMWF's ten-year Scalability Programme has reached its crucial half-way stage. Key operational benefits have been achieved as well as extensive exploratory work that shows the way forward for our high-performance computing systems. The programme is key for supporting future developments in weather forecasting and climate prediction.

The Scalability Programme is ensuring that ECMWF's high-performance computing can support the Centre's ambitious targets to deliver more accurate predictions, using higher resolution and more complex modelling, greater use of ensembles and vastly increased volumes of data of all forms. The Programme also aims to keep the Centre's computing energy usage at sustainable levels. Progress and plans were documented by the Scalability team in a special topic paper for ECMWF committees in 2019.

Over the first phase of the Programme, the existing ECMWF prediction system has been benchmarked on some of the largest supercomputing facilities in the world. A US Department of Energy (DoE) INCITE award gave ECMWF access to the largest machine in the world, called Summit, allowing both the efficiency and scalability of the Integrated Forecasting System (IFS) to be tested on central processing units (CPUs), and the performance of one of its most costly components, the spectral transforms, to be demonstrated on graphical processing units (GPUs).

The most promising options to optimise the performance of the existing code infrastructure have been explored. For example, mixed precision arithmetics, concurrent execution of model components, overlapping computation and communication, and the use of more efficient CPU-type processors and interconnects are expected to provide code speed-ups of the order of three as soon as the new machine has been fully tested.

Weather and climate dwarfs, a concept developed as part of the Programme, divide the forecasting model into functional units (e.g. the advection scheme) which have specific computational patterns. Using dwarfs, the potential optimisation with new processor technologies can be explored efficiently and the technologies benchmarked. The dwarf concept also provides a way to estimate the sustained performance of the full forecasting system on large-scale, future supercomputers.

The most computationally costly model components have been tested on GPUs and throughput speed-ups of more than 20 have been achieved, compared with CPUs. The first ever implementation of a forecast model component on a Field Programmable Gate Array (FPGA) improved the time to solution by 2.5 and reduced energy use by at least a factor of 10.

ECMWF has built its entire performance enhancement strategy on co-design of numerical methods/algorithms with code implementation. This strategy means that scientific and computing performance can be traded off against each other, and extensions to the modelling system will be future proof.

Observational data and model and product output are growing in terms of both volume and diversity. Hence a key focus of the Scalability Programme has been on tools for managing fast and flexible data access and minimising data transfer across the memory hierarchy. This has already led to modernisation of the data handling system and a 5-fold speed-up in product generation, alongside greater system robustness.

The Kronos workflow simulation and benchmark generator software is entirely new and a major step towards realistic capacity benchmarking. For the first time, Kronos can provide a full workflow representation including IFS model output and product generation. This has made the benchmarks much closer to the reality of running our operational system.

The Scalability Programme has established ECMWF as the leading centre performing cutting-edge research at the interface between computational and weather and climate science, while working with its Member States and drawing on computational expertise more widely. Leadership and involvement in European programmes is drawing in additional funding of some €1.5 million per year over 2015 to 2021.

Next phase

The main two focuses will be 'performance portability' and 'data-centric workflows'. Many elements of these already exist from developments in the first phase, but their full implementation throughout the entire forecasting system will still require a significant commitment.

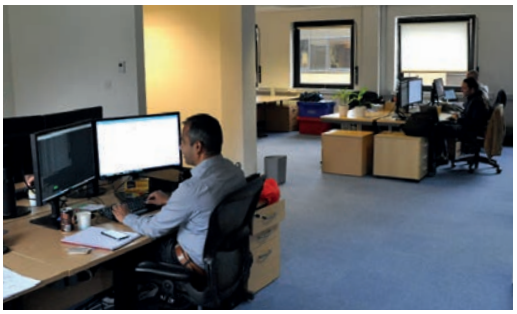
Enabling ECMWF

2019 was exceptionally busy on the administrative and governance side, with the migration of the data centre to Bologna, the procurement of a new high-performance computing facility (HPCF) and the Future Accommodation project contributing to a peak of activity. Brexit dominated the period, with diverse work carried out to understand and monitor the consequences of the departure of the UK from the EU for many aspects of the organisation.

The Enterprise Resource Planning (ERP) system went live at the start of the year, integrating HR and accounting processes. Work then focused on ensuring that the change management process was completed. Work is ongoing to exploit the reporting capabilities of the system and provide useful information for decision-making and for operating as a multi-site organisation.

Procurement, financial and legal resources were mobilised to support the procurement of the new HPCF. In January, the Centre held an industry day in Bologna to explain how ECMWF would be procuring equipment and services for the new data centre. The procurement team worked on 18 invitations to tender, with some concluded and others still open at the end of the year.

▲ **Bologna data centre**
Building work began in earnest at the start of the year.



◀ Reading office refurbishment

The aim was to increase the number of desktops and allow better collaboration among teams in a renovated and dynamic space.

Accommodation

The Centre rationalised the use of office and meeting room space at Shinfield Park, creating new open plan areas and adding a modular building. This made it possible for all staff who had been based in rented offices at the University of Reading to move back to the Shinfield Park headquarters.

Work continued apace on the design proposals for future, long-term ECMWF office and conferencing accommodation on the University of Reading campus. However, the project was paused in the autumn in light of the potential relocation of ECMWF's EU-funded activities and the impact that such a decision could have on the size and costs of the new building. In December, the Council approved the recommendation for the establishment of an ECMWF facility in a location compatible with all key European Union funding policies relevant for ECMWF and established an Evaluation Panel to review proposals for hosting such a facility.

ECMWF continued to support the establishment of the data centre in Italy, liaising also with international organisations operating in Italy to acquire valuable information to support this. The Centre obtained a Codice Fiscale, required to be quoted for all commercial transactions in Italy, and staff members received training in the use of the Italian Government's online system for registering staff members and issuing VAT exemptions.

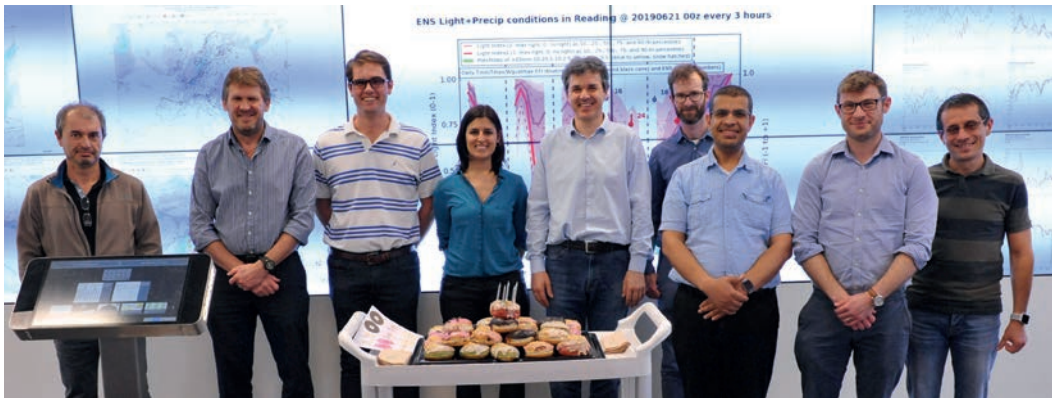
By the end of the year, 5 members of staff had transferred to Bologna. To mark the considerable data centre progress achieved during the year, all staff were invited to an Italian-themed lunch, with colleagues from Bologna joining via video link.

ECMWF staff

As an international organisation, ECMWF is proud of its multicultural environment with 372 members of staff from 30 different countries at the end of 2019. During the year ECMWF hosted 4 graduate trainees from Croatia, Germany, Hungary and Serbia; 7 visiting scientists from China and Japan; and 6 visiting scientists as part of a new short-term secondment scheme developed with Member States.

The implications of Brexit for staff and their families, and the transfer of staff to Bologna were given much consideration throughout the year. The Centre continued to interact with the relevant authorities in the UK Government, notably the Foreign and Commonwealth Office (FCO), regarding matters related immigration control, the right to work for spouses of ECMWF staff, and access to higher education for staff dependants.

Enabling ECMWF



▲ **Weather discussion** ECMWF analysts on the 5th anniversary of the weekly Weather Discussion, where staff consider forecast performance and interesting weather events.

A pilot teleworking scheme introduced in 2018 came to an end. A staff survey concluded that the pilot had emphatically met its objective of offering more flexible working options for staff without impacting productivity negatively. The Centre has used the lessons learned to develop a policy to be implemented during 2020. In the meantime, staff continue to be able to telework under the pilot scheme conditions.

The Centre also began a comprehensive review of family-related policies in response to ECMWF's diversity policy and staff feedback.

An initiative from staff to establish an informal well-being network was embraced by the Centre. The network was launched in October, providing a forum to discuss mental health issues and come up with initiatives in support of improving the way the Centre addresses this topic, including raising awareness, line manager training and new support mechanisms.

There were regular opportunities to keep staff up to date with developments in topical areas, and to highlight staff achievements and efforts to engage with young people and our wider community.

ECMWF funding

The ongoing uncertainty around the timing and the modality in which the United Kingdom would leave the European Union continued to influence the volatility of the sterling/euro exchange rates. With the establishment of the new data centre in Bologna, the Centre carefully monitored expenses in both currencies to reduce long-term exposure to currency variations.

The high demand for ECMWF data and products generated an increase in sales and contracts and contributed to a budgetary surplus. In parallel, the Centre continued to work on a new charging and delivery model. In December, the Council agreed that ECMWF would move towards a free and open data policy in phases over a period of several years, starting in 2020.

▲ **Well-being network**

Staff at the launch event in October.

▲ **Visiting analysts**

L-R: Jordan Rice (ECMWF) with visiting SAPP analysts Mikko Aalto (Finnish Meteorological Institute) and Volkan Firat (Turkish State Meteorological Service).

▲ **Community engagement**

ECMWF scientist Marcus Koehler visited a local primary school as part of the school's Science Week, where he gave presentations to children aged 9 to 11 years on the topics of weather, weather forecasting, climate and climate change.

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 £48 million, representing the main proportion of the Centre's £112.3 million funding. External organisations support both core research and the complementary goals of the Centre with funding of £54.7 million, while revenue from sales of data and products provides additional income of over £10.2 million.

In 2019 ECMWF continued to invest in its staff, infrastructure and systems to provide the highest quality products to its Member and Co-operating States. The main areas of expenditure are summarised below, and include capital investment of £2.8 million, principally for IT and infrastructure.

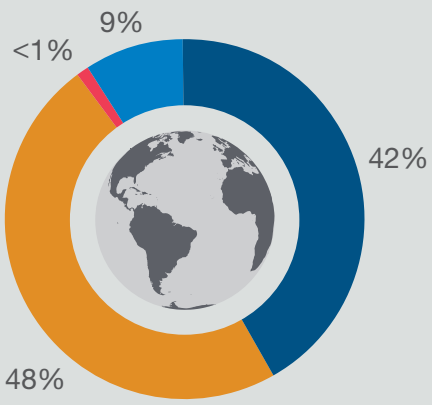
The main areas of expenditure related to remuneration and related items (£26.5 million), computer expenses (£20.1 million), buildings (£5.9 million), pension schemes (£5.6 million), and other operating activities (£4.1 million). Costs associated with externally funded projects amounted to £47 million and net finance costs were £5.9 million.

ECMWF's budget remains on a cash basis and the Financial Statements include a reconciliation of the results under IPSAS and in cash terms. Under cash accounting, the Centre generated a surplus of £0.913 million in 2019, the use of which will be decided by the ECMWF Council.

Note: all numbers exclude Centre tax.

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

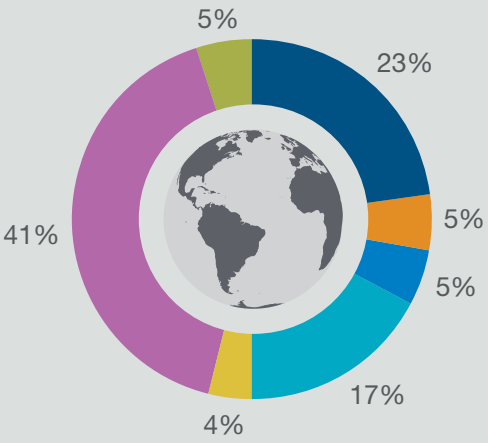
Funding



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

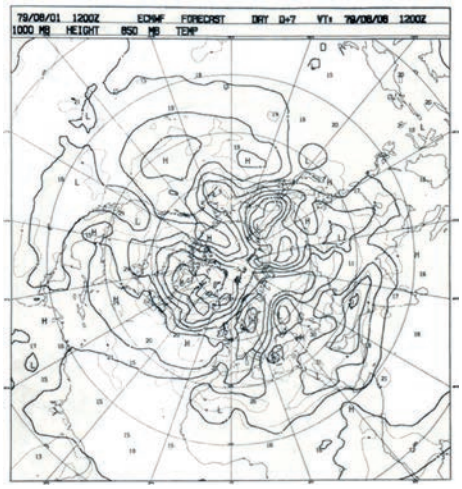
* excludes transfers to BOND reserves of £755k

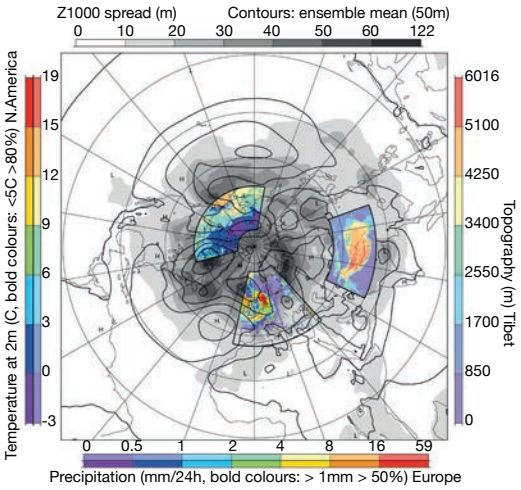
Costs



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

Serving Member and Co-operating States





◀ Forty years of operational forecasting

Ensemble re-forecast of ECMWF's first operational forecast (right). Initial conditions on 1 August 1979 at 12 UTC for the 50-member ensemble are derived from the ERA5 ensemble reanalysis. This 7-day forecast uses the current operational model (IFS Cycle 46r1). Contours show the ensemble-mean 1000 hPa height field which can be compared with the first operational forecast (left). Grey shading shows the ensemble standard deviation. The coloured regions highlight the detail and ensemble information available in present-day forecasts.

2019 marked 40 years since ECMWF disseminated its first operational medium-range forecast. In the decades since then, the Centre has continued to work with its Member and Co-operating States and other partners to improve the quality, range and accessibility of its weather forecasts. Free and open data to help address today's environmental challenges are also being provided through ECMWF's growing involvement in the EU's Copernicus Programme.

Access to forecast products and software

Several new products were introduced with Cycle 46r1 of the Integrated Forecasting System (IFS), including 200 m winds, for wind turbine related applications, and specialised wave model parameters.

In September, the dissemination of a number of products, such as daily ensemble information, moved 20 minutes earlier.

New software became operational for the generation of forecast products for our Member and Co-operating States and other users. It provides more efficient and robust user-tailored post-processing as well as making maintenance and development easier.

The Scalable Acquisition and Pre-Processing (SAPP) Optional Programme was launched early in 2019. The programme provides Member and Co-operating States with the option to install, in their own operational environment, ECMWF's system for acquiring and processing observations and other input data. By June it was supported by 15 Member and Co-operating States, and in November Met Éireann used SAPP for the first time operationally. ECMWF also hosted a number of visiting analysts from participating countries and a workshop on the programme.

The second ECMWF Summer of Weather Code invited software developers, weather professionals and scientists to work with ECMWF mentors to create new and innovative software offering benefits for forecasting models, users and training.

> A new learning platform has been developed which will significantly improve the user experience and the tracking of individual learning journeys.

◀ SAPP workshop

The first workshop was attended by more than 25 representatives from 14 Member and Co-operating States.

OpenIFS@home started as a new collaboration with the University of Oxford's e-research centre and has seen a low-resolution version of OpenIFS included within the 'climateprediction.net' framework. This framework allows the OpenIFS to run on tens of thousands of volunteer computers providing a large ensemble of experiments without the use of a supercomputer.

Developments in artificial intelligence (AI) are bringing new tools that can be used to emulate complex non-linear systems, to detect patterns in large datasets and to downscale coarse-scale products. Potential applications of machine learning, and in particular deep learning, exist across the entire workflow of NWP, environmental and climate services. The scope for widening the use of AI in Earth system applications was discussed at the '1st Artificial Intelligence for Copernicus workshop' held at the Centre in November and in a lecture for Council delegates in December.

At the end of its first year, the European Weather Cloud pilot project has implemented its first use cases and engaged Member States in the project, which in partnership with EUMETSAT aims to provide data-related services via cloud technology. Direct network connectivity was established between a user's virtual machine and the data handling system, marking an important milestone in the project.

Training, workshops and knowledge sharing

ECMWF offers a broad training programme to increase the benefit of ECMWF forecast products to Member and Co-operating States. A new 'NWP primer' was run in conjunction with the OpenIFS course. In addition to standard training activities, in May ECMWF ran an online training week, providing webinars on specific topics related to the software packages and applications used at the Centre. Over 2019 as a whole, 770 people took part in ECMWF training courses, the majority of which were delivered as blended learning (online resources augmented with face-to-face sessions).

A study commissioned to assess the ECMWF training programme found that: (i) Member and Co-operating States are keen to collaborate with ECMWF in delivering learning activities; (ii) advertising of training-relevant events needs to be improved; (iii) online learning should be expanded; and (iv) clear levels and learning pathways need to be established. A new learning platform has been developed which will significantly improve the user experience and the tracking of individual learning journeys. It is the same platform as used by the Copernicus Climate Change Service (C3S) User Learning Services, adding to synergies between core ECMWF and Copernicus activities.

▲ Events and workshops

Using ECMWF Forecasts (top), 1st Copernicus AI workshop (centre), and visit from Twente University Applied Physics students, the Netherlands (bottom).

Serving Member and Co-operating States

An active programme of events included the 'Observational campaigns for better weather forecasts' workshop to review and strengthen the synergies between observational field campaigns and numerical weather prediction. The user meeting in June (UEF 2019) focused on ensemble forecasting, while the Annual Seminar covered recent progress and future prospects for sub-seasonal and seasonal forecasting.

ECMWF has installed a higher quality live-streaming system, improving the remote access to events for delegates and speakers, as well as reducing their carbon footprint. For the first time, two online webinars were streamed ahead of the IFS upgrade in June to brief users on developments. The Centre is also encouraging staff to use webinars to share the science developed at ECMWF.

Liaison visits to Member and Co-operating States provided opportunities for knowledge sharing, networking and additional training, with visits made to Austria, Denmark, Finland, Germany, Iceland, Italy, Israel, Latvia, Lithuania and Portugal.

Fellows and secondees

In addition to its highly successful Fellowship Programme, ECMWF introduced a new programme of short-term secondments to facilitate the flow of talent between ECMWF and the national meteorological services of its Member and Co-operating States. Six such secondments were completed in 2019.

Four EUMETSAT Fellows are hosted at ECMWF. Their work spans research and operations: it ranges from assessing the quality of new satellite data before operational use to maintaining and improving the operational data assimilation system for the best use of such satellite data.

ECMWF Fellows in 2019

Professor Tilmann Gneiting, leader of Computational Statistics group at Heidelberg Institute for Theoretical Studies (HITS) and Professor of Computational Statistics at the Karlsruhe Institute of Technology (KIT), Germany

Professor Rupert Klein, Freie Universität Berlin, Germany

Professor Tim Palmer, Royal Society Research Professor in Climate Physics at the University of Oxford, UK

Professor Daniel Jacob, Vasco McCoy Family Professor of Atmospheric Chemistry and Environmental Engineering, Harvard University, USA

Professor Heini Wernli, Professor of Atmospheric Dynamics at the Institute of Atmospheric and Climate Science, ETH Zurich, Switzerland

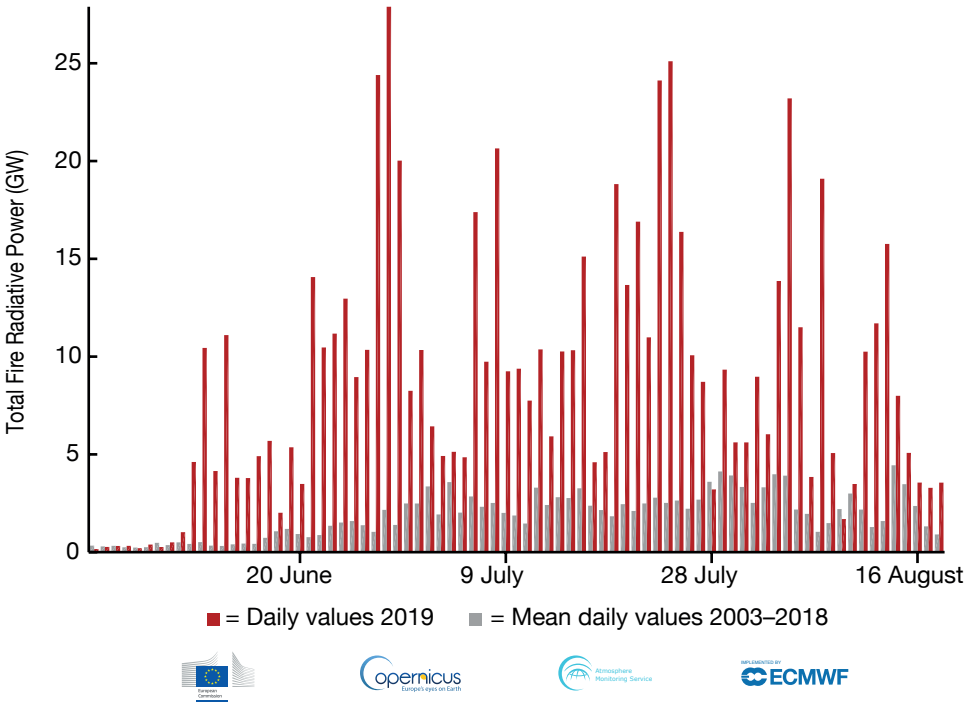
Professor Marc Bocquet, senior researcher and deputy director of CEREA, a joint laboratory of École des Ponts ParisTech and EdF R&D, and Professor at École des Ponts ParisTech, France

Dr Louise Nuijens, assistant professor in the Department of Geosciences and Remote Sensing at Delft University of Technology (TU Delft), the Netherlands

Dr Maria-Helena Ramos, research scientist in hydrology and hydrometeorology at the National Research Institute of Science and Technology for Environment and Agriculture (Irstea), France

◀ EUMETSAT Fellows

EUMETSAT Research Fellows hosted at ECMWF investigate ways to improve the use of satellite data, including data from EUMETSAT's Meteosat Second Generation satellites, a 1:4 scale model of which is shown in the picture. L-R: Katie Lean, Chris Burrows, Katrin Lonitz, Peter Weston.



◀ Global Fire Assimilation System

Data from the CAMS Global Fire Assimilation System showed that the daily radiative power from wildfires within the Arctic Circle was above the 2003 to 2018 average almost every day during summer 2019.

Copernicus services implemented by ECMWF

The use and visibility of the EU-funded Copernicus Atmosphere Monitoring Service (CAMS) and the Copernicus Climate Change Service (C3S) implemented by ECMWF continued to grow rapidly with increasing user numbers and growing coverage within traditional and social media.

2019 also saw a new Director of Copernicus Services at ECMWF. Jean-Noël Thépaut, a key player in the implementation of the C3S and CAMS at ECMWF, took up the position on 1 October when Juan Garces de Marcilla stepped down from the post.

The synergies between ECMWF and the Copernicus services it implements continue to bring benefits. Collaboration between C3S and CAMS and the Copernicus Emergency Management Service (CEMS) resulted in Global Flood Awareness System (GloFAS) and European Flood Awareness System (EFAS) flood forecasts being made available through the C3S Climate Data Store.

A new Data and Information Access Service (DIAS) platform called WEkEO became operational, with 1,000 users by the end of 2019. Developed collaboratively with EUMETSAT and Mercator Ocean, WEkEO consists of cloud-based services that make all Copernicus data and information available to users, as well as providing data processing tools.

Copernicus Atmosphere Monitoring Service (CAMS)

In July the CAMS global forecasting system was successfully upgraded to IFS Cycle 46r1. CAMS-specific improvements included a doubling of vertical levels from 60 to 137; an increased number of aerosol species; and updated emissions datasets.

In the course of 2019 CAMS products were used extensively during a number of incidents, including air pollution and Saharan dust episodes affecting Europe, and wildfires over the Arctic and Brazil. During these incidents CAMS products were highly visible in social media and national news websites across Europe.

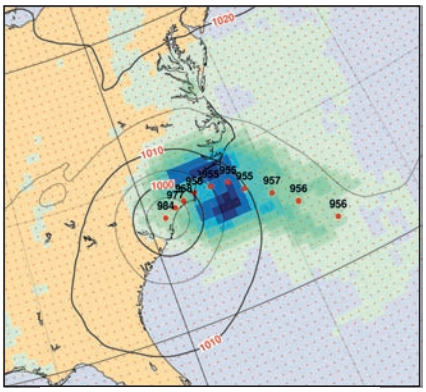
The European Environment Agency (EEA) is using regional air quality forecasts from CAMS as input to the European Air Quality Index platform. The European Commission's DG-CLIMA Ozone Layer Unit is using CAMS ozone layer information for its website. A partnership with CNN International began in October to include CAMS data in their daily air quality bulletins.

By the end of 2019 the number of CAMS users had reached 13,000.

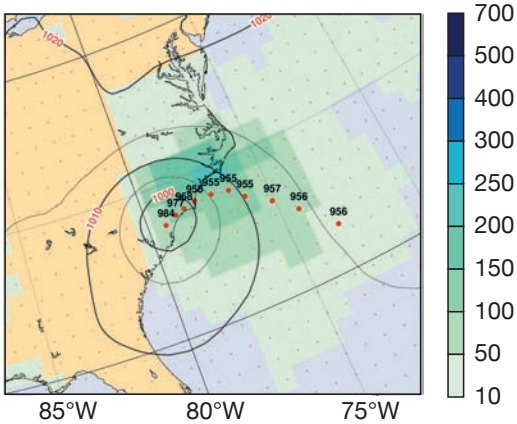
> "The synergies between ECMWF and the Copernicus services it implements continue to bring benefits."

Serving Member and Co-operating States

ERA5



ERA-Interim



◀ ERA5

Hurricane Florence struck the east coast of the US in September 2018. The plot shows the track (red dots), intensity (contours, in hPa) and accumulated rainfall (shading, in mm) at 09 UTC on 15 September 2018 from ERA5 and ERA-Interim (ECMWF's previous reanalysis dataset).

Copernicus Climate Change Service (C3S)

By the end of 2019, the Climate Data Store (CDS) of the C3S had more than 30,000 users, provided access to 45 datasets, and was delivering an average of 50 TB of data per day. The first set of public applications were released in the CDS Toolbox, allowing users to interact with the data in a simple way.

A major milestone for the C3S was reached at the beginning of 2019 with the availability in the CDS of 40 years of the latest ECMWF reanalysis dataset (ERA5, the successor of ERA-Interim), from 1979 to present. Work to extend ERA5 back to 1950 continued through the year. ERA5-Land data from 2001 to 2019 were also included in the CDS. ERA5-Land is a downscaled version of ERA5 at 9 km resolution providing more detailed land-surface variables, such as soil moisture and run-off.

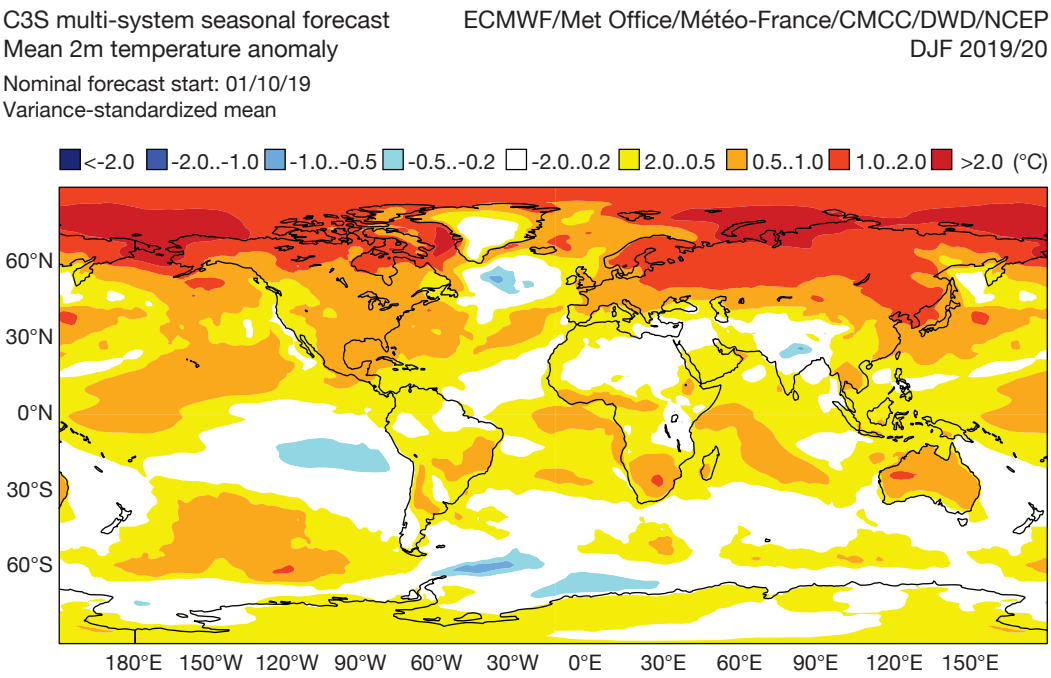
Last but not least, the long awaited ERA5T was released in the CDS in December. ERA5T provides preliminary data for ERA5 on a daily basis, with a 5-day delay from real time.

Based on ERA5, the world's first near real-time hydrological and fire danger reanalyses were released in the Climate Data Store in November. They provide an invaluable resource to help understand how unusual present-day wildfires and river flows are, and how they are changing.

Seasonal forecasts

The C3S multi-model seasonal forecasting system took over from EUROSIP, the project through which ECMWF had been providing multi-model seasonal forecasts since 2005. The C3S system has become mainstream for a number of users, including the European Commission's Joint Research Centre.

The resources made available by C3S have allowed the inclusion of more forecasting systems, with contributions from the German meteorological service (DWD), the Euro-Mediterranean Center on Climate Change (CMCC) in Italy and, most recently, the US National Centers for Environmental Prediction (NCEP) adding to the original three EUROSIP partners, (ECMWF, Météo-France and the UK Met Office).



◀ Seasonal forecasts

Example C3S multi-model forecast from 1 October 2019 of the ensemble mean 2-metre temperature anomaly for December 2019 to February 2020.

Copernicus Emergency Management Service (CEMS)

ECMWF continued to contribute to the Copernicus Emergency Management Service (CEMS), in particular the early warning systems for flood and fire danger. A new web interface was released for EFAS that offers a more intuitive map viewer and provides new functionalities and access to old forecasts. The EFAS climatology and forecasts were also made available to the Copernicus Climate Data Store.

Working with the Universities of Reading and Bristol and the UK Government, real-time flood risk analyses were provided through GloFAS during a number of severe cyclone events in Mozambique and Zimbabwe. Information was shared through the United Nations Office for Coordination of Humanitarian Affairs, the Mozambique disaster management agency and NGOs in the region.

ECMWF started operational delivery of probabilistic extreme forecast information for the fire weather index. This represented the first issue of a fully probabilistic fire product by the European Forest Fire Information System.

The Climate Data Store

> The Copernicus Climate Change Service's Climate Data Store supports climate services in Europe by providing seamless access to high-quality climate datasets, past, present and future.

EMS Technology Achievement Award citation

The Copernicus Climate Change Service's Climate Data Store is going from strength to strength. In 2019 its importance was recognised with a major prize and a number of other important milestones were reached.

In 2019, the ECMWF team that developed the Climate Data Store (CDS) was awarded the prestigious European Meteorological Society (EMS) Technology Achievement Award for supporting "climate services in Europe by providing seamless access to high-quality climate datasets, past, present and future".

The award recognised that the CDS is "empowering a wide range of user communities worldwide to work on addressing climate change".

Launched in 2018, the CDS provides easy access to a huge wealth of data from the EU's Copernicus Programme, including climate-related Earth observations, reanalyses, seasonal forecasts, and projections of future climate. It is open to all and free to use. By the end of 2019, the number of registered CDS users had gone up from just over 5,000 at the end of 2018 to about 30,000.

The CDS is a cloud-based tool which, through a single web-based interface, gives users access to vast amounts of data distributed across many locations. The CDS also includes an application programming interface and a toolbox which allow users to extract, manipulate and plot data and to create their own web-based applications. The first set of toolbox applications was released to the public during the year, representing a game changing achievement.

CDS users have access to petabytes of data, but because of the CDS architecture and its ability to process data, the amount of data that users need to download can be as low as in the order of kilobytes.

Catering for a range of interests and levels of expertise, the CDS allows users including policy-makers, businesses and scientists to access and process data in a way that suits them and to convert those data into information to support decision-making.

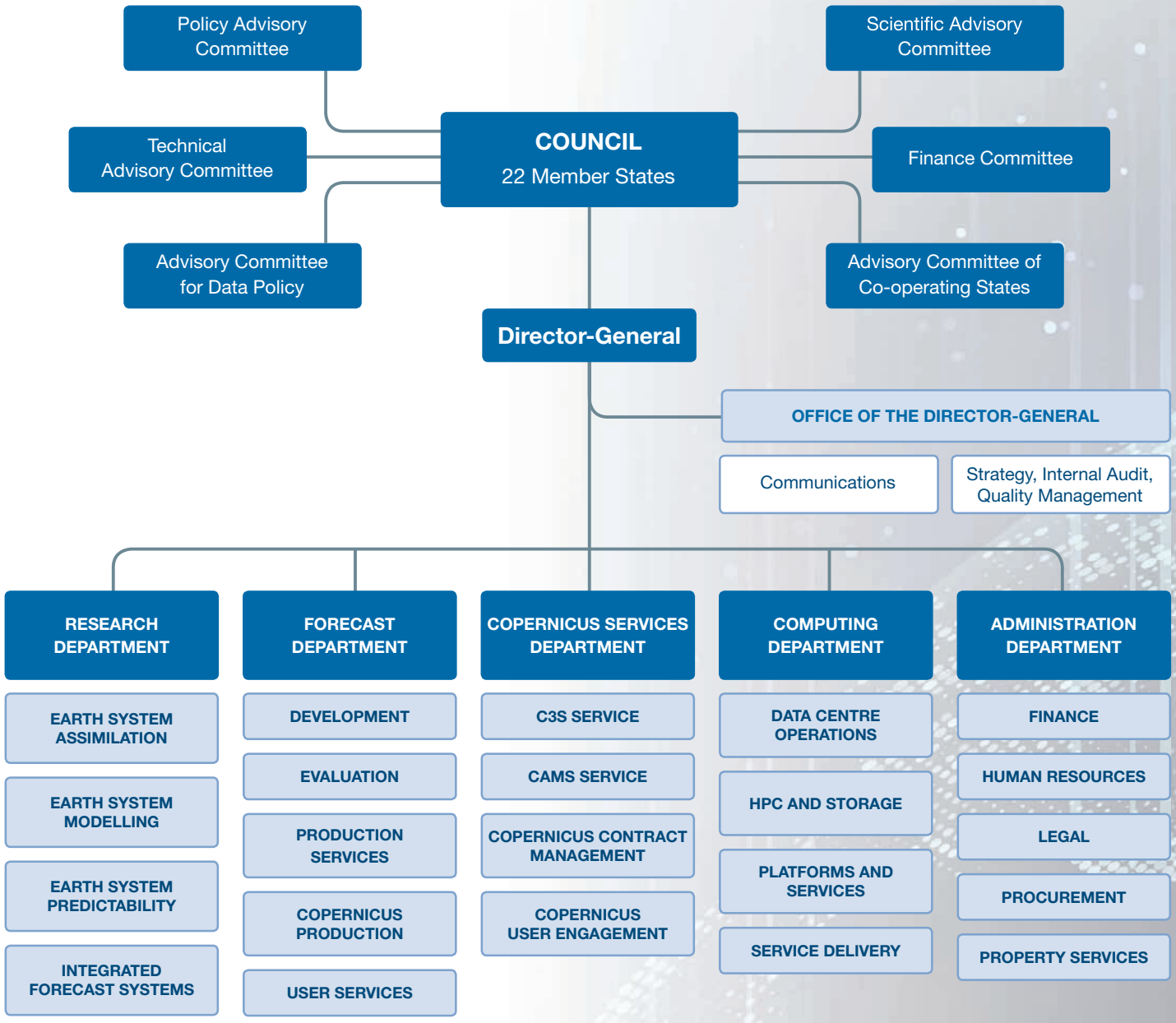
The year also saw a number of other key milestones for the CDS. Forty years of data from the latest ECMWF reanalysis dataset (ERA5) were released through the CDS. Covering 1979 to present, the data represent the highest-quality reanalysis produced to date by ECMWF. A detailed land dataset, ERA5-Land, also became available. Based on ERA5 data, the world's first reanlayses of fire and river flow data were also included within the CDS. Such reanalysis data provide a globally complete picture of weather, land surface, fire and river flow conditions which are consistent over time. They are invaluable for understanding current conditions in a wider climate perspective.

The success of the CDS is now being extended to serve the users of the Copernicus Atmosphere Monitoring Service (CAMS), which is also operated by ECMWF on behalf of the European Commission.

◀ The EMS Technology Achievement Award

EMS President Bob Riddaway (middle) presented the Technology Achievement Award certificate to Climate Data Store senior team members Baudouin Raoult (left) and Cedric Bergeron (right) during the Society's Annual Meeting.

How we work



Organisation of ECMWF at June 2020

Co-operating States as of January 2020

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

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