Fifty years of meeting users’ needs

ADVANCING WEATHER SCIENCE
THROUGH COLLABORATION

ECMWF | 50

Fifty years of meeting users' needs

ABSTRACT

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At the forefront of meteorological science and technology, ECMWF is a user-driven organisation.

Over the past 50 years, ECMWF has developed a comprehensive ecosystem of products and services, grounded in its core strengths: research in Earth system modelling and use of observations, cutting-edge technology and infrastructure, advanced data science, and, crucially, always through deep collaboration with its Member and Co-operating States.

With our Member and Co-operating States remaining at the core of our user community, the last 50 years have seen our user base broaden and diversify significantly to cover a range of research, academic and governmental bodies, as well as the private sector. This evolution reflects a growing range of meteorological, climate and environmental services, driven partly in response to the increasing risks from high-impact weather and climate change.

Engaging with our user community, ECMWF has responded over time to meet these needs in several ways: by continuously improving forecast quality, through an evolving range of fit-for-purpose products, and by enhancing access to data and information. Furthermore, supporting our users underpins all that we do, not least through an increasingly comprehensive range of support services and training.

This paper reflects on that journey, a defining feature of which has been, and continues to be, the two-way interaction between ECMWF and its users, with Member States playing a central role in shaping ECMWF's direction.

INTRODUCTION →

At the forefront of meteorological science and technology, ECMWF is a user-driven organisation. Over the past 50 years, ECMWF has developed a comprehensive ecosystem of products and services, grounded in its core strengths: research in Earth system modelling and use of observations, cutting-edge technology and infrastructure, advanced data science, and deep collaboration with its Member and Co-operating States.

When ECMWF was established in 1975, its mandate was clear: to provide its Member States with high-quality medium-range atmospheric forecasts, to make meteorological data available on an operational basis for their purposes, and to offer advanced training and computing resources for research in numerical weather prediction (NWP). Since then, ECMWF's portfolio has expanded significantly, keeping pace with scientific and technological progress (which ECMWF and its Member States have themselves helped to drive) and continuously responding to evolving user needs. With the amendment of the Convention in 2010, ECMWF's mission was expanded to encompass the monitoring of the Earth system, clearly highlighting reanalysis as a key aspect of ECMWF's offerings.

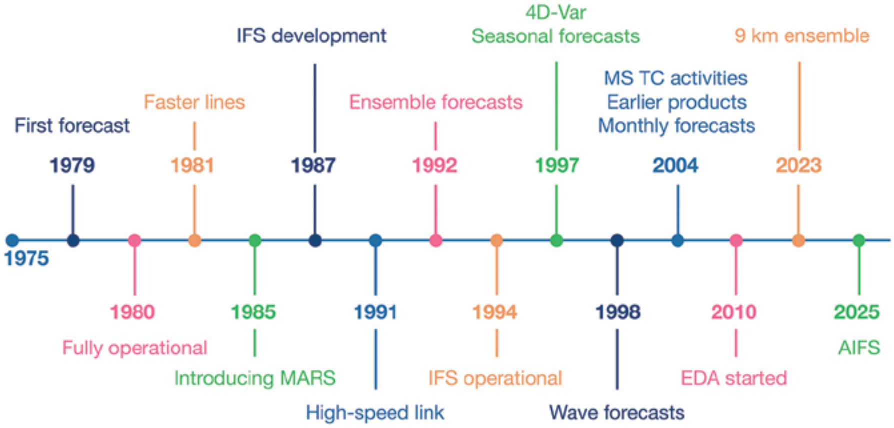
The user community has also transformed. Initially almost exclusively made up of the national meteorological services of Member States, and still very much centred on these, it now spans a wide spectrum: academia and research, governmental organisations in Member States, satellite agencies such as EUMETSAT and ESA, other European and international organisations, other WMO National Meteorological and Hydrological Services (NMHSs), and an increasingly diverse private sector engaged in weather, climate, and environmental services. This growth reflects broader shifts in the accessibility of meteorological data and the rising demand for reliable information in the face of climate change and growing weather-related risks.

ECMWF's response to this evolution has been multifaceted. First, it has continuously improved its forecasting systems and the quality of the forecasts. Second, it has developed fit-for-purpose products that enable users to make decisions and create value from ECMWF forecasts and analyses. Third, it has ensured easy and reliable access to these products and the underlying data, allowing seamless integration into users' workflows. Fourth, it has empowered users through dedicated support, training, and services. Finally, it has fostered a culture of dialogue and co-development, with regular workshops, meetings and exchanges, ensuring that ECMWF's services evolve hand-in-hand with user requirements.

FORECAST AND REANALYSIS PRODUCTS ACROSS TIMESCALES →

At the heart of ECMWF's ecosystem of forecast products are the ensemble-based configurations across multiple timescales – medium-range, sub-seasonal and seasonal. While the detailed evolution of the forecasting system is discussed elsewhere, it is worth recalling that the introduction of ensemble-based forecasts in 1992 marked a fundamental shift in quantifying uncertainty in weather forecasting. This was complemented by the launch of seasonal forecasting in 1997, which also established a multi-model capability through the EUROSIP initiative. This initiative laid the groundwork for the seasonal multi-system forecast within the Copernicus Climate Change Service (C3S) (see the ECMWF 50th anniversary paper on Copernicus at ECMWF). The sub-seasonal (monthly) forecast system, introduced in 2004, bridged the gap between medium- and long-range prediction (see Figure 1).

Figure 1: A timeline of key forecasting developments at ECMWF.

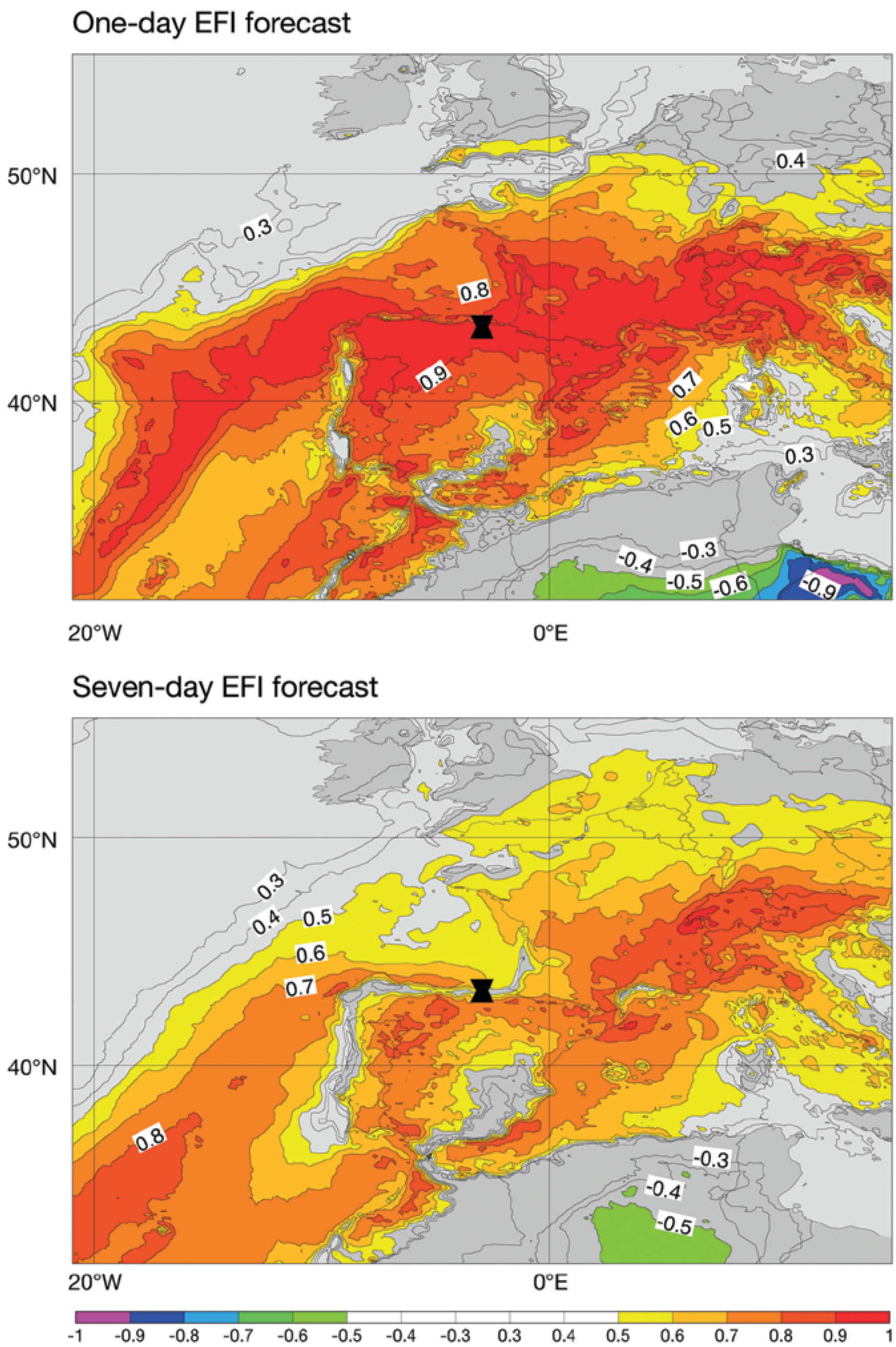


ECMWF products are now routinely used in the operational forecasting chains of Member and Co-operating States, as well as in downstream applications across various sectors. Forecast data serve as inputs for limited-area models (LAMs) and drive a wide range of models, including ocean, wave, atmospheric composition, hydrology, dispersion, and oil-spill forecasting (Hewson and Chevallier, 2024). Such applications also include environmental forecast products provided by ECMWF in the context of Copernicus, such as those offered through the Copernicus Atmosphere Monitoring Service (CAMS) and the Copernicus Emergency Management Service (CEMS) (see the ECMWF 50th anniversary paper on Copernicus at ECMWF). In parallel, the need for calibrated products from the ensemble forecast has led to the delivery of re-forecast (hindcast) sets for each configuration, used to estimate a “model climate” or assess forecast skill.

With the increased focus on supporting Member States in forecasting severe weather events, ECMWF has built derived products to enable forecasters to extract the appropriate information. The overall philosophy was that ECMWF should provide generic products to support forecasters, helping them extract relevant information from the ensemble to inform their decision-making, particularly for early warnings and impact-based forecasting. When ensemble forecasts were first introduced, a limited number of products was available. This included “stamp” maps, displaying all ensemble members’ solutions, probability maps, “plume diagrams” showing the evolution of a small number of surface parameters through the forecast range for selected locations, and cluster products. The product set has now evolved to encompass a wide range of data and products that provide information tailored to meet the needs of different users. Web-based platforms like ecCharts (Lamy-Thépaut et al., 2013) and OpenCharts have further expanded access, allowing forecasters to visualise and interpret ensemble forecast outputs interactively. They include diverse flavours of meteograms, from general surface weather parameters to visibility ranges and precipitation types, leveraging enhanced representation of physical processes in the Integrated Forecasting System (IFS).

A key success story is the Extreme Forecast Index (EFI, see Figure 2) (Lalaurette and van der Grijn, 2003; Zsótér, 2006), introduced in 2003. Developed following the two destructive 1999 storms (named Lothar and Martin), the EFI identifies regions where the ensemble forecasts predict unusually severe weather compared to the model’s own climatology, as assessed using re-forecasts over the past 20 years. It was complemented in 2010 with the Shift of Tails (SOT) index, designed to highlight when the most extreme values in the ensemble forecast shift significantly from the model’s climate extremes. Initially applied to wind, temperature, and precipitation, EFI and SOT have been extended, based on user requirements, to new variables, such as snowfall, significant wave height, and convective indices, as well as to longer forecast ranges, including sub-seasonal forecasts. EFI verification is performed routinely against station observations. Since its inception, the EFI has been regularly mentioned by forecasters as one of the most popular ensemble products, particularly relevant for impact-based forecasting, as it focuses on anomalies relative to the local climate (as opposed to predefined thresholds).

Figure 2: Extreme Forecast Index (EFI). The EFI for maximum 2-metre temperature on 23 August 2023 in a 1-day and 7-day forecast.



Another example of successful product development across timescales is ECMWF's suite of tropical cyclone products (Magnusson et al., 2021). They are based on the output of the cyclone tracker from Vitart et al. (2012). Tropical cyclone activity maps, including genesis, are produced for both medium-range and sub-seasonal forecasts. Basin-wide statistics of tropical storm frequency and accumulated cyclone energy are produced for sub-seasonal and seasonal forecasts. For medium-range forecasts, a combined product displays strike probability and track plumes, along with intensity along-track, for each active tropical cyclone (as reported at the initial forecast time by a competent designated centre). This product was enhanced in 2024/2025 to also display tracks from ECMWF's Artificial Intelligence Forecasting System (AIFS) (both AIFS Single and AIFS ENS), as well as experimental data-driven deterministic models. These tropical cyclone products have become an essential part of early warning capabilities in cyclone-prone regions and are provided to all WMO NMHSs as part of ECMWF's WMO Core data.

Collaboration with Member and Co-operating States has been central to product innovation. Many new products – such as point rainfall forecasts, the extratropical cyclone database, and the expansion of the EFI and meteograms – originated from user feedback in ECMWF Member and Co-operating States or through collaborative development projects. ECMWF regularly engages with its user base through workshops, surveys, and forums to ensure that the product portfolio meets users' needs. Feedback from Member and Co-operating States on their use of ECMWF products is also reported regularly in the so-called "Green Book" (see for example, Hewson and Chevallier, 2024).

Finally, a valuable by-product of the IFS is the generation of observation-monitoring diagnostics from the data assimilation system. These statistics provide a near-real-time assessment of the quality and impact of ingested satellite and in situ observational data. Over time, this capability has evolved into an advanced alarm system that automatically detects anomalies and data outages, enhanced with machine-learning techniques. In spring 2024, ECMWF operationalised this through a web-based observation dashboard designed to offer both high-level "traffic light" status indicators for non-specialists and interactive drilldowns for experts. All these products are publicly provided to the wider user community.

ENSURING PRODUCT QUALITY: CONTINUOUS EVALUATION AND USER FEEDBACK →

From the early days of its operations, ECMWF has systematically assessed the performance of its forecasting systems to inform both users and internal development. Forecast evaluation serves two essential purposes: providing users with insight into forecast skill and offering model developers diagnostic information to guide improvement. Together, these two functions create a feedback loop that ensures the forecasting system continues to evolve in line with both scientific advances and user needs.

Typically, an ensemble forecast should provide estimates of the probability of events which satisfy the criteria of reliability and sharpness. The forecast is considered reliable if, considering all past situations in which a given probability was forecast for a specific event, the event actually occurred with the same probability. The other desirable property of ensemble forecasts is sharpness, which is characterised by the accuracy of a probability distribution with a minimised width. Another area of interest is any day-to-day jumpiness in the forecasts, as it presents a challenge of interpretation for forecasters.

Since the early 1980s, ECMWF has published verification results to demonstrate the benefit of model upgrades and to compare configurations, including in early

Newsletter articles. A significant milestone in this verification framework came in the 2010s with the introduction of headline scores[1]. Developed jointly with Member and Co-operating States, headline scores provide a concise, standardised summary of model performance across key variables and time ranges. Initially focused on upper-air metrics – such as 500 hPa geopotential anomaly correlation and 850 hPa temperature continuous ranked probability skill score (CRPSS) – the set was later expanded to the sub-seasonal range, and to include near-surface indicators (e.g. fraction of large 2 m temperature errors, see Figure 3) and high-impact weather parameters (EFI). These additions reflected the growing operational importance of user-relevant parameters and the need to evaluate not just average skill, but also extreme event prediction.

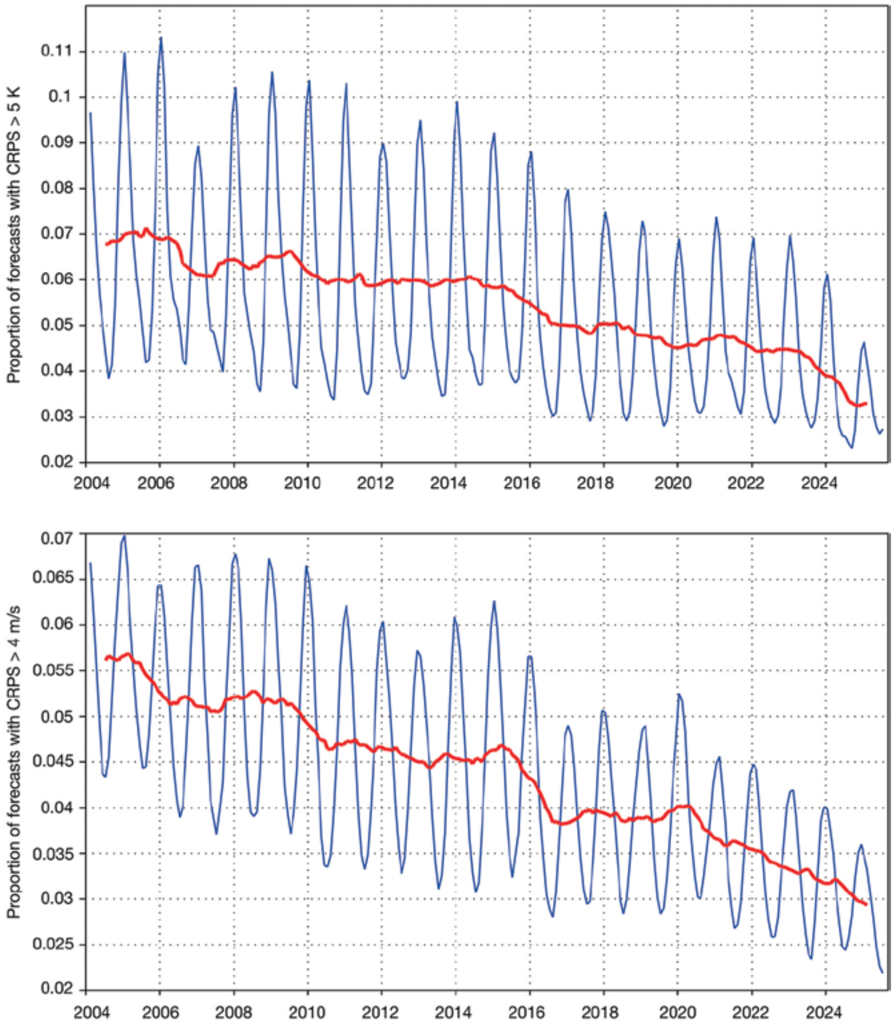


Figure 3: Evolution of the fraction of large IFS-ENS 2 m temperature errors (CRPS > 5 K, top) and 10 m wind speed errors (CRPS > 4 m/s, bottom) at forecast day 5 in the extratropics. Verification is against SYNOP observations. 12-month running mean shown in red, 3-month running mean in blue.

Continuous work has been undertaken to enhance forecast verification. First, by defining more user-relevant measures, as exemplified by the introduction of supplementary headline scores for near-surface parameters. Then, by defining measures that are informative about model developments, particularly with increased resolution (double penalty effect – see Lledó et al., 2023). Verification of precipitation forecasts has been a specific focus, for example, stimulating concerted efforts among Member and Co-operating States to collect high-density observational data (Haiden and Duffy, 2016). Finally, with the increasing complexity

1 https://www.ecmwf.int/en/forecasts/quality-our-forecasts

of the IFS and increased visibility of IFS outputs, it has become necessary to expand ECMWF's verification capability to other Earth system components through collaborative efforts and leveraging third-party projects.

An annual report summarises recent verification results of ECMWF's systems (e.g. Haiden et al., 2024), which are also presented in various fora. Member States also provide input and feedback on ECMWF forecast quality. This began in 1980 with an annual "meeting of forecasters", established by ECMWF's Technical Advisory Committee, to exchange views on the synoptic quality of the products and produce a summary assessment of forecast quality. Intelligence gained from user feedback is made accessible through the website, for instance, the known IFS forecasting issues.[2] Since 2014, the Severe Event Catalogue[3] has displayed a collection of materials for specific weather events, focusing on meteorological and environmental forecast performance and including feedback and input from Member and Co-operating States. Verification results were also made available on OpenCharts.

Another cornerstone of ECMWF's quality assurance process is daily in-house monitoring. Forecast performance is reviewed close to real time and reported each weekday, together with regular reports from forecasters in Member and Co-operating States. It is discussed weekly across the entire organisation in the internal Weather Discussion, a forum established in 2014 that supports rapid awareness of emerging issues. Quarterly meetings examine the performance of forecasting systems over the recent season. All these analyses trigger further investigation into identified model features or systematic errors, leading to immediate actions, informing priorities for future model improvements, and stimulating external collaborations. Diagnostic studies have consistently played a crucial role in understanding systematic errors, model sensitivities, and the impact of observation changes.

DATA SERVICES: FUTURE-PROOFING DATA PROVISION THROUGH FLEXIBLE CLOUD-BASED SERVICES →

One of ECMWF's objectives is to make the results of its research and operations available to Member States "in the most appropriate form". In the late 2010s, ECMWF projected a sharp rise in data volumes, from approximately 100 terabytes per day to more than 1 petabyte by the mid-2020s, while only a third of the data was being disseminated. At the same time, cloud computing and big data technologies had matured, offering the ability to process data where they reside rather than transferring massive volumes.

In December 2018, ECMWF's Council approved a pilot project, in collaboration with EUMETSAT, to establish a federated cloud infrastructure known as the European Weather Cloud (EWC). Its aim was to bring users to the data, allow access to data holdings across the European Meteorological Infrastructure (EMI), and provide flexibility beyond ECMWF's high-performance computing facility (HPCF) and ecgate services. The initiative began in 2019, and on 26 September 2023, the EWC was declared operational at ECMWF's Bologna data centre.

The EWC is the cloud-computing-based collaboration platform for meteorological applications in Europe. It consolidates computing resources, data access, and tools in one place to support data exploitation and value-added services. Users can customise and deploy workflows, co-develop new weather and climate applications, and run them close to the data, avoiding costly transfers.

The service is available to eligible users from ECMWF and EUMETSAT Member and Co-operating States, their NMHSs and public institutions, research users through Special Projects and research and development calls, and EUMETNET activities

2 https://confluence.ecmwf.int/display/FCST/Known+IFS+forecasting+issues

3 https://confluence.ecmwf.int/display/FCST/Severe+Event+Catalogue

relevant to ECMWF's mission, ECMWF Optional Programmes and certain WMO-aligned activities (see Figure 4).

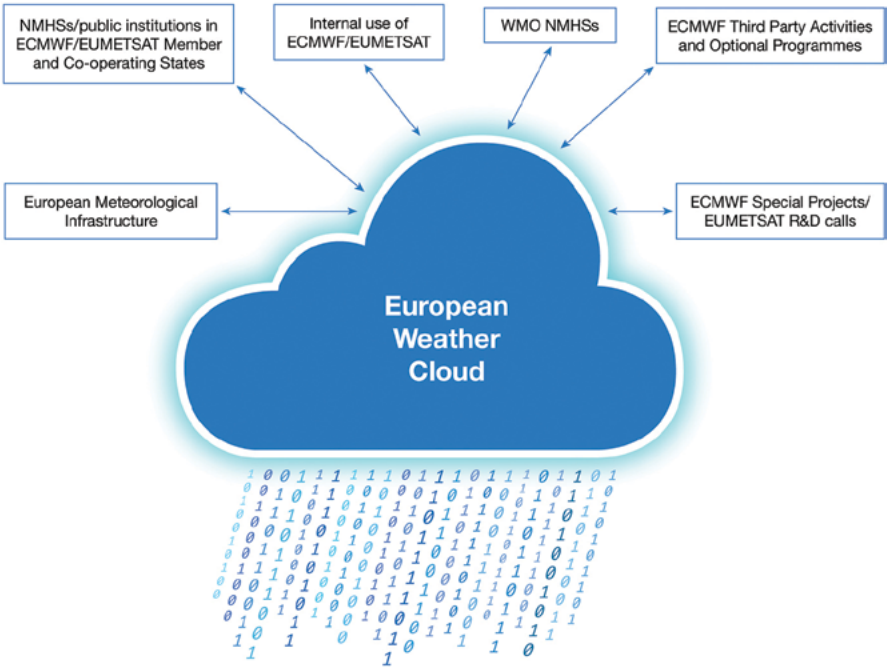


Figure 4: The European Weather Cloud service is available to different groups of users (Abellan et al., 2024).

Because it runs in the same data centre, the EWC benefits from co-location with ECMWF's broader infrastructure:

- The ECMWF Production Data Store (ECPDS) can deliver tailored data directly to EWC storage for immediate processing.
- The Meteorological Archival and Retrieval System (MARS) provides hundreds of petabytes of data with fast local access.
- The Copernicus Data Stores enable efficient API access to climate and atmospheric composition data.

The EWC complements ECMWF's high-performance computing facility (HPCF). The HPCF is best suited for large-scale parallel workloads, while the EWC provides customisable environments, such as running public web services. Integrated workflows can link the two: models run on the HPCF, with outputs post-processed and visualised on the EWC.

Over one hundred projects have utilised the EWC, encompassing a range of technical and scientific applications. Examples include:

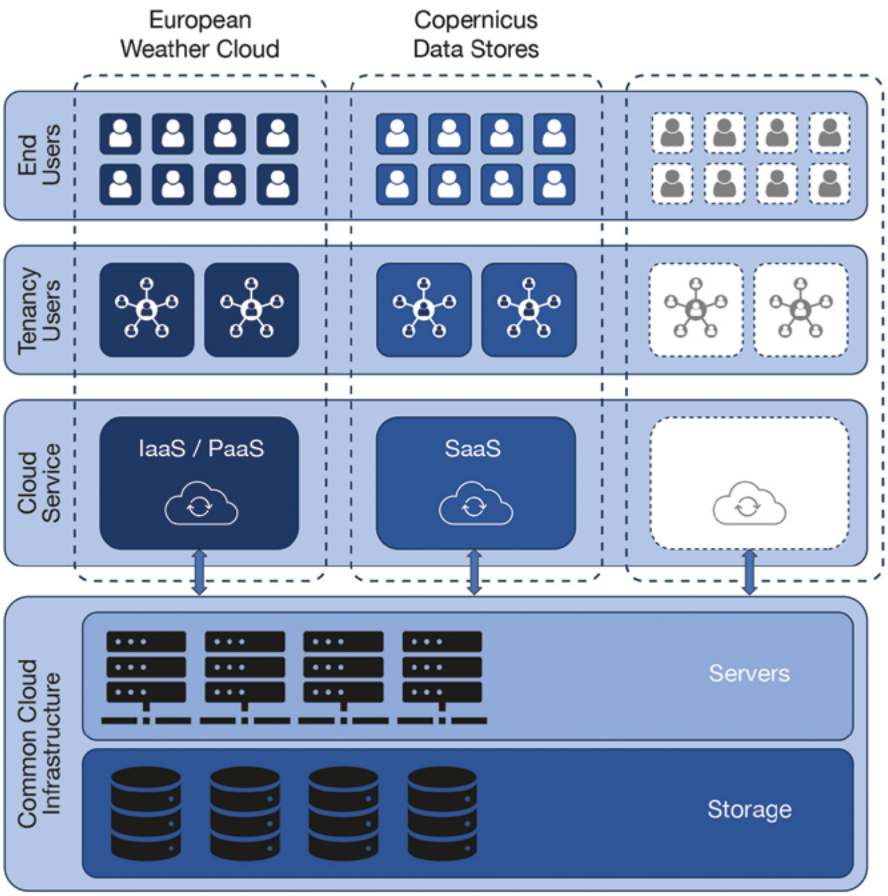
- Machine learning (ML) pilots: Member States and ECMWF collaborate on ML applications for data-driven forecasting, leveraging EWC graphical processing units (GPUs) and collaborative environments.
- International collaborations and system complementarity: a WMO multi-hazard early warning system (the South-East European Multi-hazard Early Warning Advisory System (SEE-MHEWS-A)), hosted at ECMWF. Data from the HPCF flows directly into the EWC, enabling efficient web-based services for participating NMHSs.

- Support for emergency response: in 2020, after an earthquake damaged the headquarters of the Croatian Meteorological and Hydrological Service (DHMZ), a backup system was deployed on the EWC within days, ensuring service continuity.
- System interoperability: whilst use of the EWC is primarily intended for ECMWF and EUMETSAT Member and Co-operating States, it is also available for WMO activities. Météo-France, one of the main contributors to the WMO Information System 2.0 (WIS2.0) (Fucile et al., 2023), used the EWC to host one of the core components of the WMO's new information system, showing how the EWC can interconnect with other cloud-based systems worldwide.

From pilot to operational service, the EWC has demonstrated its value in supporting diverse applications, fostering collaboration, and enabling innovation. Its growing user community benefits from tailored tools, workshops, and an active forum. ECMWF continues to improve the service in line with evolving needs, integrating it with wider initiatives such as the RODEO project[4] and ML pilot activities. The EWC is now a key element of ECMWF's data strategy: making data accessible, actionable, and collaborative for the European meteorological community and beyond.

The EWC at ECMWF is hosted within the ECMWF Common Cloud Infrastructure (CCI). This is a cloud-computing-based IT infrastructure that hosts and serves multiple projects and services offered at ECMWF. The CCI has been established in ECMWF's data centre in Bologna, Italy, co-located with other ECMWF facilities and services, including the HPCF and the Data Handling System (DHS).

Figure 5: ECMWF's Common Cloud Infrastructure (CCI) supports the European Weather Cloud, the Copernicus Data Stores and other applications and services. IaaS, PaaS and SaaS stand for 'infrastructure as a service', 'platform as a service', and 'software as a service'.



4 https://rodeo-project.eu

The CCI is also the home of the Climate Data Store (CDS) for the Copernicus Climate Change Service (C3S) and the Atmosphere Data Store (ADS) for the Copernicus Atmosphere Monitoring Service (CAMS): the main data storage system and backend for the two Copernicus operational services implemented by ECMWF on behalf of the EU. Figure 5 shows the relationship between the CCI, the EWC and the Copernicus Data Stores.

The CCI is divided into two production clouds, designated as CCI1 and CCI2. Each production cloud is hosted in a different computing hall at ECMWF's data centre for redundancy and resilience purposes.

OpenStack, a well-known open-source cloud computing software platform, is the technology used to manage these computing capabilities and expose them to various applications, services, and users. Backing the computing capabilities, approximately 5.5 PiB of usable hard-disk-drive-backed (HDD) storage and around 300 TiB of solid-state-drive-backed (SSD) storage are available on each of the two CCI cloud clusters. Ceph is the storage solution behind them, ensuring scalable and robust access to the data. This storage capacity is used for both classic block storage by the virtual infrastructure deployed in the cloud, as well as object storage using popular APIs, such as Amazon S3 and OpenStack Swift.

HIGH-PERFORMANCE COMPUTING SERVICES: ENABLING MEMBER STATE TIME-CRITICAL BIG DATA PROCESSING →

A key ECMWF objective, established in its Convention, is to make a share of its supercomputing resources available to Member States: at least 25% of HPC capacity and 10% of data storage. Since ECMWF's creation, these have been used for research and Special Projects (scientific or technical experiments of general interest).

In the early years, access to ECMWF computing was possible only via dedicated leased lines with limited bandwidth, mainly used for disseminating forecasts. The introduction of a dedicated Member State Unix system in the mid-1990s, along with Internet access, opened the way for applications to run directly at ECMWF, with outputs transferred more efficiently.

Some applications required near-real-time access to operational forecasts. To meet this need, ECMWF developed the mechanism of job submission under SMS (Supervisor Monitor Scheduler) control, enabling Member State jobs to run as soon as new data became available. By 2004, about 300 jobs from 60 users ran daily under this system, but monitoring and recovery from failures remained the users' responsibility.

As more complex requests arose (e.g. data for ocean wave forecasts, boundary conditions for deterministic and ensemble-based limited area models (such as COSMO-LEPS), ECMWF recognised the need for a formal framework. In 2004 the Council approved the framework for time-critical applications (Dando and Modigliani, 2025), offering three options:

- **TC-1:** simple time-critical job submission
- **TC-2:** Member State suites monitored by ECMWF
- **TC-3:** Member State suites managed by ECMWF

TC-1 replaced the earlier SMS mechanism. Supported by ECaccess (which gives registered users access to ECMWF's computing and archive facilities), jobs are triggered by "events" linked to ECMWF's operational schedule. Today, about 150 users run 1,800 jobs daily under TC-1, for tasks such as generating bespoke products from MARS, running trajectory calculations, analysing ensembles, or producing ENS meteograms.

TC-2 supports complex workflows, such as running limited-area models (LAMs) with ECMWF boundary conditions. Suites have high-priority HPC access and are monitored by ECMWF's 24/7 operations staff.

The first official TC-2 application, COSMO-LEPS (a limited area ensemble prediction system), was launched in July 2005, providing high-resolution ensemble forecasts of high-impact weather. Other TC-2 applications have included:

- The UK Met Office's global ensemble (MOGREPS-15)
- The pan-European GLAMEPS multi-model ensemble
- Austria's limited-area ensemble forecasting system (LAEF and later convection-permitting C-LAEF)
- The German National Meteorological Service's Boundary Condition Ensemble Prediction System - Multi Model (BCEPS MuMo)

Several Member States (e.g. Portugal, Germany, Spain and Italy) also use TC-2 to run backups of operational NWP, ensuring continuity in the event of local HPC outages.

TC-3 provides the closest integration with ECMWF operations, with ECMWF managing Member State suites and testing them during IFS upgrades. A long-running TC-3 activity provides boundary conditions for LAMs (AROME, ALADIN, ALARO) and for the MOCAGE chemistry model, with output disseminated via ECPDS. Other TC-3 suites run for Météo-France and partners.

The time-critical framework has twice been critical in emergencies. In 2012, when the Danish Meteorological Institute's HPC failed, ECMWF provided high-priority access, allowing them to continue NWP production. In 2020, following an earthquake that damaged DHMZ's headquarters, its NWP system was quickly ported to ECMWF's HPC, utilising TC framework priority access again.

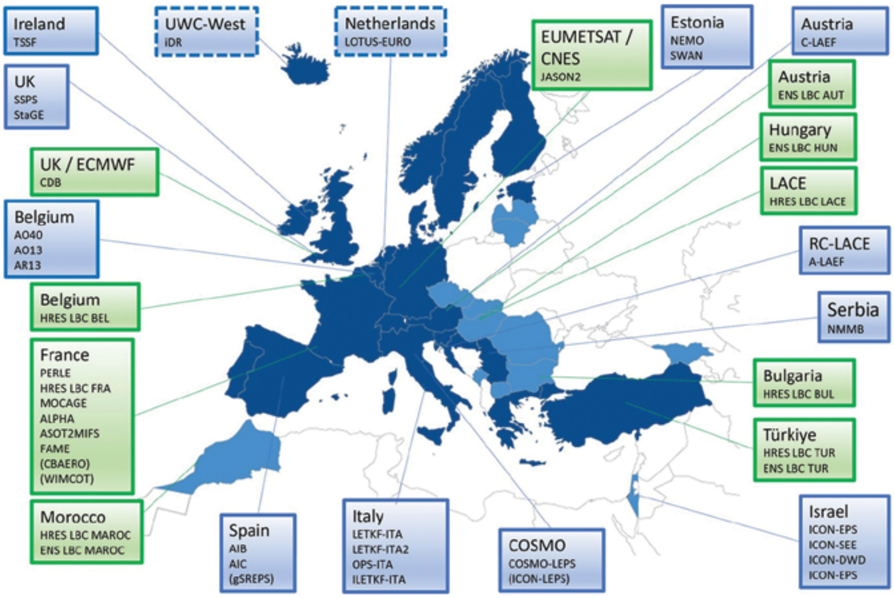


Figure 6: TC-2 (in blue boxes) and TC-3 (in green boxes) suites on 1 September 2025, grouped by country, organisation or consortia. Those in boxes outlined with dotted lines or enclosed in round brackets denote new activities expected to be approved within the following 12 months.

Twenty years on, the TC framework remains central to how Member and Co-operating States use ECMWF's HPC for time-critical activities. Around 2,000 time-critical jobs and suites now run daily (see Figure 6). A recent review considered improvements, including containerised workflows, virtual machines for ecFlow (ECMWF's workflow package) servers, and synergies with the European Weather Cloud.

The TC framework has enabled Member States to run workflows they could not easily run themselves – such as LAMs, ensemble forecasts, and large-scale post-processing – delivered routinely and on time. It continues to provide significant benefits, underpinning both resilience and innovation, and will remain a cornerstone of ECMWF's service to its Member States in the years ahead.

USER SERVICES: SUPPORTING AND ENGAGING WITH USERS →

Since its establishment, ECMWF has realised the importance of having a strong user support service. User support services are vital because they enhance productivity by helping users overcome challenges with products or systems, leading to greater job satisfaction and operational efficiency. They also benefit users by improving the user experience, making them feel supported and encouraging continued engagement.

This has been particularly relevant for ECMWF in assisting and advising users, especially in Member States, on the effective use of its products and services.

A User Support section was established almost immediately, and to facilitate communication with Member States, specific focal points, known as Computing Representatives, were created. Similarly, focal points in the User Support section were established to facilitate more direct contact with Computing Representatives. Regular meetings between ECMWF and these focal points have been organised, aiming to improve information flow in both directions and to facilitate the exchange of experiences among the focal points themselves. This allowed ECMWF to create a tight and effective community, which has enabled, over the last 50 years, access to services, their regular updates and improvements, and the introduction of new activities, such as the framework of time-critical applications or the European Weather Cloud described above. User support services have been a fundamental enabler of ECMWF's success, allowing its Member States to greatly benefit from its products and services, and will continue to be so in the next 50 years.

Equally important is the two-way engagement with ECMWF's user community. Forecast evaluation is enriched by user feedback, particularly from forecasters in Member and Co-operating States. Regular meetings with national meteorological representatives, liaison visits to Member and Co-operating States, the regular collection of input on "Use and Verification of ECMWF forecast products in Member and Co-operating States" ("the Green Book"), and the Using ECMWF's Forecasts (UEF) event (see Figure 7) all contribute to keeping up to date and maintaining an active, ongoing dialogue. The biennial High Performance Computing in Meteorology workshop is also one of our regular engagement activities with the HPC community (see Figure 7). Through this collaboration, users not only share insight into the strengths and limitations of ECMWF forecasts but also shape the evolution and development of new products, ensuring they meet users' needs.

Figure 7: Attendees of the 2025 edition of the Using ECMWF's Forecast (UEF) event (above) and the 21st High Performance Computing in Meteorology workshop (below), both held in Bologna 15–19 September 2025, as part of the 50th anniversary celebrations of ECMWF.

TRAINING AND OUTREACH →

Training and capacity building are central to ECMWF's mission of fostering skilled and informed users. Our training programme spans advanced numerical weather prediction (NWP), ensemble forecasting, seasonal and sub-seasonal techniques, and cutting-edge domains such as machine learning (ML). Courses range from week-long in-person sessions to Massive Open Online Courses (MOOCs) and target diverse audiences: forecasters, scientists, data analysts, and computing specialists. These programmes are aligned with broader initiatives such as Copernicus services and Destination Earth.

ECMWF extends its educational impact through partnerships with the WMO, EUMETSAT, ESA, and national meteorological services, delivering joint training that deepens competence across the European meteorological community. Tailored course offerings are regularly co-organised under the Copernicus Climate Change Service (C3S) and Copernicus Atmosphere Monitoring Service (CAMS) National Collaboration Programmes, embedding training into national capacity-building efforts. These collaborative efforts extend beyond coursework to include workshops, seminars, and webinars – particularly important for onboarding new Member and Co-operating States and strengthening ties with global partners.

Looking ahead, ECMWF plans to further diversify and democratise its educational efforts by scaling-up online learning, launching new MOOCs on climate monitoring, expanding ML course offerings, and establishing new training facilities in Bonn. A deeper emphasis on "training by doing together" – wherein participants actively collaborate on real-world problems – highlights ECMWF's aspiration to foster an EU-wide community of skilled users capable of harnessing advanced NWP tools in support of societal resilience.

CONCLUSION

Over the past 50 years, ECMWF has developed a comprehensive ecosystem of forecast and analysis products that spans multiple timescales and Earth system components. This ecosystem is underpinned by a versatile and robust operational infrastructure that enhances data accessibility, enabling users to explore, transform, and apply ECMWF data in diverse operational and research contexts. Collaborations with Member and Co-operating States, as well as EU programmes such as Copernicus and Destination Earth, research projects, and international partnerships (e.g. with the WMO) have played an instrumental role, acting as powerful multipliers of value and extending the reach and impact of ECMWF products and services.

Since 1 October 2025, all data in the ECMWF Catalogue of real-time products have been available under a CC-BY-4.0 open licence, with a core subset freely accessible at 0.25 degrees resolution and delivered without additional delays compared to operational availability. This milestone marks the start of a new era of open data at ECMWF, with further expansion planned for 2026 and beyond through a tiered approach that will gradually open higher-resolution products. By partnering with cloud providers and harmonising catalogues and APIs across ECMWF, Copernicus and Destination Earth, ECMWF aims to make data discovery and access more seamless, aligned with European data space initiatives. At the same time, user experience will be enhanced with streamlined documentation, integrated dashboards, and AI-powered support.

The open data policy strengthens ECMWF's role in providing greater support to WMO national meteorological and hydrological services. This effort is further enabled by stronger relationships with WMO programmes, such as recent initiatives like the WMO's Systematic Observations Financing Facility (SOFF). This also includes the recent European initiative "Strengthening Early Warning in Africa" under the Africa–EU Space Programme.

Beyond data access and computing services, ECMWF offers specialised software packages tailored to the needs of national meteorological services. With ECMWF's robust software suite (now known as ECMWF software EnginE (ESEE)), ECMWF Member States have access to a powerful suite of software tools for efficiently retrieving, processing, and analysing the vast meteorological data archive maintained by ECMWF. Some of these software packages are already co-developed with Member States. This empowers Member States to not only leverage ECMWF's data for their own forecasting models but also seamlessly integrate them with their national observational networks and research datasets.

Today, the user base of ECMWF is broader than ever before. Access to open and free products has brought ECMWF data to new audiences, while traditional users are still at the heart of our user base and continue to rely on ECMWF for critical operational applications. The number of active users across data services, web platforms, and training initiatives illustrates both the scale of the community and the trust placed in ECMWF outputs. This expansion highlights the growing demand for accessible data that can be applied across various sectors to anticipate high-impact weather events and support informed decision-making.

Such growth also brings new responsibilities. The pressure to respond to an increasing number of users with diverse and sometimes competing needs underscores the importance of staying focused while remaining collaborative.

Engagement with Member and Co-operating States, together with mechanisms for user feedback, has been – and will remain – instrumental in ensuring that ECMWF products meet the highest standards of quality, while being adapted to evolving requirements. Co-development, shared tools, and open dialogue are key to sustaining this balance.

Looking ahead, ECMWF is committed to further advancing its open data offering, supporting the joint development of a European meteorological data space, and integrating machine learning both as a source of new capability and as a tool to improve accessibility, interpretation, and delivery. The AI/ML revolution in weather and climate forecasting, described in the ECMWF 50th anniversary paper on machine learning, will certainly be an additional stimulus for the review of products and the means of providing them. It will prompt ECMWF and its Member and Co-operating States to reconsider their workflow and how to best integrate ECMWF forecast products and services. These efforts will ensure that ECMWF data remain not only scientifically excellent but also user-oriented, easily accessible, and actionable.

The story of ECMWF's first 50 years has been one of doing things together: building world-leading forecast systems through shared infrastructure, co-developed tools, and close engagement with its community of users. The next 50 years will continue this journey, harnessing Earth system science, AI, technology, open data, and collaboration to maximise the societal impact of forecasts – helping more users, enabling and supporting them in the best way, and ensuring that the products developed together deliver lasting value to society.

CONTRIBUTORS

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REFERENCES →

Abellan, X., V. Baousis, R. Correa, R. Cuccu, C. Duma, C. Kominos, S. Langlois & **U. Modigliani**, 2024: The European Weather Cloud is now operational. *ECMWF Newsletter* **No. 180**, 37–43. https://doi.org/10.21957/xawe573ul9

Dando, P. & U. Modigliani, 2025: Twenty years of the Framework for Member State time-critical applications. *ECMWF Newsletter* **No. 182**, 24–32. https://doi.org/10.21957/p31dmu80sd

Fucile, E., J. Tandy, T. Kralidis & **R. Giraud**, 2023: WIS 2.0: WMO data sharing in the 21st century. *ECMWF Newsletter* **No. 176**, 35–39. https://doi.org/10.21957/rg3f1ky704

Haiden, T. & **S. Duffy**, 2016. Use of high-density observations in precipitation verification. *ECMWF Newsletter* **No. 147**, 20–25. https://doi.org/10.21957/hsacrdem

Haiden, T., M. Janousek, F. Vitart, M. Tanguy, F. Prates & **M. Chevalier**, 2024: Evaluation of ECMWF forecasts. *ECMWF Technical Memorandum* **No. 918**. https://doi.org/10.21957/52f2f31351

Hewson, T. & **M. Chevallier**, 2024: Use and Verification of ECMWF products. *ECMWF Technical Memorandum* No. 919. https://doi.org/10.21957/734d5d4d39

Lalaurette, F. & **G. van der Grijn**, 2003: Ensemble forecasts: Can they provide useful early warnings? *ECMWF Newsletter* **No. 96**, 10–18. https://www.ecmwf.int/en/elibrary/78236-newsletter-no-96-winter-200203

Lamy-Thépaut, S., C. Sahin & **B. Raoult**, 2013: ecCharts service. *ECMWF Newsletter* **No. 134**, 7–9. https://www.ecmwf.int/en/elibrary/78196-newsletter-no-134-winter-201213

Lledó L., T. Haiden, J. Schröttle & **R. Forbes**, 2023: Scale-dependent verification of precipitation and cloudiness at ECMWF. *ECMWF Newsletter* **No. 174**, 18–22. https://doi.org/10.21957/c92loli749

Magnusson, L., S. Majumdar, R. Emerton, D. Richardson, M. Alonso Balmaseda, C. Baugh et al., 2021: Tropical cyclone activities at ECMWF. *ECMWF Technical Memorandum* **No. 888**. https://doi.org/10.21957/zzxzzygwv

Vitart, F., F. Prates, A. Bonet & **C. Sahin**, 2012: New tropical cyclone products on the web. *ECMWF Newsletter* **No. 130**, 17–23. https://doi.org/10.21957/ti1191e2

Zsótér, E., 2006: Recent developments in extreme weather forecasting. *ECMWF Newsletter* **No. 107**, 8–17. https://doi.org/10.21957/kl9821hnc7

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