ECMWF

European Centre for Medium-Range Weather Forecasts

ANNUAL REPORT 2022

www.ecmwf.int

Member States as of January 2023

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

Foreword

Scores in 2022 showed the full extent to which our last forecasting system upgrade in 2021 has impacted our predictions, with very positive results notably in upper-air ensemble scores.

© Stephen Shepherd

Florence Rabier
Director-General

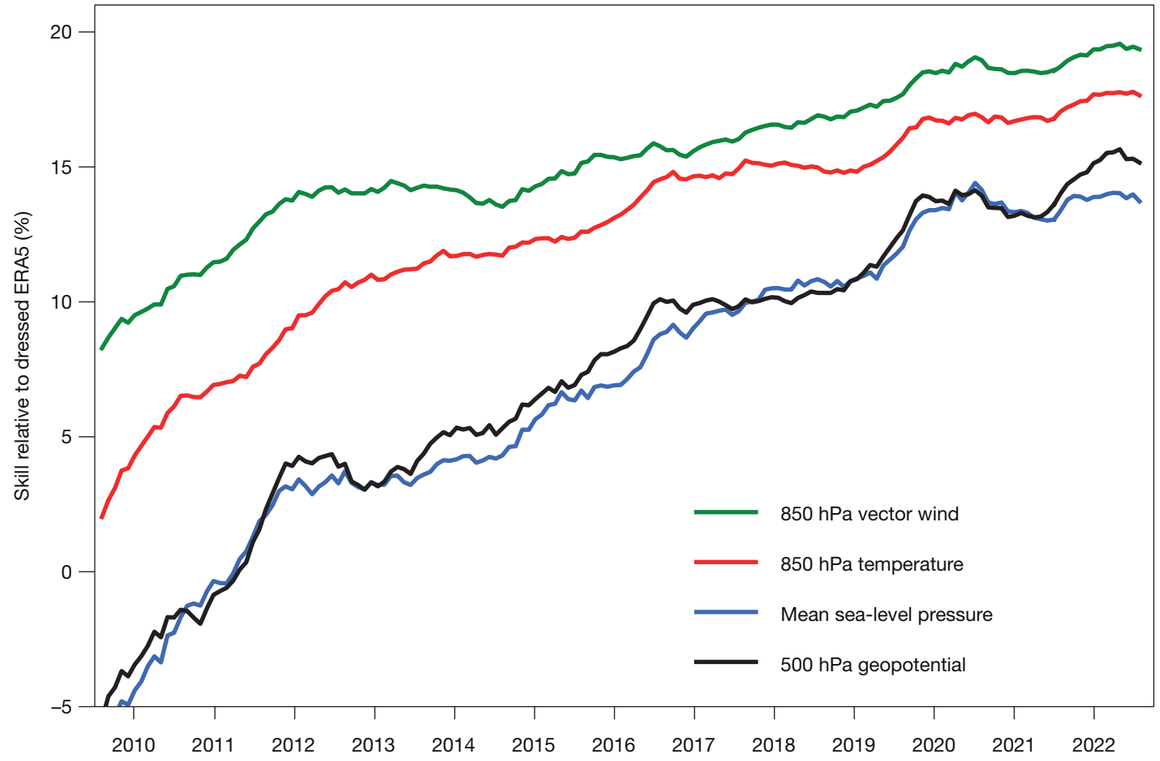
2022 was a completion year for us at ECMWF, when we saw several years of hard work in different fields bear fruit. It was the first full year operating as a multi-site organisation, with staff and systems in place in our three locations and with the Hosting Agreement with Germany formally signed in Berlin on 9 December. It was the year that we started to thoroughly reap the benefits of the changes introduced at ECMWF in the wake of COVID: more flexible working patterns with a generous teleworking policy enabling a better work-life harmony, and more sustainable and wider-ranging events, with all workshops and seminars being either livestreamed or fully hybrid.

2022 was also marked by more diversity in our recruitment, with more diverse pools of candidates showing interest in positions we advertised, leading to a more diverse workplace.

From a scientific perspective, it was the year when Cycle 48r1 was handed over from research to implementation, allowing scientists to focus on the next cycle of the Integrated Forecasting System (IFS). Towards the end of the year, on 18 October, we ran and disseminated our first operational forecast on the new Atos computing system, illustrating what our new technology could deliver.

2022 was also the year when results achieved through the implementation of our Machine Learning Roadmap clearly showed the potential that this technology can and will certainly have on numerical weather prediction.

2022 saw the formal launch by the European Commission of the EU-funded initiative Destination Earth, which ECMWF is jointly implementing with EUMETSAT and ESA.



ECMWF's role is to develop two digital twins – one on climate change adaptation and one on extreme weather – as well as the digital twin engine. This initiative is a great opportunity for collaboration not just with our partners at EUMETSAT and ESA, but also with our Member States. This is because the two largest tenders were awarded to a coalition led by Météo-France for the extremes twin and to one led by the CSC – IT Center for Science in Finland for the climate change twin.

From an operations perspective, scores in 2022 showed the full extent to which our previous IFS upgrade, Cycle 47r3, has impacted our predictions, with very positive results notably in our upper-air ensemble scores, as shown in the figure. Using the ERA5 reanalysis as a reference reduces the effect of interannual variability on scores and allows a more reliable quantification of performance changes due to individual model cycles.

A lot more happened in 2022, which you can see in the pages of this Annual Report. As usual, thanks go to our staff, whose dedication and talent never fail; our Member States, whose support and contribution are a constant reminder of the importance of working collaboratively; and of course all our partners, users, and delegates of our workshops and seminars – all of you from the meteorological community who are making it all not just possible but inspiring.

Florence Rabier, June 2023

▲ Upper-air skill of ENS relative to ERA5 reanalysis

Skill of the ensemble forecast (ENS) for upper-air parameters at day 5 in the northern extratropics, relative to a baseline ensemble created around ERA5 forecasts by a simple probabilistic approach. Values are running 12-month averages, and verification is performed against own analysis.

2022 At a glance

January

Open dataset released

In a further step towards making more forecast data publicly available, we released a new set of real-time data based on high-resolution and ensemble forecasts with a free and open data policy. The accompanying Jupyter Notebooks help users to build their own charts using the dataset, which was available directly from ECMWF as well as via Microsoft Azure. By the end of the year, our open numerical products were being accessed hundreds of thousands of times a day.

ERA5 climate reanalysis extended

We released a new segment of the ERA5 global climate reanalysis, extending the dataset back in time to include the period 1959–1978. Produced as part of the Copernicus Climate Change Service (C3S), which we operate on behalf of the European Commission (EC), ERA5 gives more than 100,000 registered users access to hourly data on many atmospheric, land-surface and sea-state parameters together with estimates of uncertainty from 1959 to the present. The production of an additional extension to 1940 was completed in October, to be released in 2023.

Copernicus Fire contract renewed

ECMWF was selected to continue providing the fire forecast data to the EU's Copernicus Emergency Management Service (CEMS) for the period 2022–2027, in collaboration with Météo-France. This includes operating and enhancing the fire danger forecast of the European Forest Fire Information System (EFFIS) and helping to develop the Global Wildfire Information System (GWIS). Fire forecasts support national authorities responsible for the management of forest fires in the EU and neighbouring countries and provide the EC and the European Parliament with reliable information on trends associated with these incidents.

Sarah-Jane Lock, ECMWF scientist, at the workshop on model uncertainty in May.

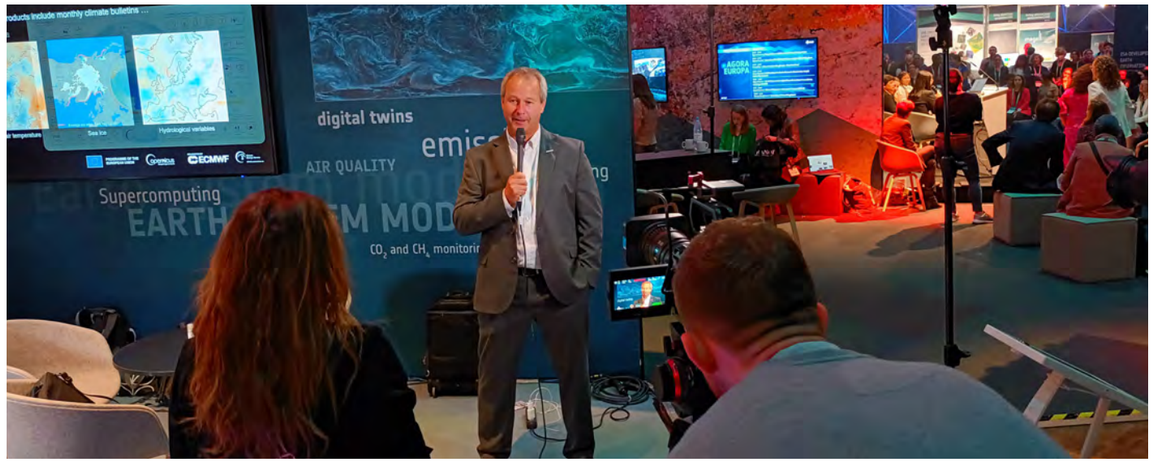
CAMS supports COVID-related air quality study

Following on from its work to support COVID-related research into weather, air quality and the spread of the pandemic, the Copernicus Atmosphere Monitoring Service (CAMS), with the London School of Hygiene & Tropical Medicine (LSHTM) and other leading institutions, published a study on the impact of lockdowns on air quality. It quantitatively evaluated the link between various lockdown measures and decreased pollution levels, and an associated drop in mortality, across 47 European cities in February–July 2020. CAMS is operated by ECMWF on behalf of the EC.

February

Workshop considers radio spectrum issues

Our workshop on radio frequency interference (RFI) attracted over 160 scientists from fields such as radio astronomy, meteorology, Earth remote sensing and spectrum management. The workshop series offers the opportunity for science users of the radio spectrum to share their experiences and discuss monitoring and possible mitigation strategies, as well as how best to influence the regulatory process.



Nils Wedi, Digital Technology Lead for Destination Earth at ECMWF, at the ESA Living Planet Symposium in May.

Storm Eunice hits north-west Europe

Mid-February was very cyclonic over north-western Europe, with three named storms affecting the area in one week. Cyclone Eunice was one of those; it delivered major wind-related impacts in many countries on 18 and 19 February. More than a week before the event, ECMWF ensemble forecasts predicted a risk for windier-than-normal conditions. The forecast from 12 February showed high Extreme Forecast Index (EFI) values over northern Europe six days ahead.

March

First operational services provided from Bologna

The Copernicus Data Service started running from our data centre in Bologna, supporting the Copernicus Climate and Atmosphere Data Stores on a new cloud infrastructure. At the time, the data stores were serving over 130,000 users, with close to 100 terabytes of data being downloaded daily.

Destination Earth initiative launched

Representatives of ESA, EUMETSAT, ECMWF and the EC came together virtually on 30 March to formally inaugurate Destination Earth (DestinE), an ambitious EU initiative to develop a highly accurate digital twin of our planet. ECMWF's role is to create the software and data environment needed to power the high-resolution digital twins (the digital twin engine) and to provide the first two digital twins.

Machine learning focus of two virtual workshops

Machine learning (ML) took centre stage at two virtual workshops. One focused on ML applications for numerical weather predictions and climate services. The second presented the work of the MAELSTROM project, a project funded by the European High-Performance Computing Joint Undertaking and coordinated by ECMWF. It provided a high-profile forum on the present and future of ML-based weather and climate forecasting in a high-performance computing context.

April

European climate report reviews 2021

C3S released its flagship publication, the European State of the Climate (ESOTC) report, providing a timely, transparent and detailed description of Earth's evolving climate. The report for 2021 showed a year of contrasts for Europe, which experienced its warmest summer on record, severe floods in western Europe, and heatwaves across the region, particularly in the Mediterranean. Globally, atmospheric concentrations of greenhouse gases continued to increase.

Handover ceremony held for new data centre

The premises of our new data centre in Bologna were officially handed over to ECMWF at a ceremony attended by Director-General Florence Rabier and representatives of the Emilia-Romagna region and the Italian Ministry of Foreign Affairs. The event provided an opportunity to showcase the close partnership between all involved.

In-person training courses return

After a two-year break, we returned to offering face-to-face training courses for our Member and Co-operating States. Alongside our established programme of meteorological and computing courses, a new course on machine learning proved popular.

May

Science showcased at European conferences

With the return of in-person international conferences, we shared our science at ESA's Living Planet Symposium and the General Assembly of the European Geosciences Union (EGU). Alongside updates from our regular research programme for medium-range weather prediction, we presented results from CAMS and C3S and our plans for the EU's Destination Earth initiative.

2022 At a glance

Experts discuss model uncertainty in weather forecasting

More than 100 online and 47 in-person participants attended our event on model uncertainty in weather forecasting. Model uncertainty is an important topic for ensemble forecasting, in which several slightly different forecasts are run to present the range of future weather possibilities. The outcomes of the event will feed into model development at ECMWF.

June

Forecasts benefit from Spire satellite data

We began using Spire satellite data operationally through a licence from EUMETSAT, after an extended test period in which a significant impact on forecasts was demonstrated. We anticipate an additional supply of Spire data purchased by NOAA in 2023, which is also expected to have a positive impact on ECMWF forecast quality.

User meeting focuses on visualising meteorological data

More than 40 people took part in person in Reading and up to 85 participated online at any one time in our Using ECMWF's Forecasts meeting (UEF2022), dedicated to the theme of visualising meteorological data. The meeting was followed by a hackathon exploring how weather and climate data could be visualised to be more useable, understandable and impactful for users and the broader public.

June/July/August

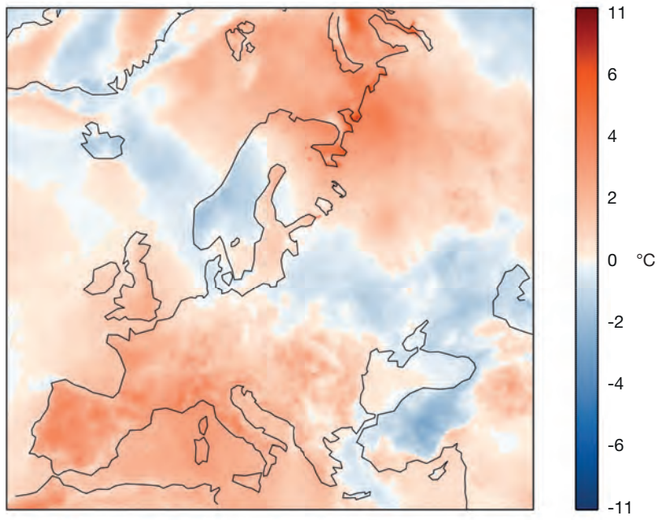
Europe experiences intense and prolonged heatwaves

During the summer of 2022, Europe saw several heatwaves and much drier conditions than normal in western Europe. Some temperature records were broken, including in France and the UK. In ECMWF forecasts, a signal for a warmer-than-normal summer was consistently present in 6-week forecasts from the extended-range system. CAMS forecast very high levels of surface ozone pollution across a large region of Europe as temperatures soared. CEMS repeatedly warned of increased fire danger due to the lack of rain and the resulting dry vegetation, combined with high temperatures.

August

WMO Fellow develops agriculture application for Africa

A meteorologist from Cameroon's National Department of Meteorology completed a 12-month WMO fellowship at ECMWF. He developed an application to support agriculture in Africa, based on ERA5 climate reanalysis data and climate projection data from the World Climate Research Programme's Coupled Model Intercomparison Project Phase 6 (CMIP6). The 'African Agroclimatic Indicators' application will provide long-term past and future climatic information required by agro-industries for their farming practices and crop yield projections and will help policy-makers.



(Data: ERA5. Reference period: 1991-2020. Credit: C3S/ECMWF)

PROGRAMME OF THE EUROPEAN UNION · Copernicus · IMPLEMENTED BY ECMWF · Climate Change Service

C3S map of temperature anomalies in Europe in July 2022.

Attendees at the Annual Seminar in September considered challenges in physics across forecast model resolutions and timescales.

September

Data Handling System move begins

The relocation of our meteorological archive and Data Handling System from the headquarters in Reading to the new data centre in Bologna started on 8 September. The relocation took just over two months, finishing on 11 November, with minimal disruption to operational, research and user activity. The total data volume transferred was 700 petabytes.

Annual Seminar focuses on seamless prediction

At our first in-person Annual Seminar in three years, over 100 scientists and students considered the large range of physical processes and scales that have to be represented in seamless weather prediction. The seminar was also followed daily by over 50 attendees on a livestream.

Coding programme produces open-source solutions

The 2022 edition of the ECMWF Summer of Weather Code (ESoWC) concluded with the presentation of six innovative open-source software solutions at the intersection of web development, software development, and applied data science. From 2023, the programme will be renamed Code for Earth.

October

SPARC General Assembly trials multi-hub format

The World Climate Research Programme SPARC project held its General Assembly across three 'hubs' for the Americas, Europe and Asia. The new format was designed to retain the face-to-face element and international collaboration while reducing the carbon footprint of the meeting. ECMWF was selected to host the European hub in Reading.

CESOC agreement fosters collaboration in Earth system science

We signed a memorandum of understanding with the Center for Earth System Observations and Computational analysis (CESOC), marking the start of a broad scientific collaboration between ECMWF and several German academic institutions.

First operational forecasts produced from Bologna

On 18 October, we started issuing operational forecasts from Italy using our new Atos high-performance computing facility. The high-performance computing services provided by the two Cray clusters at our headquarters in the UK finished at the end of October.

2022 At a glance

November

ECMWF participates at COP27 climate change conference

At the COP27 climate change conference in Sharm el-Sheik, Egypt, we made high-level interventions at the UN-led Earth Information Day and at events presenting the WMO Systematic Observations Financing Facility (SOFF) and the EU Destination Earth initiative. The Copernicus services run by ECMWF had a strong presence, with events highlighting the wealth of Earth observation data provided by CAMS and C3S, collaboration with the Union for the Mediterranean and the European Investment Bank, and the Copernicus contribution to a new CO_2 Monitoring and Verification Support Capacity.

SOFF pilot project to provide high-resolution real-time data

To support the implementation of the WMO Unified Data Policy, we agreed to provide a first set of countries selected by the SOFF with a high-resolution dataset in real time and with the operational support of the WIGOS Data Quality Monitoring System. Data provision will begin following a gap analysis to guide the next steps towards compliance with the Global Basic Observation Network minimum requirements.

Interest grows in machine learning in Earth sciences

We hosted the third in our series of joint workshops with ESA on machine learning for Earth observation and prediction, with about 120 participants on site in Reading and about 700 registered for online participation. It was apparent that increasingly sophisticated ML techniques had further spread into research and operational practice in the Earth sciences and were being tailored to this specific domain with compelling results.

Photographer: Stefano Marzoli

Michele Toni, Senior Site Engineer, at ECMWF's Atos high-performance computing facility in Bologna.

High-resolution hydrological data released

A new, substantially upgraded hydrological reanalysis dataset of the Global Flood Awareness System (GloFAS) from 1980 to July 2022 was produced by the Joint Research Centre of the EC in collaboration with ECMWF and released as part of CEMS. It is available in the Copernicus Climate Data Store and includes daily maps of discharge over the globe at a resolution of 0.05 degrees (about 5 km).

December

Thirty years of ensemble forecasting

The first operational medium-range ensemble forecasts were introduced at ECMWF in 1992 and have since transformed the way weather forecasts and their uncertainties are understood, communicated and used. Events and information marked the anniversary and the significance of ensemble forecasts.

Council appoints new scientific advisers

Dr Oliver Fuhrer from the Federal Office of Meteorology and Climatology (MeteoSwiss), Prof. Simon Vosper from the Met Office and Prof. Dr Nedjeljka Žagar from the University of Hamburg were elected as members of the ECMWF Scientific Advisory Committee.

New satellite to benefit meteorology

EUMETSAT launched a new geostationary satellite, MTG-I1, carrying two instruments of particular importance for meteorology: the Flexible Combined Imager (FCI), which provides images in the infrared and visible part of the spectrum, and the Lightning Imager (LI), which is a new instrument observing lightning flashes and their intensity. At ECMWF, preparatory work to develop an assimilation architecture, using data from similar existing instruments on GOES satellites, is expected to lead to an early and effective operational exploitation of the new satellite.

© EUMETSAT, using 3D models from ESA

EUMETSAT's MTG-I1 satellite launched in December.

CAMS monitors third unusual ozone hole in a row

Similarly to what was observed in the previous two years, monitoring data from CAMS showed the 2022 Antarctic ozone hole closed much later than those of the previous 40 years and was one of the 15 largest in the CAMS record dating back to 1979. While this needs to be investigated further in the context of a changing climate, the variability seen in recent years is thought to be largely dynamically driven, and it does not challenge the eventual recovery of the ozone layer in the 2060s as that is determined by the already observed declining amount of ozone-depleting substances in the stratosphere.

CO_2 emissions monitoring prototype on track

The CoCO2 EU-funded research project coordinated by ECMWF presented progress towards creating a prototype system to monitor anthropogenic CO_2 emissions worldwide. The project's wide-ranging work includes data sources, vegetation models, transport models, and data assimilation methods, and will feed into the anthropogenic greenhouse gas emissions Monitoring and Verification Support Capacity (CO2MVS) being developed as part of CAMS.

Europe records second-warmest year on record

The year 2022 was the second warmest on record in Europe, and the summer was the hottest in Europe, according to data released by C3S in January 2023. Persistent low levels of European rainfall, in combination with high temperatures and other factors, led to widespread drought conditions. Atmospheric carbon dioxide concentrations increased at a similar rate to recent years, while methane concentrations increased more than average.

Machine learning in numerical weather prediction

> 2022 saw incredible progress in machine learning both inside and outside of weather forecasting. The coming years will see a revolution as we find the optimal combination of NWP models and machine learning.

Matthew Chantry, machine learning scientist and member of ECMWF's machine learning coordination team

Collaborative events are an important part of ECMWF's machine learning activities. The third joint ECMWF-ESA Workshop on Machine Learning for Earth Observation and Prediction took place in Reading from 14 to 17 November 2022.

The year saw progress at ECMWF towards operational use of machine learning tools and external developments that could mark a shift in thinking.

As data volumes grow, and the demands for energy-efficient computing become ever greater, machine learning has a key role to play in numerical weather prediction (NWP), and in Earth system modelling and prediction more generally.

Machine learning (ML) is one branch of artificial intelligence (AI) where computer algorithms can be trained to reproduce patterns within large amounts of data and so represent complex processes, such as those within the Earth system. With applications much wider than just NWP, AI is a field where new developments are emerging almost daily.

Recognising the opportunities, but also the challenges involved, ECMWF launched a ten-year Roadmap in 2021 which set out a path towards the integration of ML into NWP and environmental services. In 2022, we transitioned to a three-person ML coordination team, with members from across the organisation, to take activities forward.

A huge amount of progress has already been made in exploring and developing ML techniques that could play a role in the NWP workflow, such as the data assimilation process and the model physics.

In 2022 we moved closer to bringing ML systems into our operational forecasts. For example, a new ML-based technique which improves the identification of errors in observations will become operational in 2023.

While not yet operational, there were also further successes in using neural networks to emulate Earth system model components, by training them with input/output data from conventional physically-based code.

The radiation scheme from the Integrated Forecasting System (IFS) was successfully emulated as part of MAELSTROM, a European High-Performance Computing Joint Undertaking project. Using the graphical processing unit (GPU) nodes in ECMWF's Atos HPC facility and running decoupled from the IFS, the emulator is around 60 times faster than the conventional solver run on central processing units (CPUs).

Work was then extended to emulate three-dimensional cloud effects in the radiation scheme – something that is currently too computationally expensive to incorporate within operational predictions.

Another pillar of the ML Roadmap is ECMWF's leading role in helping to build the knowledge and skills needed within NWP communities in our Member and Co-operating States and more widely, through training, events and the sharing of relevant datasets.

2022 saw the development of a Massive Open Online Course (MOOC) on Machine Learning in Weather and Climate, produced with the International Foundation on Big Data and Artificial Intelligence for Human Development (IFAB), and with contributions from a wide range of experts.

Developments in ML are also key for our contribution to the EU Destination Earth Initiative (DestinE), in which ECMWF is working alongside EUMETSAT and ESA. The use of ML is being explored for the post-processing of the output of digital twin simulations and in particular for developing techniques to quantify the uncertainties of the kilometre-scale simulations.

Within the wider AI community, there were very significant developments. Making use of ECMWF's publicly available ERA5 reanalysis dataset, groups at Google, NVIDIA and Huawei each produced pure machine-learning weather forecasting models which, for the first time, were comparable in quality to the IFS.

Their experiments did not include the data assimilation part of the NWP process, and forecasts were performed for only a small sample of years, but nonetheless, these were landmark results, and they will encourage further exploration of weather forecasting based entirely on machine learning models.

We are considering the implications and formulating recommendations for our machine learning plans going forward. 2023 promises to be a particularly exciting year.

Science and technology

The year saw much progress in science and technology at the Centre. On the scientific front, an upgrade of the Integrated Forecasting System (IFS) to Cycle 48r1 was prepared for implementation in 2023. This will be the first upgrade on the new high-performance computing facility (HPCF) in Bologna, Italy. It will increase the horizontal resolution of our ensemble forecasts from 18 km to 9 km, the current resolution of our single high-resolution forecast.

Among many other changes, the upgrade will also revise the extended-range configuration from twice-weekly to daily production and from 51 to 101 ensemble members. To help prepare optimal initial conditions of weather forecasts by means of data assimilation, one change in Cycle 48r1 will be the addition of surface-sensitive microwave imager channels over land surfaces.

Research on even finer resolutions in global weather forecasting found that increasing the horizontal resolution of the atmosphere from 9 km in the operational IFS to 4.5 and 1.4 km markedly improves predictions of tropical cyclone intensity. Experimental use of a higher-resolution ocean model revealed for the first time sea ice cracks developing in the Arctic, with repercussions on cloud cover and two-metre temperature.

Monitoring visible radiances by satellites for information on clouds was explored, showing potential benefits for data assimilation. Progress was made in preparing a new record of land cover and vegetation observations for the benefit of reanalysis and seasonal-to-decadal prediction systems. The Ensemble of Data Assimilations was used to show that it would be beneficial to have more passive microwave sounding observations. And progress was made in estimating sea-surface temperature inside ECMWF's coupled atmosphere–ocean data assimilation system.

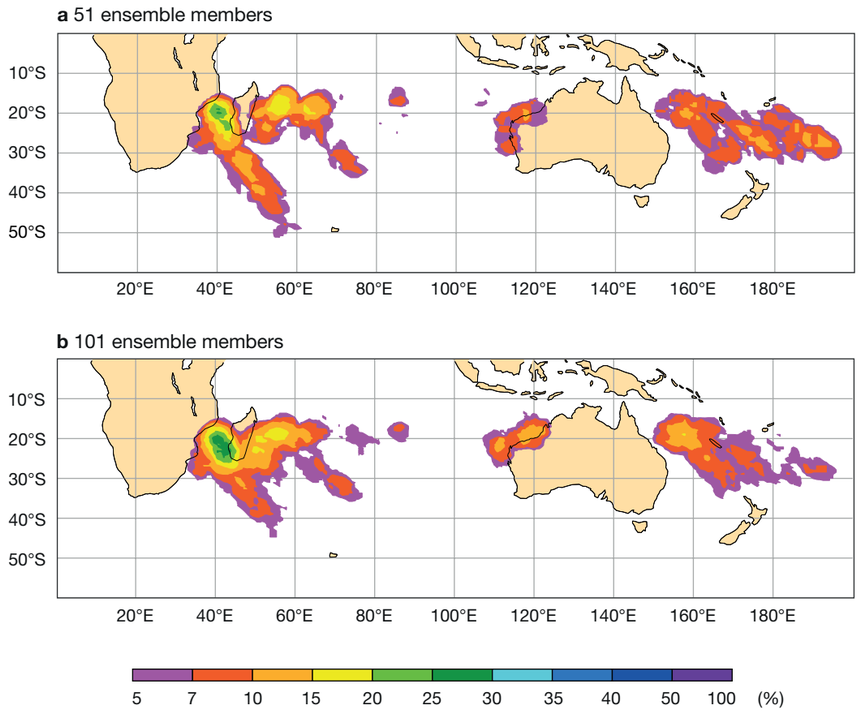
Over the course of 2022, ECMWF was successful in adding 30 externally funded projects to its portfolio. Three of these are projects we coordinate. They will ultimately lead to improvements of the EU-funded Copernicus Climate Change Service (C3S) and Copernicus Atmosphere Monitoring Service (CAMS) we provide.

Scientific advances were supported by progress in the technological field. In particular, we started to produce our forecasts on the new Atos HPCF in Bologna in October 2022. As early as March 2022, the Copernicus Climate and Atmosphere Data Stores (CDS/ADS) run by ECMWF were successfully migrated from Reading to new cloud infrastructure installed in the Bologna data centre.

The IFS was also tested on the world's most powerful supercomputer in mid-2022, Fugaku, at a global resolution of just 4 km, and ECMWF started to make some of the IFS available on an open-source basis to facilitate collaboration on the code. Finally, we developed a new Software Strategy in 2022.

More developments regarding technology, such as progress in machine learning, preparations for the use of future computing architectures, the move of the Data Handling System to Bologna, and the launch of ECMWF's participation in the EU's Destination Earth initiative, are presented in separate sections.

"We started to produce our forecasts on the new Atos HPCF in Bologna in October 2022. As early as March 2022, the Copernicus Climate and Atmosphere Data Stores were successfully migrated from Reading to the Bologna data centre."



◀ Tropical storm strike probability with a 51-member and a 101-member ensemble

Tropical storm strike probability maps for week 4 for the extended-range forecast starting on 7 January 2021, showing (a) the strike probability produced with a 51-member ensemble and (b) the strike probability produced with a 101-member ensemble, both in the real-time forecast configuration. The 101-member ensemble forecast displays higher probabilities of a tropical cyclone strike over the Mozambique Channel and west and northeast of Australia than the 51-member ensemble. It also shows lower probabilities east of 180°E. In the event, tropical cyclones did strike in the first three locations and did not strike in the fourth.

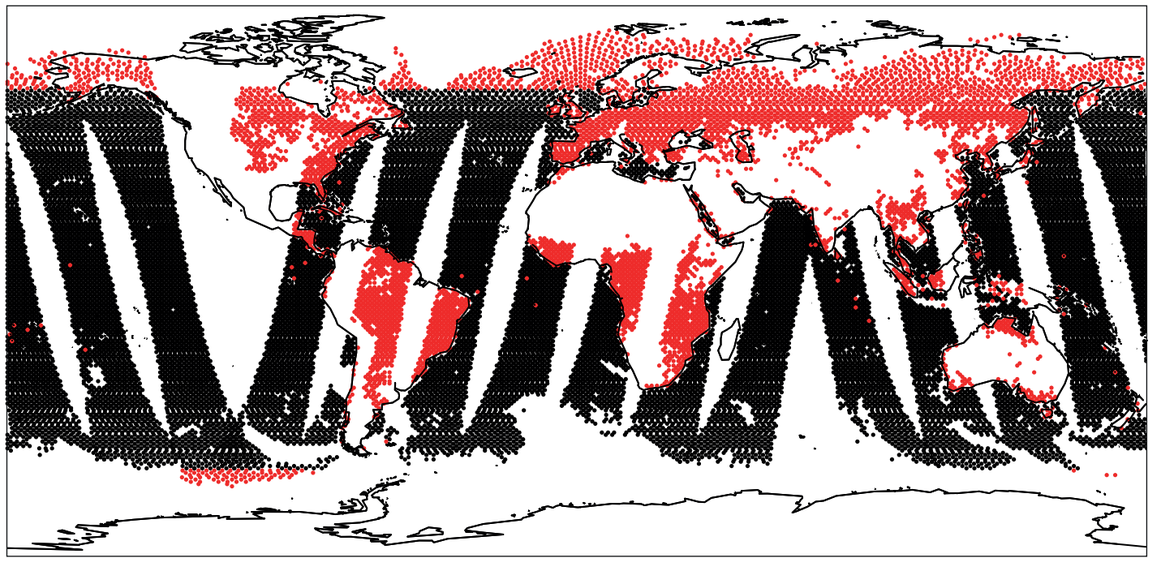
Revising the extended-range configuration

Extended-range forecasts are predictions beyond two weeks but less than a season. In 2022, they were produced at ECMWF as 46-day integrations issued every Monday and Thursday at 00 UTC. They were made up of a 51-member ensemble at a horizontal resolution of about 18 km up to day 15 and about 36 km beyond that.

The availability of the new Atos HPCF in Bologna provided an opportunity to enhance the extended-range forecasting system. From IFS Cycle 48r1, to be introduced in 2023, extended-range forecasts will be produced daily instead of twice weekly, and they will have 101 ensemble members instead of 51. They will be run separately from higher-resolution medium-range forecasts at a horizontal resolution of about 36 km from day 0 to 46.

This will significantly increase the quality of extended-range forecasts for days of the week other than Monday and Thursday. Moreover, doubling the ensemble size to 101 members will provide a more accurate representation of the forecast probability distribution function. In particular, this will ensure a more accurate prediction of the tail of that function, which is important for a more accurate prediction of the probability of extreme events.

Science and technology



All-surface capability for all-sky satellite observations

We make extensive use of satellite observations to help establish the initial conditions for our forecasts. We have recently made progress towards an 'all-surface' use of satellite microwave observations. Some of these observations will be included in IFS Cycle 48r1 to be introduced in 2023.

A lot of data from surface-sensitive microwave channels has previously been screened out due to surface types that are hard to simulate. These surface types include land, snow, sea ice and mixtures of all surface types. In some channels, the new developments increase the number of observations being assimilated into the forecasting system by around 30%.

One change in Cycle 48r1 will be the addition of surface-sensitive microwave imager channels over land surfaces. This is a first in global weather forecasting. It depends on having a well-developed 'all-sky' assimilation framework, in which satellite data are used in areas of cloud and precipitation rather than just in clear-sky areas.

The figure illustrates expected improvements in observational coverage in Cycle 48r1 compared to the current Cycle 47r3. It uses the example of a microwave imager channel from the AMSR2 sensor. The figure shows big additions in coverage over land surfaces. It also reveals that in Cycle 48r1 it is still too difficult to use such observations over sea ice, snow, desert or high-altitude surfaces. However, we expect to see these surface types included in the near future – for example, sea ice is expected to be included in Cycle 49r1.

▲ New observations assimilated

The chart shows the coverage of observations to be assimilated in Cycle 48r1 from the Advanced Microwave Scanning Radiometer – 2 (AMSR2) in channel 11, with black dots indicating data assimilated in Cycle 47r3 and red dots the data added in Cycle 48r1. Data are for the 00 UTC cycle on 20 June 2019.

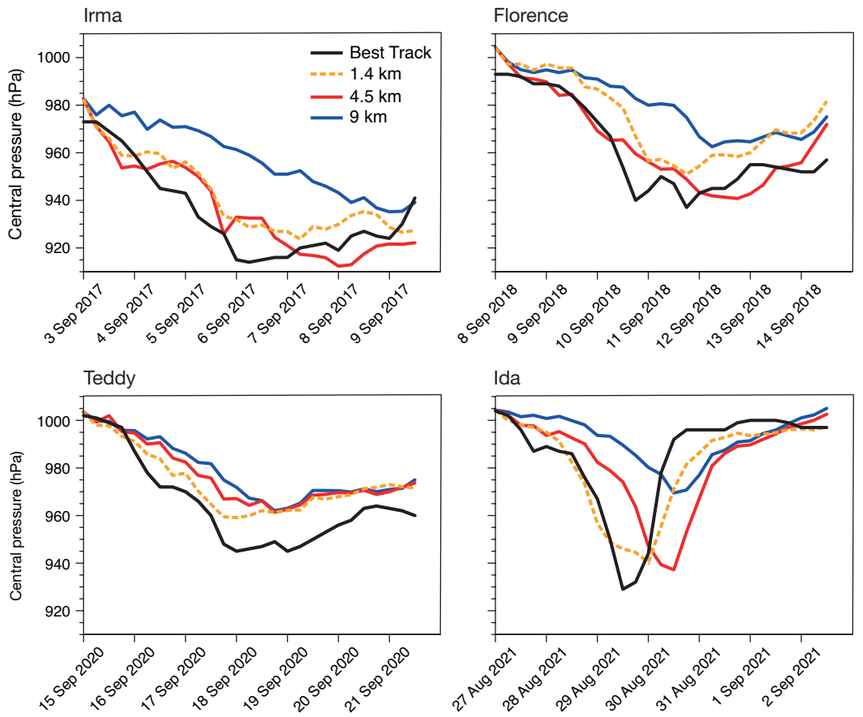
Predicting tropical cyclones at greater resolution

Simulations showed that increasing the horizontal resolution of the atmosphere from 9 km in the operational IFS to 4.5 and 1.4 km markedly improves predictions of tropical cyclone intensity. It also improves the ocean response to the passing of a tropical cyclone. The simulations were carried out as part of the INCITE 2022 project awarded to ECMWF and US Oak Ridge National Laboratory scientists.

Extreme tropical cyclones Irma (September 2017), Florence (September 2018), Teddy (September 2020) and Ida (August 2021) were chosen for the investigation.

The figure shows that the tropical cyclones are more intense at higher horizontal resolution and in better agreement with observations (Best Track data). This is a result of the fact that tropical cyclones require high spatial resolution to be represented accurately. It was found that the benefit of increased horizontal resolution can already be achieved at 4.5 km.

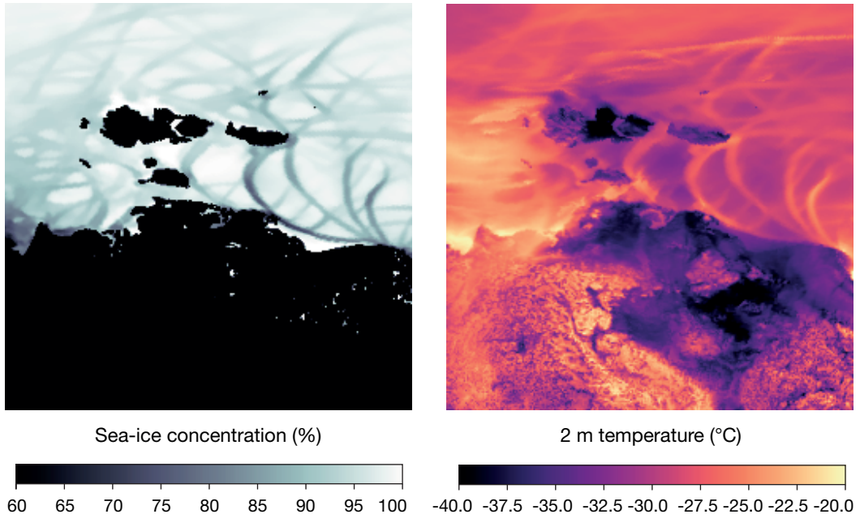
In addition, it was found that sea-surface temperature during a tropical cyclone is better represented if a higher atmospheric resolution and a higher ocean resolution are used. An accurate representation of sea-surface temperature is important because it may influence the intensity of the tropical cyclone.



◀ Central pressure forecasts for tropical cyclones

The charts show central pressure forecasts up to 6 days ahead for tropical cyclones Irma, Florence, Teddy and Ida at different horizontal resolutions of the atmosphere, and Best Track observations. The ocean resolution is 1/12 degree. The 9 km forecast is currently operational at ECMWF. The higher-resolution forecasts are better able to forecast tropical cyclone intensity.

Science and technology



◀ Effects of changes in sea ice on the atmosphere

Sea-ice concentration and two-metre temperature around the New Siberian Islands in the Arctic Ocean in the IFS at a resolution of 2.8 km, coupled to a FESOM sea-ice/ocean model at a resolution of 4 to 5 km in the Arctic. The panels show the results of simulations for 13 February 2020 at 08 UTC.

Predicting sea ice at greater resolution

Increasing the horizontal resolution of forecasting models makes it possible to resolve more processes at smaller spatial scales and ultimately improve forecast skill, but conservation properties of models can also have such an impact. As part of the EU-funded Horizon 2020 project nextGEMS, we thus looked into modelling small-scale sea-ice cracks and fixing water and energy budget imbalances.

The operational IFS currently uses the NEMO ocean model at 1/4 degree resolution (about 25 km at the equator). For nextGEMS experiments, the IFS was coupled to the multi-resolution FESOM sea-ice/ocean model. This was run at a resolution of about 4–5 km in mid- and high latitudes.

In this high-resolution model of the ocean and sea ice, sea-ice cracks develop in the Arctic. The atmosphere responds to the exposed warm waters within sea-ice cracks through changes in evaporation rates, cloud cover, and two-metre temperature. Such sea-ice-related imprints on the atmosphere have not previously been considered in global Earth system models, such as the IFS.

We also significantly improved the conservation of water and energy in the IFS as part of work that was triggered by the nextGEMS project. The multi-year simulations performed in the project had shown that water and energy imbalances became considerably worse at km-scale resolutions. Ensuring global water conservation now improves the quality even of our medium-range weather forecasts at a resolution of 9 km.

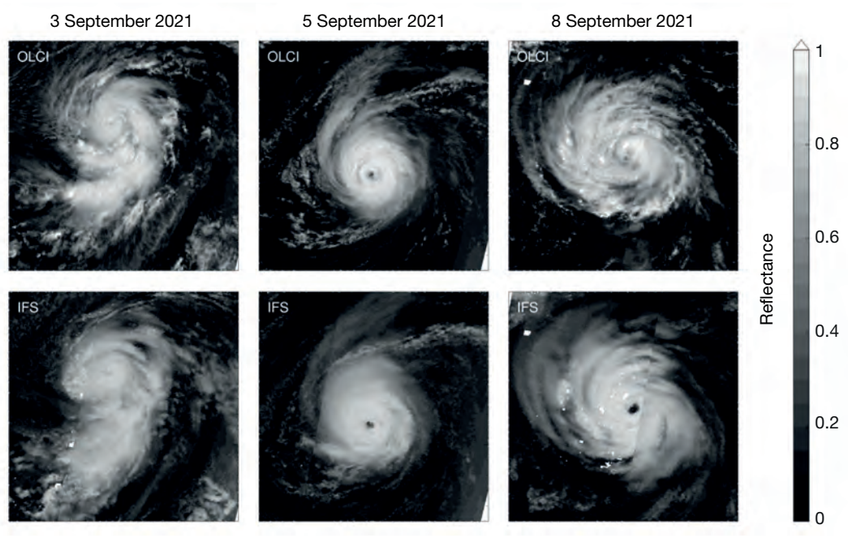
> “Such sea-ice-related imprints on the atmosphere have not previously been considered in global Earth system models.”

Monitoring cloudy visible radiances

Visible radiances monitored by satellites contain a wealth of information on clouds. However, they have never been assimilated to help establish the initial conditions of forecasts in global numerical weather prediction models. This is due to the complex scattering of light.

We performed experiments to see whether cloudy visible radiances can be used in the IFS. Due to the complexities of the scattering of visible radiation from land and ice surfaces, only data over ice-free oceans were used. Data were obtained from the Ocean and Land Colour Imager (OLCI) instruments, OLCI-A and OLCI-B, which are aboard the Sentinel-3A and Sentinel 3B satellites, respectively.

These data were compared to IFS predictions of spectral radiances, which were converted into reflectances. The images show some of the results of the comparison. The experiments performed in 2022 reveal the potential benefits of visible data assimilation. It could provide information ranging from the large scale, such as highlighting where regions of frontal clouds are located, to the smaller scale, such as revealing the structure of hurricanes or convective cells.



◀ Observed and predicted reflectances of Hurricane Larry on three separate days

The top row shows reflectances from the OLCI observations, while the bottom row shows short-term IFS predictions. Each panel covers 15° in latitude and longitude.

Science and technology

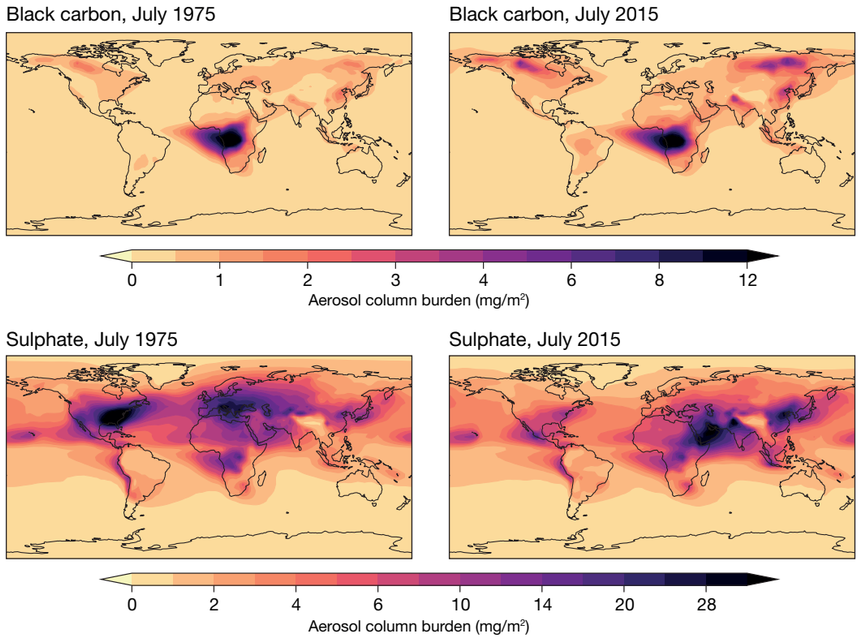
Improving reanalyses and seasonal forecasts

ECMWF coordinates a European Horizon 2020 research project, CONFESS, that aims to improve climate reanalyses and seasonal forecasts by updating land and aerosol properties. CONFESS will evolve the capabilities of the EU-funded Copernicus Climate Change Service (C3S), run by ECMWF, to monitor and predict extreme events and represent climate trends. It is set to end in 2023.

In 2022, this project made progress in preparing a new record of land cover and vegetation observations. This is important to properly constrain the land surface models included in current reanalysis and seasonal-to-decadal prediction systems.

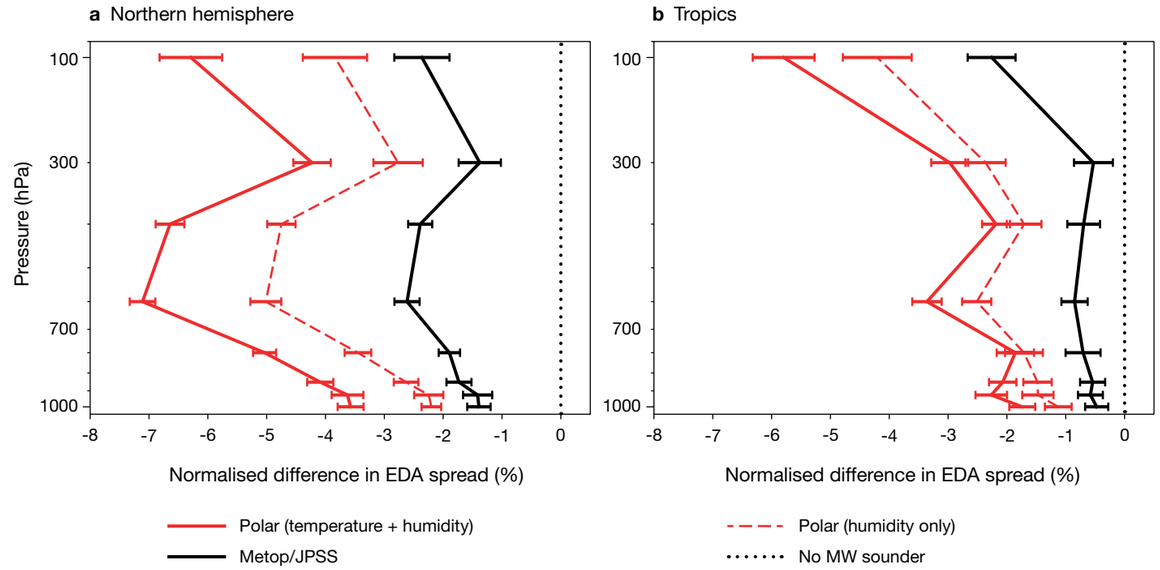
In particular, ECMWF produced a harmonised temporal record spanning the period 1993–2019 of Land Cover, Land Use and Leaf Area Index by merging records from C3S and the Copernicus Global Land Services.

CONFESS also produced a homogenous and consistent multi-decadal record of tropospheric aerosols. To do this, it exploited the atmospheric composition capabilities that the EU-funded Copernicus Atmosphere Monitoring Service (CAMS) has introduced into ECMWF's IFS. This was done in preparation for ECMWF's next reanalysis, ERA6, and its next seasonal forecasting system, SEAS6. Having an up-to-date aerosol climatology that is consistent with the latest CAMS aerosols will also help to benchmark the impact of interactive aerosols on numerical weather prediction.



◀ Change in tropospheric aerosol between 1975 and 2015

The figure shows the change in vertically integrated black carbon (top) and sulphate (bottom) between July 1975 (left) and July 2015 (right). The effects of increased forest fires at high latitudes, pollution controls in Europe and North America, and the growth of emissions in India and the Middle East are all visible. Sulphate aerosols over China have peaked and are now declining.



Forecast impact of future observing systems

ECMWF's weather predictions rely on global weather observations to help determine the initial conditions of forecasts. A key question for the evolution of the global observing system is how much benefit we expect from new observing capabilities. One of the tools to investigate this is the Ensemble of Data Assimilations (EDA). The EDA estimates in a statistical sense the expected reduction of uncertainty in the forecast from adding observations to our forecast system.

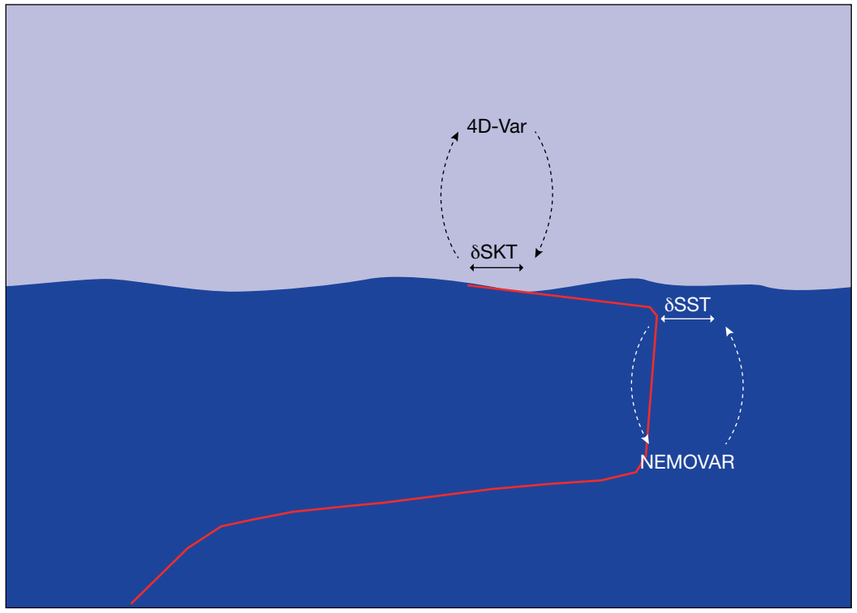
The EDA has been used to assess the value of more passive microwave (MW) sounding observations. Currently, MW sounders are flown on a few large satellites. Results from the EDA experimentation show a clear continued benefit from adding further MW sounders.

An illustration of this is provided by the figure. It shows the reduction in short-range ensemble forecast spread of two constellations of eight hypothetical MW satellites (Polar) compared to the four existing MW sounders (Metop/JPSS) and a constellation without any MW sounders. The figure shows a very clear benefit of having temperature and humidity sounding channels available for the additional MW sounders.

▲ Impact of additional MW satellites

Impact on short-range wind forecasts from the 'Polar' constellation (red), with humidity sounding and window channels only (dashed) and with temperature channels added (solid line), and the 'Metop/JPSS' baseline (black), relative to a 'no MW sounder' EDA experiment. Data are over (a) the northern hemisphere extratropics and (b) the tropics, for the period 8–28 June 2018.

Science and technology



Ocean temperature schematic

The schematic shows how ocean temperature can vary from the subsurface to the surface skin that is measured by satellites. An assumption in RADSST is that any mismatches between the parametrization of temperature in the surface skin (SKT) and the values sensed by radiance observations is attributed to an error of the same magnitude in the bulk water temperature below (SST).

Coupled sea-surface temperature analysis

An accurate knowledge of the ocean has a profound impact on our ability to forecast the weather over a variety of timescales. In particular, the sea-surface temperature (SST) needs to be determined extremely accurately to make successful forecasts. In 2022, we made progress towards a new way of determining SST.

Currently SST fields are produced by blending satellite information with in-situ ocean observations from ships and buoys. This depends on assumptions about how significantly the composition of the atmosphere has affected satellite radiation measurements, and on crude persistence assumptions when there are no observations at all.

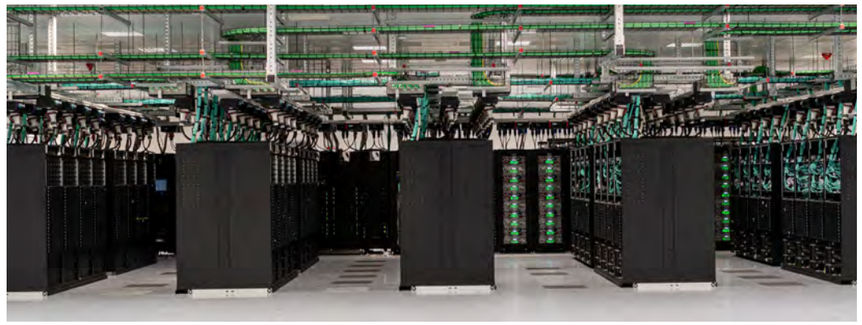
These challenges prompted us to investigate the possibility of estimating SST inside our coupled atmosphere–ocean data assimilation system. That system combines all the latest observations with a short-range forecast constrained by previous observations to obtain the best possible estimate of the current state of the Earth system. It uses atmospheric 4D-Var data assimilation and ocean NEMOVAR data assimilation. A new system that has been developed to estimate SST is called RADSST.

New high-performance computing facility

Up until the end of October 2022, the two Cray XC40 supercomputing clusters in Reading, UK, continued to provide a good and stable service. On 18 October, our new high-performance computing facility (HPCF) in Bologna, Italy, comprising four Atos BullSequana XH2000 complexes, started to be used for operational production while acceptance was still ongoing. The move marked an important milestone in the BOND (Bologna Our New Data Centre) programme.

IFS Cycle 47r3 was successfully migrated to the new system after extensive testing demonstrated that the facility could provide a platform for current time-critical forecast production. Meanwhile, Atos continued to improve the HPCF's performance and stability. With over 1,000,000 cores in the new facility, 25% of the supercomputing capacity is dedicated to Member States, of which up to 10% is reserved for Special Projects. The new HPCF will significantly increase the resources for these activities.

In addition to the standard 'compute nodes' for parallel jobs, each of the four complexes of the new HPCF has 'GPIL (general purpose and interactive login) nodes' for general purpose and interactive workloads. Also, one of the complexes includes a number of NVIDIA GPUs to support application development on accelerators.



ECMWF's new HPCF

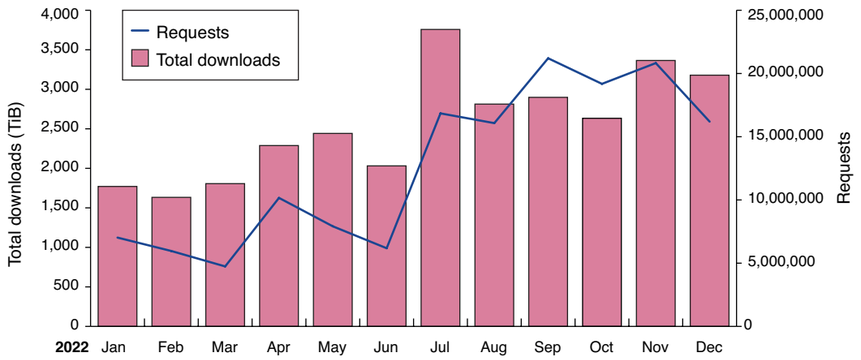
The Atos high-performance computing facility in ECMWF's new data centre in Bologna, Italy.

Climate and Atmosphere Data Stores migrated

In March 2022, the Copernicus Climate and Atmosphere Data Stores (CDS/ADS) run by ECMWF were successfully migrated from Reading to new cloud infrastructure installed in the Bologna data centre. This required careful planning and close collaboration, both with external contractors and between teams across ECMWF.

On the day of migration, the impact on users was kept to a minimum with a downtime of only five hours. After migration, the CDS/ADS performed well. The existing equipment in Reading was decommissioned and reconditioned. It was installed in Bologna at the end of June to further enhance the capacity of the data stores' infrastructure.

Genetic algorithms (GAs) were deployed to tune the CDS/ADS in Bologna. GAs simulate evolution to find the best solution to a problem. They were used to find an optimal placement of virtual machines onto physical hosts in order to optimise the service offered by the CDS/ADS. This is an example of the increasing use of machine learning at the Centre, in this case to optimise the performance of a service.



Data delivered by the Climate Data Store

2022 saw a rise in the volume of data downloaded and the number of requests.

Science and technology

Fugaku scalability test

In mid-2022, Fugaku was the fastest supercomputer in the world with a sustained performance of 440 PFLOP/s. Fugaku relies on 160,000 Fujitsu A64FX CPUs, which use an ARM instruction set to achieve its extremely fast calculation speed. Fugaku CPUs also have an extremely wide vector register, of 512-bit, while they also natively support FP16 'half-precision' floating-point arithmetic.

We were very interested to evaluate the scalability performance of the IFS on this type of architecture. The IFS was ported to Fugaku during the first half of 2022. The same IFS forecast was repeated by increasing the resolution and the number of nodes, so that the same amount of work was assigned to each processor.

The result is shown in the figure. The desired outcome is a line which is as horizontal as possible. The discrepancy that appears in the last datapoint shows a reduction in efficiency. This is probably due to a lack of sufficient memory in the current version of the Fujitsu chip on Fugaku. As this could be addressed by a chip with more memory, the outcome of this study was overall encouraging. It suggests that ARM CPUs could be considered for future ECMWF needs.

Open-source IFS

In 2022, we started to make some of the IFS available on an open-source basis to facilitate collaboration on the code. A GitHub space was created to host open-source IFS components. The main aim of partially removing restrictions on redistribution was to make working with ECMWF more attractive to collaborators who wish to work with their partners.

Contributing to open-source codes could also be more attractive to academic partners. Another aim was greater efficiency as, for example, some journals require open access to the codes used. Finally, the move positioned ECMWF and our Member States at the centre of international efforts on emerging high-performance computing architectures. Making IFS code open source was deemed to encourage work by computational science experts in academia and vendors.

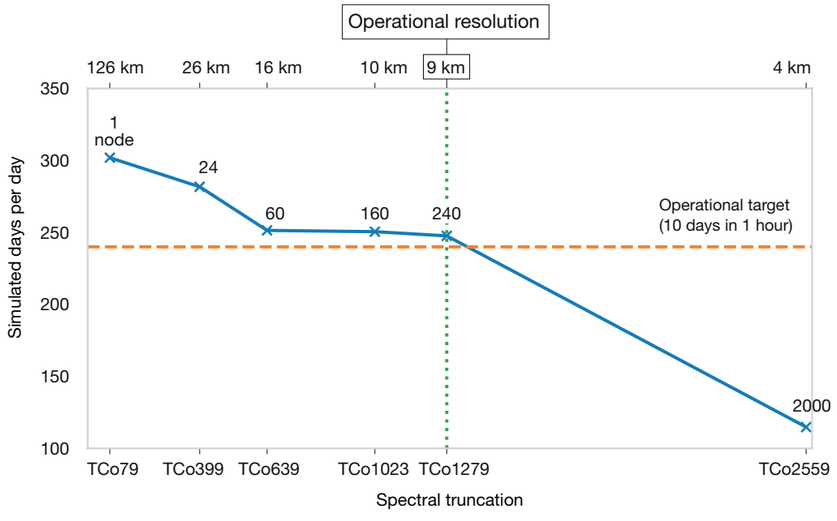
Discussions about the future approach were ongoing at the end of the year. The approach was to continue to release specific components of the IFS on demand and to periodically review whether this approach remained appropriate.

New Software Strategy

We developed a new Software Strategy in 2022, which sets out our plans for the development of software outside the weather prediction process until 2027. One of the guiding ideas is for software to be developed openly, with interaction and feedback from the community. Software components are also to be made smaller, more usable, and simpler to integrate with each other.

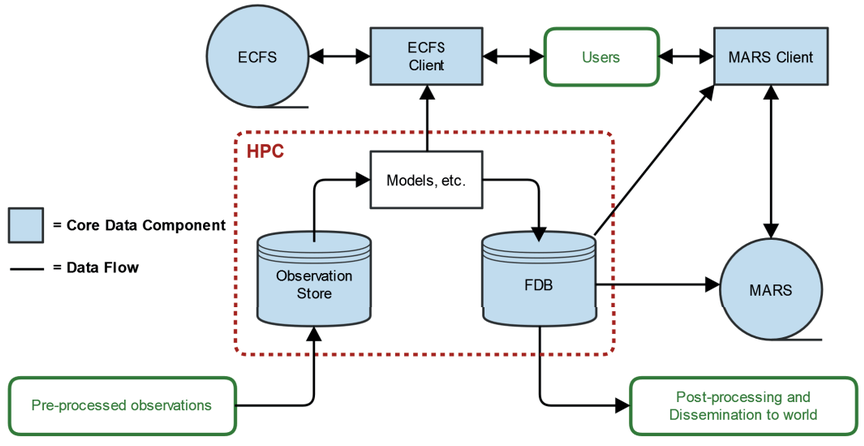
The Software Strategy aims for a good balance between in-house development of software that is critical for ECMWF on the one hand, and well-maintained and supported community software on the other. It emphasises the need for improved scalability of data handling as the amount of forecast data continues to grow rapidly.

The turn towards the open development of new software is based on the belief that interaction and feedback from the community, including in particular our Member and Co-operating States, leads to increased quality. We have already had an open-source policy for all software not related to the IFS for many years. However, this did not enable continuous feedback and contributions from external users. To encourage greater collaboration, we aim to widen our use of GitHub and other open platforms.



Scalability performance

The graph shows the scalability performance of the IFS on Fugaku. The x-axis shows the spectral truncation, with the equivalent horizontal grid resolution provided on top. The y-axis shows simulated days per day, measured from a simulation on Fugaku without output. All runs were performed up to ten days ahead.



Core data storage software

This is an example of the areas described in the Software Strategy. The MARS (Meteorological Archival and Retrieval System) ecosystem includes the FDB (Fields DataBase). In addition, ECFS (ECMWF's File Storage system) provides an unstructured archive for data outside metadata-driven workflows.

Next-generation computing architectures

Adapting to a growing range of high-performance computing (HPC) architectures is contributing to a transformation in our capabilities to model planet Earth.

> To achieve faster computer simulations of the Earth system with a lower energy footprint, we need our forecasting codes to be optimally mapped to heterogenous HPC architectures – something that we can only achieve through our collaboration with hardware architecture experts, software experts and domain specialists.

Martin Palkovič, ECMWF's Director of Computing

Computer accelerators, such as graphics processing units (GPUs), offer increased computer power coupled with greater energy efficiency. Today, supercomputers are combining central processing units (CPUs) with GPUs and other types of accelerators, in a hybrid architecture to get the benefit of a range of technologies, and the promise of exascale performance.

However, it is an enormous task to optimise our whole Integrated Forecasting System (IFS) to get the most from accelerators, while ensuring it is sufficiently flexible to cope with the diversity of current and emerging technology and, at the same time, continue scientific developments.

Harnessing developments in HPC is vital to make operational kilometre-scale weather forecasts a reality, to assimilate a growing range of observations and to model the Earth system in more detail. This underpins ECMWF's key goal of more accurate predictions of high-impact weather up to two weeks ahead, as well as wider collaborative ambitions in environmental monitoring and prediction focused in the EU Destination Earth initiative (DestinE).

Building on work within ECMWF's Scalability Programme, the Hybrid2024 project is preparing our forecasting system for the future. Exploring a variety of approaches, core model components are being restructured to ultimately achieve a full accelerator-enabled multi-architecture IFS. The computationally expensive spectral transform code has now been run successfully on a range of accelerators including NVIDIA and A100 GPUs and for the first time on the newer AMD GPUs. We have also seen success in adapting the cloud scheme, and work will continue on other model physics components.

Efficient use of the emerging European high-performance computing platforms is fundamental to DestinE, in which ECMWF is working alongside EUMETSAT and ESA to create a digital replica of the Earth. Part of our work in the first phase is to develop the Digital Twin Engine, the complex software and hardware environment needed for very high-resolution modelling of the Earth system.

Within DestinE, we are beginning to run the IFS on some of the world's top supercomputers across Europe, made available through the European High Performance Computing Joint Undertaking (EuroHPC), such as Meluxina in Luxembourg and the pre-exascale machines LUMI in Finland, Leonardo in Italy and MareNostrum5 in Spain. Such developments open up the possibility of distributed computing and data handling.

We have also achieved a major step toward kilometre-scale Earth system modelling with the world's first kilometre-scale coupled atmosphere–ocean global simulations achieved with the CPU/GPU hybrid architecture of the Summit computer (under the US INCITE programme) and the JUWELS booster in Germany (under PRACE (Partnership for Advanced Computing in Europe)).

Our close collaboration with computer scientists, vendors, and the HPC and numerical weather prediction communities is crucial to progress.

ECMWF's continuing leadership role enables us to support our Member and Co-operating States in their own digital goals, and to provide a forecasting system set to reap the benefits of the exascale age.

Impact

Many activities and developments in 2022 improved the quality, usefulness and accessibility of our products and services, helping national meteorological and hydrological services in our Member and Co-operating States to produce weather forecasts and early warnings of severe weather.

The positive impact of our 2021 forecasting system upgrade to Cycle 47r3 became evident in 2022. Extreme weather events, such as Storm Eunice and the European summer heatwave, were well predicted, and environmental consequences such as wildfires and poor air quality were monitored by the EU Copernicus services we run or contribute to.

Open data continued to grow, and with new products and additional Copernicus datasets available in 2022, users had greater access to high-quality Earth system data. In response to the crisis in Ukraine, we worked with the World Meteorological Organization (WMO) and partners in the South-East European Multi-Hazard Early Warning Advisory System (SEE-MHEWS-A) project to provide numerical weather prediction products to the Ukrainian Hydrometeorological Centre and an EU programme that strengthens disaster risk reduction and crisis management in the region.

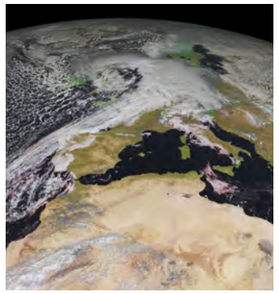
Throughout the year, the Copernicus Atmosphere Monitoring Service (CAMS) monitored global atmospheric composition and European regional air quality such as pollen levels in the atmosphere, emissions from global wildfires, episodes of Saharan dust, and other sources of pollution to provide consistent, quality-controlled information to support decision- and policy-making. Its monitoring of the 2022 Antarctic ozone hole showed that it closed later than most of those of the previous 40 years and was the third unusual ozone hole season in a row.

The Copernicus Climate Change Service (C3S) generated a wide range of authoritative, open-access information and datasets, such as ERA5-LandT, with its reduced latency for those that need land data in close to real time, to support climate change adaptation strategies and planning. Interest continued to grow in products such as the C3S monthly climate bulletins and the Service's flagship publication, the European State of the Climate (ESOTC).

For the Copernicus Emergency Management Service (CEMS), we were selected to continue providing fire forecast data for the period 2022–2027, in collaboration with Météo-France. We worked on improving the hydrological representation of the European and Global Flood Awareness Systems (EFAS and GloFAS) and we contributed to an upgraded reanalysis dataset offering daily river discharge simulations for every river across the world from 1980 onwards.

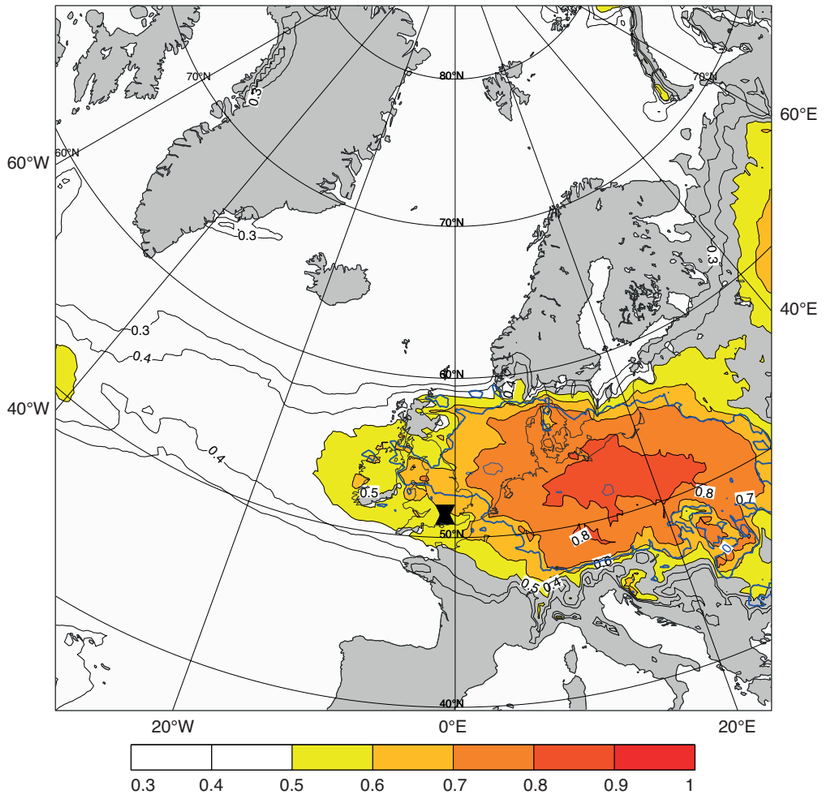
Wind gust predictions for Storm Eunice

The middle of February 2022 was very cyclonic over north-western Europe, with three named storms affecting the area in one week. Cyclone Eunice (also known as Nora and Zeynep) was one of those and it delivered major wind-related impacts in many countries on 18 and 19 February.



▲ Storm Eunice

Satellite image of Storm Eunice on 18 February 2022 from EUMETSAT's Meteosat-11 satellite.



◀ Extreme Forecast Index (EFI)

EFI (shading) and Shift-of-Tail (SOT – blue contour encloses positive values) forecast for 10 m wind gusts from 12 February valid on 18 February. The location of London Heathrow Airport is indicated by an hourglass symbol.

The forecast from 12 February had high Extreme Forecast Index (EFI) values over northern Europe six days ahead, showing the potential for widespread impacts.

Eunice brought very strong wind gusts of more than 30 m/s quite widely over southern England on 18 February. More than a week before the event, the ensemble system predicted a risk for windier-than-normal conditions at Heathrow.

In this case, high-resolution forecast gusts were generally a few m/s stronger than observation reports over southern England.

A closer look at the statistics of the wind gusts during the stormy period (12–20 February) shows that overall there was good correspondence between forecast and observations over Europe.

Whilst the gust forecast bias is generally small, in individual cases errors of different sign may occur. For example, the overprediction for Eunice contrasts with an underprediction for storm Franklin, which arrived a few days later, on 21 February. It is worth noting that the accuracy of synoptic pattern forecasts will play a major role in wind gust prediction errors.

> "The positive impact of our 2021 forecasting system upgrade to Cycle 47r3 became evident in 2022."

Impact

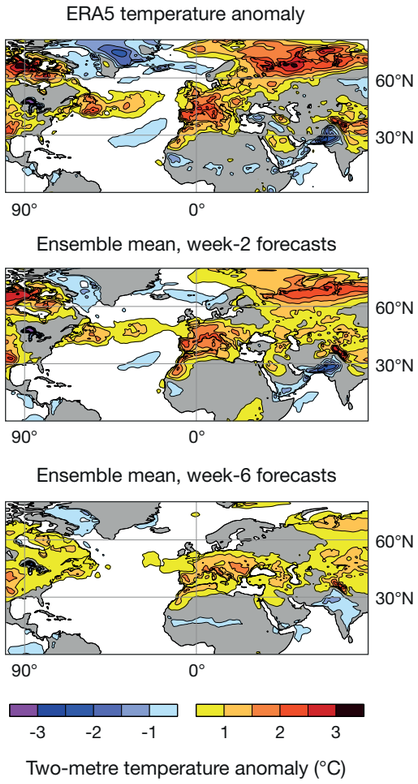
European summer heatwave forecasts

During the summer of 2022, Europe experienced several heatwaves, and much drier conditions than normal, especially in western Europe. A record high temperature of 40.3°C was reached in the UK, exceeding the previous record by 1.5°C. Temperatures also exceeded 40°C in France, 45°C in Spain and 46°C in Portugal.

The figure shows average weekly temperature anomalies for 6 June to 28 August from the ERA5 reanalysis, and for all ensemble mean forecasts that verified during that period, with different lead times. The strong anomaly over western Europe is evident in ERA5 as well as in the week-2 forecasts. In the week-6 forecasts, the warm anomaly over western Europe is still present, but it is weaker.

On a two-week timescale, the forecast started to distinguish between the extreme weeks and the more normal weeks. Forecasts failed to capture the full magnitude of the extreme event of the record-breaking day over the UK. Similar conclusions were found for other recent heatwaves.

CAMS forecast very high levels of surface ozone pollution across a large region of Europe as temperatures soared. Fire danger forecasts from ECMWF, available through CEMS, repeatedly warned of increased fire danger due to the lack of rain and the resulting dry vegetation, combined with high temperatures.



◀ Summer heatwave 2 m temperature anomalies

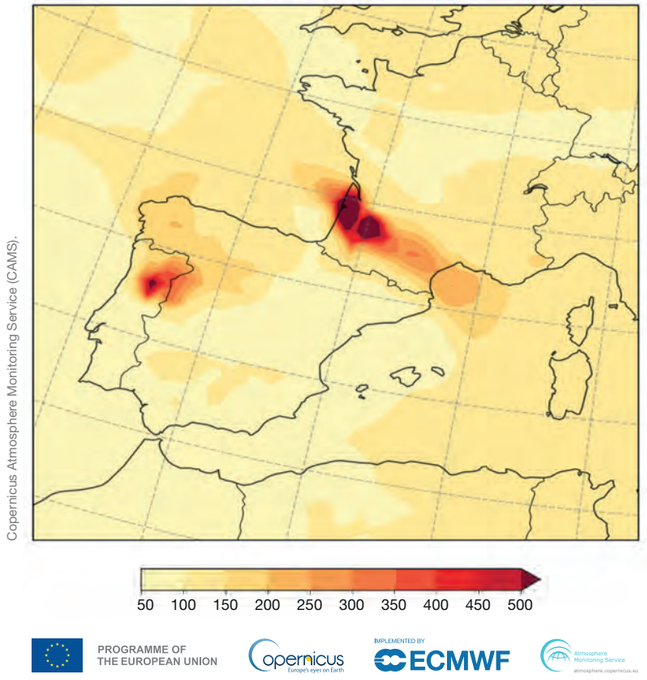
Mean weekly 2 m temperature for the weeks commencing 6 June to 28 August 2022 from the ERA5 reanalysis (top), the ensemble mean from week-2 forecasts (middle), and the ensemble mean from week-6 forecasts (bottom).

CAMS monitoring of wildfire emissions and air quality

Emissions from wildfires are a significant source of atmospheric pollutants. 2022 saw increased wildfire activity in some regions around the world, with associated rises in emissions.

The CAMS Weather Room routinely monitors wildfire emissions, providing up-to-date information on the location, intensity and estimated emissions of wildfires around the world through its Global Fire Assimilation System (GFAS), as well as monitoring smoke transport and atmospheric composition/air quality impacts. CAMS forecasts are widely used in air quality apps, to help people limit their exposure to pollution, and by policy-makers and local authorities to manage and mitigate the air quality impact of fires.

In general, CAMS GFAS data for 2022 showed the continuing downward trend in global wildfires and vegetation fires over the last two decades, although several regions, particularly in parts of Europe and South America, saw the highest estimated emissions during their peak wildfire seasons. France and Spain were two of the worst-affected European countries, with emissions at their highest level since at least 2003.



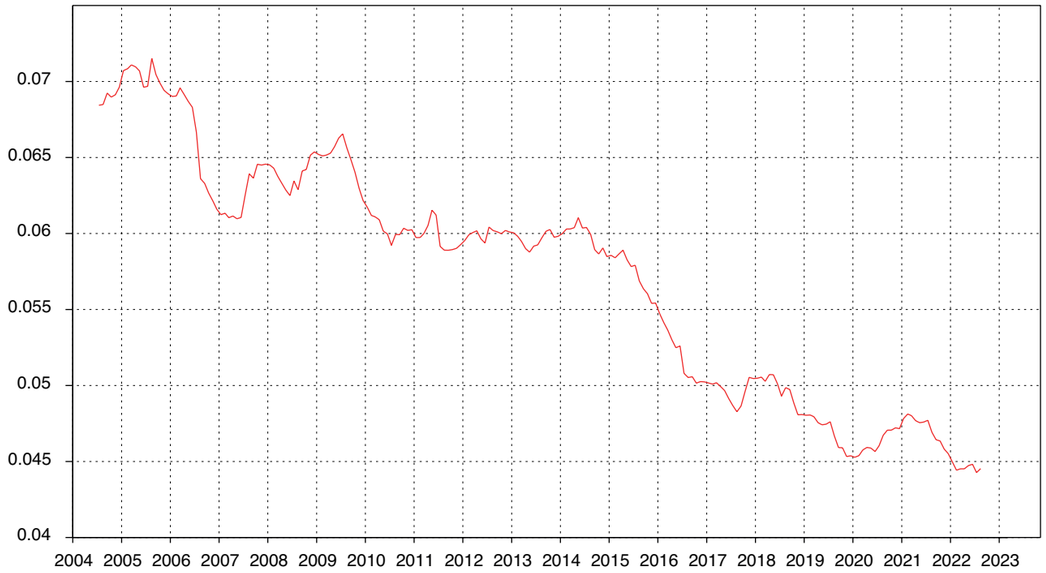
◀ Impact of wildfire emissions on air quality

CAMS global forecast of daily maximum carbon monoxide mixing ratio at 850 hPa for 12 August 2022.

This had a major impact on atmospheric composition and air quality in the region. For example, smoke plumes from the large blazes in south-western France and northern Portugal during August's heatwave were clearly reflected in the daily maximum mixing ratio of carbon monoxide at 850 hPa for 12 August 2022.

GFAS is based on satellite observations of active fires and fire radiative power (FRP), a measure of fire intensity, to estimate emissions of carbon and a wide range of other air pollutants that constitute smoke, and it provides a dataset from 2003 to present. GFAS emissions are used by CAMS global and regional (Europe) forecasting systems to predict the resulting smoke transport and impact on air quality.

Impact



Forecast performance

We maintain a range of verification statistics to evaluate the accuracy of our forecasts. The headline scores are computed as 12-month running averages to filter out the annual cycle and better identify trends in forecast performance. This means the beneficial effect of new model cycles is fully visible only 12 months after implementation.

The implementation of Cycle 47r3, which included a major upgrade of the moist physics of the model together with several other changes, on 12 October 2021 further increased medium-range forecast skill. The evolution of upper-air ensemble forecast (ENS) skill relative to ERA5 is shown in the figure in the Foreword.

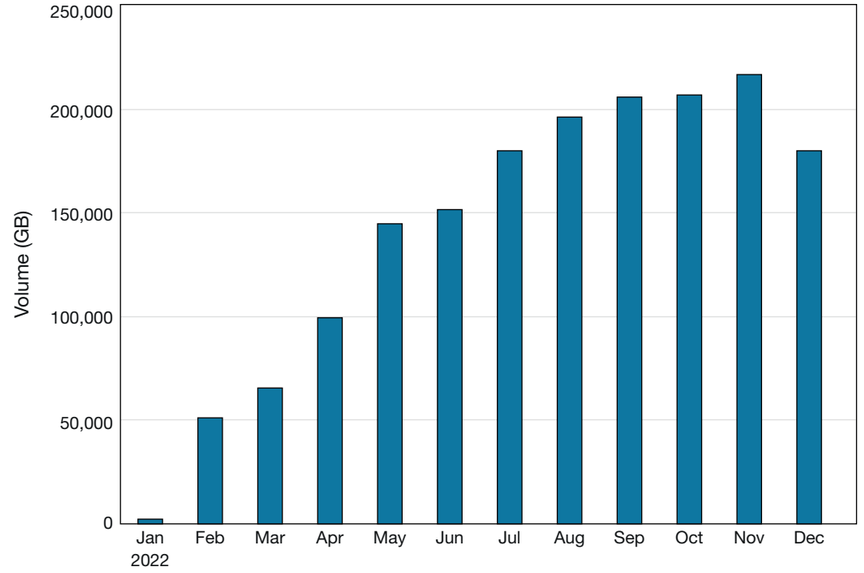
Compared to forecasts from other global centres, ECMWF has been able to maintain the overall lead for upper-air parameters in the medium range. The number of large two-metre temperature errors in ensemble forecasts (ENS) has been further reduced, according to one of our headline scores.

Improvements were observed for surface parameters, with Extreme Forecast Index (EFI) scores for 2 m temperature and 10 m wind speed reaching new high points in 2022. Cycle 47r3 also improved forecasts of ocean wave peak period, putting ECMWF ahead of other global centres.

Early in 2022, ECMWF's seasonal forecast predicted a gradual return from La Niña towards more neutral conditions within a few months, but in the observations La Niña conditions persisted throughout the year. Later in 2022, the forecast got closer to observations and shifted the return to neutral into early 2023. In the extratropics, a strong signal for a warm anomaly in the summer of 2022 in Europe was present in the forecast but its magnitude towards Scandinavia and Siberia was underestimated.

▲ Ensemble forecast headline score improvements

Fraction of large 2 m temperature errors in ensemble forecasts (defined as having a Continuous Ranked Probability Score (CRPS) exceeding 5 Kelvin) in the extratropics. Shown are 12-month running average values.



◀ Data retrieved from the ECMWF open data portal

Approximately 1,700 TB of data was downloaded from the ECMWF open data portal in 2022, corresponding to about 140 TB per month.

Wider range of open data

Our move towards making more data openly accessible is key to increasing the impact of our products and activities in Member States and beyond.

In January we released a new free and open dataset called 'ECMWF Open Data (real-time)'. Users could access the data through ECMWF channels as well as via Microsoft Azure. The data are based on a range of high-resolution forecasts (9 km horizontal resolution) and ensemble forecasts (18 km horizontal resolution) at a resolution of 0.4 x 0.4 degrees.

We worked on making the data Findable, Accessible, Interoperable and Reusable (FAIR), by developing an Application Programming Interface (API) so they are easy to download, and by developing open-source Python libraries to process and visualise them. To present the new tools and help users understand how to retrieve and process our data, we created a set of Jupyter notebooks, each reproducing a workflow for one open weather forecast chart from downloading the data to visualisation.

By the end of the year, we were producing approximately 700 GB of open data each day. User uptake has been positive: daily requests rose from 38,000 in 2021 to 860,000 in 2022, and the data provided daily increased from approximately 2.8 TB in 2021 to 7.5 TB in 2022. Microsoft Azure reported 400,000 user retrievals in one week and the delivery of 7.5 TB of data.

These steps to provide more open data were accompanied by other measures to facilitate access to ECMWF products. These included licence changes and a gradual reduction in fees for chargeable data, and updated documentation for our open forecast charts.

> "By the end of the year, we were producing approximately 700 GB of open data each day."

Impact

ERA5 back extension

A further segment of the ERA5 global atmospheric reanalysis was released, extending the archive to include data from 1959 to 1978. The production of an additional extension to 1940 was completed in October 2022, to be released in 2023, after which the total ERA5 archive will cover over 80 years.

These important historical data help us to build a globally complete picture of the climate over the past decades, using the past to learn more about the present climate and to measure change over time. The data are updated daily with a time lag of just five days and they are available from C3S.

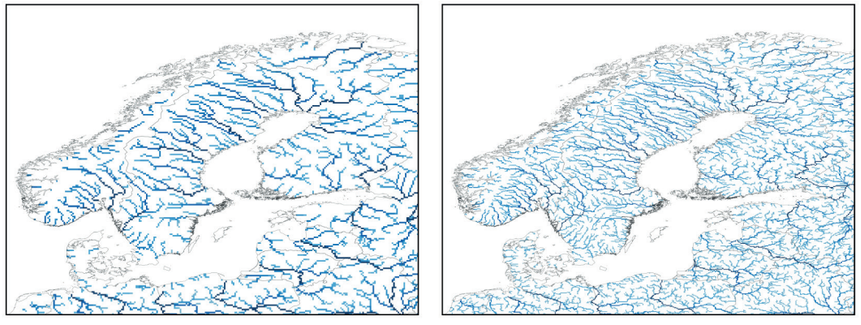
The ERA5 dataset creates 'maps without gaps' by filling in where information is lacking – for example at times when clouds prevent satellites from observing Earth's surface, or in places like the Arctic that are difficult to access with ground-based instruments. Covering temperature, surface pressure, wind, ocean wave height and more, the data are in demand and, as of December, ERA5 had over 100,000 users worldwide.

The further extensions to 1959 (published in 2022) and 1940 (production completed in 2022) replace a preliminary extension back to 1950 that was characterised by sub-optimal tropical cyclone properties.

GloFAS hydrological reanalysis

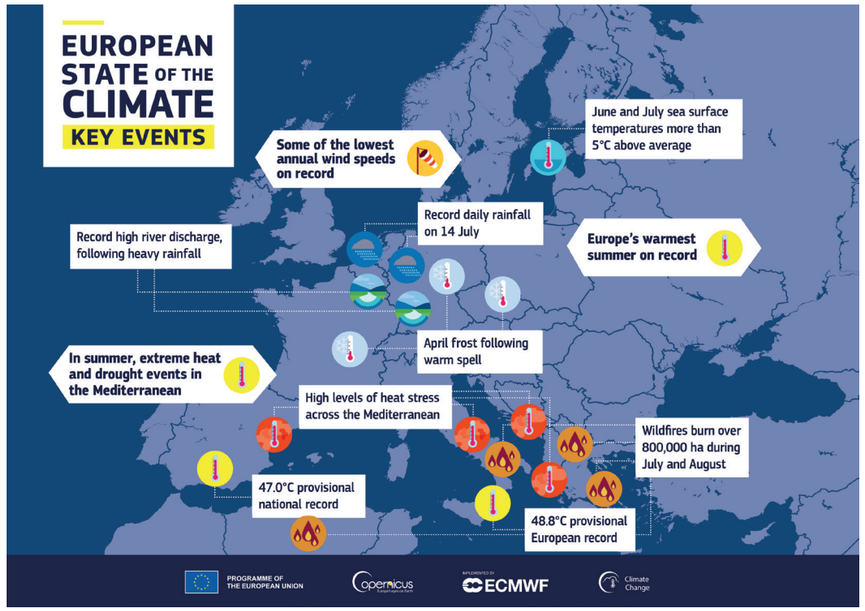
In our role as the hydrological forecast computing centre for the Copernicus Emergency Management Service, we worked with the Joint Research Centre (JRC) of the European Commission to produce a substantially upgraded hydrological reanalysis dataset of the Global Flood Awareness System (GloFAS).

The high-resolution global hydrological reanalysis dataset GloFAS-ERA5 (version 4) was launched publicly in November and made available through the Copernicus Climate Data Store, offering daily river discharge simulations for every river across the world from 1980 onwards. Other variables, such as soil moisture and snow water equivalent, will become available during 2023.



◀ High-resolution reanalysis

Representation of rivers in Scandinavia in GloFAS v3.1 (left) and in the updated version, GloFAS v4.0 (right).



◀ European State of the Climate 2021

The flagship publication from the Copernicus Climate Change Service (C3S) included a comprehensive report of conditions in Europe.

The reanalysis includes daily maps of discharge over the globe at a resolution of 0.05 degrees (about 5 km) – the previous version used a 0.1 degree grid (about 10 km). It helps the study of flood events and droughts globally during a much longer time frame than the period during which GloFAS has been operational.

The dataset is updated in near-real time, with a delay of about three days, to include the latest available forcing data. Generating such a high-resolution reanalysis is made possible by our new Atos high-performance computing facility, combined with work by ECMWF and the JRC on the parallelisation of routines in the hydrological model LISFLOOD. The LISFLOOD model determines to what extent water that comes down as rain evaporates, is absorbed by the soil and plants, or runs off into rivers.

Many places have no data on river discharge, meaning a country may for example have no way of knowing how much water is going to be discharged into it from rivers outside its borders. Global simulations thus close an information gap.

European State of the Climate report

The European State of the Climate 2021 (ESOTC) report was published by C3S with contributions from national meteorological services, partners and other Copernicus services. It included an overview of the previous year's climate in a global context, a more comprehensive report of conditions in Europe, and a focus on the Arctic.

The report highlighted that, globally, atmospheric concentrations of greenhouse gases continued to increase. Levels of carbon dioxide were higher in 2021 than at any time in at least two million years. The last seven years were the warmest on record, contributing to continued loss of ice mass from glaciers and ice sheets, which in turn has an impact on sea level rise.

The report provides consistent, dependable data that policy-makers can use to understand climate change and its impacts, and its findings were widely covered by media around the world.

Also in 2022, through C3S the first State of the Climate in Europe report was co-authored and launched with the WMO, with extensive media coverage.

Impact

© WMO

COP27 and Earth observation data

The 2022 United Nations Climate Change Conference, COP27, was held in Sharm el-Sheik, Egypt. It brought together policy-makers from around the world to reaffirm their commitment to the goals of the Paris Agreement and to accelerate global climate action through emissions reduction, scaled-up adaptation efforts and enhanced flows of appropriate finance.

ECMWF was well represented, speaking at high-level events on the WMO Systematic Observations Financing Facility (SOFF) and the EU Destination Earth initiative.

The SOFF financing mechanism was launched at COP27 to help address the long-standing problem of missing weather and climate observations from Least Developed Countries and Small Island Developing States. It aims to help the most vulnerable countries to predict and adapt to extreme weather events such as floods, droughts and heatwaves.

Our Director-General and Director of Forecasts highlighted ECMWF's support for the renewed funding efforts for SOFF, emphasising the importance of closing the basic weather and climate data gaps in developing countries.

▲ COP27 World Bank ministerial event

Left to right: Petteri Taalas (WMO), Nirivololona Raholijao (Madagascar Bureau of Climate and Meteorology), Florian Pappenberger (ECMWF Director of Forecasts) and Alexia Latortue (United States Department of the Treasury) at a session co-hosted by the Coalition of Finance Ministers for Climate Action and the WMO.

The Copernicus services run by ECMWF organised an active programme of events highlighting the wealth of Earth observation data provided by CAMS and C3S and real-life applications of the models and data. Lead scientists from CAMS and C3S discussed the Copernicus contribution to the CO2 Monitoring and Verification Support Capacity (CO2MVS) and collaboration between the services and the Union for the Mediterranean, with a focus on health and cultural heritage preservation.

Cooperation with the European Investment Bank (EIB) was highlighted, showing how Copernicus data could support investment in climate adaptation, particularly in Africa.

On the Earth Information Day, both CAMS and C3S had the opportunity to address parties directly, giving updates on progress and how the Copernicus services support climate change adaptation efforts.

European partnerships

Two pilot projects to further enhance collaboration with our Member and Co-operating States were selected to begin in 2023. They will tackle topics of importance to ECMWF and our community: adaptation to future technologies, and Internet of Things (IoT) observations for numerical weather prediction.

Our Fellowship programme strengthens links with the scientific community to advance research on specific topics of common interest.

In 2022, we worked with 11 ECMWF Fellows, from France, Germany, Hungary, the Netherlands, Sweden, Switzerland, the UK and the USA, on areas including ensemble post-processing; atmospheric momentum transport; warm conveyor belts; heatwave prediction and predictability; and the RTTOV radiative transfer model.

Heini Wernli (ETH Zurich, Switzerland) completed his second Fellowship term in February 2022. Research with Heini and his group contributed greatly to our understanding of warm conveyor belts.

Operating from multiple sites brought opportunities to forge closer partnerships with NMHSs and academic institutions in the regions.

With the German national meteorological service DWD, we developed early career fellowship and visiting scientist programmes for the Bonn site. Four early career fellowships were awarded to start in 2023 for projects related to Arctic clouds, altimeter measurements, water cycles and atmospheric composition.

With the Italian Government, we signed an agreement as part of the Copernicus Mirror Programme to help institutions and public bodies access relevant Copernicus information and tools. More widely, contracts with Denmark, France, Germany and Italy were concluded under the new CAMS National Collaboration Programme, a scheme designed to support uptake of CAMS products by public authorities in Europe.

> "At COP27, lead scientists from CAMS and C3S discussed the Copernicus contribution to the CO2 Monitoring and Verification Support Capacity (CO2MVS)."

Impact

◀ Multi-hub for a lower carbon footprint

ECMWF in Reading was the European hub for the SPARC General Assembly, linking with two other hubs for the Americas and Asia.

Knowledge-sharing and supporting the scientific community

Whilst 2022 saw many events return to in-person attendance, we built on experiences gained during the COVID pandemic to provide a virtual experience as well, to share knowledge with Member States and the wider scientific community while reducing the carbon impact.

The year began with over 160 experts from fields such as radio astronomy, meteorology, Earth remote sensing and spectrum management meeting virtually to discuss radio frequency interference (RFI). The radio spectrum is used to support many critical services, and the workshop discussed 5G, how RFI is being monitored, the importance of the radio spectrum in numerical weather prediction, and how best to influence the regulatory process.

We were selected to host the European hub for the 7th SPARC General Assembly, which reviewed research into atmospheric variability and prediction. SPARC is a World Climate Research Programme (WCRP) programme, coordinating international research efforts that apply knowledge of the atmosphere to understand climate variability and prediction. The two other hubs were in the USA and China. The multi-hub format was chosen to reduce the carbon footprint of the meeting, which was also held virtually, enabling engagement between communities across the world.

◀ Visualising meteorological data

Interactive session at the Using ECMWF's Forecasts meeting, UEF2022.

The third ESA-ECMWF Workshop on Machine Learning for Earth Observation and Prediction was also held in Reading, combining in-person and virtual attendance. Participants discussed the state of the art in this rapidly evolving field in areas such as machine learning for Earth observations and hybrid machine learning in data assimilation, among many other topics.

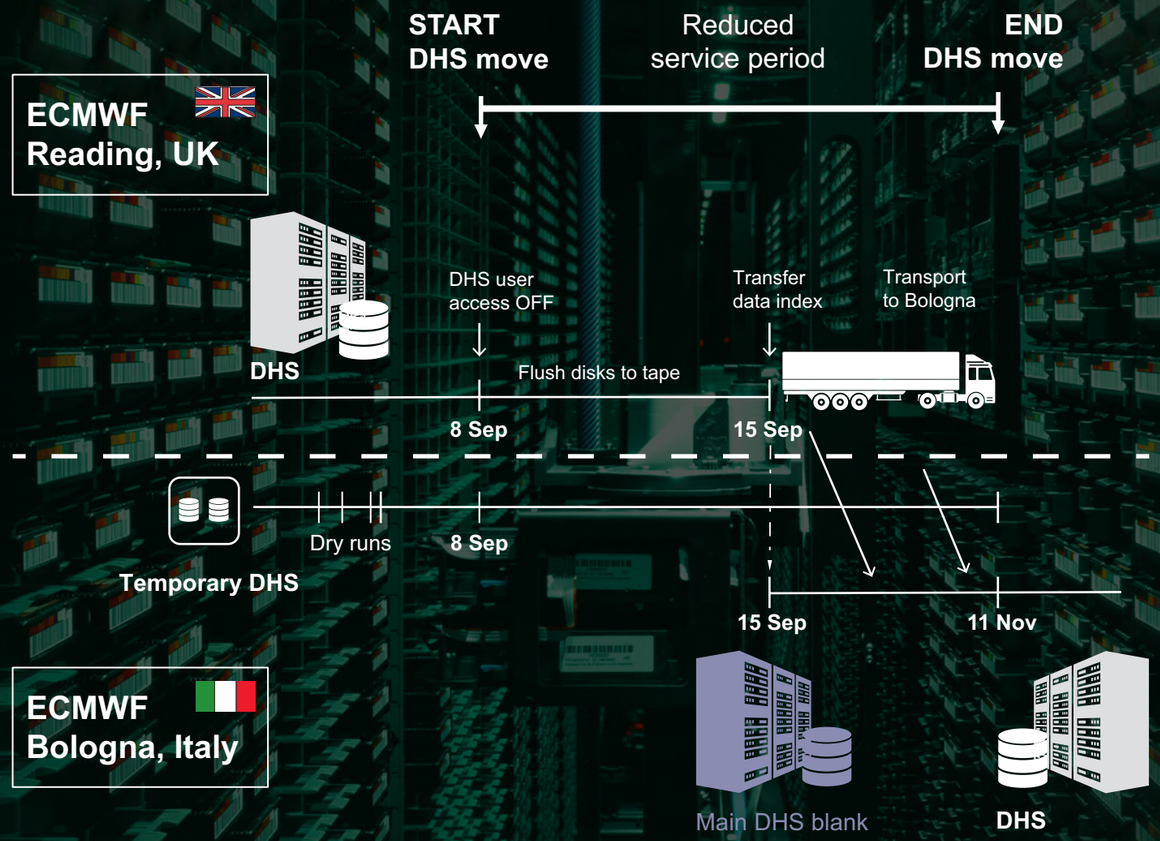
There were many opportunities through workshops and seminars to engage with Member States and share knowledge on key topics. These included a workshop on model uncertainty, our Using ECMWF Forecasts meeting and hackathon on the theme 'visualising meteorological data', the CAMS and C3S General Assemblies, and the 6th WGNE workshop on systematic errors in weather and climate models.

At our first in-person Annual Seminar in three years, over 100 scientists and students considered the large range of physical processes and scales that have to be represented in seamless weather prediction. The seminar was also followed daily by attendees on the livestream.

An extensive programme of courses was delivered to assist Member and Co-operating States in the training of scientists in numerical weather forecasting and in making use of ECMWF forecast products.

ECMWF's Data Handling System moves from Reading to Bologna

After years of planning and a huge amount of organisation, this important move went without a hitch.



In the autumn of 2022, ECMWF's Data Handling System (DHS) was moved to our new data centre in Bologna, Italy.

The DHS is used to store and access ECMWF's real-time forecasts, as well as other meteorological data and user files. It plays a crucial role in the production and delivery of our operational forecasts.

The DHS comprises the Meteorological Archival and Retrieval System (MARS), which holds 500 billion meteorological fields, and ECMWF's file storage system (ECFS), which is used to store user files. To support these two applications, ECMWF runs the high-performance storage system (HPSS), which manages the automatic tape libraries and disk storage. More than 10,000 scripts run every day to access MARS and the ECFS, with two million requests per day for data storage/retrieval.

Moving the whole DHS to Bologna was the only cost-effective option, but it would involve some disruption. The highest priority was to ensure that there was no interruption to our operational forecasts. A temporary DHS was set up in Bologna and work began back in 2017 to identify data flows essential to operations.

A series of dry runs were carried out in the first half of 2022 to simulate the shut-down of the Reading DHS and to ensure that all the data needed to continue our operational forecast service had been included in the temporary DHS. Feedback from our Member and Co-operating States and other users was invaluable in helping us fine-tune the arrangements.

The DHS move in numbers:

700 petabytes of data	150 servers
3 tape libraries	290 tape drives
17 disk systems	24,000 tape cartridges

We worked hard to keep users well informed about the reduced access to some data that would occur during the move.

The move began on 8 September 2022. Access to the DHS in Reading was disabled and the temporary DHS in Bologna took over the storage and retrieval of essential data.

In Reading, many thousands of tapes had to be scanned and sorted. Tape libraries, disk systems and servers had to be dismantled and all equipment packed, labelled and loaded onto lorries for the journey across Europe.

On arrival in Bologna, tape libraries had to be re-assembled, calibrated and tested. All cartridges had to be inserted back into the tape libraries, each of the 24,000 cartridges in the correct tape library! Servers had to be racked, disks re-assembled, and all equipment gradually brought back online.

The equipment from Reading supplemented new equipment already set up at the Bologna data centre, giving us enhanced data handling capability for the future. We have now increased from three to eight tape libraries, for example.

On 11 November 2022, the DHS was brought fully into production in its new home in Bologna, thanks to the work of many ECMWF staff.

Photographer: Stefano Marzoli

Organisation and people

In 2022 we focused on strengthening our ‘One ECMWF’ culture to ensure that every member of staff, regardless of duty station or field of work, feels part of the same organisation, shares the same overarching vision and objectives, and is treated equally.

As pandemic restrictions eased in the spring, staff were able to return to site and also work remotely in line with our teleworking policy. Our offices gradually reopened their doors to external visitors too, allowing us to welcome ministerial delegations, host university visits and resume in-person bilateral meetings with major partners.

Opportunities for staff to engage continued to be developed with the aim of achieving a good balance between site-specific and cross-site engagement. We remain committed to promoting diversity, equality and inclusion (DE&I) through the development and implementation of a DE&I action plan, initially focused on gender diversity and cross-cultural awareness.

In the work we undertake on behalf of the European Commission, we successfully transitioned to the second phase of the Copernicus services and established strong foundations for our Destination Earth (DestinE) activities.

For Copernicus, the transition involved many contract extensions, new procurements and the move to Bonn of a sizeable fraction of our staff.

For DestinE, we launched an extensive recruitment exercise to strengthen the teams developing digital twins and began putting in place external contracts to help deliver the first phase of the initiative, involving many entities from our Member States.

▲ International organisation

The flags of the 23 ECMWF Member States at our sites in Bonn (left), Bologna (middle) and Reading (right) are a visual reminder of our status as an international organisation.

Three host countries, one ECMWF

In the UK, we continued to work with the Government on plans for new headquarters on the campus of the University of Reading. By the end of the year, the planning application was being prepared for submission to the local council and a tender had been launched for the principal design-and-build contract.

In Germany, we welcomed over 50 new members of staff and worked closely with our local hosts to create adequate working space for our growing teams. The flags of our 23 Member States were installed at the Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) headquarters, our interim home until our new building opens. In September, the first anniversary of the opening of our Bonn site was an opportunity to bring together staff across three duty stations, face to face and virtually.

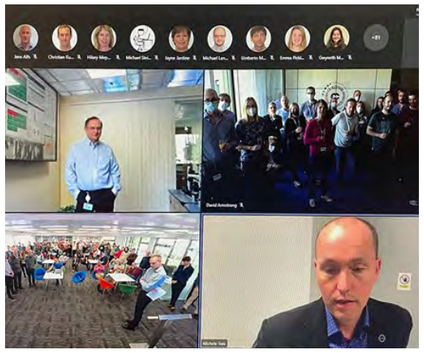
In Italy, the final handover of our new data centre took place in April with representatives of the Emilia-Romagna region and the Italian Ministry of Foreign Affairs. We issued our first forecasts using the Atos high-performance computing facility in October. Staff in Bologna, Bonn and Reading raised a toast to celebrate the successful migration, joined by many other colleagues who followed the celebrations virtually. Every department at ECMWF had a role to play, small or large, in the complex and challenging multi-year project.

◀ The Weather Room in Reading

At our UK headquarters, we gradually resumed on-site meetings, workshops and weekly internal weather discussions.

◀ One year in Bonn

Left to right: Gertrud Husch (German Federal Ministry of Transport and Digital Infrastructure), Florence Rabier (ECMWF Director-General) and Gerhard Adrian (President of Deutscher Wetterdienst, DWD) mark one year in Bonn.



◀ First forecasts from Bologna

This milestone was marked across the three sites with short addresses from Mike Hawkins, Head of HPC and Storage Section (top left), and Director of Research Andy Brown in Reading (bottom left), and from Director of Computing Martin Palkovič in Bologna (bottom right).

Organisation and people

#OneECMWF

Our UK team posing for a photo after completing their 14 km stage of the 'Running out of time' climate action relay (left), our Germany team taking the baton to set off for a 10 km leg of the relay (middle), and the 2022 Football tournament winning team (right).

ECMWF staff

As an international organisation, we are proud of our multicultural environment. At the end of 2022, we had 436 members of staff from 35 different countries.

During the year, we hosted:

- 8 visiting scientists: 3 from the Japan Meteorological Agency (JMA); 1 from the China Meteorological Administration (CMA); 1 from the Korean Meteorological Administration (KMA); 1 from the University of Sherbrooke, Canada; 1 from the Alexander Von Humboldt Foundation, Germany; and 1 from the Finnish Meteorological Institute (FMI)
- 5 EUMETSAT Fellows from Spain and the United Kingdom
- 1 WMO Fellow from Cameroon
- 5 graduate trainees from Italy, Ireland and the United Kingdom

Strengthening the 'One ECMWF' culture through sport

In October, staff in Reading and Bonn took part in the 'Running out of time' non-stop relay. They joined the thousands of runners, cyclists and sailors who covered a record-breaking 7,767 km across 18 countries over 38 days from Scotland to Egypt to deliver a message on climate action to the world's leaders at COP27.

The relay started on 30 September in Glasgow, the location of COP26, and finished on 7 November in Sharm el-Sheik.

In September, our annual six-a-side football tournament was an opportunity for staff, families and friends to enjoy a great evening together playing football, helping with the organisation or simply supporting the teams.

Investment in ECMWF

The 35 Member and Co-operating States of ECMWF are the principal sources of finance for the Centre, with contributions totalling £54.7 million, representing a large proportion of the Centre's funding. External organisations support both core research and the complementary goals of the Centre with funding of £43.8 million. Revenue from sales of data and products provides additional income of just under £12.9 million, while other operating revenue totals £12.4 million.

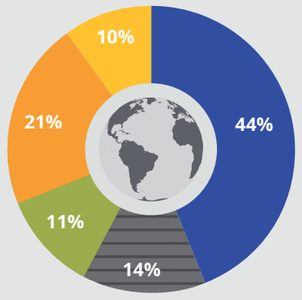
ECMWF continued to invest in its staff, infrastructure, and systems to provide the highest quality products to its Member and Co-operating States. The main areas of expenditure, including capital investment of £2.3 million principally for IT and infrastructure, are as follows: remuneration and related items (£29.6 million), pension schemes (£29.8 million), computer expenses (£14.7 million), buildings (£9.5 million) and other operating activities (£4.4 million). Costs associated with externally funded projects amounted to £34.8 million and net finance costs were £19.6 million.

ECMWF's budget remains on a cash basis and the Financial Statements include a reconciliation of the results under IPSAS and in cash terms. Under cash accounting, the Centre generated a surplus of £16.267 million in 2022, which is available either for future investment or distribution to Member States according to a decision to be made by the Council in 2023.

Note: all numbers exclude Centre tax.

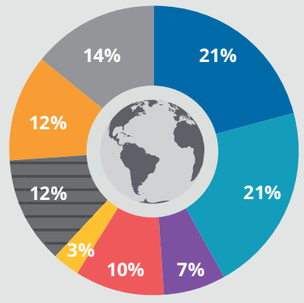
"We are proud of our multicultural environment with staff from 35 different countries."

Funding



- Member & Co-operating States' contributions
- Copernicus & Destination Earth procured industrial activities
- Sales of forecasts and data
- Externally funded income
- Other operating revenue

Costs



- Personnel costs
- Pension and post-employment benefits
- Buildings expenditure
- Computer expenditure
- Other operating expenditure
- Copernicus & Destination Earth procured industrial activities
- Externally funded expenditure
- Net finance costs

How we work

ECMWF Council
The ECMWF Council held its June 2022 session in Bologna, Italy.

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 2022

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

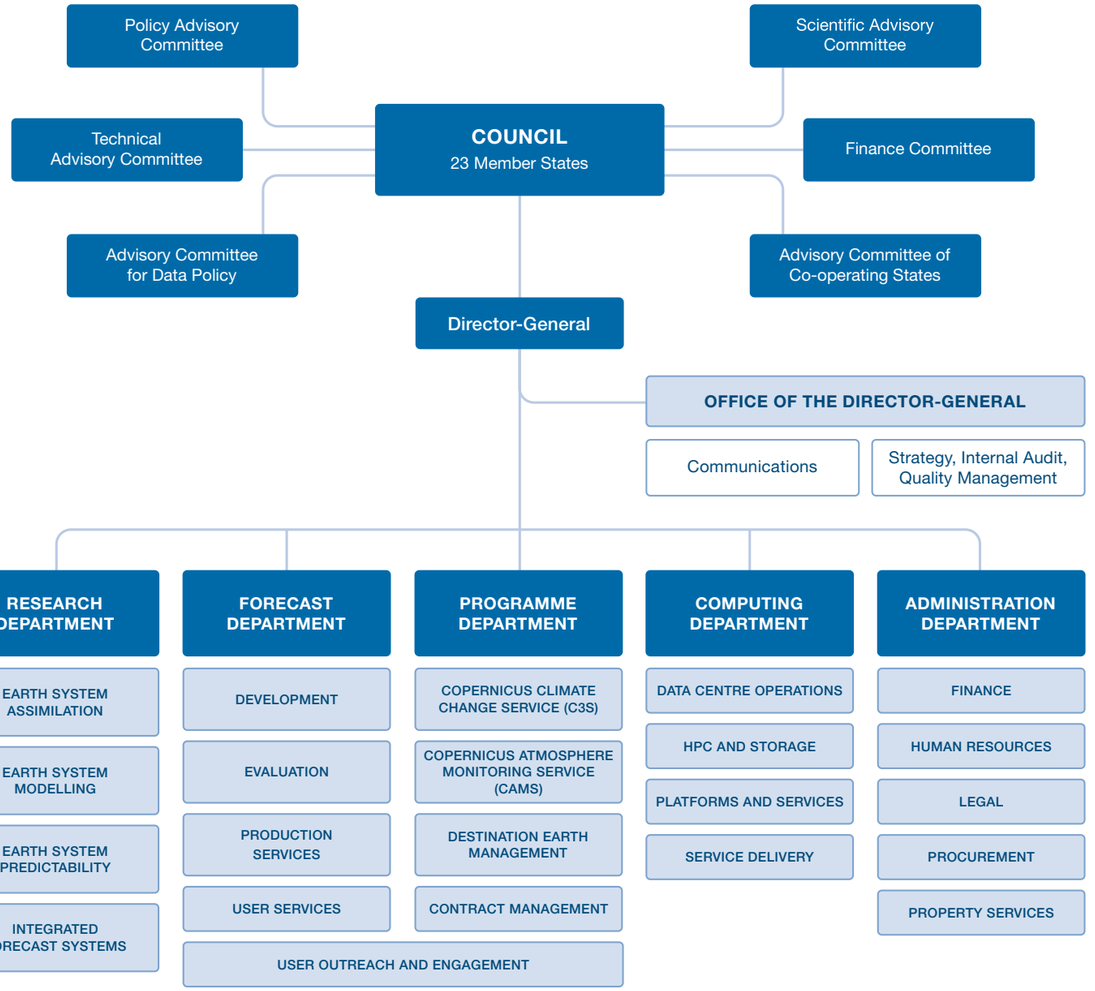
Policy Advisory Committee Chair:
Mr Eoin Moran, Ireland

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

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



Organisation of ECMWF in June 2023

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

Co-operating States as of January 2023

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

Reading, UK | Bologna, Italy | Bonn, Germany

www.ecmwf.int