Fifty years of Earth system modelling at ECMWF

ADVANCING WEATHER SCIENCE
THROUGH COLLABORATION

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ABSTRACT

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Earth system modelling at ECMWF has been a story of growth and success during the past 50 years. The first operational medium-range forecast was produced on 1 August 1979 and the first ensemble predictions on 24 November 1992. The number of simulated parameters at all grid points spanning the global atmosphere at a given time represented in ECMWF's Integrated Forecasting System (IFS) simulations went from below 1 million (208 km grid spacing, 19 vertical levels) to 452 billion (9 km, 137 vertical levels, 51 ensemble members), with single forecast predictions in research mode simultaneously involving more than 1,400 billion prediction points (0.7 km grid spacing, 137 vertical levels). The investment in physical modelling has brought world-leading advances in numerical methods and physical parametrizations for radiation, boundary-layer turbulence, convection and cloud processes. These innovations have been developed and implemented in collaboration with many Member and Co-operating States and the wider international science community.

The growing interest in prediction at sub-seasonal and seasonal timescales, as well as the growing availability of satellite data, has fostered a continuous increase in resolution and complexity of ECMWF's IFS, including extensions to represent the stratosphere, land-surface processes, ocean, sea ice and surface waves.

Targeted developments to describe initial and model process uncertainties have resulted in their trustworthy representation, and a single forecast realisation has expanded into ensembles with 51 simultaneous members, providing information on a range of different weather scenarios at time ranges from a few days to a season ahead. Moreover, the use of a variational data assimilation algorithm to create the initial conditions for successful forecasts mandated the development of tangent-linear and adjoint model versions.

The addition of a range of aerosols and chemical species as well as greenhouse gases such as CO_2, CH_4, and ozone, together with coupling to relevant chemistry models, facilitated operational atmospheric monitoring forecasts that are part of the EU Copernicus Atmosphere Monitoring Service.

Building on the IFS and other models, the EU Destination Earth initiative goes a step further in building digital twins of the Earth system to harness the power of global kilometre-scale simulations, with a high level of interactivity, and which feed the growing demand of impact sector models.

All these developments are embedded in the exponentially growing supercomputing capacity of chip, storage and networking technologies, fostering both scientific and technological evolutions, resulting in the IFS becoming one of the world's most efficient, massively parallel Earth system models and one of the leading applications of exascale supercomputing.

The model development at ECMWF is a pertinent example of what can be achieved with a common goal. An incredible amount of help and support from scientists all over the world has influenced the progress and success in both physical and now data-driven modelling. In return, ECMWF has continued to share its knowledge of how to address today's and future prediction challenges in a changing climate.

INTRODUCTION →

In 1979, the European Centre for Medium-Range Weather Forecasts (ECMWF) started to disseminate weather predictions with the remit to provide skilful and reliable medium-range forecasts to its Member States. Countries had to consider the financial and political investment in a European approach to medium-range forecasting during a time when such forecasts were not yet considered useful (see Woods (2005) for anecdotes).

The 1st ECMWF technical newsletter (1979) stated:
"The central premise of the development of these operational forecasts is that the atmosphere may be regarded as a compressible fluid, its behaviour being described by the Navier-Stokes equation and the thermodynamic equations concerned with sources, sinks and the transfer of energy."

Key for success was careful attention to the initial state of such forecasts by means of data assimilation, the physics governing the non-linear evolution of the Earth system, and the balance between accuracy and cost when solving the discrete form of these equations on the latest available high-performance computing (HPC) architectures. The model development at ECMWF was thus driven by what could be reasonably initialised considering new prognostic variables, the accurate representation of the non-linear evolution of physical processes, and the overall efficiency of execution in a parallel (multi-node) computing environment.

From the beginning this necessitated a suitable infrastructure, later termed the Integrated Forecasting System or IFS, used in both forecasts and data assimilation. In close collaboration with Météo-France, the code infrastructure of the IFS and ARPEGE (Action de Recherche Petites Echelles Grandes Echelles)[1] was born and "many scientific projects, sub-projects, and operational and research options have been built around this initial code since then, covering both data assimilation and forecasting aspects" (Pailleux et al., 2014).

This paper provides an overview of the Earth system model developments at ECMWF during the past 50 years, gives an update on what Earth system modelling entails today, and outlines how Earth system modelling will likely evolve in the future. It will tell the story of how an atmosphere-only model running on a single megaflop compute chip has turned into an Earth system model that is running at kilometre-scale resolution on exascale supercomputers and is used seamlessly for a variety of forecast products from days to seasons, for numerical weather prediction (NWP), climate scenarios and environmental forecasts.

1 ECMWF and Météo-France share a common global NWP software, termed IFS by ECMWF and ARPEGE by Météo-France.

FIFTY YEARS OF EARTH SYSTEM MODELLING AT ECMWF →

A MODEL OF THE GLOBAL ATMOSPHERE

The first ECMWF operational model in 1979 was a finite-difference grid-point model of the global atmosphere with 48 computed latitudes (today we have 2,560) and 15 vertical levels, and with the first physical parametrizations inspired primarily by early collaborations with the Geophysical Fluid Dynamics Laboratory (GFDL). In April 1983, a spectral model was introduced at ECMWF, building on significant developments of the spectral transform method (independently promoted by Eliasen et al. (1970) and Orszag (1970)). In addition, ECMWF developed a fast Fourier transform (Temperton, 1983) that facilitated the dual representation of global prognostic variables in spectral space and grid-point values at specific latitude-longitude locations that satisfied quadrature rules to determine the prognostic variables of temperature, wind, pressure and moisture (Temperton, 1991; Wedi et al., 2013, 2014).

" OPERATIONAL FORECASTS BEGAN AT ECMWF IN 1979 AND THE INTEGRATED FORECASTING SYSTEM CODE, DEVELOPED JOINTLY WITH MÉTÉO-FRANCE, WAS INTRODUCED IN MARCH 1994. THE INTEGRATED FORECASTING SYSTEM AND ITS CONTINUING DEVELOPMENT REPRESENTS A HUGE AND HIGHLY SUCCESSFUL COLLABORATIVE EFFORT WITH OUR MEMBER AND CO-OPERATING STATES AND MANY OTHERS."

The original spectral model was replaced by the IFS/ARPEGE code, with its first operational use at Météo-France in October 1993, when a stretched-tilted version of ARPEGE became operational, and at ECMWF in March 1994. The efficiency of time-stepping was boosted by a very stable semi-implicit solution procedure (Simmons et al., 1978; Benard, 2003) and an efficient two time-level semi-Lagrangian atmospheric transport scheme (Temperton et al., 2001).

The success and superior efficiency of the semi-Lagrangian, semi-implicit, spectral transform method in NWP, in comparison to alternative methods, has been overwhelming, and many operational forecast centres made the spectral transform their method of choice (Williamson, 2007), although several modelling centres have subsequently adopted alternative approaches. In contrast to the expectations of many modelling experts across the world, ECMWF still successfully

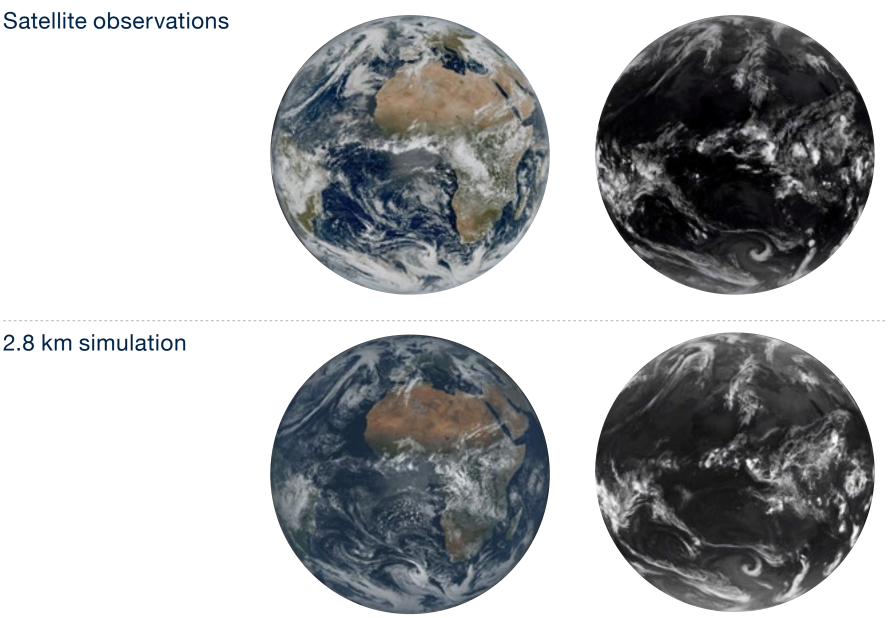
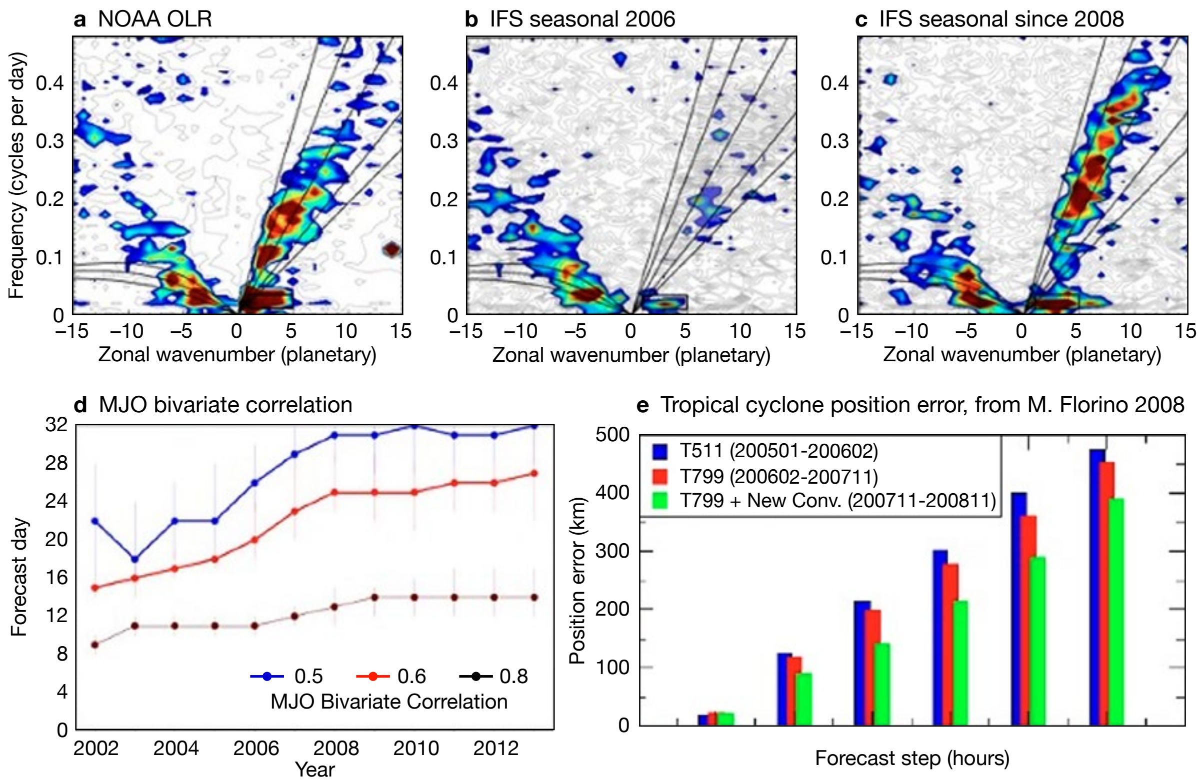


Figure 1: The detail and realism of a cutting edge 2.8 km simulation with the IFS is a striking demonstration of the progress in Earth system modelling at ECMWF over the last 50 years. Digital twinning of a 2.8 km simulation (bottom) compared to the latest in European satellite technology, EUMETSAT's Meteosat Third Generation MTG-I (top), compared in observation space during the day (left) and at night (right), from the inverse observation operator applied to the hydrostatic IFS model fields (images created by Philippe Lopez, ECMWF).

uses the spectral transform method in operations today, with significantly increased performance and horizontal resolution (Wedi 2014; Malardel et al., 2016). The numerical accuracy and stability were improved with a vertical finite element scheme (Untch and Hortal, 2004), allowing the vertical extension of the model into the stratosphere to accommodate the increasing number of satellite observations in the middle atmosphere and to exploit potential gains in longer term predictability; see Polichtchouk et al. (2021) for a review.

The Navier-Stokes and thermodynamic equations are fundamental to predictions using physical models, but their numerical solution and the non-linear transfer of energy across scales of motion can be impacted by the solution procedures and approximations. One extremely successful (stable and efficient) approximation still made in routine ECMWF forecasts is the hydrostatic approximation, although this is being continuously reviewed, with the ultimate aim of relaxing the approximation in ECMWF's global applications (cf. Wedi and Smolarkiewicz, 2009; Zeman et al., 2021). Non-hydrostatic models are routinely used in limited-area, high-resolution applications across weather services today (Bubnová et al., 1995; Benard et al., 2010) and increasingly in global forecast systems (Wood et al., 2014; Zängl et al., 2015). Research at ECMWF continues to investigate stable and efficient non-hydrostatic modelling frameworks for global kilometre-scale applications on emerging HPC (e.g. Smolarkiewicz et al., 2014; Voitus et al., 2019; Kühnlein et al., 2019; Melvin et al., 2024), in comparison with competitive hydrostatic reference solutions (Wedi et al., 2020; Rackow et al. 2024) and observations (see Figure 1).

Figure 2: Wavenumber frequency spectra of the outgoing longwave radiation (OLR) from NOAA data (a) and from multi-year integrations with the IFS using the operational cycle in 2006 (b) and with the version that became operational in 2008 (c); the Madden-Julian Oscillation (MJO) spectral band is highlighted by the black rectangle. The bottom row shows (d) skill of the IFS predictions for the MJO between 2002 and 2013 as given by the bivariate correlation with the observed empirical orthogonal functions for wind and outgoing longwave radiation, a value of 0.6 (red line) delimits skilful forecasts and (e) statistics of tropical cyclone positions errors (km) as a function of forecast lead time from the 40 km resolution forecasts in 2005/6 (blue), the 25 km forecasts in 2006/7 (red) and the 25 km forecasts in 2008 (green). Reproduced from Lin et al. (2022).



The sources and sinks of energy represented by the physical parametrizations of the IFS have undergone significant evolution over time. There have been many innovative developments in atmospheric radiation (Morcrette et al., 2008, Hogan and Bozzo, 2018), convection parametrization (Tiedtke, 1989; Bechtold et al, 2001; Lin et al., 2022), cloud microphysics and extending the grid-point prognostic variables of clouds and cloud hydrometeors (Tiedtke, 1993; Forbes et al., 2011), and turbulent (Beljaars and Holtslag, 1991) and orographic drag (Lott and Miller, 1996; Beljaars et al., 2004), all contributing significantly to enhanced medium-range forecast skill. A good example of a significant breakthrough in predictive skill is the revised representation of convection during the years 2006 to 2008; see Figure 2.

The developments in physical parametrization have also made possible the growing portfolio of specialised products for a diverse and growing range of applications requiring weather information, such as different forms of hydrometeors, clear air turbulence, Extreme Forecast Indices (EFIs), convective storm triggers, hydrological parameters, and atmospheric composition and air pollution parameters.

The modelling efforts at ECMWF have been regularly scrutinised and ideas exchanged with modelling centres worldwide. This process is facilitated through ECMWF's long-standing membership of the WMO Working Group on Numerical Experimentation (WGNE[2]), pioneering intercomparison projects such as AMIP I (Gates et al., 1998), AMIP II (Branković et al., 1999), Transpose-AMIP (Williams et al., 2013), DCMIP2016 (Ullrich et al., 2017), and DIMOSIC (Magnusson et al., 2022), assessing IFS forecast model skill within an international multi-model reference and sharing common systematic model errors and approaches (Zadra et al., 2018; Frassoni et al., 2023).

All these developments have been achieved through collaboration with many Member and Co-operating State weather services and scientists worldwide, as evidenced by the literature references in this article, to drive forward the ambition of extending the predictive skill of ECMWF's forecasts. Figure 3 shows the evolution in forecast skill of 500 hPa geopotential height and exemplifies well the progress that has been made in medium-range forecasting since ECMWF's inception.

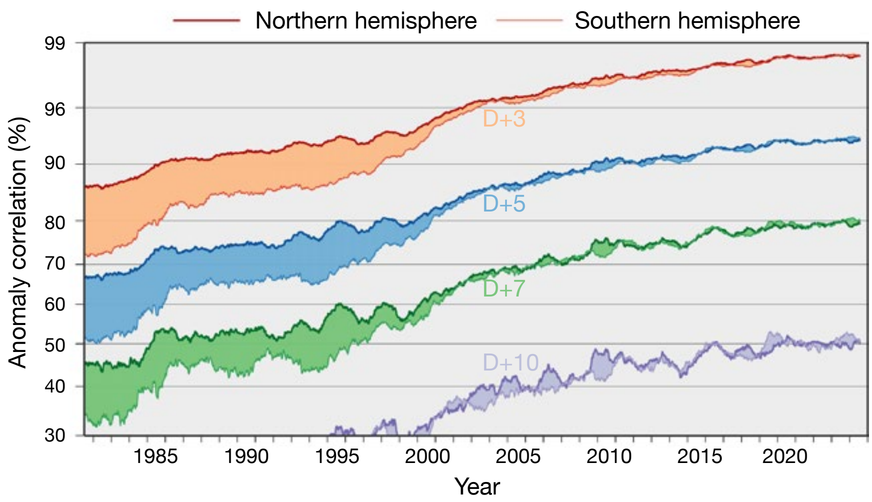


Figure 3: Anomaly correlation coefficients of 3-, 5-, 7- and 10-day ECMWF 500 hPa geopotential height forecasts for the extratropical northern and southern hemispheres, plotted in the form of annual running means of archived monthly-mean scores for the period from 1 January 1981 to 31 January 2025. Values plotted for a particular month are averages over that month and the 11 preceding months. The shading shows the differences in scores between the two hemispheres at the forecast ranges indicated. Updated version of Simmons and Hollingsworth (2002).

2 https://www.wcrp-esmo.org/working-groups/wgne

INCREASING MODEL COMPLEXITY

Extending the complexity of the IFS model in a seamless prediction approach across timescales opens the door to sub-seasonal and seasonal predictions, while offering a more complete description of the hydrological and carbon cycle required for enhanced Earth system monitoring and prediction.

The IFS system was adapted to describe the coupling between the atmosphere and the ocean through the addition of a three-dimensional ocean and sea-ice model. When introduced in 1997, this approach was only used for seasonal ensembles, before being extended to the sub-seasonal range. In 2018, the same coupled system was introduced across all forecast ranges (Buizza et al., 2017). The ocean component in both the model and the assimilation activities is based on the NEMO[3] ocean model and the associated NEMO sea-ice engine (now SI3). Alternatively, the IFS can be coupled to the FESOM-2 ocean and sea-ice model (Koldunov et al., 2019). This is done in Destination Earth[4] to create alternative warming scenarios and to explore alternative ocean discretisations in view of their scalability and skill in kilometre-scale simulations (Rackow et al., 2024).

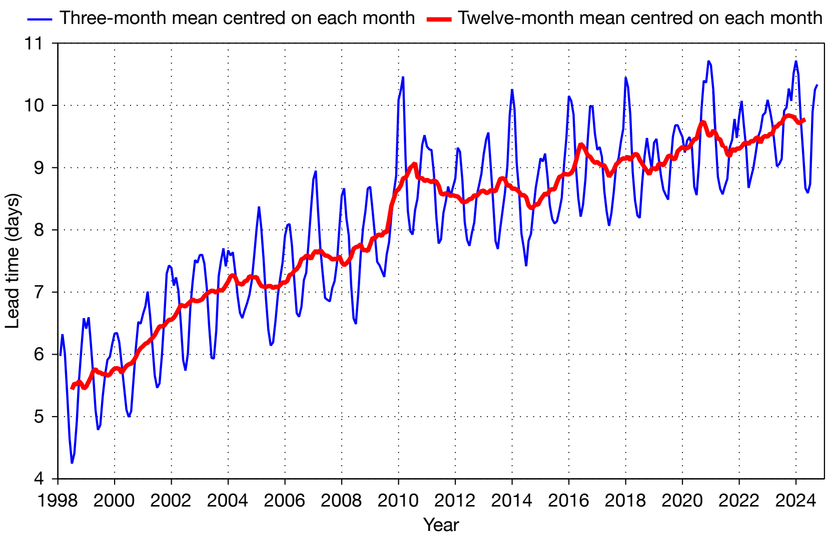


Figure 4: The graph shows the number of days into the future that the ensemble system provides useful forecasts of 850 hPa temperature for the northern hemisphere extratropics and how this has evolved over time. Useful is defined by a particular global verification metric (the continuous ranked probability skill score (CRPSS)) reaching a certain level (25%). A CRPSS score of 100% represents a perfect forecast, while 0% represents a system with no skill (compared with using long-term time averages).

The coupling between wind and waves, non-linear surface wave–wave interactions and ocean freak waves (Janssen, 2004, 2013), also has a long history at ECMWF with co-development of the surface wave model WAM (now ecWAM), which began in 1991. In the context of ocean–atmosphere coupling, turbulent effects on the ocean mixed layer have been included and wave–ice interactions are to be added in 2025. Recent improvements in the air–sea interface had significant impact on the accurate representation of extreme events (Majumdar et al., 2023).

In the same spirit, a range of land-surface interactions were added (Balsamo et al., 2009; Agustí-Panareda et al., 2014; Boussetta et al., 2021). This brought to the forefront the accurate and stable coupling across land and ocean boundary layers and the atmosphere (Best et al., 2004; Beljaars et al., 2018 for a review). In recent intercomparisons of latent and sensible heat fluxes at land observation sites, physics-based land-surface models including the IFS schemes are shown to be correct most of the time, but are still outperformed, especially in extremes, by relatively simple, out-of-sample empirical models (Abramowitz et al., 2024). This raises interesting new research questions on the required complexity of boundary layer parametrization, machine learning (ML), and parameter calibration.

3 https://www.nemo-ocean.eu/doc/

4 https://destination-earth.eu/

The step to use variational data assimilation (see ECMWF 50th anniversary paper on data assimilation) mandated the development of corresponding tangent-linear and adjoint models for both the IFS model dynamics and the physics (Mahfouf, 1999; Janiskova et al., 1999). This required highly challenging, bespoke developments, both technical and scientific, and a continuous process is needed to match and ensure compatibility with proposed innovations in the non-linear model. The rigour of this process equally ensured the quality of both the non-linear and tangent-linear models.

" IN 1992, ECMWF AND THE NATIONAL CENTRES FOR ENVIRONMENTAL PREDICTION (NCEP) WERE THE FIRST TO INTRODUCE OPERATIONAL ENSEMBLE FORECASTS. TODAY, ENSEMBLES ARE AT THE HEART OF ECMWF'S FORECASTS ACROSS MEDIUM, SUB-SEASONAL AND SEASONAL TIMESCALES."

In 1992, ECMWF and the National Centers for Environmental Prediction (NCEP) were the first to introduce operational ensemble forecasts (Buizza, 2019), initiating a distinct shift in thinking about uncertainty in weather forecast products. While the ECMWF high-resolution forecast (HRES) has been a distinct feature of the product spectrum, ECMWF concludes this shift in thinking towards ensembles at the core of medium-range weather prediction, by discontinuing HRES in 2025 and producing instead a data stream with an ensemble of forecasts (ENS) plus a single unperturbed control. Ensembles are at the core of ECMWF's forecasts across the medium, sub-seasonal and seasonal forecast ranges and they support a range of environmental services. Addressing the fundamental question of predictability using ensemble prediction forecasts, which span the envelope of likely and less likely outcomes, culminates today in forecast statistics derived from an ensemble of 50 perturbed high-resolution (9 km) ensemble members (accounting for a range of initial and model uncertainty) (plus ENS control) instead of a single deterministic forecast (Buizza and Palmer, 1995; Leutbecher et al., 2017; Lang et al., 2021). Figure 4 indicates how the skill of ECMWF ensemble forecasts has increased significantly over the past 33 years of operational use.

Moreover, the extension of ensemble predictions to sub-seasonal (Ferranti et al., 1990; Vitart et al. 2008, 2017) and seasonal (up to 1 year or more ahead, e.g. Johnson et al., 2019) time ranges added to ECMWF's product portfolio. Providing anomalies in sub-seasonal and seasonal range predictions requires robust background statistics. These statistics can be from a model climate, derived from hindcasts, or from ensemble re-forecasts made using consistent initial conditions of past years, and this takes significant computational effort. Products such as the EFI make use of these forecasts.

While model complexity increased from atmosphere-only to explicitly describe exchanges with the land, hydrosphere (soil, snow, rivers and lakes), ocean, sea ice, and waves, atmospheric composition is another key ingredient in the IFS. The description of all these processes is key to providing today's Copernicus services[5] that cover atmospheric composition, marine, land and climate monitoring. The addition of a range of aerosols and chemical species as well as greenhouse gases such as CO_2, CH_4, and ozone, together with coupling to relevant chemistry models, facilitated complementary atmospheric monitoring forecasts (e.g. depicted in Figure 5) that led to the routine offering of atmospheric monitoring services in Copernicus. Beyond monitoring, there are clear two-way interactions between the properties and evolution of the simulated atmospheric circulation and the relevant addition of atmospheric composition components. In particular, simulating the combined hydrological and carbon cycle is challenging modellers to reduce biases in transport, vegetation, land and ocean surface interactions at the highest possible resolutions to also represent anthropogenic and natural emissions (Agustí-Panareda et al., 2014, 2019).

5 https://www.copernicus.eu/

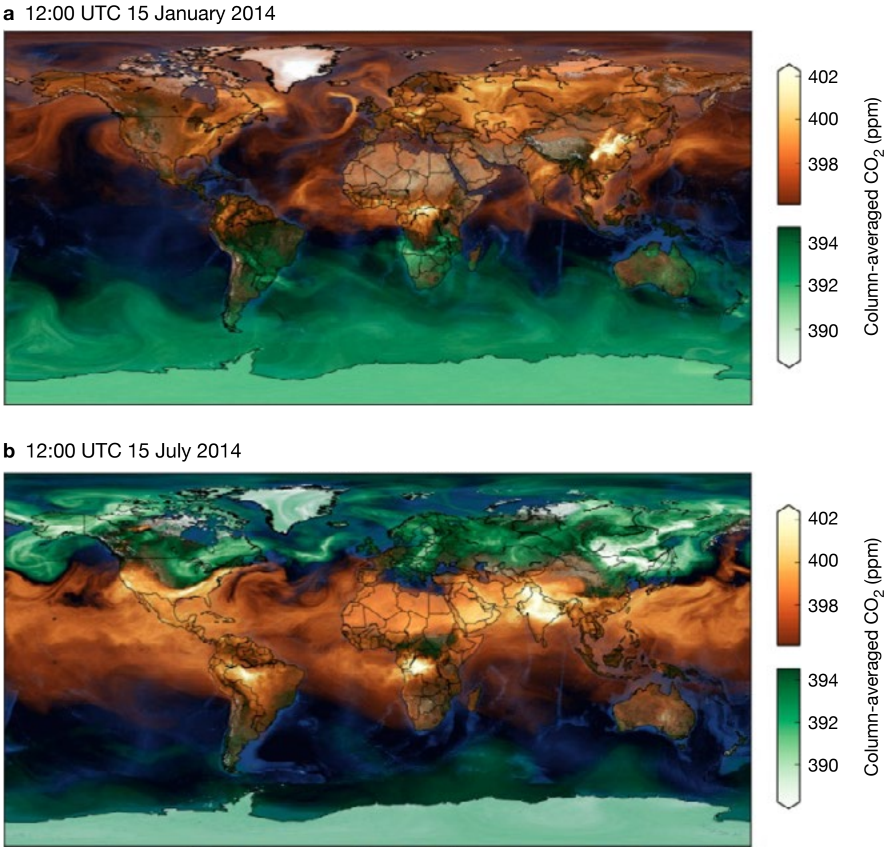


Figure 5: Snapshots of column-averaged CO_2 (ppm) above the global mean (in red colours) and below the global mean (in green colours) on 15 January 2014 (a) and 15 July 2014 (b) at 12:00 UTC from the Copernicus Atmosphere Monitoring Service global CO_2 forecast at high horizontal resolution (~9 km). Reproduced from Agustí-Panareda et al. (2019).

A SUPERCOMPUTING APPLICATION →

The time-to-solution and energy-to-solution efficiencies of the IFS model have played a significant part in the doubling of horizontal resolution every 8 years (i.e. roughly halving the distance between adjacent model grid points), depicted in Figure 6 (Schulthess et al., 2019), and significantly increasing the number of simultaneous forecast ensemble members.

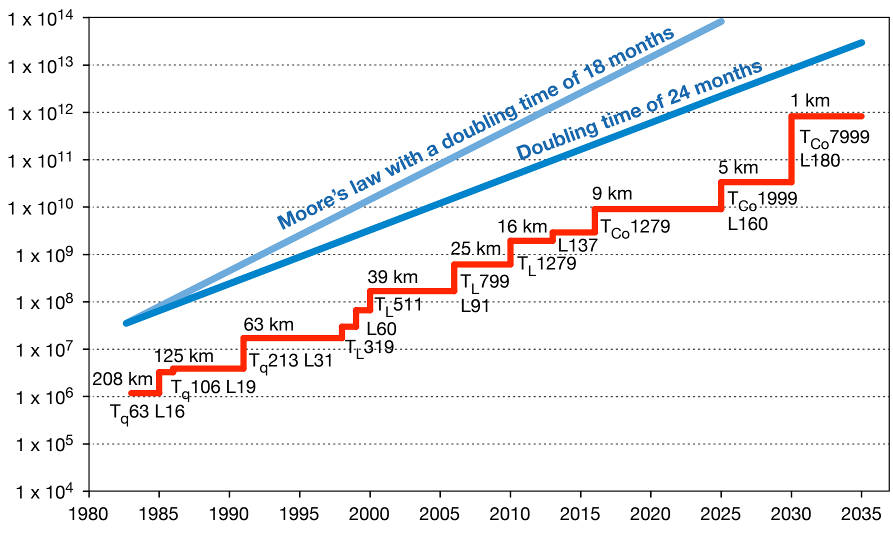
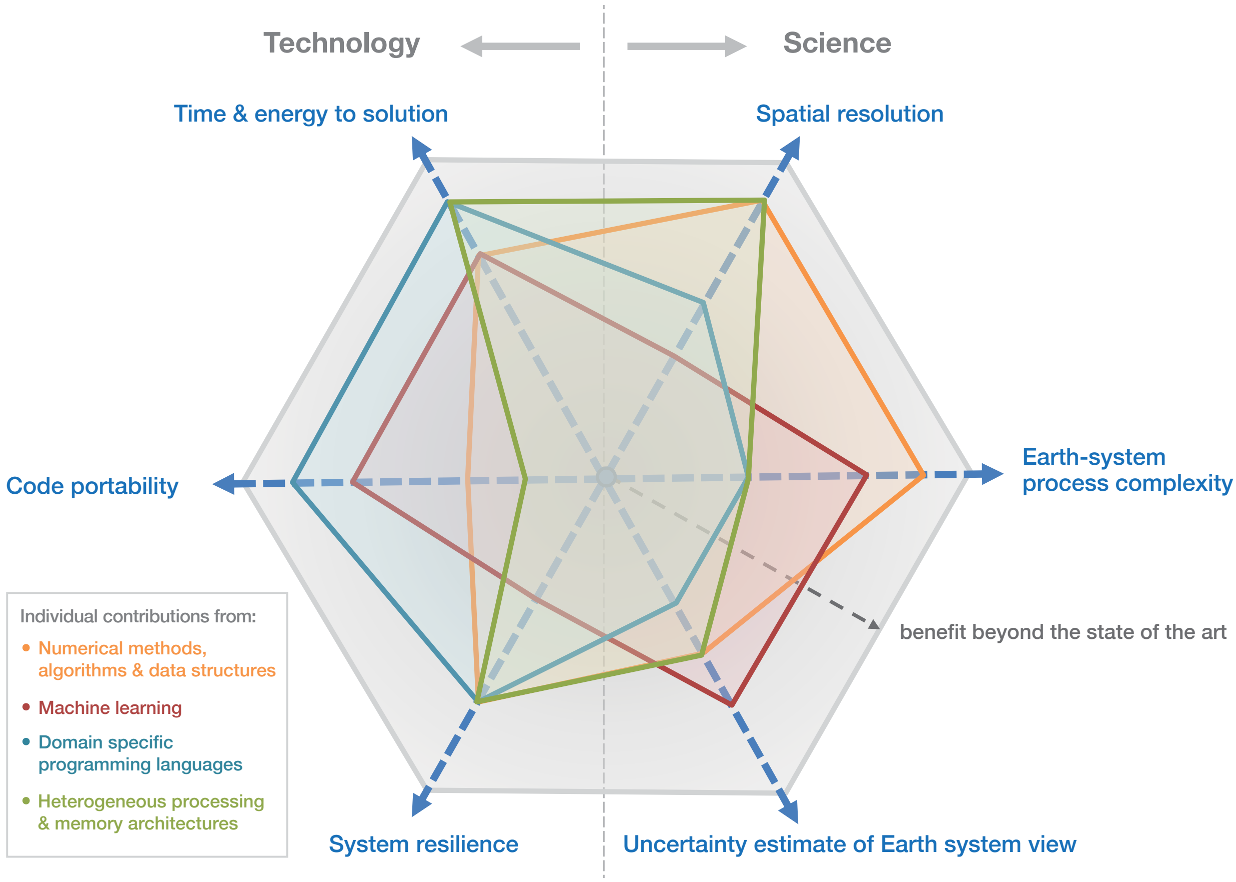


Figure 6: Steady increases in horizontal resolution (measured in degrees of freedom given by the number of grid points and vertical levels across the sphere multiplied by the prognostic variables forecast) of the IFS model at ECMWF as a result of increased computing capacity, combined with progress in numerical methods and hardware adaptation efforts. Note that the figure shows the understanding as of 2019, and while flagship simulations and research are already conducted at 1 km, their use in an operational NWP context is uncertain, as is Moore's law. The ECMWF 50th anniversary paper on high-performance computing (in preparation) provides an overview of the specific HPC evolution at ECMWF. Reproduced after Schulthess et al. (2019).

Figure 7: The expected contribution of the main system developments necessary to achieve key science and computing technology performance goals. The distance from the centre of the hexagon indicates the magnitude of the individual contributions towards enhanced efficiency for increased spatial resolution, more Earth system complexity and better uncertainty information provided by ensembles as well as resilient, portable and efficient code and workflow execution. Reproduced from Bauer et al. (2021).

With 51 members at 9 km resolution, the ECMWF ensemble is the highest-resolution global ensemble prediction system in the world today. The efficiency of the IFS has been significantly improved, arguably in equal parts by algorithmic changes, continuous refactoring, and supporting parallel computing concepts. The latter include vectorisation across multiple nodes, message passing interfaces (MPI) (Barros et al., 1995), and shared memory programming (e.g. Modzynski et al., 2015) in support of many-core architectures, and more recently accelerator offloading (using OpenMP and OpenACC programming models) in support of accelerator technologies such as graphical processing units (GPUs) (e.g. Mueller et al., 2019). New programming paradigms have been used that are not only based on modularised Fortran code (already mentioned in the 1979 ECMWF technical newsletter on the Cray!) but a mixture of Fortran, Python, C/C++, abstracting data structures such as Atlas (Deconinck et al., 2017) or the FieldAPI, and bespoke source-to-source translation tools such as LOKI[6]. One of the main motivations behind the new methods is an attempt to disentangle the tasks of HPC machine optimisation and scientific progression (known as separation of concerns) (cf. Ubbiali et al., 2025).

Together with its Member States, ECMWF has proactively invested in the Scalability Programme during the last ten years, and is continuing efforts to evolve efficiency, modularisation, coupling aspects and data structures. The announced digital revolution of Earth system science (Bauer et al., 2021) encompasses some of the different foci depicted in Figure 7.



6 https://github.com/ecmwf-ifs/loki

ECMWF'S EARTH SYSTEM MODEL TODAY →

After half a century of evolution, the IFS is still operational and efficient and has embraced many developments to serve the increasing envelope of ECMWF's activities. Today, the IFS is an Earth system model that can represent most of the relevant processes in the atmosphere, ocean, sea ice, waves and land surface, representing atmospheric chemistry and increasingly closing the water and carbon cycles.

It is used as the forecast model for NWP running medium-range 50-member ensemble forecasts and a control forecast at 9 km resolution four times a day, as well as sub-seasonal and seasonal ensemble predictions and hindcasts to build the statistics required for reliable forecasts. The IFS is also used within the Copernicus Atmosphere Monitoring and Emergency Management Services. Furthermore, past investment in the IFS has laid important foundations for today's developments in Destination Earth, which readily continues ECMWF's role in supporting the digital preparedness of its Member and Co-operating States (Wedi et al., 2025). The European community Earth System Model (EC-Earth) builds on the OpenIFS[7] framework for climate projections and Destination Earth uses the IFS in multi-decadal projections.

In Destination Earth, the IFS is combined within an innovative software framework that integrates computational, data, and application layers. This setup allows dynamic and interactive Earth system modelling, designed explicitly to simulate plausible scenarios of future weather and climate and to explore *what-if* questions. Destination Earth implements novel pathways for exploiting the geographically distributed HPC and big data infrastructure provided by EuroHPC[8]. Destination Earth advances Earth system science further by establishing an operational framework for multi-decadal, multi-model climate projections, connected to applications that transform vast climate data into actionable insights for sectors exposed to climate risks in support of both immediate and longer-term climate adaptation strategies.

The IFS is used in trailblazing daily global weather forecasts at kilometre-scale (4.4 km) as well as 5 to 10 km multi-decadal climate scenario projections. These forecasts are efficiently run routinely on several of the largest supercomputers in Europe and worldwide, including the EuroHPC machines Lumi, Leonardo and Marenostrum5. The IFS has been deployed on supercomputers in the US, including Summit and Frontier as part of several successful INCITE projects (Wedi et al., 2020; Polichtchouk et al., 2025), as well as the Fugaku supercomputer in Japan. Most recently the IFS is forming part of the JUPITER Early Access Programme, Europe's first exascale supercomputer, where the ECMWF forecast model received an "exceptionally outstanding recommendation" and has been accepted for early access on the JUPITER Booster system in 2025.

7 https://www.ecmwf.int/en/research/projects/openifs

8 https://eurohpc-ju.europa.eu/

WHAT WILL THE FUTURE BRING? →

The recent rise in pure ML models that are competitive with conventional physics-based models, in terms of their deterministic and ensemble skill scores, has generated a significant uncertainty about the future of conventional weather forecasting and Earth system predictions. ECMWF was one of the first to investigate the potential of deep learning for weather forecasting (Dueben and Bauer, 2018). ECMWF is the first operational weather centre to provide daily operational artificial intelligence (AI)-based weather predictions, with ECMWF's own machine-learned weather forecast model called the Artificial Intelligence Forecasting System (AIFS). The AIFS framework is being further developed to operate in both deterministic and ensemble mode (Lang et al., 2024a; Lang et al., 2024b).

Machine-learned models are not directly based on physical laws but rely on data generated by physics-based models and require significant compute resources during the training phase. However, they are much cheaper to execute than physical models when running forecast simulations in a critical time window and can substantially accelerate forecast production. Therefore, machine-learned approaches and the previously described Earth system modelling have different advantages and disadvantages, and the future will show how the two distinct modelling frameworks (at ECMWF the IFS and the AIFS) will co-exist and develop.

For the foreseeable future, it is unlikely that ML models will entirely replace conventional Earth system models, but physical Earth system models now have a serious competitor for operational NWP and there are many new application areas emerging for ML. The new ECMWF strategy[9] for 2025 to 2034 envisages ECMWF continuing to innovate at the cutting edge of physical, computational and data science. It also foresees an emphasis on data-driven operational predictions but crucially with an anchoring on physics-based models. Hence the continued development of these models (e.g. improved scale-aware physical processes and coupling of Earth system components) will remain crucial.

Nevertheless, there will likely be a change in the emphasis for physically-based Earth system models, away from models that are primarily targeting operational NWP and forecast scores, towards tools that are as high resolution and physically realistic as possible. For example, tools to be used in the generation of nature-emulating Earth system training datasets for ML models and to be used within data assimilation. ECMWF has a record of sharing so-called *nature runs* with the community that provide detailed, consistent simulation data over a year or more at high resolution (e.g. Hoffmann et al., 2018; Agustí-Panareda et al., 2022). Moreover, the physical understanding of weather regimes and Earth system dynamics, climate projections and adaptation decisions, will likely remain grounded with physics-based Earth system model simulations, albeit combined with other available constraints such as observational records (through techniques including ML) (O'Reilly et al., 2024).

The wide availability of machine-learned tools that can emulate fluid dynamics or even replace selected discretisations for processes as complex as the Earth system is also opening new opportunities for modelling. Combining physics-based models with ML approaches can be less or more invasive, such as post-processing of model outputs, emulation of computationally expensive model components and learning of model error for online bias correction, all the way to emulating entire physical parametrization schemes, or correcting physical models by nudging to the evolving, large-scale dynamics inferred from machine-learned models (Husain et al., 2024).

One of the reasons why ML tools are so successful is the use of software tools such as Pytorch and JAX that make developments for users extremely easy and allow for interactive programming, higher-level abstraction, and rapid development cycles that

9 https://www.ecmwf.int/sites/default/files/elibrary/2025/81641-ecmwf-strategy-2025-2034.pdf

are possible when using e.g. Python and Jupyter notebooks, previously used only for visualisation workflows. This further motivates a change in the coding paradigm for physics-based modelling towards higher abstraction and easier-to-use and portable software.

Currently, porting a complex Earth system model to the latest HPC platforms is significantly more difficult for the IFS than for AIFS. To foster collaboration and dialogue with Member States in the area of emerging technologies, such as GPU adaptation, and for data production, access and distributed data proximate compute for NWP, the pilot project on 'Adaptation to emerging technologies' led by MeteoSwiss brings together expertise to blueprint solutions for accelerated and distributed workflows.

> "FOR THE FORESEEABLE FUTURE, IT IS UNLIKELY THAT MACHINE-LEARNED MODELS WILL ENTIRELY REPLACE CONVENTIONAL EARTH SYSTEM MODELS, BUT PHYSICAL MODELS NOW HAVE A SERIOUS COMPETITOR FOR OPERATIONAL NUMERICAL WEATHER PREDICTION AND THERE ARE MANY NEW APPLICATION AREAS EMERGING FOR MACHINE LEARNING."

Moreover, the development of a portable model for multi-scale atmospheric prediction (PMAP) uses the domain-specific Python library GT4Py (GridTools for Python) with IFS (Ubbiali et al., 2025) and numerical modelling concepts of the finite-volume module (Kühnlein et al., 2019), applicable in both global and regional prediction. This has been a first step towards a separation of concerns within a modern coding environment for domain scientists. PMAP is performant but does not run in an operational context yet.

The challenges of data handling and governance, persistence and provenance of FAIR (findable, accessible, interoperable, and reusable) data are similar for both physical modelling and ML approaches. For example, serving ECMWF open data[10] into a geographically distributed computational environment, irrespective of how it is produced on the HPC, is one of the development goals needed to satisfy an increasing demand for streaming weather and climate information. Such information is vital, not only for the immediate task of protecting society from extremes in a changing climate, but also to translate and blend with other distributed data spaces[11] in relevant impact sectors such as food, energy, agriculture and health.

CONCLUSION

The model development at ECMWF (also sometimes called the European model in the Americas) is a pertinent example of what can be achieved with a common goal. A huge amount of help and support from scientists all over the world has influenced the progress and success of the forecast model. In return, ECMWF has continued to share its knowledge of how to address today's and future prediction challenges in a changing climate. Many prediction centres have adopted ideas or open source parts of the model initiated at ECMWF or its Member and Co-operating States.

We hope that this collaborative and successful path will continue long into the future, thus catalysing further shared development efforts in a flexible software infrastructure within an increasingly geographically distributed compute environment.

CONTRIBUTORS

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10 https://www.ecmwf.int/en/forecasts/datasets/open-data

11 https://digital-strategy.ec.europa.eu/en/policies/data-spaces

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