ECMWF

European Centre for Medium-Range Weather Forecasts

ANNUAL REPORT 2023

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Foreword

Increased horizontal resolution for ensemble forecasts and many other enhancements in both the model and data assimilation led to much-improved skill scores in 2023, and we launched the first version of our ML weather forecasting model – the AIFS.

Photographer: Stephen Shepherd

Florence Rabier
Director-General

2023 will very likely be remembered as the year when machine learning (ML) stormed the world of meteorology. Whilst many organisations such as ours had been experimenting with ML for a few years, including replacing or adding some ML components in our conventional forecasting systems, the fast-paced move into ML by some big corporations shook us into boldness. As a result, 2023 saw the birth of our ML weather forecasting model – the AIFS (Artificial Intelligence Forecasting System), as well as the start of an ambitious pilot project with our Member States.

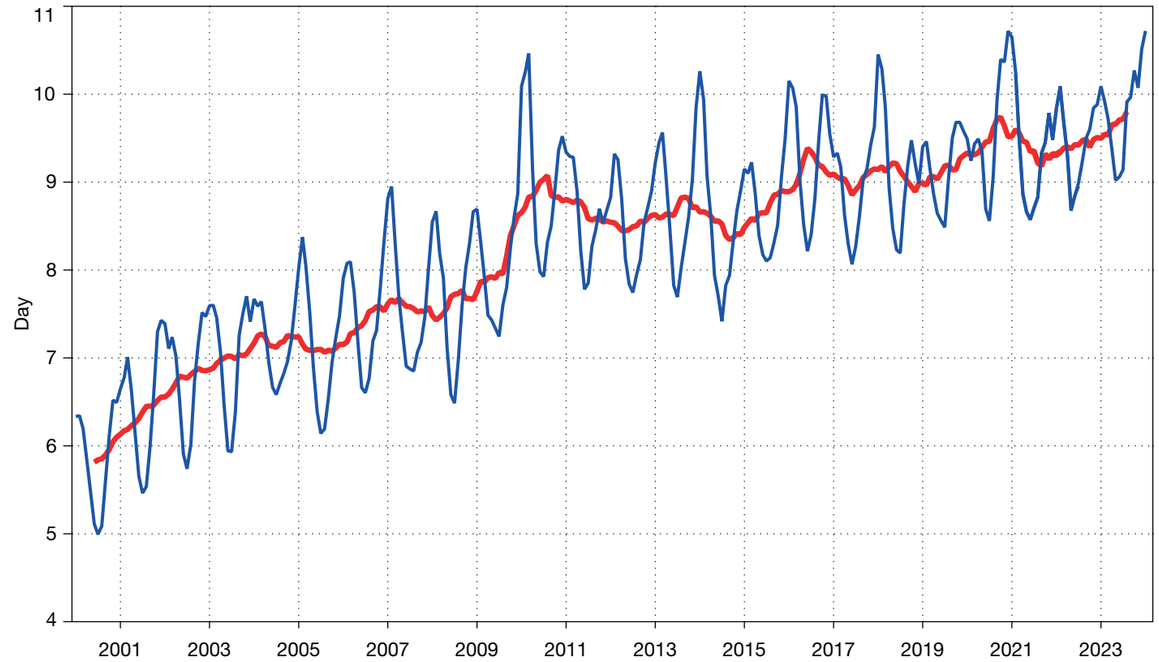
We did not rest on our laurels when it came to the Integrated Forecasting System (IFS) though. The cycle upgrade implemented in June, Cycle 48r1, saw the ensemble forecast horizontal resolution increase to 9 km, taking it to our highest resolution.

Many other enhancements came to fruition with this upgrade in both the forecast model and data assimilation, leading to much-improved skill scores.

Substantial changes were also made to extended-range forecasts, which now run daily instead of twice weekly and have 101 ensemble members instead of 51.

The European Weather Cloud, developed and run in partnership with EUMETSAT, became operational in 2023. It widens the offering of data and services from both organisations to our Member States, but also to the broader meteorological community.

Our collaboration with the European Union remained strong and effective during the period. The EU-funded Copernicus Climate Change Service (C3S) that we implement



found that the global-mean surface air temperature was more than 1.5°C above pre-industrial levels in early June, which was a first for a summer month. Over the whole year, it was at its highest level yet, close to 1.5°C above pre-industrial levels.

The ECMWF-coordinated project to monitor anthropogenic CO_2 emissions worldwide completed its final year, feeding into the much-awaited permanent anthropogenic greenhouse gas emissions Monitoring and Verification Support Capacity (CO2MVS), which is being developed as part of the EU's Copernicus Atmosphere Monitoring Service (CAMS), implemented by ECMWF. Last but not least, the EU's Destination Earth initiative, which we are developing jointly with ESA and EUMETSAT, was signed off for its second phase at the end of 2023.

A lot more happened over the year thanks to the talent and extremely hard work of our staff and the strength of partnerships with the national meteorological services of our Member States and beyond. Their dedication and support are what make ECMWF, and what made 2023 yet another fantastic year to be ECMWF.

June 2024

▲ Medium-range ensemble forecast skill

The primary headline score we use to evaluate long-term ensemble forecast performance shows the lead time at which the continuous ranked probability skill score (CRPSS) for 850 hPa temperature drops below 25% for the extratropical northern hemisphere. Red lines show 12-month running mean values, blue curves show 3-month running mean values.

2023 At a glance

January

MOOC training explores machine learning in weather and climate

Our Massive Open Online Course (MOOC) on machine learning in weather and climate ran from January to April, mixing interactive eLearning with webinars. The fully online, free training course was accessible to a global audience, with elements suitable for various levels of expertise. Over 9,000 participants registered, and more than 6,000 received certificates for completing one or more tiers. The course was organised in partnership with the International Foundation on Big Data and Artificial Intelligence for Human Development (IFAB).

February

WMO Fellow evaluates forecasts for Maldives region

Ahmed Shabin from the Maldives Meteorological Service joined us for a 12-month World Meteorological Organization (WMO) fellowship. His study into the forecast skill of IFS hindcasts/ERA5 in predicting the onset of southwest monsoon winds over the Maldives led to the development of a model product that could assist forecasters in declaring monsoon onset over the Maldives. The fellowship also provided an insight into day-to-day operations at ECMWF, as well as opportunities for training and to share expertise in weather and its impacts in the Maldives with colleagues at ECMWF.

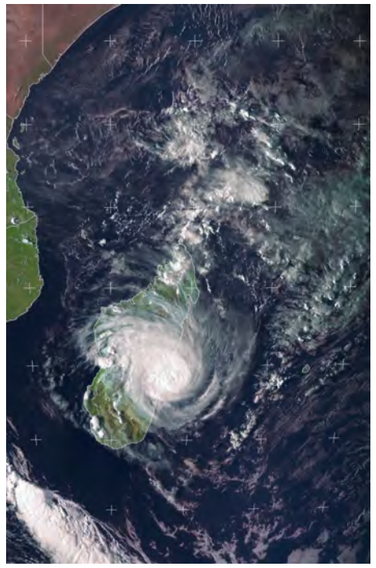
Tropical Cyclone Freddy longest on record

Tropical Cyclone Freddy tracked the entire Southern Indian Ocean from east to west, affecting Mauritius and La Réunion before crossing Madagascar. It made landfall in Mozambique twice, causing havoc in the region due to heavy rainfall and severe floods. At 34 days, the WMO said it was likely to be the longest-lasting tropical cyclone on record.

Monitoring Freddy with IFS Cycle 48r1, in testing at the time for implementation in June, highlighted improvements in cyclone track and intensity forecasts due to the increased horizontal resolution of ensemble forecasts. Early signals of severe upcoming floods over southern Mozambique were present in the Global Flood Awareness System (GloFAS) ten days before the actual flood peak was observed.

European scientists to represent radio spectrum users

In an initiative led by the European Space Agency (ESA), representatives from the European Earth observation, weather and climate science communities came together to form a new group, ESSEO (European Scientists on Spectrum for Earth Observation). Chaired by Stephen English from ECMWF, the group ensures the consensus voice of European scientists is heard in discussions about radio frequency spectrum use, in particular at the World Radiocommunication Conference 2027.



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View of Tropical Cyclone Freddy making landfall over Madagascar on 21 February 2023 from EUMETSAT's Meteosat-9 satellite.

March

ERA5 reanalysis dataset extended

The ERA5 reanalysis dataset was extended to include the period 1940 to 1958. Available from the Climate Data Store of the EU's Copernicus Climate Change Service (C3S), implemented by ECMWF, and the ECMWF Meteorological Archival and Retrieval System (MARS), ERA5 provides detailed information on historical weather and climate. It is the backbone of many C3S products and services and is also being used to train machine-learning models for weather forecasting.

Delegates at our Member State workshop on machine learning for numerical weather predictions and climate services, Reading, September.

April

European state of the climate report published

The climate in Europe in 2022 was marked by extreme heat and widespread drought, according to the European State of the Climate report (ESOTC 2022) published by C3S. The report found that Europe experienced a summer that was 0.3–0.4°C warmer than the previous warmest summer, and that high temperatures and a lack of precipitation contributed to significant drought. It also reported that, globally, 2022 was the fifth-warmest year on record, and Greenland's ice sheet experienced record melt.

May

OpenIFS users focus on atmospheric composition

Users of OpenIFS – a version of our Integrated Forecasting System for research, education and training – met at Barcelona Supercomputing Center (BSC) in Spain for the 6th user meeting. The focus was on atmospheric composition and its role in numerical weather prediction.

CAMS to contribute to Global Greenhouse Gas Watch

The WMO governing body, the World Meteorological Congress, unanimously approved the new Global Greenhouse Gas Watch (GGGW), to which the Copernicus Atmosphere Monitoring Service (CAMS), implemented by ECMWF, would contribute.

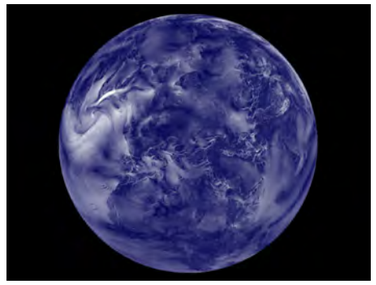
Later in the year, CAMS participated in two workshops working towards developing an integrated global observing system to support implementation of the GGGW and understand greenhouse gas cycles.

Ten teams tackle summer coding challenges

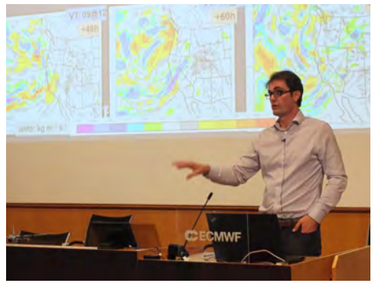
Supported by mentors from ECMWF and partner organisations, ten teams began tackling the real-world challenges set in our Code for Earth summer coding programme. They presented their results in September. The programme encourages multidisciplinary collaboration and embraces open-source principles. Since its start, it has produced more than 35 open-source software developments highly beneficial to activities at ECMWF and in our Member and Co-operating States.

2023 At a glance

Irina Sandu, newly appointed Director of Destination Earth at ECMWF.



10 m wind gusts at 9 km resolution as introduced for ensemble forecasts in June.



David Lavers, ECMWF, at the Atmospheric River Reconnaissance Workshop in June.

June

Forecasting system upgrade brings increased ensemble resolution

An upgrade of our forecasting system to IFS Cycle 48r1 increased the horizontal resolution of medium-range ensemble forecasts from 18 to 9 km. This led to big improvements in forecasts, for example of the mean sea-level pressure of tropical cyclones. Other major changes included a multi-layer snow scheme that markedly improved the realism of the snow pack in the model and a revised parametrization of microphysical processes that made it possible for the IFS to predict high-impact freezing drizzle events.

Irina Sandu becomes Director of Destination Earth at ECMWF

Irina Sandu became Director of Destination Earth (DestinE) at ECMWF, having previously been the DestinE Science Lead since January 2022. Her appointment followed the retirement of Peter Bauer from the role. DestinE is a flagship initiative of the European Union to develop a digital twin of planet Earth.

Atmospheric rivers observational campaign reviews achievements

Forty collaborators from research, operational, and academic centres came together at our Reading headquarters to discuss the latest research findings from the Atmospheric River Reconnaissance (AR Recon) observational campaign. AR Recon aims to improve the forecast skill of landfalling atmospheric rivers and their impacts in western North America, and the data collected has provided unique opportunities for ECMWF IFS diagnostic studies. The workshop highlighted accomplishments of the campaign so far, and coordinated and inspired future work on data collection, data assimilation, metric development, and impact assessment.

Funding boosts ML activities for numerical weather prediction

A four-year programme to accelerate machine learning activities in numerical weather prediction was approved by the ECMWF Council. The programme will increase resources within ECMWF to broaden the scope of work on machine learning, from intensifying work on a hybrid model combining conventional and ML methodologies, to developing a fully data-driven forecasting system.

Of the £8.365 million programme funding, £1.30 million was allocated to initiate a collaboration between Member and Co-operating States and ECMWF, details of which were approved by the Council in December.

Ensemble forecasting theme of annual user meeting

Our annual user meeting, ‘Using ECMWF’s Forecasts’, enjoyed record attendance in Reading and online and focused on the theme of ensemble forecasting. Presentations covered the use of ensembles in meteorology, hydrology and climatology.

July

New WMO roles for sub-seasonal predictions

The WMO designated ECMWF as a Global Producing Centre for sub-seasonal predictions (GPC-SSP) and a Lead Centre for sub-seasonal prediction multi-model ensembles (LC-SSPMME). Responsibilities include enhancing the consistency and usability of forecast information, facilitating the exchange of data, and coordinating multi-model ensembles of sub-seasonal forecasts.

‘User Voice Corner’ at Using ECMWF’s Forecasts meeting in June.

Historic end for Aeolus wind mission

After five years of improving weather forecasts, ESA’s Aeolus satellite mission came to an end. Aeolus was the first satellite mission to acquire profiles of our planet’s winds on a global scale, using LiDAR. Its end was also remarkable, with ESA’s mission control using the satellite’s remaining fuel to steer it to Earth’s atmosphere for a safe re-entry. We started assimilating Aeolus wind data operationally in January 2020, soon after launch, after tests demonstrated a positive impact on forecasts.

August

Intense wildfire activity continues around the globe

Throughout the year, CAMS monitored the wildfire situation around the globe, providing accurate data on wildfire intensity and carbon emissions through its Global Fire Assimilation System (GFAS). Many regions experienced record-breaking wildfire activity in 2023. GFAS data showed wildfire emissions in Canada’s Northwest Territories in August to be significantly higher than the 20-year average.

In the final days of August and the start of September, smoke from the Canadian wildfires was transported across the Atlantic, resulting in hazy skies across the UK and Ireland, and northwestern, central and southern Europe. Meanwhile, Greece experienced the largest wildfire recorded in history in the EU.

September

European Weather Cloud operational

With both clusters of ECMWF and EUMETSAT’s distributed cloud computing infrastructure installed, the European Weather Cloud became operational. It is a hub for users in our Member and Co-operating States to collaborate and share resources, running applications and services next to where the data is produced and avoiding large data movements over the network.

Machine learning forecasts available from ECMWF charts

Daily forecasts starting from ECMWF initial conditions and using machine learning models from NVIDIA’s FourCastNet, Huawei’s Pangu-Weather and Google DeepMind’s GraphCast became freely available on ECMWF’s public charts pages. Verification charts showed the skill levels of the models for different users and applications in a comparable environment. In December, forecasts from the FuXi model were added. To enhance transparency and reproducibility, we developed a software solution that let the public access the models with a single command, and we provided a plug-in system to allow anyone to install and access the different models.

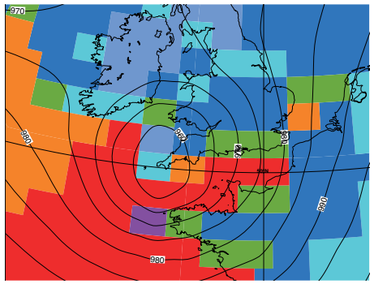
Annual Seminar spotlights reanalysis science and research

Science and research in Earth system reanalysis was the topic of our 2023 Annual Seminar. We welcomed around 100 scientists and students to our headquarters in Reading for a week of lectures, poster presentations and discussions, with more attendees following on the livestream.

Member States share visions for machine learning

A workshop for the national meteorological services of our Member States evaluated our collective progress in the application of machine learning. Delegates shared their visions for machine learning and progress at their organisations.

2023 At a glance



Extract from a forecast for mean sea-level pressure and wind speed from an early, low-resolution version of the AIFS.

Newly elected ECMWF Council President Penny Endersby, Chief Executive of the UK Met Office.

Vincent-Henri Peuch was appointed Director for Engagement with the EU.

October

AIFS data-driven forecasting system unveiled

The release of the alpha version of our Artificial Intelligence Forecasting System (AIFS) represented a first step towards our goal of creating a world-leading data-driven ensemble forecasting system. Experimental graphical products from the AIFS were made available to all in our open charts, while Member States could access numerical data for analysis. We developed the end-to-end tooling required to develop deterministic and probabilistic models that could be provided to Member and Co-operating States and serve as a basis for co-development. A new blog space was created to provide regular updates from the team developing the AIFS.

HPC workshop moves to Bologna

Our biennial workshop on high-performance computing (HPC) in meteorology took place in Bologna, Italy, for the first time. Delegates had the opportunity to visit the ECMWF data centre in addition to joining discussions on the theme of diversifying HPC, in terms of both technology and the research domains using the facilities.

November

Copernicus Health and Energy Hubs launched

EU Space Week in Seville, Spain, saw the official launch of the Copernicus Health and Energy Hubs, coordinated by CAMS and C3S, respectively. The hubs are two in a series of new Copernicus thematic hubs that will help users in specific domains navigate the wide range of products and information provided by the Copernicus Services.

December

DestinE phase II confirmed

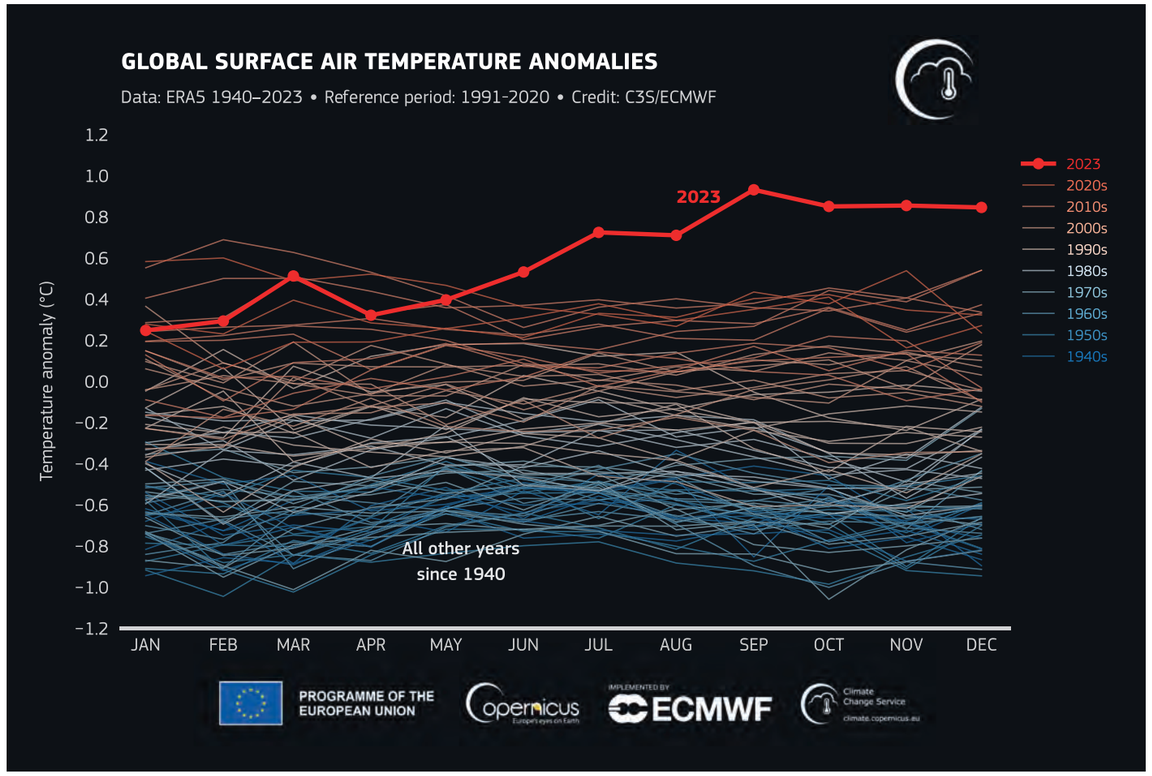
The second phase of the Destination Earth (DestinE) initiative, to begin in June 2024, was confirmed by the European Union and unanimously endorsed by the Councils of the three implementing entities delivering DestinE: ESA, EUMETSAT and ECMWF. This European endeavour to create a digital twin of Earth will considerably enhance Europe's ability to respond and adapt to extreme weather and climate change, strengthening its implementation of the green and digital transition.

Council President and Vice-President elected

Penny Endersby (Chief Executive of the UK Met Office) was elected President of the ECMWF Council, to succeed Daniel Gellens, who had held the office since December 2020. Dr Roar Skålin (Director General of the Norwegian Meteorological Institute) was appointed Vice-President.

Director for Engagement with the EU appointed

Vincent-Henri Peuch was appointed Director for Engagement with the EU from 1 January 2024, following on from his previous role as Director of the Copernicus Atmosphere Monitoring Service (CAMS). Laurence Rouil from the French National Institute for Industrial Environment and Risks was appointed to the role of Director of CAMS with effect from 1 February 2024.



Credit: C3S/ECMWF

Monthly global surface air temperature anomalies (°C) relative to 1991–2020 from January 1940 to December 2023, plotted as time series for each year. 2023 is shown with a thick red line while other years are shown with thin lines and shaded according to the decade, from blue (1940s) to brick red (2020s). Data source: ERA5.

Forecasts provided to SOFF participants

We continued to support the UN Systematic Observations Financing Facility (SOFF) through participation in the advisory board and funding events. At COP28, we announced the provision of ECMWF forecasts to some of the participating countries for use in initialising their higher-resolution regional models. An ECMWF study to estimate the impact of observations that would become available thanks to SOFF was agreed for 2024.

2023 confirmed as hottest year on record

Global temperatures reached exceptionally high levels in 2023. C3S monitored several key climate indicators throughout the year, reporting on record-breaking conditions such as the warmest September on record with the biggest departure from the climate average of any month in any year. In November, daily global temperature averages briefly surpassed pre-industrial levels by more than 2°C.

Unprecedented global temperatures from June onwards led 2023 to become the warmest year in the ERA5 record. Media interest in C3S monthly bulletins was high, and UN Secretary-General António Guterres referred to C3S data for the warmest summer on record in his July press conference on climate.

Developing a forecasting system powered by machine learning

> A significant reason that our AIFS, and other experimental models, exist is because of the ERA5 reanalysis, produced by the Copernicus Climate Change Service at ECMWF. High-quality data are vital for training high-quality models, so the open and easy-to-access ERA5 database has been pivotal in driving this new generation of models.
>
> *Florian Pappenberger, Director of Forecasts and Services*

> ECMWF is advancing the science of prediction with physics-based systems, hybrids of physics and data-driven approaches, and fully data-driven models. All of these strands will contribute to continuing to improve forecasts for our users.
>
> *Andy Brown, Director of Research*

Machine learning (ML) is an emerging tool that will help us solve some problems in weather and climate forecasting that are difficult to address with conventional, physics-based approaches. In 2023, we built a first version of a forecasting system powered by ML and brought it to a preoperational stage.

Artificial intelligence and particularly ML have dominated headlines, and their use in weather forecasting is no exception.

We continued following our ML Roadmap, published in 2021, which targeted bringing ML into conventional forecasting workflows, including into our Integrated Forecasting System (IFS). At the beginning of the year, we began to use ML in the operational pipeline, to help monitor meteorological observations. By the end of the year, we had developed a fully ML-based forecasting system.

In 2023 our Member States approved two initiatives aimed at intensifying the development, testing and implementation of ML across weather forecasting processes, and expanding our existing applications of ML to Earth system modelling.

The first project, approved in June, looks at increasing resources within ECMWF to broaden the scope of our ML work. This will include a range of approaches, from expanding existing work to bring ML into the IFS, to developing a fully data-driven forecasting system.

Resources were also allocated for a collaboration with our Member and Co-operating States. This new ‘pilot project’ was approved by the December session of Council. Working together, we can move faster in the rapidly evolving discipline of applying ML to weather prediction.

The two projects together recognise the potential of ML and build on substantial activities in this field, both at ECMWF and within European meteorological services.

A significant output of the first project was the Artificial Intelligence Forecasting System, or AIFS, with a first version launched in October. This data-driven model is trained to go from analysis to future forecast with a system that learns physical relationships in historical weather data. Development of data-driven models, including the AIFS, will be carried out in collaboration with Member States, led by Norway and Switzerland.

To assess the effectiveness of the AIFS, we evaluated its ability to forecast Storm Ciarán. This exceptional weather event in early November 2023 was well forecast by traditional methods, allowing warnings to be issued and authorities and individuals to take effective actions. The evaluation showed that the AIFS predicted the development of the cyclonic system very well but underestimated the most severe winds. This is a known current weakness of the AIFS, which partially stems from the fact that the training data used at the time was at a low resolution. For the scientific team, this test case was a positive demonstration of its potential use as a primary forecasting tool.

On release, the AIFS was added to our open charts. During 2023, we also added graphical products from experimental models developed by Huawei, NVIDIA and Google DeepMind, and one built through a higher education collaboration led by Fudan University (China). By showcasing the models in this way, we allow the meteorological community to compare these systems, and demonstrate their strengths and weaknesses.

Towards the end of 2023, we also began work on another angle of ML: a radical project to investigate if weather forecasts can be made directly from meteorological observations, without the use of reanalysis. The year was ambitious and successful for our ML work, coming a very long way in a very short space of time, and laying solid foundations for us to expand and improve the IFS and AIFS even further in 2024.

AIFS alpha version | October 2023

Architecture: graph neural networks

Grid: reduced Gaussian grids

Pressure levels: 13

Resolution: ~1 degree

Predicted parameters: wind, temperature, humidity, geopotential, surface pressure

Training data: ERA5 reanalysis and IFS operational analysis

Background image: extract from a 48-hour forecast for mean sea-level pressure and wind speed for 00 UTC on 2 November 2023 (Storm Ciarán) from an early, low-resolution version of ECMWF’s experimental AIFS machine learning model.

Science and technology

The year saw much progress in science and technology. It brought, for example, scientific developments in a new cycle of the Integrated Forecasting System (IFS) implemented in June 2023. IFS Cycle 48r1 included a horizontal resolution increase in ensemble forecasts, a major upgrade of extended-range forecasts, the introduction of a multi-layer representation of snow, and a revised parametrization of microphysical processes. In parallel, the operational forecasting system for global atmospheric composition of the EU's Copernicus Atmosphere Monitoring Service (CAMS), implemented by ECMWF, was substantially extended with the upgrade to IFS Cycle 48r1. We also developed an Artificial Intelligence Forecasting System (AIFS), which is the subject of a separate section.

Other advances included work towards IFS Cycle 49r1, to be introduced in 2024. This involved, for example, improvements to surface vegetation fields. Also, two-metre temperature measurements were to be used in 4D-Var data assimilation, the process that establishes the initial conditions of forecasts. In addition, we improved the prediction of clear-air turbulence (CAT), and we successfully predicted the 2023 El Niño event. We explored the real-time use of remote observations to improve fire danger forecasts, and we upgraded OpenIFS, a version of the IFS provided for research and education.

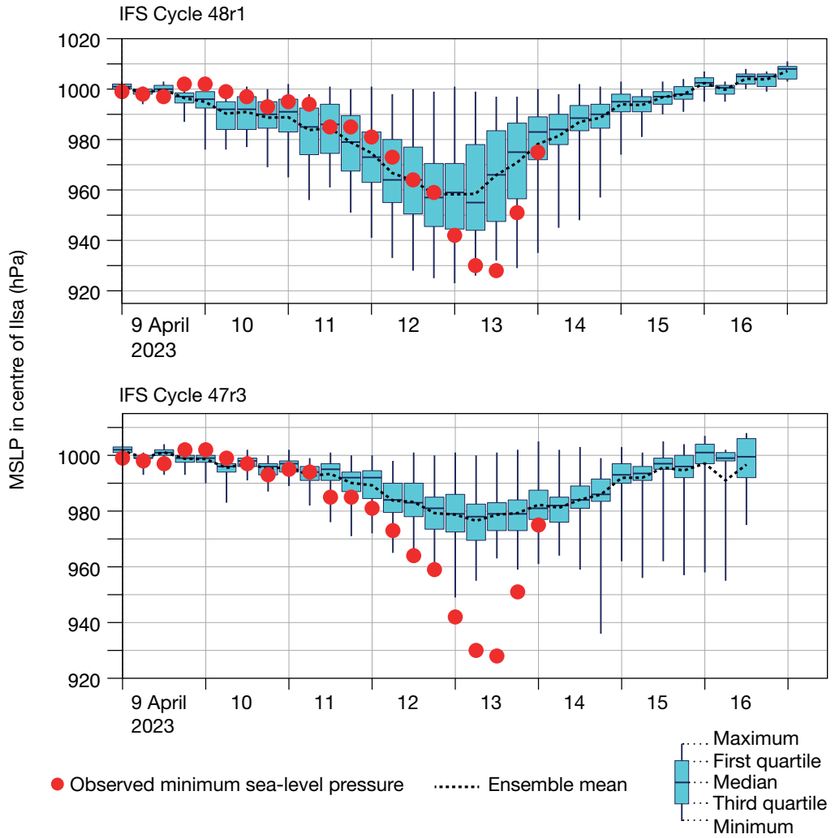
To follow changes in the Arctic climate with unprecedented detail and accuracy, scientists from the EU's Copernicus Climate Change Service (C3S), implemented by ECMWF, developed the Copernicus Arctic Regional Reanalysis (CARRA). An ECMWF-coordinated project for a prototype system for a Copernicus CO_2 service (CoCO2) to monitor anthropogenic CO_2 emissions worldwide concluded its programme, and a new, decadally-varying climatology of tropospheric aerosol was developed. Data from new satellite missions were investigated or final preparations were made for receiving them.

In technology, we continued a multi-year effort to migrate daily operations data output from the file format GRIB edition 1 (GRIB1) to GRIB edition 2 (GRIB2). Time-critical forecasts ran well on the Atos high-performance computing facility (HPCF), and there were no delays in the production of forecasts due to issues with the system. The Data Handling System (DHS) provided a reliable service over the year, and a multi-purpose cloud infrastructure, called the Common Cloud Infrastructure (CCI), was installed in our data centre in Bologna (Italy). Finally, work was carried out to make the IFS ready for a hybrid CPU–GPU compute model.

IFS Cycle 48r1

In June 2023, we upgraded our Integrated Forecasting System (IFS) to Cycle 48r1. This increased the horizontal resolution of medium-range ensemble forecasts (ENS) and substantially improved the skill of our weather predictions. The resolution increased from 18 to 9 km, the same resolution as the high-resolution forecast (HRES).

> "The horizontal resolution of medium-range ensemble forecasts increased from 18 to 9 km. This led to big improvements in forecasts."



◀ Tropical cyclone forecast

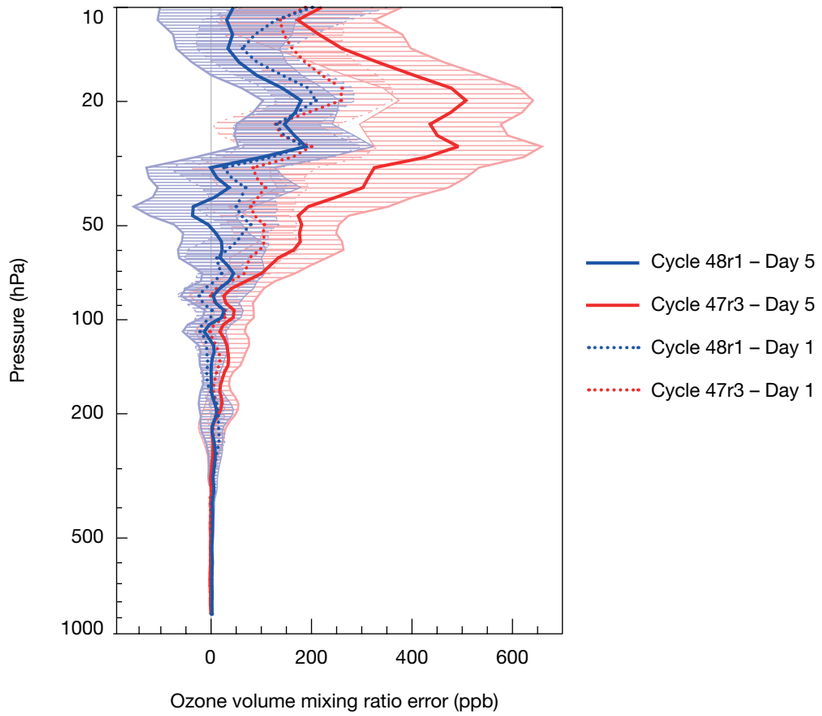
Mean sea-level pressure (MSLP) in the centre of Tropical Cyclone Ilsa, forecast from 9 April 2023, 00 UTC, using the IFS Cycle 48r1 ensemble with a resolution of 9 km, and using the IFS Cycle 47r3 ensemble with a resolution of 18 km.

This led to big improvements in forecasts, for example of tropical cyclone tracks and intensity, but also of upper-air and surface variables. Extended-range forecasts now have 101 instead of 51 ensemble members and they run more frequently than before.

Another major change in the forecast model was from a single-layer to a multi-layer representation of snow in the surface scheme. The multi-layer snow scheme markedly improved the realism of the snow pack in the model. The impact on two-metre temperatures in snow-prone regions included an improved daily cycle, and there were reduced snow depth forecast errors.

The parametrization of microphysical processes was also revised in Cycle 48r1. The aim was to allow supercooled drizzle drops to be formed and only to freeze if they come into contact with pre-existing ice or snow particles, or if they experience much colder temperatures. This made it possible for the IFS to predict high-impact freezing drizzle events, where supercooled rain/drizzle drops freeze on impact at the surface and form a glaze of ice.

Science and technology



◀ CAMS ozone forecast errors

Error of the CAMS ozone forecast for day 1 and day 5 of Cycle 48r1 (blue) and Cycle 47r3 (red) against five ozone sondes over Antarctica in October 2022 during the ozone hole event. The ozone forecasts for day 1 are similar as they are initialised from the respective ozone analysis. The forecast errors for day 5 in the stratosphere (50–10 hPa) are much smaller in Cycle 48r1 than in Cycle 47r3. The horizontal lines show variability within +/–1 standard deviation.

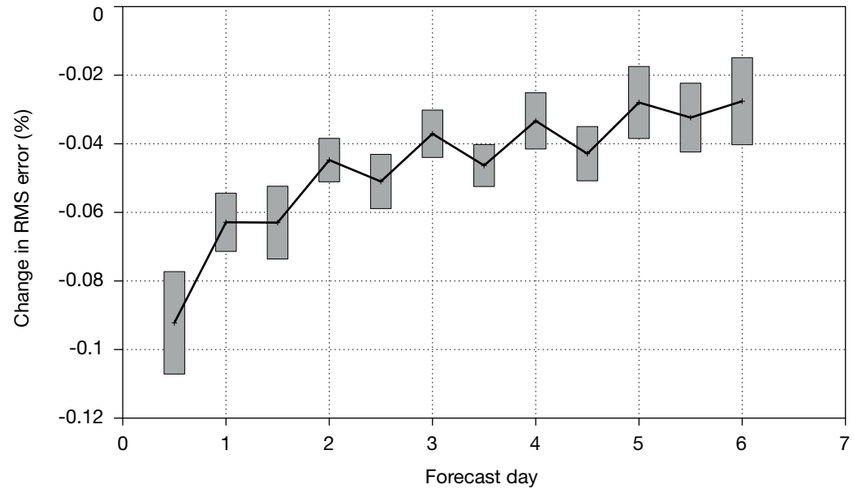
Upgrading atmosphere monitoring

The operational forecasting system for global atmospheric composition of the EU's Copernicus Atmosphere Monitoring Service (CAMS), implemented by ECMWF, was substantially extended with the upgrade to IFS Cycle 48r1. This included, for example, the introduction of the Belgian Assimilation System for Chemical ObsErvations (BASCOE) in CAMS. Together with the Carbon Bond Mechanism 5 (CB05) scheme, it became possible to fully represent chemistry throughout the atmosphere in the IFS for CAMS.

Other improvements were the addition of secondary organic aerosols and new tropospheric species; the improved treatment of emissions from specific sectors; and the assimilation of carbon monoxide retrievals from the Sentinel-5P satellite.

Work towards IFS Cycle 49r1

Meanwhile, work continued on improving the IFS in readiness for Cycle 49r1, to be introduced in 2024. For example, physics changes were to include extensive improvements to surface vegetation fields and changes to make the interpolation of the temperature to two metres more realistic.



◀ Two-metre temperature improvements

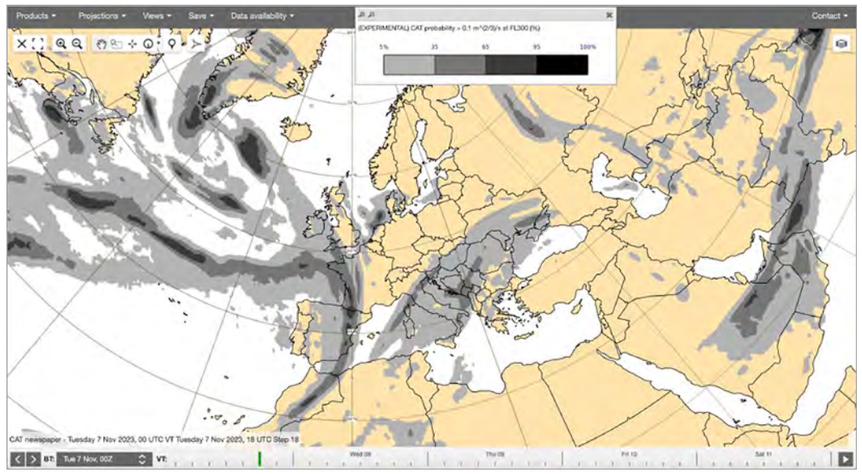
The plot illustrates the improvement (negative) Cycle 49r1 brings for two-metre temperature forecasts verified against weather station observations (SYNOP). It shows the percentage change in root-mean-square error for December 2021 to February 2022 and the region 20° to 90°N. The grey rectangles show 95% confidence intervals.

Also, for the first time, two-metre temperature measurements were to be used in 4D-Var data assimilation, the process that establishes the initial conditions of forecasts. This proved beneficial after extensive testing and tuning. In addition, there were improvements to snow data assimilation. Overall, better two-metre temperature forecasts could be achieved, especially in northern hemisphere winter.

Other changes to be implemented in Cycle 49r1 include the introduction of an urban scheme into the IFS to improve temperature and wind speed forecasts for urban areas. This is important because the temperature in cities is often elevated due to an effect known as the urban heat island.

Probabilistic clear-air turbulence

In 2023, we improved the prediction of clear-air turbulence (CAT), which is the main weather threat to civil aviation at cruising level in the lower stratosphere. CAT was originally made available from ECMWF's high-resolution forecast in October 2021, and in 2023 it became a fully probabilistic product. This approach can help to judge the significance of this intermittent and rare process, and to obtain reasonably smooth fields. At the time of its introduction in June 2023, it was the highest-resolution probabilistic CAT product worldwide in terms of vertical and horizontal resolution.



◀ CAT in ecCharts

The image shows an 18-hour forecast of the probability of CAT to exceed 0.1 $m^{2/3}s^{-1}$ at Flight level 300 (about 9,200 m). In ecCharts, a suite of web-based applications to inspect, explore and visualise ECMWF forecast data, different parameters can easily be overlayed, and any region globally can be considered at different zoom settings.

Science and technology

Predicting the 2023 El Niño event

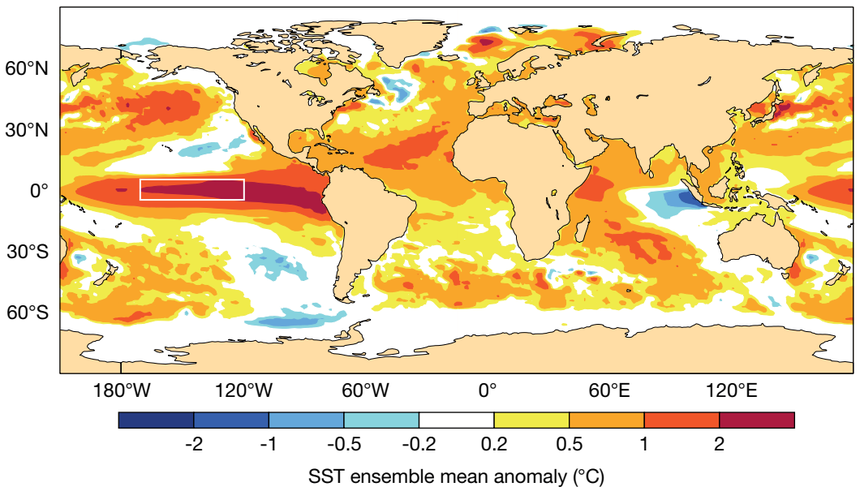
ECMWF forecasts, and forecasts provided by the EU-funded Copernicus Climate Change Service (C3S) implemented by ECMWF, were consistent throughout the first half of 2023 in indicating the development of an El Niño event. Such an event is a prolonged period of abnormally high sea-surface temperatures (SST) in the tropical Pacific Ocean. It goes hand in hand with changes in atmospheric conditions and can have strong repercussions on global weather patterns. As the year progressed, an El Niño event did in fact materialise. The figure shows a prediction made by ECMWF in the summer of how the El Niño might look towards the end of 2023. C3S forecasts from different centres generally agreed about the trend.

The figure shows a mean anomaly forecast. Uncertainty stems from unpredictable wind variations over the equatorial Pacific. We account for this uncertainty by running ensemble forecasts – the details in each ensemble member evolve differently, and we obtain a 'plume' of forecast SST values.

Remote observations in fire forecasting

As part of a project funded by the European Space Agency (ESA), we explored the real-time use of remote observations to improve fire danger forecasts. The proposed fire occurrence probability index (FOPI) combines the most-used model of fire danger, the Canadian fire weather index (FWI), with remote observations of vegetation optical depth (VOD) as a proxy of fuel amount and moisture.

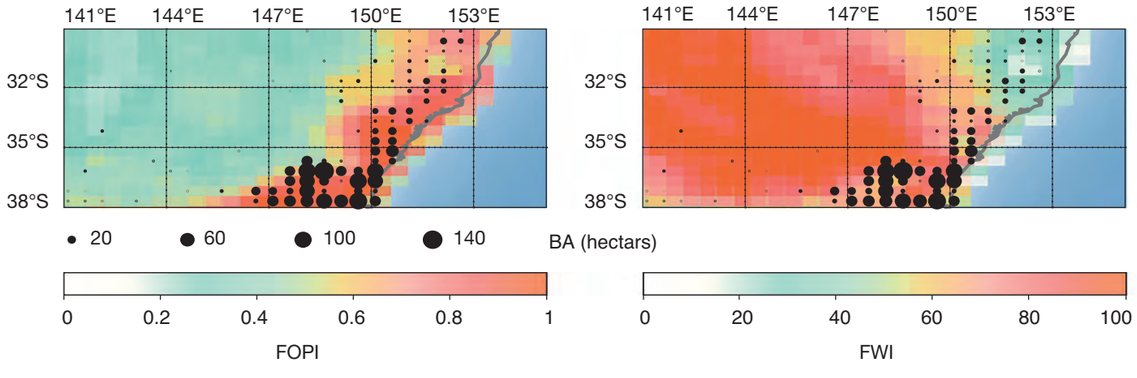
There are two innovative aspects in FOPI. The first is that it provides a framework to account for real-time fuel availability. FOPI thus limits unrealistically high values registered in desert areas, where fire activity is hindered. The second advantageous aspect of FOPI is that it expresses a probability of fire occurrence based on previous observations.



◀ SST ensemble mean anomaly forecast

The chart shows the SST ensemble mean anomaly forecast from July 2023 for October–November–December 2023, according to ECMWF's seasonal forecasting system SEAS5. The NINO3.4 region is indicated by the box.

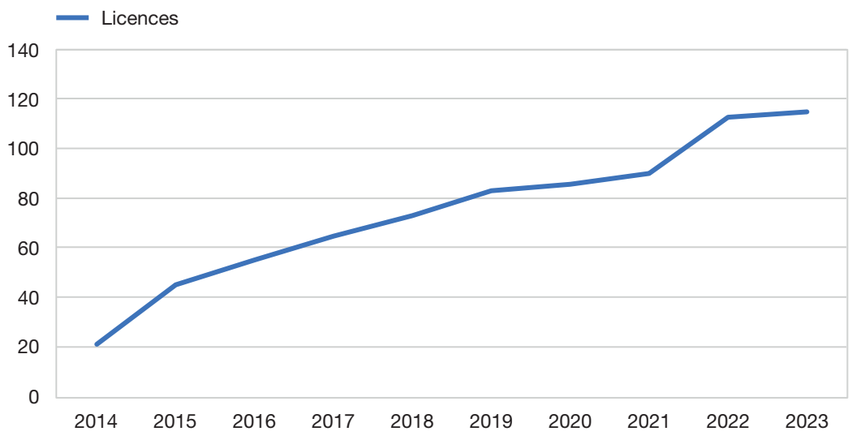
"We explored the real-time use of remote observations to improve fire danger forecasts."



OpenIFS adopts new version

OpenIFS, a supported and easily accessible version of the IFS provided for research and education, was upgraded to the latest IFS model cycle. A beta release of OpenIFS 48r1 was made available for testing by some licensees in September 2023, and by the end of the year the new version was nearly ready for all users. It has the forecast capabilities of IFS Cycle 48r1, which became operational in June 2023.

The upgrade heralds the release of more frequent model releases, planned about every two years. Many infrastructure and code changes had to be implemented to move from OpenIFS 43r3 to 48r1. Users can now run the model in double or single precision, and they benefit from improvements such as moist physics upgrades and the new multi-layer snow scheme.



▲ Forecasts for large fire events in 2020 in New South Wales, Australia

The maps show same-day forecasts for 4 January 2020. The left panel shows the FOPI prediction for that day, and the right panel shows the FWI prediction. FOPI and FWI are both dimensionless. Recorded burnt areas (BA) for the same day are provided as black circles. The size of the symbols is proportional to the burnt area expressed in hectares.

◀ OpenIFS licences

The graph shows the number of OpenIFS licences active any year since 2014.

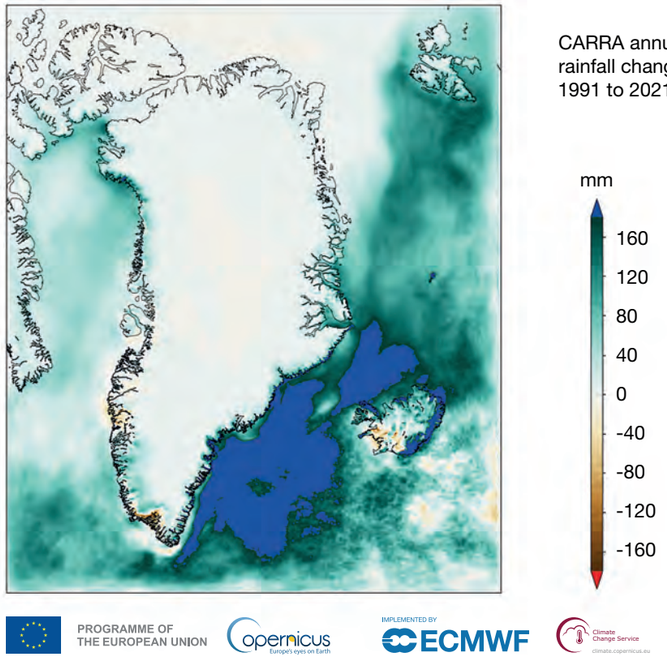
Science and technology

New data show wetter and warmer Arctic

Scientists from C3S have observed major changes in Arctic precipitation, air temperature and sea-ice coverage over the most recent three decades. The changes have big impacts in the Arctic, but they also affect northern hemispheric weather and climate more generally. One trend is increasing precipitation in the Arctic, particularly rain at the expense of snow over ocean regions. To follow these changes with unprecedented detail and accuracy, C3S developed the Copernicus Arctic Regional Reanalysis (CARRA): a state-of-the-art, data-driven reanalysis that enables a new focus on the Arctic climate. The CARRA dataset is now updated every month adding one month of new data close to real time.

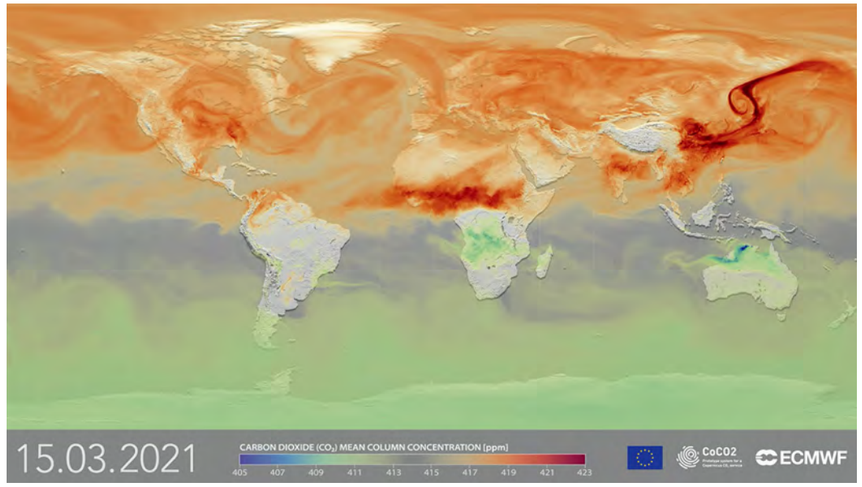
Copernicus CO_2 project concluded

A three-year, ECMWF-coordinated project for a prototype system for a Copernicus CO_2 service (CoCO2) to monitor anthropogenic CO_2 emissions worldwide concluded its ambitious programme successfully at the end of 2023. The purpose of this EU-funded initiative was to feed into a permanent anthropogenic greenhouse gas emissions Monitoring and Verification Support Capacity (CO2MVS). This capacity was going to provide continuous monitoring of carbon dioxide (CO_2) and methane (CH_4) emissions and fluxes using a combination of observations and Earth system modelling.



◀ Increase in rainfall

A map of change in annual rainfall from 1991 to 2021 shows a particularly marked increase along the southeast coastline of Greenland.



◀ CO_2 fluxes

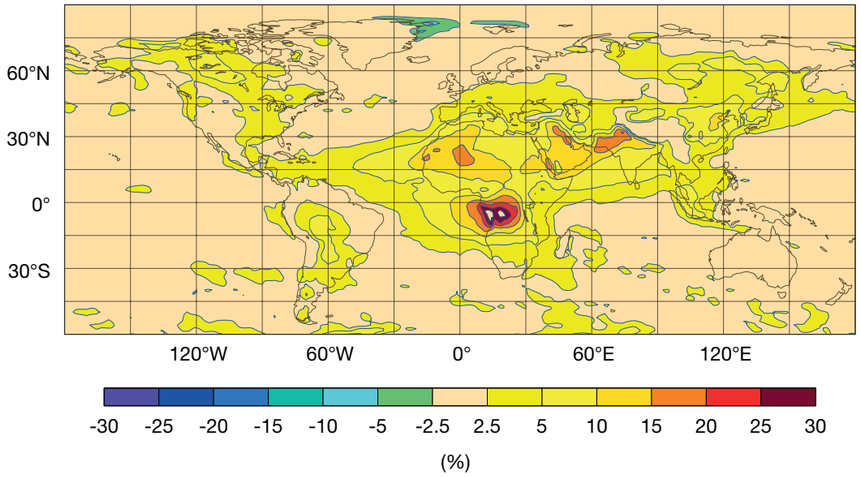
This is a screenshot of a high-resolution 'nature run' of fluxes of CO_2 produced by CoCO2 for the year 2021. It is intended to represent environmental conditions as accurately as possible.

CO2MVS is being developed as part of CAMS. Among other things, CoCO2 provided an assessment of the current state of in-situ observation sites to monitor anthropogenic greenhouse gas emissions; prior knowledge of emissions and natural fluxes used as input to CO2MVS; the assimilation of observations into models; and the consideration of local as well as global scales.

Preparation for SEAS6 and ERA6

Tropospheric aerosol has an important radiative impact on the atmosphere and wider Earth system. In configurations of the IFS for medium-range, extended-range and seasonal forecasting, it is represented as a fixed climatology. A new, decadally-varying climatology of tropospheric aerosol was developed to represent the large changes in anthropogenic aerosol that have occurred over recent decades. It was derived from and is compatible with the aerosol modelling used by CAMS. The target implementation was IFS Cycle 49r2, for use in ERA6 and the forthcoming SEAS6 seasonal forecast upgrade.

Clear benefits on forecasts as well as reanalysis were also seen as a result of using stronger ocean–atmosphere coupling in the data assimilation system, which establishes the initial conditions of forecasts. There is a target implementation in IFS Cycle 49r2, which was also going to be used to produce the ERA6 reanalysis.



◀ Impact of removing tropospheric aerosols

Regional variation in the importance of aerosols can be demonstrated with an experiment in which all tropospheric aerosols are removed from the IFS. The figure shows the impact of doing so on the net surface solar radiation. It covers the period of June–July–August, calculated from 10 years of 10-member seasonal forecasts starting on 1 May.

Science and technology

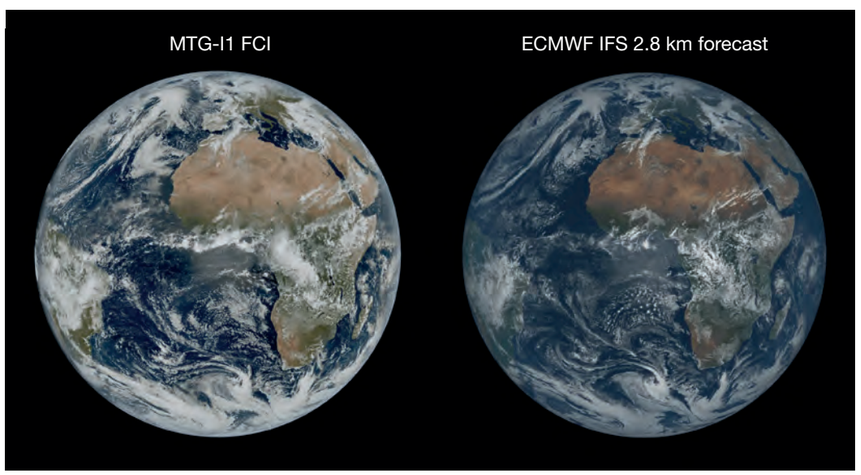
New satellite missions

Following the successful launch of the first satellite in EUMETSAT's Meteosat Third Generation series (MTG-I1) in December 2022, the first images from the new Flexible Combined Imager (FCI) became available to ECMWF. All of the advanced features of the new sensor were clearly demonstrated: more spectral channels, finer horizontal resolution and enhanced time sampling capability. As a preliminary step, ECMWF constructed a simulation of the first FCI images using high-resolution forecasts (2.8 km fields from a dedicated DestinE model run of the IFS). The realism of the model simulation compared to the real MTG image was quite striking. The Lightning Imager (LI) has also been successfully activated by EUMETSAT, and initial evaluations of the data have been performed by ECMWF.

We also made final-stage preparations for monitoring and assimilation of cloud radar and lidar observations from the EarthCARE satellite to be launched in 2024. EarthCARE data will be available in near-real time, facilitating the potential operational assimilation of space-borne cloud radar and lidar observations into numerical weather prediction models for the first time. EarthCARE is a joint venture between the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA).

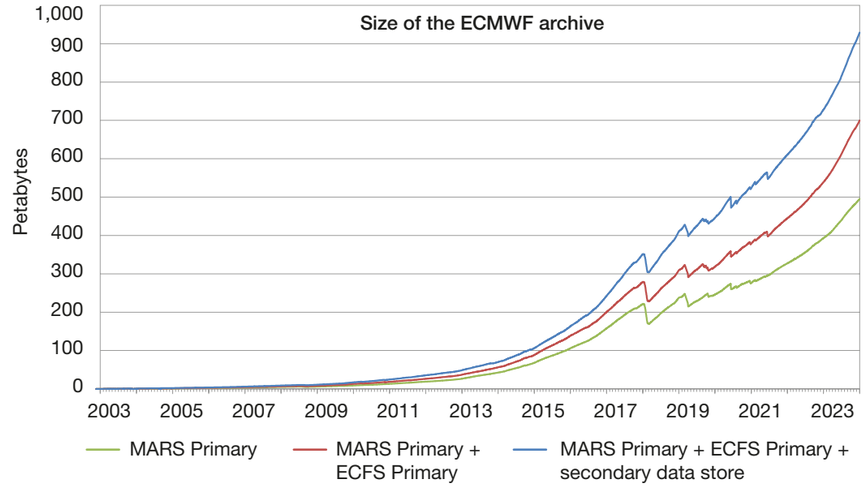
HPCF performance and archive status

Following the migration of computing from Reading to Bologna, in the autumn of 2022 ECMWF became settled into providing operational services from the new data centre as business as usual. The greater power and cooling capacity provided by the data centre compared to what was available in Reading made it possible to install the new Atos high-performance computing facility (HPCF). This provided sufficient computational performance to deliver the major scientific upgrade of IFS Cycle 48r1 in June 2023.



◀ MTG-I1 and Integrated Forecasting System

True colour image constructed from the enhanced visible bands of the MTG-I1 FCI (left) and a visible radiative transfer simulation from the Integrated Forecasting System model run at 2.8 km.



◀ Storage growth

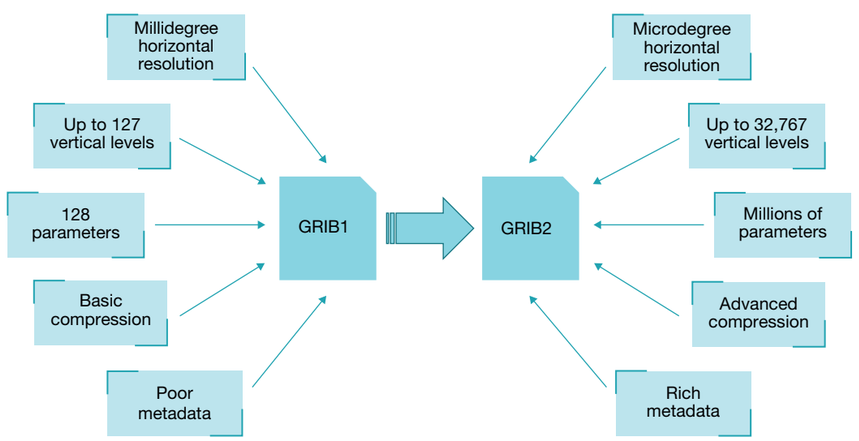
This chart shows the storage growth in ECMWF's Meteorological Archival and Retrieval System (MARS) and in ECMWF's File Storage (ECFS) system, which together amount to 700 PB of primary data. On top of that, a secondary data store duplicates some of the primary data.

Time-critical forecasts and research workloads were running well and reliably on the Atos HPCF. However, as with all large and complex HPC systems, supporting the service was a constant challenge. In 2023, Atos/Eviden continued detailed technical investigations into the remaining stability issues and worked closely with ECMWF to maintain the overall system availability and reliability. The Atos work was expected to bear fruit in 2024 and result in further stability improvements.

The Data Handling System (DHS) is a large, tiered storage system that uses ten robotic tape libraries, more than 450 tape drives, almost 300 Linux servers, 34 petabytes of disk space, and about sixty thousand tapes. It provided a reliable service over the year. At the end of 2023, the data archive stood at 700 PB of primary data. The most important part of this data, amounting to 229 PB, is duplicated in different tape libraries for safety and recovery.

Migration from GRIB1 to GRIB2

During 2023, we continued a multi-year effort to migrate our model output data from the file format GRIB edition 1 (GRIB1) to GRIB edition 2 (GRIB2). This will enable us to exploit the much richer metadata available in GRIB2. It also responds to the call for global numerical weather prediction (NWP) at convection-permitting resolutions set out in ECMWF's ten-year Strategy 2021–2030. Such resolutions require GRIB2 rather than GRIB1 data because of the limitations of GRIB1 grid definitions. We had already produced IFS output on vertical model levels using the GRIB2 format for several years. In 2023, we continued the transition to GRIB2 by applying it to the new ocean reanalysis, ORAS6, which was to become operational in 2024.



◀ GRIB1 and GRIB2 characteristics

The chart shows some limitations of GRIB1 and some of the benefits GRIB2 will bring.

Science and technology

> A new cloud computing service entered operations in the summer of 2023.

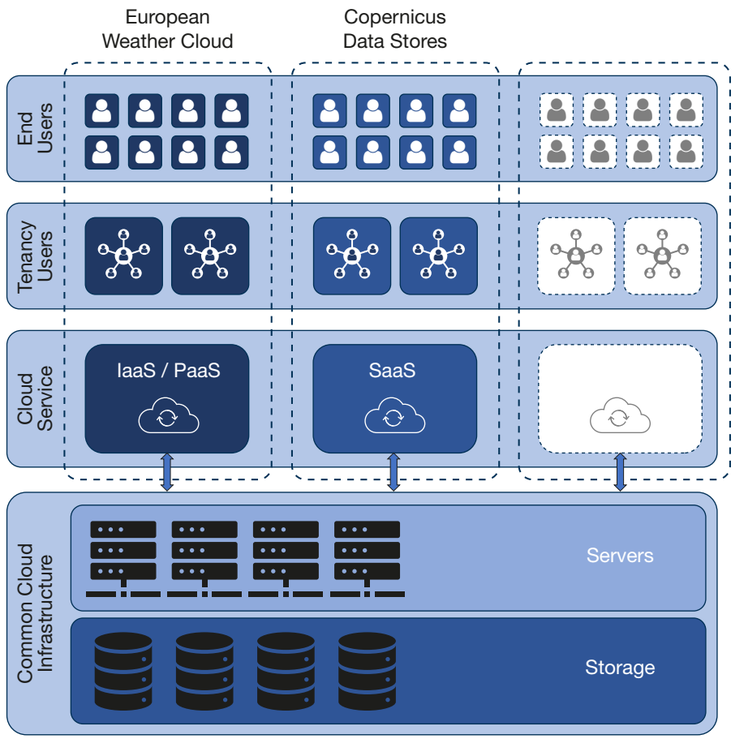
Start of operational cloud service from Bologna

Following a pilot project to gather use cases and requirements from Member States, a new cloud computing service was procured and entered operations in the summer of 2023.

The cloud service complements the existing HPC compute and DHS storage services by providing Member States with the flexibility to self-provision Virtual Machines (VMs) with the operating system and software stack of their choice, as well as object storage with a de-facto standard Amazon Simple Storage Service (S3) interface for interoperability.

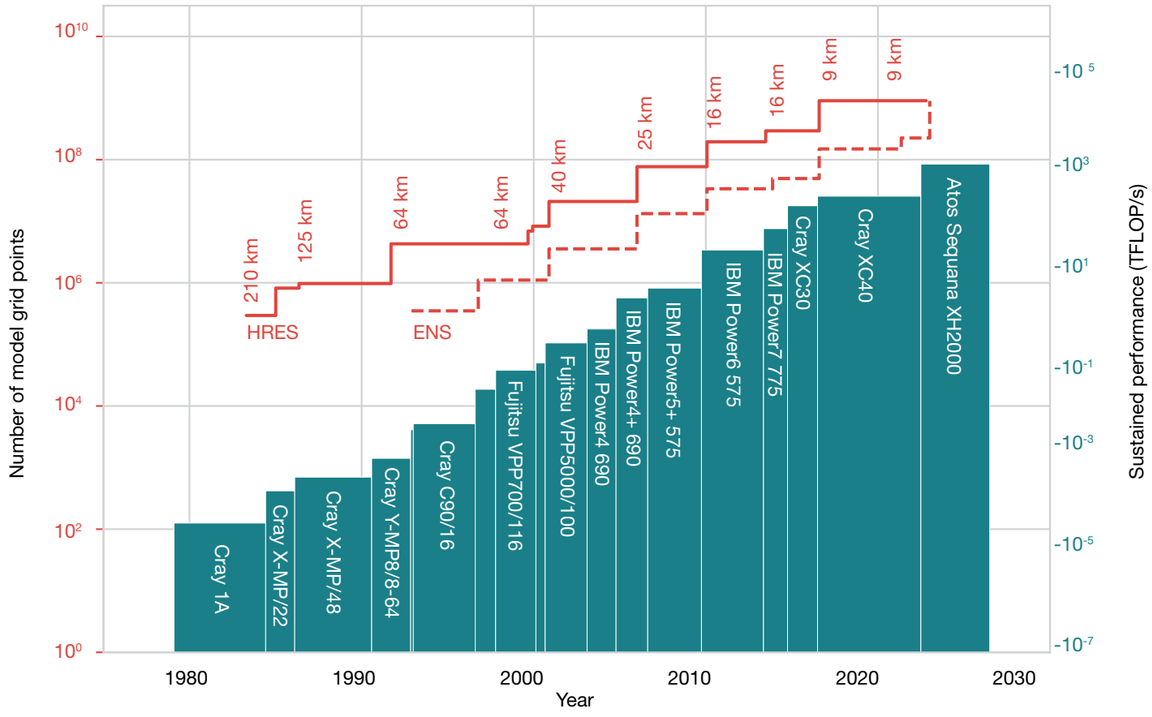
The architecture is based on a Common Cloud Infrastructure (CCI) layer, on top of which the different services, such as the European Weather Cloud (EWC) and the Copernicus Data Stores (CDS), are built. This architecture also enables ECMWF to improve efficiency by starting to consolidate a number of user-facing and internal compute services into the same hardware platform.

The EWC service is the result of a distributed cloud computing project jointly developed with EUMETSAT to provide a community cloud for the European Meteorological Infrastructure. In 2023, it was running at ECMWF over 60 Member-State-driven use cases for research purposes and operational official duties. The service is also used for some collaborative projects driven by organisations such as the World Meteorological Organization (WMO) and EUMETNET.



◀ The Common Cloud Infrastructure

This diagram shows the CCI and its support of the European Weather Cloud and the Copernicus Data Stores. IaaS, PaaS and SaaS stand for 'infrastructure as a service', 'platform as a service', and 'software as a service'.



▲ Supercomputers used at ECMWF

This chart shows how increasing the model resolution from 210 km in the 1980s to 9 km in 2023, for high-resolution forecasts (HRES) and ensemble forecasts (ENS), has involved ever more powerful high-performance computing facilities.

Progress in Hybrid 2024

Hybrid 2024 is an internal ECMWF project to adapt the IFS so that it is ready for a hybrid CPU–GPU compute model. Increasing the forecast resolution relies on greater performance of the HPCF used, and powerful modern GPUs can potentially provide this if the application can be mapped to them effectively.

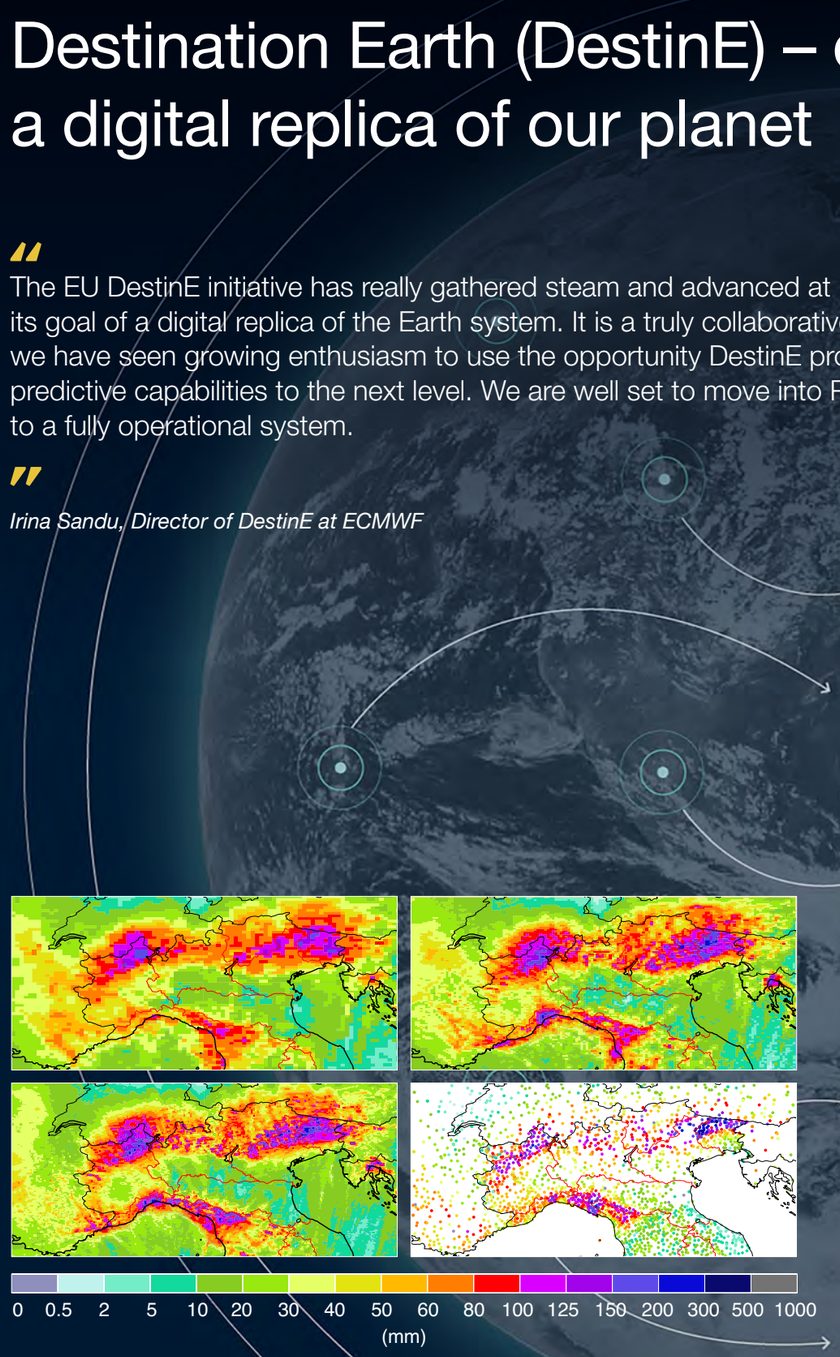
Hybrid 2024 aims to incrementally adapt IFS model components to different accelerators and programming models, focussing both on developing GPU capabilities and a sustainable technical evolution of the model code itself.

The initial GPU adaptation work, which was expected to conclude in 2024, was carried out in close collaboration with ECMWF Member States. There are also strong synergies with the EU-funded Destination Earth initiative, in which ECMWF is one of the partners. This involvement provides ECMWF with access to EuroHPC exascale-class systems that feature large GPU partitions.

Destination Earth (DestinE) – developing a digital replica of our planet

The development and implementation of DestinE's key elements advanced rapidly in 2023 – routine simulations with prototype digital twins provide just one example.

> "The EU DestinE initiative has really gathered steam and advanced at pace in 2023, towards its goal of a digital replica of the Earth system. It is a truly collaborative European effort and we have seen growing enthusiasm to use the opportunity DestinE provides to take our predictive capabilities to the next level. We are well set to move into Phase 2 and closer to a fully operational system."
>
> *Irina Sandu, Director of DestinE at ECMWF*



Early tests with a prototype global Extremes DT demonstrate the ability to better predict precipitation maxima in mountainous areas such as the Alps with kilometre-scale resolution. The figure shows for example, 78-hour forecasts of precipitation (accumulated over a 24-hour period) for Storm Alex (in October 2020) with the operational IFS (9 km resolution) (top left) and at 4 km (top right) and 2.8 km (bottom left) resolution. Available observations are shown bottom right.

DestinE is a flagship initiative of the European Commission, implemented by ECMWF, ESA and EUMETSAT, to develop a digital replica or twin of planet Earth. It represents a new type of information system with unprecedented levels of detail, quality and interactivity. Designed to help address the growing environmental challenges posed by extreme events and climate change, DestinE complements national capabilities and other European-level initiatives, such as the Copernicus Programme. For ECMWF, DestinE also offers a great opportunity to work very closely with our Member and Co-operating States.

Working with over 90 European partners, ECMWF leads the development of the first two priority digital twins (DTs) on Weather-Induced Extremes (Extremes DT) and Climate Change Adaptation (Climate DT), and of the Digital Twin Engine which provides the software environment needed to power the digital twins and allow users to interact with their data.

A partnership with the European High Performance Computing Joint Undertaking (EuroHPC JU) means DestinE can work with some of the top supercomputers in the world. The efficient use and ongoing development of next-generation high-performance computing, artificial intelligence and other digital technologies are fundamental to DestinE.

In 2023 complex Earth system models were successfully deployed on the EuroHPC LUMI machine in Finland, Europe's first pre-exascale high-performance computer, and we began piloting global kilometre-scale simulations. We built end-to-end workflows for the Climate and Extremes DTs and novel data handling capabilities to cope with the huge volumes of data involved. These developments involved, for example, adapting code to LUMI's mixed computer architecture containing AMD graphical processing units (GPUs).

In December, less than a year after gaining access to LUMI, the first-ever prototype multi-decadal projections at 5 to 10 km scales were run with the Climate DT, in work led by the CSC – IT Center for Science.

In August, a prototype of the global component of the Extremes DT, based on ECMWF's Integrated Forecasting System (IFS), began producing daily simulations out to five days on ECMWF's Atos supercomputer at a horizontal resolution of 4.4 km. This represents the highest-resolution global medium-range forecasts ever performed routinely.

The successful prediction of hurricane Idalia as a category 3 storm, just weeks after the DestinE forecasts started, confirmed earlier results that kilometre-scale models can improve predictions of tropical cyclone intensity. Improvements in orographically induced precipitation maxima were also seen. However, there have also been some examples of poor tropical cyclone forecasts. Higher-resolution data assimilation and new ways of modelling convection are two key areas of development that may improve forecasts.

Led by Météo-France, the on-demand regional component of the Extremes DT also progressed well. A configurable and modular sub-kilometre-scale prediction framework was set up, based on the ACCORD system, and runs at resolutions of 500 to 750 m were piloted.

In May 2023, Irina Sandu became the new director for the ECMWF component of DestinE, taking over from Peter Bauer who had been instrumental in the initial development of the initiative.

After such a successful year, we were also delighted to have confirmation in December of the second phase of the initiative, to run from June 2024 for two years.

A boost in funding for artificial intelligence and machine learning highlights the importance of harnessing rapid advances in this area. ECMWF will lead developments towards a machine-learning-based Earth system model that will help to quantify uncertainties of the Earth system DTs and enhance their interactivity capabilities.

Destination Earth is a European Union funded initiative and is implemented by three Entrusted Entities, ECMWF, ESA, and EUMETSAT under the leadership of DG CNECT.

Funded by the European Union **Destination Earth** implemented by ECMWF esa EUMETSAT

Impact

Our research, collaborations, and product developments improve the quality, usefulness and accessibility of ECMWF products and services for Member and Co-operating States and the broader meteorological community.

The quality of our forecasts was consistently high in 2023, and the forecasting system upgrade to IFS Cycle 48r1 in June led to much-improved skill scores. In addition to the new products introduced with the upgrade (described earlier in the report), other products were developed to help the prediction of extremes following feedback from Member States. These included updated parameters for the detection of convection-related high-impact weather, and new visibility meteograms developed with the Hungarian and Dutch meteorological services with display options tailored for aviation forecasting and public warnings.

Open data, coupled with development of open-source tools to facilitate the use of data, are fundamental to increasing the impact of our products; 200,000 graphical products were served on average every day through our open charts, while numerical data were available from our open data portal, Microsoft platforms and Amazon Web Services.

The EU Copernicus services we run supported scientists and policy- and decision-makers with consistent, quality environmental information. The Copernicus Atmosphere Monitoring Service (CAMS) monitored the ozone hole and the effects of various events on the atmosphere and released a back extension for the CAMS atmospheric composition reanalysis.

The Copernicus Climate Change Service (C3S) published updates on the evolving state of the climate as well as seasonal forecasts and its flagship European State of the Climate report. New data included a gridded monthly climate projection dataset and a back extension for ERA5. Through the Copernicus Emergency Management Service (CEMS), we contributed to major upgrades of the European and Global Flood Awareness Systems.

Understanding the operational requirements of our users is key to improving forecasting systems and forecast quality. Visits to national meteorological and hydrological services in eight of our Member and Co-operating States were opportunities for us to listen to their experiences and discuss the evolution of products and services. Annual forums for computing representatives and meteorological users, and a new forum for users from Co-operating States, were further occasions to hear from our members.

Workshops – in person, virtual and hybrid, training courses, and a Massive Open Online Course (MOOC) on machine learning for weather and climate facilitated knowledge-sharing on a wide range of topics. These were complemented by participation at international events such as COP28, where we joined partners to highlight support for WMO programmes and demonstrate the use of Copernicus data and services.

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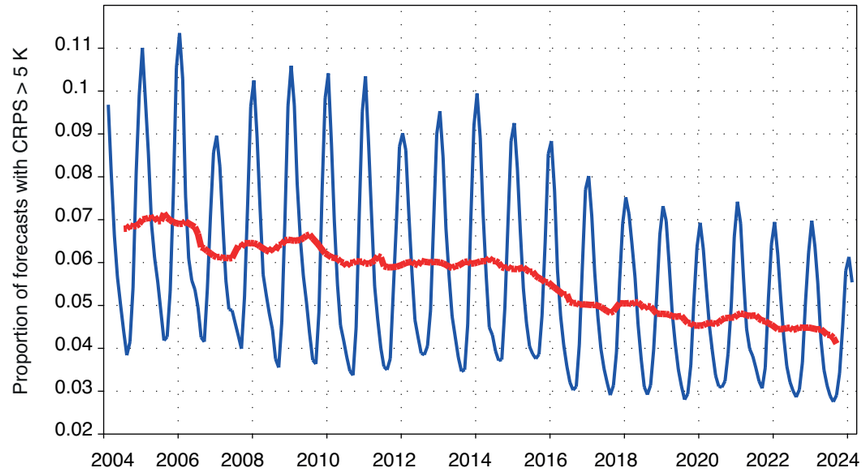
◀ Extreme heat

ECMWF forecasts help users prepare early warnings of severe weather, such as the extreme heat experienced in Europe in summer 2023.



Forecast performance

We use a comprehensive range of verification statistics to regularly evaluate and compare the accuracy of our forecasts.

The upgrade to Cycle 48r1 of the IFS in June included new physics and an increased horizontal resolution of medium-range ensemble forecasts (ENS) from 18 to 9 km. This brought further improvements in upper-air forecast skill, with the ENS headline score for June–August 2023 showing the highest skill ever when compared to previous summer seasons, and the 12-month running average of the score reaching its highest value so far. The resolution increase also improved ENS tropical cyclone track and intensity forecasts.

In the medium range – which is ECMWF's primary priority – compared to other global forecast centres, we maintained the lead for upper-air parameters. For surface parameters, in particular 2 m temperature and 10 m wind speed, some other centres took the lead in the short range.

However, the number of large ENS errors for 2 m temperature and 10 m wind speed has further decreased. For ocean wave parameters, we maintained the lead over other global centres for both peak period and significant wave height.

An increase in ensemble size from 51 to 101 for extended-range forecasts led to improvements in forecast performance across all parameters over the forecast range from week one to week four. The change in forecast frequency from twice a week to daily provides additional lead time for major events and transitions in weeks two to four.

Our seasonal forecast gave very good predictions of the transition early in 2023 from La Niña to El Niño conditions, even on the long-range (one year) timescale. The exceptionally warm northern hemisphere autumn 2023 season was well captured, while the cold anomaly in northern Europe was missed.

> "Understanding the operational requirements of our users is key to improving forecasting systems and forecast quality."

◀ Ensemble forecast headline score improvements

The number of large 2 m temperature errors in ensemble forecasts reached an all-time minimum in 2023. The chart shows the proportion (%) of forecasts with such errors (defined as having a Continuous Ranked Probability Score (CRPS) exceeding 5 Kelvin) at day 5 in the extratropics. Shown are 3-monthly values (blue) and a 12-month running average (red). Verification is against SYNOP observations.

Impact

Heatwave over southwest Europe

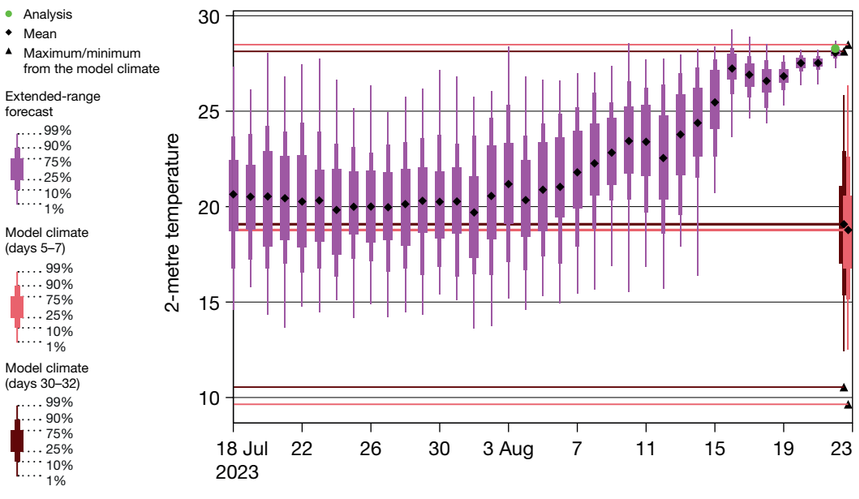
During July and August, Europe experienced two major heatwaves in the south, while northern Europe saw a lot of rain with flooding in Norway and Sweden. The July heatwave affected countries around the Mediterranean Sea, with major wildfires, especially in Greece, while the August heatwave affected southwestern Europe in Spain, France, and Switzerland.

Globally, the average surface air temperature of 16.77°C over the northern hemisphere summer season (June–July–August) 2023 was by far the warmest in the ERA5 record. July and August 2023 were the two warmest months on record and were estimated to have been around 1.5°C warmer than pre-industrial levels, based on the 1850–1900 reference period.

During this heatwave, the city of Lyon in France saw 17 days in a row with temperatures above 30°C (9–25 August), which peaked at 41.4°C on 24 August. In Spain, Bilbao on the north coast set a record of 44.0°C on 23 August.

In general, the predictability of the August heatwave over southwestern Europe was good. For southeastern France, extended-range predictions showed that 30 days before the peak of the August heatwave, the ensemble mean was slightly above the model climate mean. About 20 days before the peak, the ensemble mean became progressively warmer than the model climate mean, crossing the 99th percentile six days before the peak of the event.

In the medium-range forecasts, the Extreme Forecast Index indicated extreme values (0.8 and above) for maximum temperatures on 23 August over southeastern France and Switzerland from 17 August. However, errors in predicting the winds along the Atlantic coast of Spain and France meant medium-range predictions missed the extreme surface temperature in those locations, despite a good signal in 850 hPa temperature.



◀ Forecast evolution

Forecast evolution plot for 3-day (22–24 August 2023) 2-metre temperature over southeastern France.

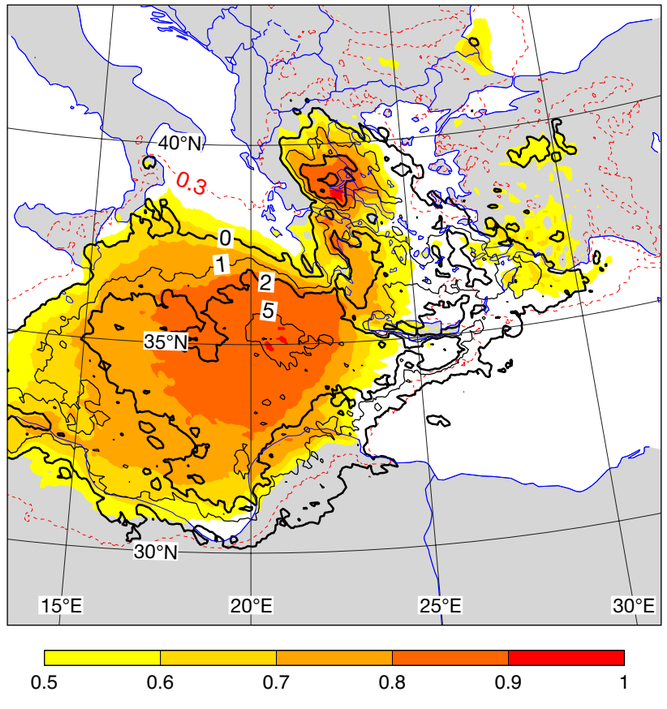
Storm Daniel

In early September 2023, a set of extreme rainstorms led to devastating flooding in parts of Greece, Bulgaria and Türkiye. These events related to development of a surface cyclone nearby on the night of 4 September, assigned the name ‘Daniel’.

For rainfall associated with Storm Daniel over Greece and the Mediterranean from 4 to 8 September, the signal for an extreme event appeared in the ECMWF ensemble (ENS) 3 to 4 days in advance, between 30 August and 1 September.

In subsequent days, Daniel meandered slowly across the Mediterranean before adopting an east-south-eastward trajectory near northern Libya late on 8 September, whereupon it became a medicane. Landfall was near Benghazi around 23 UTC on 9 September.

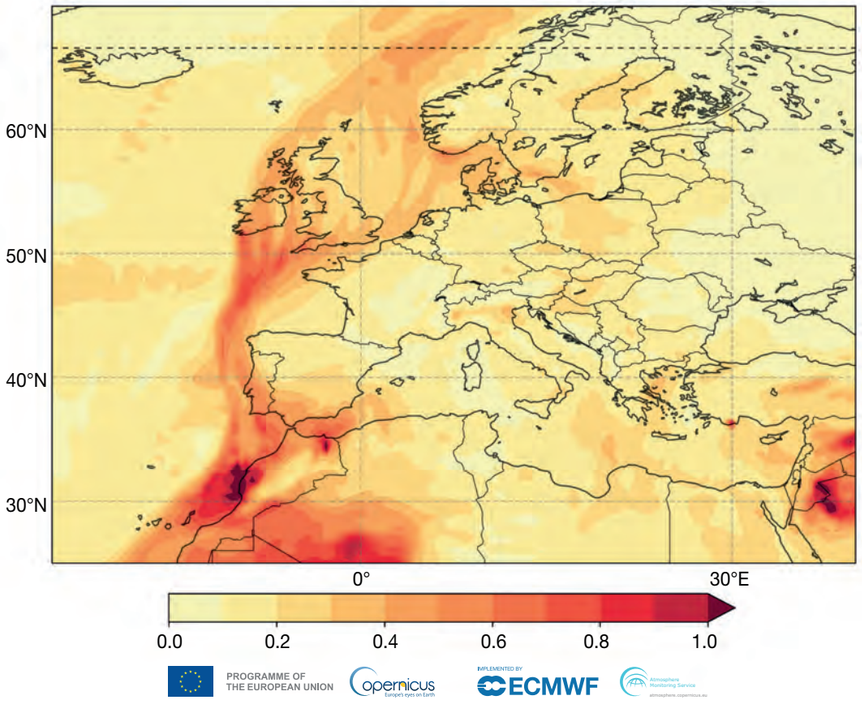
The resulting intense rainfall over the mountains of northern Libya on the night of 10/11 September led to two dams bursting, and there were 5,000–15,000 fatalities as buildings were swept away. This was likely the deadliest rainfall-related flooding disaster since ECMWF started producing operational forecasts in the late 1970s, and the second most deadly dam-related disaster of all time. While the ECMWF ensemble indicated the risk of the extreme rainfall roughly a week in advance, the magnitude was likely underestimated in the forecasts.



◀ Extreme Forecast Index for rainfall

Extreme Forecast Index (EFI, shading and red contours) and Shift Of Tails (SOT, grey and black contours; 0, 1, 2, 5) for 5-day accumulated rainfall on 4–8 September 2023, from operational forecasts with a start time of 00 UTC on 1 September 2023.

Impact



Saharan dust transport

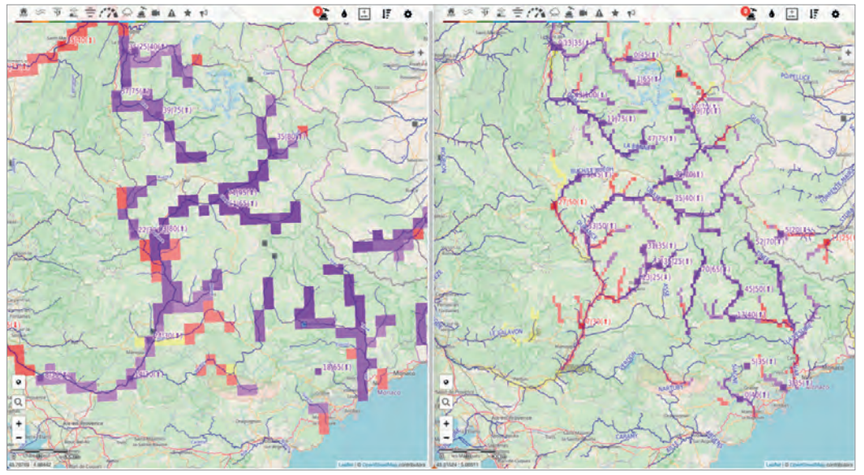
Daily maximum total aerosol optical depth (AOD) at 550 nm initialised on 15 February 2023 at 00 UTC and valid for 15 February. Source: Copernicus Atmosphere Monitoring Service.

Transport of Saharan dust across Europe

Atmospheric dust can lead to adverse health effects and impact solar energy generation. For the first major transport of Saharan dust across Europe in 2023, CAMS forecasts showed high values of aerosol optical depth and dust concentrations across the Iberian Peninsula on 20 February, with forecasts from 21 February showing transport across France and further north between 21 and 23 February, reaching as far north as Denmark. The forecasts also showed high PM10 concentrations (particulate matter where particles are less than 10 micrometres in diameter) at the surface for Spain, and at higher elevations, for example in the Pyrenees and the Alps.

The dust transport followed a similar, if less pronounced, episode the week before. On 13 February, the Calima wind carried Saharan dust to the Canary Islands. On 14 and 15 February, the dust transport continued northwards as far as Ireland and the UK.

Evaluation of the CAMS forecasts against independent measurements from the Aerosol Robotic Network (AERONET) showed good agreement in the timing and magnitude of the aerosol optical depth evaluations at several sites in Spain and Portugal in February.



EFAS reporting points for flood events

EFAS mapviewer showing the increase in spatial resolution when looking at rivers (coloured segments), with EFAS v5 (right) better representing small rivers than EFAS v4 (left). The plots show EFAS reporting points for 17 October 2023 (12 UTC) over southern France.

EFAS and GloFAS kilometre-scale forecasting

For the Copernicus Emergency Management Service (CEMS), we work with the Joint Research Centre (JRC) of the European Commission. In 2023, as part of our activities as CEMS hydrological forecast computation centre, together with the other CEMS centres and the JRC, we implemented operationally kilometre-scale hydrological forecast systems for both the European and Global Flood Awareness Systems (EFAS and GloFAS). This increased the spatial resolution of EFAS 12-fold (to ~1.4 km grid size), and that of GloFAS by a factor of 4 (to ~5 km). GloFAS version 4 was released in July 2023, and EFAS version 5 in September 2023.

The changes in the modelling set-up also included an update in the physical property maps used in the hydrological model and new model parameters, thanks to a complete recalibration of both EFAS and GloFAS models (for GloFAS undertaken by the JRC).

The increase in spatial resolution allowed us to increase the number of calibration points, for EFAS considering river basins from 150 km^2, and a much better representation of the river network, with more reporting points being highlighted during a flood event.

Impact

ERA5 data extended to 1940

A significant new segment of ERA5 reanalysis data for 1940 to 1958 was made available, helping build a globally complete picture of historical weather and climate, and extending the data record for global atmosphere, land surface and ocean waves to over 83 years, from 1940 to the present.

The reanalysis dataset is available from C3S and the ECMWF Meteorological Archival and Retrieval System (MARS). By the end of 2023, ERA5 had well over 125,000 users, ranging from researchers to professional consultants, big data experts, journalists, policy-makers and the public.

ERA5 makes use of all available observations, in-situ and from satellites. Although in the past observations were sparser than today, from 1940 ERA5 provides a good estimate of the actual situation for large regions over the northern hemisphere. The figure shows the representation of a severe storm over the Iberian Peninsula in 1941, which led to significant damage and disruption over Portugal and northwest Spain.

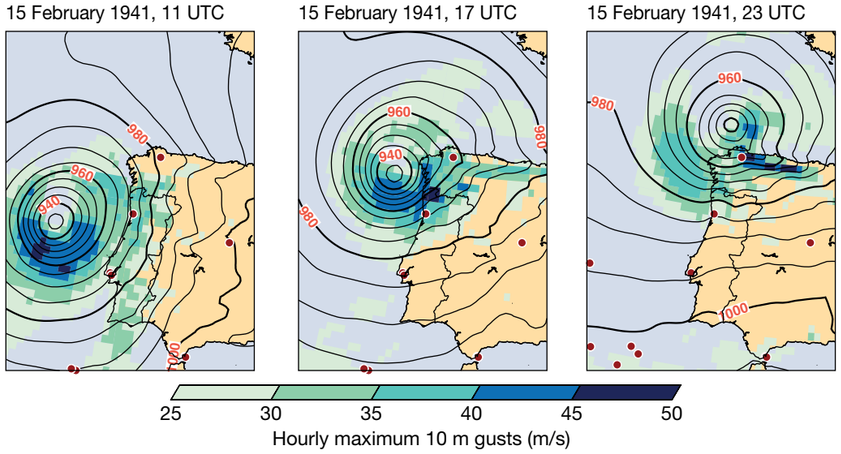
Copernicus Health and Energy Hubs

CAMS and C3S launched two ‘hubs’ to help users in the health and energy sectors navigate the wealth of Copernicus data and information products. Each hub brings together information from all of the Copernicus services. ECMWF acts as the central contact point on behalf of the other entrusted entities for institutional user requests on any Copernicus-related data products within the domains of health and energy.

The Health Hub supports users working on physical and mental health, and wellbeing, by gathering information that was previously distributed and less accessible to people with limited experience in using data based on Earth observations. Such information is increasingly being used in the health sector, for assessing environmental drivers that affect health, such as temperature, humidity, air quality, UV radiation and the evolution of habitats for disease vectors. They can help stakeholders to make informed decisions, develop applications, and ultimately improve public health outcomes.

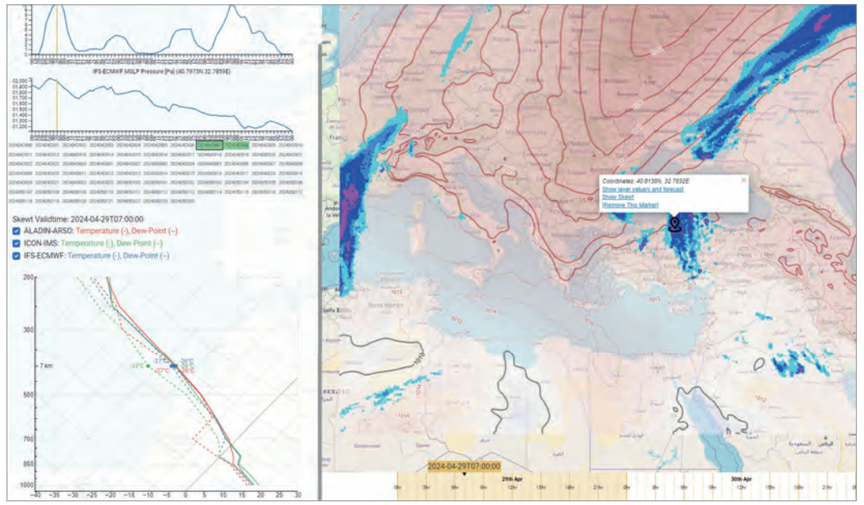
The Energy Hub supports the EU’s efforts to make Europe’s energy supply more sustainable and secure at a crucial time. Copernicus data provide invaluable insights to support energy production, from planning to distribution, enabling operators to improve energy efficiency and reduce emissions. For example, forecasts of global ocean physics and waves are important for the offshore wind, tidal and wave energy sectors, while solar radiation timeseries can be used to plan, monitor and improve the efficiency of solar energy systems and integrate them into energy supply grids.

> “ERA5 has well over 125,000 users, ranging from researchers to professional consultants, big data experts, journalists, policy-makers and the public.”



◀ The Iberian Storm of 1941

Three snapshots of the Iberian Storm of 1941, showing ERA5 mean sea-level pressure (contours, in hPa) and hourly maximum 10 m gusts (colours, in m/s). The locations of assimilated pressure and marine-wind observations from which the ERA5 reanalysis fields were constructed are shown as red dots.



◀ Shared resources

The national meteorological and hydrological services in southeast Europe participate in the South-East European Multi-Hazard Early Warning Advisory System (SEE-MHEWS) project, which uses the EWC to run the frontend web application displaying products generated by the partners at ECMWF they can all access.

Cloud computing for Europe’s meteorological community

A community cloud computing platform jointly operated by ECMWF and EUMETSAT became operational in September. Called the European Weather Cloud (EWC), it provides a hub for the meteorological community in our Member and Co-operating States to collaborate and share resources.

Users can customise their applications and workflows, as well as build and expose services through the web. Running applications and services next to where the data is produced avoids large data movements over the network.

Most of the pilot use cases transitioned seamlessly into operational use. They include the use of the EWC as a collaboration platform on which training courses can be run, and by the South-East European Multi-Hazard Early Warning Advisory System (SEE-MHEWS) to make data produced at ECMWF by participating countries available to the other partners.

A workshop introduced users to new aspects of the EWC and ways to benefit from it, while two webinars in November gave an introduction for new and prospective users.

Impact

European State of the Climate 2022

The sixth annual European State of the Climate (ESOTC) report was published in April. Produced by C3S with contributions from national meteorological services, partners and other Copernicus services, the flagship report contains analysis of the past calendar year, with updates on long-term trends of key climate indicators.

The 2022 report included a snapshot of the global context, confirming that, globally, 2022 was the fifth-warmest year on record and the second-warmest year on record in Europe. Europe experienced its hottest summer on record, and summer wildfire carbon emissions were at their highest since 2007. The report detailed significant drought in Europe, as well as record loss of glacier ice in the European Alps, and the record surface melt experienced by the Greenland ice sheet in September 2022.

The findings were widely covered by media around the world, with the most media coverage and website traffic of an ESOTC to date. More than 100 journalists attended the briefing introducing the report's findings. Later in 2023, we were able to engage further with policy-makers, for example with the German Embassy in Brussels, a Q&A session with the European Commission Directorate-General for Climate Action (DG CLIMA) and a presentation to the European Parliament Committee on Environment, Public Health and Food Safety (ENVI) in Brussels, to raise awareness of the report and its findings.

We also worked with the World Meteorological Organization to produce a joint State of the Climate in Europe report for 2022, which was published in June 2023.

◀ Europe's climate in 2022

The flagship ESOTC report uses consistent, dependable, freely available data that assist policy-makers in understanding climate change and its impacts.

Early warnings and climate data at COP28

ECMWF, C3S and CAMS brought expertise in the use of observations, modelling and technology to the discussions at the COP28 to help shape actions in the WMO's priority areas at the United Nations Climate Change Conference: early warnings for all, the Systematic Observations Financing Facility (SOFF), water and climate, global greenhouse gas monitoring infrastructure, and climate science for climate action.

A joint ECMWF–SOFF event brought together partners to discuss how more observations and better forecasts could help climate adaptation efforts. Director-General Florence Rabier and Daniel Gellens, then ECMWF Council President, announced that ECMWF had approved real-time access to forecasts for 25 countries in relevant geographical areas as part of the scheme. Those countries would be able to use the four-day forecasts with a grid spacing of 9 km as boundary conditions to initialise higher-resolution limited-area models.

Through panels and meetings organised by international partners and extensive media engagement, C3S and CAMS demonstrated how their Earth observation data and climate services could support the green transition; climate monitoring; national planning, policies and reporting; and the Global Stocktake. On behalf of the EC, the two services organised an event that was broadcast live from Brussels, in which speakers from different domains discussed how climate monitoring, adaptation and mitigation required collaboration across different sectors.

As well as speaking on machine learning, we presented our work in the EU Destination Earth initiative, which contributes to efforts to boost Europe's digital capabilities and the Green Deal actions on climate change.

◀ Real-time access to forecasts

The first set of countries receiving forecasts from ECMWF through the Systematic Observations Financing Facility (SOFF), located in Africa, Asia, Latin America, and the Pacific.

Impact

High-performance computing workshop

The 20th edition of the HPC workshop in October brought together over 140 people in Bologna, as well as 170 online registrants. It included 55 talks, 3 keynote talks from leading HPC specialists, plus an expert panel discussion and a tour of our data centre.

Predominant themes were realising the potential of HPC and artificial intelligence (AI), with rapid advances in machine learning techniques exploiting GPU technologies and the growth in cloud computing environments to tackle challenges associated with climate and weather prediction. Strong emphasis was placed on embracing the diversity of services and communities to realise the full research potential.

Using ECMWF's Forecasts (UEF)

Our forecast users convened in June at our headquarters for the annual UEF to learn about the latest developments in ECMWF products and services. The UEF2023 on the theme 'Ensemble forecasting' was the largest ever UEF, with 80 attendees in person and up to 80 online at any one time. Discussions provided useful feedback on ECMWF products and services. In addition to presentations and posters from invited speakers, ECMWF staff and users, interactive sessions included the User Voice Corner, a re-forecasting session, and ensemble discussions on 12 questions exploring forecasting, research, data and outreach.

▲ HPC workshop

Talks and the poster session took place at the San Domenico centre in Bologna.

Annual Seminar

About 100 scientists and students came together in September for the Annual Seminar on the topic of Earth system reanalysis, in Reading and livestreamed. It was aimed at early career scientists as well as more established scientists wishing to engage more with reanalysis and to learn about the history and state of the art of Earth system reanalysis activities. There were 32 presentations and 22 posters.

Reanalyses provide gapless fields of historical weather and climate, as well as of the land surface, ocean waves, the ocean, hydrology, and atmospheric composition. They are usually a blend of observations with short-range forecasts rerun with modern forecasting models. Reanalyses are very popular datasets that are used for a wide spectrum of applications.

Destination Earth User eXchanges

Two 'User eXchange' events were co-organised by ESA, EUMETSAT and ECMWF to share progress with the Destination Earth (DestinE) community and to listen to users' requests and feedback. Over 200 people from across Europe gathered for the 2nd Destination Earth User eXchange, which we hosted in Bonn, Germany, in November.

Presentations showed the main components of the future digital twin of the Earth system were taking shape and were soon to be assembled for the first tests. The event cemented these meetings as the forum for exchanges with DestinE stakeholders, building on the success of the first User eXchange in June.

> "Predominant themes at the HPC workshop were realising the potential of HPC and artificial intelligence (AI)."

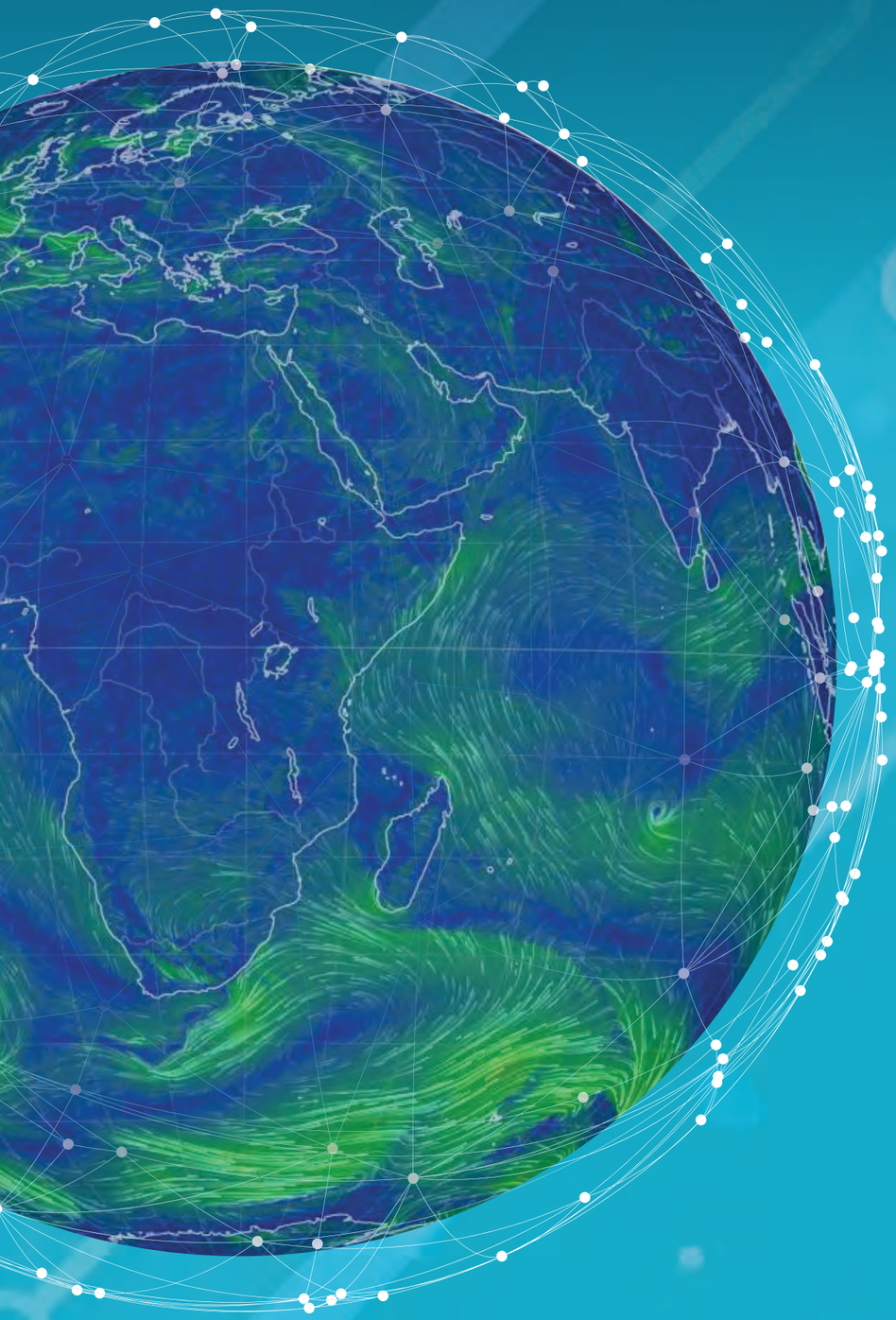
◀ Using ECMWF Forecasts (UEF)

Attendees at ECMWF's headquarters in Reading in June 2023.

◀ Destination Earth User eXchange

Over 200 people attended the 2nd DestinE User eXchange forum in Bonn.

MOOC on machine learning in weather and climate



9,026
Participants

159
Countries

60
Experts

40
Hours of content

47
Videos

15
Webinars

37
eLearning modules

1,147
Participants 1st webinar

1,235
Forum messages

6,021
Certificates

4.3/5
Satisfaction rate

The Massive Open Online Course (MOOC) on Machine Learning in Weather and Climate was the first MOOC carried out by ECMWF. It aimed to train a wider community on the impact and use of machine learning in numerical weather and climate predictions.

Sixty experts from ECMWF and other organisations contributed to the course materials. Pictured here are some of the ECMWF contributors; left to right: Matthew Chantry, Mariana Clare, Jesper Dramsch, Peter Düben, Siham El Garroussi.

The MOOC ran from 9 January to 30 April 2023 in partnership with the International Foundation on Big Data and Artificial Intelligence for Human Development (IFAB). It brought together experts throughout Member and Co-operating States and beyond to provide a shared vision across the communities of Earth system sciences, high-performance computing and machine learning.

The free online training course was accessible to a global audience. To maximise inclusivity, participants could follow one or more tiers and select optional modules within each tier according to their interests. To allow for self-paced learning, participants could complete at least four hours of study per week, for a total of at least 40 hours of training.

Tier 1, 'Machine Learning in Weather and Climate', was an introduction, aimed at anyone interested in the topic. Only a basic knowledge of weather and climate science, statistics and computing was assumed. The programme covered the use of machine learning across various themes, from the processing of observations to data assimilation, forecasting and post-processing.

Tier 2, 'Concepts of Machine Learning', delved into the technical aspects of machine learning. It was a lot more hands-on, including coding assignments using Jupyter notebooks in addition to eLearning modules covering the theory behind machine learning algorithms. This tier was more targeted to technical data users from academia or industry across different sectors.

The aim of tier 3, 'Practical Machine Learning applications in weather and climate', was to demonstrate how the techniques presented in tier 2 could be practically applied to real-world applications across the same topics introduced in tier 1. The end of the MOOC coincided with the application phase of ECMWF's Code for Earth programme, and participants were encouraged to submit proposals for coding projects with ECMWF mentoring and the chance to win a cash stipend.

More than 6,000 certificates were issued for completion of one or more tiers. After the live run had ended, the MOOC materials remained freely accessible in ECMWF's online eLearning resources. This was the first MOOC carried out by ECMWF and it established and cemented collaborations across the wider machine learning in weather and climate community. The interest generated by the initiative encouraged us to consider other topics for future MOOCs.

Organisation and people

In 2023, we continued to embrace our ‘OneECMWF’ culture across our three locations (UK, Germany and Italy) whilst building on the specificities of each duty station.

To create a sense of unity, we provided regular opportunities for staff to get together, socialise and network, in person or virtually, and major milestones were marked simultaneously across our three duty stations.

We launched ‘Life at ECMWF’, a set of online resources created to help new staff familiarise themselves with corporate services and processes such as procurement, event organisation, and contract management for EU-funded programmes.

In line with our four-year programme, we continued modernising our Human Resources functions, regulations and policies to align them with our strategic requirements, and to move from a heavily transactional model to an efficient business partnering model.

Various measures from our Diversity, Equality & Inclusion (DE&I) Action Plan were implemented, intended particularly to help support gender equality and encourage female job applicants, and create a more diverse, inclusive and flexible working environment. Provisions for paid and unpaid parental leave were updated to give staff greater choice in how they share parenting responsibilities as well as flexibility in when they take such leave. We also changed our recruitment policy to enable us to offer part-time and job-share positions.

We ran our first DE&I staff survey in October. The results will be used to prepare the next Action Plan and build a DE&I Network. This network will create opportunities for staff to share ideas and contribute to the action plan.

▲ Early Career Fellows

Katerina Anesiadou, Luise Schulte, Florentine Weber and Paolo Andreozzi (left to right) met in January at the DWD headquarters in Offenbach, Germany.

▲ Collaboration with academia

MSc Meteorology students from the University of Reading visited our headquarters, where they had the opportunity to meet scientists and understand more about the work we do.

Early in 2023, we welcomed four research graduates to be hosted by ECMWF for two years as part of the Early Career Fellowship Programme that we run in collaboration with the German meteorological service DWD and the Center for Earth System Observation and Computational Analysis (CESOC) at the Universities of Bonn and Cologne and the Forschungszentrum Jülich. The vacancies for this first cohort of fellows attracted applications from over 100 young scientists from ECMWF Member and Co-operating States.

Other measures to promote collaboration and teamworking across ECMWF and our Member States included work on a new ECMWF internship programme.

Three host countries, one ECMWF

In Reading, we continued to work with the UK Government on our new headquarters, which will be located on the campus of the University of Reading. The main contractor was appointed, and the design of the new building was presented to our staff in November. The completion and handover of the new building is projected to take place in June 2026.

Our current site will remain operational until all activities are transferred to the new site, in line with our decommissioning plan.

In Bonn, we worked with the German authorities to increase the capacity of our interim offices and accommodate a fast-growing team. The original layout was redesigned to include an additional floor. The new refurbished area will be completed early 2024. Work on our new facilities continued to progress, and the final design was presented to staff in October. The first stone will be laid in June 2024, with the building expected to be completed in April 2027.

In Bologna, our data centre is now in full operation with facilities spreading over three halls. A fourth hall is currently under development to become a state-of-the art conference centre. The project is led by the Emilia-Romagna regional authorities and scheduled to be completed in July 2024. This welcome addition to the Tecnopolo complex will provide us with new opportunities to host large events on site.

▲ Celebrating staff achievements and showcasing our work

Staff in Reading mark the successful forecasting system upgrade to IFS Cycle 48r1 (left); Bologna staff welcome a delegation from the Emilia-Romagna region and present our supercomputing facilities and operations (middle); and staff in Bonn present our Copernicus activities at ‘Europatag’, organised every year by the city of Bonn to showcase European initiatives (right).

Organisation and people

ECMWF staff

As an international organisation, we are proud of our multicultural environment. At the end of 2023, we had 475 members of staff from 35 different countries.

Number of staff by duty station:

- Reading 273
- Bonn 162
- Bologna 40

During the year, we hosted:

- 8 visiting scientists:
  - → 3 from the Japan Meteorological Agency (JMA)
  - → 1 from Deutscher Wetterdienst (DWD), Germany
  - → 1 from the Swiss Federal Institute of Technology Zurich/Swiss Federal Institute for Forest, Snow and Landscape Research WSL (ETH/WSL), Switzerland
  - → 1 from the University of Reading, UK
  - → 1 from the University of Freiburg, Germany
  - → 1 from the University of Maryland (UMD/CISESS), USA
- 3 EUMETSAT Fellows from the United Kingdom
- 1 WMO Fellow from the Maldives
- 3 graduate trainees from Ireland and the United Kingdom
- 4 DWD Early Career Fellows from Germany, Greece and Italy

Strengthening the 'One ECMWF' culture through sport

#OneECMWF

In Reading, every summer, our football tournament brings staff, family and friends of all ages together (top); in Bonn, our team joins the 'Firmenlauf' charity race (middle); and in Bologna, ECMWF is represented at the annual StraBologna all-inclusive event (bottom).

Investment in ECMWF

The 35 Member and Co-operating States of ECMWF are the principal source of finance for the Centre, with contributions totalling £62.5 million in 2023, representing a large proportion of the Centre's funding. External organisations supported both core research and the complementary goals of the centre with funding of £71.2 million. Revenue from sales of data and products provided additional income of just under £13.7 million, while other operating revenue totalled £9.4 million.

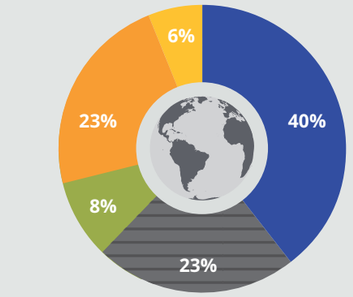
ECMWF continued to invest in its staff, infrastructure and systems to provide the highest quality products to its Member and Co-operating States. The main areas of expenditure, including capital investment of £8.5 million principally for IT and infrastructure, were as follows: remuneration and related items (£32.1 million), pension schemes (£13.7 million), computer expenses (£27.3 million), buildings (£11.1 million) and other operating activities (£4.9 million). Costs associated with externally funded projects amounted to £57.7 million and net finance costs were £10.5 million.

ECMWF's budget remains on a cash basis and the Financial Statements include a reconciliation of the results under IPSAS and in cash terms. Under cash accounting, the Centre generated a surplus of £5.9 million in 2023, which is available either for future investment or distribution to Member States according to a decision to be made by the Council in 2024.

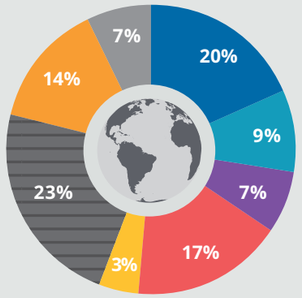
Note: all numbers exclude Centre tax.

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

Funding



Costs



Pilot projects to drive collaborative working

> Making effective operational use of non-standard IoT observing systems is hugely challenging. But we believe the potential benefits are equally significant and that the key to unlocking this potential lies in the development of autonomous machine-learned assimilation systems.

Tony McNally, Head of Earth System Assimilation, ECMWF

> Through our pilot project on adapting to emerging technologies, we are paving the way for national weather services to deploy data services using the polytope/FDB software stack, allowing efficient feature extraction from large hypercubes of operational numerical weather prediction data.

Carlos Osuna, Lead computing team in numerical development, MeteoSwiss

Background image: © monsitj/iStock/Getty Images Plus

Collaborative working is a founding principle of ECMWF and one of our key strengths. The concept of 'pilot projects' was established by our Council in December 2022 as a route to enhance collaboration on specific aspects of our work and share expertise with our Member and Co-operating States.

It is important that the benefits of any selected pilot projects should link to our Strategy and focus on areas where activities can be challenging to carry out in isolation. This is of particular value in activities where expertise and excellence within the Member States can complement our core competences. The overall aim is to provide benefits both to ECMWF and to all Member and Co-operating States.

Two pilot projects were initially agreed by the Council in December 2022: 'Internet of Things (IoT) observations for numerical weather prediction' and 'Adaptation to emerging technologies'.

Many countries expressed their interest in these pilots, so in March 2023, ECMWF organised two workshops to refine the scope of the projects and select lead organisations. An important aspect of the projects is the organisation of workshops and other knowledge dissemination events. By the end of the year, both projects were set up and ready to start.

The IoT pilot project, led by the EUMETNET network of 33 European national meteorological services, is an initial exploration of how data from non-traditional sources might be exploited. The focus includes data from private weather stations and smartphone pressure observations.

The project will first explore how such data are currently collected, managed, quality controlled and distributed. The quality of the data must be consistently high, which can be a challenge with new types of observations. If those issues can be successfully addressed, being able to tap into potentially vast amounts of data, particularly where more traditional observations are less available, could have huge benefits for weather forecasting and for verification. The project aims to build a test community-based platform to ingest, pre-process, format and make available the data.

The second project, led by MeteoSwiss, will look at adapting existing code to support Member States in making use of emerging technologies. This would allow them to modify their workflows to maximise opportunities arising from advances in high-performance computing processing and storage. It will explore the use of such technologies for data production and data sharing, while developing workflows that involve our supercomputing and European Weather Cloud resources. There will also be regular dialogue on scientific supercomputing and on merging adaptation strategies. Part of the project will be to explore funding opportunities to sustain these activities in the long term.

The project is being developed in parallel with the EU's Destination Earth initiative to create digital twins of the Earth system. Solutions and technologies built as a result of the research into developing Destination Earth will, through this project, become available to all our Member States.

At the end of 2023, the Council approved a third pilot project, on artificial intelligence and machine learning, recognised as a disruptive technology that requires new ways of collaborating. We will work with experts from the national meteorological services of Member and Co-operating States to co-develop and evaluate a range of machine learning approaches to global, regional and local modelling, with an emphasis on open development and knowledge sharing. The lead coordinators are Met Norway and MeteoSwiss, and the aim is to ensure that all the entities of the European Meteorological Infrastructure maximise the benefits from the activities in this rapidly evolving domain. There is particular emphasis on creating a supporting infrastructure and taking the machine learning developments into operations, along with the necessary training and support.

How we work

Council President

Daniel Gellens, Director of Royal Meteorological Institute of Belgium.

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 2023

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

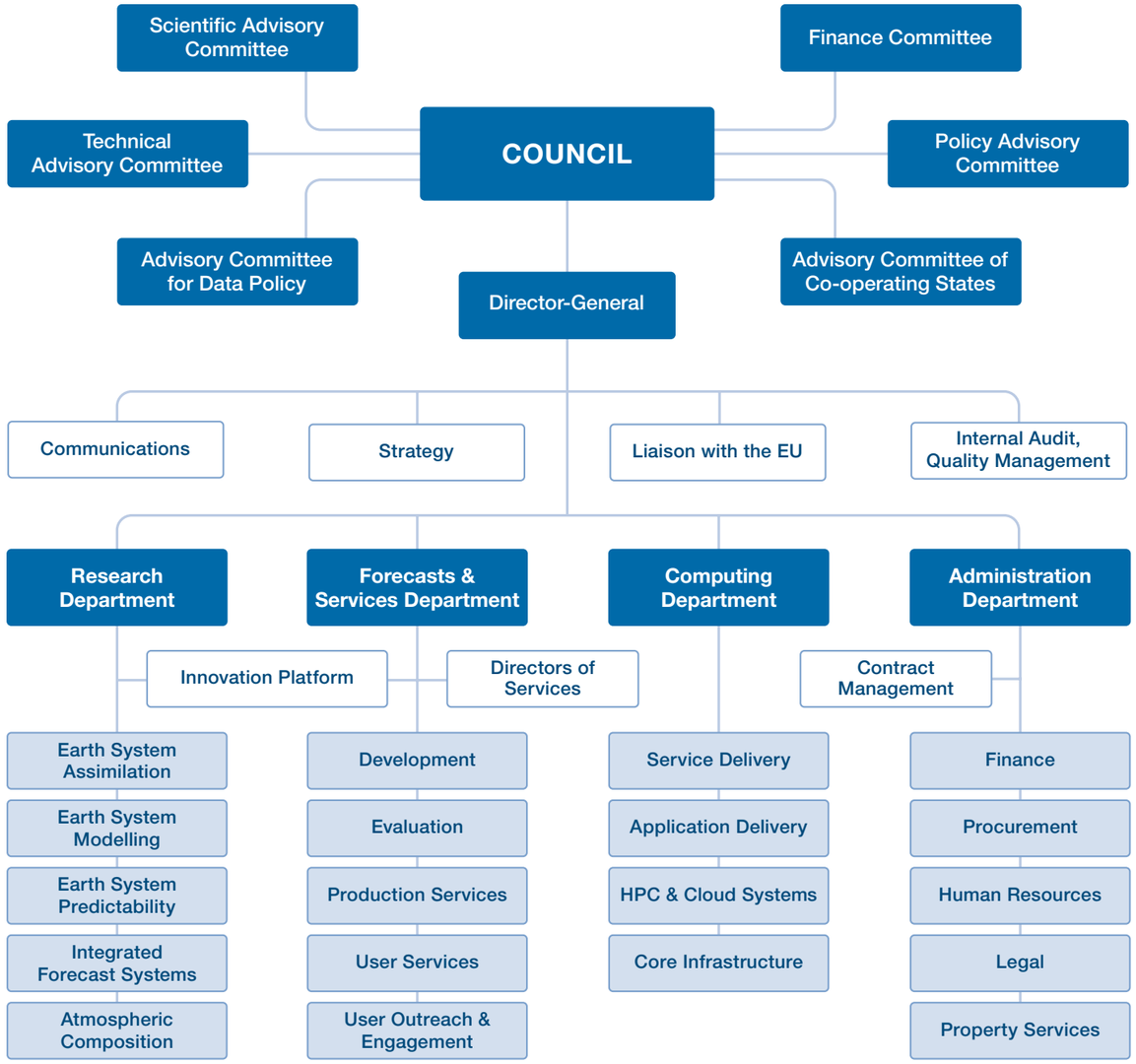
Technical Advisory Committee Chair:
Dr Sarah O'Reilly, Ireland

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

Advisory Committee for Data Policy Chair:
Lt. Col. Paolo Capizzi, Italy;
Ms Monika Koehler, Austria

Scientific Advisory Committee members and experts:

Prof. Dr Thomas Jung (Chair)
Dr Susanna Corti (Vice-Chair)
Dr Henk Eskes
Dr Christina Köpken-Watts
Prof Dr Nedjeljka Žagar
Dr Oliver Fuhrer
Prof. Simon Vosper
Prof. Dr Pier Siebesma
Prof. Gunilla Svensson
Dr Isabel Trigo
Dr Anthony Weaver
Dr François Bouyssel



▲ **Organisation of ECMWF in June 2024**

European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading, RG2 9AX, UK

Co-operating States as of January 2024

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

Reading, UK | Bologna, Italy | Bonn, Germany

www.ecmwf.int