ECMWF

European Centre for Medium-Range Weather Forecasts

Annual Report 2020

www.ecmwf.int

Member States as of January 2021

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

Foreword

At ECMWF, the impact of the 2020 global pandemic will be felt for many years to come, but it has also strengthened the great partnership that connects us to our Member and Co-operating States.

Florence Rabier
Director-General

We often tend to look at the year that has just gone by as a ‘special’ year. We review all the challenges we had to overcome, we take pride in all the achievements, and appreciate the great partnership that connects us to our colleagues in our Member and Co-operating States. 2020 is in a category of its own.

2020 gives the notion of ‘special’ a new dimension. It was a year when we had to learn to do without things we took for granted. Like aircraft data, which had come to play an important role in numerical weather prediction. From one day to the next, they were gone, and rather quickly replaced by data that some Member States produced through an increased radiosonde programme and by satellite data which were just starting to reach us. Or working from our offices, together, exchanging views in corridors and comparing test results over a coffee, smoothly replaced by remote and virtual exchanges thanks to a fantastic infrastructure implemented in recent years by our Computing teams.

You will find in the following pages a review of many achievements, such as the implementation of a wide-ranging Integrated Forecasting System (IFS) upgrade which is improving global weather forecasts and substantially improving analyses and forecasts in the stratosphere.

We also had major upgrades for our EU-funded Copernicus Atmosphere Monitoring Service (CAMS) and the European Flood Awareness System (EFAS) that is part of the Copernicus Emergency Management Service. For CAMS, the model upgrade, which uses IFS 47r1, brought improved forecasts of sea salt and dust aerosol, particulate matter and stratospheric ozone. For EFAS, major new upgrades brought a step change in time resolution and deliver a huge volume of open-access data, fundamentally changing the way the forecasts are calculated and the quality of what is being provided.

The extension of the ERA5 reanalysis backward in time to 1950 and later on to 1940, possibly 1925, will complete a century-long global dataset that can be used, for example, to provide lateral boundary conditions for a century-long European reanalysis.

A detailed report on the state of the European climate, released in 2020 by our EU-funded Copernicus Climate Change Service, confirmed that 2019 was the warmest year on record, continuing a trend that meant 11 of the 12 warmest years in Europe had occurred since 2000.

Hundreds of our forecast maps and charts became accessible to all, allowing users to share, redistribute and adapt the information as they require, even for commercial applications. This latter change also included historical information in ECMWF’s huge data repository – the Meteorological Archival and Retrieval System (MARS).

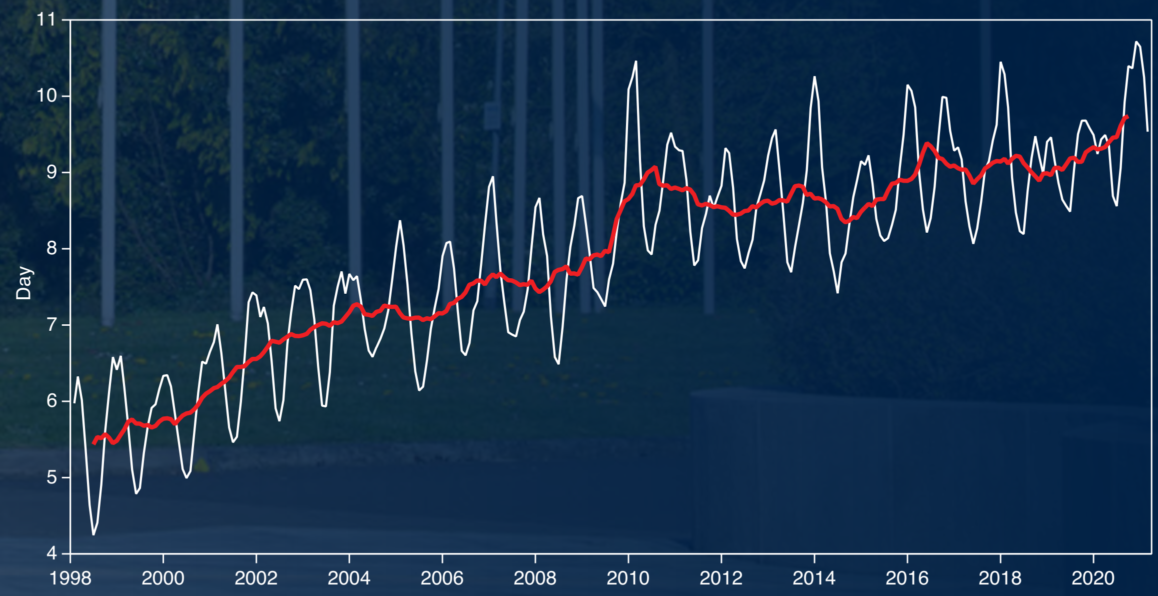
The close partnership between ECMWF and EUMETSAT showed once again its strength through the joint cloud computing infrastructure for the meteorological community, the European Weather Cloud, which entered a new phase. The focus has been on working with users in the Member States currently trialling applications on the pilot infrastructure to evaluate the platform and to shape the future operational services.

However, not everything went smoothly, and the impact of the pandemic on some of our activities will be felt for a while yet.

Our data centre in Bologna as well as the Atos supercomputers we contracted at the beginning of the year have suffered delays, which we cannot ignore. They will not be as damaging as they could have been, had it not been for the efforts of the Italian authorities and the steadfastness of our staff, but they will be felt nonetheless.

It is difficult to pat oneself on the back in light of the pain and suffering that 2020 has brought. However, the weather did not stop affecting our society, and we have continued to deliver data to our Member and Co-operating States, supporting them in their duty to protect life and property in their countries, as they were facing the same challenges. We have continued to advance weather science for the benefit of our community, and for this, credit goes to our staff, whose dedication and talent have prevailed over the challenging situation, and to our colleagues and partners across the Member and Co-operating States, whose team spirit has ensured that our common mission could endure.

June 2021



▲ **Ensemble forecast skill**

Changes to ECMWF’s Integrated Forecasting System (IFS) introduced with recent upgrades had a clear positive impact on the skill of ensemble forecasts. The chart shows 850 hPa temperature for the northern hemisphere extratropics. Shown are 12-month (red) and 3-month (white) running average values of the forecast range at which the continuous ranked probability skill score (CRPSS) drops below 25%.

2020 At a glance

January

Aeolus satellite data assimilated

On 9 January, ECMWF started assimilating wind data from the European Space Agency's Aeolus satellite operationally, after tests showed that they significantly improve weather forecasts.

Atos supercomputing contract signed

ECMWF signed a four-year contract worth over 80 million euros with Atos for its BullSequana XH2000 supercomputer, to be installed in ECMWF's new data centre in Italy. The new system will deliver an increase in sustained performance by a factor of about five compared to ECMWF's current high-performance computing facility.

40-year thermal stress dataset released

ECMWF released global data on weather-induced, outdoor thermal stress and discomfort in human beings covering the period from 1979 to the present. The data were calculated using weather information from ECMWF's ERA5 reanalysis coupled with models of human thermoregulation and clothing insulation.

Early warning advisory system strengthens capacity in SE Europe

ECMWF joined the second phase of a project to build a South-East European Multi-Hazard Early Warning Advisory System (SEE-MHEWS-A). The initiative aims to strengthen the existing early warning capacity in the region and is funded by the World Bank.

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Aircraft-based observations available to weather prediction centres decreased.

INCITE award enables 1 km resolution simulations

ECMWF scientists embarked on a project to carry out ground-breaking global weather and climate simulations at 1 km resolution after they were awarded time on the Summit supercomputer at the Oak Ridge National Laboratory in the US – the fastest computer in the world at the time. The award was one of 47 granted by the US INCITE programme.

February

New ocean and sea ice variables added to forecast database

Nine new ocean and sea-ice variables were added to the multi-model sub-seasonal to seasonal (S2S) weather prediction database hosted by ECMWF. They help researchers to explore the predictability of ocean and sea-ice conditions and to compare the representation of air–ocean–sea-ice interactions in different models. The database includes ensemble forecasts three weeks behind real time and re-forecasts, up to 60 days ahead, from 11 forecasting centres.

WMO Task Team meets at ECMWF

A World Meteorological Organization (WMO) Task Team met at ECMWF to work on guidelines to help WMO Members make more effective use of ensemble forecasts, including those produced by ECMWF.

Artworks inspired by weather and climate

Over 80 artworks from 27 artists were displayed at ECMWF's first art exhibition. The sculptures, paintings and photography all conveyed weather-related topics in their own beautifully unique ways.

March

Web tools launched to monitor global meteorological observations

The WMO and ECMWF launched a new web-based interface to help monitor the availability and quality of global meteorological observations.

© Madeleine Cotter

ECMWF headquarters in Reading, UK.

Moving online as pandemic grows

ECMWF staff based in Bologna began working remotely in February. By late March, Reading-based staff were also working remotely, apart from a small number of key staff needed on site. ECMWF began moving all its training courses and workshops online, starting with a workshop on the challenges posed by warm conveyor belts. In addition to its usual programme of events and training, the Centre held a series of ten seminars by international experts to explore the use of machine learning in weather prediction and climate studies.

Coordinated response to drop in aircraft observations

The COVID-19 pandemic resulted in a sharp drop in flights and thus in the aircraft-based observations available to weather prediction centres. Between mid-March and mid-April, the number of aircraft reports received at ECMWF went down by about 75%. A coordinated response involving EUMETNET, national meteorological services and private companies helped to mitigate any adverse effects of the loss of aircraft-based observations on weather forecasts.

COSMIC-2 data improve forecasts

ECMWF started assimilating GNSS radio occultation (GNSS-RO) measurements from the FORMOSAT-7 /COSMIC-2 mission (COSMIC-2) on 25 March. COSMIC-2 represents a significant increase in the number of occultations available for operational assimilation at ECMWF, from around 3,000 per day to around 8,000. The new measurements have a large impact in the tropics, improving temperature, humidity and wind forecasts in the short and medium range.

Support for Croatian met service following earthquake

Following an earthquake that severely damaged the Croatian Meteorological and Hydrological Service's (DHMZ) headquarters, DHMZ successfully backed up its operational production and essential services on ECMWF's high-performance computing facility (HPCF) and the European Weather Cloud.

April

ECMWF data supports COVID research

ECMWF extended the EC's Joint Research Centre's existing licence to provide additional forecast outputs and expertise to support the response to the COVID-19 emergency situation. The Copernicus Climate Change Service (C3S) and the Copernicus Atmosphere Monitoring Service (CAMS) – both implemented by ECMWF on behalf of the EC – helped researchers, policy-makers and citizens alike with quality-assured data and tools.

Strong contribution at EGU assembly

Global scientific engagement continued through the COVID-19 pandemic. More than 30 ECMWF scientists participated in the virtual European Geosciences Union (EGU) General Assembly.

2020 At a glance

TIGGE archive continues to grow

The TIGGE database of global medium-range ensemble forecasts hosted by ECMWF holds a growing range of data from 13 forecasting centres readily available to researchers worldwide. The Australian Bureau of Meteorology (BoM) rejoined TIGGE in April. In December, outputs from the global model ICON produced by the German national meteorological service (DWD) also started to be added to the TIGGE archive.

2019 warmest year on record

A detailed report on the state of the European climate confirmed that 2019 was the warmest year on record, continuing a trend that meant 11 of the 12 warmest years in Europe had occurred since 2000. The European State of the Climate 2019 report was published by the Copernicus Climate Change Service (C3S).

May

Summer coding challenges begin

From May to August, nine developer teams worked closely with ECMWF and Copernicus mentors on a range of open-source projects as part of ECMWF's Summer of Weather Code (ESoWC). A virtual presentation day on 16 October showcased the outcomes, including applications using machine learning and artificial intelligence, projects using Copernicus open data and responses to challenges related to ECMWF's model performance, data storage and archiving.

European Weather Cloud users share progress

At a joint workshop, ECMWF and EUMETSAT introduced users to the features of the cloud computing systems being developed for their European Weather Cloud and presented existing projects. A second workshop followed in October. The European Weather Cloud is expected to become operational in 2022, with the pilot phase having been extended by one year.

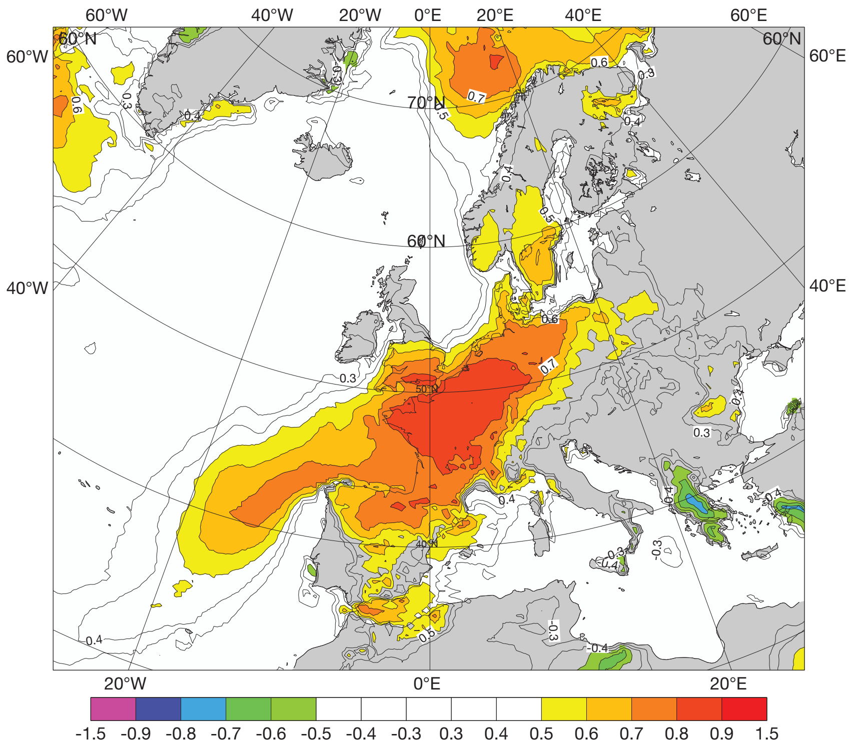
June

Forecasting system upgrade improves forecasts in the stratosphere

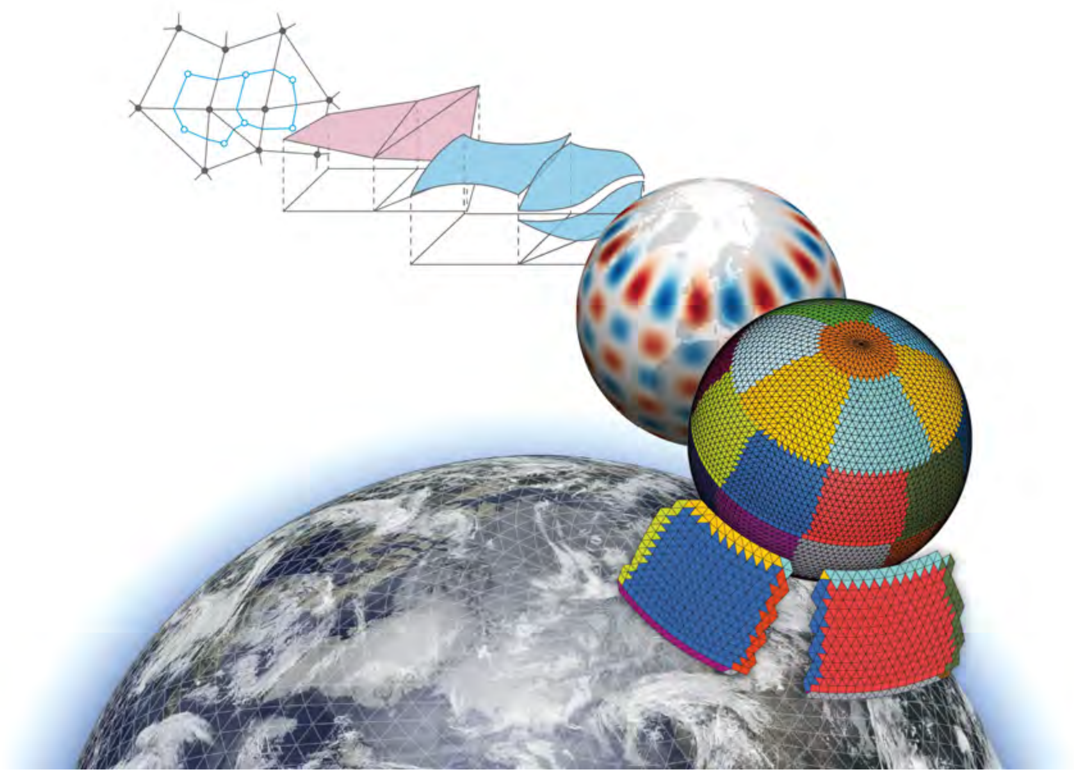
A wide-ranging upgrade of ECMWF's Integrated Forecasting System (IFS), implemented on 30 June, improved global weather forecasts and substantially improved analyses and forecasts in the stratosphere. The upgrade to IFS Cycle 47r1 brought many changes in data assimilation and Earth system modelling. It also introduced a new tropical cyclone wind radii product, which will facilitate the identification of wind-related hazards.

Virtual user meeting extends its reach

Going online, the Centre's annual user meeting – Using ECMWF's Forecasts (UEF) – attracted 227 people from over 40 countries, increasing the reach of the event to the wide community of ECMWF users. The theme was 'Keeping users at the heart of operations', and participants discussed how weather and environmental information providers can meet end-users' needs by delivering added-value outputs.



Extreme Forecast Index (EFI) (shading) for mean 2m temperature between 7 August 00 UTC and 12 August 00 UTC 2020 in the forecast from 3 August 2020, 00 UTC.



Annual Seminar 2020, on numerical methods for atmospheric and oceanic modelling.

Silvio Cau elected Council President

ECMWF's Council elected Gen. Isp. G.A. Silvio Cau, then Head of the Italian National Meteorological Service, as its President, to succeed Prof. Juhani Damski from Finland.

Additional data accessible to WMO Members

ECMWF extended the set of 'Additional' products available to WMO Members for non-commercial use to include variables from the 06 and 18 UTC forecast runs as well as those already available for 00 and 12 UTC. These 'high-frequency' products can help forecasters to provide up-to-date information about extreme weather situations. In addition, four more high-resolution forecast products, surface skin temperature, surface pressure, soil temperature and total column water vapour, were also made available.

Strategy 2021–2030 approved

The ECMWF Council approved a new long-term Strategy for the Centre for the period 2021–2030. The Strategy foresees a pushing of the boundaries of weather science to achieve improved global ensemble forecasts at much finer resolution, maximising the use of current and upcoming observations and using machine learning methodologies throughout the numerical weather prediction chain.

July

Warnings help Bangladesh prepare for monsoon floods

Large floods hit Bangladesh on 15 July and affected nearly 5 million people, with 41 casualties reported. Forecasts from the Global Flood Awareness System (GloFAS), produced by ECMWF as part of the Copernicus Emergency Management Service (CEMS), were used by the Bangladesh Flood Forecasting Warning Centre to provide advance notice to prepare for the floods. UN agencies, with NGOs such as the Red Cross, launched a disaster response pre-activation on 4 July, allowing parties involved in disaster response to take advance action to mitigate the impact.

August

Strong heatwave affects western Europe

Western Europe underwent a strong heatwave, with Paris for example measuring above 35°C and London Heathrow above 33°C during 6 consecutive days (7–12 August). The heatwave later propagated to the north-east and affected Scandinavia. The ensemble forecast started to pick up the signal for the anomaly around 28–30 July, and the ensemble median was consistently above the 99th percentile of the model climate from 3 August onwards.

September

Annual Seminar focuses on atmospheric and oceanic modelling

More than 300 researchers from across the world joined ECMWF's virtual Annual Seminar 2020. The topic was 'Recent developments in numerical methods for atmospheric and oceanic modelling'. The 27 speakers at the online event described state-of-the-art computational methods for solving the equations that govern atmospheric, wave, ocean and sea-ice dynamics.

2020 At a glance

October

Atos and ECMWF launch centre of excellence

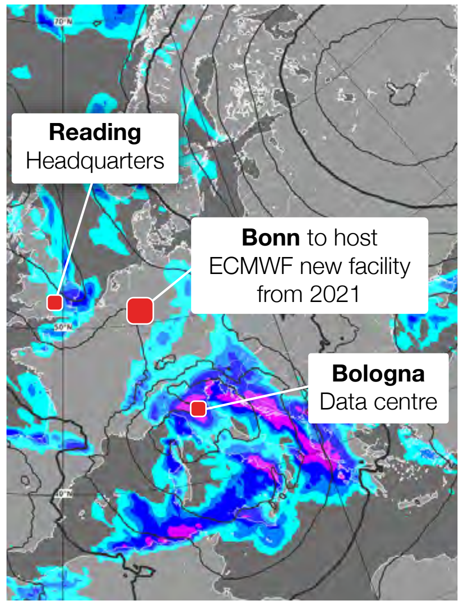
Atos and ECMWF launched a Centre of Excellence in HPC, AI and Quantum Computing for Weather and Climate. It will provide ECMWF researchers with access to emerging artificial intelligence (AI) and quantum computing technologies and expertise, and benefit from ECMWF's high-performance computing (HPC) resources that will be in Bologna, Italy.

Forecast charts made freely available

Hundreds of previously restricted ECMWF forecast charts became free and accessible to all. Products include medium-range, extended-range and long-range forecast charts of temperature, wind, precipitation, clouds and ocean waves. There was also a move to an open data policy for historical information contained in ECMWF's archive. This will expand the use of the data and allow re-use, stimulating further research and development of applications.

Step-change for European Flood Awareness System

The European Flood Awareness System (EFAS) was upgraded to version 4.0, benefiting from a recalibrated hydrological model (LISFLOOD) using sub-daily steps. The hydrological skill improvement provided by the new calibration and the higher time resolution of the products based on LISFLOOD outputs will allow for more timely notification of the beginning and peak of predicted flood events. ECMWF operates the computational centre for EFAS, a component of the EU Copernicus Emergency Management Service.



ECMWF sites in the UK, Germany and Italy.

Support for WMO Systematic Observations Financing Facility

ECMWF signed a joint statement with the WMO, EUMETNET and EUMETSAT urging European governments and institutions and all multilateral climate and environment financing institutions to consider funding a new initiative called the Systematic Observations Financing Facility (SOFF). The SOFF aims to increase the availability of observational data by involving national meteorological services, global data producing centres, aid agencies and the private sector.

CAMS forecasting model upgraded

The CAMS global forecasting system was upgraded on 6 October, bringing improved forecasts of sea salt and dust aerosol, particulate matter and stratospheric ozone. The new operational system uses the latest version of ECMWF's Integrated Forecasting System (IFS Cycle 47r1).

© Ministry of the Environment of Estonia; photo: Karoliine Mäeots

Taimar Ala (Director of the Estonian Met Service) and Rene Kokk (then Estonian Minister of the Environment).

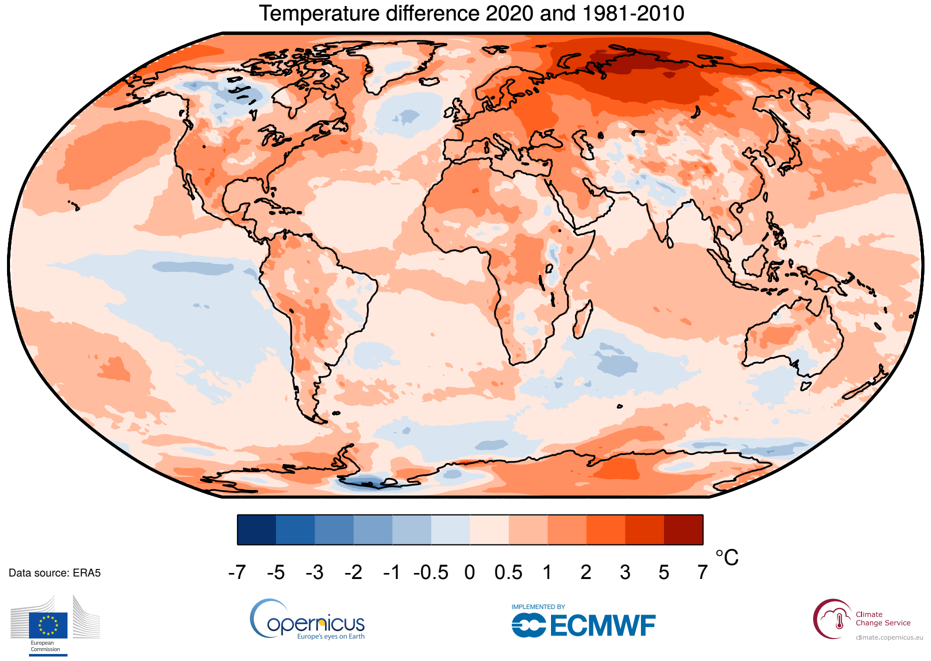
November

ERA5 reanalysis extended back to 1950

C3S released an extension to the ERA5 reanalysis dataset to help users analyse how the climate is changing. Previously covering 1979 to the present day, ERA5 now extends back to 1950. ERA5 is the backbone of many C3S products and services, including the monthly climate bulletins. It provides hour-by-hour information on a wide range of climate variables covering the atmosphere, land surface and ocean waves.

Workshop reviews error handling in satellite data assimilation

Almost 200 experts from around the world joined a four-day, online workshop on the treatment of random and systematic errors in satellite data assimilation for numerical weather prediction (NWP), organised by ECMWF and the EUMETSAT-funded NWP



Air temperature at a height of 2 m for 2020, shown relative to its 1981–2010 average. Source: ERA5. Credit: Copernicus Climate Change Service/ECMWF

Satellite Application Facility (SAF). Speakers reviewed the strong progress in recent years, both in the treatment of errors in the assimilation and in the understanding of their characteristics.

December

Estonia welcomed as a Member State

On 1 December, Estonia became ECMWF's 23rd Member State, having been a Co-operating State since 2005.

Bonn to host new ECMWF premises

The ECMWF Council selected the German city of Bonn to host new, additional premises from late 2021. This third site will complement the Centre's headquarters in the UK and the data centre being developed in Bologna, Italy.

Council President and scientific advisors appointed

The ECMWF Council elected Dr Daniel Gellens, Director-General of the Royal Meteorological Institute of Belgium, as its President, following the retirement of Silvio Cau from the Italian national meteorological service. At the same time, it re-appointed five members of the Scientific Advisory Committee (SAC) for a second term: Dr Inger-Lise Frogner, Dr Susanna Corti, Prof. Gunilla Svensson, Dr Anthony Weaver and Prof. Dr Pier Siebesma.

Member States support ECMWF involvement in Destination Earth

The ECMWF Council authorised ECMWF to enter into formal negotiations with the EC, ESA and EUMETSAT to conclude an agreement for the Destination Earth programme, which aims to support the EU's green transition by providing a new Earth system simulation and observation capability.

Fellowship programme grows

Seven highly respected scientists from Europe and the United States were confirmed as ECMWF Fellows from 1 January 2021: Prof. Sándor Baran, Prof. Hannah Cloke, Prof. Dr Daniela Domeisen, Prof. Patrick Eriksson, Dr Christian Grams, Prof. Dr Daniela Jacob, and Dr Gabriele Pfister. Their appointments bring the number of Fellows to 11, after the 3 inaugural Fellows completed their terms in July 2020.

ecFlow5 improves computational workflows

ECMWF released a new version of its ecFlow workflow package that is used by ECMWF and Member and Co-operating States for managing workflows for large-scale data-intensive computational processes. Version 5 of ecFlow brought many modernisations and improvements in terms of features, performance, security and maintainability.

CO2 emissions project, an H2020 success story

A three-year, EU Horizon 2020 project to build a European monitoring capacity for anthropogenic CO2 emissions ended, having successfully met all its targets. A key outcome of the CO2 Human Emissions (CHE) project coordinated by ECMWF was a new global simulation that realistically illustrates the variability of CO2 in the atmosphere, which will assist research studies monitoring anthropogenic CO2 emissions in support of the Paris Agreement. CHE was presented as an H2020 success story at the EU Space Week, and its work will continue in the CoCO2 project.

CAMS monitors unusual ozone Antarctic hole

The 2020 long-lived Antarctic ozone hole finally came to an end in late December, after a highly unusual and record-breaking season. The large size, very low ozone levels and duration of the 2020 southern hemisphere ozone hole were all unusual, and the hole finally closed almost a month later than has been average since the 1980s. Overall, it was one of the largest and deepest ozone holes of the past 40 years, according to CAMS and C3S records, due to an exceptionally cold Antarctic stratosphere, and a strong and persistent polar vortex that persisted right into December.

2020 marks end of warmest decade on record

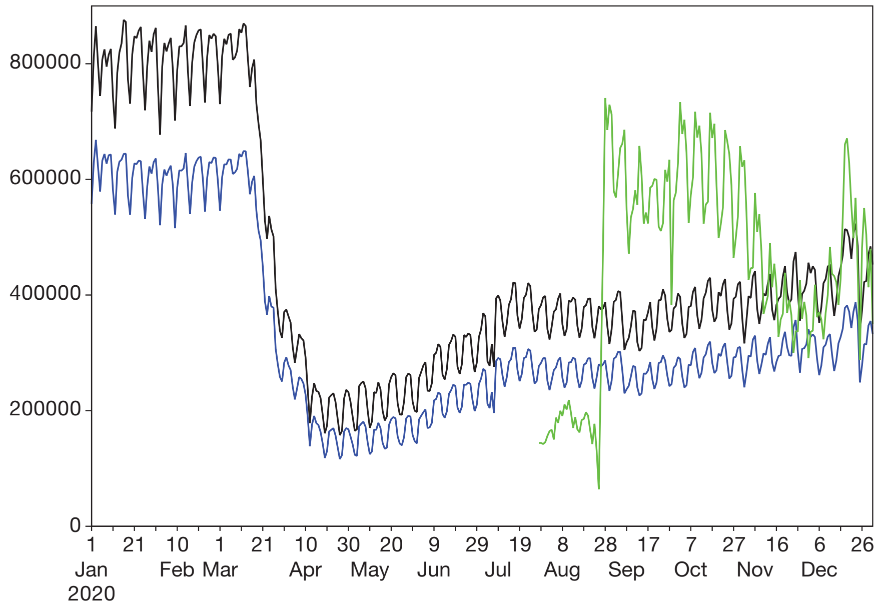
Data released by C3S showed that globally 2020 was on par with the warmest year ever recorded (2016), marking the end of the warmest decade on record. Europe saw its warmest year on record, 0.4°C warmer than 2019, which was previously the warmest year.

Advancing weather science

In 2020, ECMWF scientists continued to push for advances in numerical weather prediction (NWP) despite the obstacles set up by the COVID-19 pandemic. The impact of the pandemic on the aircraft data used in weather prediction is a case in point: as the availability of the data decreased, efforts were stepped up to find alternatives. The case is also a good example of working with other agencies, especially European ones, to address the shortfall in weather data.

The year was also marked by attempts to exploit machine learning in NWP; the finding that reduced North Atlantic sea-surface temperature biases led to significantly improved sub-seasonal to seasonal forecasts; progress towards reducing near-surface forecast biases as part of a three-year project; and, in the case of intense tropical cyclones, advances in the estimation of maximum wind speed, which previously tended to be severely underestimated even given the correct central pressure.

We also report on the final stages of refinements and verification of major changes to the moist physics in ECMWF forecasts. This work will be reflected in a future update of the Integrated Forecasting System (IFS). Finally, in a historic first in NWP, wind data from the new Aeolus satellite began to be assimilated into forecasts.



▲ Numbers of global aircraft reports received at ECMWF per day

There is some thinning and a small proportion of rejections in the aircraft reports normally received at ECMWF, so that the number assimilated (blue) is less than the number received (black). Most of these reports are received as part of the World Meteorological Organization's Aircraft Meteorological Data Relay (AMDAR) programme. In addition, the European Meteorological Aircraft Derived Data Center (EMADDC) at the Dutch national meteorological service (KNMI) has been processing 'Mode-S' air traffic control signals to derive wind and temperature information. ECMWF started using the data (green) in July.

Coordinated response to loss of aircraft weather data

A coordinated response involving EUMETNET (a network of 31 European national meteorological services), national meteorological services and private companies helped to mitigate any adverse effects of the COVID-19-related loss of aircraft-based observations on weather forecasts.

In March and April 2020, there was a sharp drop in flights and thus in aircraft-based observations available to ECMWF. The continued availability of complete sets of satellite observations ensured that there was no severe impact from the loss of aircraft observations. Aircraft reports include temperature and wind and in some cases humidity and turbulence. They are used together with many other observations to help estimate the state of the Earth system at the start of forecasts.

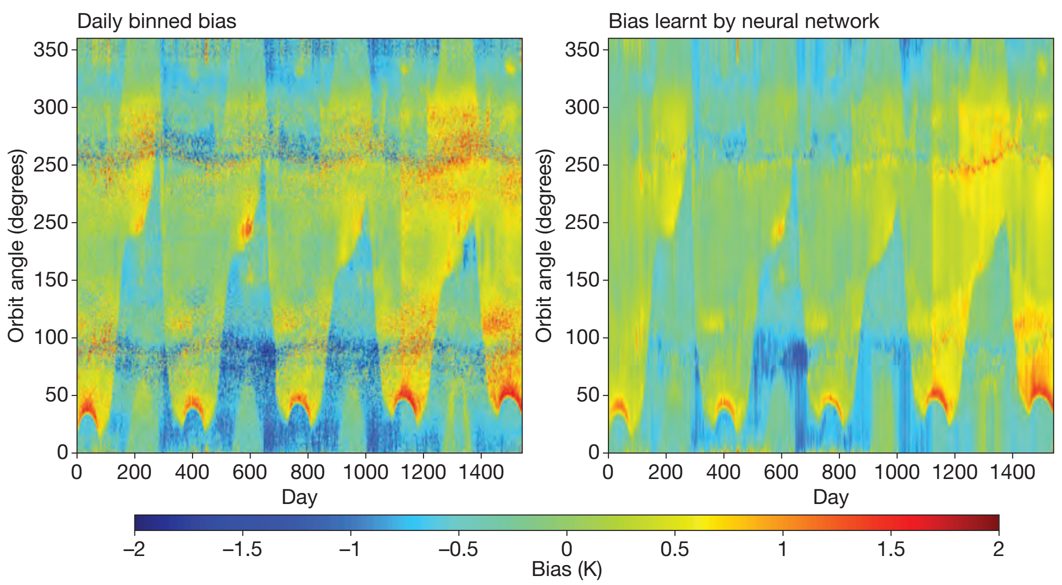
Responses to the drop in observations included the use of previously untapped aircraft-based observations; an increase in the number of radiosonde launches from some locations; and the assimilation of additional satellite data. In an example of successful collaboration with the private sector, the companies FLYHT and Spire stepped in to provide additional aircraft-based observations and radio occultation satellite data, respectively.

Machine learning at ECMWF

In 2020, ECMWF made a significant effort to see how applications of artificial intelligence and machine learning may improve numerical weather prediction at the Centre. There has recently been a surge in new methods which have the potential to bring significant changes to the work of operational weather prediction centres. Such methods include the use of deep neural networks, which can learn the behaviour of very complex non-linear systems from data.

Take the example of Earth system data assimilation. This combines the latest observations with a short-range forecast constrained by previous observations to obtain the best possible estimate of the current state of the Earth system. Patterns of bias in observations can be learnt through machine learning where this is hard to understand by purely physical reasoning.

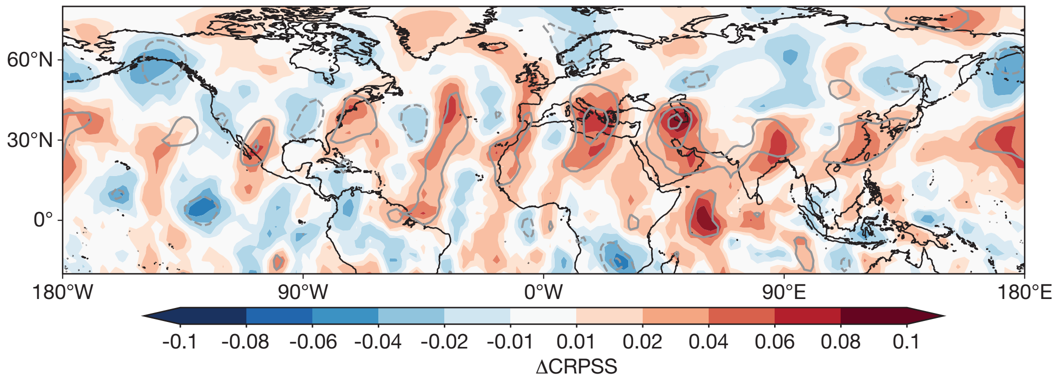
The example shown here uses an offline neural network bias correction applied to the solar-dependent bias of the Special Sensor Microwave Imager/Sounder (SSMIS). This varies through the orbit and through the year in a complex pattern. The red arches near the bottom of the plot are the most difficult part. The difficulties of applying a neural network are a lack of training data and the fact that it would need to be continually re-trained to keep up with the evolving bias. Other development areas for machine learning in data assimilation that are equally promising are targeting the problem of model error estimation and corrections.



◀ Bias diagrams

Bias diagrams showing daily binned bias in Kelvin between SSMIS F-17 channel 11 observations and the simulations from the IFS, stratified by the angle around the orbit (left) and bias learnt by an evolving neural network that is then used as a bias prediction model for the next day (right).

Advancing weather science



◀ Impact of SST bias correction on forecast skill of meridional wind at 200 hPa

Changes in the continuous ranked probability skill score (CRPSS; shading) and anomaly correlation (grey contour spacing of 0.1) shown for weekly mean anomalies derived from forecast days 26 to 32.

Gulf Stream errors and sub-seasonal forecasts

ECMWF has established that reducing North Atlantic sea-surface temperature (SST) biases leads to significantly improved sub-seasonal to seasonal (S2S) forecasts of atmospheric circulation anomalies over Europe. The results from sensitivity experiments suggest that higher-resolution ocean models, with a grid spacing of less than 10 km rather than the 25 km currently used, would be beneficial. In particular, they would be able to better resolve the position of the Gulf Stream. Such models will be investigated at ECMWF during the next few years.

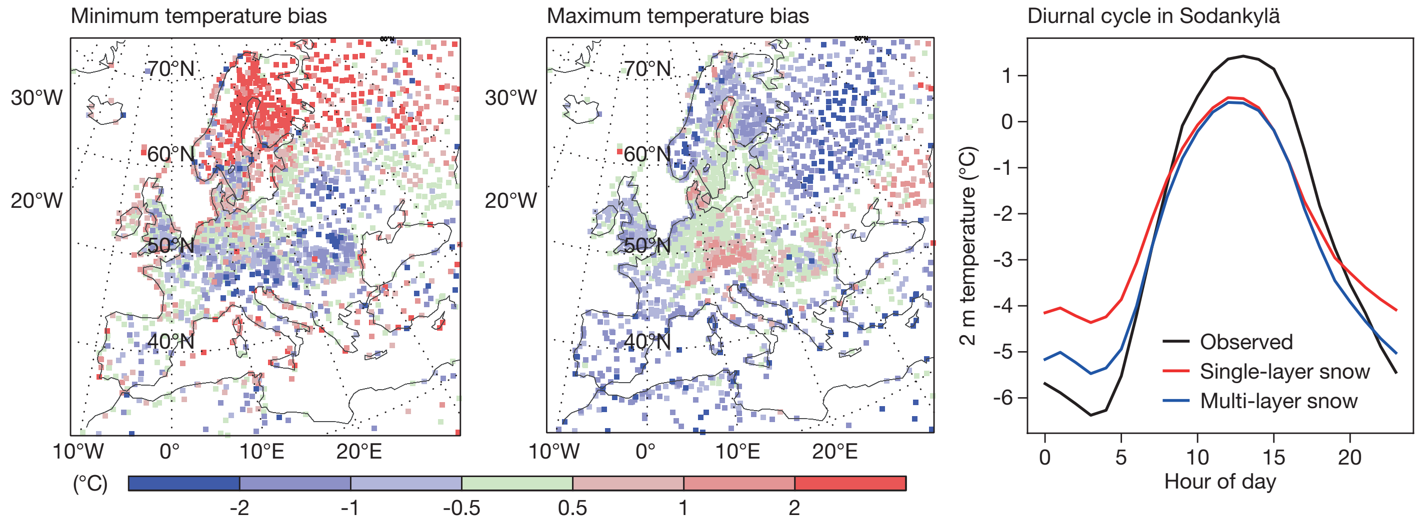
The results were achieved by evaluating the impact of SST errors on S2S forecasts using an SST-bias correction methodology. The applied bias correction effectively reduces SST biases in the North Atlantic region. The resulting southward shift of the Gulf Stream has consequences for atmospheric predictability that extend beyond the North Atlantic. For example, the image shows that reducing North Atlantic SST biases leads to significantly improved S2S forecasts of meridional wind at 200 hPa in Europe and elsewhere.

Progress towards reducing near-surface forecast biases

In 2020, ECMWF brought to a close a three-year project on ‘Understanding uncertainties in surface–atmosphere exchange’ (USURF). The aim was to investigate the systematic forecast biases in near-surface weather parameters, like temperature or winds, disentangle their sources and identify ways to reduce them in the future. These biases limit predictive skill from hours to seasons ahead.

These systematic errors often have complicated geographical patterns and temporal structure and result from an interplay between atmospheric and land surface processes. USURF defined a plan to address some of these issues. This will include an improved representation of snow and a revision of the land cover and vegetation maps, accompanied by a retuning of uncertain parameters in the surface–atmosphere coupling.

USURF has also provided further evidence that increases in near-surface forecast skill not only depend on an improved representation of physical processes. They also rely on the availability of comprehensive observations and in-depth studies using process-based diagnostics that can correctly attribute model error. Ongoing improvements to the diagnostic and verification tools used at ECMWF are therefore an important contribution towards further enhancements of forecast skill, alongside model developments.



Moist physics upgrade

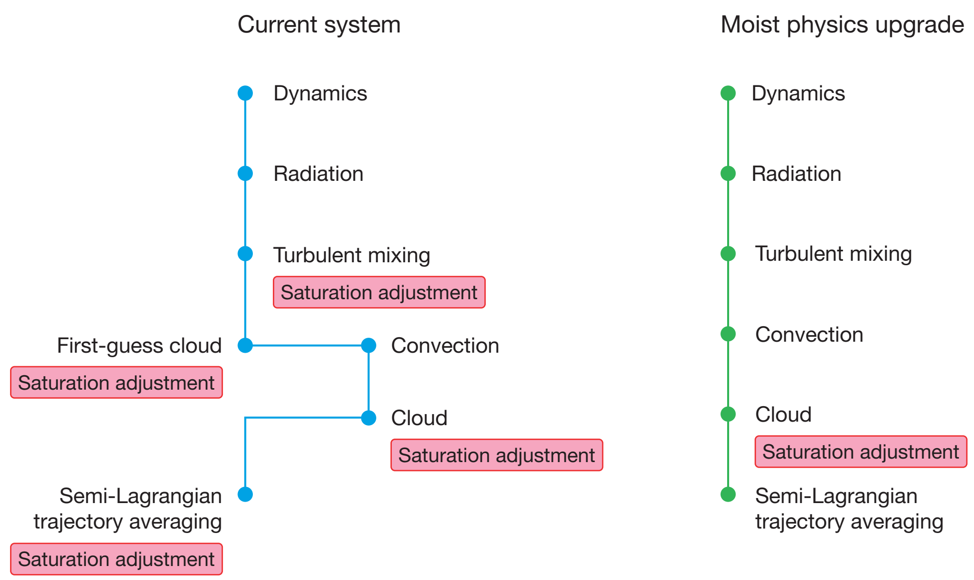
In 2020, the final stages of refinements and verification of major changes to the moist physics in ECMWF forecasts took place. One of the main drivers of this project was ECMWF’s strategic decision to move towards an ensemble forecast horizontal grid spacing of about 5 km, down from 18 km in 2020. The goal was thus to make it possible for the IFS to be run across a broader range of horizontal resolutions, including convection-permitting resolutions.

To this end, the complicated interactions between turbulence in the lowest part of the atmosphere, convective motions and the cloud physics should be described as simply, efficiently, accurately and scale-independently as possible. Longstanding systematic model errors in clouds, precipitation and radiation across all resolutions and forecast lead times should also be addressed.

For example, moist processes in the IFS are represented with physically based parametrizations for turbulent mixing, convection, subgrid clouds and microphysics. Each parametrization is called sequentially during every model time step. Individual developments over many years have led to some complications and inconsistencies in the way these schemes work together. These inconsistencies have been resolved in the moist physics upgrade.

▲ Temperature biases

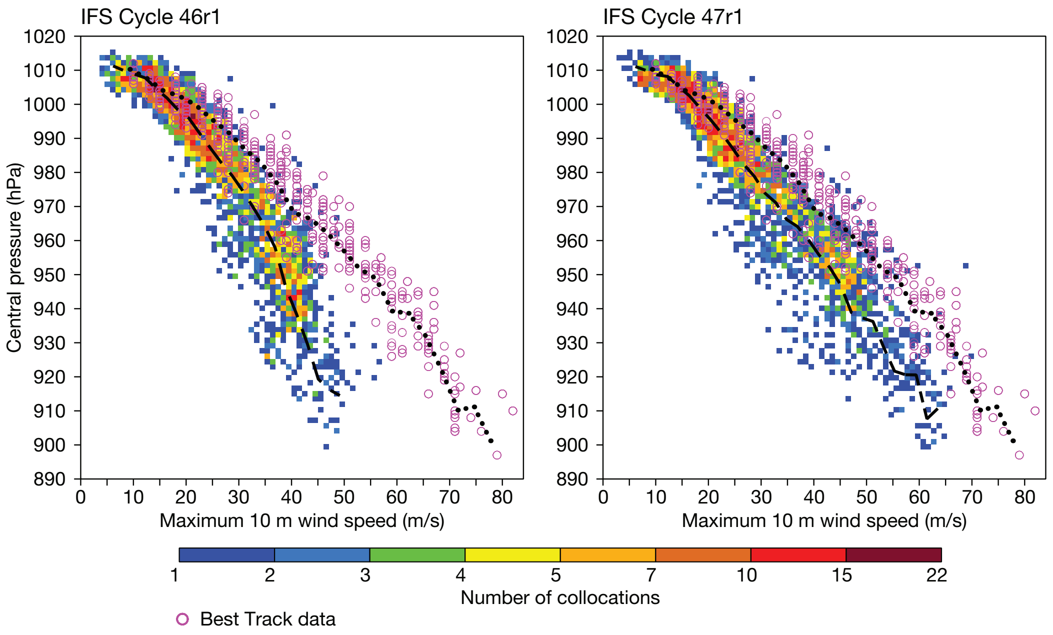
The first two figures show spatial maps of March–April 2014 daily minimum and maximum temperature biases for the ECMWF operational system at a lead time of 2 days. The third panel shows the March–April 2014 mean diurnal cycle of 2-metre temperature at Sodankylä (Finland) in observations and in the ECMWF forecasting system with single-layer and multi-layer snow. It shows that the underestimation of the amplitude of the diurnal cycle of 2-metre temperature is due to a lack of sensitivity to changes in radiation, which is partly the result of using a single-layer snow model.



◀ IFS physics parametrization call sequence

The two flow charts highlight the differences in saturation adjustment between moist physics in the IFS in 2020 and the moist physics upgrade planned for IFS Cycle 48r1.

Advancing weather science



◀ Relationship between maximum 10 m wind speed and corresponding minimum mean sea level pressure

Scatter plots for maximum 10 m wind speed and corresponding minimum mean sea level pressure for all 10-day forecasts at TCo1279 resolution (corresponding to a grid spacing of about 9 km) from 00 UTC for the period 25 August 2019 to 1 January 2020 (coloured squares; the dashed line indicates mean central pressure for a given wind speed), and corresponding reported values (6-hourly Best Track data: purple circles; the dotted line indicates mean central pressure for a given wind speed), for 20 tropical cyclones, showing results for IFS Cycle 46r1 (left) and IFS Cycle 47r1 (right).

Maximum wind speed in tropical cyclones

Prior to the summer of 2020, ECMWF forecasts generally severely underestimated maximum wind speed for intense tropical cyclones even given the correct central pressure. This was found to be closely linked to the modelling of momentum exchange at the ocean surface.

The momentum exchange is generally expressed in terms of the drag coefficient, which connects the magnitude of the surface stress to the square of the wind speed at a certain height above the surface. In the IFS, there is an active two-way coupling between the atmosphere and ocean waves, which results in an extra dependency of the drag coefficient on the sea state (waves).

Over the last decade, it has been suggested that the drag coefficient should tail off for strong winds. Recent wave model developments tried to address this issue, but not sufficiently for hurricane-force winds. A further reduction for such winds was tested at a horizontal grid spacing down to about 5 km to probe its limits.

For the operational high-resolution forecast with a grid spacing of about 9 km, it was found that, generally, the new system yields a much better maximum wind speed – minimum pressure relation. It was therefore implemented in June 2020 in IFS Cycle 47r1. However, as the figure indicates, forecasts continue to underestimate some of the most intense cases compared to observational estimates.

“Observing system experiments have shown that Aeolus winds provided a statistically significant positive impact.”

Assimilating Aeolus

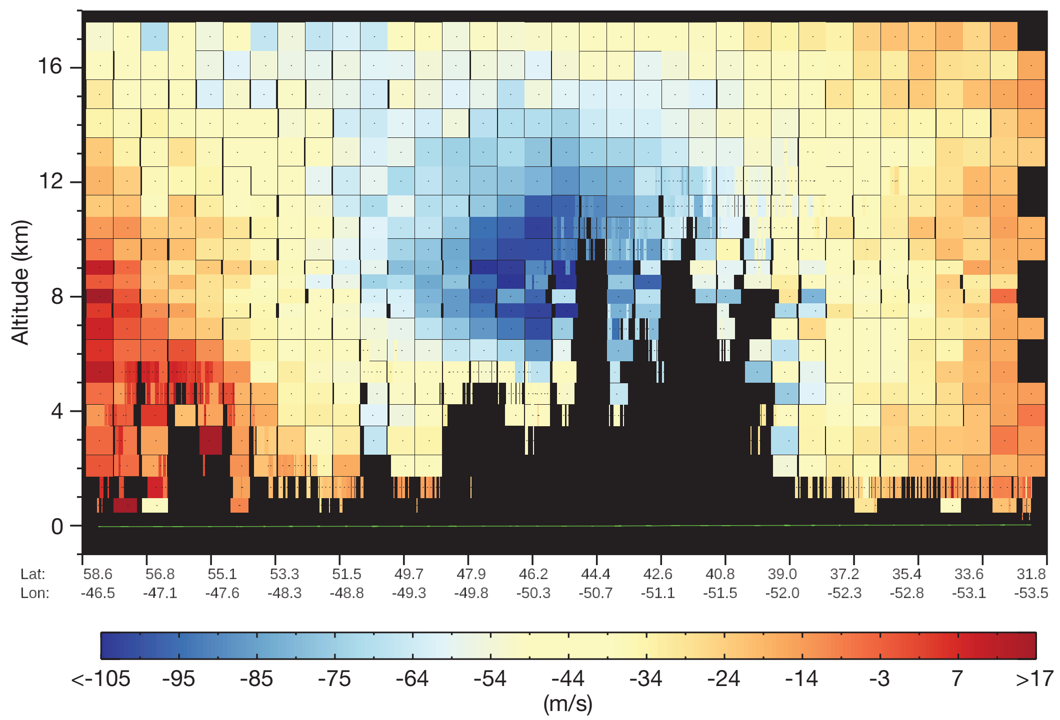
ECMWF started to assimilate wind observations from the European Space Agency’s (ESA) pioneering Doppler wind lidar mission Aeolus on 9 January 2020, 16 months after the first wind profiles became available. It was the first numerical weather prediction centre to go operational with Aeolus, followed by the German national meteorological service (DWD), Météo-France and the UK Met Office later in 2020. ECMWF was able to benefit from the data quickly because of its strong involvement with the mission since its conception in the 1980s and its selection as an ESA Earth Explorer Mission in 1999.

Aeolus is carrying the world’s first functioning space-based Doppler wind lidar and Europe’s first space-based lidar.

The aim of the mission is to demonstrate this new technology in space for the benefit of weather forecasting and to improve the understanding of atmospheric dynamics, especially in the tropics.

Thanks to careful investigations, in which ECMWF model winds were used as a reference, the Aeolus wind biases were found to be strongly correlated with the instrument’s main telescope temperature, which varies slightly with the Earth’s top of atmosphere radiation. The telescope temperatures are fortunately available in real time. A bias correction scheme using these temperatures as predictors went operational on 20 April 2020.

Observing system experiments have shown that Aeolus winds provided a statistically significant positive impact, especially in the tropics and in the polar regions.



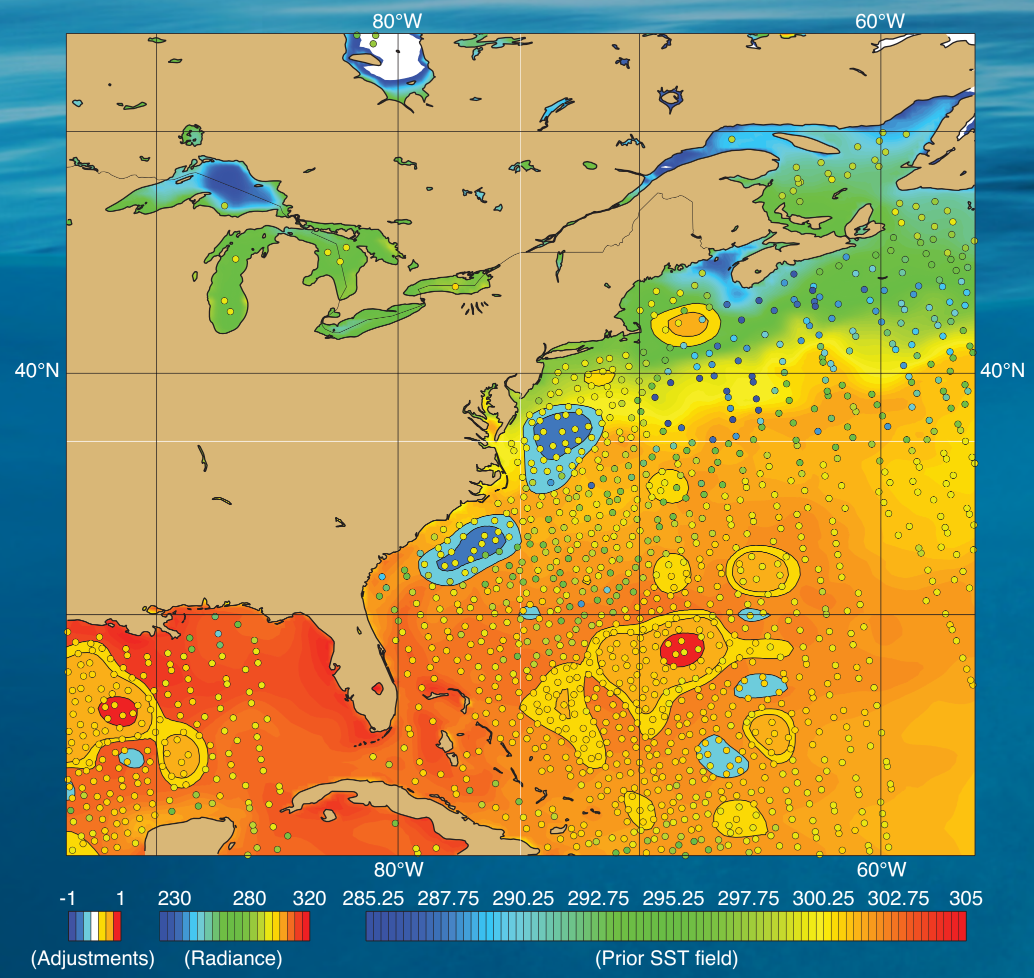
◀ Aeolus wind profiles

The plot shows the Aeolus Level-2B Rayleigh-clear and Mie-cloudy horizontal line-of-sight wind speed profiles on 14 February 2020 over the North Atlantic. The blue area highlights the location of a jet streak with wind speeds up to about 100 m/s. Around this period, some records were broken for the speed of transatlantic flights due to the strength of the jet stream.

A new ocean skin temperature analysis

> For many years sea-surface temperature (SST) has been just an imported lower boundary condition for the atmosphere or an upper boundary condition for the ocean, but it is now at the centre of our coupled prediction system and will be treated as such.

Tony McNally, Principal Scientist in Earth System Assimilation Section at ECMWF



A proof-of-concept test

For the first time, ECMWF scientists saw the potential impact of satellite radiances on surface ocean temperatures within the coupled 4D-Var/ NEMOVAR data assimilation system. The plot shows the underlying prior SST field and corrections to this (contours) in response to radiance observation forcings (circles) from the infrared atmospheric sounding interferometer (IASI) onboard EUMETSAT's MetOp-C satellite.

During 2020, a major project got under way to fundamentally change the way that the temperature of the sea surface is derived within ECMWF's data assimilation system. The new scheme will use satellite radiances directly to capture important variations of the ocean surface.

The sea surface is where the ocean and atmosphere interact, and it sits at the very heart of ECMWF's Earth system approach to forecasting. Coupling between the atmosphere and ocean provides a key source of predictability in medium- and extended-range forecasts.

The new scheme will use infrared and microwave satellite radiances directly within the four-dimensional variational data assimilation scheme (4D-Var) to produce an analysis of ocean skin temperature – a thin interface surface layer to which the satellites are extremely sensitive. This will replace an imported analysis of daily mean, bulk sea-surface temperature (SST), representative of the top several metres of the ocean.

It is anticipated that the new approach will improve the accuracy of the sea-surface temperature and produce an ocean skin in balance with the atmosphere and ocean state, leading to improved weather forecasts. Early tests have shown significant sensitivity of large-scale atmospheric circulation to changes in ocean skin temperature of just a few tenths of a degree.

Using half-hourly observations from geostationary satellites and frequent overpasses from a constellation of polar-orbiting satellites, the diurnal cycle and other rapid variations in ocean skin temperature will be captured within the new analysis. Heating of the ocean surface through the day is an important source of energy transfer to the atmosphere. Other rapid changes in ocean temperature should also be better represented – such as cold ocean wakes that develop in response to the strong winds in tropical cyclones. In addition to the satellites already being used in 4D-Var, highly accurate data from the Copernicus Sentinel-3 Sea and Land Surface Temperature Radiometer (SLSTR) will be used for the first time at ECMWF.

Ocean skin temperature is a completely new variable that has been incorporated within ECMWF's data assimilation system and successfully coupled between the atmosphere and the ocean. The thin ocean skin can behave quite differently to the deeper surface layers and must be treated appropriately. ECMWF scientists now have a better understanding of the physics of how the skin interacts with the ocean below and atmosphere above.

There has also been a major upgrade of the infrared radiative transfer modelling to use a consistent state-of-the-art spectroscopy for all satellites. This has benefits across the ECMWF Integrated Forecasting System, as well as being an important prerequisite for obtaining accurate ocean skin temperatures from the available satellite radiance observations.

Proof-of-concept experiments have already been performed that successfully demonstrate the technical feasibility of the new approach, and the next step will be a full end-to-end science test of the system. Only then will the teams see the full effects of the new scheme. There are still unknowns and more work to do, but if all goes well, the new scheme may be ready for operational use by the end of 2022.

Delivering global predictions

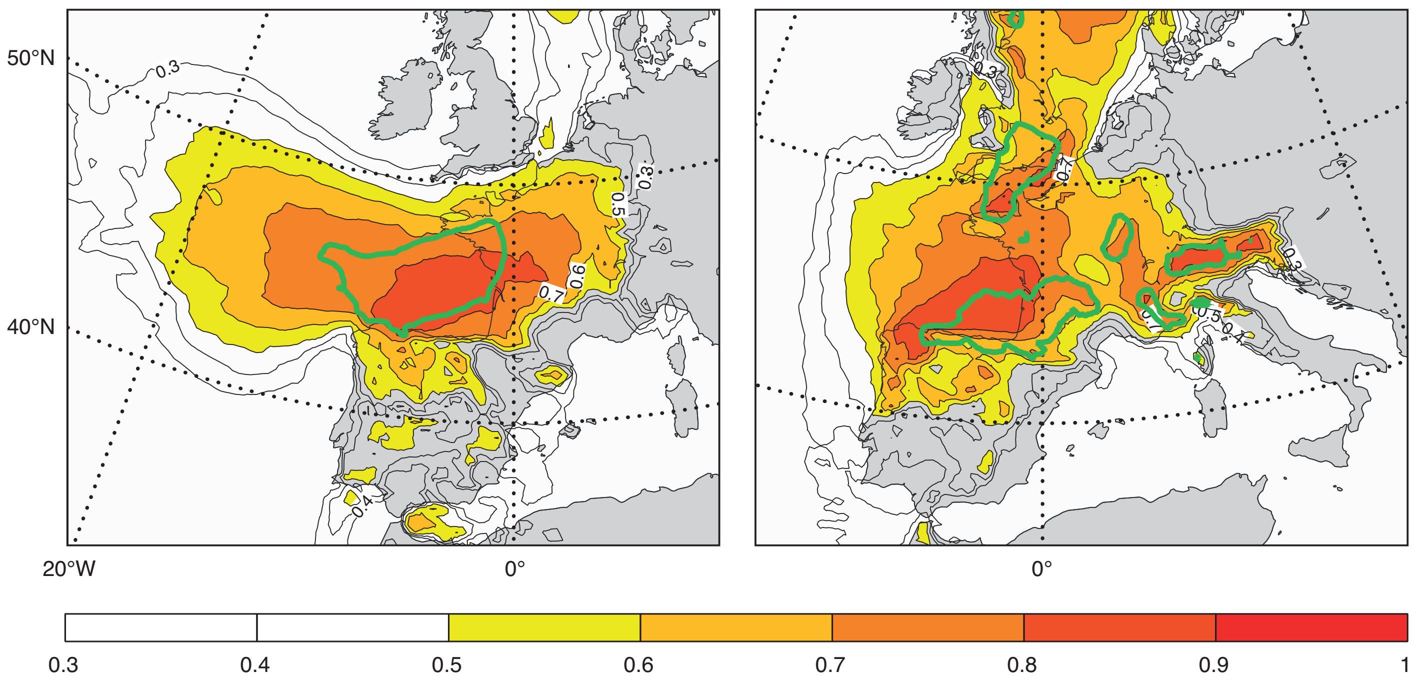
The year 2020 was marked by high-quality weather predictions ECMWF provided to its Member and Co-operating States and other users of its data and products across the globe. Severe weather events that were well predicted by ECMWF forecasts include wet and stormy weather in Europe in February, Hurricane Laura making landfall as a category 4 hurricane in Louisiana, USA, and a storm in October that affected large parts of western Europe, bringing significant wind gusts and high precipitation.

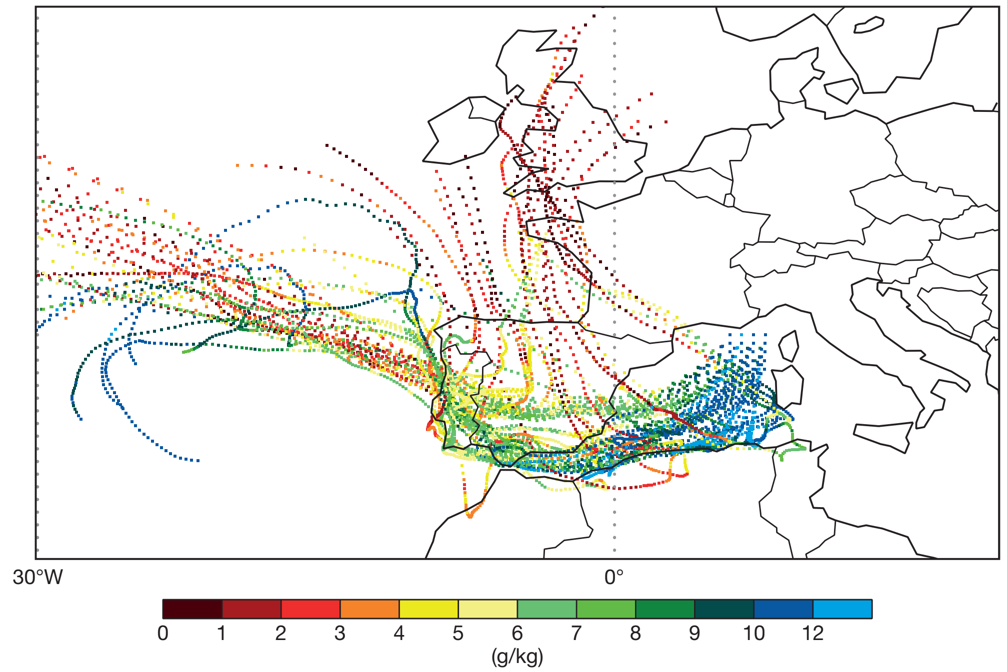
An upgrade of the Integrated Forecasting System (IFS) implemented in June improved global forecasts and substantially improved analyses and forecasts in the stratosphere. IFS Cycle 47r1 also introduced a new tropical cyclone wind radii product, which facilitated the identification of wind-related hazards. The year saw significant improvements related to upper-air ensemble forecast skill and surface parameters due to IFS Cycle 46r1, which was implemented in June 2019. Compared to other global modelling centres, ECMWF was able to maintain the overall lead in the medium range.

In an example of cooperation with the World Meteorological Organization (WMO), ECMWF joined up with the WMO to launch a new web-based interface in March 2020, to help monitor the availability and quality of global meteorological observations.

▼ Extreme Forecast Index

Extreme Forecast Index (EFI) for 24-hour maximum wind gusts on 1 October (left) and precipitation from 00 UTC on 2 October to 00 UTC on 5 October (right) in forecasts from 27 September. The plots also show areas as green lines where the values are greater than 0.9 in the one-day EFI maximum wind gust forecast on 1 October and the three-day EFI precipitation forecast starting on 2 October.





◀ Specific humidity analysis

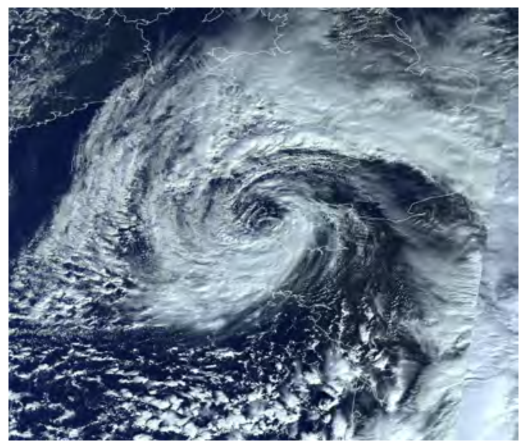
Backward air trajectories ending off the Mediterranean coast on 2 October 12 UTC between 925–850 hPa, based on ECMWF analyses and calculated with LAGRANTO, a software package to calculate parcel trajectories in the atmosphere provided to ECMWF by ETH Zurich. The colour of the trajectories indicates the specific humidity.

Windstorm Alex

At the beginning of October 2020, storm Alex affected large parts of western Europe, bringing wind gusts above 50 m/s to northwest France and precipitation locally more than 500 mm/24 hours to northern Italy and southeast France that resulted in multiple fatalities.

The most severe band of wind gusts over Brittany had some of the hallmarks of a sting jet. The maximum wind gusts in forecasts three days before (initialised at 12 UTC on 29 September) and onwards ranged from 44–51 m/s, compared to 51 m/s in observations. Such predictions give confidence that the model can simulate this type of fine-scale feature. In earlier forecasts, strong wind gusts were predicted, but not at the observed levels. Those gust forecasts had more broadscale characteristics, more reminiscent of a cold jet phenomenon (see the Extreme Forecast Index in the left-hand panel on the preceding page).

For the precipitation over southeast France and northern Italy, we find that the signal for this extreme rainfall event gradually became stronger, even if we see a slight jump on 29 September that coincides with the much clearer jump for the wind gust event (see the right-hand Extreme Forecast Index chart). The extreme rainfall was due to strong advection of moisture from the Mediterranean Sea towards the southern Alps, as seen in the specific humidity analysis.



◀ Storm Alex

This was the first storm of the 2020–21 European windstorm season, making landfall in Brittany, France, on 2 October 2020 while at peak intensity. (Image: EUMETSAT)

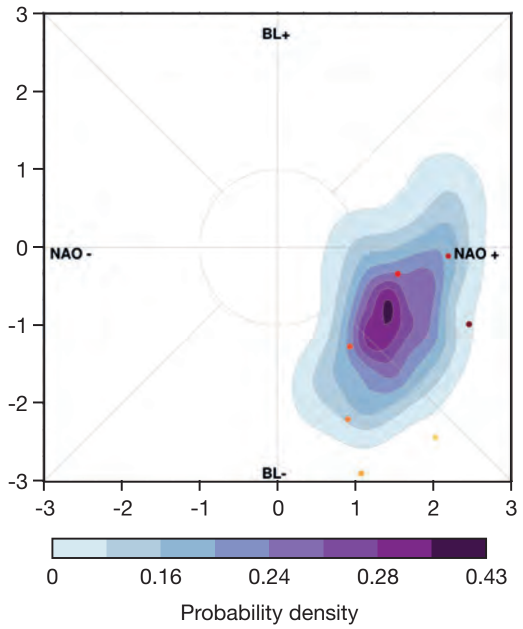
Delivering global predictions

February's wet and stormy weather

February 2020 was dominated by a strong westerly flow over northwest Europe. Several severe cyclones affected the region. These included storm Ciara on 8–9 February and storm Dennis on 15–16 February (as named by Met Éireann and the UK Met Office), and further systems on 22–23 February and 28–29 February. The cyclones brought strong winds and heavy precipitation leading to extreme accumulations over the month. New monthly precipitation records were set in England and Wales, Denmark and parts of southern Sweden, and there was some flooding in those countries.

The strong cyclonic activity over the North Atlantic was associated with a strong positive phase of the North-Atlantic Oscillation (NAO). An NAO+ signal for the week from 10 to 16 February was present in the extended-range forecast from 23 January and became stronger in the forecast from 30 January. The predicted flow-regime anomaly is visualised in a new two-dimensional plot of NAO-Blocking regime phases for the northeast Atlantic.

Although this product was originally designed to give early warnings about cold spells, it also highlights the likelihood of a westerly flow across the Atlantic with warm and wet weather over western Europe. The 30 January flow-regime anomaly forecast was shifted towards a combination of NAO+ and a trough over Scandinavia (Blocking–). The verifying analysis was in the same region of the diagram but somewhat more extreme.



Weather regime outlook for the northeast Atlantic

The plot shows the NAO-Blocking weather regime probability density function for an ensemble forecast starting on 30 January 2020 for the week from 10 to 16 February. Daily values of the verifying analysis are represented by dots: yellow (first day) to brown (last day of the target period).

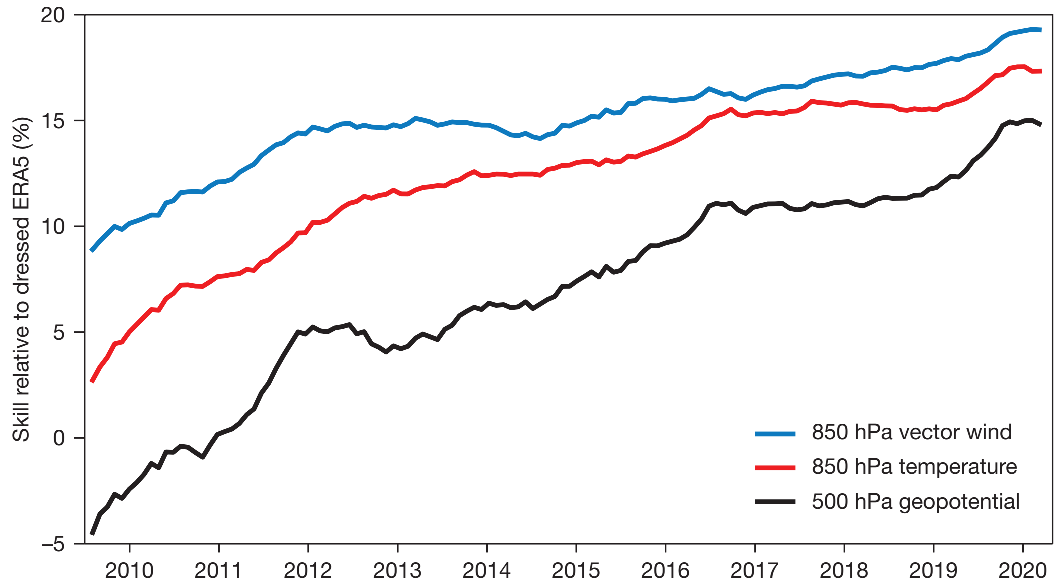
Forecast performance

On 30 June 2020, ECMWF implemented Cycle 47r1 of the Integrated Forecasting System (IFS). This brought substantial improvements in the stratosphere as well as slight improvements in the troposphere.

ECMWF's headline scores are computed as 12-month running averages to filter out the annual cycle and better identify trends in forecast performance. This means that the beneficial effect of new model cycles is fully visible only 12 months after implementation.

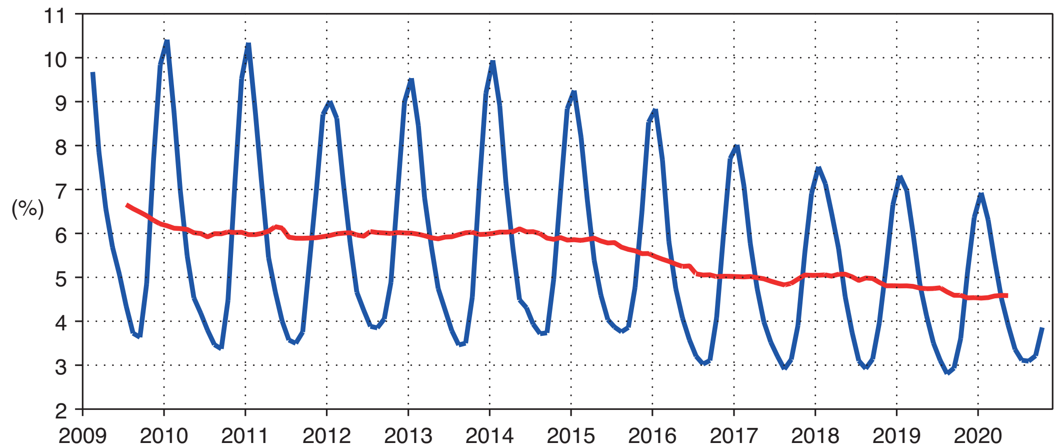
The first figure shows the significant improvement of upper-air ensemble forecast (ENS) skill due to IFS Cycle 46r1, which was implemented in June 2019. Results are shown for vector wind and temperature at 850 hPa and geopotential at 500 hPa.

> "Compared to other global modelling centres, ECMWF was able to maintain the overall lead in the medium range."



Upper-air ENS skill improvements

Skill of the ENS at day 5 for three upper-air parameters in the northern extratropics, relative to a Gaussian-dressed ERA5 forecast as a reference. Values are running 12-month averages, and verification is performed against own analysis.



Reduction in the occurrence of large ENS 2-metre temperature errors

Evolution of the fraction of large 2-metre temperature errors (CRPS > 5K) in the ENS at day 5 in the extratropics. Verification is against SYNOP observations. The 12-month running mean is shown in red, the 3-month running mean in blue.

The second figure shows that the beneficial effect of this cycle includes surface parameters, specifically a further reduction of the fraction of large ensemble forecast (ENS) errors in 2 m temperature. Substantial improvements were also seen in the precipitation forecast.

Compared to other global modelling centres, ECMWF was able to maintain the overall lead in the medium range, both for upper-air and surface parameters. It is worth noting that the medium-range forecast performance of the IFS did not show any obvious degradation due to reduced aircraft observations from March 2020 onwards as a result of COVID-19.

The signal was apparently sufficiently small to get masked by natural performance variations within the annual cycle, year-to-year atmospheric variability, as well as the positive effects of new and additional observations and the most recent model upgrade.

Delivering global predictions

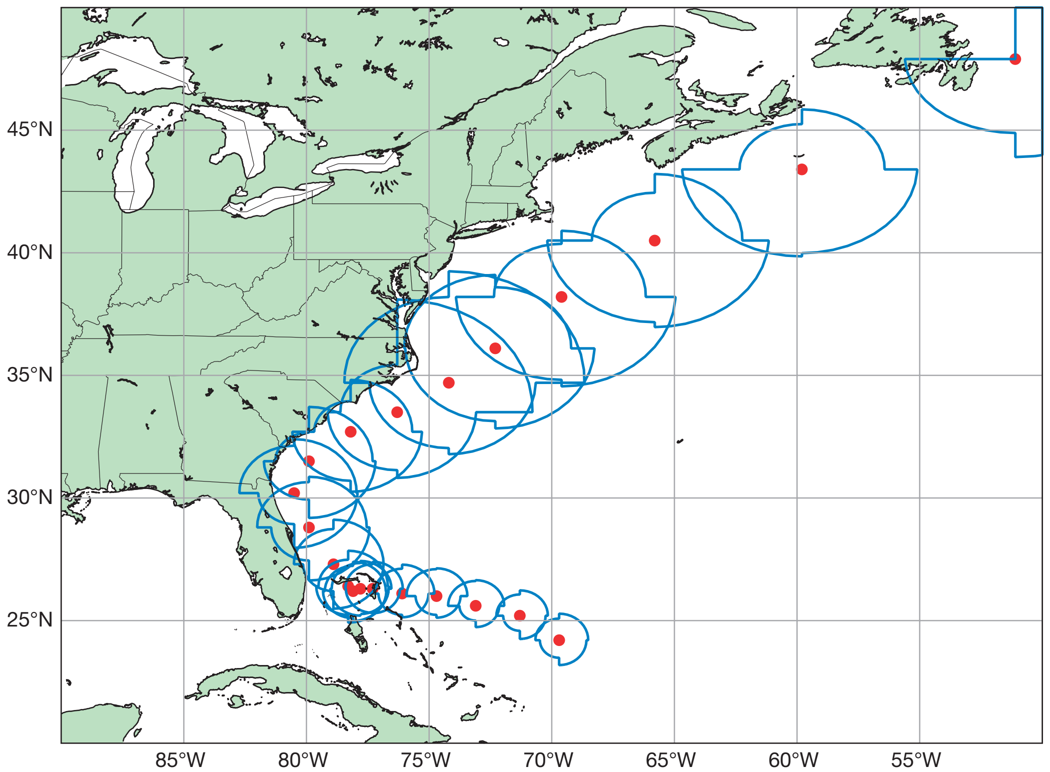
Wind radius of tropical cyclones

To assess wind-related hazards associated with tropical cyclones, it is useful to see the areas where winds are predicted to exceed certain thresholds. In Cycle 47r1 of the Integrated Forecasting System (IFS), introduced in June 2020, this was made possible by introducing a new wind radii parameter. The parameter indicates the maximum distance from a tropical cyclone centre within which the surface wind speed is predicted to exceed certain thresholds.

The thresholds have been set at 34, 50 and 64 knots, in line with the values used by tropical cyclone warning centres. A module from the Vortex Tracker package developed at the Geophysics Fluid Dynamics Laboratory (GFDL) is used to compute the wind radii.

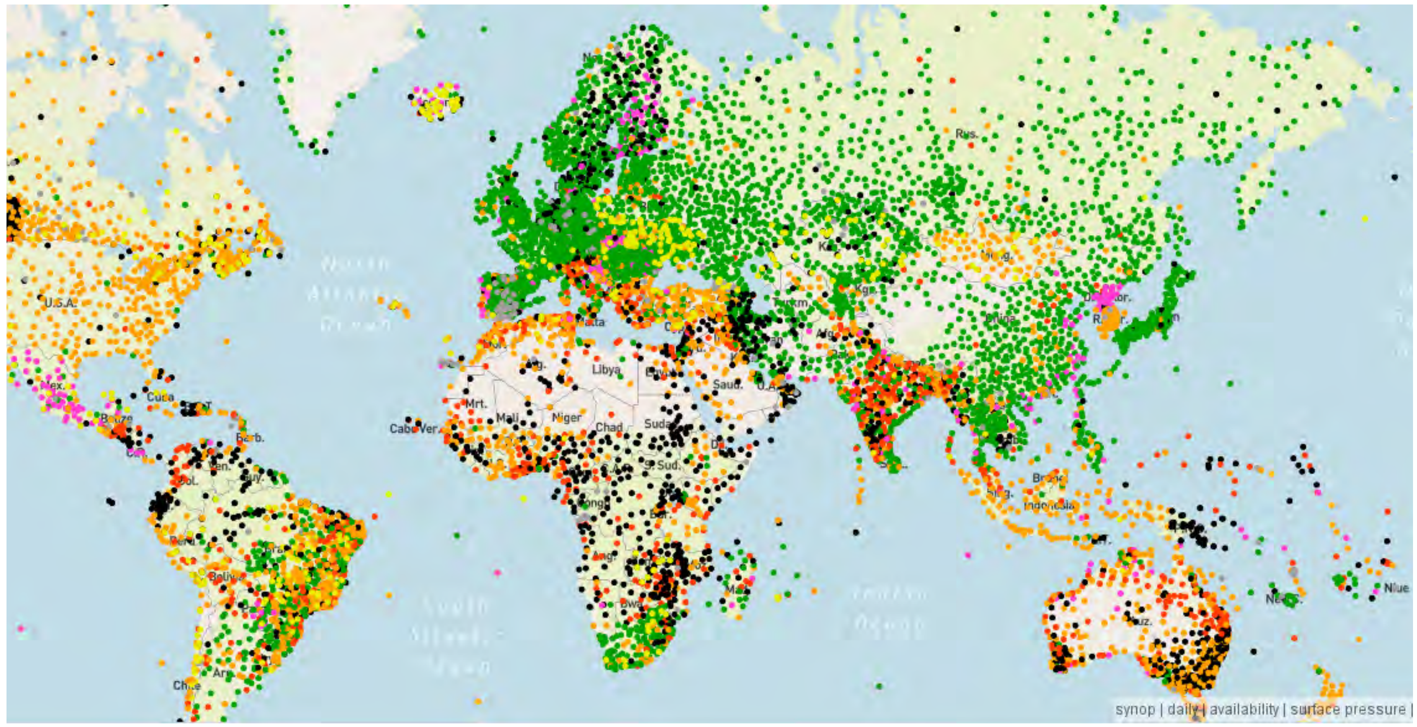
The wind radii computation is performed after the ECMWF tropical cyclone tracker has completed the identification of cyclonic features for both high-resolution forecasts (HRES) and ensemble forecasts (ENS). To start, the algorithm establishes four sectors (NE, SE, SW and NW quadrants) centred on each tropical cyclone's predicted positions. The wind radii represent, for each sector, the maximum extent from the storm centre at which the wind thresholds are exceeded.

The figure shows an example of a high-resolution wind radii forecast for Hurricane Dorian starting from 12 UTC on 30 August 2019. It shows that 34-knot winds are predicted within the sectors shown. Similar charts can be produced for 50- and 64-knot wind radii if such wind speeds are present in the forecast.



◀ **Wind radii forecast**

HRES wind radii forecast (IFS Cycle 47r1) applied to Hurricane Dorian in 2019 as an example for the change made in 2020. The forecast shows the 34-knot wind threshold up to 240 hours ahead, initialised at 12 UTC on 30 August 2019. The red dots indicate the predicted centre of the hurricane at 12-hour intervals.



New web tool for monitoring the quality of observations

The World Meteorological Organization (WMO) and ECMWF launched a new web-based interface in March 2020 to help monitor the availability and quality of global meteorological observations. The new tool monitors the performance of the in-situ observing systems that are a key component of the WMO Integrated Global Observing System (WIGOS) and is part of the WIGOS Data Quality Monitoring System (WDQMS).

The WDQMS web tool monitors the availability and quality of land-based surface and upper-air observations, based on near-real-time monitoring information provided by four participating global numerical weather prediction (NWP) centres: the German national meteorological service (DWD), ECMWF, the Japan Meteorological Agency (JMA) and the US National Centers for Environmental Prediction (NCEP).

The new system is able to collect six-hourly quality monitoring reports from the four WIGOS Monitoring Centres and store the data in the WDQMS database at ECMWF. The data are then aggregated, and the calculated statistics are compared against performance thresholds. An important function of the tool is to routinely compare the number of observations delivered from the national meteorological services (NMS) all over the world with the number of observations the NMS were expected to deliver. Under this function, the system flags up any discrepancies between what was scheduled and what was observed and highlights any issues.

▲ **The WDQMS web tool**

This screenshot shows the daily status of the land surface network for 17 March 2020 based on the monitoring information aggregated across the four NWP centres. The map highlights inhomogeneities in global data coverage (black means not reporting during the period) and reporting practices (orange and red mean underperforming and green means fully reporting) as well as issues in the station metadata (pink means reporting more than expected and yellow means that the station ID is not known).

A major upgrade of the European Flood Awareness System

A significant upgrade of the European Flood Awareness System (EFAS) was launched in 2020, which provides more precise forecasts of the timing and magnitude of flooding events. Enhancements were also made to the user platform, and large amounts of past EFAS forecast data were made available.

> This represents one of the biggest changes to EFAS, if not the biggest, since it began running operationally in 2012.
>
> *Christel Prudhomme, Manager of the EFAS Computational Centre at ECMWF*

The new version of EFAS benefits from a complete recalibration of the hydrological modelling system at six-hourly time steps and it can make better use of sub-daily weather data. The twice-daily forecasts produced with ECMWF ensembles now provide six-hourly, rather than daily averaged, information.

River levels can rise rapidly, over a matter of hours for smaller catchments, and so the new system provides much more precise guidance on when peak river discharge might occur. Six-hourly information also means that peak river flows can be represented more realistically in small to medium catchments where timing is crucial in the decision-making process.

The aim of EFAS is to support preparatory measures ahead of major flood events in the pan-European domain, particularly in Europe's large trans-national river basins. Managed by the EU Joint Research Centre, EFAS is part of the Copernicus Emergency Management Service (CEMS) and involves many partners across Europe. ECMWF operates the EFAS computational centre, which produces forecasts and hosts the EFAS Information System platform. ECMWF is also responsible for developing and integrating improvements to EFAS.

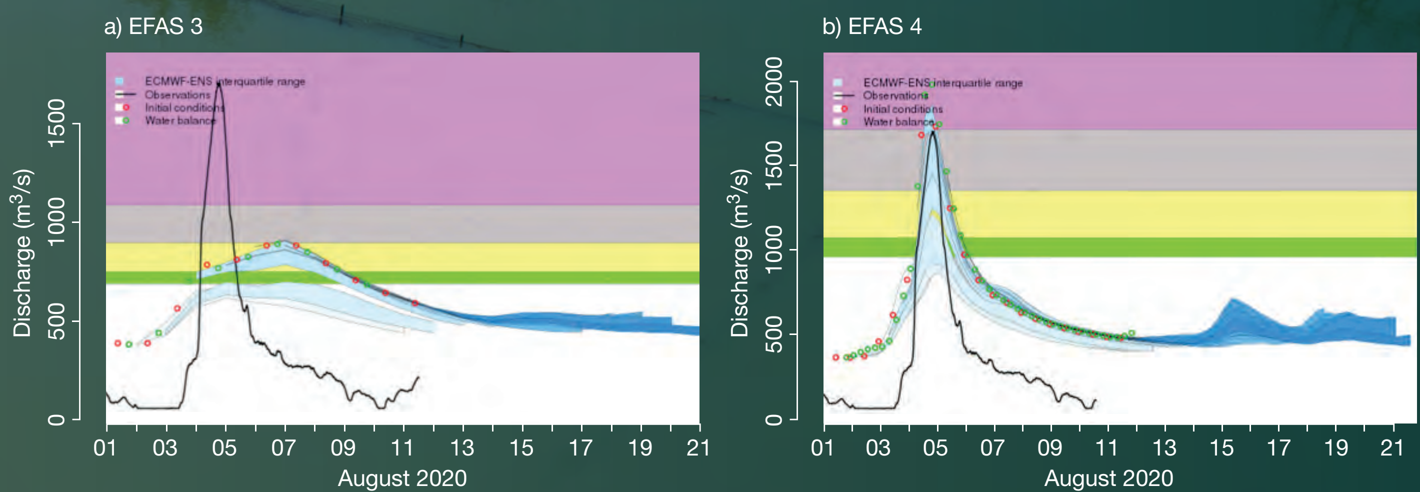
EFAS uses a hydrological model (LISFLOOD), with weather and hydrological observations and medium-range weather forecasts from a range of centres, to produce an ensemble of flood forecast information.

The new release, EFAS v4.0, follows a complete recalibration of LISFLOOD at six-hourly time steps using data from over 1,100 river stations across the EFAS domain. A dataset containing daily and six-hourly discharge data at river gauges for the period 1990 to 2017 was put together at ECMWF, based on data provided by the EFAS Hydrological Data Collection Centre. The EFAS Meteorological Data Collection Centre produced new datasets with six-hourly gridded meteorological maps of precipitation and other variables.

Overall, EFAS 4.0 shows a marked improvement in the hydrological performance, except in strongly regulated catchments, where the new calibration did not bring much change. Improvements were seen in both the magnitude and timing of simulated flood peaks.

The EFAS Information System platform was also upgraded. A new evaluation tab helps users assess hydrological model performance and forecast skill, and there are new descriptions of the way LISFLOOD represents rivers and locates reservoirs and lakes, for example.

As part of ECMWF's wider move towards open access and transparency, a huge volume of 're-forecast' or 'hindcast' EFAS data were also made available via the Copernicus Climate Change Service's Climate Data Store.



Improvement in forecasts

Example of the improvement to simulated hydrographs between (a) EFAS 3 and (b) EFAS 4 for the river Inn at Mühldorf (Germany). The observed discharge is represented by the black line; LISFLOOD outputs are represented by the green and red dots. Flood thresholds bands are shown on the background, expressed as return period levels: 1.5- to 2-year (green), 2- to 5-year (yellow), 5- to 20-year (grey), >20-year (pink). The range of the forecast ensemble is shown in blue.

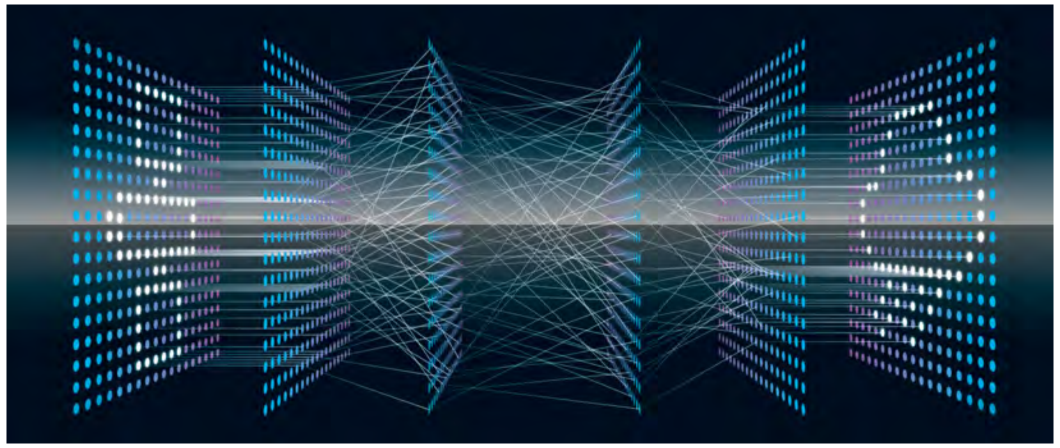
Image: Copernicus Emergency Management Service

Sustaining high-performance computing

ECMWF's world-class supercomputing facility is at the core of its operational and research activities and is upgraded typically every four or five years.

At the start of the year, ECMWF signed a contract with Atos worth over 80 million euros for a new system made up of four Atos Sequana XH2000 clusters. It will deliver about five times the performance of the current system, allowing the Centre to run higher-resolution ensemble forecasts to improve the prediction of extreme weather events significantly ahead of time.

In addition to maintaining the current operational infrastructure for forecast production, research and Member State use, the Centre completed significant preparatory work for the installation of the new machines and the migration of applications and data. The Scalability Programme also entered a new implementation phase, driving forward cutting-edge work to improve the efficiency and scalability of computer code to exploit the potential of future IT infrastructures.



Operational supercomputing facility

The Cray XC40 high-performance computing facility (HPCF) in Reading provided a good and stable service throughout 2020, processing more than half a million jobs per day on average, with availability over 99.6%. Forecast production was uninterrupted during the COVID-19 pandemic.

The Cray system will be replaced by the Atos machines in the Centre's new data centre in Bologna, Italy, to be operational in 2022.

With the entire data centre operations moving to Bologna, the migration comprises much more than just high-performance computing (HPC) applications, such as ECMWF's Integrated Forecasting System (IFS). Scientific applications must also be migrated, along with the hundreds of petabytes of operational and research data held in the Data Handling System.

By November 2020, the meteorological data archive contained 372 petabytes of primary data and 138 petabytes in the secondary data store. On average, around 290 terabytes of new data is added to the archive daily, and 210 terabytes is retrieved. Data stewardship remained important to limit the growth of the archive. Throughout the year, the Centre made strong progress transferring data from Oracle to IBM tape drives.

The first stages of the implementation phase were successfully completed in 2020. Test systems at the Atos factory in France and the Centre's UK data centre allowed the Centre and Member States to start preparing for the main system in Bologna.

Details of the ICT system design for Bologna and how Member State users will interact with and access facilities were presented at the IT User Forum in October (formerly Computing Representatives' meeting).

Despite a necessary slowing down of activities in the middle of the COVID-19 crisis, the Bologna building site progressed well through the year, made possible by the strong involvement of Italy and the Emilia-Romagna Region and the commitment of ECMWF staff in Bologna.

© Stephen Shepherd photography

▲ Representatives from Atos and ECMWF

In January ECMWF signed a contract with Atos for the supply of the BullSequana XH2000 supercomputer, authorised by the Council in December 2019.

Sustaining high-performance computing

▲ Bologna data centre

The new facility is planned to become operational in 2022. Top: external facades completed; left: racks inside Data Hall.

By the end of the year, the data centre was close to completion, with the handover to ECMWF planned to take place after full testing and commissioning. The Cray contract was extended to cover delays in the availability of the new data centre, and Atos test systems mean that any delays can be productively used for preparation work ahead of the main system deliveries.

For day-to-day operations, the security and availability of ECMWF's office environments remain a high priority. A significant milestone in 2020 was the operational roll-out of a new SSH (Secure Shell) service allowing secure remote access to ECMWF computer systems.

The advent of COVID-19 brought a sudden need for home-working at scale. ECMWF's IT infrastructure was well prepared, with robust and well-proven technologies such as Windows and Linux Virtual Desktops, laptop deployment and remote management, and video-conferencing applications already in place. Increased system capacity, coupled with training and equipment for staff, allowed for a smooth transition to remote working.

> *"Several teams in ECMWF, together with the security teams in the Member States, worked hard to successfully protect staff and organisation data."*

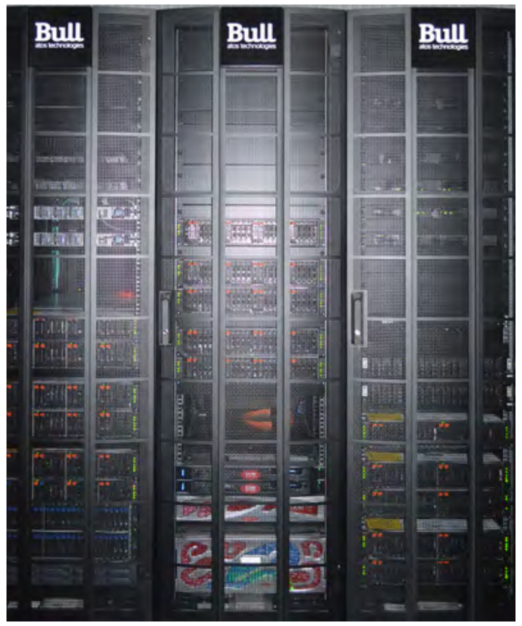
Almost four months of intensive efforts came to fruition towards the end of the year with the smooth switchover to a new firewall cluster in the Reading data centre. This major upgrade reduced complexity and doubled capacity to each network zone, in particular eliminating the network congestion which had caused slight delays to dissemination of forecast products earlier in the year.

The Centre's IT security was also put to the test in October when the meteorological community was subjected to a large-scale cyber-attack targeting email services. Several teams in ECMWF, together with the security teams in the Member States, worked hard to successfully protect staff and organisation data while minimising the disturbance.

Atos HPC test systems

In mid-January, Atos provided a core group of ECMWF developers with access to a Familiarisation System, a four-node system hosted in the Atos factory in Angers, France. Featuring the full Atos software stack, the system allowed developers to make a quick start on porting libraries and codes to the new platform.

For porting and testing work for the new Atos machines to start as quickly as possible, a temporary Test and Early Migration System (TEMS) was installed at ECMWF's data centre in the UK in February. The TEMS is a 60-node, air-cooled cluster with half a petabyte of high-performance parallel storage.



◀ Test system

The HPC Test and Early Migration System supplied by Atos was installed at ECMWF in February 2020.

After the initial integration of the TEMS into the Centre's systems, ECMWF installed the environment 'module' system and other third-party software packages commonly required. Soon after, several teams across the organisation started to explore which different combinations of compilers and Message Passing Interface (MPI) implementations work best for different scenarios.

The test system was opened to Member State developers at the beginning of July. It is fully representative of the software environment on the future system and makes it possible to port and test all libraries, utilities and applications, and is being used to develop the monitoring and operations tools that will be needed for the final system.

Sustaining high-performance computing

Scalability

The Centre's Scalability Programme encompasses internal and collaborative projects to ensure ECMWF can exploit the full potential of future computing architectures. A four-year implementation phase started in January and concentrates on the headline themes of portable and performant code; data-centric workflows; and machine learning – themes that form the core of the emphasis on computational science in ECMWF's next ten-year Strategy to 2030.

A key target is to prepare the prediction system for CPU-GPU processor and deeper-memory architectures, so that a larger variety of technologies can be considered for the HPC infrastructure that will follow the Atos Sequana system. ECMWF won another HPC resource award on the second-largest infrastructure in the US (Summit) through the DOE INCITE programme to test km-scale ensemble simulations at scale and assess both scientific and computing performance of future prediction systems.

Partnerships created through external funding continue to drive progress in this area, notably EU-funded projects such as ESCAPE-2, EPiGRAM-HS, LEXIS and MAESTRO and the ESiWACE-2 and HiDALGO centres of excellence. A joint initiative launched by Atos and ECMWF in October will complement this work. This new Centre of Excellence in HPC, AI and Quantum computing for Weather and Climate will be a platform for collaborative research and development between ECMWF and Atos and their key technology partners AMD, DDN, Mellanox and Nvidia.

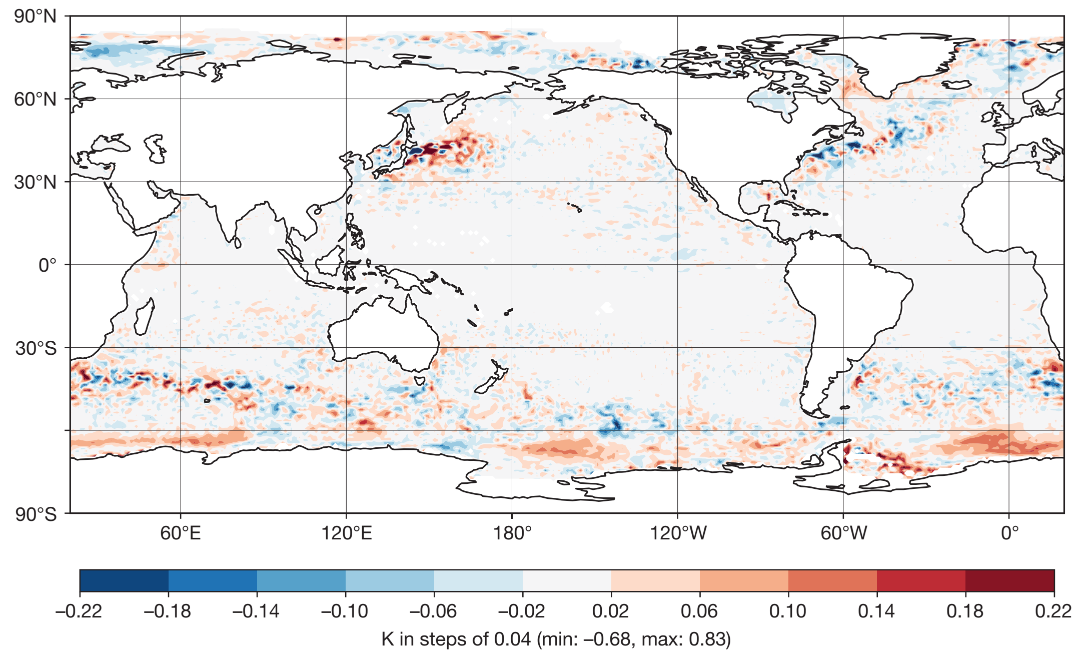
Its focus will be on investigating and exploiting state-of-the-art technologies for weather and climate applications, such as advancing machine learning methods, exploiting GPU technology for weather and climate applications, and the development or provision of tools and libraries to improve the usability and utilisation of operational HPC systems. The EU-funded MAELSTROM project to be coordinated by ECMWF will particularly focus on pushing machine learning methods for supporting data processing and computing along the entire prediction workflow.

During the year, ECMWF contributed to the Strategic Research Agenda (SRA-4) of the European Technology Platform for High-Performance Computing (ETP4HPC), resulting in the inclusion of weather and climate prediction as a feature application. This has also pushed prediction into a new multi-disciplinary digital technology activity, the trans-continuum initiative joining ETP4HPC, ECSO, BDVA, 5G IA, EU-Maths-In, CLAIRE, AIOTI and HiPEAC.

The Centre was granted Observer status in the European Open Science Cloud (EOSC) Association. Being an Observer will allow ECMWF to follow developments in this area and endeavour to contribute to the Association's vision through the Strategic Research and Innovation Agenda.

Alongside this scalability work, ECMWF worked with ESA and EUMETSAT to define the baseline architecture and first-generation deliverables of a new European Commission initiative called Destination Earth (DestinE), which could substantially accelerate the community developments in this area.

> "A key target is to prepare the prediction system for CPU-GPU processor and deeper-memory architectures."



◀ Single precision

The chart shows the change in sea-surface temperature (SST) error (K) compared to observations when moving from double precision to single precision for NEMO simulations at the high-resolution operational configuration of 0.25° global resolution, for a 26-year period. The change in error is practically zero across most of the globe.

Single precision to accelerate forecast production

ECMWF is investigating ways of reducing the computational cost of producing weather forecasts by using reduced numerical precision in the calculations.

The use of single precision – 32-bit calculations rather than the traditional 64-bit (double precision) – will be key in moving towards finer-resolution operational ensemble forecasts. It will free up vital computational resources for forecast production and will thus maximise the benefits from the investment in ECMWF's new HPCF.

Development of a single-precision variant of the IFS took place in collaboration with the University of Oxford, and this will go into operations in 2021. The use of single precision allows a higher vertical resolution in the ensemble forecast for no extra cost, with a concomitant improvement in forecast skill.

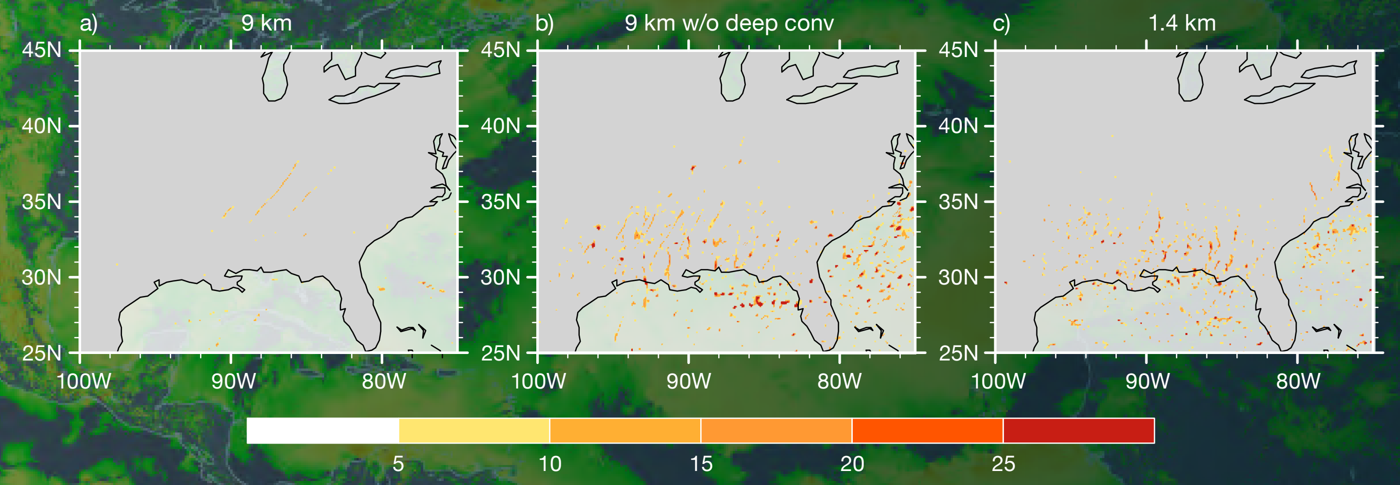
This work is being extended to the NEMO community ocean model used operationally at ECMWF, in collaboration with the Barcelona Supercomputing Center.

The single-precision variant of NEMO has been tested for long ocean-only integrations, and early results indicate favourable forecast performance compared with double precision. Yet, as in the atmosphere, the single-precision NEMO integrations are up to 40% cheaper.

The next stage of testing will consider coupled simulations. The technical infrastructure to allow the first ever fully single-precision coupled atmosphere–ocean simulations has already been established. This development will be especially important for the seasonal forecasting system, where the ocean model accounts for about 60% of the computational cost.

The world's first 1 km global seasonal simulation of the Earth's atmosphere

The world's weather has been simulated in astounding detail with the first-ever 1 km scale seasonal simulation of the atmosphere, completed on the US Summit supercomputer. It represents a major contribution towards the development of a 'digital twin' of the Earth system.



▲ Convective storm activity

Convective storm activity over the Gulf of Mexico shows a realistic distribution in the 1.4 km simulation (c). At 9 km resolution, convective activity is less realistic – being much too weak with parametrized convection (a) and too strong when the parametrization is switched off (b). Convective activity is illustrated with updraft helicity (> 5 $m^2 s^{-2}$), a combined measure of updraft strength and cyclonic vorticity, which is dominated here by the impact of more realistic vertical velocities.

From Wedi, N. P., Polichtchouk, I., Dueben, P., Anantharaj, V. G., Bauer, P., Boussetta, S., et al. (2020). A baseline for global weather and climate simulations at 1 km resolution. Journal of Advances in Modeling Earth Systems, 12, e2020MS002192. https://doi.org/10.1029/2020MS002192

◀ Hurricane Dorian

The 1 km simulation captures the intricate cloud structure of category 5 hurricane Dorian making landfall in the Bahamas on 1 September 2019.

Image in collaboration with NVIDIA, created by OMNIVERSE.

ECMWF scientists were given the unprecedented opportunity to run two seasonal simulations (winter and autumn) of the global atmosphere at a resolution of 1.4 km on Summit, one of the world's fastest supercomputers. This was part of the US INCITE[1] (Innovative and Novel Computational Impact on Theory and Experiment) programme for 2020.

ECMWF's operational medium-range weather forecasts are currently run at a horizontal resolution of 9 km, and coarser still in the long- and extended-range set up. Increasing that to nearly 1 km in a global simulation of several months represents a huge step both scientifically and computationally.

The work showed that at resolutions close to 1 km, it is possible to resolve the impact of deep convection on the circulation. Deep convection is a process that plays a key role in the re-distribution of energy and moisture in the tropics, driving the wider-scale circulation, and influencing mid-latitude weather. Typically, deep convection is parametrized using assumptions to represent convection as a subgrid process expressed through its bulk effect on the larger-scale flow. ECMWF has been very successful in the past 20 years in designing and improving convection parametrization.

In the 1.4 km experiment, the parametrization schemes for deep convection and gravity wave drag were switched off. For comparison, experiments were also run at 9 km resolution, both with and without parametrized deep convection and gravity wave drag. The simulations were uncoupled (no ocean or wave model), with 137 vertical levels.

Albeit only single realisations, the seasonal 1 km data provide a reference to evaluate the strengths and weaknesses of ECMWF's operational numerical weather prediction forecasts and indeed to further improve the existing convection parametrization, when operating at horizontal resolutions affordable in the near future.

The 1.4 km simulation showed a remarkably realistic large-scale circulation, with improved representation of convective storm activity compared with simulations at 9 km. However, other aspects such as the magnitude of tropical rainfall and the Madden Julian Oscillation, an important source of predictability, did not improve.

The simulations were conducted on only a fraction of Summit, at a speed of about one simulated week per day. The set up initially focused on efficient use of Summit's central processing units (CPUs). First steps have also been taken to move parts of the model to graphics processing units (GPUs), which hold the promise of substantial further speed enhancements. This successful use of a hybrid computer architecture is a testament to the success of ECMWF's Scalability Programme, and is key to realising km-scale simulations at speeds required for time-critical global numerical weather prediction.

The fidelity and realism of the 1.4 km simulations, with respect to the well-calibrated simulation at 9 km with parametrized deep convection, is remarkable, and achieved without adjustments to the remaining parametrizations in the model.

These ground-breaking simulations are a major step towards the development of digital twins of the Earth system and a core contribution to the European Destination Earth programme. Used in observing system simulation experiments, such high-resolution models could also support the planning of future satellite missions. Routine use of 1 km resolution simulations may become possible within the next decade.

[1] *This research used resources of the Oak Ridge Leadership Computing Facility (OLCF), which is a DOE Office of Science User Facility supported under Contract DE-AC05-00OR22725.*

> “Going down to 1 km is a quantum leap. It allows us to see how explicitly simulated deep convection interacts with and induces global changes in weather patterns. The results will help us to advance global numerical weather prediction as well as climate science.”
>
> *Nils Wedi, Head of Earth System Modelling Section at ECMWF*

Supporting ECMWF

▲ Last day in the office before the first lockdown

Staff gather around the iconic duck pond at the Reading headquarters for a last farewell. The COVID-19 lockdown measures were initially put in place for 3 weeks, but the global pandemic prevented ECMWF from reopening its offices in 2020.

2020 will be remembered as the year of the global pandemic. At ECMWF, we endeavoured to manage the implications of COVID-19 to ensure business continuity whilst mitigating the impact of the outbreak on staff health and well-being.

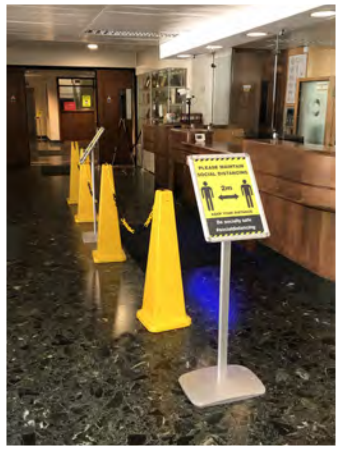
We developed new remote-working policies and provided staff with the technology and flexibility they needed to work safely and efficiently, whilst protecting their work and life balance.

We continued to engage with staff through virtual gatherings and events.

After a thorough evaluation process, our Member States completed the search for a new location compatible with European Union (EU) funding policies. Bonn, Germany, was selected as the site for our third facility.

2020 was also the year the UK left the EU. Brexit remained on our agenda, and we continued to monitor the development of intergovernmental negotiations and the implications they would have on our organisation.

Staff were commended and thanked for their exceptional work during the pandemic.



▲ Social distancing

Following a COVID-19 Risk Assessment, strict safety measures were put in place to protect essential workers on site.

> “Staff were commended and thanked for their exceptional work during the pandemic.”

▲ Collaboration with academia

PhD students visit ECMWF as part of the Doctoral Training Programme, a partnership with the University of Oxford, the University of Reading and Imperial College London. The programme provides a world-class training environment for research students across the breadth and at the frontiers of environmental research.

◀ Virtual DG talk

Director-General Florence Rabier engages with staff during her virtual weekly address.

ECMWF accommodation

Reading, UK

We continued to manage the requirements and space limitations of the ageing headquarters at Shinfield Park, focusing on adequate maintenance to prevent any risk of disruptions.

With the opening of a third facility on the horizon, the relocation of the headquarters to the University of Reading was put on hold, as the UK Government needed a better understanding of space requirements before relaunching the project.

Bologna, Italy

With the new data centre expected to be fully operational by early 2022, we started planning for the decommissioning of our UK data centre, located at the headquarters in Shinfield Park.

Supporting the implementation of the new data centre continued to be an important part of our activities. Key procurements were finalised, and we prepared for the transfer of our supercomputing facilities from the UK to Italy.

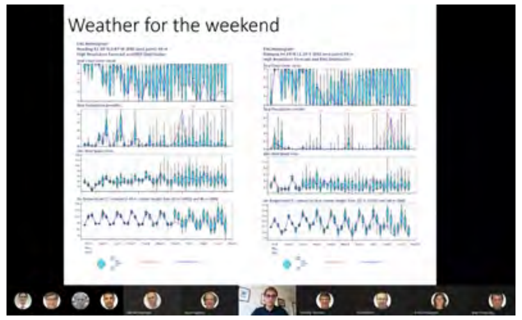
We remained engaged with our Italian counterparts at the Ministry of Foreign Affairs to ensure a smooth relocation and settling process for our staff.

Bonn, Germany

The city of Bonn will start welcoming ECMWF staff around summer 2021 in temporary offices. New and permanent offices will become available in 2026. The new German location will place ECMWF at the heart of Europe, surrounded by many world-class scientific institutions.

This in turn will enable us to foster and expand our collaboration across Europe.

Supporting ECMWF



◀ **Weather Room discussion**

Our Friday afternoon gathering became a virtual event, providing a platform for staff to discuss forecasting model performance.

ECMWF staff

As an international organisation, we are proud of our multicultural environment. At the end of 2020, we had 378 members of staff from 30 different countries. During the year, we hosted 10 visiting scientists from the Netherlands, Germany, China, Japan and the USA; a visiting scientist from France as part of the short-term secondment scheme developed with our Member States; and a graduate trainee from Austria.

We actively monitored all developments related to Brexit. Administrative processes increased significantly due to new regulations.

We continued to interact with the relevant authorities in the UK Government, notably the Foreign and Commonwealth Office (FCO), to discuss certain aspects of our Protocol. We worked on the future ability of our staff and their dependants to access housing, education and work opportunities in the UK.

With the COVID-19 outbreak, additional procedures related to quarantine requirements were implemented and required constant interaction with the FCO.

The staff-led Well-Being Network provided invaluable mental health support to staff during the pandemic, from webinars covering topics such as nutrition, relaxation and remote working, to virtual coffee mornings and yoga classes.

ECMWF funding

Following the withdrawal of the UK from the EU, the volatility of the sterling/euro exchange rates remained a challenge at the beginning of 2020. In March, sterling stabilised and we were able to record exchange rate gains.

We continued to thoroughly monitor developments in negotiations between the UK and the EU and the implications that the outcome of these discussions would have on activities in which VAT was incurred.

With the COVID-19 outbreak, the world saw a significant disruption for business operations and an unprecedented increase in economic uncertainty. At ECMWF, we closely monitored the financial implications of the pandemic and reached year-end with no negative impact on our finances.

▲ **Christmas party**

We transformed our annual event to a virtual party. We created festive rooms, invited carol singers, organised online games, and provided staff with an opportunity to celebrate together, from anywhere in the world.

Investment in ECMWF

Our 34 Member and Co-operating States are our principal source of finance with contributions totalling £51.3 million, representing a large proportion of our £125.2 million funding. External organisations support both our core research and our complementary goals with funding of £61 million. Revenue from sales of data and products provides additional income of just under £11 million. Other operating revenue totals £1.9 million.

In 2020, we continued to invest in our staff, infrastructure, and systems to provide the highest quality products to Member and Co-operating States. The main areas of expenditure are summarised below, and include capital investment of £3.7 million, principally for IT and infrastructure.

The main areas of expenditure related to remuneration and related items (£26.2 million), pension schemes (£21.6 million), computer expenses (£21 million), buildings (£4.9 million) and other operating activities (£3.5 million).

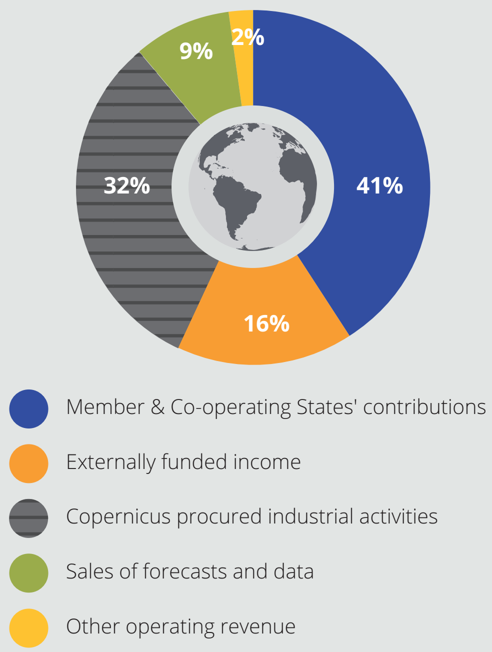
Costs associated with externally funded projects amounted to £52.8 million, and net finance costs were £5.8 million.

Our 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, we generated a surplus of £7.4 million in 2020, which is available either for future investment or distribution to Member States according to a decision to be made by our Council in 2021.

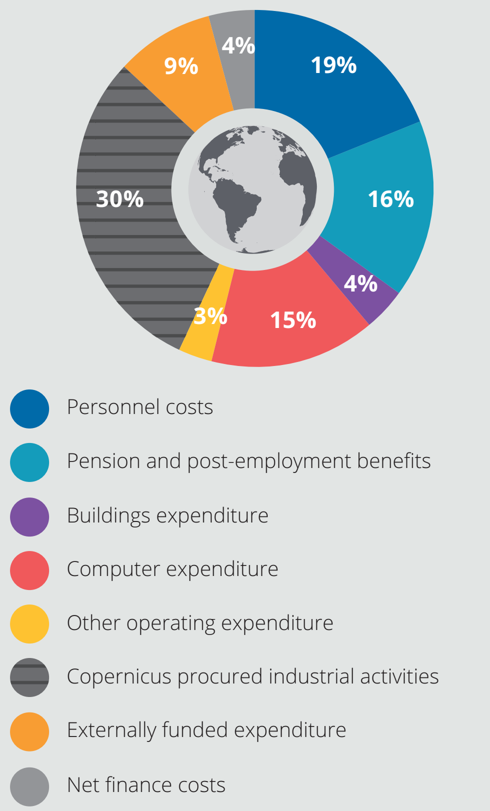
Note: all numbers exclude Centre tax.

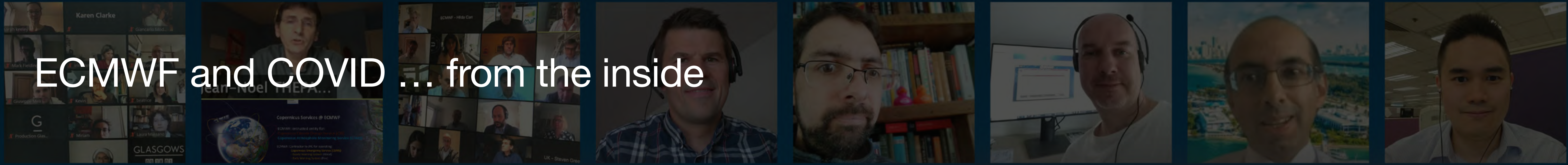
> "ECMWF continued to invest in its staff, infrastructure, and systems to provide the highest quality products to its Member and Co-operating States."

Funding



Costs





ECMWF and COVID … from the inside

The COVID pandemic affected the whole world. At ECMWF, just like our partners, we had to adjust and adapt to new challenges to ensure continuity in the delivery of numerical weather predictions to our users.

This successful adaptation is attributed to three key factors. The infrastructure developed and implemented over the year across our IT processes, together with the sustained support from our Service Desk and analysts, allowed us to seamlessly transition from all staff working in our offices to almost all staff working remotely. The steadfast reaction of our Human Resources section adapting policies, increasing the health care available to staff and demonstrating the highest level of flexibility, supported staff across the dire period. Last but by far not least, staff caring for each other brought some much valued comfort. From the discreet phone calls to those we knew to be more affected, to the Well-Being Network – a staff initiative started just before the COVID pandemic, to increasing opportunities for staff to interact, peer support was present over the whole period.

Here are some key moments that marked life at ECMWF during 2020:

January

31 January: ECMWF suspends all missions to areas affected by the outbreak, in line with the UK Foreign and Commonwealth Office.

February

ECMWF bans all work-related travel and closes its doors to external visitors and workshop delegates.

An internal event is maintained, our first science and art exhibition. Over 80 pieces created by staff and their families are displayed in the Weather Room. The artworks range from sculptures to paintings and photography, and all convey weather-related topics in their own beautifully unique ways. By combining science and art, we make space for our scientists to express their creativity through work topics they are passionate about and reflect on their scientific field in a very different way from their daily routines.

The artwork will be used to decorate the space we work in and bring science to life.

ECMWF delivers its first-ever virtual training courses. Staff are still on site, whilst students attend remotely.

24 February: Bologna premises close. This will remain the case for most of the year, with presence on site limited to staff required there.

March

20 March: Reading headquarters close. Access to site is restricted to essential workers only, with all other staff switching to working remotely.

Technical support, troubleshooting and installation of software is carried out remotely. Virtual connection to office workstations is put in place for all staff, existing and new.

25 March: A weekly address by Director-General Florence Rabier starts, allowing all staff an opportunity to gather, albeit virtually!

Weather Room discussions turn to virtual events too, with over 100 members of staff joining every Friday to exchange views on the performance of our forecasting model.

April

7 April: The Well-Being Network and Staff Committee launch a weekly Virtual Coffee Break for staff.

19 April: The 'International Employee Assistance Programme' and 'Telehealth Programme' provided by our healthcare insurance provider are launched, giving staff access to confidential counselling support and to virtual medical advice.

20 April: Mind and body classes for staff move online, and the Well-Being Network organises the first in a series of webinars to help staff over the period.

The Advisory Committee for Data Policy, Finance Committee, and Policy Advisory Committee meet virtually for the first time since the creation of ECMWF.

May

28 May: The Service Desk organises a virtual drop-in session covering the tools and options available for remote working (a second session is held on 18 June).

June

We roll out a plan for a gradual limited and reversible return to site in four phases dependent on the evolution of the pandemic. The first phase (mid-June to September) enables us to reopen the site to staff members whose personal circumstances make it very difficult to work from home.

3 June: First virtual signature of Convention accession agreement sets Estonia on course to become a Member State in December.

22 June: First return to site date.

23 June: First Virtual Council, which amongst other decisions, approves ECMWF Strategy for 2021 to 2030.

July

13–16 July: In this long series of 'firsts', the Staff Committee members are elected electronically.

August

26 August: With workshops and seminars proving to work extremely well virtually, ECMWF hosts its first virtual group visit: University of Reading (ESiWACE summer school).

September

4 September: A second 'Voluntary Return to the Office' survey aims to gauge staff interest in returning to site. Around 40 staff volunteer to gradually return.

October

12–14 October: The Scientific Advisory Committee and the Advisory Committee of Co-operating States hold their first virtual sessions.

30 October: In light of the worsening situation in the UK, remote working is extended till 31 March 2021 for staff located in Reading.

November

5 November: The UK Government announces new lockdown measures, which do not affect the working of ECMWF, still under remote-working policy.

December

11 December: A virtual staff Christmas party rounds off the year.

◀ ECMWF science and art exhibition, February 2020

Visitors to the exhibition voted for their three favourite pieces of artwork.

Serving Member and Co-operating States

ECMWF's commitment to working with Member and Co-operating States and other partners to improve the quality, range and accessibility of weather forecasts was strengthened by the common necessity to tackle the challenges brought about by the global pandemic with enduring solutions.

During this unprecedented year, ECMWF made more data openly available to all and made strong progress with the European Weather Cloud to create a cloud computing infrastructure for the meteorological community. Despite the lockdowns, ECMWF delivered its training and workshop programmes in earnest. In many ways, events achieved a much broader reach, whilst reducing the associated carbon footprint. All ECMWF's governance meetings went virtual for the first time, in some instances allowing larger delegations to attend.

ECMWF also continued to serve its community through its contribution to the European Union's Copernicus Services, publishing key reports such as the European State of the Climate, and maintaining its regular and critical user engagement programme.

Making deliverables and expertise available

ECMWF's operations remained unaffected despite the lockdowns caused by COVID-19, with staff working remotely thanks to the Centre's reliable IT infrastructure and online resources.

Events moved to virtual platforms during the year, which saw the number of attendees rise to 1,305, up 98% from 2019. There was also a significant reduction in the carbon footprint associated with events. Staff and participants did miss the face-to-face engagement of events and networking, a consideration that will help shape the Centre's future approach to serving Member and Co-operating States and will inform the use of a range of different video-conferencing software.

The flexibility enabled by digital tools made shorter events of just one-hour duration viable, such as the Machine Learning series of seminars. As a result, ECMWF ran 19 events in 2020, compared with 7 in 2019. Speakers and guests were able to attend shorter events without the need to travel.

A wide-ranging and comprehensive programme of workshops, seminars, training, and task groups covered topics including assimilating satellite cloud and precipitation for numerical weather prediction; aircraft weather observations and their use; warm conveyor belts; and guidelines for post-processing ensemble forecasts to enable WMO Members to make more effective use of ensemble forecasts.

The Using ECMWF Forecasts (UEF) event in June attracted 227 people from 43 countries for the theme 'Keeping users at the heart of operations'. The Annual Seminar in September was on the topic 'Recent developments in numerical methods for atmospheric and oceanic modelling', exploring the latest developments in computational techniques for solving the equations that govern atmospheric, wave and sea-ice dynamics. Speakers and participants at both events embraced the digital format to interact and engage with other guests.

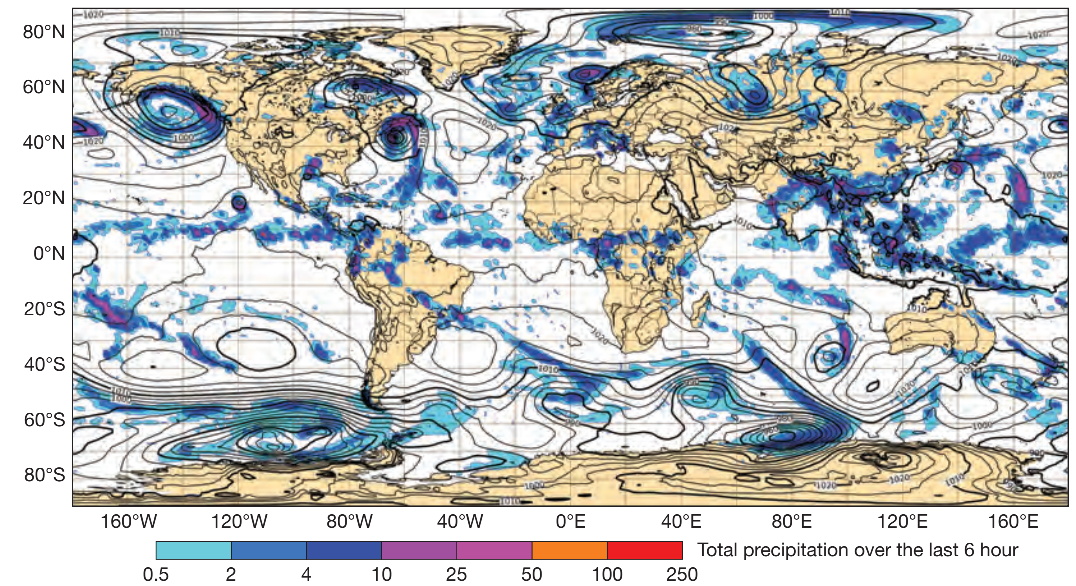
98%

Increase in attendance with virtual events compared to 2019.

1.2 million kilograms

CO_2 saved through virtual events.*

*Figures based on average distances and modes of transportation, not taking into account that some of those travelling from outside Europe would likely combine several meetings in the same trip.



Open charts

Forecasts of precipitation and mean sea level pressure are just one example of the hundreds of ECMWF charts that became available.

Liaison visits, which are a key part of our engagement with the Member and Co-operating States on ECMWF's plans and products, also evolved as the pandemic unfolded. Before lockdown, knowledge sharing, networking and training visits were made to Ireland, Montenegro, the Netherlands, and Serbia, while virtual visits were made to Belgium, Estonia, Luxembourg and Switzerland before the end of 2020.

Strong progress was made on a number of initiatives to improve ECMWF products. To monitor and improve the transparency and performance of the dissemination system, ECMWF is working on producing regular key performance indicator (KPI) reports for Member and Co-operating States.

A new way to browse ECMWF's website allows searches of all ECMWF datasets in one place. The data is also discoverable by Google's Data Search portal, and the retrieval of archive data online has also greatly improved. A reorganisation of services means users get a much faster turn-around for their requests.

The European Weather Cloud being piloted in collaboration with EUMETSAT made good progress, with Member States testing applications and providing feedback for configuring the future operational cloud services.

Open data for all

Since October 2020, ECMWF has made hundreds of its forecast maps free and available to all to encourage innovation and to support a thriving, data-based digital economy.

The open data covers the whole world and includes medium-range, extended-range and long-range forecast charts of temperature, wind, precipitation, clouds and ocean waves as just some of the products available. With ECMWF's focus on ensemble prediction, charts also cover probability-based information, which provides a guide to forecast confidence. The likelihood of extreme conditions, as well as tropical and extratropical cyclone activity, are also included.

Users can share, redistribute and adapt the information as they require, even for commercial applications, as long as they acknowledge ECMWF as the source.

Previously, full access to ECMWF's forecast charts was restricted to the national meteorological and hydrological services of Member and Co-operating States, World Meteorological Organization Members and commercial customers, and access was subject to a range of licences and often incurred charges.

The changes also mean a move to an open data policy for historical information in ECMWF's huge data repository – the Meteorological Archival and Retrieval System (MARS). MARS contains hundreds of petabytes of data including recent and past forecasts, analyses, climatological data and research experiments; it represents the largest archive of such data in the world. Opening MARS data simplifies and expands their use and re-use, stimulating further research and the development of applications related to weather and beyond.

Serving Member and Co-operating States

Warm conveyor belts – a challenge to forecasting

ECMWF's first virtual workshop took place in March, bringing together observation, assimilation, model, forecast and research communities to explore all aspects of warm conveyor belts (WCBs).

WCBs are ascending, poleward-moving warm moist airstreams in the warm sector of extratropical cyclones. They can have major repercussions on downstream weather, but their evolution is often associated with great uncertainty. The aim of this workshop was to bring communities together to discuss how the latest research can improve understanding of WCBs. Extended knowledge of this type of air flow can help to inform improvements in operational ensemble forecasting – a goal which would be very difficult for a single such community to achieve on its own.

In recent years, close work with ECMWF Fellow Heini Wernli and his team at ETH Zurich has helped to improve our understanding of WCBs and how they can be represented well in numerical weather prediction. Heini co-organised the workshop, and helped to set the scene with an overview of the history and relevance of warm conveyor belts and by posing some opening questions.

Questions addressed in the 31 talks and four working group sessions covered aspects such as predictability, observations, models and impacts.

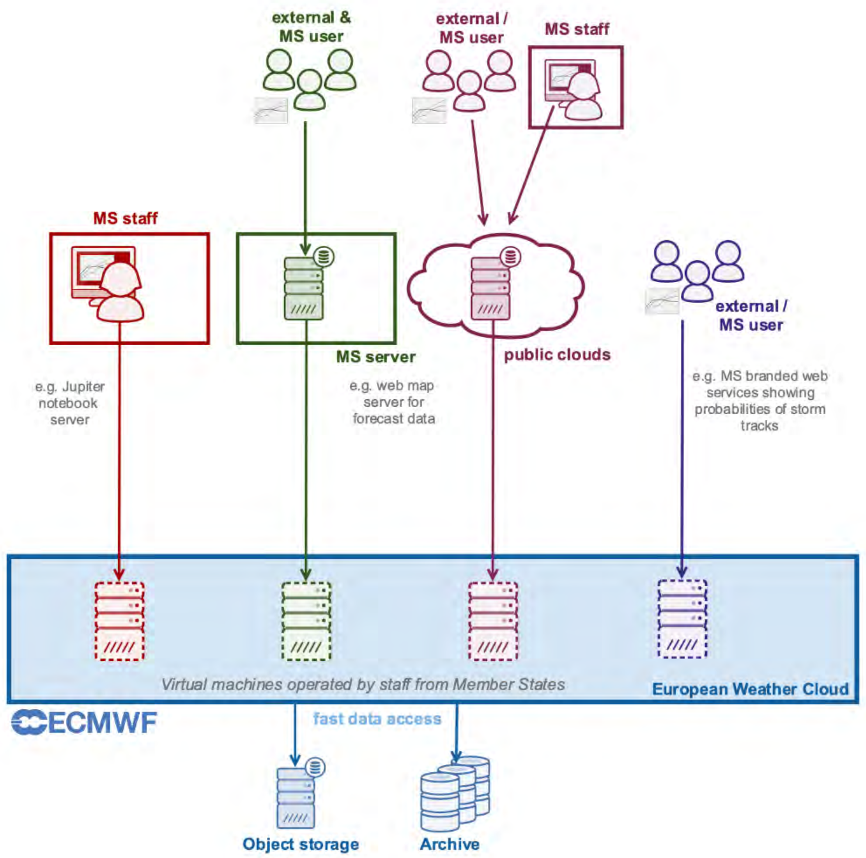
◀ **Virtual workshops**

Within 48 hours ECMWF transformed the workshop to a virtual format in response to the COVID-19 pandemic, allowing over 100 experts to probe WCBs to improve weather forecasts.

Predictability is an issue because WCBs are associated with great atmospheric instability. This leads to a rapid growth in forecast uncertainty. It is therefore important to identify the key aspects of WCBs which lead to such uncertainty.

Another topic was how well we can estimate the features of WCBs at the start of weather forecasts and whether new observation sources would help. Talks also addressed the question of how well models represent the complex physical processes in WCBs and what aspects deserve particular attention.

In terms of impacts, the workshop looked into the role WCBs play in weather extremes, regime transitions, and global climate.



◀ **Service users**

Example scenarios of how 'service users' may interact with the cloud. The 'system users' of the national meteorological services of a Member State offer hosted processing/services to internal service users (left, red), or hosted processing services for locally hosted services (middle, green) or hosted in another cloud (middle, purple) to internal or external service users. Finally, hosted services can be made accessible directly to external users and branded as a 'Member State service'.

Strong progress with European Weather Cloud

The joint project by ECMWF and EUMETSAT to create a cloud computing infrastructure for the meteorological community entered an exciting new phase. Following the procurement and deployment of the clusters for development and production, as well as storage, networks, and monitoring, the focus in 2020 was on working with users. This involved trialling applications on the pilot infrastructures to evaluate the platform and to shape the future operational services.

The cloud will lay the foundations for a strong, domain-specific European IT infrastructure enabling direct access to and effective processing of data. This means that observation data, forecast data and meteorological products can be accessed together as if they were collocated. Federation with relevant cloud infrastructures from other partners will make it possible to further widen the range of accessible data.

The project has consistently attracted more use cases, showing a good range of the possibilities offered by the cloud. Users were able to port existing services or develop new ones, benefiting from the fast access to archive and forecast data.

The pilot also demonstrated how users can bring their processing to the data and apply new forms of data analytics, like machine learning, on the large datasets they require.

In May and November, joint workshops with EUMETSAT hosted over 325 participants, and 120 participants joined a virtual 'Cloud IT technical workshop', providing a technical overview and sharing updates on recent developments, experience gained, and next steps.

In real-world practice, the European Weather Cloud was used to support Croatia in the aftermath of an earthquake that shook Zagreb. The quake and aftershocks damaged the 17th century building hosting the Croatian meteorological service (DHMZ). Fortunately, no staff were hurt so they were able to keep their operations running, and ECMWF's User Services were pleased to be able to support them using the European Weather Cloud to continue to fulfil their official duties.

The European Weather Cloud has benefited from technical expertise accumulated with cloud developments of the Copernicus Climate Data store and WEkEO Data and Information Access Service (DIAS). It is expected to become operational in 2022 after the pilot phase was extended by another year.

> "The European Weather Cloud was used to support Croatia in the aftermath of an earthquake."

Serving Member and Co-operating States

◀ **Departing Fellows**

From left to right:
Prof. Tilmann Gneiting,
Prof. Rupert Klein and
Prof. Tim Palmer.

Fellowship programme

ECMWF's strength relies on a variety of collaborations and partnerships with individuals, institutions and international organisations. Seven highly respected scientists from Europe and the United States were appointed as ECMWF Fellows in December 2020: Prof. Sándor Baran (University of Debrecen); Prof. Hannah Cloke (University of Reading); Prof. Dr Daniela Domeisen (ETH Zurich); Prof. Patrick Eriksson (Chalmers University of Technology); Dr Christian Grams (Karlsruhe Institute of Technology (KIT), Institute of Meteorology and Climate Research (IMK-TRO)); Prof. Dr Daniela Jacob (Climate Service Center Germany (GERICS)); and Dr Gabriele Pfister (Atmospheric Chemistry Observations and Modeling Lab (ACOM)).

During their initial three-year terms, the Fellows will work closely with ECMWF on scientific and technical research in a range of areas related to Earth system modelling, ensemble forecasting, and applications.

The Centre extended its thanks to Prof. Tilmann Gneiting (Heidelberg Institute for Theoretical Studies (HITS) and Karlsruhe Institute of Technology (KIT)), Prof. Rupert Klein (Freie Universität Berlin) and Prof. Tim Palmer (University of Oxford), who were appointed in July 2014 when the Fellowship scheme launched and completed their terms in July 2020.

The programme has helped strengthen links between ECMWF, the Fellows and their wider research groups in several areas, including the calibration and post-processing of forecasts; novel numerical methods; the use of 'single precision' in ECMWF's Integrated Forecasting System (IFS); predictability; and machine learning.

11 Fellows

The new appointments take the total number of ECMWF Fellows to 11.

Delivering environmental information

The Copernicus Atmosphere Monitoring Service (CAMS) and Copernicus Climate Change Service (C3S), both implemented by ECMWF on behalf of the EU, made strong progress throughout the year. ECMWF also contributed to scientific improvements for the Copernicus Emergency Management Service (CEMS), in particular the early warning systems for flood and fire danger.

Copernicus Atmosphere Monitoring Service

Two significant system improvements were realised in CAMS in 2020.

The CAMS Atmosphere Data Store launched in late spring, designed to eventually replace the Service's data catalogue and allow CAMS data to be downloaded in one place and in a few easy-to-use formats. In addition, the CAMS global forecasting system was successfully upgraded on 6 October. The upgrade combined four significant scientific changes, making the CAMS global forecasts even more accurate and robust.

Throughout the year CAMS continued to provide near-real-time monitoring and global and regional forecasting of events such as desert dust storm emission, transport and deposition, and wildfire activity; 2020 was a year of extremes for the latter in particular.

The Arctic and western US saw record high levels of activity during the summer, whilst Canada and tropical Africa saw below-average activity. In fact, the reduced activity, especially in tropical Africa (which typically accounts for about a third of total global wildfire emissions), helped to make 2020 one of the least active years in the CAMS Global Fire Assimilation System dataset, going back to 2003.

CAMS continued to monitor the ozone layer as it has since launch, combining information from its detailed numerical models of the atmosphere with satellite and ground-based (in situ) observations through data assimilation. Currently, CAMS uses ozone satellite observations from the SBUV-2, OMI, MLS, GOME-2 and Sentinel-5P/TROPOMI instruments. In addition to its ongoing monitoring and reporting of the Antarctic ozone hole, which regularly attracts press attention for CAMS, the Service also recorded that ozone levels over the Arctic reached record-breaking low values during 2020's northern hemisphere spring, generating broad interest.

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> "CAMS continued to provide near-real-time monitoring and global and regional forecasting of events."

Serving Member and Co-operating States

Copernicus Climate Change Service

In April the third annual European State of the Climate (ESOTC) report looking at key climate indicators in 2019 was published. A key focus was that 2019 was the warmest year on record for Europe. All seasons of the year were warmer than average, but some parts of Europe reached daily average temperatures up to 9°C higher than normal during the summer months. The ESOTC also explored the record-breaking levels of rainfall in autumn 2019 that resulted in the wettest November on record for some countries, and flooding in parts of western and southern Europe.

The launch of the ESOTC 2019 coincided with an expansion of the media partnership with Euronews to include Climate Now Social Live – an hour-long live social media programme featuring specialists discussing a topic relevant to climate change, with the opportunity for the audience to have their questions answered. The programme went from strength to strength through the year, covering topics such as biodiversity, health and use of artificial intelligence (AI). By the end of 2020, the C3S-sponsored Euronews online content had received over 1.1 million page views in total.

Later in the year the Climate Data Store (CDS) hit a major milestone with the registration of its 60,000th user in October. Nearly 36,000 TB of data have been delivered since the service launched in June 2018, and by the end of 2020 total data requests were rapidly approaching 200 million. At the end of the year, a significant back extension to the ERA5 reanalysis dataset was released, going all the way back to 1950. The dataset provides information on a wide range of climate variables; initially preliminary, the ERA5 Back Extension was separated from the main ERA5 dataset, with plans to relaunch at the end of 2021, and, in the future, extend it back even further.

Last but not least, C3S supported the response to the COVID pandemic by quickly developing an application allowing scientists to study how temperature and humidity conditions affect the spread of COVID-19.

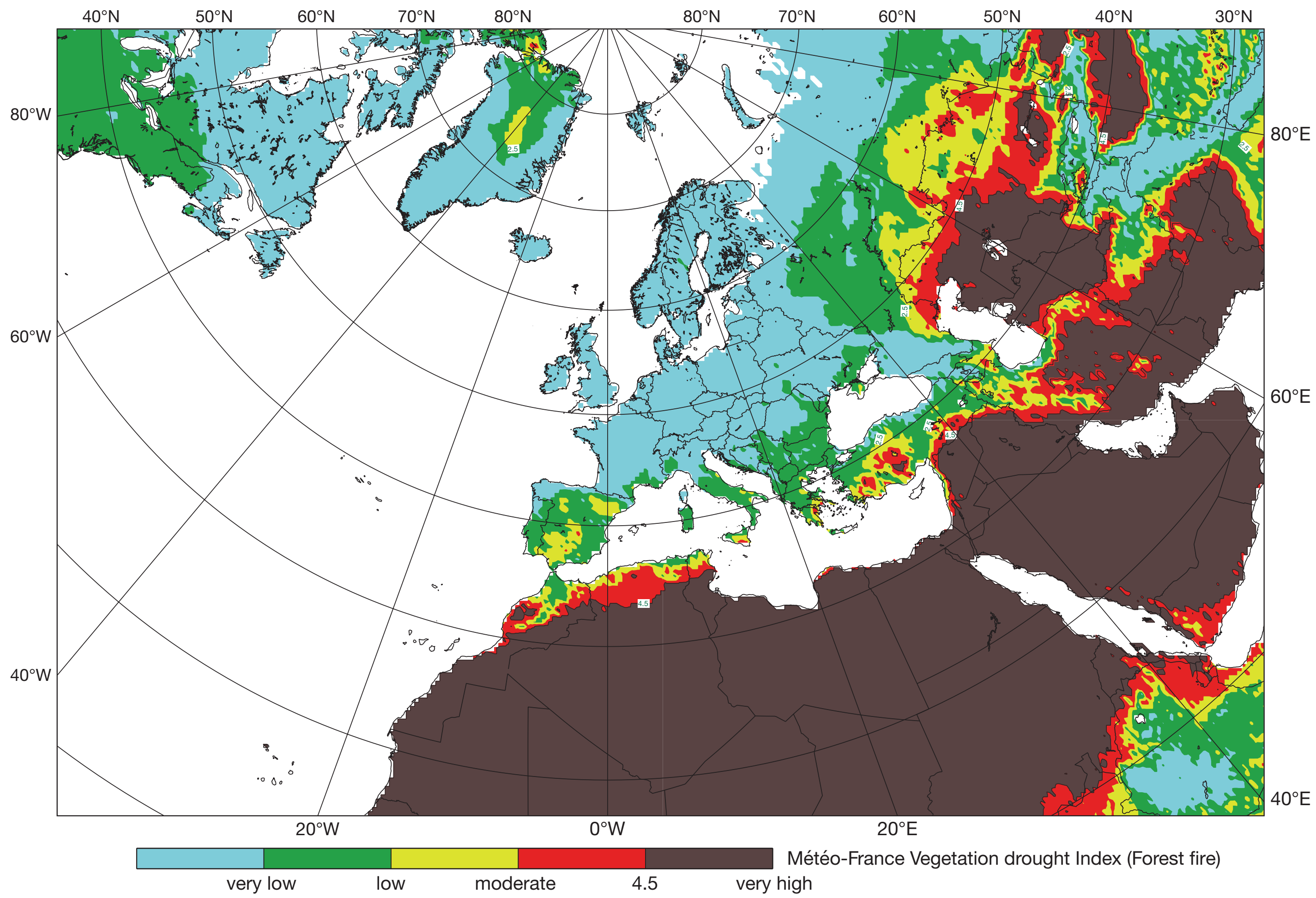
Copernicus Emergency Management Service

ECMWF operates the computational centre for both the European Flood Awareness System (EFAS) and the Global Flood Awareness System (GloFAS). Highlights in 2020 included a major upgrade of the European system, multiple resolution global land surface maps, new forecast skill layers for both EFAS and GloFAS, and a thorough investigation of global hydrological simulations and work towards improving hydrological representation in ECMWF's Integrated Forecasting System (IFS).

In the summer, GloFAS forecasts helped to mitigate the impacts of monsoon floods in Bangladesh. Over five million people were affected, there were 41 casualties and tens of thousands of people were evacuated with their livestock. The flood forecasts delivered with a ten-day lead-time gave local authorities the opportunity to warn vulnerable communities.

ECMWF continues to contribute to scientific improvements for the CEMS Early Warning Systems Fire component.

> "GloFAS forecasts helped to mitigate the impacts of monsoon floods in Bangladesh."



A new AI product estimating the probability of ignition from lightning, the first release of a global fire weather index reanalysis dataset based on ERA5 in the CDS, and a first attempt to perform calculation for the fire weather index at different times of the day were particular highlights in 2020.

CEMS-Fire has helped the collaboration between ECMWF and some Member States (Météo-France, IPMA, and AEMET) in activities related to fire danger control in Europe under the umbrella of the ARISTOTLE-ENHSP partnership.

A kick-off meeting was hosted at ECMWF in February 2020 to design a 24/7 European multi-hazard virtual advice service for natural disasters, to support the work of the EU's Emergency Response Coordination Centre (ERCC).

As a result, in addition to providing fire-related meteorological data such as drought indices, CEMS-Fire made the ecCharts interactive web chart platform available to display new products developed by Member States to support fire management in their own countries.

▲ **ecCharts**

An example of the Vegetation Drought Index developed by Météo-France and calculated at ECMWF, which became available on the ecCharts service.

Air pollution, COVID and the Copernicus Atmosphere Monitoring Service

During the COVID-19 pandemic, air pollution emerged as an area of strong scientific and general public interest, and information from the Copernicus Atmosphere Monitoring Service (CAMS) has been in great demand.

From the early days of COVID-19, questions were raised about the potential benefits of lockdown measures for air quality and the links between wider health issues, air pollution and the virus.

An area on the CAMS website was established, dedicated to COVID-19. This facilitated a very strong uptake of data products, confirming CAMS as a go-to source for timely and accurate information and expertise about air pollution.

The CAMS team looked in detail at how lockdown measures (such as restrictions on travel and other activity) affected air pollution. CAMS helped convey caveats about the interpretation of data, pointing to the importance of considering weather conditions, which can affect pollution levels, along with any changes in emissions of pollutants and their precursors.

A specific study used data from Sentinel-5P/TROPOMI (tropospheric monitoring instrument) and machine learning techniques to estimate changes in NO2 (emitted from traffic and burning of fossil fuels) accounting for changes in both emissions and weather.

The CAMS regional and global modelling systems have the advantage that they can be run with either ‘business as usual’ (BAU) emissions or the reduced emissions actually seen in 2020, in order to quantify the effects of COVID restrictions.

Indeed, a ‘COVID-19’ 2020 European emissions dataset was prepared for CAMS by the Barcelona Supercomputing Center, from publicly available data, such as mobility/traffic information and energy and flight statistics. These emissions were then used in the ensemble of 11 regional air quality models involved in CAMS, alongside control experiments with BAU emissions.

The main conclusions were that over Europe, during March and April 2020 surface concentrations of NO2 were estimated to have more than halved in some places as a result of COVID restrictions, but there were marked differences across the region. Over China, reductions of 20–30% in fine particulate concentrations were estimated for February 2020.

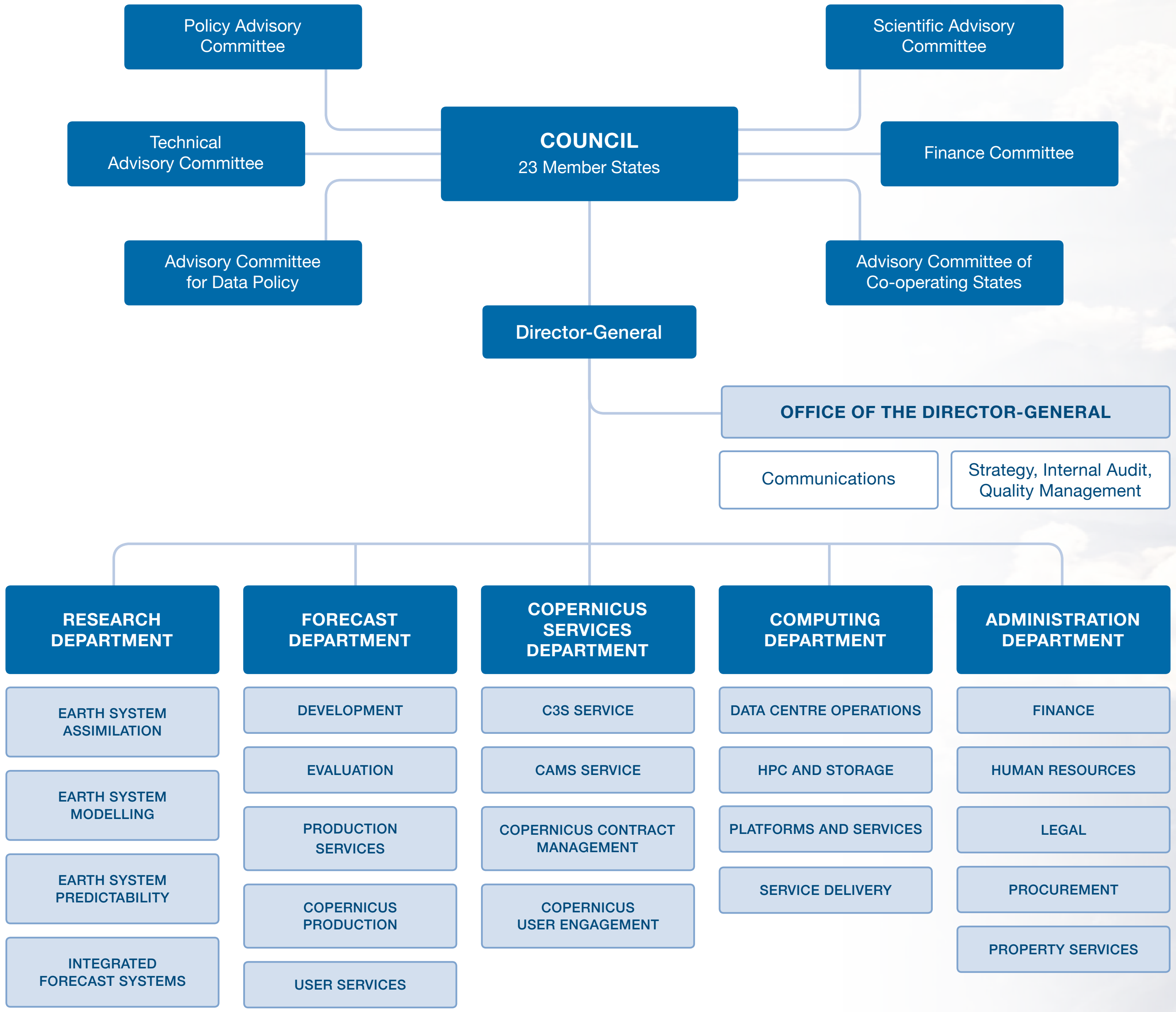
CAMS modelling work made a major contribution to the Air Quality in Europe 2020 Report, produced by the European Environment Agency, which featured a specific section looking at COVID-19 and air pollution. CAMS has also been very actively supporting the World Meteorological Organization’s efforts to support governments worldwide in assessing the impact of meteorology and air quality impacts on the pandemic.

CAMS data have also been used in studies looking at health impacts related to air pollution and COVID-19. Epidemiologists are investigating several questions. Have the reductions in NO2 and particulates led to a decrease in deaths related to air pollution? Can exposure to air pollution contribute to reduced immune response and higher risk of developing severe COVID-19? To what extent is the virus transmitted by inhalation of fine particulate matter that could have been contaminated?

For example, one ongoing study is examining the short- and long-term impacts of air pollution on COVID-19 development and outcome. It is looking at the exposure to air pollution of over a thousand elderly people in France and Belgium, from 2018 to early 2020. CAMS data about air pollutants, UV radiation and weather parameters are being used for this. The complete spatial coverage of CAMS data, the availability of past data and their high quality have proved extremely valuable for such studies.

[1] *CAMS is implemented by ECMWF on behalf of the European Commission.*

How we work



Organisation of ECMWF at June 2021

Co-operating States as of January 2021

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

ECMWF
Shinfield Road
Reading RG2 9AX
United Kingdom

Tel: +44 118 949 9000

www.ecmwf.int