ECMWF

European Centre for Medium-Range Weather Forecasts

Annual Report 2021

www.ecmwf.int

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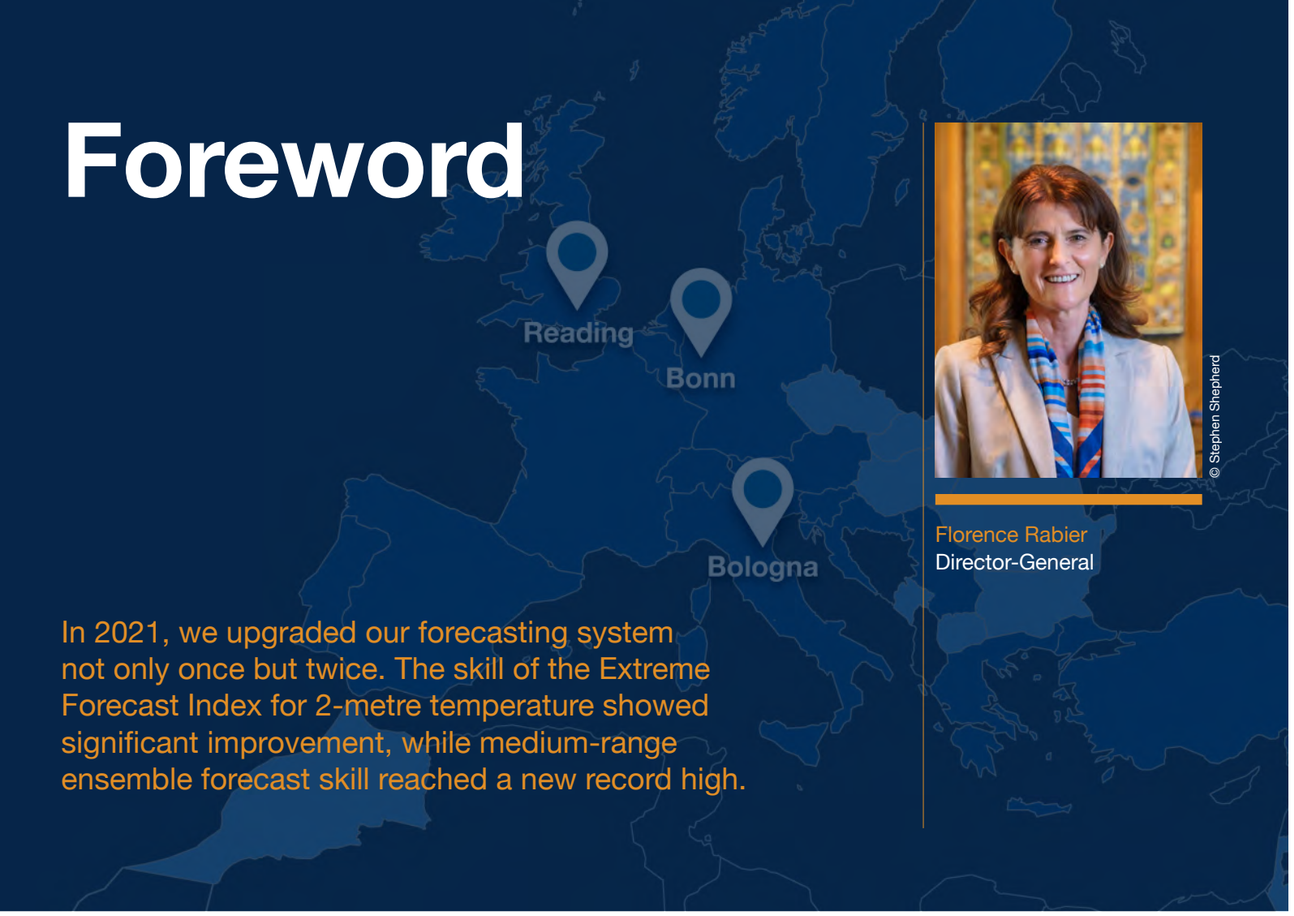
Member States as of January 2022

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

Foreword



In 2021, we upgraded our forecasting system not only once but twice. The skill of the Extreme Forecast Index for 2-metre temperature showed significant improvement, while medium-range ensemble forecast skill reached a new record high.

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Florence Rabier
Director-General

The year 2021 had its fair share of challenges and opportunities, and this report highlights some of the year's achievements that stand out as important or inspiring. But 2021 will in particular be remembered as the year when ECMWF became a multi-site organisation. The Centre was created in 1975 with its offices and data centre located together in Reading, United Kingdom. Our new setup, with headquarters in the UK, data centre in Italy, and additional offices in Germany certainly marks a turning point in the life and functioning of ECMWF. New processes and ways of working were implemented as we embarked on this adventure.

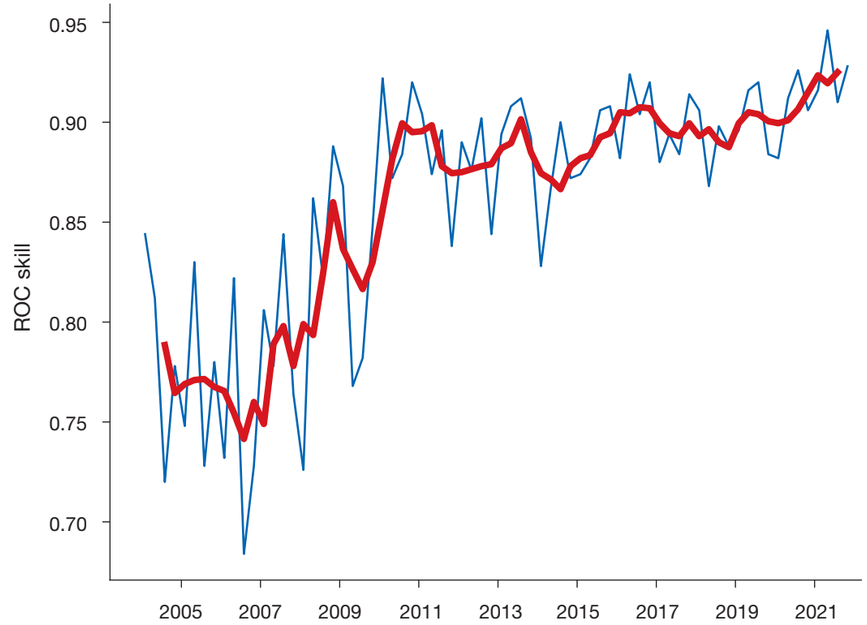
The year also saw the launch of our Strategy to 2030, developed with our Member and Co-operating States and with a strong emphasis on providing ever more skilful forecasts to their national meteorological and hydrological services.

As a perfect illustration, 2021 saw not one but two upgrades of ECMWF's Integrated Forecasting System (IFS). The first, IFS Cycle 47r2 implemented on 11 May, introduced single precision for high-resolution and ensemble forecasts and increased the vertical resolution in the ensemble. The second, IFS Cycle 47r3 implemented on 12 October, improved the representation of moist physics in the model and increased satellite observation usage in cloudy regions in data assimilation.

ECMWF membership continues to grow. Last year was the first full year with Estonia as a Member State, and we were pleased to be able to raise the Estonian flag at our Reading headquarters in June, as well as to welcome Georgia as a Co-operating State in December. Our partnership with the European Union was also strengthened. We signed an agreement with the European Commission to continue implementing the EU-funded Copernicus Climate Change Service (C3S) and Copernicus Atmosphere Monitoring Service (CAMS) for the next seven years.

This agreement includes the implementation of the European anthropogenic CO_2 emission monitoring and verification support capability, which will support action on climate change in line with the Paris Agreement. ECMWF's role as the computational centre for the hydrological forecasting activities of the EU-funded Copernicus Emergency Management Service (CEMS) was also renewed until 2027. As computational centre, we will continue to help deliver the European and Global Flood Awareness Systems, EFAS and GloFAS.

To finish the year in style, the long-awaited Destination Earth agreement was signed with the European Commission, ensuring that ECMWF and its Member States, alongside ESA and EUMETSAT, can contribute to developing a highly accurate digital twin of our planet.



◀ Extreme Forecast Index (EFI) for 2-metre temperature skill

The chart shows the relative operating characteristic (ROC) skill at forecast day five in Europe. After a decade of little systematic change, the ROC skill at day five increased beyond its previous average value of 0.9. Three-monthly values are shown in blue and the 12-month running average in red.

This was our second 'COVID year', one in which working remotely had become a habit and we built on what we had learned from this to revisit some of our operational policies, processes, and structures. We have started to rethink our environmental plan and to question our engagement modus operandi. It is still very early to assess how many of the changes we have been forced to make will remain. It is clear, however, that speaking at or attending a workshop or seminar remotely is no longer looked down upon, having fully virtual gatherings has become part of our business as usual, and hybrid meetings look set to become our new normal. As a new multi-site organisation, this changed way of functioning will no doubt be key to remaining 'One ECMWF'.

June 2022

2021 At a glance

January

Strategy and machine learning roadmap launched

Our ten-year Strategy for the period 2021 to 2030 came into force, with an emphasis on providing ever-more skilful forecasts to Member and Co-operating States and users around the world. It was accompanied by a machine learning roadmap setting out our plans to integrate machine learning into numerical weather prediction (NWP) and climate services to improve predictions and their use in many areas of the workflow.

CO2 monitoring project to deliver prototype system

A European programme to build a monitoring and verification support capability for global emissions of carbon dioxide (CO_2) related to human activities got under way. The ECMWF-coordinated Copernicus CO_2 (CoCO2) project will deliver the prototype for a new European anthropogenic CO_2 emissions monitoring and verification support capacity which will be implemented as part of the EU's Copernicus programme. The project went on to hold its first General Assembly in November.

ECMWF science presented at AMS Annual Meeting

With international conferences continuing to take place virtually due to the COVID-19 pandemic, our scientists took the opportunity to hear from colleagues and present ECMWF research and plans at the Annual Meeting of the American Meteorological Society (AMS).

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ECMWF Member State flags outside the headquarters in Reading, UK.

Emergency bulletins support humanitarian work in Mozambique

ECMWF helped to produce emergency bulletins to the UK Foreign Commonwealth and Development Office in response to flooding in Mozambique caused by tropical cyclone Eloise. We provided meteorological guidance about the cyclone itself and streamflow forecasts from the Global Flood Awareness System (GloFAS), run on behalf of the EU Copernicus Emergency Management Service (CEMS). The bulletins were produced with the Universities of Reading and Bristol, HR Wallingford and Fathom and enabled the deployment of aid resources to the affected areas.

February

Workshops explore cloud technologies

Participants at our 'Weather and climate in the cloud' workshop shared experiences and plans for using cloud technologies to improve services for users. Two more workshops in May and November provided an opportunity for Member and Co-operating States of EUMETSAT and ECMWF to review achievements in the pilot phase of the European Weather Cloud project and look ahead to a future operational phase.

The UEF2021 user meeting explored the theme 'Weather in extraordinary circumstances'.

March

Destination Earth and digital twin plans presented

We held the first of our science and technology seminars presenting the European Commission's planned Destination Earth programme from the perspectives of ECMWF, ESA and EUMETSAT. Two more followed in April and May. These seminars gave participants a preview of how digital twins of the Earth will make it possible to interactively explore various natural processes and human activities.

April

European State of the Climate published

The EU-funded Copernicus Climate Change Service (C3S) implemented by ECMWF published a comprehensive overview of the 2020 European climate, including a focus on the Arctic and a summary of global conditions. The report confirmed 2020 was the warmest year on record for Europe. Winter temperatures were particularly notable, 3.4°C higher than the 1981–2010 average and 1.4°C higher than the second-warmest winter on record.

Atmospheric composition forecasts added to data store

The Copernicus Atmosphere Monitoring Service (CAMS) run by ECMWF made it easier to access its atmospheric composition global forecasts by making them available in the CAMS Atmosphere Data Store (ADS). Archived past data and past forecasts are also available in the store, where they can be downloaded in one standard format, so that scientists, businesses and policymakers can access atmospheric data for research or decision-making.

MAELSTROM project to prepare for machine learning applications

A three-year project to help prepare the weather and climate community for large-scale machine learning applications began, funded under the EuroHPC Joint Undertaking and coordinated by ECMWF. The 'Machine learning for scalable meteorology and climate' project (MAELSTROM) puts an emphasis on co-design to allow feedbacks between application, software, and hardware developments.

May

Single precision and higher vertical resolution in IFS upgrade

An upgrade of ECMWF's Integrated Forecasting System (IFS) to Cycle 47r2 introduced single precision for high-resolution and ensemble forecasts, freeing up computing power for other improvements. One such improvement was an increase in the vertical resolution of ensemble forecasts, which enhanced many aspects of forecast skill across different time ranges.

Summer coding challenges begin

The coding period for the fourth ECMWF Summer of Weather Code (ESoWC) ran from May to August. Nine developer teams worked on projects at the intersection of machine learning, web development, visualisation, data compression and open data exploration and showcased their results at a final presentation day in September.

Extratropical cyclone database updated

Updates to ECMWF's extratropical cyclone database products brought improvements to the visualisations and behind-the-scenes changes to the software. Developed in collaboration with the UK Met Office, the extratropical cyclone database products have been available from ECMWF for more than a decade. They provide forecasters with familiar synoptic-style charts, showing fronts and low-pressure (cyclonic) weather systems that can be associated with hazardous conditions such as strong winds, snow and rain.

Scientists share results at EGU General Assembly

Our scientists made a strong contribution to the European Geosciences Union (EGU) General Assembly, with virtual presentations touching on many aspects of weather prediction as well as work done by the EU Copernicus services on climate change and atmospheric composition run by ECMWF.

2021 At a glance

June

First phase of data centre project completed

A handover agreement between the Italian authorities and ECMWF marked the end of Phase 1 of the data centre project. Responsibility for managing the centre and ownership of certain equipment such as the chillers and dry coolers were transferred to ECMWF. We also had the opportunity to show Italian Prime Minister Mario Draghi around the facility and explain its importance for the delivery of services to our Member States.

User meeting looks at weather in extraordinary circumstances

Our second fully virtual Using ECMWF's Forecasts (UEF) event attracted 228 people from 53 countries to discuss and provide feedback on ECMWF products and services. The theme of 'Weather in extraordinary circumstances' encompassed topics such as the impacts of COVID-19 on forecasting and other extraordinary events that impact forecasting, modelling, users and the public. New elements this year included a full day focused on the EU's Copernicus services linked to ECMWF, five-minute 'lightning talks' on a variety of topics, and a Science and Art event.

Saildrone data to help understand the Gulf Stream

ECMWF joined a new partnership with Saildrone, the University of Rhode Island and Google to use data from the highly turbulent Gulf Stream to improve the understanding of ocean processes in the region. In December, three Saildrone uncrewed surface vehicles set off on a six-month mission to gain observations.

July

Intense rainfall leads to devastating floods in Europe

July saw very heavy rainfall in western central Europe in a region with soils close to saturation. This led to severe floods in several countries, with the most heavily impacted including Germany, Belgium, Luxembourg, and the Netherlands. ECMWF high-resolution forecasts predicted the broad location and intensity of the rain three days in advance. Flood forecasts were issued by the European Flood Awareness System (EFAS), part of CEMS.

Copernicus contracts renewed

ECMWF signed an agreement with the European Commission to continue implementing the Copernicus Climate Change Service (C3S) and Copernicus Atmosphere Monitoring Service (CAMS) for the next seven years. We will also continue as the computational centre for the hydrological forecasting activities of the Copernicus Emergency Management Service (CEMS) until 2027.

New forum and virtual assistant help users

We opened a Forecast User Forum for users to comment on topics related to weather and forecasting, join conversations and provide feedback to ECMWF. It complements existing forecast user pages such as the Forecast User Guide and Severe Event Catalogue and provides a space where users of our forecasts can interact with other users and ECMWF experts. We also launched a virtual assistant – the knowledge duck – in the C3S Climate Data Store to help users make the most of the information and support services available.

© Saildrone, Inc.

Data from Saildrone unmanned surface vehicles will help to improve the understanding of ocean processes in the Gulf Stream region.

Our biennial high-performance computing workshop considered exascale computing in NWP.

August

Europe experiences warmest summer on record

The Mediterranean region experienced extreme temperatures with a heatwave moving from east to west during August. At the beginning of the month, severe wildfires hit Greece and Turkey. On 11 August, a provisional European temperature record of 48.8°C was set in Syracuse in Sicily. Later the heatwave continued to the Iberian Peninsula, with temperatures of 46.9°C in Cordoba on 14 August. The ECMWF Extreme Forecast Index (EFI) showed a consistently strong signal for the extreme temperatures up to a week ahead.

Atos user acceptance testing begins

User acceptance testing began on the Atos supercomputers in Bologna and was continuing at the end of the year.

CAMS and C3S data in IPCC climate assessment report

CAMS and C3S data and products were used extensively in the Intergovernmental Panel on Climate Change (IPCC) Working Group 1 contribution to the Sixth Assessment Report. Several CAMS datasets were used, and ERA5 was cited more than 200 times. ERA5 is the latest climate reanalysis produced by ECMWF, providing hourly data on many atmospheric, land-surface and sea-state parameters together with estimates of uncertainty.

September

WMO fellow to develop Climate Data Store application for Africa

ECMWF welcomed a meteorologist from the National Department of Meteorology, Cameroon, to work on a Climate Data Store application for Africa as part of a one-year World Meteorological Organization (WMO) Fellowship. The Fellowship is part of a long-standing WMO scheme to provide specialised training placements to develop capacity in least-developed and developing countries.

Annual Seminar focuses on Earth system observations

Thirty-seven experts set out the latest thinking on Earth system observations at ECMWF's Annual Seminar. Our flagship educational event was held online and attracted 520 attendees.

Workshop considers exascale computing in NWP

Experts from national weather centres, academia and industry came together online for our biennial event on the use of high-performance computing in meteorology. With more than 50 talks on the theme 'Towards Exascale Computing in Numerical Weather Prediction', the workshop attracted 313 participants from 43 countries.

NextGEMS project begins

A new, four-year EU-funded project to contribute to developing a new generation of Earth system models began, with 26 partners involved and ECMWF as co-coordinator. The NextGEMS project aims to develop models that will help fill gaps in our understanding of how the Earth system works and how the world's climate will change over the next three decades.

2021 At a glance

ECMWF becomes a multi-site organisation

Following opening ceremonies at our new offices in Bonn, Germany, and our data centre in Bologna, Italy, ECMWF officially became a multi-site organisation. The headquarters remain in the UK, while the focus in Bonn is on work conducted in partnership with the EU and the Bologna data centre houses the new Atos Bull Sequana high-performance computing facility.

ERA5-Land reanalysis dataset extended

C3S made the back-extension period of its high-resolution ERA5-Land reanalysis dataset available through the Climate Data Store. This subset of ERA5-Land covers the period 1950–1980 and is designed to improve the knowledge of land evolution from the last seven decades. The ERA5-Land dataset is the first of its kind, providing global, hourly, historic and high-resolution land-focused information for a more accurate representation of water and energy cycles.

October

OpenCharts catalogue extended

New products added to our OpenCharts Catalogue included parameters such as lightning and visibility. The new products and most of the existing ones also benefited from increased time steps, moving from 12–24 hours down to 3–6 hours, in line with our normal forecasting processes. Ensemble-based products in OpenCharts were also enhanced, providing more detailed information for users, such as probabilities for additional variables and weather types.

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ECMWF staff at the formal opening of offices in Bonn, Germany, in September.

Improved moist physics and use of satellite observations

A second forecasting system upgrade in 2021, Cycle 47r3, improved the representation of moist physics in the model and increased satellite observation usage in cloudy regions in data assimilation. The developments are a culmination of work spanning several years and are part of a long-term development of the moist physics in the IFS in preparation for the transition to higher horizontal resolutions (3–5 km) in future operations. Separately, the CAMS global forecasting system was also upgraded to use IFS Cycle 47r3 and began operationally assimilating NO_2 observations from ESA's Sentinel-5P satellite.

Antarctic ozone hole large and long-lived

CAMS scientists monitoring the ozone hole over the south pole reported that it was one of the deepest in CAMS or C3S records. The hole closed in December, ending another of the longest lasting Antarctic ozone hole seasons on record. 2021 was marked by very cold temperatures in the stratosphere and a very stable polar vortex, which contributed to the duration of the hole.

November

ECMWF attends COP26 Climate Change Conference

At the United Nations Climate Change Conference of the Parties (COP26), ECMWF showed how data and services from the EU's Copernicus Earth observation programme can support countries in meeting the goals of the Paris Agreement and the UN Framework Convention on Climate Change. Staff spoke on topics including a future anthropogenic CO2 emissions monitoring and verification support capacity and the importance and use of reanalysis and essential climate variables data held by C3S.

Partnership to support EIB adaptation strategies

The European Investment Bank (EIB) and ECMWF signed a Memorandum of Understanding setting out a framework for cooperation on the enhanced use of Copernicus Earth observation data. The partnership will see the two parties work together to enable Copernicus climate and atmosphere data to support EIB activities as the EU's Climate Bank.

December

Georgia becomes ECMWF Co-operating State

A Co-operation Agreement between ECMWF and Georgia came into force on 1 December, granting Georgia full access to ECMWF real-time products, archive data and software tools, and ECMWF training facilities.

New site approved for ECMWF headquarters

Our Council of Member States approved an offer from the UK Government to transfer the ECMWF headquarters from Shinfield Park near Reading to a new site on the campus of the University of Reading, planned to be ready in 2026.

CONFESS project hosts General Assembly

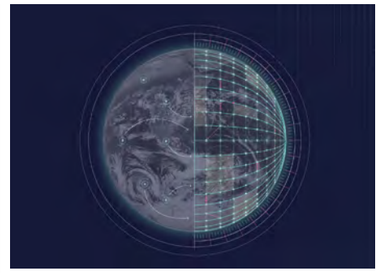
The EU-funded CONFESS project coordinated by ECMWF hosted its first General Assembly. Over 70 online participants from Europe and beyond heard about the objectives and progress of the project, which is contributing to the development of the next C3S reanalysis, ERA6, and of C3S seasonal forecast products.

ECMWF to develop digital twins for Destination Earth

Following approval from our Council, we officially became part of the EU's ambitious Destination Earth initiative to create a digital twin – an interactive computer simulation – of our planet. ECMWF, ESA and EUMETSAT are the three organisations entrusted by the EU to achieve this unprecedented endeavour for weather, climate and computing sciences.

OpenIFS turns ten

Our OpenIFS initiative marked its tenth anniversary. OpenIFS began in 2011 to provide supported versions of the operational IFS for research, education and training in NWP and meteorology by Member and Co-operating States and academic institutes. Licences are now held by 90 institutions.

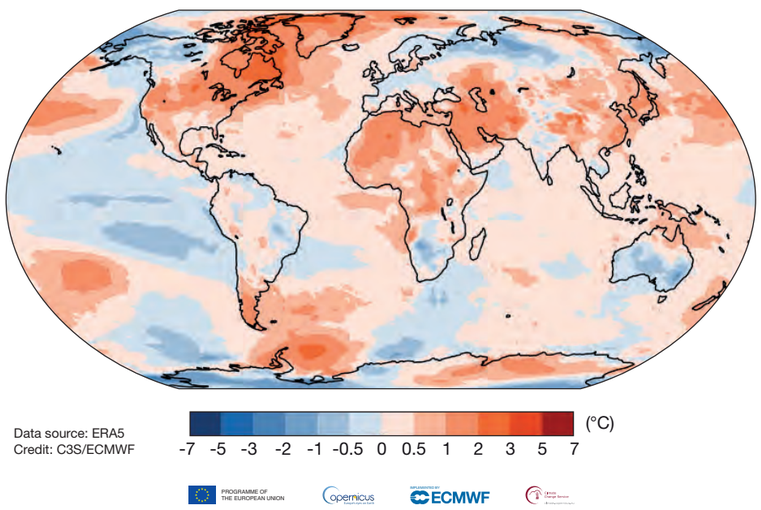


Science and technology seminars presented plans for digital twins.

2021 fifth-warmest year on record

Globally 2021 was the fifth-warmest year on record, according to findings released by C3S. The annual average temperature was 0.3°C above the 1991–2020 reference period, and 1.1–1.2°C above the pre-industrial level of 1850–1900.

Temperature difference 2021 and 1991–2020



Air temperature at a height of two metres for 2021, shown relative to its 1991–2020 average. Source: ERA5. Credit: Copernicus Climate Change Service/ECMWF.

Science and technology

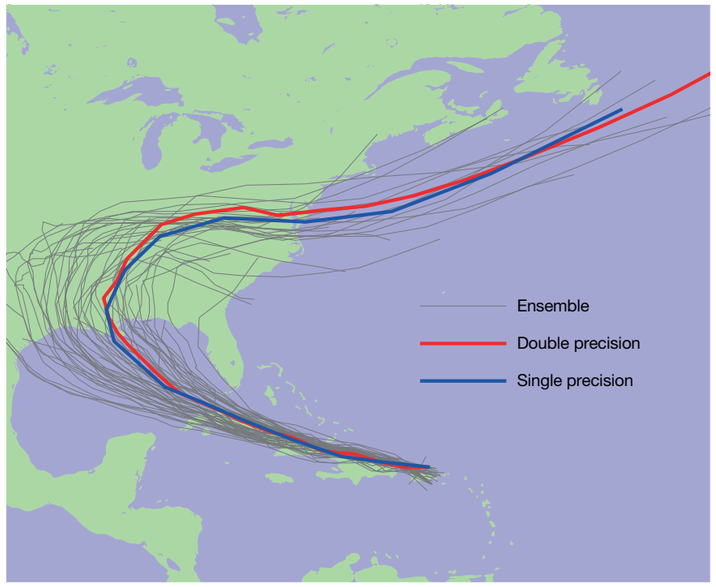
Many scientific and technological developments were achieved in 2021. On the scientific front, they include the implementation of single precision in the Integrated Forecasting System (IFS) and the increase in vertical levels in ensemble forecasts made possible by it. In a second upgrade in 2021, ‘all-sky’ data assimilation was extended to some of the most powerful observations assimilated into the IFS to achieve a good estimate of the current state of the Earth system.

Machine learning made big strides in emulating components of the IFS, such as the gravity wave drag parametrization scheme. We also began to ingest data from Saildrone uncrewed surface vehicles to better understand the behaviour of the Gulf Stream, and we applied the Ensemble of Data Assimilations to the ocean. Finally, we started to use more radiosonde data, and we made additional efforts to assimilate spaceborne radio occultation data.

ECMWF’s supercomputing facility is at the core of our operational and research activities and is upgraded typically every four or five years. In 2021, we set up the new Atos high-performance computing facility (HPCF) in Bologna, Italy, while the previous HPCF continued to be used to produce forecasts.

Progress was also made in the Scalability Programme, set up to ensure we can exploit the full potential of future computing architectures. A project helping to prepare weather prediction for the exascale concluded. Tests were also performed on the use of half precision in the IFS, and progress was made on the European Weather Cloud, a federated cloud computing infrastructure focused on meteorological data, created jointly with EUMETSAT.

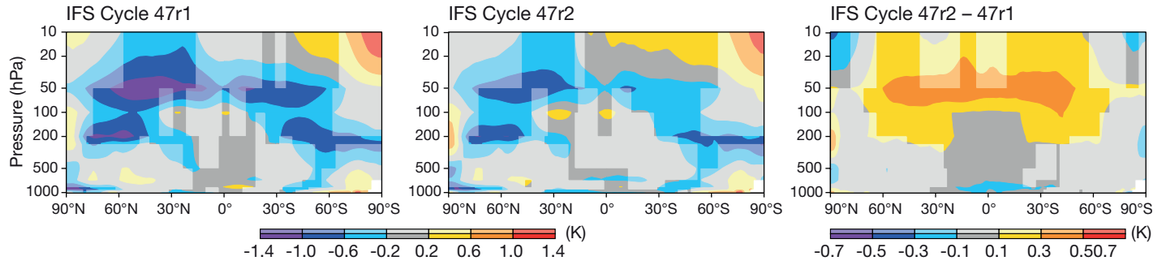
This was the first year implementing our new Strategy for the period 2021–2030 as agreed by Member States. A key goal in the science and technology area is to use advanced high-performance computing, big data and artificial intelligence methodologies to continue developing our models into a digital twin of the Earth with a breakthrough in realism. This work will now also contribute to the new EU Destination Earth initiative that was launched at the end of 2021.



▲ Impact of single precision in the case of Hurricane Laura

Eight-day tracks of Hurricane Laura from 12 UTC on 22 August 2020 in high-resolution deterministic forecasts with double precision (red) and single precision (blue) along with those from the operational ensemble at the time (grey).

> “Single precision frees up memory and increases processor speeds.”



From double precision to single precision

The year saw a major change in the precision of the calculations made in the IFS. Many of the previous ‘double precision’ calculations were replaced by ‘single precision’ calculations, which are computationally less demanding. In double precision, each number is stored using 64 bits of memory. This is often more precise than required when observational errors and model approximations are considered. Single precision, in which each number is stored with 32 bits of memory, frees up memory and increases processor speeds.

In an upgrade of the forecasting system on 11 May 2021, single precision was used both in high-resolution forecasts (HRES) and in ensemble forecasts (ENS). Double precision was still used throughout the process which determines the initial conditions for each forecast. Some calculations in the forecast also still required double precision, but these represented a very small part of the total computational load.

The goal of the implementation of single precision was neutrality in HRES performance scores, as well as major computational cost savings. This was indeed achieved. The cost savings enabled an increase in the number of model levels from 91 to 137 in ENS forecasts.

An illustration of the neutrality in HRES scores is given by track forecasts of Hurricane Laura in August 2020. While agreement cannot be perfect for a chaotic system, the medium-range track differences between single and double precision are much smaller than the spread of the ensemble, which represents the impacts of initial and model uncertainty.

More ensemble vertical levels

The number of vertical levels in ensemble forecasts (ENS) was increased from 91 to 137 in the upgrade of the IFS implemented on 11 May. The 51 members of ENS thus reached the same number of vertical levels as high-resolution forecasts (HRES). The change led to statistically significant improvements to many ENS performance scores of about 0.5–2%.

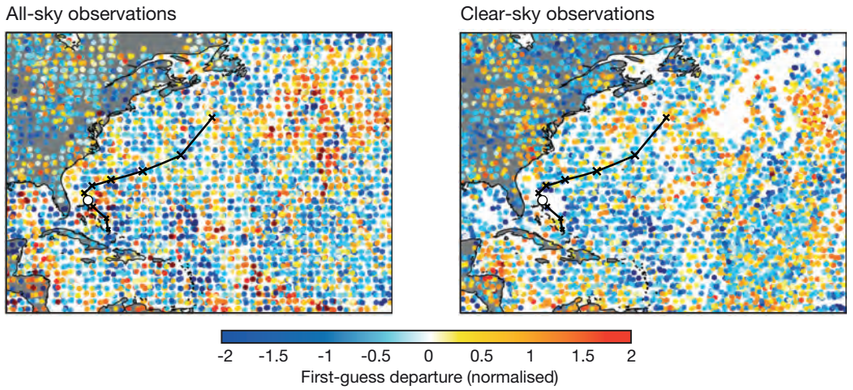
The change was made without any additional demands on the high-performance computing system. This is because at the same time most of the calculations for HRES and ENS forecasts changed from double precision to single precision.

A particular improvement relates to stratospheric temperature scores, which went up by 5–20%. This is partly due to a weaker growth of temperature biases. The reason is that the ENS can better resolve gravity waves in the vertical. The figure shows this improvement at day 10, but it persists into the extended range.

▲ Reduction of temperature errors in the stratosphere

The first two plots show zonal means of mean temperature errors at a lead time of 10 days in the ensemble control forecast for IFS Cycle 47r1 (left) and IFS Cycle 47r2 (middle). The difference between IFS Cycles 47r2 and 47r1 is shown in the right-hand plot. More saturated colours indicate statistical significance at the 5% level using a t-test accounting for temporal correlation. The evaluation took place over all forecasts between 25 November 2019 and 28 February 2020 as well as 10 May 2020 and 7 November 2020.

Science and technology



◀ All-sky observations using AMSU-A near Hurricane Humberto

The images show differences between observations and the model background (first-guess departures) for all-sky observations (left) and clear-sky observations (right) assimilated during the 12-hour long window starting at 00 UTC on 15 September 2019. Best track locations at 00 UTC over the life of Humberto are given by a black X, with a white circle showing the hurricane location at 00 UTC on 15 September 2019, just east of Florida. Departures are normalised by the assigned observation errors.

Wider all-sky data assimilation

There has been a trend in recent years to use satellite data in all-sky conditions, in other words including in cloudy and rainy situations. In an upgrade of the IFS to Cycle 47r3 in October 2021, the all-sky strategy was extended to AMSU-A microwave temperature sounding observations.

These observations have been among the most powerful assimilated into the IFS to achieve a good estimate of the current state of the Earth system. The upgrade to all-sky conditions led to an improved fit of that estimate to independent observations, and to an improvement in forecast scores.

An example of the filling of data gaps in cloudy regions is provided by the case of Hurricane Humberto. Coverage is improved in the immediate vicinity of Humberto, which in the figure is indicated by the white circle. It is also more extensive in the wider region, which is likely to be important for influencing Humberto's subsequent track.

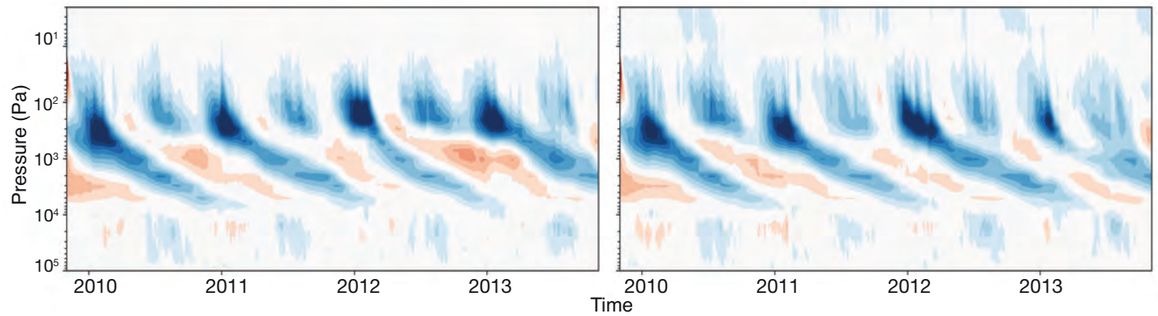
IFS Cycle 47r3 also introduced a wide-ranging moist physics upgrade, which has been described in the previous Annual Report.

Machine learning to emulate parts of the IFS

First steps were taken at ECMWF in 2021 to emulate components of the IFS using machine learning techniques. Machine learning tools can learn to represent complex tasks and dynamics from a large amount of data. Neural networks are particularly promising. They learn by adjusting the strength of connections between a set of neurons during a training period.

Such networks were used to emulate the radiation scheme ecRad in collaboration with the technology company NVIDIA, and the gravity wave drag parametrization scheme in collaboration with the University of Oxford. For example, ECMWF successfully built an emulator for the representation of non-orographic gravity waves.

The emulator was not only faster – up to ten times if graphics processing units (GPUs) are used – but also better. This was because it was trained from a version of the parametrization scheme with higher fidelity compared to the default scheme used in operations (see the figure). The emulator was also used to build so-called tangent-linear and adjoint versions of it. These were used successfully in data assimilation experiments.



▲ IFS forecasts of the zonal-mean zonal jet

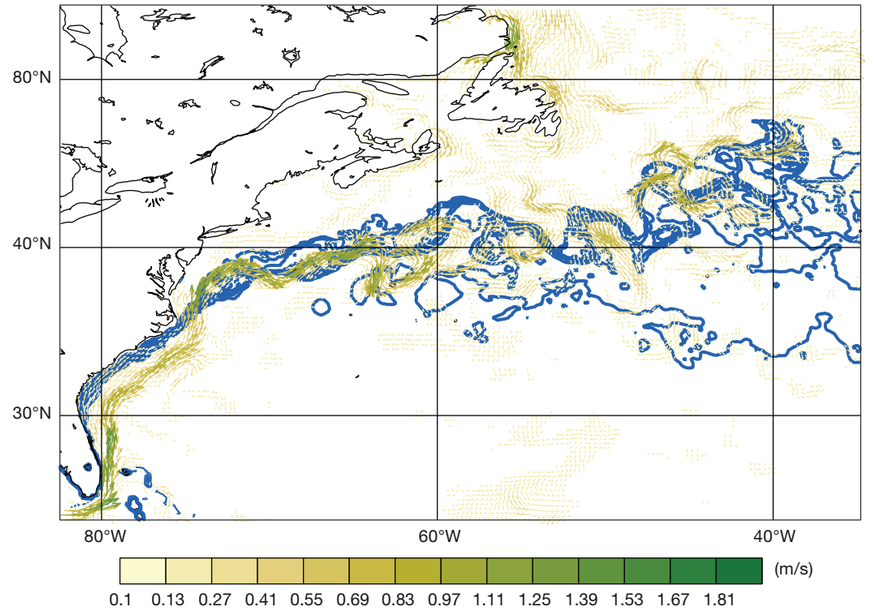
The images show IFS forecasts of the zonal-mean zonal jet averaged between latitudes –5° to 5°, depicting the quasi-biennial oscillation (QBO). The left-hand image shows the result of using an increased complexity version of the existing non-orographic gravity wave drag scheme. The right-hand image is the result of using a neural network to emulate non-orographic gravity wave drag. Both forecasts capture the phases of the QBO and only diverge after significant simulation time.

Saildrone to help ECMWF understand the Gulf Stream

We began to ingest data from Saildrone uncrewed surface vehicles (USVs) in 2021 to better understand the behaviour of the Gulf Stream and its influence on weather. Under an agreement with Google and Saildrone Inc., three solar-powered USVs began to cover a part of the Gulf Stream that is crucial for forecasts.

One of them was stationed east of the US states of North Carolina and Virginia, where the current is relatively narrow, a second was stationed mid-stream, and the third was stationed downstream off the Grand Banks of Newfoundland where the current broadens, meanders, and breaks into eddies. The three USVs were set to sail back and forth across the current to capture as many ocean features as possible.

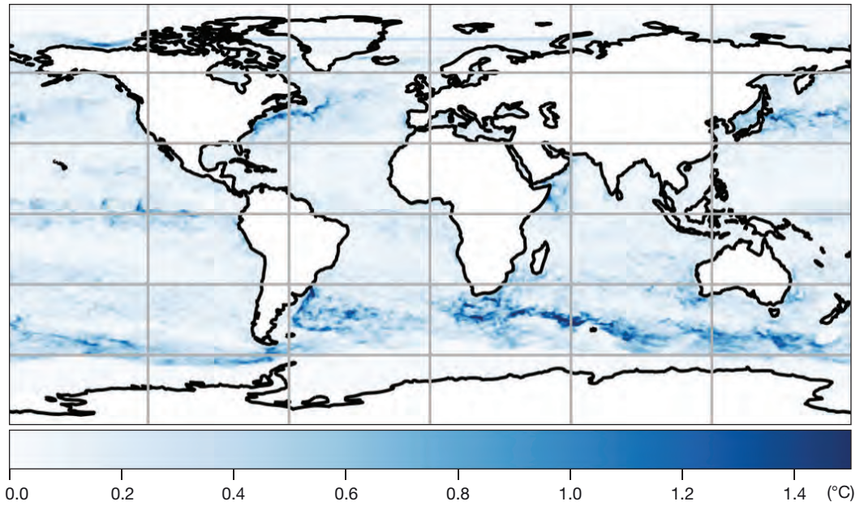
Real-time measurements of the atmosphere and ocean conditions to a depth of 100 metres were going to provide detailed data to support the modelling of this powerful ocean current. The Gulf Stream in the northwest Atlantic Ocean is important to ECMWF because of the magnitude of ocean temperature errors caused by mispositioning it. The goal is to improve weather forecasts at all timescales, from medium-range to extended-range forecasts.



◀ Discrepancies between sea-surface temperature and ECMWF's analysis of ocean current

The map shows errors in the Gulf Stream position in the ECMWF analysis at 12 UTC on 2 December 2019. The contours of sea-surface temperature from an observation-based satellite product are shown in blue. The green arrows show the ECMWF analysis of ocean currents. Off the coast of North Carolina, one can see a large meander in the analysis of ocean currents, which is not visible in the observed sea-surface temperature contours.

Science and technology



◀ EDA temperature spread

The image shows the ocean temperature spread at the surface from an Ensemble of Ocean Data Assimilations. The highest values can be found in western boundary current and Antarctic Circumpolar Current regions.

Ensemble of Data Assimilations in the ocean

A project to improve ocean model initialisation for the EU-funded Copernicus Climate Change Service (C3S) run by ECMWF ended in July 2021. It resulted in a big improvement of ocean data assimilation capabilities at ECMWF. The basic idea was to apply the Ensemble of Data Assimilations (EDA) to the ocean rather than just to the atmosphere. Experts from ECMWF Member States as well as ECMWF worked on the project.

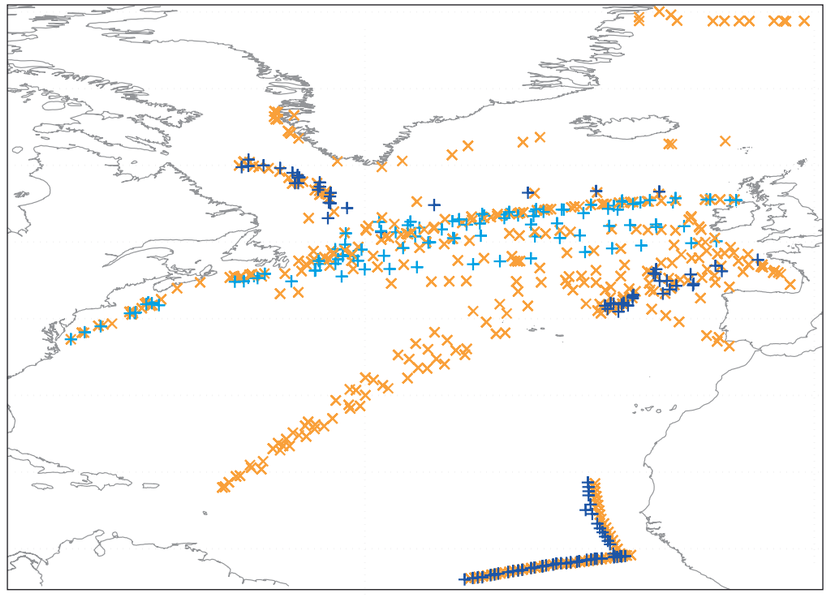
The classical EDA helps to determine the initial conditions for ECMWF's ensemble forecasts and its higher-resolution deterministic forecast. The ocean work aimed in particular to develop efficient ensemble-based models of the errors of short-term ocean forecasts. An example of the results can be seen in the figure. The assimilation of sea-surface height was also improved, and capabilities to assimilate sea-surface temperature were developed.

These developments will enhance the quality of service of C3S products and ECMWF operations. They will also be the basis for the ocean data assimilation used in OCEAN6 and ERA6, the next generation of ocean and coupled reanalysis.

More radiosonde data

In May 2021, a number of ships started reporting radiosonde descent data. Most of these were from the European Automated Shipboard Aerological Programme (ASAP) in the North Atlantic (see the map). Four of these ships were using RS41 radiosondes, and the descent quality looked good. The data are useful to help determine the initial conditions of weather forecasts.

ECMWF started using the data operationally on 8 September 2021. Data use is restricted to pressures greater than 150 hPa, as for land stations, to avoid very fast fall rates. These radiosondes have pressure sensors but not parachutes. They use smaller balloons than most land stations, and the temperature bias problems at upper levels are slightly less because they do not go as high.



◀ Radiosonde data in the North Atlantic

The map shows radiosonde data from ships in the North Atlantic in August 2021. The marks correspond to launch and balloon burst locations. The burst occurs usually 1.5 to 2 hours after launch. There were 17 ASAP ships at the time, but typically only five or so were active on any given day. Some of the profiles are from research vessels.

On average, radiosonde profiles from ships have more impact than land profiles because they are in data-sparse regions. At land stations, the descent reports often stop some kilometres above the surface due to hills blocking the radiosonde signal, but for ships the descent reports can get very close to the surface.

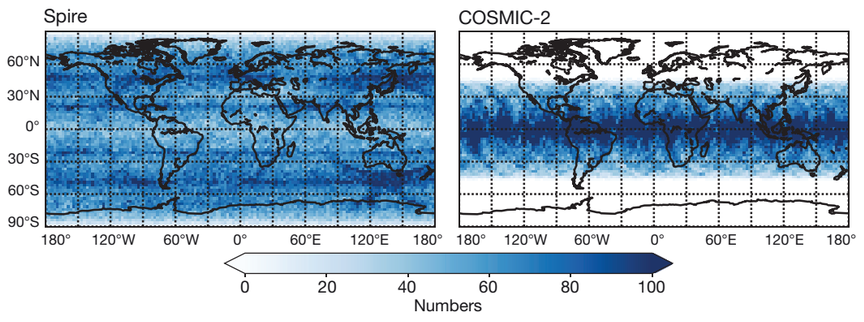
Assimilating Spire and COSMIC-2 data into the IFS

During the COVID-19 pandemic, additional efforts were made to assimilate spaceborne radio occultation data. Such data are sent by Global Navigation Satellite System (GNSS) satellites and measured with a receiver on a satellite in Low Earth Orbit.

The path of the radio signal is bent as a result of refractive-index gradients in the atmosphere. This makes it possible to derive information on temperature and humidity profiles.

A study of assimilating GNSS radio occultation data from commercial data provider Spire Global and from COSMIC-2 satellites into the IFS was conducted. It found that assimilating the data improves medium-range and short-range forecasts.

The results were achieved by running a system of observing system experiments (OSEs). In addition, we ran corresponding Ensemble of Data Assimilations (EDA) experiments. The experiments investigated the relationship between EDA spread estimates and OSE short-range forecast error statistics. A reasonably good agreement between the EDA spread and the OSE error statistics was found, suggesting that the EDA technique is a useful method for assessing future observing systems.



◀ Spire and COSMIC-2 data

Number of occultations for Spire (left) and COSMIC-2 (right) between January and March 2020, regridded to a 2.5 x 2.5 latitude–longitude grid.

Science and technology

High-performance computing: the Atos system

ECMWF's world-class high-performance computing facility (HPCF) is at the core of its operational and research activities and is upgraded typically every four or five years.

At the start of 2020, we signed a contract with Atos worth over 80 million euros for a new facility comprising four Atos Sequana XH2000 clusters. It will deliver about five times the performance of the current system, allowing us to run higher-resolution ensemble forecasts to improve the prediction of extreme weather events significantly ahead of time. The Atos clusters were installed in our new data centre in Bologna, Italy, during 2021.

The Test and Early Migration System (TEMS) component of the Atos system was initially installed in the Reading data centre, to provide a platform for developers through the second half of 2020 and first half of 2021. This system was generally available to internal and external users of the HPCF and ECGATE. Several training courses were provided by Atos and ECMWF staff to introduce users to the new system.

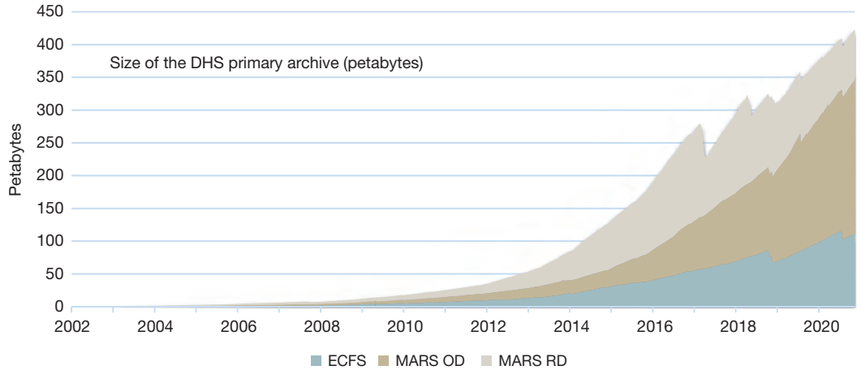
By the end of 2021, Atos had completed delivery of the hardware components of the new HPCF, building three of the clusters and all the storage systems. The remaining final cluster was on schedule with only the cabling of the high-performance interconnect remaining.

In August, one of the clusters was used for the Site Functional Test. The testing was to validate performance targets on the benchmark suite that Atos had committed to in their plan, including demonstrating significant improvements to the metadata performance of the Lustre file systems. This stage identified two additional issues with the Lustre file system, one of which was resolved in 2021 while the other remained under live investigation. The user acceptance test phase started in August 2021 and was continuing at the end of the year.

> "Forecast production was uninterrupted during the COVID-19 pandemic."

◀ Atos Sequana

The Atos Sequana XH2000 system in the new data centre in Bologna, Italy.



◀ Growth of primary data in ECMWF

Growth of primary data in ECMWF. The ECFS curve represents ECMWF's File Storage system, the MARS OD curve the operational archive, and the MARS RD curve the archive linked to research experiments.

High-performance computing: the 2021 system

The Cray XC40 HPCF continued to provide a good and stable service in 2021 with excellent availability on both systems of over 99.9%. Forecast production was uninterrupted during the COVID-19 pandemic.

Despite this overall highly satisfactory performance, there were some incidents with the Cray machines, reflecting the age of the systems. A major problem occurred in June 2021, which led to a severe delay in the operational suite. The issue was caused by a hardware failure on one of the research filesystems, which should have had no impact on the operational forecast suite. However, during the running of the Ensemble of Data Assimilations, operational jobs began to overrun significantly. To resolve this required a full reboot of the system. Recognising the operational risks, monitoring on the system was enhanced to detect similar situations.

Data Handling System

The Data Handling System (DHS) provided a generally reliable service over the year, with a data archive of 442 petabytes of primary data and 166 petabytes in the secondary data store at the end of the year. With the management of significant volumes of data, some problems were experienced with the tape libraries that were visible in the MARS (Meteorological Archival and Retrieval System) and ECFS (ECMWF's File Storage) services.

The testing of Spectra Logic libraries was completed with mixed success. In the Bologna data centre, we were going to continue with a mixed IBM/Spectra Logic environment, primarily using shorter IBM libraries, with the Spectra Logic tape library retained in its role as a production library for primary data and to monitor the development of software.

◀ Cray XC40

One of two identical Cray XC40 clusters in ECMWF's high-performance computing facility in Reading, UK.

Science and technology

Data centre infrastructure

Due to the design and management of the cooling service, problems with the data centre infrastructure did not impact operations. A major failure to one of the chillers during this time was to a compressor, which required a complete rebuild. The diesel rotary uninterruptible power supply (DRUPS) machine KS3 also suffered from a failure causing the machine to switch to bypass. The repair was carried out and full operations were restored in two days without impacts on service delivery.

The Hybrid2024 project

During the first half of 2021, the Hybrid2024 project was developed as part of the Centre's Scalability Programme. This programme aims to adapt weather prediction codes to emerging computing paradigms.

The Hybrid2024 project aims to prepare the IFS for HPC accelerators. Emphasis was placed on creating a full accelerator-enabled multi-architecture IFS in which scientists can develop efficiently. At the same time, the aim is to ensure that the code is portable and performant on current and future accelerator-based architectures. The current IFS is heavily optimised for deep-cache central processing unit (CPU) architectures and needs a significant re-design to take advantage of technologies like graphics processing units (GPUs). This will be achieved through:

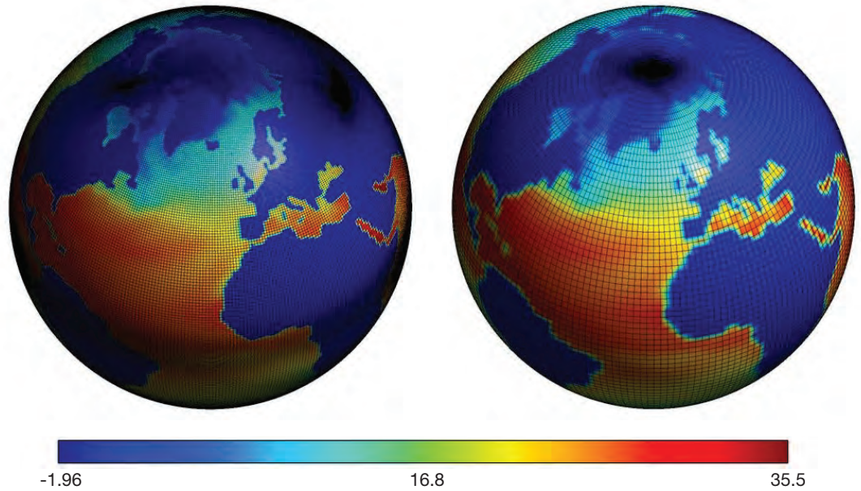
- developing programming approaches and tooling for a multi-architecture paradigm
- restructuring the code and supporting infrastructure accordingly
- demonstrating the IFS on available GPU technologies in advance of the next HPC procurement; and
- monitoring HPC accelerator development beyond current GPU technology.

The IFS restructuring is based on the concept of using build-time specialisation to bridge the gap between a single, maintainable source base that scientists can develop efficiently, and code that is portable and performant on current and future accelerator-based architectures. Individual components of the code will be adapted into separate libraries with clean Application Programming Interfaces (APIs), which ultimately separates scientific developments from the layout and placement of data in memory. Then, source-to-source code generation via the in-house Loki tool will be used to produce highly optimised, bespoke kernels for desired target architectures.

Hybrid2024 has many synergies and links, most obviously with IFS-ARPEGE, through which significant amounts of code are shared between ECMWF and Météo-France and in turn with the many members of the wider ACCORD consortium. Close coordination was going to ensure continued alignment of the major developments to the code. The primary role of Hybrid2024 is to coordinate the technical development of accelerator capabilities between different projects.

The project is targeting a significant re-design of the code and supporting infrastructure. It aims to increase the flexibility of the IFS through the use of accelerator-enabled libraries and data structures, as well as build-time specialisation through automated source-to-source translation. Hybrid2024 aims to develop, maintain and evaluate IFS accelerator capabilities on available GPU technologies. It will prepare the ground for the next HPC procurement.

> "The Hybrid2024 project will prepare the IFS for HPC accelerators, with a vision ultimately of a full accelerator-enabled multi-architecture IFS."



◀ Remapping of sea water

Remapping of sea water potential temperature from the eORCA1_T grid (left) to a 2-degree regular longitude-latitude grid (right) using linear finite-element interpolation methods based on meshes generated by Atlas.

The Atlas software library

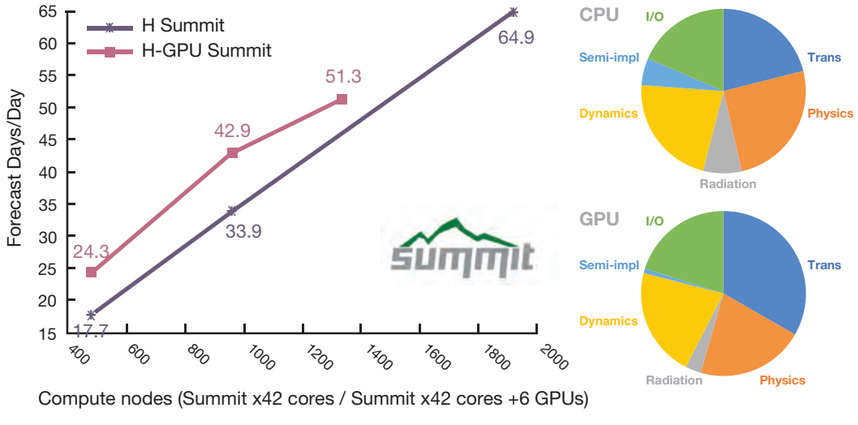
Atlas is a software library developed and maintained at ECMWF for the purpose of abstracting complex grid data structures, and associated parallelisation concerns. It has been made publicly available on the Github software platform. During recent years, we have seen increasing interest from the wider numerical weather prediction (NWP) community, and ECMWF Member States, in adopting Atlas in their software. Moreover, Member States have started to collaborate with ECMWF to improve or implement missing features that stand in the way of their adoption of Atlas.

The ORCA tripolar grid is the ocean grid used by the NEMO ocean model. Due to the very specialised nature of the ORCA grid, special functionality was added to Atlas as an external library, 'atlas-orca', using a newly developed Plugin architecture. This serves as a great example of Atlas's flexible and extensible software design.

The figure shows the flexibility of Atlas by using its own native functions to represent and remap a potential temperature field from the ORCA grid to a standard latitude-longitude grid.

First order and second order conservative remapping methods between arbitrary spherical meshes supported by the Atlas library were developed. Further work to finalise this effort and incorporate it in the IFS infrastructure was due to be completed. The implemented method works well with various meshes and, in general, unstructured and structured grids. Second order remapping much better preserves the smoothness of the function in higher-resolution target meshes. Experiments show that the second order method is ten times more accurate in the remapping step.

Science and technology



Compute nodes (Summit x42 cores / Summit x42 cores +6 GPUs)

◀ Hydrostatic IFS GPU

Performance of the hydrostatic IFS GPU and CPU version at 1 km on Summit in forecast days per day as a function of the number of compute nodes used. The pie charts on the right-hand side show how the runtime is spent in the main parts of the model.

Novel programming approaches

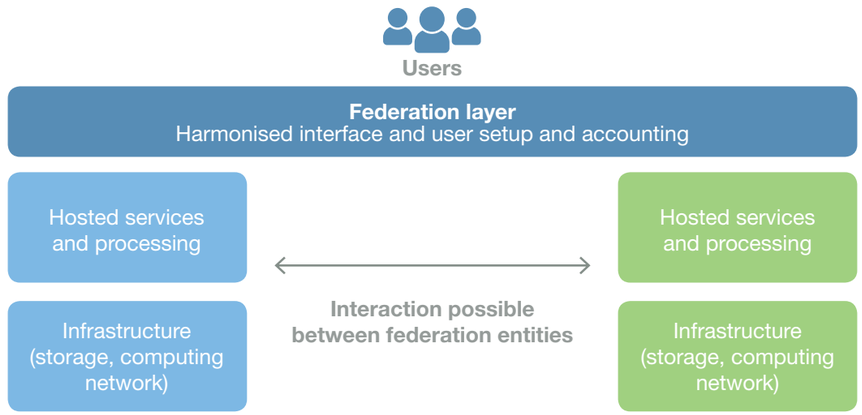
During the second half of 2021, work continued on developing novel programming approaches and tools for a multi-architecture paradigm. Significant progress was made towards GPU-enabled physics parametrizations. Developments were also under way to further utilise accelerator-enabled data structures and to integrate GPU-enabled versions of the spectral transform library (TRANS) into the IFS release cycle. The goal was to prepare for and evaluate hybrid CPU–GPU execution. These efforts were also supported by the Atos/ECMWF Centre of Excellence and were planned to be further boosted by Destination Earth, as well as various European projects.

The IFS spectral transforms library was the first to see a working vendor-specific port developed. In the previous year, we created a first hybrid version of RAPS18 IFS, which was able to perform a low-resolution forecast run by computing the spectral transform on NVIDIA GPUs. In 2021, we were able to run this version at 1 km resolution on the Summit supercomputer.

Rewriting the finite-volume module

A comprehensive rewrite was in progress in 2021 of the finite-volume module (FVM) non-hydrostatic dynamical core that is under development. It was based around the GT4Py (GridTools for Python) domain-specific language (DSL) framework, developed by our close partners at CSCS (Swiss National Supercomputing Centre) and ETH Zurich.

An important milestone reached was the GT4Py DSL implementation of the FVM in a 3D structured grid with an additional limited-area model (LAM) configuration. The adopted GT4Py enabled clear and flexible programming with emphasis on the physical and numerical model aspects. Both GPU and CPU architectures can be targeted by the same Python-like frontend code. In addition to portability and targeted optimisation, this design promised enhanced scientific productivity.



◀ European Weather Cloud

The European Weather Cloud will be a federation of different entities held together by a federation layer. Users can interact with different entities. By interacting with one, they can also access the others. Their European Weather Cloud activities are logged centrally in the federation layer.

Half-precision tests

Changing to single precision in the medium-range forecast model allowed a higher vertical resolution for no extra cost, resulting in a boost in forecast scores. By gaining access to the world's top two supercomputers, Fugaku and Summit, ECMWF was able to test half precision natively for the first time. Tests of spectral transform code on Fugaku indicated that half precision can be safely used up to the current operational high-resolution forecast.

The coupling model framework between the NEMO ocean model and the atmosphere and wave models was made precision agnostic, allowing fully single-precision coupled forecasts for the first time. Forecast testing on this coupled system started at a low resolution. Initial results were encouraging, with very minor differences in skill so far for extended-range ensemble forecasts. Preliminary scalability tests were carried out on the Atos Test and Early Migration System. At the operational 0.25° resolution, single precision resulted in a speed-up by the factor 1.7 on this system for the ocean part.

European Weather Cloud

In December 2018, ECMWF's Council approved a pilot project to create, jointly with EUMETSAT, a federated cloud computing infrastructure focused on meteorological data. This European Weather Cloud was designed to continue to make the results of the Centre's research and operations available to its Member States in the most appropriate form.

In late 2020, a Tender Evaluation Board (TEB) was formed in order to agree the strategic procurement approach for the necessary equipment/service. The TEB agreed to initially seek market feedback, and then to follow this up with an invitation to tender (ITT).

To this end, an invitation to pre-qualify was published. This included a number of minimum requirements, but also allowed responders to propose their own recommended technical solutions, as well as indicative pricing. Responders were advised that their responses would be evaluated for short-listing purposes for the subsequent ITT. A good number of responses were received, and in December 2021 ECMWF's Council authorised ECMWF to issue a tender.

Working with space agencies

Our long-standing collaboration with space agencies, ESA and EUMETSAT in particular, brings mutual benefits. Here, we mention just some of the highlights from 2021.

> EUMETSAT is Europe's main source of operational Earth observation satellite data and a major contributor of observations assimilated in ECMWF models. We expect that our next-generation satellites systems will further that trend, and we look forward to continuing our long-standing and fruitful cooperation with ECMWF for the benefit of all citizens.
>
> *Phil Evans, Director-General, EUMETSAT*

The Sentinel-5 Precursor satellite carries an imaging spectrometer called TROPOMI. © ESA/ATG medialab

Working with space agencies has enabled ECMWF to exploit more fully the benefits of Earth observation data to improve our forecast skill. We also provide vital feedback on satellite data quality and assess the impacts of new and enhanced satellite observations on numerical weather prediction (NWP). Through collaboration we help to guide future missions and the evolution of the satellite observing system and ensure the needs of NWP are well represented.

In 2021 we became an associate member of the Committee on Earth Observation Satellites, which adds to our strong representation on many international panels and mission advisory groups. We also host EUMETSAT Research Fellows and other visiting scientists, are involved in EUMETSAT Satellite Application Facilities (SAFs) and undertake joint research projects, events and training.

EUMETSAT Research Fellows have contributed significantly to progress towards our 'all sky/all surface' data assimilation scheme. We now assimilate EUMETSAT's AMSU-A data under cloudy conditions in our operational forecasts – a major step forward in the all-sky use of all passive microwave observations and improved observational capability. Joint work to enhance the radiative transfer models of the NWP SAF, which underpin all-sky radiance assimilation work, was also key.

In preparation for the ESA-JAXA EarthCARE mission we have demonstrated the world's first direct all-sky 4D-Var assimilation of cloud radar and lidar, using historical observations from NASA's CloudSAT and Calipso missions.

Following the successful demonstration of the benefits to NWP of Doppler wind data from ESA's Aeolus mission, we are now contributing to discussions about the implementation and economics of an operational follow-on.

In a study funded by ESA, we have provided input on the optimal design of a future constellation of small satellites carrying microwave sounding instruments. Our Ensemble of Data Assimilations was used with simulated microwave data to investigate which set-up of satellites might reduce forecast uncertainty the most.

Collaborations have also continued with NOAA and other partners to provide feedback on satellite data developments, such as evaluation of planned updates to the Atmospheric Motion Vector products from the GOES satellites or assessments of the Clear-Sky Radiance product from GOES-17, which is affected by instrument anomalies.

With CMA and other partners, we have evaluated the world's first hyperspectral infrared sounder in geostationary orbit (GIIRS on FY-4A), exploring the value and challenges of these new observations, with a view towards the upcoming MTG IRS.

Our work with space agencies is also key to our environmental services under the European Union's Copernicus Earth observation programme, and we have continued to see the rewards this year.

For example, NO_2 observations are now assimilated into Copernicus Atmosphere Monitoring Service (CAMS) forecasts, along with other trace gas observations from the Sentinel-5P/TROPOMI instrument, following several years of work with ESA and its contractors.

The range of datasets available from the Copernicus Climate Data Store has continued to benefit from our links with EUMETSAT SAFs, ESA Climate Change Initiative, NOAA, NASA and JMA.

The Copernicus Climate Change Service (C3S) is also working with EUMETSAT to reprocess old satellite data from the 1960s, 70s and 80s. This will provide enhanced characterisation of key climate variables and supplement observational data for our next major reanalysis project (ERA6).

ECMWF, ESA and EUMETSAT are working together in preparation for ESA's high-priority Sentinel expansion missions, which will enhance Copernicus Earth observation capability for a range of environmental applications. Investigations have begun, for example, on how to assimilate observations from the CO2M mission into the CAMS forecasting system, as part of the ECMWF coordinated CoCO2 project that is developing a prototype system for the new CAMS CO_2 monitoring service.

AMSU-A = Advanced Microwave Sounding Unit-A
CMA = China Meteorological Administration
CO2M = Copernicus Carbon Dioxide Monitoring mission
ESA = European Space Agency
EUMETSAT = European Organisation for the Exploitation of Meteorological Satellites
GIIRS = Geostationary Interferometric Infrared Sounder
GOES = Geostationary Operational Environmental Satellite
JAXA = Japan Aerospace Exploration Agency
JMA = Japan Meteorological Agency
MTG-IRS = Meteosat Third Generation – Infrared Sounder
NASA = National Aeronautics and Space Administration (US)
NOAA = National Oceanic and Atmospheric Administration (US)
TROPOMI = Tropospheric Monitoring Instrument

Impact

It was a very busy and successful year engaging and sharing knowledge and expertise with Member and Co-operating States and users, with operations and innovation maintained through the pandemic restrictions thanks to our dedicated staff, reliable IT infrastructure and online resources.

Many developments in 2021 aimed to maximise the quality, usefulness and accessibility of our products, helping national meteorological and hydrological services in our Member and Co-operating States to produce weather forecasts and early warnings of severe weather.

The year was notable with two Integrated Forecasting System (IFS) upgrades bringing improvements in forecast skill and new and improved products. Extreme temperatures and heavy rain during the summer in Europe were well predicted by ECMWF forecasts, while consequences such as flooding and wildfire emissions were forecast and monitored by the EU Copernicus services we run or contribute to.

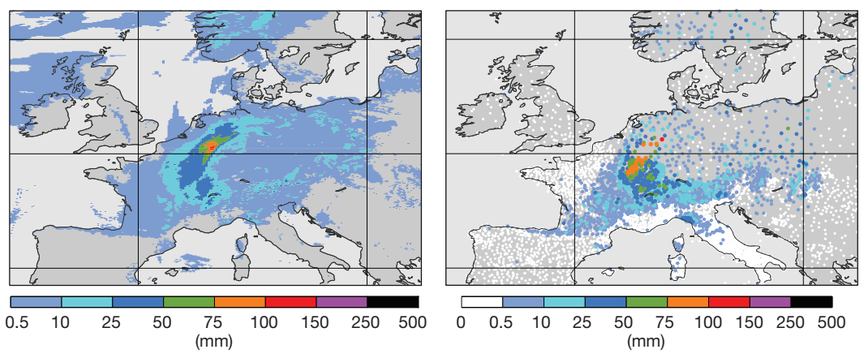
The release of more of our products as open data and of additional Copernicus datasets gave more users access to high-quality weather and climate data.

Our membership continued to expand as we welcomed Georgia as our 12th Co-operating State in December, and through the opening of our data centre in Bologna and offices in Bonn, our presence in and engagement with Member States strengthens. We signed an agreement with the European Commission to continue implementing the Copernicus Climate Change Service (C3S) and Copernicus Atmosphere Monitoring Service (CAMS) for the next seven years, and our role as the computational centre for the hydrological forecasting activities of the Copernicus Emergency Management Service (CEMS) was renewed for a further six years until 2027.

A summer of extreme weather

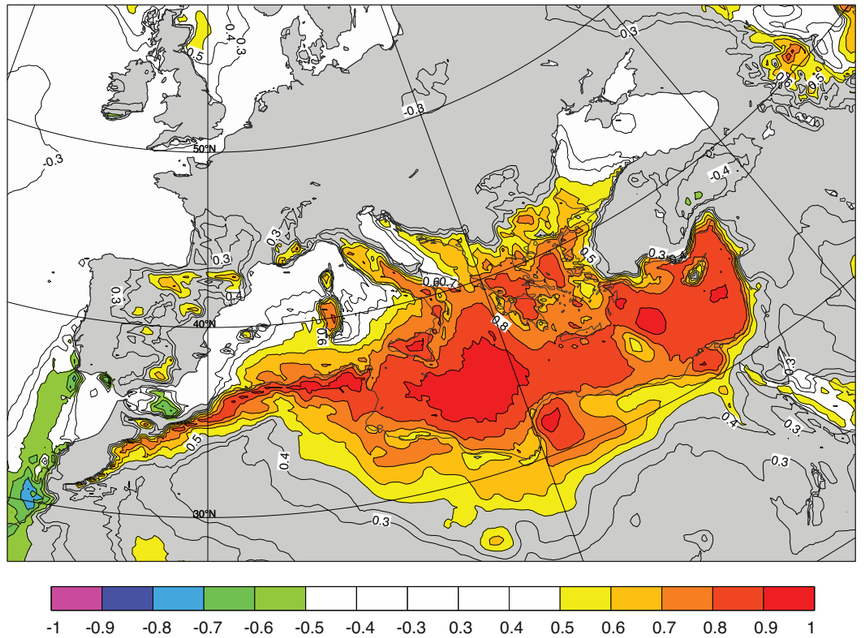
The European summer of 2021 stands out for heavy rain, which brought devastating floods, and also for great heat, which came with regional fires.

A period of intense rainfall in July, especially over parts of Germany and Belgium, led to devastating floods in some areas.



◀ Predicted rainfall

The charts show the predicted rainfall in the 24-hour period starting on 14 July 2021 at 06 UTC, 78 hours in advance (left) and recorded amounts in the same period (right).



◀ Extreme heat

ECMWF Extreme Forecast Index for 2-metre maximum temperature on 11 August, from 144–168 hours before.

ECMWF high-resolution forecasts predicted with high confidence the broad location and intensity of the rain three days in advance.

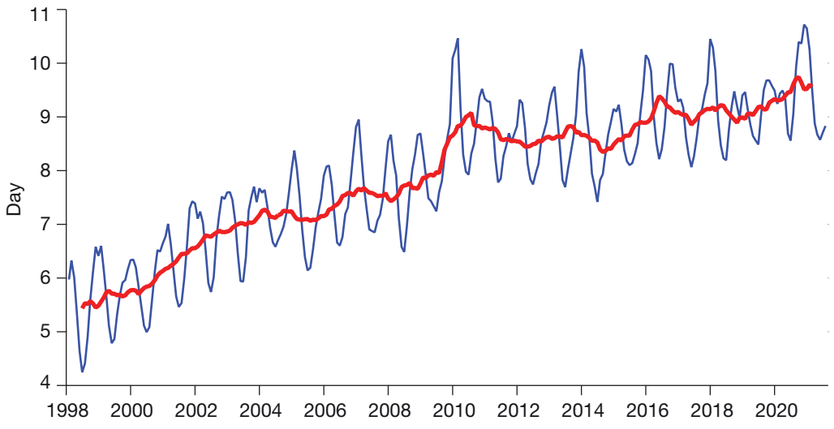
Flood forecasts from the European Flood Awareness System (EFAS) also indicated points on the river network where the flood signal was predicted to exceed the 1-in-5-year flood return period threshold. EFAS is part of CEMS, for which ECMWF is the computational centre for the hydrological forecasting activities.

Europe experienced its second-warmest June on record, with temperatures 1.5°C higher than the average for 1991–2020, according to the Copernicus Climate Change Service. It also experienced its second-warmest July, with temperatures 1.4°C above the average, while August was close to the 1991–2020 average, making the period June–July–August the warmest European summer. Particularly high temperature anomalies were recorded in the eastern part of the continent.

The Mediterranean experienced a long and exceptionally warm heatwave during July and August, which gradually shifted from east to west. On 11 August, a provisional new temperature record for Europe, of 48.8°C, was set in Sicily. The ECMWF Extreme Forecast Index (EFI) showed a consistently strong signal for the extreme temperatures up to a week ahead.

The high temperatures contributed the development of regional fires, and their emissions were forecast by the Copernicus Atmosphere Monitoring Service. According to CAMS, global wildfires in 2021 caused an estimated total of 1,760 megatonnes of carbon emissions, 148% more than the total EU fossil fuel emissions in 2020.

Impact



◀ Ensemble skill

Medium-range ensemble forecast skill reached a new record high in 2021. This ensemble forecast headline score shows the lead time at which the continuous ranked probability skill score (CRPSS) for 850 hPa temperature in Europe drops below 25%. Red lines show 12-month running mean values, blue curves show 3-month running mean values.

Forecast performance

We maintain a comprehensive range of verification statistics to evaluate the accuracy of ECMWF forecasts to ensure we meet our goals of providing high-quality products. In 2021, medium-range ensemble forecast skill reached a new record high. Summer performance has been consistently high over the last three years, and winter 2020/21 showed the highest skill ever. In Europe, the highest-ever 12-month running mean was reached.

Compared to forecasts from other global centres, ECMWF maintained the overall lead for upper-air parameters in the medium range. For surface parameters, especially in the short range, some of the other centres have drawn closer to ECMWF. The upper-air meteorological forecast performance of the CAMS forecasting system was similar to that of other global centres.

The IFS upgrade to Cycle 47r2 in May increased the number of levels in the vertical for the ensemble forecast (ENS), leading to a small but statistically significant improvement in upper-air ENS skill.

A second upgrade in October, to IFS Cycle 47r3, included a major upgrade to the moist physics of the model, resulting in more realistic precipitation characteristics. Together with a number of other changes, this cycle brought small improvements in upper-air skill in the early medium range.

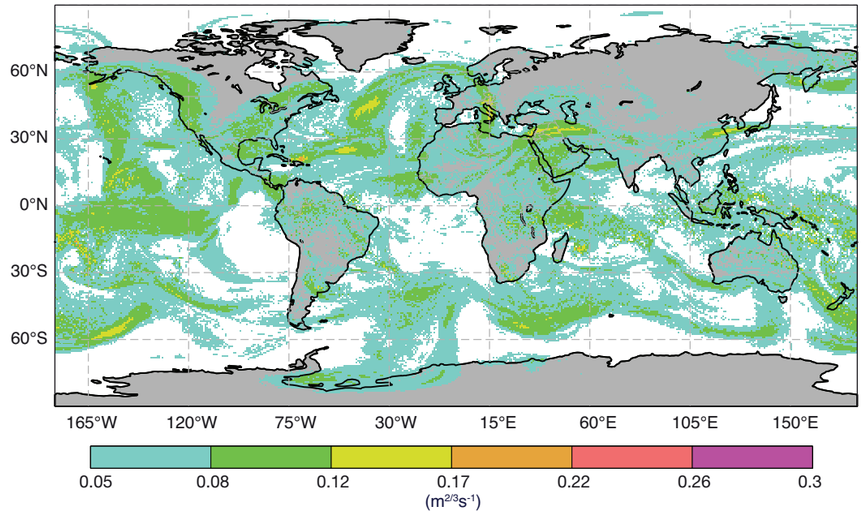
Position errors for forecasts of tropical cyclones were smaller than in 2020, but the decrease was paralleled by forecasts based on the ERA5 reanalysis system, which indicates it was part of natural variability.

As in previous years, ECMWF has a modest but consistent lead in ocean wave forecasting over other centres in terms of significant wave height.

The skill of the Extreme Forecast Index (EFI) for 2-metre temperature increased, and we saw a significant improvement for 2-metre temperature in week three.

ECMWF's seasonal forecast system, SEAS5, predicted the change from La Niña conditions in the equatorial Pacific at the end of 2020 to more neutral conditions in 2021 reasonably well. Due to the absence of strong tropical forcing in 2021, the skill of the extratropical seasonal forecast was relatively low.

> "Several new products were introduced following requests from Member and Co-operating States."



◀ Clear-air turbulence (CAT) product

Example of a high-resolution forecast of the average CAT ($m^{2/3}s^{-1}$) at 11,800 m (flight level 385). Data is provided on model levels and on specific flight levels on request by the Member States.

New and improved products

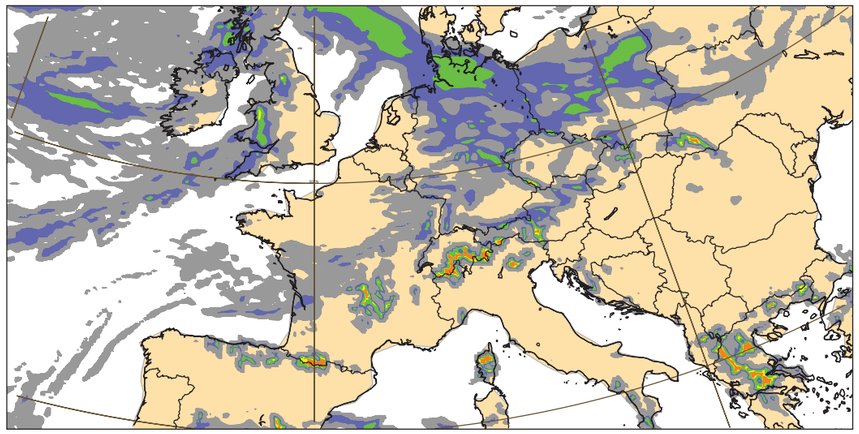
With the upgrade to IFS Cycle 47r2, we started operationally disseminating tropical cyclone track products from the 06 and 18 UTC runs as 'WMO Essential' products, including a graphical product. Users now have access to four sets of runs per day for these high-impact phenomena. The seasonal forecast products for tropical cyclones were revised to better account for the forecast's inability to capture observed trends.

Working with the UK Met Office, we upgraded our extratropical cyclone product suite in May, making the products cleaner, clearer, less costly, more supportable and more future-proof.

With IFS Cycle 47r3 in October, we introduced several new products following requests from users across our Member and Co-operating States, such as new improved convective available potential energy (CAPE) output developed in close collaboration with the European Severe Storms Laboratory, and a clear-air turbulence product developed with the German Aerospace Center (DLR). The diagnostic should be useful for both forecasters and research in turbulence, particularly the development of turbulence parametrizations in the free troposphere and stratosphere. Improved visibility and wind gust forecast products were also introduced.

C3S's flagship reanalysis product, ERA5, offered considerable analytical support to the IPCC Working Group 1 sixth Assessment Report released in August, being referenced over 200 times throughout the report. C3S continued to release new and updated datasets providing improvements to the empirical evidence needed to understand the current climate and better predict changes. These included a back-extension for the ERA5-Land reanalysis dataset. This dataset is the first of its kind, providing global, hourly, historic and high-resolution land-focused information, and now covers the whole period from 1950 to the present.

Impact



◀ Visibility

One new forecast parameter available in OpenCharts is visibility. In response to user feedback, the product, which was one of several to be upgraded in IFS Cycle 47r3, represents the real-life situation much more accurately.

Move to open data

We continued the move towards providing open data products covering the whole world. This is a key aspect of increasing the availability and impact of hundreds of real-time forecast maps and products to organisations and individuals in Member and Co-operating States and beyond.

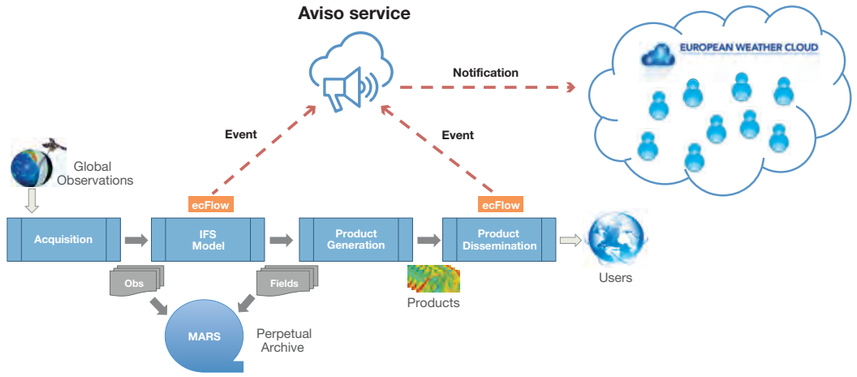
Downloads of OpenCharts dramatically increased from about 50,000 each day following the release in autumn 2020 to an average of 190,000 a day in autumn 2021, when we added more than 50 new products and increased the number of available forecast steps. In the summer we made an application programming interface (API) available for downloading the products. It follows OpenAPI specifications and offers documentation and an interactive test environment. A new feature called ChartSet allows users to see their selections side by side and change time steps or areas in one click for the entire set of selected products.

The free charts are based on the popular ecCharts licensed products, used by professional forecasters in ECMWF's Member States, for example. OpenCharts aims to provide key information from the vast suite of tools available for ecCharts, delivering a pre-generated set of forecast charts that are of wide use to a broad audience.

Resources for the weather and climate communities

We continued developing tools and services to improve user access to our computing and data resources.

ECMWF's Metview software provides straightforward ways to access, process and visualise ECMWF forecasts and related data. 2021 saw the addition of new features for post-processing meteorological data. We also added new Python-based functions to Metview to meet the needs of users wishing to use new environments like Jupyter Notebooks for exploring large datasets.



◀ Aviso notification system

Events submitted to Aviso from the ECMWF data flow. The goal is to enable time-critical workflows across HPC and Clouds.

Participants at our new hands-on introduction to NWP modelling training course used the new features to create datasets to work on a case study for a past storm event.

The US National Oceanic and Atmospheric Administration (NOAA) announced it would use the Global ECMWF Fire Forecasting (GEFF) model, which is publicly available, for its operational forecast. The GEFF model is also used by the Copernicus Emergency Management Service.

To ensure timely use of our data, we developed a new system called Aviso which notifies users when real-time forecast data or derived products are available and triggers user-defined workflows. By the end of the year there were roughly 400,000 notifications daily. The pre-operational Aviso service has been available since the beginning of 2021 to users of the European Weather Cloud, with some Member States exploring its advantages by executing time-critical workflows in the European Weather Cloud.

The European Weather Cloud is a joint ECMWF and EUMETSAT project to create a cloud computing infrastructure for the meteorological community. In this third and final year of the pilot phase, the European Weather Cloud allowed us to support hands-on practical training sessions by providing remote access to individual lab instances running on the cloud with all the required software, tools and training material. The instances were equipped with JupyterLab, which allowed students to easily connect through their browsers.

We held two joint workshops with EUMETSAT for users in the Member and Co-operating States of our two organisations to give updates on developments. In December, the ECMWF Council decided to go ahead with the operational phase and a tender was issued for the technical infrastructure.

The C3S Climate Data Store (CDS) is an invaluable resource for a wide variety of users, providing easy access to a range of climate datasets and a toolbox for users to build workflows and applications. In October the number of registered users reached 100,000. New datasets added include the CMIP6 dataset – the most up-to-date, scientifically advanced database for climate science and services.

Atmospheric composition global forecasts from CAMS were made available through the CAMS Atmosphere Data Store (ADS), making the data much easier to access and use.

Impact

Ten years of OpenIFS

The OpenIFS, a complex operational numerical weather prediction (NWP) model, marked ten years' operation in December, and its original aims since it began in 2011 remain relevant today: providing and supporting versions of the operational IFS for research, education and training in NWP and meteorology for the benefit of Member and Co-operating States' meteorological services, academic institutes, and the wider community.

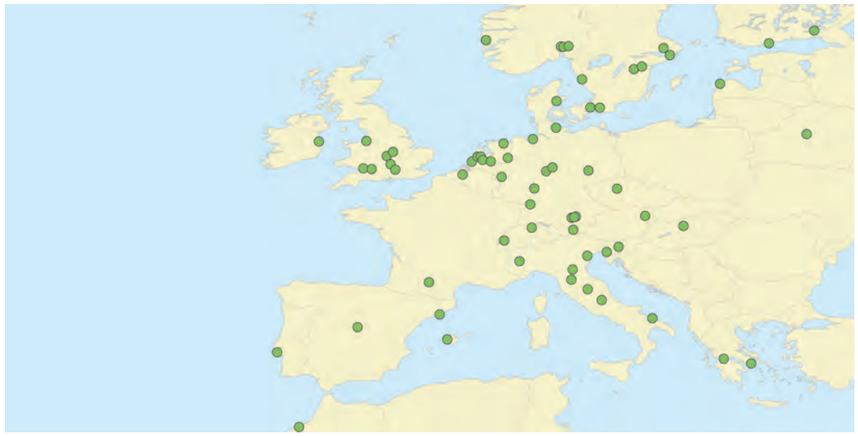
Over the decade, OpenIFS has produced improvements in the IFS; established a growing user community amongst Member and Co-operating States; enabled new collaborations; increased research and training opportunities in universities; created an international scientific workshop series; and improved knowledge of the IFS and ECMWF in the wider meteorological community.

Ease of use, dedicated support from our team, an OpenIFS workshop series, and training in online user guides and public forums have helped the external use of the IFS to be successful and of great benefit to the wider community.

The number and range of research and teaching applications using OpenIFS over the last ten years are impressive, including many NWP studies often featured in peer-reviewed literature or our Newsletter articles.

OpenIFS has also been the focus of several Earth system modelling groups. The EC-Earth consortium (which includes 30 research institutes from 12 European countries collaborating on the development of an Earth system model) have chosen the OpenIFS model as the atmospheric component of their next model release, whilst other research groups are working to build their own Earth system models based on OpenIFS.

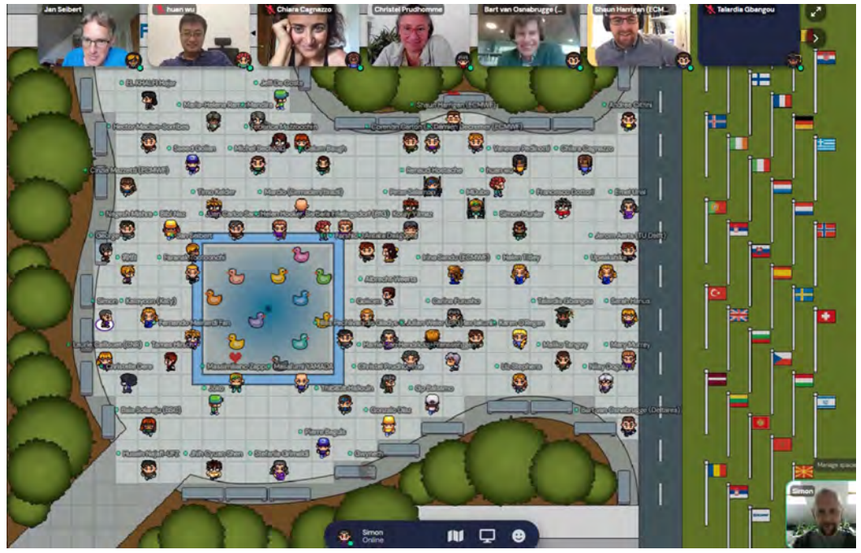
OpenIFS has also played a key role in collaboration with the University of Oxford on the use of reduced precision in the IFS. This led to significant savings in computing resources at ECMWF for operational forecasting. OpenIFS was ideal for the proof-of-concept development as its reduced code base allowed rapid prototyping and testing.



◀ OpenIFS licensees in Member and Co-operating States

The map shows the locations of most OpenIFS licensees. The growth in the number of OpenIFS licensees in recent years was in part driven by the steady adoption of the OpenIFS model by EC-Earth consortium partners.

> "A new hands-on introduction to NWP course included practical experiments using OpenIFS."



◀ Virtual workshops

The gather.town platform was used for interactive activities at our training courses and workshops and to facilitate networking opportunities for attendees.

Knowledge-sharing and support for the scientific community

All our events and training activities remained on virtual platforms in 2021 due to the ongoing COVID-19 pandemic and varying international restrictions. As technology and requirements changed, we continued to develop our digital event offer, making the most of the technology available to foster scientific engagements with Member and Co-operating States, members of the European Meteorological Infrastructure (EMI) and the wider user communities.

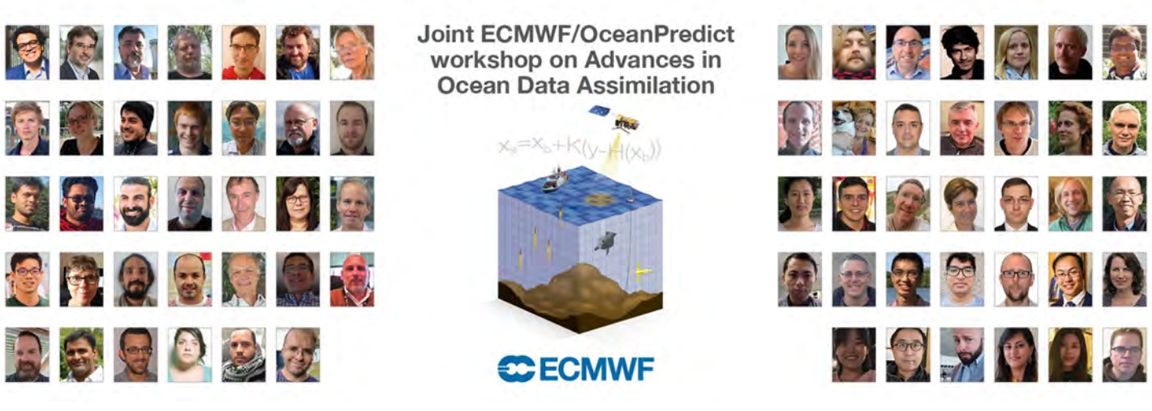
Our workshops saw attendance increase by just over a third from 2020 to 2,911 registrants in 2021, and training course attendance almost doubled to 676 registrants. This remains significantly higher than pre-pandemic times, while also reducing the carbon footprint through virtual events. Naturally, staff and participants missed face-to-face engagement, but we are optimistic about serving Member and Co-operating States and the wider scientific community in hybrid formats in 2022.

The flexibility of technology and the reduced need to travel enabled us to host shorter events, including a Science and Technology Seminar series featuring Destination Earth; machine learning for numerical weather prediction; and aircraft data, COVID-19 and global weather forecasting. The series was popular and attracted 1,748 viewers.

Faced with another period of online training, we set out to replicate the classroom practical learning experience as far as possible in our NWP training courses.

Over 130 participants were taught in our virtual classroom. In May we were able to run a new hands-on introduction to NWP training course that included practical experiments using the OpenIFS model.

Impact



To further increase the reach of training, we introduced a pilot scheme offering two levels of participation in learning events.

In May a joint ECMWF and OceanPredict workshop provided a forum to link oceanic and atmospheric communities helping to identify priorities for developments in ocean data assimilation methods. The collaboration with OceanPredict – a science programme for the coordination and improvement of global and regional ocean analysis and forecasting systems – was timely as 2021 marked the beginning of the UN Decade of Ocean Science for Sustainable Development and it will help the joint efforts planned under this.

Experts from different domains addressed the multidisciplinary science underpinning climate and environmental monitoring and predictions, the exploitation of novel observations, and interactions between the ocean, atmosphere, sea ice and biogeochemistry at global and regional scales.

Later in the year, further flagship events brought together experts from across national weather services, academia and industry, all held virtually.

The Using ECMWF Forecasts (UEF2021) meeting on the theme ‘Weather in extraordinary circumstances’ attracted 228 people from 53 countries. During UEF, we opened a new forum where users can interact with each other and our staff by posting comments and joining conversations on topics related to weather and forecasting. Any feedback received may be used in our ongoing research and diagnostics work.

The Annual Seminar provided an Earth system view of observations, with 520 participants exploring how effectively the current observing system is being used for NWP and reanalysis, and science and technical issues common to observations. It was held jointly with the WCRP-WWRP Symposium on Data Assimilation and Reanalysis. The 19th edition of our high-performance computing (HPC) workshop was entitled ‘Towards Exascale Computing in Numerical Weather Prediction’. The events were well received, with feedback and discussions featuring prominently.

▲ Joint ECMWF and OceanPredict workshop

More than 170 scientists from around the world discussed progress and challenges in ocean data assimilation.

◀ Copernicus data for policymakers

The European State of the Climate Report, published annually by C3S, is an example of the consistent and dependable Copernicus data that policymakers can use to understand climate change and its impacts.

We developed a user-friendly learning web page as a signpost to all our learning resources, which range from in-person and online training courses to e-learning lessons and webinars, as well as articles on topics related to forecasting, research, and computing.

C3S published its annual European State of the Climate, with contributions from national meteorological services and the other Copernicus services. The 2020 report included an overview of the global context, a more comprehensive overview of conditions in Europe, and a focus on the Arctic. Its findings were widely covered by media from around the world.

As in previous years, CAMS tracked the formation and evolution of the Antarctic ozone hole. The 2021 ozone hole was one of the largest and longest-lived on record, attributed to very cold temperatures in the stratosphere and a very stable polar vortex.

CAMS scientists continued to contribute to research on the relationship between COVID and air quality. They collaborated in a study led by the London School of Tropical Hygiene and Medicine on air pollution levels in Europe during spring and early summer 2020, with results to be published in a peer-reviewed paper early in 2022. They examined the quantitative effects of reduced pollution levels and, for the first time, compared quantitatively the impact of different policy measures that were taken.

Impact

New phase of Copernicus

In July we signed an agreement with the European Commission to continue implementing the Copernicus Climate Change Service (C3S) and Copernicus Atmosphere Monitoring Service (CAMS) for the next seven years. This new phase builds on the success of the first, which began in 2014.

The services are part of the EU's Copernicus Earth observation programme, which draws data from satellite and in situ (land, air and sea) stations to monitor our planet and its environment through six streams.

The signing for this new phase allows our Copernicus services to continue critical work in supporting Europe's climate change mitigation and adaptation policies across many sectors from agriculture to energy.

It will help decision-makers move forward with their roadmaps and evidence-based frameworks towards the goals of both the Paris Agreement and the European Green Deal, which aims to make Europe the first climate-neutral continent by 2050.

Separately, our role as the computational centre for the hydrological forecasting activities of CEMS was renewed for a further six years until 2027. The computational centre helps to deliver the European and Global Flood Awareness Systems, EFAS and GloFAS.

With Météo-France as a partner, we also submitted a proposal to support the operations and further enhancement of the European Forest Fire Information System (EFFIS) and to contribute to the development of the Global Wildfire Information System (GWIS), which are also part of CEMS.

"The signing for this new phase allows our Copernicus services to continue critical work in supporting Europe's climate change mitigation and adaptation policies across many sectors from agriculture to energy."

◀ ECMWF and Copernicus

ECMWF implements and contributes to services providing free-to-use data on climate change, atmospheric composition, flooding and wildfire prediction.

◀ New partnership with European Investment Bank

ECMWF Director-General Florence Rabier (left) and EIB President Werner Hoyer signed a Memorandum of Understanding at COP26 in Glasgow.

Extending European partnerships

We continued to enhance synergies with Member States and other collaborations through the signing of new Memorandums of Understanding (MoU) during 2021, as well as our ongoing informal partnerships.

The Secretariat of the Union for the Mediterranean and ECMWF signed an agreement in October establishing cooperation to maximise the uptake and impact of the Copernicus services implemented by ECMWF, and to make best use of the products, services and tools developed or made available by C3S and CAMS to support the implementation of relevant EU and UN policies. Regular consultations have been agreed, and joint meetings twice a year will ensure the cooperation continues to achieve its aims.

During COP26 in November, we signed an agreement with the European Investment Bank to support it with enhanced use of Copernicus data for its climate and atmosphere monitoring data needs and ambitions to support climate change adaptation and mitigation activities by becoming the EU's Climate Bank.

In addition, an MoU was prepared to be signed with the University of Bologna and an MoU finalised and ready to be signed with the Italian Government regarding collaboration on the Copernicus Mirror Programme, strengthening formal and informal collaboration.

Following approval from our Council in December, we became part of the European Union's ground-breaking Destination Earth initiative that brings together scientific and digital technology excellence from across Europe.

The ECMWF contribution agreement covers the first 30 months of a seven- to ten-year programme.

With the existing Copernicus Programme, the newly created DestinE initiative, and our partnerships in Europe, we are contributing to and creating tools, infrastructure and capability to better plan and act for our planet's future.

Working with the WMO

Supporting the World Meteorological Organization (WMO) is one of our founding objectives and holds an important place in our ten-year Strategy to 2030.

> Our partnership with ECMWF is one that we greatly value. We share the same ambition and mission to protect our communities and achieve universal access to early warning systems. We share the same vision of a society better informed of the risks and impact of climate change. We seek to support mitigation through improved monitoring of greenhouse gas emissions.
>
> *Professor Petteri Taalas, Secretary-General of the WMO*

We are proud of our wide-ranging close collaboration, which includes the provision of free datasets to WMO Members and discounted access to our full catalogue of products; the support of fellowships and projects to improve severe weather forecasting in developing countries; participation in expert teams on scientific, technical and policy matters; and training in numerical weather forecasting and in making use of our forecast products. Observations sourced via the WMO's global exchange programmes also provide vital data for all our Earth system modelling activities.

As a Global Centre in the WMO Severe Weather Forecasting programme, we provide high-resolution and ensemble products to support national meteorological services in developing and least-developed countries.

Our experts also contribute to the WMO Research Board, as well as various committees; working, study and advisory groups; and expert teams, such as the Expert Team on Data Standards, and on issues relating to the World Weather Watch – a programme which combines expertise in weather forecasting to make meteorological and related environmental information available in all countries.

During 2021 we agreed key changes to our policies to significantly reduce the cost of accessing ECMWF real-time data for WMO national meteorological and hydrological services (NMHSs). From 2022, we will remove the 'information cost' of such data and apply only handling charges for the provision of the service.

We also made the decision to release the ECMWF Open Data (real-time) dataset. Two datasets, which we were providing according to WMO's policy, were consolidated ready to be made available early in 2022 under a licence that allows the data to be freely redistributed and used commercially.

We have also supported WMO NMHSs with access to data through project collaborations such as the South-East European Multi-Hazard Early Warning Advisory System (SEE-MHEWS-A), which aims to strengthen the existing early warning capacity in the region. During the year, free access to our web-based ecCharts forecasts for Europe was provided to all SEE-MHEWS-A countries that provided additional observations, which can be used for verification purposes or improved analysis.

In October we welcomed the release of a WMO resolution on the international exchange of Earth system data. We had contributed to the drafting of this new Unified Data Policy and will continue to engage with the WMO as it is implemented.

Another key project during 2021 was our involvement with the new Systematic Observations Financing Facility (SOFF). This partnership between the WMO, UN Environment Programme (UNEP) and UN Development Programme (UNDP) aims to provide financial support to the least-developed countries to aid investments in observational capacity. Our role has been to participate in working groups to develop the concept and in events to publicise the initiative. We also provided supporting material to demonstrate the necessity of making investments to support least-developed countries, where observations are scarcer. In terms of forecast quality, investing in these areas gives better results than investing in regions which are already data rich.

We renewed our Memorandum of Understanding for the WMO Integrated Global Observing System (WIGOS) Data Quality Monitoring System (WDQMS). The system is considered by the WMO to be one of the key tools for monitoring the progress of the implementation of the Global Basic Observing Network – a set of global standards that aims to ensure consistent access to essential observations.

In September we welcomed a WMO Fellow from the National Department of Meteorology of Cameroon to join ECMWF for one year to develop an application for Africa using the Copernicus Climate Data Store. The scheme is part of long-standing efforts by the WMO and ECMWF to raise the level of scientific knowledge in weather forecasting across the globe.

Background image: extract from ECMWF open chart for geopotential at 500 hPa and temperature at 850 hPa for South East Europe.

Organisation and people

◀ Bologna opening ceremony

The data centre was officially opened on 14 September.

Our life in 2021 continued to be dominated by the impact of the COVID-19 pandemic and Brexit.

During this challenging period, our organisation saw an exceptionally high level of activity across all departments. We became a multi-site organisation with the formal inauguration of our data centre in Bologna, Italy, and the opening of our new offices in Bonn, Germany.

We kept our focus on the safety and well-being of our staff by implementing a gradual return to site in all three duty stations, in line with the guidance provided by our host countries, and we remained committed to mitigating the impact of COVID whilst ensuring business continuity.

The fast transformation of our working environment imposed by the pandemic, and the lessons learnt during this challenging time, led to our first steps towards the development of a new teleworking policy.

2021 also saw the renewal of our Copernicus Contribution Agreement and the finalisation of our negotiations on Destination Earth with the European Commission.

We continued our discussions on the development of an improved environmental sustainability action plan. Our goal is to stay aligned with the most innovative, efficient and environmentally friendly practices which in turn will offset our remaining carbon emissions.

Three host countries, one ECMWF

The concept of 'One ECMWF' was created to establish and enhance synergies across our three host countries and to continue working as one organisation, regardless of separation. We started to work on the deployment of new technology and platforms to provide a seamless virtual dimension across all sites, and we continued to create opportunities for staff to engage and interact regularly, albeit virtually. These included a bi-monthly Director-General address to all staff, the Weekly Weather Discussion and the Quarterly Evaluation and Diagnostics meetings to discuss forecast performance.

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▲ One ECMWF

Sunrise over three little ducks, one for each ECMWF duty station.

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Multi-site organisation

In 2021, we became a multi-site organisation with duty stations across three countries. This marked an exciting new phase, strengthening ties with Member States through new locations in Europe. The new geographical structure was designed with a 'centre of gravity' approach aimed at nurturing synergies and avoiding loss of efficiencies.

Using the latest cloud-based management techniques, we rolled out a new operating model for end-user device management to provide consistent IT support across all three locations and optimise remote working conditions.

Reading, UK – ECMWF Headquarters

In January, we resumed discussions with the UK Government regarding our new headquarters project at the University of Reading. The original footprint of the building was adjusted to take into account the reduced number of staff based in the UK, and the final design was approved by our Council in December. The new building is scheduled to be completed in 2026.

Bologna, Italy

The implementation of the new data centre continued to be a key part of our activities. We started to prepare for the decommissioning of our UK data centre and the migration of our supercomputing activities to Italy.

A key milestone was the handover of the premises from the Emilia-Romagna region to ECMWF in June, marking the end of the first phase and the beginning of our period of occupancy. Soon after Atos began delivering and installing the new supercomputers. The Bologna data centre formally opened on 14 September and is planned to become fully operational in 2022.

ECMWF Director-General Florence Rabier opened the facility alongside Council President Daniel Gellens and representatives from Italian local, regional and national governments, including Undersecretary of Foreign Affairs Manlio Di Stefano, Minister of Education Patrizio Bianchi, and President of the Emilia-Romagna Region Stefano Bonaccini.

Bonn, Germany

Following an international tender amongst our Member States, our third site opened on 13 September in Bonn, a city already known as home to several international and intergovernmental organisations. Our work in Bonn focuses on our partnership with the European Union, including our role within the Copernicus Earth observation programme and the Destination Earth initiative.

This location also enables further collaboration with scientific institutions across Germany and the region, and closer connection with our Member and Co-operating States in central Europe.

Welcome speeches from the Ministry of Transport and Digital Infrastructure (BMVI), the North Rhine-Westphalia Ministry for Environment (MULNV), and the Mayor of Bonn's office were followed by a flag-raising ceremony and words by our Director-General and Council President. The ECMWF flag will fly outside the interim offices until we transfer to a brand-new building in 2026.

▲ New headquarters and Bonn opening ceremony

Left: artist's impression of the new headquarters building planned for 2026 in Reading. Right: opening of offices in Bonn; l-r Viktor Haase (MULNV, North Rhine-Westphalia); Daniel Gellens (ECMWF Council President); Florence Rabier (ECMWF Director-General); Gerhard Adrian (President of Deutscher Wetterdienst); Ursula Sautter (Deputy Mayor, City of Bonn); Tobias Miethaner (BMVI).

Organisation and people

ECMWF staff

As an international organisation, we are proud of our multicultural environment with 388 members of staff from 33 different countries at the end of 2021.

Visiting scientists

During the year, we welcomed six visiting scientists from five different countries:

- A scientist from China, funded by the Max Plank Institute
- A scientist from Luxembourg, on secondment from Météo-France
- A British scientist from International Foundations Big Data & AI for Human Development
- A Finnish scientist from the Danish Meteorological Service
- Two Japanese scientists from the Japanese Meteorological Service

Awards and recognitions

American Meteorological Society

ECMWF Director-General Florence Rabier (below left) was made an Honorary Member of the American Meteorology Society (AMS). ECMWF Copernicus consultant Adrian Simmons (centre), previously MACC coordinator and Head of the Research Department Data Division, became an AMS Fellow. Senior Scientist Bruce Ingleby (right) received the AMS Editors' Award for "timely and excellent reviews provided over the years" in the Journal of Atmospheric and Oceanic Technology (JTECH).

Royal Meteorological Society Buchan Prize

Senior Scientist Antje Weisheimer received the Buchan Prize. This prize is awarded annually to members of the UK's Royal Meteorological Society (RMetS) for the publication of a paper judged to contain the most important original contribution to meteorology. Antje had two papers published in the Quarterly Journal, describing results from a novel approach to quantifying seasonal predictability.

Tromp Foundation Travel Award

Scientist and PhD student Chloe Brimicombe received the Tromp Foundation Travel Award to Young Scientists for her paper on 'Borderless Heat Stress'.

EGU virtual Outstanding Student and PhD candidate Presentation Award

Scientist and PhD student Nikolaos Mastrantonas was awarded the European Geosciences Union (EGU) virtual Outstanding Student and PhD candidate Presentation Award (vOSPP) for his presentation on 'Predictability of large-scale atmospheric flow patterns connected to extreme precipitation events in the Mediterranean'.

"We are proud of our multicultural environment with 388 staff members from 33 different countries."

Investment in ECMWF

The 35 Member and Co-operating States of ECMWF are the principal source of finance for the Centre, with contributions totalling £51.2 million, representing a large proportion of the Centre's funding. External organisations support both core research and the complementary goals of the Centre with funding of £49 million. Revenue from sales of data and products provides additional income of £12 million, while other operating revenue totals £7.5 million.

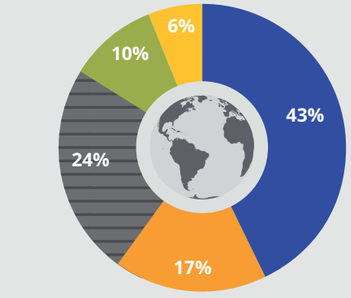
ECMWF continued to invest in its staff, infrastructure, and systems to provide the highest quality products to its Member and Co-operating States. The main areas of expenditure are summarised below, and include capital investment of £3.7 million, principally for IT and infrastructure.

The main areas of expenditure related to remuneration and related items (£26.4 million), pension schemes (£28 million), computer expenses (£16.4 million), buildings (£7.6 million) and other operating activities (£3.4 million). Costs associated with externally funded projects amounted to £42.4 million and net finance costs were £7.6 million.

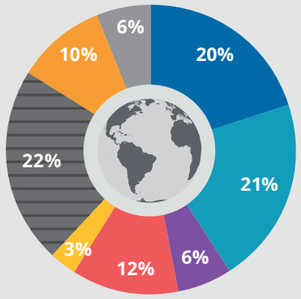
ECMWF's budget remains on a cash basis and the Financial Statements include a reconciliation of the results under IPSAS and in cash terms. Under cash accounting, the Centre generated a surplus of £7.175 million in 2021, which is available either for future investment or distribution to Member States according to a decision to be made by the Council in 2022.

Note: all numbers exclude Centre tax.

Funding



Costs



Working with researchers around the world

> Seven scientists began ECMWF Fellowships in 2021, exploring topics such as atmospheric dynamics and composition, extreme events and predictability, and ensemble forecast post-processing.

Collaboration in research sits at the heart of our approach to numerical weather prediction. Partnerships with the Member and Co-operating State national meteorological services and academia are a key part of how we work.

Research should not be carried out in isolation; fresh viewpoints and sharing ideas and expertise across disciplines are vital. Whilst our core mission is to support our Member States and the wider community, through prediction in the medium and extended ranges, academic institutions add value to our research through their expertise and their flexibility to explore further into the future. For example, a research partnership with the University of Oxford and Météo-France led to a significant upgrade in our Integrated Forecasting System (IFS) this year, with a move from double to single precision. This change is computationally less expensive and the efficiency savings will greatly facilitate model improvements.

We have partnerships with academic institutions and individuals around the world, but primarily with organisations in our Member and Co-operating States. Our staff may act as co-supervisors for doctoral research students, contribute to research proposals, or undertake postgraduate studies that feed into our programmes of activity.

During 2021, we marked ten years of OpenIFS activity, which aims to provide access to the IFS for research and education, including for academic institutions. Institutions within our Member States may also apply to run ‘Special Project’ experiments through our supercomputing facility.

Seven scientists began ECMWF Fellowships in 2021, exploring topics such as atmospheric dynamics and composition, extreme events and predictability, and ensemble forecast post-processing. Fellows have access to our computing facilities and databases and share their results through our website and relevant publications.

Collaborations provide wide-ranging benefits that feed into our strategic objectives, through general scientific advances and through targeting specific challenges.

For example, the prediction of tropical cyclones is extremely important at ECMWF and provides us with valuable meteorological information. These powerful storms cause destruction through the action of waves and storm surges as much as through high wind speeds. The uncertainties associated with their intensity and tracks make it essential to use ensemble forecasts that provide a range of possible outcomes and so can be used to assess risk. Accurate forecasting can help communities prepare for, and recover from, the impacts of these devastating events.

As a visiting scientist, Professor Sharan Majumdar, from the University of Miami, was an active member of our research team during 2021. With an interest in ECMWF ensemble data, he focused on improving tropical cyclone prediction, through investigating genesis and intensity prediction. He diagnosed a suite of experiments for an active tropical cyclone period during 2020, and the outcomes were published in an ECMWF Technical Memorandum.

During the year, we also started work on NextGEMS, a project funded through the European Union’s Horizon 2020 research and innovation programme, which aims to substantially increase the realism of Earth system simulations to study anthropogenic climate change. The consortium comprises 26 institutes, including from the Member States, and is generating strong collaborations with the Max Planck Institute for Meteorology, the Alfred Wegener Institut and the Barcelona Supercomputing Center, amongst others.

The NextGEMS team at ECMWF produced the first 75-day simulations at around 4 km resolution, with the IFS. Feedback from academic partners on the quality of these simulations helped us improve the representation of moist processes in our forecasting system. Consortium members also held a hackathon; a key finding of the event was that water and energy are not well conserved in the simulations. Our teams quickly identified solutions that will also lead to a better representation of precipitation and the large-scale atmospheric state.

Our new multi-site setup has opened further opportunities to strengthen partnerships. For example, with the University of Reading and with the Center for Earth System Observations and Computational analysis (CESOC), which brings together research at the Universities of Bonn and Cologne and the Jülich Research Centre. Discussions also commenced with the University of Bologna on a new Memorandum of Understanding.

How we work

ECMWF was created by a Convention that came into force on 1 November 1975 and was amended on 6 June 2010.

The governing bodies are the Council, the Director-General, and the Council's advisory committees, whose functions are defined in the Convention.

ECMWF governance in 2021

Council President:
Dr Daniel Gellens, Director of Royal Meteorological Institute of Belgium

Council Vice-President:
Prof. Penny Endersby, Chief Executive of UK Met Office

Director-General:
Dr Florence Rabier

Finance Committee Chair:
Dr Gisela Seuffert, Germany

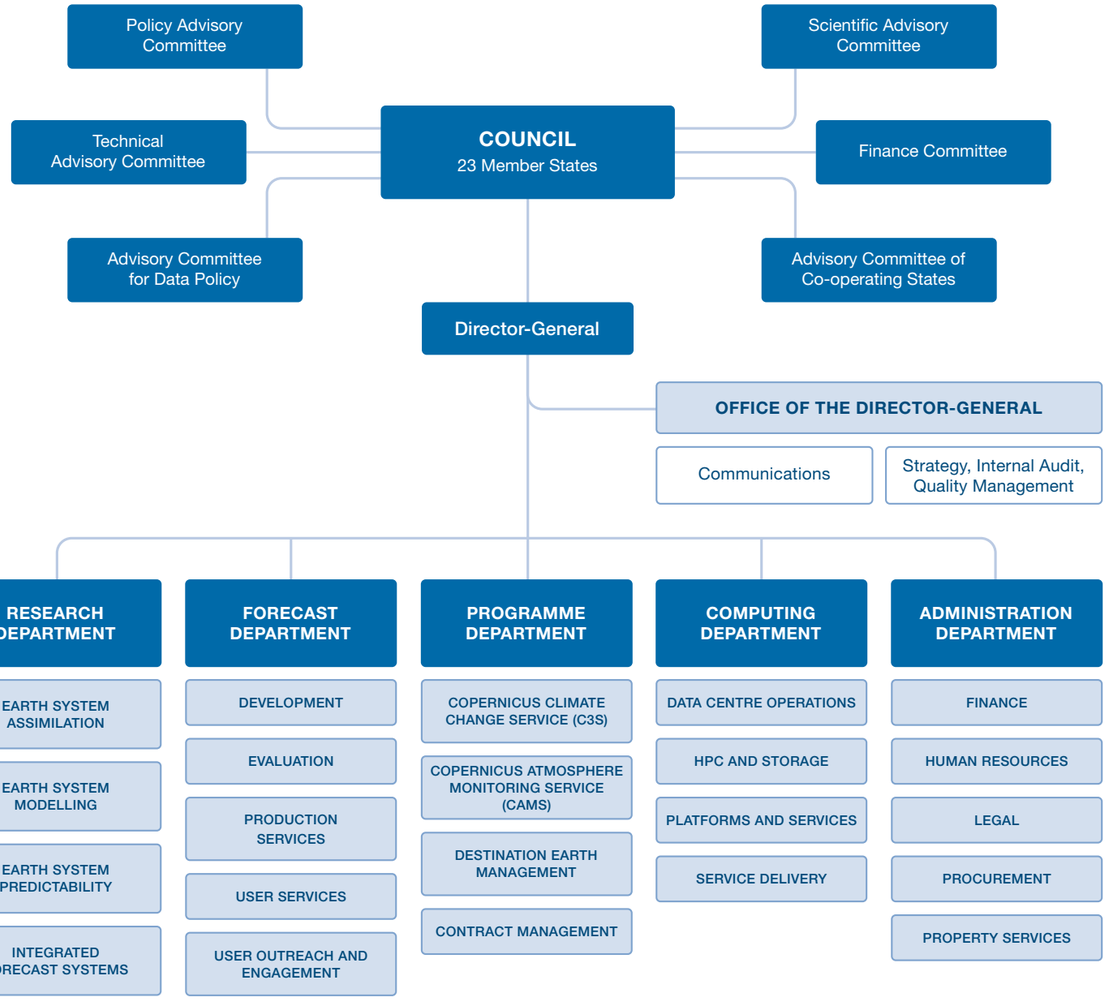
Policy Advisory Committee Chair:
Mr Eoin Moran, Ireland

Technical Advisory Committee Chair:
Dr Philippe Steiner, Switzerland

Advisory Committee of Co-operating States Chair:
Mr Nir Stav, Israel

Advisory Committee for Data Policy Chair:
Mr Paolo Capizzi, Italy

Scientific Advisory Committee:
Dr Inger-Lise Frogner (Chair)
Dr Susanna Corti
Dr Henk Eskes
Dr Alain Joly
Prof. Dr Thomas Jung
Prof. Eigil Kaas
Dr Christina Köpken-Watts
Dr Chiara Piccolo
Prof. Pier Siebesma
Prof. Gunilla Svensson
Dr Isabel Trigo
Dr Anthony Weaver



Organisation of ECMWF at June 2022

Co-operating States as of January 2022

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

Reading, UK | Bologna, Italy | Bonn, Germany

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