ECMWF

European Centre for Medium-Range Weather Forecasts

Newsletter

No. 184 | Summer 2025

Publication policy

The ECMWF Newsletter is published quarterly. Its purpose is to make users of ECMWF products, collaborators with ECMWF and the wider meteorological community aware of new developments at ECMWF and the use that can be made of ECMWF products. Most articles are prepared by staff at ECMWF, but articles are also welcome from people working elsewhere, especially those from Member States and Co-operating States.

The ECMWF Newsletter is not peer-reviewed.

Any queries about the content or distribution of the ECMWF Newsletter should be sent to Mike.Morrissey@ecmwf.int

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Changes

Numerical weather prediction is changing fast, and this Newsletter bears witness to that. Consider, first of all, the introduction of ECMWF operational ensemble forecasts driven by artificial intelligence and machine learning at the beginning of this month. The ensemble edition of the Artificial Intelligence Forecasting System (AIFS ENS) had already been available as an experimental version for some time, but we have now made it operational. Ensembles are used to provide a range of likely scenarios in our forecasts, so this is an essential step. It completes the operationalisation of the AIFS, which started earlier this year with the AIFS Single, but it is of course not the end of the story. Just as our traditional Integrated Forecasting System (IFS) is continually upgraded, so will the AIFS evolve, notably by increasing its resolution. While the AIFS still uses initial conditions derived in the conventional way, via data assimilation, a more radical approach is to use artificial intelligence to derive forecasts from observations directly. This method, which we reported on in the winter 2024/25 Newsletter, is still being worked on. Some of the news articles in this Newsletter also bear witness to the growing role of machine learning in hybrid numerical weather prediction, with articles detailing methods to combine the best of the physics-based and data-driven methods in a hybrid system, for both forecasting and data assimilation.

Change is also coming to us as an organisation, with the announcement that Florian Pappenberger will take over the role of ECMWF's Director-General from January 2026. As Director of Forecasts and Services and Deputy Director-General, Florian has played a pivotal role in the introduction of machine learning into our forecasts. He has in particular guided the operationalisation of the AIFS, while also continuing to oversee the implementation of new versions of the traditional IFS. The future of ECMWF will be in safe hands when I retire at the end of this year.

More novelties and changes are set out in other articles of this Newsletter. One reports on progress in the use of satellite observations of visible and near-infrared radiances to help establish the initial conditions of forecasts, while another describes the impact of Mode-S aircraft data. These are also examples of the benefits that come from close collaboration with Member and Co-operating States, as some of this work builds on progress made at the German National Meteorological Service (DWD), and Mode-S data benefit from the data processing and distribution performed by the Royal Netherlands Meteorological Institute (KNMI) and the UK Met Office. Our computing services must also move with the times. As the last feature article explains, the continuing increase in data volumes and the potential of cloud computing and machine learning have created new challenges, to which we are responding.

Finally, as he is about to retire, I would like to acknowledge the fantastic work performed by Georg Lentze, the editor of these Newsletters, whose science communication skills have been greatly appreciated at ECMWF.

Florence Rabier
Director-General

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doi: 10.21957/gl19of62ab

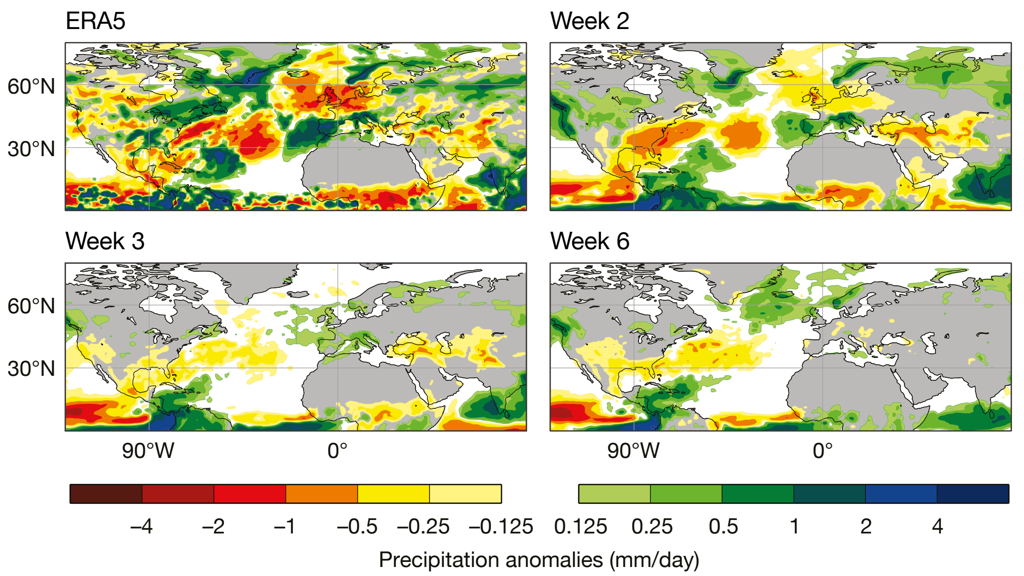
Prediction of precipitation contrasts over western Europe during spring 2025

Linus Magnusson

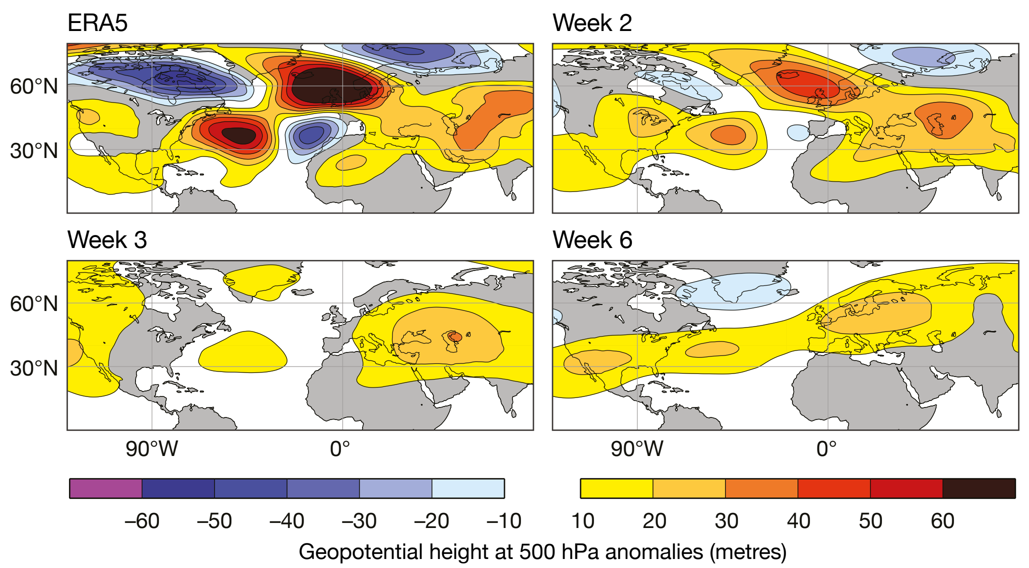
During the spring of 2025, western Europe experienced strong contrasts in the weather. As seen in the precipitation anomalies from ECMWF's ERA5 reanalysis for 25 February to 1 June, Portugal, Spain, and the northern-central Mediterranean coasts were much wetter than normal, while large parts of north-western Europe were much drier than normal. For example, according to the UK Met Office, spring in the UK was the warmest and sunniest on record. The exception was the Norwegian mountains, which experienced a wet anomaly. More information about the hydrological conditions can be found in the Copernicus C3S Climate Bulletin (https://climate.copernicus.eu/precipitation-relative-humidity-and-soil-moisture-may-2025). Here, ECMWF's sub-seasonal and seasonal forecasts for western Europe in this year's spring will be discussed.

Sub-seasonal forecasts

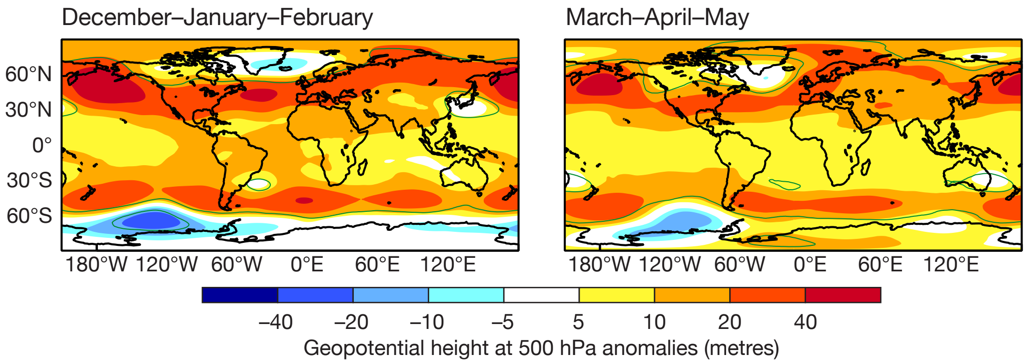
To evaluate the predictability of mean anomalies over the three-month period, we use composites of ensemble mean, weekly anomaly forecasts issued on Mondays from the sub-seasonal forecasting system (see the first image). The reference climatology is the past 20 years, as used in the ECMWF re-forecast dataset. The period covered is 25 February to 1 June. For the week-2 composite (forecast day 7–14), the general precipitation pattern over western Europe was well captured, but with lower amplitude, as expected



Precipitation anomalies in ERA5 and in forecasts. The charts show precipitation anomalies (mm/day) for March–April–May 2025 according to ERA5 and in the ensemble mean from sub-seasonal forecasts with different lead times.



Geopotential height at 500 hPa anomalies in ERA5 and in forecasts. The charts show geopotential height at 500 hPa anomalies for March–April–May 2025 according to ERA5 and in the ensemble mean from sub-seasonal forecasts with different lead times.



Geopotential height at 500 hPa anomalies in seasonal forecasts. The charts show seasonal forecasts from 1 November for geopotential height at 500 hPa ensemble mean anomalies for December–January–February (left) and March–April–May (right).

from an ensemble mean on this time range. However, in the composite of week-3 forecasts, the signal disappears. Instead, the forecasting system predicted a slightly wet anomaly over the period for Britain and Ireland, which experienced the strongest dry anomaly over Europe in ERA5. Looking further out (composite of week-6 forecasts), not many European anomalies were predicted. On the other hand, a clear wave pattern appears over the Atlantic, with a wet node over the Caribbean, a dry node over the western Atlantic and a wet node over the north-eastern Atlantic centred around Iceland.

To further understand the anomalies, the next image shows the corresponding anomalies for geopotential height at 500 hPa. In the seasonal mean, the spring was characterised by a strong positive anomaly over north-western Europe with a centre between Scotland and Iceland, and a trough located west of the Iberian peninsula. In line with the precipitation anomalies, the pattern for geopotential height at 500 hPa was somewhat captured in the week-2 forecasts, but it vanished in the week-3 forecasts. For week 6, a zonal positive anomaly was predicted in a diagonal from the southern US over the Atlantic to Europe, and a negative anomaly centred over Iceland. It probably resulted in the predicted wet anomaly centred around Iceland, which became a dry anomaly in the outcome.

Seasonal forecasts

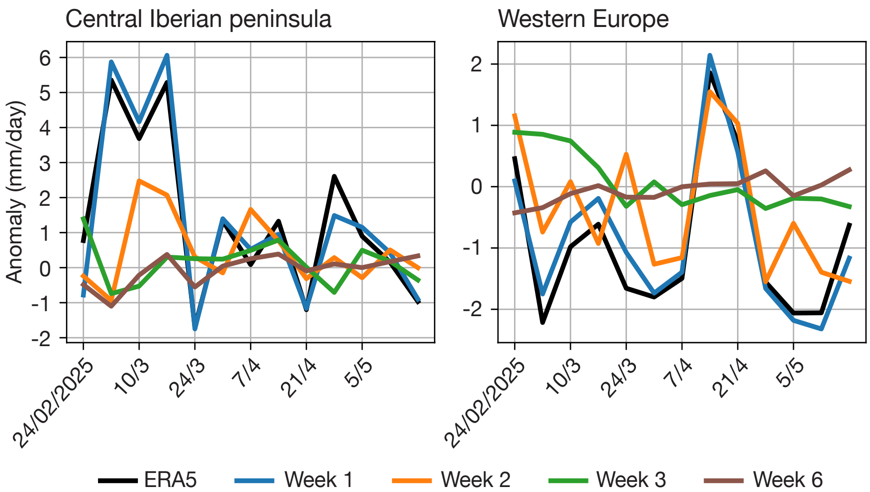
The anomaly pattern of geopotential height at 500 hPa seen in week 6 was also present in the ensemble mean seasonal forecast valid for March–April–May from November (anomalies calculated with reference to the period 1993 to 2016). The anomaly seems to have been persisted from the previous season (December–January–February) in the same forecast (see the third image). It indicates that a similar forcing was present in the forecasts for the winter and spring. Further investigation is required to understand the origin of the incorrect pattern, present in both week-6 and seasonal forecasts.

Intra-seasonal variability

The intra-seasonal variability of the precipitation anomalies over the central Iberian Peninsula shows that especially March was particularly wet but with additional wet weeks later on (see the first plot of the fourth image). Even the week-2 forecast struggled with the onset of the wet March, and the wet period was totally missed in the week-3 forecasts. For the full 3-month (13-week) period, the correlation between week-2 forecasts and ERA5 was 0.28 and for week-3 forecasts –0.34. It shows that the sub-seasonal forecasts did not capture the intra-seasonal variability. For the box over western Europe, the week-2 forecast was better (correlation of 0.75), and it captured the break in the dry period in the second half of April, as well as the transition back to drier conditions afterwards (see the second plot of the fourth image). But again, the week-3 forecasts missed the intra-seasonal variability (correlation of 0.09).

Conclusion

While spring 2025 was exceptional in terms of the weather in western Europe, predictability on the sub-seasonal and seasonal scale seems to have been low. One could speculate that the anomalies were a result of a sequence of synoptic events which were not connected to a large-scale forcing on the seasonal scale. However, with the relatively strong and persistent pattern seen in the seasonal forecast, which did not verify, further investigations of the drivers of predictability for the past season are warranted.



Weekly precipitation anomalies. The charts show weekly precipitation anomalies for a box over the central Iberian peninsula (38°N–42°N, 9°W–0°W; left) and a box over western Europe (48°N–53°N, 5°W–10°E; right).

ECMWF's ensemble AI forecasts became operational this month

ECMWF took the ensemble version of the Artificial Intelligence Forecasting System (AIFS) into operations on 1 July 2025, to run side by side with its traditional physics-based Integrated Forecasting System (IFS). The ensemble version, called AIFS ENS, is a collection of 51 different forecasts with slight variations at any given time to provide the full range of possible scenarios. A first operational version which runs a deterministic forecast, called AIFS Single, was released at the end of February.

The new ensemble model outperforms state-of-the-art physics-based models for many measures, including surface temperature, with gains of up to 20%, but it runs at a lower resolution of 31 km compared to the physics-based ensemble system, which runs at 9 km. More information on the AIFS ENS can be found on our website: https://www.ecmwf.int/en/about/media-centre/news/2025/ecmwfs-ensemble-ai-forecasts-become-operational. A detailed article on the AIFS ENS is planned for the next Newsletter.

Florian Pappenberger to be next ECMWF Director-General

ECMWF's Council has appointed the current Deputy Director-General and Director of Forecasts and Services, Florian Pappenberger, as the Centre's next Director-General from 1 January 2026. He will take over the post from Florence Rabier, who has served as ECMWF's Director-General since 2016 and will retire at the end of 2025.

Florian Pappenberger has been ECMWF's Deputy Director-General since 2021 and has led the Centre's forecasting operations for nine years. In these roles, he has focused on the needs of Member and Co-operating States and the wider user community and has driven technological innovation. Florian has championed ECMWF's AI and machine learning activities, recently guiding the operationalisation of the Artificial Intelligence Forecasting System (AIFS) alongside implementations of traditional physics-based models. For more details, see the article published on the ECMWF website: https://www.ecmwf.int/en/about/media-centre/news/2025/next-director-general-ecmwf-will-drive-innovation-and-collaboration.

Florian Pappenberger. He will become ECMWF's Director-General on 1 January 2026.

Five events provided science updates at ECMWF's anniversary week in Bonn

ECMWF's traditional Annual Seminar and four international workshops at ECMWF's 50th anniversary week in Bonn (Germany) in April surveyed a field that is facing a lot of change, in particular from advances in machine learning. There was great participation from all three ECMWF locations in Reading (UK), Bologna (Italy), and Bonn.

The Annual Seminar was dedicated to the theme of 'Forecasting in a changing climate' (https://events.ecmwf.int/event/418/), while the other events were on 'data assimilation: initial conditions and beyond' (https://events.ecmwf.int/event/428/); 'surface process coupling and its interactions with the atmosphere' (https://events.ecmwf.int/event/427/); 'ancillary data for land surface and Earth system modelling' (https://events.ecmwf.int/event/422/); and the 'evolution of Copernicus Services at ECMWF:

challenges and opportunities' (https://events.ecmwf.int/event/426/). This Newsletter includes a closer look at three of the workshops: on data assimilation, surface process coupling, and ancillary data.

The week in Bonn will be followed by another anniversary week in Bologna in September and a concluding set of events in Reading in December. Up-to-date information on anniversary events can be found on our website: https://www.ecmwf.int/en/about/media-centre/stories/anniversary.

Surface coupling workshop brings different communities together

Sarah Keeley, Charles Pelletier, Jasper Denissen, Josh Kousal, Luise Schulte, Peter Düben

The aim of the two-day workshop held in Bonn on 9 and 10 April 2025 was to approach the challenges of coupled numerical weather prediction (NWP) by bringing together different modelling communities working across the Earth system. In the past, many of the Earth system components used in NWP were developed in isolation and then brought together. With that in mind, discussion was a key element of the workshop, with talks at the start of each discussion session providing initial food for thought about challenges and issues. Discussion groups were formed with diverse ranges of scientific backgrounds to exchange ideas across disciplines. These groups covered various topics across the two days, revolving around the energy and water cycles, and coupling technologies and strategies for both physical and data-driven models. The poster session, held in conjunction with concurrent workshops, enabled lively and cross-thematic discourse in an informal atmosphere, and it was great to see such interest across all the workshops' attendees.

Main workshop themes

The workshop discussions focused on what had been achieved and what we saw as the main challenges going forward. Talks on the first day of the workshop were about the current state of the art in coupled systems and the coupling technologies that are being used or currently developed. ECMWF alongside national meteorological services, such as the UK Met Office, the German National Meteorological Service (DWD) and Environment and Climate Change Canada (ECCC), shared details of their operational systems and the progress that has been made so far in coupled NWP. The day continued with presentations discussing the methodology and tools for coupling and an example of the impact of ocean surface observations to help develop prediction systems. Finally, we considered the role of coupling within machine-learned forecasting systems, new developments in representing Earth system components, and what we could learn from this rapidly developing field. The second day had presentations looking at energy and water cycles. Talks concerned the model components of ocean surface waves and land, which have historically been tightly coupled to the atmosphere in ECMWF's Integrated Forecasting System (IFS), as well as the ocean and sea ice. This work showcased what processes could be important to include in our systems in the future and elements that could be improved.
The workshop concluded with discussion about next steps and possible avenues for future collaboration.

The participants. The workshop involved over 20 oral and poster presentations and had 61 participants.

Lively discussion

A common theme we kept returning to was conservation between coupled components. It was also emphasised that, when we couple different elements, we must ensure consistency across our systems in terms of how we parametrize physical aspects or make assumptions about how the components interact. Conservation properties of the system, which were perhaps considered less important in the past within the framework of NWP, are now becoming more important as we run our models at higher resolutions.

The discussion also recognised the challenge of modelling a complex system and the fact that we still need fundamental research in many areas. We will not only have to understand the processes we are trying to capture that govern exchanges between the interface of the atmosphere and the underlying surface, but also to represent missing processes. This also highlighted the need for pragmatic choices in the ongoing development of modelling systems. It was recognised that increasing the complexity within our system does not necessarily lead immediately to better scores as we have compensating biases in our system. We noted the time and domain-specific expertise required to retune parametrization schemes within the coupled system when we bring in new developments. We also need to have appropriate observation-based datasets which describe the processes we are trying to capture. We saw value in the community coming together for intercomparison studies focused on observational campaigns that target surface processes. Beyond field campaigns, the discussion also highlighted the need for coupled assimilation systems to initialise forecasts.

Feedback from participants was that they found the interdisciplinary nature of the meeting useful and that it was important to openly discuss the various issues that were highlighted. There is still a lot of work and interesting science to be done to improve our coupled systems.

More details of the talks and discussion can be found on the workshop page on the ECMWF website: https://events.ecmwf.int/event/427/.

Data assimilation workshop probes traditional and machine learning methods

Massimo Bonavita

Traditional data assimilation is about achieving a statistically optimal blending of observations and model information to provide the best estimate of the state of the Earth system and its uncertainty for both monitoring and prediction purposes. The recent advent of machine learning (ML) in numerical weather prediction (NWP) and climate studies has shown that data assimilation and observations can be effectively used to directly improve NWP and climate prediction capabilities beyond providing initial conditions for both physics-based and data-driven machine learning forecast models. The focus of a two-day workshop held in Bonn on 9 and 10 April 2025 was to discuss current development directions in both traditional data assimilation and observations for NWP and climate and the emerging area of hybridising aspects of the data assimilation workflow, or even fully replacing data assimilation with machine learning technologies.

The participants. The workshop involved 23 presentations and had 88 participants.

Main themes

During the first day of the workshop, attention was focused on the current status of Earth system data assimilation systems in major operational NWP centres; the sources and limits of weather predictability and how this could be extended by further gains in the accuracy of initial conditions; and the prospects for improvements in this area from, e.g., advances in resolution, model complexity, coupling, and new observations.

The talks by Massimo Bonavita, George Craig (Meteorological Institute, LMU Munich) and Nedjeljka Žagar (University of Hamburg) discussed the prospects and challenges of bridging the gap between current predictive capabilities (about nine days) and theoretical predictability limits for weather (about two weeks). The role of improved initial conditions, especially in the tropics, was highlighted as the likely biggest driver of future improvements in predictive capabilities.

One recurrent theme in the talks by representatives of NWP centres present at the workshop (the German National Meteorological Service, DWD; Météo-France; the UK Met Office; the HIRLAM Consortium) was the drive to improve the use of current and future observations in the data assimilation workflow. To achieve this objective, an increasingly accurate representation of observation errors (Sarah Dance, University of Reading) and a concurrent increase in the resolution of the analysis updates (Žiga Zaplotnik and Emiliano Orlandi) both in space and frequency are necessary.

The second day of the workshop was devoted to discussing the rapidly emerging area of hybridising traditional data assimilation methodologies with ML techniques. As discussed by Marc Bocquet (ENPC and ECMWF Fellow) in his introductory talk, the field is rapidly evolving, and it is still too early to say which of the many competing proposals will ultimately become the new paradigm for data assimilation.

Broadly speaking, one large area of development can be framed as ML-aided data assimilation and prediction. Here people are using ML tools to improve the quality and/or the computational efficiency of parts of the standard NWP workflow. Examples of this kind of activities were discussed, e.g. in the talks of Alban Farchi and Marcin Chrust (model error estimation and correction); Elias Holm and Wei Pan (building an ML emulator for the ECMWF Ensemble of Data Assimilations); Vincent Chabot (Météo-France; estimation of uncertainties in the data assimilation cycle); Alberto Carrassi (University of Bologna; hybrid sea-ice data assimilation and modelling); and Alan Geer (hybrid physical and data-driven observation models). In this area, the importance and challenges connected to maintaining physical consistency in the resulting analyses was stressed by many speakers, e.g. Tijana Janjic (MIDS, KU Eichstätt-Ingolstadt).

At the other end of the spectrum, ML can be viewed as a general-purpose tool that can provide end-to-end solutions to both state estimation and state prediction problems. In this area, Jan Keller (DWD) provided an overview of DWD's long-term strategy of transitioning from the current NWP-based DA and forecast system to a fully data-driven one. An even more disruptive development idea was presented by ECMWF's Mihai Alexe in his presentation of the DOP (Direct Observation Prediction) project, where ML is used to construct a generalised regression tool which, starting from recent and current observations, can extrapolate to predict their future values.

Wide range of views

A panel discussion concluded the second day of the workshop with the participation of all speakers and the on-site and on-line audiences. Given the wide range of views expressed in the talks, it was not surprising that a consensus on the way forward proved hard to reach. On the other hand and for similar reasons, it was also clear that data assimilation remains central for the success of the forecasting enterprise, and it is one of the areas where rapid and exciting progress can be expected to take place. For more details, consult the workshop page on the ECMWF website: https://events.ecmwf.int/event/428/.

Workshop addresses need for high-quality ancillary data for Earth system modelling

Souhail Boussetta, Gabriele Arduini, Margarita Choulga, Peter Düben, Nina Raoult, Christoph Rüdiger, Birgit Sützl (all ECMWF), Martin Best, John M. Edwards (both UK Met Office), Eleanor Blyth (UK Centre for Ecology & Hydrology), Anne Verhoef (University of Reading)

As part of ECMWF's 50th anniversary celebration, a two-day workshop was organised on 9 and 10 April 2025 in Bonn, Germany, bringing together leading modelling consortia and data providers to address a pressing issue in land and Earth system modelling: the need for high-quality, consistent, and high-resolution ancillary data, which characterise the physical, biological, and chemical properties of the land surface. Participants reached consensus on several key points and developed recommendations to guide the future of ancillary data provision and use.

Main issues

The workshop emphasized that the accuracy and performance of Land Surface Models (LSMs) depend heavily on the quality of ancillary data. As modelling resolutions increase (approaching 1 km and finer), the demand for detailed, consistent, and temporally relevant inputs becomes critical. Practical examples showed how improvements in spatial and temporal resolution can directly enhance model outputs.
For instance, the importance of spatial representation becomes particularly clear in regions with complex terrain or quite heterogeneous land cover types. Another example is the proper representation of phenology seasonality and inter-annual variability, which was shown to substantially impact the surface fluxes and the near-surface atmosphere.

Sessions across the two days explored challenges and potential solutions for ancillary data in three thematic areas: surface, subsurface, and anthropogenic inputs.
Key questions included:

- How can we get good-quality source datasets at high resolution globally?

- What is an acceptable level of uncertainty/consistency (data sources + algorithms)?
- What temporal resolution do we require for each data type?
- What are the priorities for data provision and modelling needs?
- What collaborative framework and tools are needed to ensure that data producers and modellers are aligned?
- What are the current/future ancillary requirements?
- How could parameter optimisation or machine learning solutions lead to a more desirable outcome?

The first day was split in two parts: the main modelling consortia and data providers gave an update on the state of the art of their modelling components and related use of ancillaries on the one hand, and screening of the best available data and future capabilities for data provision on the other. Besides introducing their up-to-date data streams focusing on their high resolution and quality estimation, data providers were also keen to get the modellers' feedback on current data and future needs, which was one of the workshop objectives.

On the second day, in-depth sessions focused on specific data categories. Discussions tackled key issues such as scaling mismatches, dataset inconsistencies, and data gaps. Participants worked toward establishing updated requirements and identifying paths forward for each data type.

Main recommendations

The workshop ended with the following main recommendations, which will be detailed in a position paper:

- Resolution enhancement is needed across all types of ancillary data to support the trend toward higher-resolution modelling. This includes not only spatial resolution but also temporal frequency and thematic detail.
- Uncertainty characterisation must become a standard practice for all ancillary datasets. Quantitative estimates of uncertainty at the pixel level should be aimed for.
- Consistency across variables is critical for a realistic representation of coupled processes. Efforts ought to focus on ensuring physical and ecological consistency between related datasets (e.g. land cover, vegetation parameters, and soil properties) to avoid introducing artificial patterns or impossible combinations.
- There is a need to better include anthropogenic impacts, such as urban area characterisation, agricultural management, water infrastructure, and other human modifications that affect land surface processes but are still poorly represented in global datasets.
- Evolving machine learning techniques should be used to improve data quality and availability, for instance parameter optimisation or data fusion that allow information from multiple sources (for example point data + satellite data) to be combined in a consistent physically based way.
- Better collaborative frameworks should be established, where data producers and modellers engage to ensure datasets meet specific modelling needs while remaining scientifically robust and observationally grounded.

The participants. The workshop involved 13 presentations and had 35 in-person and 18 online participants.

Background

LSMs simulate the exchange of energy, water, and carbon between terrestrial ecosystems and the atmosphere, providing boundary conditions for weather forecasting, climate projections, hydrological predictions, and ecosystem monitoring. The accuracy and reliability of LSMs depend heavily on the quality, consistency and resolution of the inputs used to parametrize and initialise these models, also referred to as ancillary data.

Ancillary data can be categorised into two groups:

- static parameters that change slowly over time (land use/land cover types, soil texture, and topography)
- dynamic variables that exhibit higher temporal variability (vegetation indices, surface albedo, ...).

As LSMs evolve with finer resolution and more complexity, so too must the ancillary datasets they rely on. This workshop was a good step to ensure better collaboration between major land modelling consortia and data providers toward aligning around these evolving needs. For more details, consult the workshop page on the ECMWF website: https://events.ecmwf.int/event/422/.

Widening the forum service to all of ECMWF

Michela Giusti, Kevin Marsh, Anabelle Menochet, Xiaobo Yang

The original (Confluence-based) ECMWF forums, such as the Copernicus and OpenIFS forums and the Forecast User Forum, have been a useful resource as a first step on the road to building a self-supporting user community. However, as ECMWF has rapidly evolved over recent years, we now need to support the wider range of data and services made available by the organisation in the best way possible. Creating a forum to support 'One ECMWF' is a way to achieve this, providing an effective, valuable and essential resource for all ECMWF users.

Four phases

An in-depth analysis of the original forums identified the changes necessary to meet this requirement. These changes included:

- identifying a more suitable forum platform
- extending the scope of the Forum and merging all existing forums
- re-designing and re-styling the interface
- the addition of new categories and subcategories.

From November 2023, the new Forum went through four different improvement phases. The first phase was focused on three main goals. Firstly, to choose a new, more suitable platform and do an initial test migration of one of the Confluence-based forums. Discourse (https://www.discourse.org/) was chosen as the forum platform, and the Copernicus User Forum content was migrated from Confluence to it, with the help of our contractor. The second goal was to widen the scope from the original target audience by reviewing the structure of the forum to make it more general for all ECMWF users. The third goal was to assess how the new Discourse platform worked both technically and in terms of usability for our users. This also allowed us to learn how to monitor and moderate the user content in this new context.

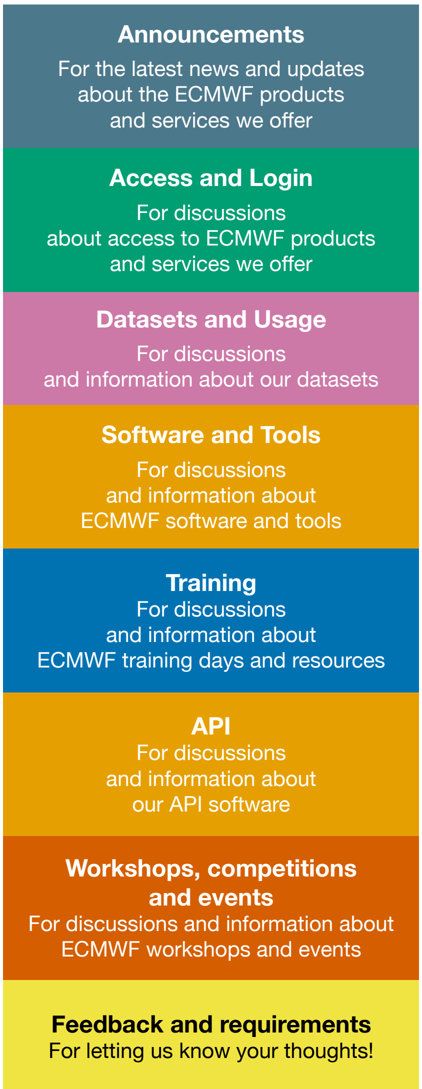
The new Forum was launched on schedule in February 2024, and it was immediately clear that the migration to Discourse was a major success both in terms of platform choice and user uptake. The 'Announcements' category has been particularly popular as a way for users to be informed of the latest developments (see the image).

Motivated by the very good results of the first phase, the second phase was implemented later in 2024. Crucially, the existing contents of the OpenIFS Forum and the Forecast User Forum were reviewed to identify what content was still relevant, and they were migrated with the support of our contractor. New categories and subcategories were created, with the main additions focused on the Artificial Intelligence Forecasting System (AIFS), the Integrated Forecasting System (IFS), and OpenIFS. These are intended for discussions about ECMWF systems, model settings, and upgrades.

Existing moderators for the Copernicus User Forum content were migrated to the new environment, and new moderators were added to the Forum to cover other areas more focused on other ECMWF products and services. As the scope of the Forum is now significantly wider, the moderation of the user content will be handled by a larger group of people. To support this, a new Standard Operating Procedure (SOP) was created to provide guidance to moderators. As a public-facing tool, the Forum plays an increasingly important role in the area of information exchange with users and management of user expectations.

The third phase included the addition of DestinE-relevant tags and subcategories, and re-styling of the forum theme to comply with the ECMWF official styling. The Forum was also migrated from virtual machines to Kubernetes clusters, to make it easier to manage as an ECMWF application.

The fourth and final phase included the advertising of the outcomes from the previous phases in different channels both internally in ECMWF and externally, such as on the ECMWF LinkedIn channel in May 2025.



Forum main categories. The new Forum has eight categories to access information, ask questions, and leave feedback on different topics.

The result

The Forum is now accessible at https://forum.ecmwf.int. Here, users can engage in discussions and share information (when logged in using their ECMWF account) and access the latest news about many exciting ECMWF products and services. Looking to the future, we will continuously improve and evolve the Forum to make it an invaluable resource for all our users.

Solar-induced fluorescence satellite data in the land assimilation system

Sébastien Garrigues, Patricia de Rosnay, Peter Weston, Christoph Rüdiger, David Fairbairn, Ewan Pinnington, Souhail Boussetta, Anna Agusti-Panareda, Richard Engelen (all ECMWF), Pierre Vanderbecken, Jean-Christophe Calvet (both Météo-France)

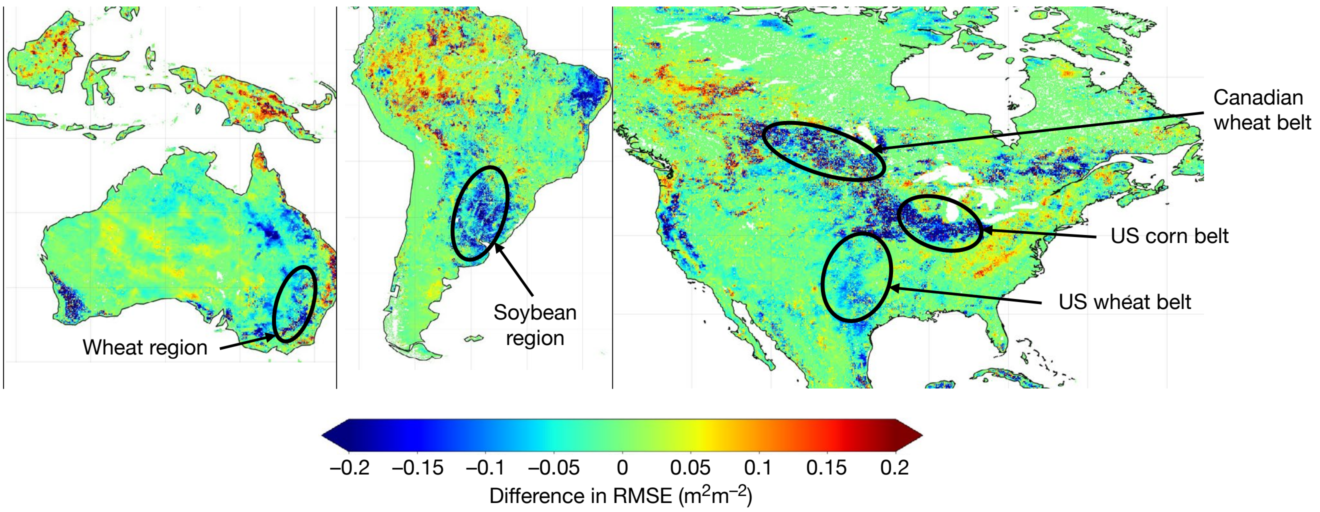
Land carbon fluxes represent the largest sources of uncertainties in the global carbon budget. Improving the estimation of their spatial and temporal variability is therefore crucial for the global monitoring of anthropogenic CO_2 emissions in the framework of the future Copernicus CO_2 Monitoring and Verification Support (CO2MVS) service. The Gross Primary Productivity (GPP), which is the largest biogenic carbon flux, is difficult to model due to the complexity of the processes involved and the lack of direct observations. One of the objectives of the EU-funded CO2MVS Research on Supplementary Observations (CORSO) project is to exploit new types of Earth observations, such as solar-induced chlorophyll fluorescence (SIF), in land data assimilation systems to improve the prediction of GPP in Earth system models.

SIF represents the emission of electromagnetic radiation in the red and far-red by chlorophyll under visible light conditions. While SIF is directly sensitive to changes in leaf photosynthetic activity and thus GPP, the canopy structure, represented by leaf area index (LAI) in Earth system models, is the prevailing driver of the SIF signal measured by the satellite. Assimilating satellite observations requires an observation operator to predict the model-simulated counterpart of the observation (here SIF) from the model fields. Machine-learning-(ML)-based observation operators are good alternatives to process-based models, which are generally computationally expensive and associated with large uncertainties over land. We present here the work, conducted by ECMWF at global scale and Météo-France (MF) at regional scale, to assimilate SIF observations from the TROPOMI instrument on board the Sentinel-5P satellite. This is done by leveraging an ML-based observation operator to update LAI, which is a key driver of GPP.

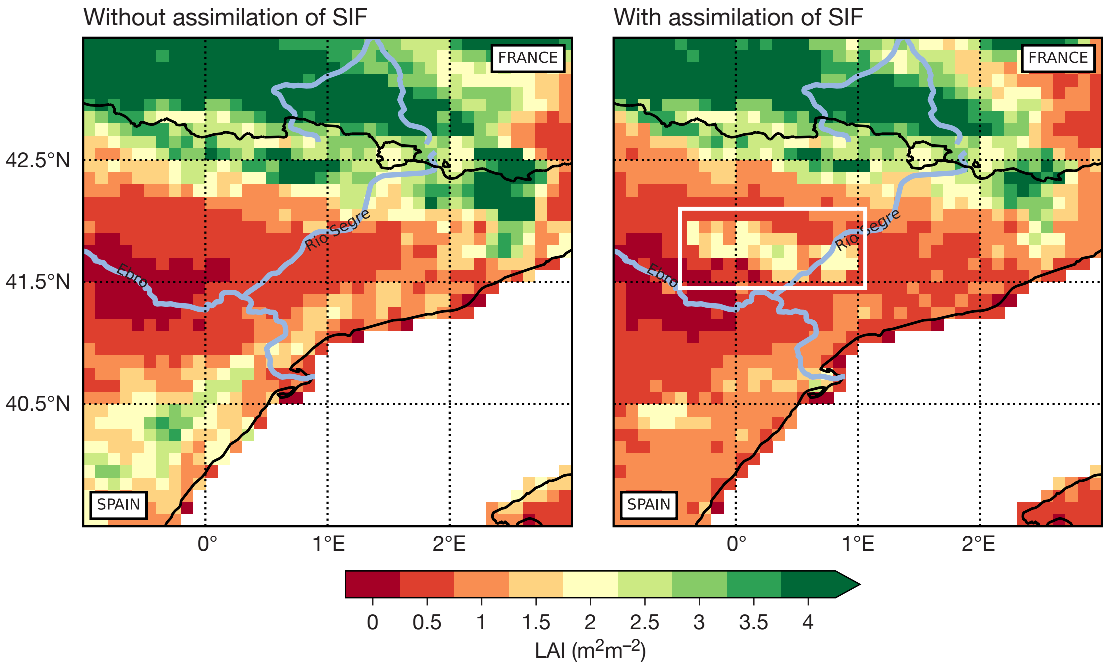
Assimilation of SIF at ECMWF

The representation of vegetation in the Integrated Forecasting System (IFS) developed at ECMWF relies on a satellite-based LAI monthly mean climatology, which does not capture the impacts of climate anomalies. The approach chosen in this work consists in (1) assimilating SIF in the offline land data assimilation system (LDAS) to update the IFS LAI climatology and (2) using the updated LAI in the IFS coupled model to evaluate the impacts on GPP forecasts.

The ML technique involving XGBoost gradient-boosted trees was employed to develop an observation operator using the Copernicus Land Monitoring Service (CLMS) LAI satellite dataset and spatiotemporal localisation variables (week of the year, latitude, longitude) as predictors. The ML model was trained over 2019–2020 and tuned over 2021. The evaluation, which was conducted in 2022, indicates that the ML model has a good global prediction performance (determination coefficient of 0.83 and root-mean-square error of 0.1 mW $m^{-2}nm^{-1}sr^{-1}$). It also accurately reproduces the spatial variability and the temporal evolution of the satellite SIF at global scale.



Impact of SIF data assimilation at ECMWF. The images illustrate the impact of SIF data assimilation on cropland regions, shown as the differences in LAI root-mean-square error (RMSE) with and without data assimilation, between the IFS LAI and the Copernicus satellite LAI for 2022 over Australia, South America and North America. Blue colours indicate that the SIF data assimilation improves the LAI accuracy evaluated against the CLMS satellite LAI dataset used as reference.



Impact of SIF data assimilation at Météo-France. Leaf Area Index (LAI) simulated by the ISBA land surface model of Météo-France over the Ebro basin without the assimilation of SIF (left panel) and with the assimilation of SIF (right panel) in August 2021. The irrigated area is highlighted after assimilation (within the white rectangle).

The ML model was then implemented in the ECMWF LDAS to assimilate the TROPOMI SIF at 0.1° spatial resolution and update the IFS LAI climatology once a day. The assimilation of SIF generates meaningful spatial patterns of LAI increments, such as the reduction of LAI over western Europe in July 2022 in response to the summer 2022 drought. Evaluation against the satellite-based CLMS LAI dataset, for a different year than the one used in the training of the ML observation operator, shows that the assimilation of SIF improves LAI over cropland (see the first figure). Here, the strong correlation between the SIF satellite signal and canopy structure variability is well captured by the ML-based observation operator. However, degradations are obtained over rainforest in the Amazon region, central Africa and Indonesia. This is due to higher cloud contamination of the SIF satellite observations and the inability of the ML model observation operator to resolve the variability of light use efficiency, which has a larger impact on SIF compared to LAI for rainforest.

The comparison of the GPP forecasts with a satellite-based GPP dataset showed improvements over limited regions, such as central Europe and part of North America. However, the improvements obtained for LAI do not systematically translate into improved GPP, which is likely due to the prevailing effect of other sources of biases in the current coupled IFS model.

Assimilation of SIF at Météo-France

To assimilate the TROPOMI-SIF product within the Météo-France LDAS, a deep-learning operator was trained to replicate the product. This operator was then used as the observation operator, in line with the ECMWF methodology. While the ML model used in the Météo-France LDAS is different from the one used by ECMWF (XGBoost), both are trained using the same set of predictors, which was found to be the most influential component of the observation operator for the SIF assimilation results. Once the required level of accuracy was achieved, assimilation experiments were conducted over the Spanish Ebro basin at a resolution of 0.1° between 2018 and 2021.

The Ebro basin was selected because in situ and airborne observations for verification were available from the Land Surface Interactions with the Atmosphere over the Iberian Semi-Arid Environment (LIAISE) field campaign in July 2021. The area includes an intensively irrigated region within a dry zone. The second figure compares the estimated monthly average LAI in August 2021 without the assimilation of SIF (left panel) and with the assimilation of SIF (right panel).

The irrigated area between the Ebro and Rio Segre basins, which is not resolved by the modelled LAI ('Without assimilation of SIF'), is clearly visible on the analysis map ('With assimilation of SIF'). This demonstrates the benefit of assimilating SIF to improve the monitoring of vegetation, which is influenced by the impact of irrigation, over cropland.

Lessons learned and future directions

The assimilation of SIF at ECMWF and Météo-France both demonstrate the potential of ML to exploit new types of observation in numerical weather prediction systems at global scale. These studies highlight the potential of SIF data assimilation to improve LAI over cropland regions, which is promising for the monitoring of anthropogenic emissions over agricultural regions in the context of CO2MVS.

Acknowledgment

The CORSO project (grant agreement No. 101082194) is funded by the European Union. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the Commission. Neither the European Union nor the granting authority can be held responsible for them.

Hybrid forecasting: nudging large scales of the IFS to the deterministic AIFS

Inna Polichtchouk, Mariana Clare, Matthew Chantry, Michael Maier-Gerber, Simon Lang

Recently, weather forecasting models based on machine learning (ML) have surpassed physics-based models in their ability to predict large-scale weather patterns. However, deterministic ML forecast models have a tendency to unrealistically damp small-scale features, which impairs their ability to represent extreme events. In addition, they are usually run at lower resolution than physics-based models. Here, we build a hybrid forecasting system by combining our physics-based numerical weather prediction (NWP) model, the Integrated Forecasting System (IFS), with the deterministic version of our ML model, the Artificial Intelligence Forecasting System – Single (AIFS Single). The result is a forecasting system that inherits AIFS large-scale skill and IFS physics-based realism of small-scale weather systems and extreme events. To combine the two forecasting systems, we make use of spectral nudging. This technique constrains the large-scale components of virtual temperature and vorticity in the IFS forecast to follow the AIFS forecast. By only constraining the large scales, we allow small-scale features to evolve freely under the IFS's physics-based dynamics.

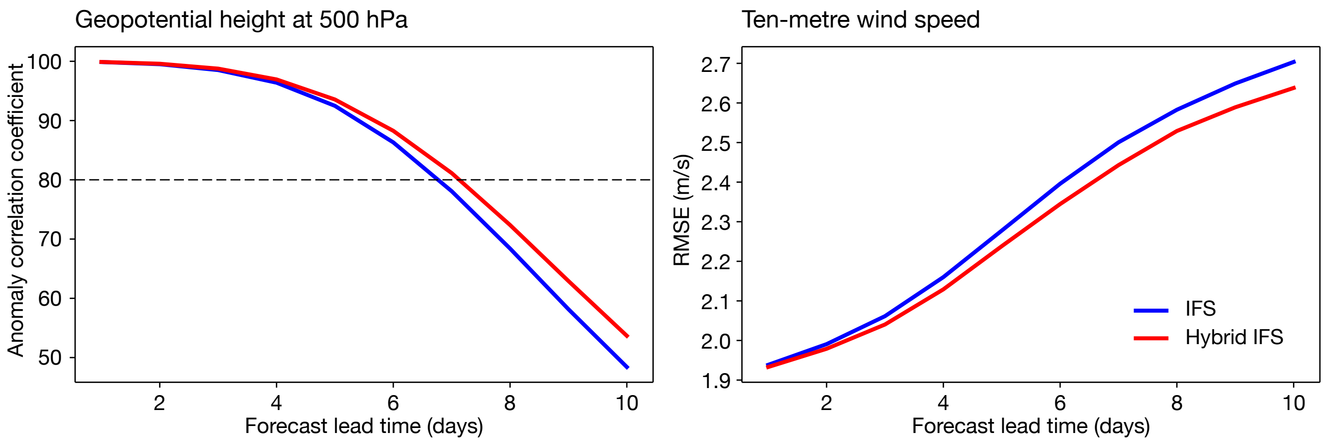
Our approach

A similar hybrid system has already been pioneered at Environment and Climate Change Canada (ECCC) using a variant of the GraphCast ML model and the ECCC's GEM NWP model. We are also collaborating and sharing experiences on a hybrid approach with national meteorological services in our Member States, such as the UK Met Office and Météo-France. A major difference in our approach to that used in Canada is that we make use of a version of our AIFS Single that produces forecasts directly on IFS model levels instead of pressure levels. This ensures vertical consistency and computational efficiency within the nudging framework and enables nudging to be applied from the surface to the tropopause.

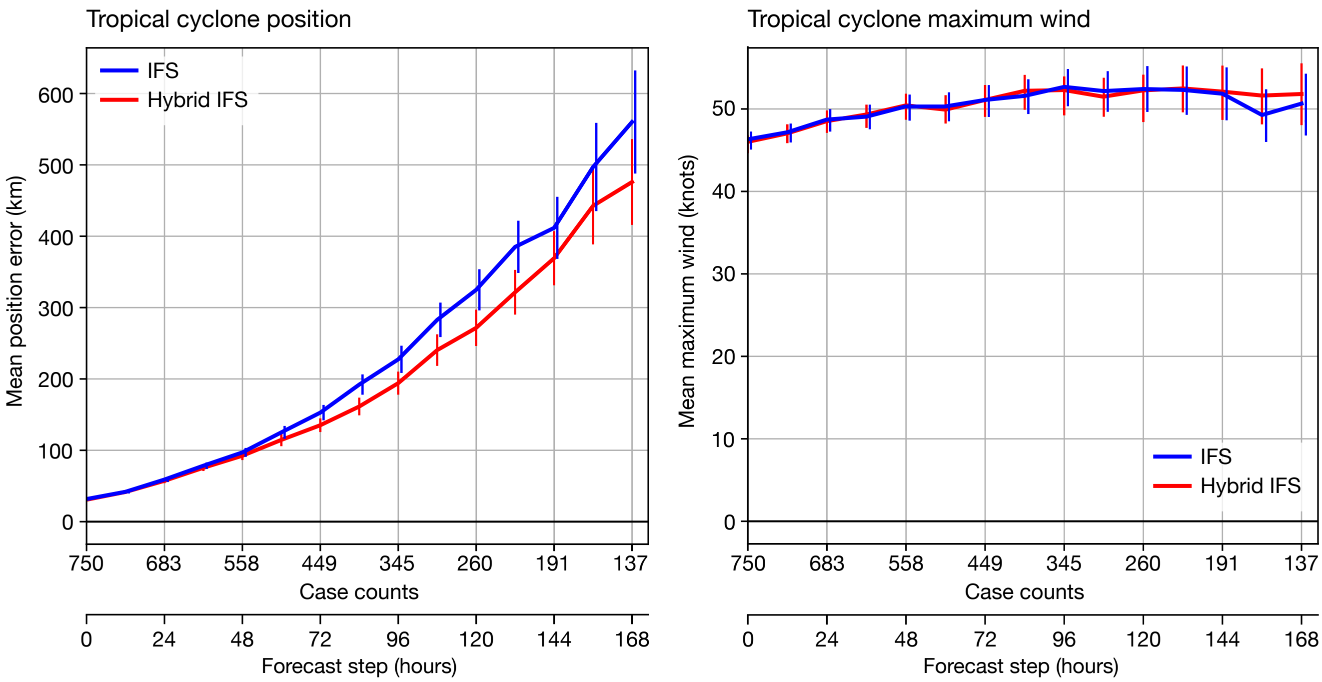
We find that nudging the zonal wavenumber-2 divergent wind component leads to temporal aliasing of the semi-diurnal tidal signal, due to the availability of AIFS Single forecasts only at 6-hourly intervals. For this reason, only virtual temperature and the rotational wind component (vorticity) are spectrally nudged up to total wavenumber 21 (approximately 2,000 km length scale), using a nudging timescale of 12 hours. Moreover, we introduce a gradual ramp-up to the nudging so that full strength is reached after 12 hours of forecast lead time. This is because, at very short lead times, the un-nudged model performs better than the nudged one when initialised from the operational analysis.

Results

Validation over 1.5 years of medium-range control forecasts at 9 km resolution shows that the hybrid model improves northern hemisphere skill scores by 15–20% for upper-air and surface fields (see the first figure). The biggest gains in large-scale skill occur in the tropics (up to 30% improvement, not shown). The better large-scale representation leads to better tropical cyclone track forecasting due to a more accurate steering flow. At day 5, the hybrid model reduces track errors by ~50 km (left-hand plot in the second figure) and halves the mean propagation speed error compared to the operational control forecast. Moreover, tropical cyclone (TC) intensity is unaffected (right-hand plot



Geopotential anomaly and wind speed forecast results. The left-hand plot shows the anomaly correlation coefficient for geopotential height at 500 hPa, and the right-hand plot shows the root-mean-square error (RMSE) of 10 m wind speed, both in the northern hemisphere extratropics, as a function of forecast lead time for operational (blue) and hybrid (red) forecasts. They both show improved scores for the hybrid forecasts. Scores are verified against the operational analysis on the left and SYNOP weather station observations on the right. Forecasts were initialised at 00 UTC from June 2023 to December 2024.



Tropical cyclone forecast results. The left-hand plot shows the mean position error and the right-hand plot the mean maximum wind for tropical cyclones as a function of forecast lead time for the hybrid forecasts (in red) and operational forecasts (in blue). Verification statistics are computed with respect to data from the international best track archive for climate stewardship (IBTrACS) for forecasts initialised at 00 UTC from June 2023 to February 2025. Case counts for each lead time are shown immediately below the graphs, and vertical bars show 2.5%–97.5% confidence intervals.

in the second figure), unlike in deterministic ML models, which tend to produce storms that are too weak. This makes the hybrid approach the best of both worlds for TC forecasting.

It is important to ensure that the nudging framework does not introduce unintended effects, such as degrading the conservation of axial angular momentum or total energy compared to the un-nudged model. Our checks confirm that this is not the case – both energy and angular momentum conservation are similar to, or slightly better than, those in the operational forecasts.

Outlook

At present, since the deterministic AIFS model tends to damp features smaller than approximately 2,000 km (total wavenumber 21) with lead time, nudging at scales below about 2,000 km is not performed. However, ongoing research is exploring the use of alternative loss functions for training deterministic ML models. This could help reduce the excessive smoothing of small-scale features and potentially allow nudging to extend to finer spatial scales. Additional developments include the use of AIFS hourly output to mitigate the current issue of temporal aliasing. Finally, the nudging framework is being investigated for ensemble forecasting, combining the AIFS–Continuous Ranked Probability Score (CRPS) model with the IFS ensemble system. Since the AIFS–CRPS does not exhibit the same level of small-scale smoothing as the AIFS Single, it offers a promising avenue for a more spatially detailed hybrid ensemble.

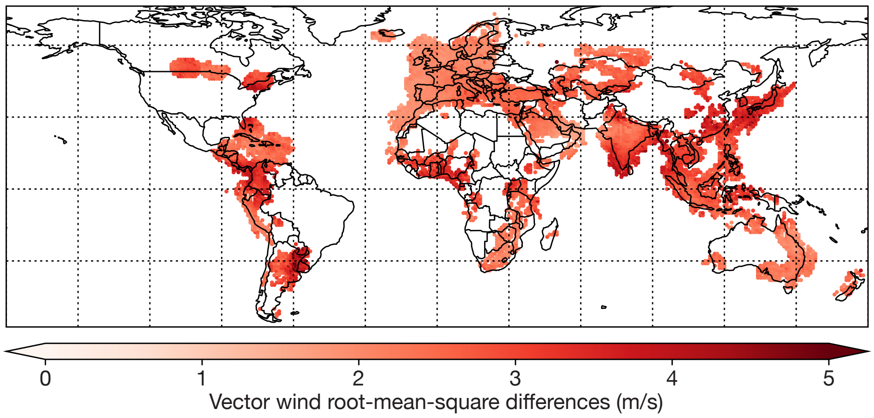
New observations April – June 2025

The following new observations have been activated in the operational ECMWF assimilation systems during April – June 2025.

Observations	Main impact	Activation date
Atmospheric Motion Vectors from GOES-19 (replacing GOES-16)	Tropospheric wind	9 April 2025
Clear Sky Radiances from GOES-19 (replacing GOES-16)	Tropospheric humidity and wind	29 April 2025
Global Mode-S aircraft winds	Tropospheric wind	8 May 2025
Meteosat-12 Atmospheric Motion Vectors (AMVs)	Tropospheric wind	16 June 2025

Assimilation of global Mode-S aircraft winds

Bruce Ingleby



Cruise level coverage. This chart shows 1x1 degree boxes with at least 100 used winds, from 8 to 31 May 2025, at 175–225 hPa. It includes European and Global Mode-S observations. The colour coding shows root-mean-square (RMS) vector wind differences from a short-range forecast (the background). Lower tropospheric coverage is less extensive and only available near airports.

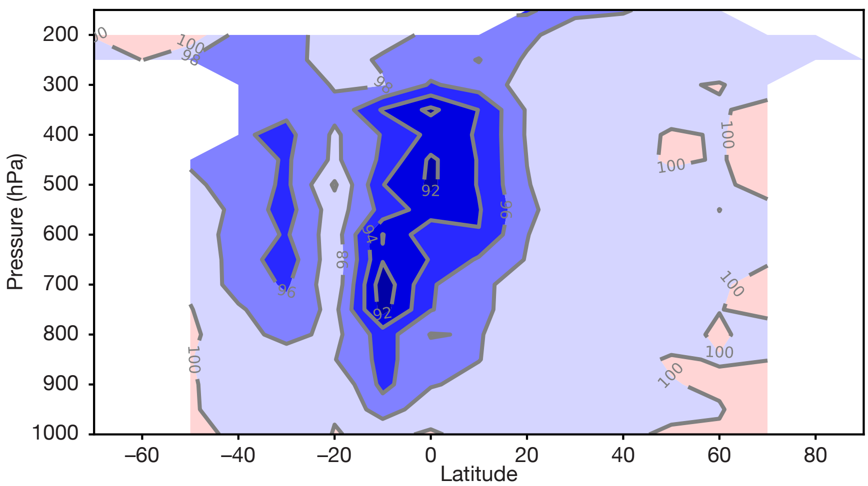
In July 2020, ECMWF started assimilating European Mode-S winds. These are derived from aircraft Mode-S messages to air traffic control by the European Meteorological Aircraft Derived Data Center (EMADDC, part of the Royal Netherlands Meteorological Institute, KNMI). The EMADDC processing is documented by de Haan et al. (https://amt.copernicus.org/preprints/amt-2024-110/). Numbers of flights were severely depressed by the COVID-19 pandemic in summer 2020, but they have since recovered to near pre-pandemic levels.
In summer 2022, it was discovered that ECMWF was assimilating too many Mode-S reports in central Europe, degrading the analysis.
We stopped assimilating Mode-S for a year whilst a revised ‘box-thinning’ algorithm was tested. This was implemented and Mode-S usage reinstated in November 2023 (Ingleby, 2025, *QJRMS*, under review). Mode-S messages are available elsewhere, depending on the local air traffic control system, and this encouraged the setting up of the EMADDC Met Office Global Mode-S data stream: https://emaddc.com/participate/data+users/emaddc-met-office-global/default.aspx. ECMWF is now assimilating some of these global data to improve the starting conditions of its weather forecasts.

Global Mode-S winds at ECMWF

Global Mode-S Enhanced Surveillance (EHS) messages are procured by the UK Met Office from Flightradar24 and routed directly from Flightradar24 to EMADDC, where they are processed into derived meteorological observations. The data became available to ECMWF in mid-October 2024, and several trials were run from 15 October to 31 January 2025.
The results were very encouraging, and the Global Mode-S winds have been assimilated operationally at ECMWF from 8 May 2025. The first figure shows the cruise level coverage in May 2025. In parts of eastern Europe and the Middle East, there are gaps due to GPS interference, and also occasional bad data that was not detected. Compared to European Mode-S, there are some additions, e.g. Iceland and parts of the Mediterranean, but the main benefits are elsewhere. The upper tropospheric root-mean-square (RMS) vector wind differences are particularly large in the tropics. It is thought that this is due to deep convection and to the relative lack of wind observations in the tropics.

The selection of used aircraft data

The 2025 change includes modifications to the aircraft thinning so that where available other aircraft data types, such as from the Aircraft Meteorological Data Relay (AMDAR) programme, are chosen ahead of Mode-S. Different box sizes were also tested, including longer horizontal scales in the upper troposphere, based on correlation results in Ingleby (2025). The configuration implemented operationally uses box sizes of 44 km in the lower troposphere, up to



Effect of the change. Changes in the background (12-hour forecasts) vector wind RMS fit to AMDAR (contours at 2% intervals, no change is given as 100%) when assimilating Mode-S data, calculated for 10° latitude bands and 50 hPa vertical intervals, 15 October 2024 to 31 January 2025. Blue colours indicate an improvement.

500 hPa, increasing to 95 km at 200 hPa. The boxes are 20 hPa in the vertical and 30 minutes in time – only one aircraft report is assimilated in each box. Assimilation of Mode-S temperatures was retested, but the impact was small and mixed, so this was not implemented operationally. The largest impact of radiosonde temperatures is in the lower troposphere, and because they are not reported directly but must be rederived, Mode-S temperature errors are larger in the lower troposphere.

Results

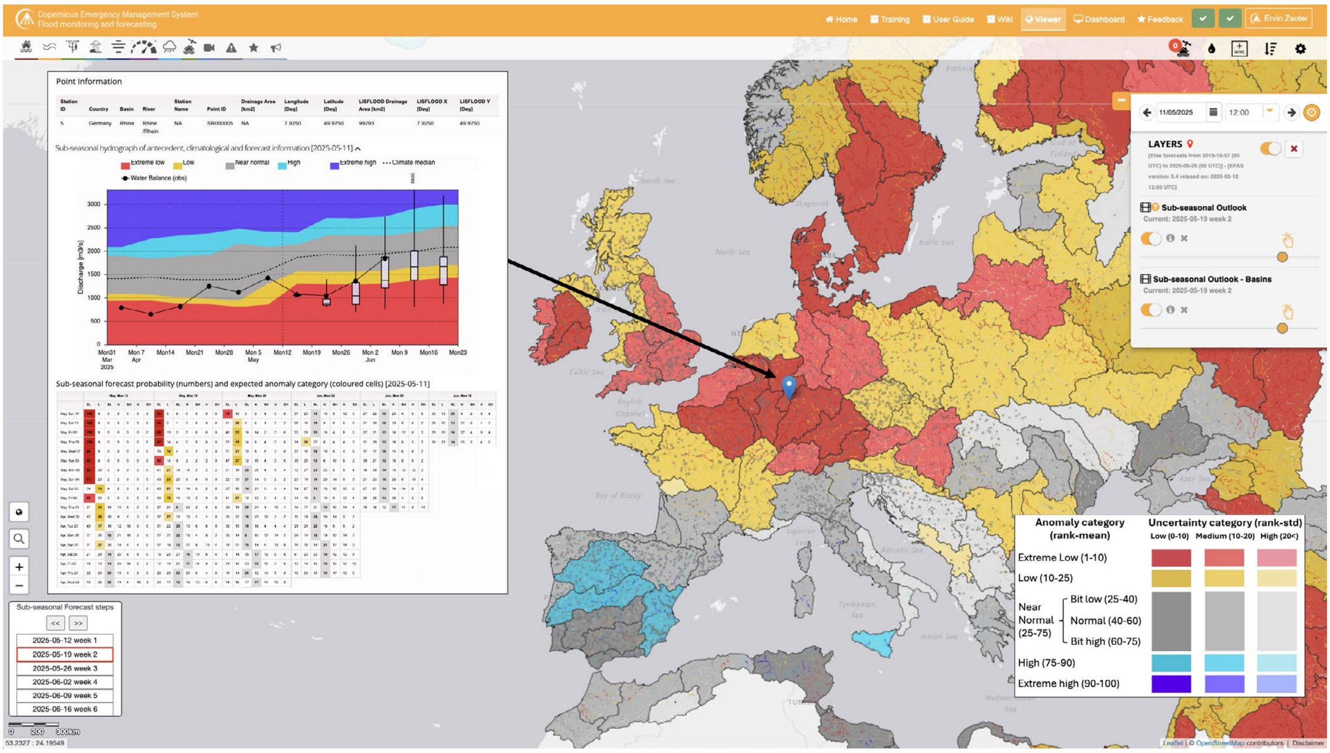
The second figure shows the effect of the change on 12-hour forecast fit to AMDAR aircraft winds – the effect measured against radiosondes and satellite data shows similar patterns. At short range, the largest improvement (up to about 8%) is in the tropical winds, with southern mid-latitudes also showing large improvement. In the medium range, there are significant improvements to mid-latitude forecasts measured against both observations and analyses. The impact over Europe is largely neutral, because Mode-S was already used there, but there is clear benefit over Asia. The number of used aircraft winds per day increased from 691K to 1,695K in the trial. This is a huge increase, and it gives a large benefit to short- and medium-range weather forecasts. The extra wind data in the tropics are especially welcome, and we thank our partners at the Met Office and KNMI for making these data available.

New sub-seasonal and seasonal river flow outlook products

Ervin Zsoter, Christel Prudhomme, Matthieu Chevallier

In a significant milestone, a new generation of sub-seasonal and seasonal (longer-range) river flow outlook products was implemented recently in the European and Global Flood Awareness Systems (EFAS & GloFAS) of the Copernicus Emergency Management Service (CEMS). ECMWF is the computational centre of CEMS, which is led by the EU's Joint Research Centre (JRC).

The new longer-range river outlook products provide improved



EFAS sub-seasonal forecast example. The map shows the predicted river flow anomalies over Europe, initialised on 11 May 2025, for week 2 (19–25 May). Expected forecast anomalies are displayed on simulated rivers and as an aggregated signal on predefined basins. Five main anomaly categories, defined by climate percentile ranges, are displayed by colouring from 'Extreme low' (red) to 'Extreme high' (blue), supplemented by three uncertainty subcategories from 'Low' to 'High' (lighter colours for increasing uncertainty). Further information is available in pop-up windows at selected points, which show the evolution of antecedent and forecast conditions against the background model climatology as well as a table with forecast probabilities from all recent forecasts. *Source: EFAS, https://european-flood.emergency.copernicus.eu/.*

consistency in the applied styles and methods across forecast horizons (i.e. sub-seasonal and seasonal) and geographical domains (i.e. European and global). Other novelties include better usability with a navigation option in the web map viewer to see maps of different lead times; the quantification and representation of forecast uncertainty on the map products; and the introduction of more anomaly categories, especially for the extreme tail of the distribution and near-normal conditions.
The anomaly categories are all provided with associated uncertainty (see the example snapshot of one of the sub-seasonal forecasts in EFAS in the first figure).

Main novelties

The revamping of the products was done consistently with existing ECMWF products. For example, the sub-seasonal forecasts are now produced daily, consistent with ECMWF's sub-seasonal forecasts since Cycle 48r1 of the Integrated Forecasting System (IFS), introduced in June 2023. They are valid for the next six calendar weeks (Monday to Sunday). Similarly, seasonal products are produced monthly and are valid for the next seven calendar months, consistent with seasonal forecast products provided by the Copernicus Climate Change Service (C3S).

Real-time longer-range EFAS and GloFAS forecasts, based on river discharge averaged over calendar weeks and calendar months, are generated using ECMWF and C3S forecasts: sub-seasonal forecasts, enhanced by high-resolution medium-range forecasts in the first 15 days, and SEAS5 seasonal forecasts. These serve as input for the LISFLOOD distributed hydrological model developed by the JRC.

The reliability of any forecast anomaly product strongly depends on the relevance of the underlying reference model climatology.
The new longer-range river flow outlook products have adopted the approach of using re-forecasts to generate a model climatology that changes both with seasons and with forecast lead times, similar to how it is done for ECMWF sub-seasonal and seasonal forecast anomalies.

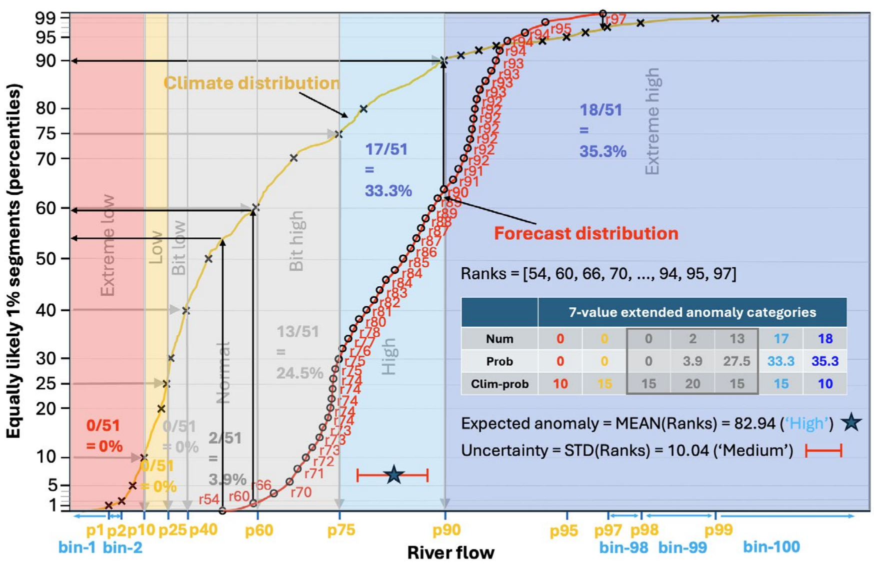
The forecast anomaly and uncertainty information is derived by comparing the real-time 51-member ensemble to the underlying reference model climatology, represented by 100 equally likely bins, and by ranking the members in the climatological distribution (see the second figure for a schematic representation of the method). These ranks define how usual, unusual or extreme the weekly-averaged or monthly-averaged river flow values are at the time of year and at the specific forecast lead time.
The expected forecast anomaly is then determined by the mean of the 51 rank values, while their standard deviation defines the uncertainty around the predicted anomaly.

Accessing the products

There are four new, freely accessible product layers introduced on the EFAS (https://european-flood.emergency.copernicus.eu/) and GloFAS (https://global-flood.emergency.copernicus.eu/) websites. The 'Sub-seasonal/Seasonal Outlook' maps highlight the expected forecast anomaly/uncertainty signal on simulated rivers, and the 'Sub-seasonal/Seasonal Outlook – Basins' maps show the spatial summary of the 'Outlook' layer by aggregating the signal onto larger scales at predefined basins. This is done as an arithmetic mean of the rank mean and rank standard deviation values at the river pixels in the basins, weighted by the square root of the catchment area, which gives more weight to larger rivers.

In addition, the 'Outlook' map also includes the reporting point pop-up products, which give detailed information on antecedent and forecast conditions and can be accessed by clicking on point markers.

Please go to the dedicated wiki page (https://confluence.ecmwf.int/display/CEMS/Sub-seasonal+and+seasonal+forecast+products) for detailed documentation on the EFAS and GloFAS sub-seasonal and seasonal products and the generation methodology.



CEMS-flood anomaly and uncertainty signal diagram. The red line with the black circles shows the 51-member ensemble river flow forecast, while the orange line shows the underlying river flow model climatology, which is represented by 100 equally likely river-flow-value bins (using percentiles, indicated as 'p-values' on the x-axis).
The 51 ensemble members are ranked in the 100-bin climatology and, using these ranks, the probability for the 5+2 predefined anomaly categories (indicated by vertically separated and coloured segments) are determined. In addition, the expected anomaly category for the whole ensemble forecast (one of five main categories) and the related uncertainty category (one of three categories) are defined by the mean and standard deviation of the ensemble member ranks.

Visible radiances in ECMWF's analysis

Tobias Necker, Cristina Lupu, Samuel Quesada-Ruiz, Volkan Firat (all ECMWF), Leonhard Scheck (DWD), Angela Benedetti (ECMWF)

Successful weather forecasts begin with accurate estimates of the current state of the Earth system. These estimates combine the latest observations with a short-range forecast constrained by previous observations through a process called data assimilation. At ECMWF, direct 'all-sky' assimilation of satellite radiances has become an essential part of forecasting by providing improved initial conditions in the presence of clouds and precipitation. Until recently, mainly microwave satellite observations have delivered detailed insights into cloud- and precipitation-affected regions. In previous Newsletters, we reported on initial efforts towards exploiting visible radiances (Benedetti et al., 2020; Steele et al., 2022). This article highlights ECMWF's advanced initiatives to leverage underutilised visible and near-infrared radiances, uncovering parts of the electromagnetic spectrum that have previously been inaccessible to numerical weather prediction (NWP). Progress was achieved by close collaboration with the German National Meteorological Service (DWD). DWD's Hans Ertel Centre for Weather Research (HErZ) pioneered the use of visible radiances in NWP in recent years. Researchers within HErZ developed advanced observation operators for visible radiances (Scheck, 2021; Baur et al., 2023), which are now distributed to the broader community through the NWP Satellite Application Facility (SAF) (EUMETSAT, 2025).

Preparing the ground

ECMWF has long led the way in utilising cloud-affected satellite observations. In 2009, ECMWF began assimilating humidity-, cloud-, and precipitation-sensitive microwave data for NWP (Geer & Bauer, 2011). Over the past decade, the use of microwave instruments has expanded a lot, substantially improving forecasts, especially in the medium range. Efforts are currently deployed to exploit information on cloud and precipitation in 'all-sky' conditions, using a broad range of available observations, including passive and active satellite instruments. Particularly relevant is the recently launched EarthCARE satellite with a lidar and Doppler radar, which will be assimilated and used to evaluate the model cloud and precipitation (Fielding et al., 2025). Recently, ECMWF has also started exploring visible radiance satellite observations for NWP, and this activity is now reaching pre-operational maturity.

Visible observations possess unique properties compared to other observation types. They can offer highly detailed cloud information at much higher spatial and temporal resolutions than microwave sounder observations. Broadband visible observations are among the first satellite measurements taken from space (see Figure 1). Nowadays, geostationary satellite imagers provide unprecedented high-resolution data at both visible and infrared wavelengths. However, integrating visible radiances into weather models has historically faced substantial challenges, preventing their operational use in global NWP models until recently (see Box A).

Radiative transfer simulations of visible and near-infrared radiances noticeably differ from previously used observation types. Visible radiation originates directly from sunlight, and how it is reflected or scattered is highly sensitive to details of the optical properties of the atmospheric constituents, particularly cloud and aerosol particles. In the visible and near-infrared part of the spectrum, multiple-scattering processes dominate the radiative transfer, significantly increasing computational demands of 'observation operators' – radiative transfer models that translate model atmospheric profiles and surface properties into simulated radiances for comparison with the observed values.

ECMWF employs RTTOV (Radiative Transfer for TOVS; EUMETSAT, 2025), a fast radiative transfer model, as a forward model to simulate satellite radiances in the Integrated Forecasting System (IFS). RTTOV is developed within the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) NWP SAF. RTTOV now also incorporates a fast visible wavelength radiative transfer model, called the Method for Fast Satellite Image Synthesis (MFASIS; Scheck 2021), enabling real-time monitoring and assimilation of visible and near-infrared radiances. This crucial development enables the operational use of visible observations in NWP today.

Insight from visible light: monitoring visible reflectances

The CLOud VISible (CLOVIS) projects funded by the European Space Agency (ESA) and the CERTAINTY project (*https://certainty-aci.eu/*) from the EU's

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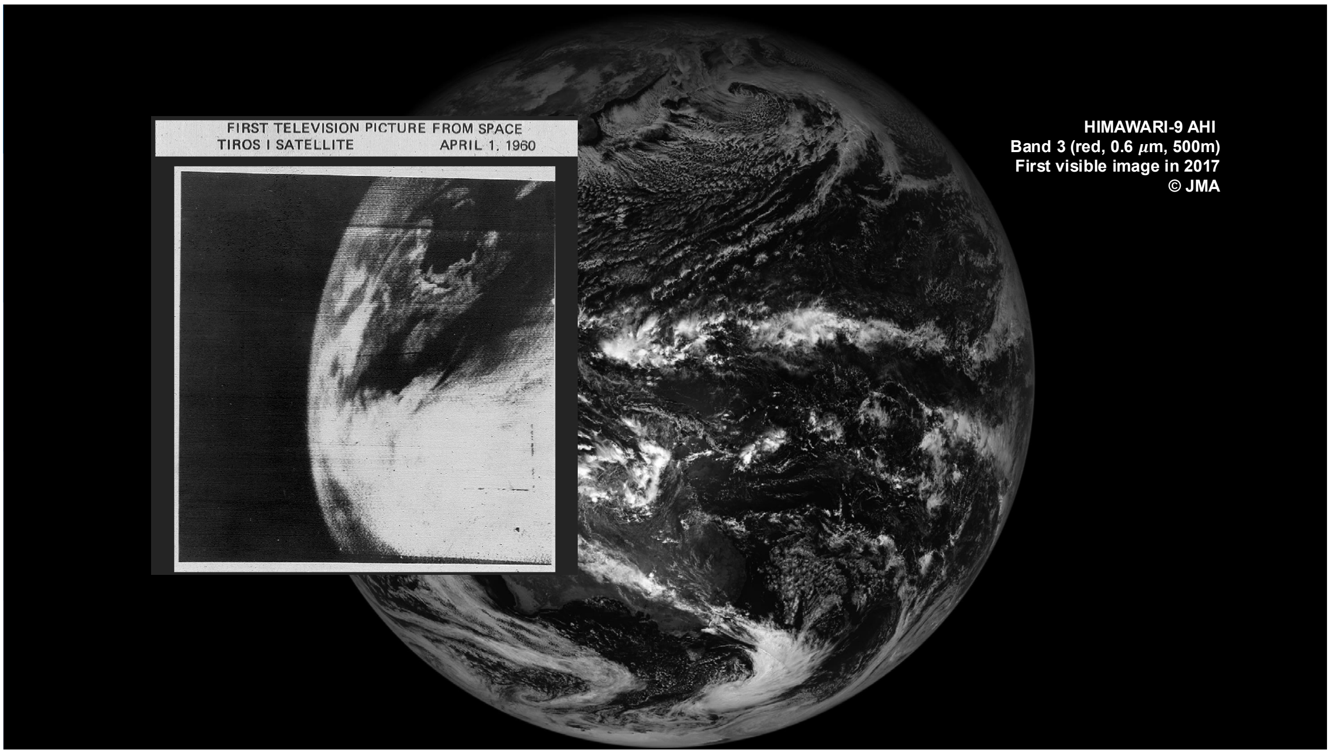

FIGURE 1 Collage showcasing the evolution of visible satellite observations over 60 years: (left) the first satellite observation from space as observed by the US TIROS-1 satellite on 1 April 1960, comprising a visible broadband observation, and (right) the first visible satellite image observed by the Japanese geostationary satellite Himawari-9 using the Advanced Himawari Imager (AHI) in 2017.

a Using visible radiances

Three major developments today enable the use of visible satellite observations in numerical weather prediction:

1. Higher model resolution and improved simulations of clouds, as data assimilation algorithms can only assimilate what models can simulate. These developments have been incorporated into successive model versions, which have been shown to have a growing degree of realism in the simulation of cloud features, including correct positioning.
2. Development of advanced linearised moist physics in tangent linear and adjoint models, allowing forecasts to be adjusted effectively by fitting models to cloudy observations. This has been one of the greatest achievements for the exploitation of cloud-affected observations within the four-dimensional variational data assimilation framework (4D-Var).
3. Continual efforts to improve the observation operator accuracy and speed for the simulation of visible and near-infrared satellite images (Scheck 2021; Baur et al., 2023). Until recently, the computational cost of radiative transfer calculations in this part of the electromagnetic spectrum was prohibitive for forecasting applications. Thanks to the development of fast codes, supported also by machine learning, these calculations can be achieved sufficiently fast.

Horizon programme have significantly advanced ECMWF's capabilities by enabling experimental monitoring and assimilation of visible reflectances from Ocean and Land Colour Instruments (OLCI) (see Necker et al., 2025).

The two OLCI instruments onboard ESA’s low Earth orbit Sentinel-3A/B satellites provide nearly daily global observation coverage (see Figure 2). After observation preprocessing, they can deliver about half a million visible reflectance observations per channel daily. Many visible observations are ‘window’ channels, as they see the Earth's surface under cloud and aerosol-free conditions. This feature also emphasises the need for accurate surface reflectivity models for land and ocean surfaces. This is indicated, for example, by differences between the model and observations over the ice-covered poles (see Figure 2).

Monitoring observations against radiances simulated by state-of-the-art NWP models is crucial to ensuring the reliability of both satellite observations and model performance. The operational use of OLCI visible reflectances also requires reliable instrument monitoring to allow rapid responses in case of any instrument anomalies, and timely notifications for planned changes that could impact data quality. Initial near-real-time monitoring experiments with OLCI visible reflectance data at 665 nm have emphasised the need for careful data screening, especially for areas affected by ice, snow, or observations at extreme sun or satellite angles (see Figure 3). Early evaluations confirmed a known observation reflectance brightness bias of about 1% between the two OLCI instruments on Sentinel-3A and -3B. Systematic comparisons between model and observed data also made it possible to identify cloud biases in the model, for instance in maritime stratus clouds, predominantly near coastal areas in the Pacific and at high latitudes. Detected cloud biases showed a seasonal dependence. These results highlight that visible observations can inform model cloud physics developments. Opportunities involve statistical model evaluation, tuning of parametrizations that describe unresolved model processes, or the estimation of uncertain model parameters.

Comparing the climatology of observed and simulated reflectances before and after observation screening underlines the need to address systematic differences between the model and observations (see the histograms in Figure 3). For example, finding optimal cloud overlap schemes or handling heterogeneous land surfaces poses challenges for visible assimilation. Insufficient model performance in clear-sky conditions

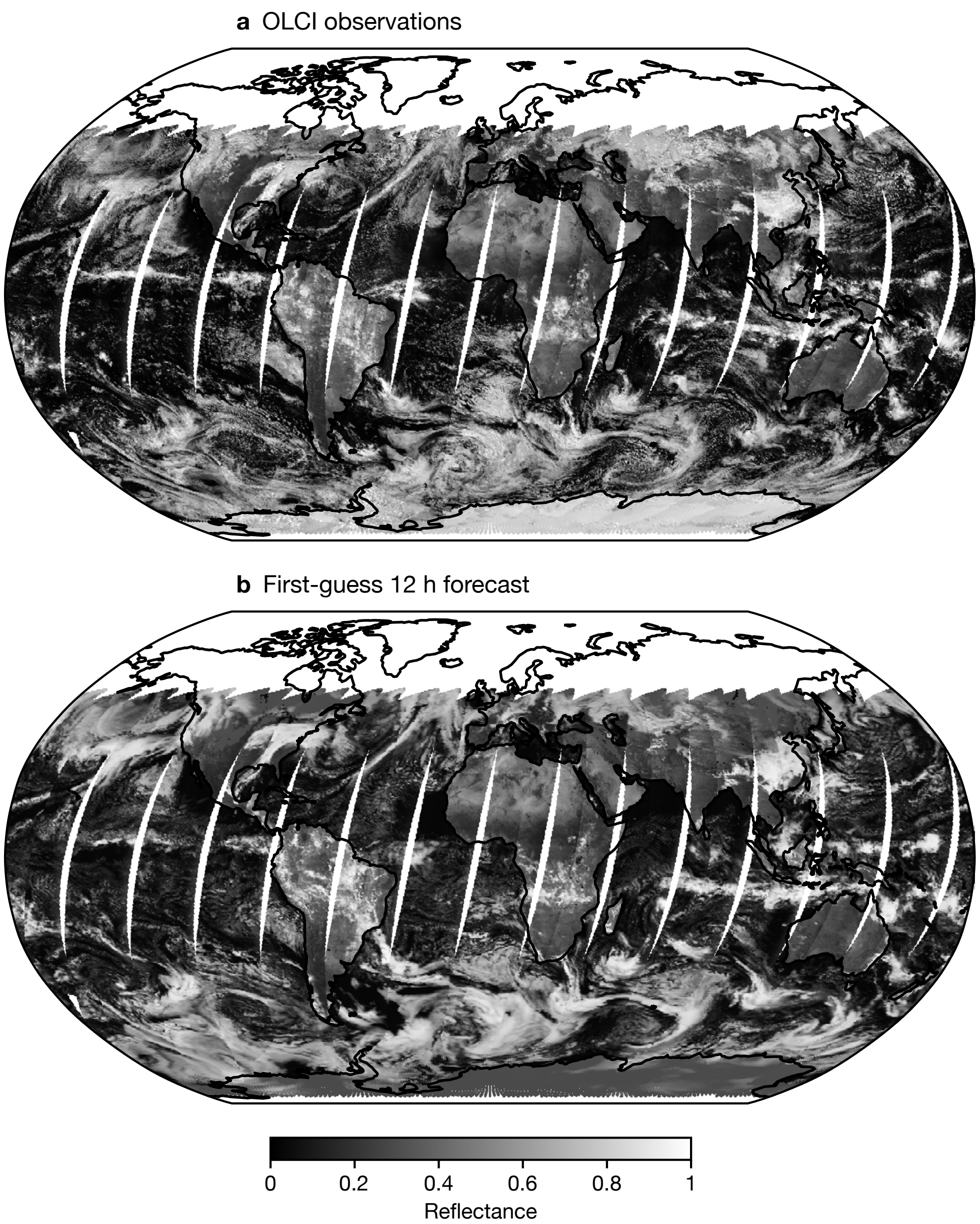

FIGURE 2 Comparison of real and simulated satellite images on 31 January 2025, showing (a) OLCI 655 nm visible reflectance observations, and (b) model equivalents based on the IFS first-guess 12 h forecast. The model produces realistic cloud structures, which have broadly similar reflectance values as the observations.

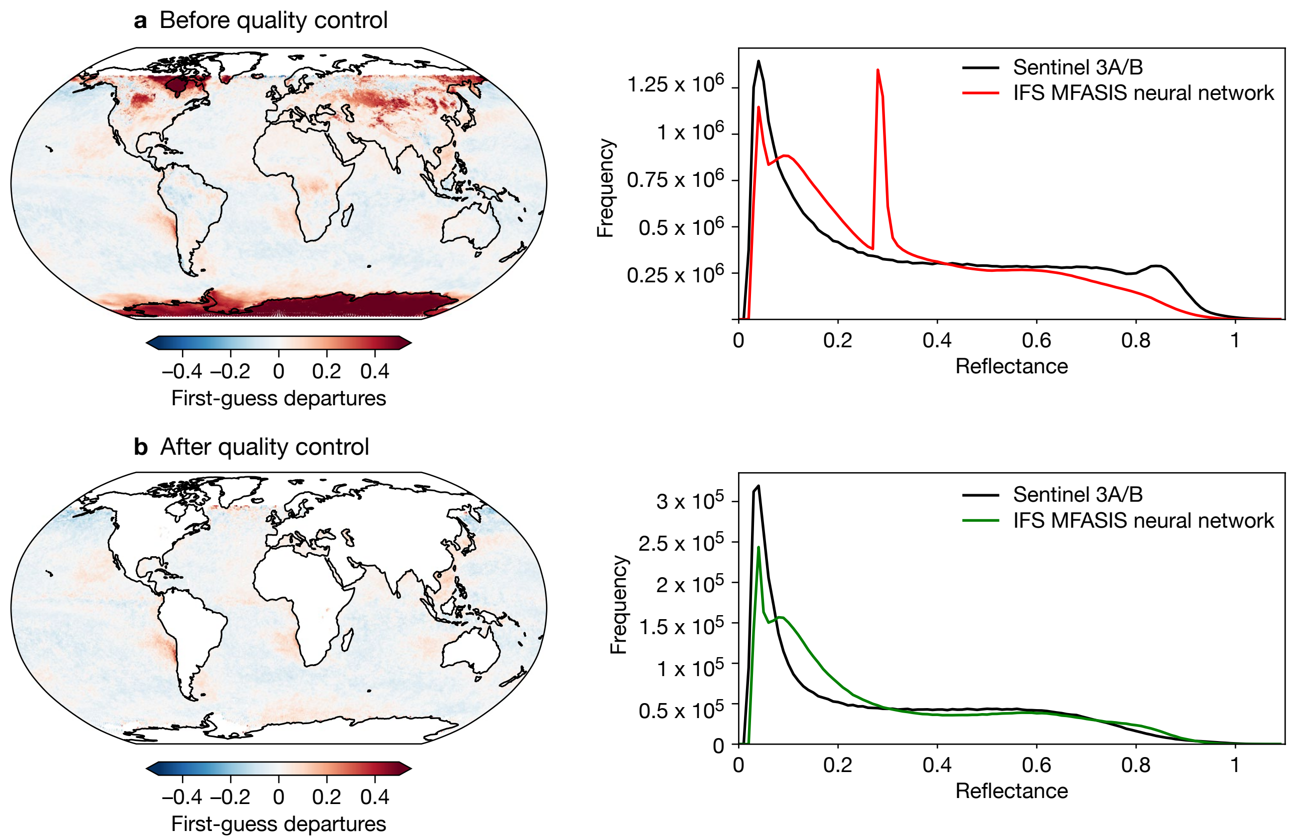

FIGURE 3 Evaluation of OLCI 655 nm visible reflectance observations and first-guess model equivalents (a) before and (b) after quality control. The left-hand maps of first-guess departures show 3-month averages of observations minus model and the right-hand reflectance frequency histograms provide the number of observed and forecast reflectances.

can harm assimilation efforts without proper observation screening. Exclusively using data over homogeneous ocean surfaces and removing areas affected by snow and ice effectively reduces systematic differences, therefore enhancing the possibilities for successful assimilation.

ECMWF is currently expanding the developments implemented for OLCI to visible reflectances observed by imagers on geostationary operational satellites, an initiative undertaken in collaboration with DWD. This collaboration will further progress towards assimilating geostationary visible reflectances for improved cloud analysis, marking a natural evolution of current capabilities. Establishing operational monitoring of visible satellite observations in the next round of IFS model improvements (Cycle 50r1, to be introduced this autumn) will represent a significant milestone, setting the stage for future operational assimilation of such observations.

In addition, ECMWF is preparing to exploit visible reflectances to improve the initialisation of aerosol forecasts provided by the EU's Copernicus Atmosphere Monitoring Service (CAMS), operated by ECMWF. This effort is supported by the CAMS EvOlution project (CAMEO; *https://www.cameo-project.eu/*) from the EU's Horizon programme, and it involves the use of visible observations from which the effect of clouds is removed. These observations can be used to infer the amount of aerosol particles which are present in the atmosphere, using 4D-Var data assimilation. A bespoke new fast radiative transfer operator for aerosols is currently being developed by DWD and will be included in the next RTTOV release v14.1. The challenges are similar to those faced when using cloud information. However, the signal from the aerosols is often masked by more reflective clouds, and extra processing is required to be able to identify the aerosol contribution. Efforts are ongoing to exploit the newly developed operators within the IFS for this specific application.

First visible reflectance assimilation in the IFS

DWD has successfully demonstrated the benefits of using visible satellite data in its operational regional weather prediction model (ICON) – see Scheck et al., 2020. Building upon this, ECMWF's first experiments with assimilating OLCI 655 nm visible reflectances have also shown encouraging results on the global scale, significantly reducing cloud biases and enhancing the accuracy of model-simulated reflectances in cloudy regions (see Figure 4). These advances at DWD and ECMWF, working collaboratively, represent a significant advance, opening a previously unexplored part of the electromagnetic spectrum for global NWP.

The impact of assimilating OLCI 655 nm visible data was assessed through Observing System Experiments (OSEs). Data from Sentinel-3A/B satellites were incorporated into a baseline experiment presenting either the full or a depleted observing system to evaluate improvements in analyses and forecasts. These experiments proved that the IFS 4D-Var system can successfully assimilate visible radiance data. Figures 5 and 6 illustrate the impact observed in the case of tropical cyclone Sean near Australia on 20 January 2025. Assimilating only a single visible channel on top of the full observing system led to adjusted cloud fields. This case study emphasises the potential for visible satellite observations to enhance forecasts of high-impact weather events, which heavily depend on accurate simulations of cloud structures. While initial assimilation trials are highly promising, ongoing research and development are just the beginning of an exciting endeavor. Future successful operational assimilation of visible observations will require demanding work and further improvements of forecast models, observation operators, and observation processing (see Box B).

A new look at old observations

Experiments using a depleted observing system, which added OLCI visible reflectances to a baseline control using only conventional data, have shown significant improvements in model analysis and forecasts.

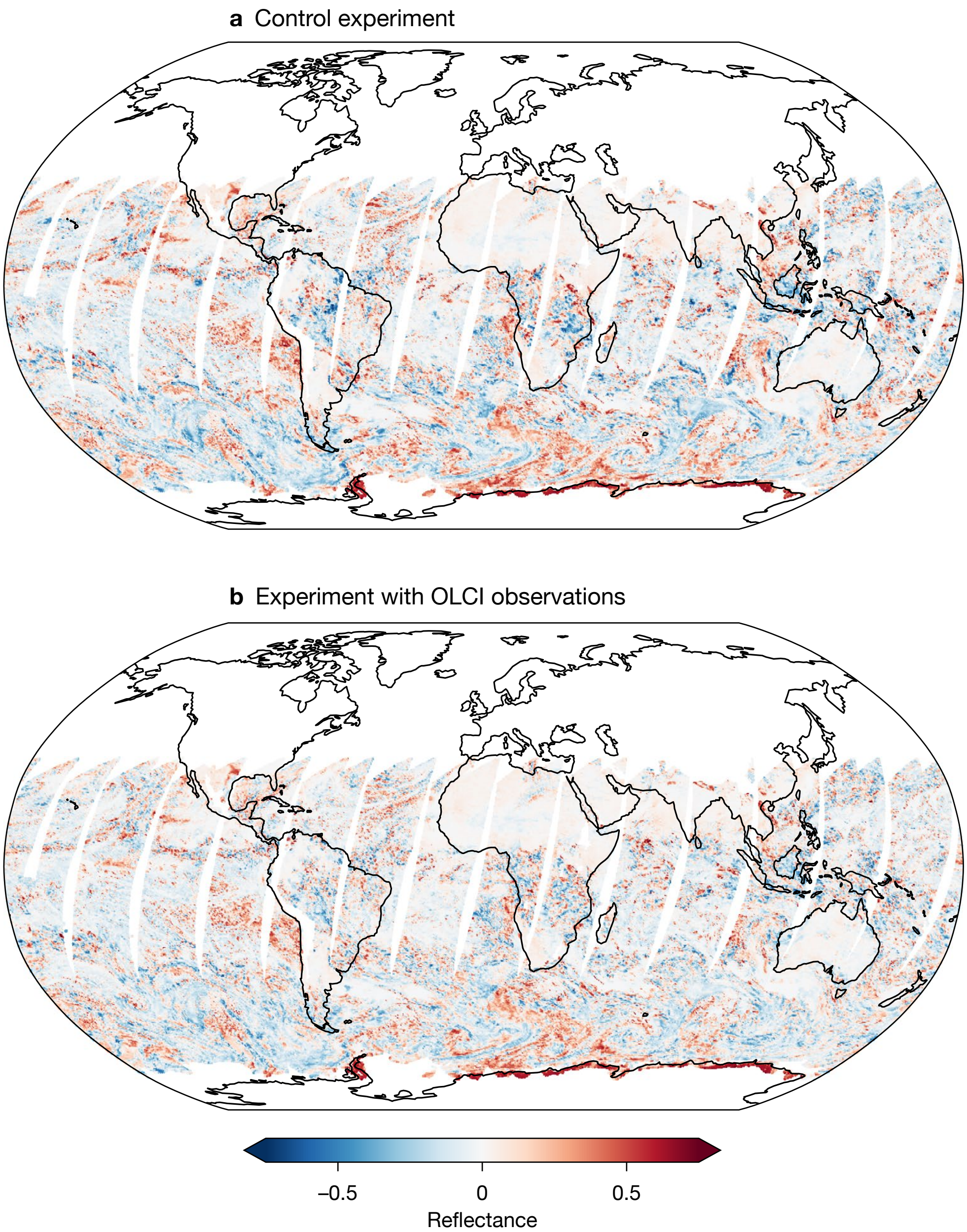

FIGURE 4 Global maps of visible reflectance analysis departures (observation minus model), showing the impact of adding visible observations in the full observing system on 20 January 2025, with (a) a control experiment using the default full observing system and (b) an experiment using additional OLCI 655 nm observations. The colours under (b) are more muted, indicating that the use of OLCI observations reduces analysis departures.

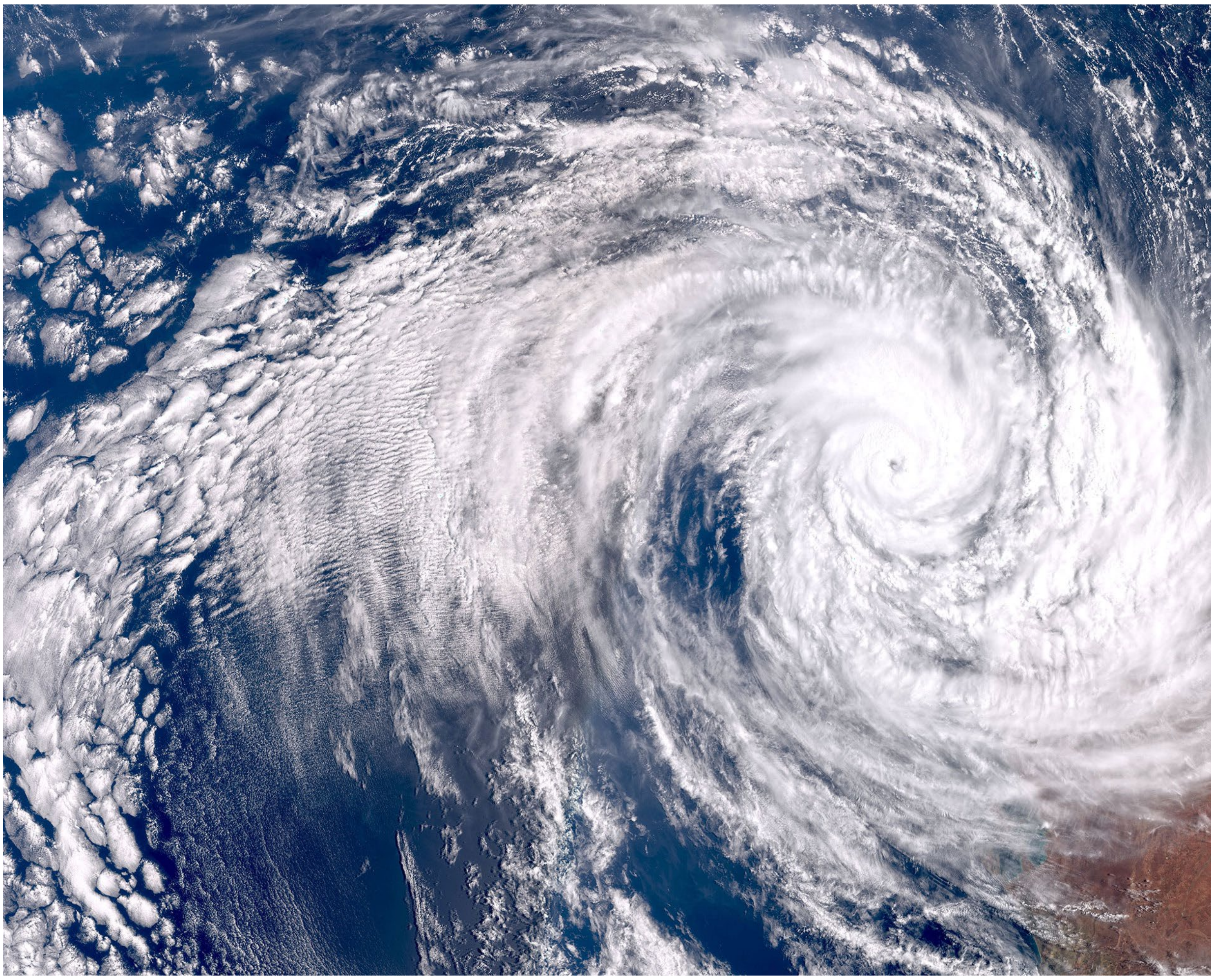

FIGURE 5 Real-colour image of tropical cyclone Sean as observed by OLCI instruments onboard Sentinel 3 satellites on 20 January 2025.

Revisiting the case study of tropical cyclone Sean in a depleted setting highlights the potential of visible observations (see Figure 7). Incorporating visible observations notably improved the analysis of the cyclone's structure and surrounding cloud fields.

Depleted system experiments demonstrated that visible observations could not only enhance cloud

b Towards operational use of visible observations

ECMWF already provides operational real-time simulated images for top-of-the-atmosphere visible reflectance products on ecCharts (*https://eccharts.ecmwf.int* – restricted access) and OpenCharts (*https://charts.ecmwf.int/*). For NWP, visible observations from both polar-orbiting and geostationary satellites will offer more direct benefit through their use in data assimilation. Operational monitoring of visible reflectances is planned to become an operational standard with the upcoming model upgrade (IFS Cycle 50r1). However, before visible observations can be assimilated operationally, several improvements are required:

- Advanced methods for variational quality control and bias correction must be put in place.
- Improved models of observation errors must be developed and implemented.
- Model and operator settings must be refined to mitigate systematic differences between the observation and the model.
- Technical updates to the IFS are necessary to handle additional visible channels and large amounts of new high-resolution data from several satellite instruments with different characteristics, both on geostationary and low-Earth-orbiting platforms.

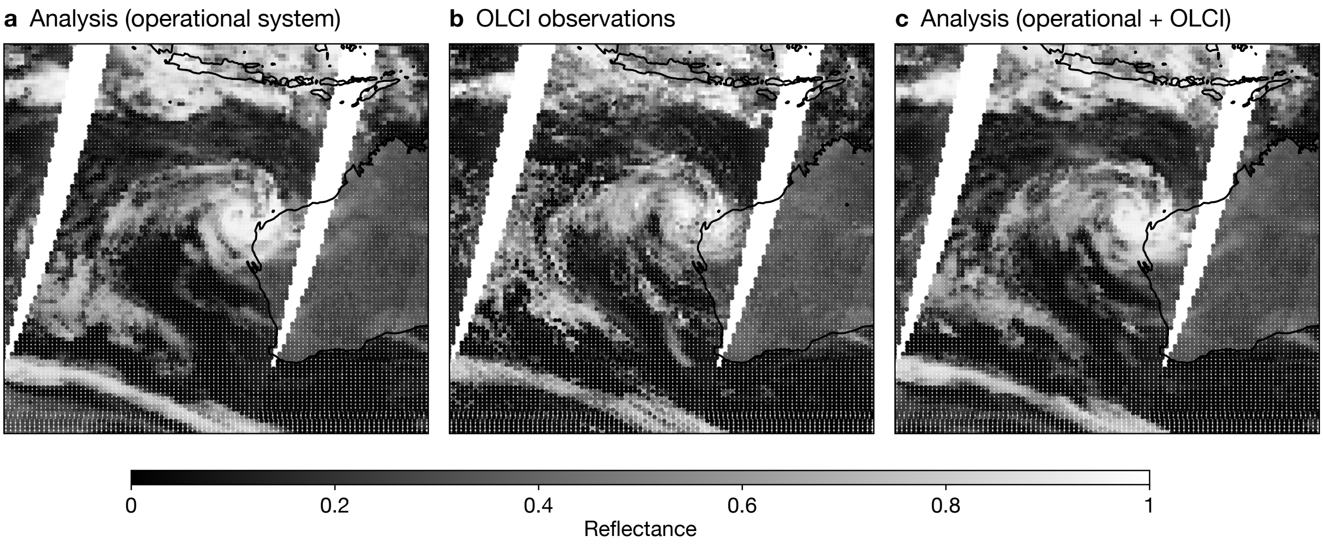

FIGURE 6 These images illustrate the visible assimilation impact in the *full* observing system, showing a case study of tropical cyclone Sean focusing on OLCI 655 nm visible reflectances on 20 January 2025. They show (a) the IFS analysis, (b) OLCI observations, and (c) the improved IFS analysis when also assimilating OLCI data.

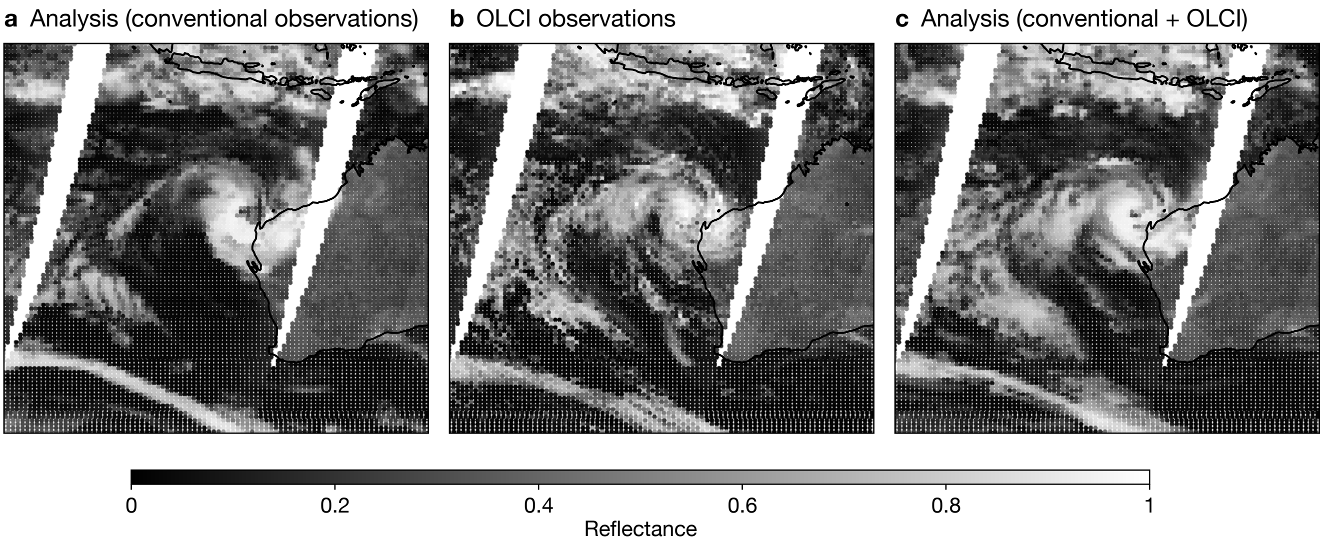

FIGURE 7 These images illustrate the visible assimilation impact in a *depleted* observing system, showing a case study of tropical cyclone Sean focusing on OLCI 655 nm visible reflectances on 20 January 2025. They show (a) the IFS analysis assimilating only conventional observations, (b) OLCI observations, and (c) an improved IFS analysis when also assimilating OLCI data.

analysis but could also improve initial conditions and forecasts of other key variables. Our results indicate that the most significant impacts of visible observations are on temperature and humidity. Moreover, the assimilation of visible observations in such scenarios could also improve wind forecasts (see Figure 8). Larger impacts were seen in the southern hemisphere, which was less observed by conventional observations and had more OLCI observations due to better observation coverage during the southern hemispheric summer.

These initial results are encouraging and build confidence that visible observations will be beneficial for future weather forecasts and climate reanalysis products. Importantly, historical broadband visible observations are available from as far back as the 1960/70s from missions such as Landsat, offering an invaluable long-term observational record of clouds to enhance future reanalysis datasets.

Outlook

Integrating visible reflectances into ECMWF's forecasting system through projects like CLOVIS, CAMEO, and CERTAINTY represents a substantial step forward for ECMWF and the global NWP community. The progress achieved emphasises the value of close collaborations with Member States, illustrated by DWD's

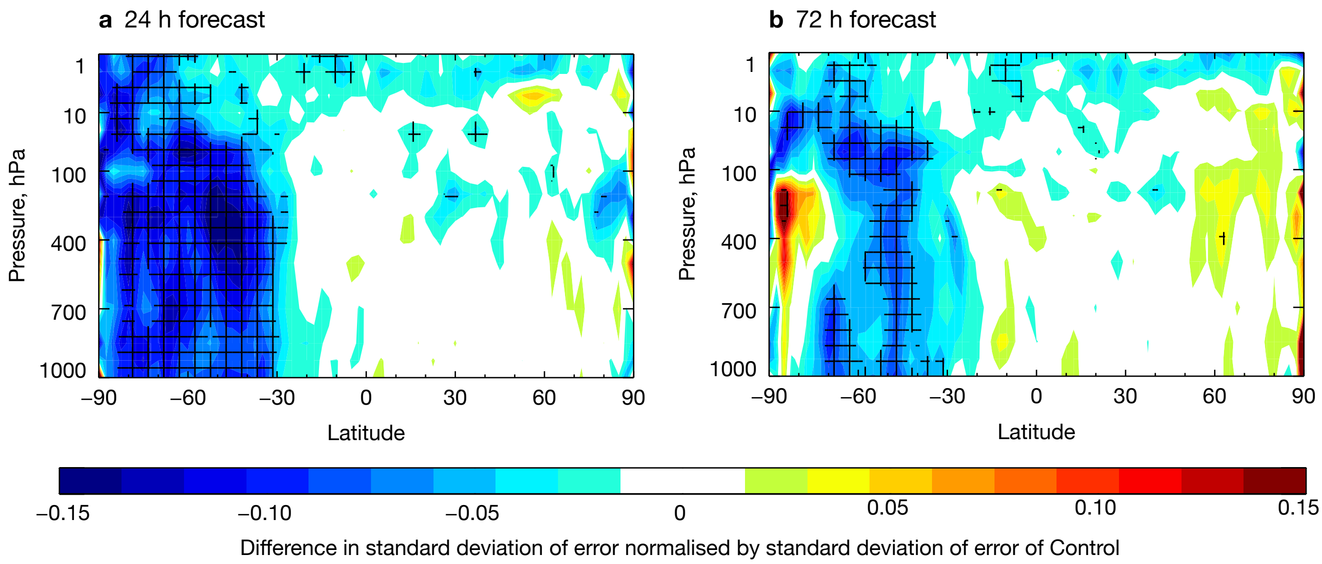

FIGURE 8 Difference in standard deviation of vector wind error between an OLCI-assimilated experiment and a Control experiment, normalised by the standard deviation of the Control experiment, for (a) 24-hour forecasts and (b) 72-hour forecasts. Verification is against own analysis in a depleted observing system. Cross-hatching shows statistical significance at the 95% confidence level based on 20 independent tests per panel.

leadership, bringing substantial mutual advantages to ECMWF and its users. Ongoing developments will improve our ability to analyse and simulate clouds and aerosols. Continued developments and operational integration of visible observations promise improvements in NWP analysis and forecast accuracy. To fully capitalise on visible data assimilation, crucial steps are needed to refine the assimilation and to improve model and operator performance. Leveraging historical visible satellite records dating back several decades presents an opportunity to enhance our understanding of clouds in past weather and climate conditions and to improve climate reanalyses. Successfully monitoring and assimilating visible satellite observations opens the door to exploiting the visible and near-infrared parts of the spectrum. These new capabilities not only advance all-sky data assimilation but also spark the imagination regarding new possibilities for understanding and predicting clouds and aerosols in ways previously unseen.

Further reading

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A new approach for using altimeter measurements

Sean Healy, Katerina Anesiadou (formerly a STEP UP! Fellow at ECMWF, now DWD), Noureddine Semane, Philip Browne, Hao Zuo, Sebastien Massart, Saleh Abdalla

Data assimilation (DA) is used in numerical weather prediction (NWP) to establish the initial conditions of forecasts based on the latest observations and an earlier short-range forecast. A new approach for exploiting satellite radar altimetry sea-surface height (SSH) information in a coupled DA system has been investigated as part of the German National Meteorological Service's (DWD's) STEP UP! Fellowship programme for ECMWF. One of the Fellowships from 2023 to 2025 built upon preliminary ideas developed at ECMWF: the project was based on recognising that the 'atmospheric delay corrections' currently applied in the retrieval of ocean SSH information from altimeter measurements are essentially the same information as the ground-based Global Navigation Satellite System (GNSS) observations now assimilated in many operational NWP systems, which provide useful humidity information over land. Therefore, it was investigated whether, instead of correcting the altimeter measurements, it is possible to retrieve potentially useful humidity information over the ocean in a similar way to ground-based GNSS. This has required running a complex, state-of-the-art coupled data assimilation system. Some of the initial, proof-of-concept results are reviewed here, and areas for further work are suggested.

Until relatively recently, we usually characterised observations as ocean, atmosphere or wave observations, based on which assimilation system the observations were going to be used in. However, the move towards an Earth system approach, exploiting an increasingly coupled model and data assimilation framework, means that some of these distinctions are being reconsidered. We now talk about using 'interface observations', which are sensitive to more than one component of the Earth system and may have been under-exploited to date because of this additional complexity. Improved use of interface observations was the subject of an important NWP Satellite Application Facility (SAF) workshop hosted by ECMWF in 2024 (see *https://events.ecmwf.int/event/420/*). For example, at the workshop it was shown how microwave and infrared radiance measurements used in the atmospheric DA system are now also being used to constrain sea-surface temperatures and sea-ice concentrations. It was also shown that ocean current information improved the use of scatterometer wind retrievals in the atmospheric system.

Altimeters can also be considered interface observations, and in this work we have been investigating whether the developments in coupled DA mean more useful information can be retrieved from these measurements.

The use of altimeter measurements at ECMWF has been discussed before by Saleh & Zuo (2016). Briefly, altimeters on satellites emit electromagnetic pulses vertically downwards, towards the ocean's surface, and then measure the reflected signal (see Figure 1). The time taken for the signal to travel to the sea surface and then back to the satellite provides information on SSH, assuming we know the position of the satellite accurately. Other characteristics of the received signal provide important information related to significant wave height (SWH) and near-surface (10 m) wind speed. Currently at ECMWF, SSH information is assimilated in the ocean data assimilation system, SWH is assimilated in the wave system, and wind speed information is used for verification. The Fellowship work has focused on SSH information retrieved from altimeters.

Retrieving altimeter sea-surface height information

A series of 'corrections' is required before accurate SSH information can be derived from the transit times of the altimeter signals. These corrections include accounting for instrumental issues, tidal effects, the interaction with the sea surface and various other geophysical effects. The set of geophysical corrections also includes terms accounting for the delays in propagation time introduced by both the ionosphere (about 90 to 965 km above sea level) and the neutral atmosphere below (see Fernandes et al., 2021, for a more detailed discussion).

The ionospheric delays can usually be estimated accurately because the altimeter emits signals at two frequencies, usually either a Ku-band or Ka-band and C-band. The ionosphere is 'dispersive', meaning that it affects the propagation times of the two signals slightly

 doi: 10.21957/sh82vcy05d

FIGURE 1 The Copernicus Sentinel-3A and -3B satellites, launched in 2016 and 2018, carry a synthetic aperture radar altimeter, which is the cone-shaped structure at the bottom of the satellite. (*Credit: ESA/ATG Medialab*)

differently in a known way. This is why the ionospheric signal can be isolated by taking a linear combination of the two measurements. Although this represents noise in the context of altimeter processing, it is useful information about the ionospheric state below the altimeter in the form of a vertically integrated total electron content (VTEC) estimate.

The additional path delay (PD) caused by the neutral atmosphere is usually partitioned into a 'dry' path delay (DPD) and a 'wet' path delay (WPD). By convention, the negative of these quantities represents two corrections applied in the processing, and these are called the 'dry tropospheric correction' (DTC) and the 'wet tropospheric correction' (WTC). These corrections are called 'tropospheric' because most of the delay occurs there, but they also contain a small stratospheric component.

The dry term is the largest, typically around 2.3 m or around 80–90% of the total path delay (we convert a time delay to distance by multiplying by the speed of light). However, it has relatively low variability and it can be predicted and corrected accurately using surface pressure information from an NWP analysis or forecast. In contrast, the wet delay/correction is more variable, ranging from 0 to 35 cm. To a reasonable approximation, the wet delay is linearly related to the total column water vapour (TCWV) at the observation location (TCWV = 0.16 WPD is a useful rule of thumb).

The WPD/WTC used in the altimeter preprocessing is usually estimated using a geophysical retrieval based on radiances from a microwave radiometer flown on the satellite with the altimeter. When a radiometer is not available, NWP-based correction can be applied.

Ground-based GNSS measurements

Ground-based GNSS (also referred to as 'ground-based GPS' or 'GPS meteorology') measurements have been assimilated at operational NWP centres for many years (e.g. Poli et al., 2007). They became operational at ECMWF in 2024 with the introduction of IFS Cycle 49r1.

This measurement technique first emerged in the 1990s with a pioneering paper by Bevis et al. (1992). In this work, they explained how geodesists using GPS needed to correct for propagation delays caused by both the ionosphere and the neutral atmosphere. They noted that scientists were beginning to use these GPS measurements to study the ionosphere. They discussed whether similar applications could be found for the neutral atmosphere, in particular estimating TCWV. More broadly, they posed the question whether the neutral atmospheric delay was a source of geodetic noise or meteorological signals.

In subsequent years, ground-based GNSS networks became fundamental for monitoring the ionospheric state. This data is now routinely used in operational limited-area and global NWP, primarily providing TCWV information over land.

The ground-based GNSS quantity assimilated at most NWP centres is called the zenith total delay (ZTD). Although the naming convention differs, this is equivalent to the sum of the delay terms (ZTD = PD = DPD + WPD) identified in the altimeter corrections. The GNSS ZTD can also be partitioned into the sum of zenith hydrostatic delay (ZHD) and zenith wet delay (ZWD) to aid interpretation and comparison, where clearly ZHD = DPD and ZWD = WPD, but this partitioning is not required when assimilating the data as the combined ZTD. It should also be noted that GNSS zenith information is usually estimated by fitting multiple 'slant delays', for non-vertical signal paths from the GNSS transmitter to receivers on land. So, in some sense, the GNSS information we currently assimilate is based on a more complex measurement geometry than the analogous altimeter corrections.

To summarise, the similarities between the corrections applied in the processing of altimeter SSH information and the quantity assimilated in ground-based GNSS are clear and well known. In fact, ground-based GNSS ZWD information can be used to improve the altimeter wet delay correction in coastal regions, where the radiometer-based retrieval can become contaminated by land and difficult to use. However, as far as we know, no one has tried to assimilate altimeter measurements in an NWP system to provide TCWV information over the ocean as if they were GNSS measurements, but with the additional complexity of an unknown surface height.

Data used for this study

The EUMETSAT level-2 altimeter data for Sentinel-3A and -3B is used for this work. These datasets are ideal for this research project because they contain all the altimeter corrections applied, meaning we are able to pick and choose which corrections we want to apply for this particular application. In practice, we use all the corrections provided in the EUMETSAT files, except for the dry and wet delay corrections.

For the purposes of this work, a new assimilation variable has been defined that is sensitive to both the atmospheric state and SSH. Currently, at ECMWF this variable is called sea surface to satellite delay (S3D), primarily to avoid confusion with ZTD and PD. It can be written as S3D = ZTD – SSH, where SSH is the absolute sea-surface height above a geoid.

When processing the EUMETSAT level-2 altimeter observation information to S3D, the dry and wet atmospheric corrections are effectively added back to sea level anomaly (SLA) values. Note that the level-3 SLA is the quantity usually assimilated in ocean DA systems, such as NEMOVAR used at ECMWF. The S3D values are defined as relative to the geoid and this must be reflected in the measurement processing. The approach adopted here is mathematically equivalent to the current method used for SLA assimilation. More specifically, the observed SLA values are given relative to a two-dimensional mean sea surface field (MSS) above a reference ellipsoid. The MSS is derived from the mean value of observations taken over an extended period.
In contrast, the anomalies simulated in ocean DA systems are given relative to a two-dimensional mean dynamic topography (MDT) field, derived from the ocean forecasting system. The MDT is computed by running the ocean forecasting system for an extended period – ideally the same period used for the MSS estimate – but only assimilating a subset of observations. The implicit assumption here is that the MDT is given relative to the geoid, even though the actual, rather complex geometrical shape of the geoid is not used in ECMWF's NWP systems.

This formulation of the SLA assimilation problem – where we compute the difference between the observed and simulated anomaly information – is equivalent to assuming the observed information is given relative to a geoid model, G, defined as G = MSS – MDT. Therefore, in the S3D processing, we use both the model MDT and the observed MSS in the observation processing to provide the S3D values relative to G = MSS – MDT. We have tried using other geoid models to produce the S3D values, such as EGM2008 and GOCO06s, but to date the MSS – MDT approach appears to provide the smallest biases when computing the S3D departures in experiments.

The S3D values are then converted to a ground-based GNSS format using the EUMETSAT ROM SAF 'GBGP software' (see *https://rom-saf.eumetsat.int/gbgp/*). They are then ingested and processed in the same way as ground-based GNSS information when running the assimilation experiments.

Assimilating the S3D values

A schematic of the assimilation system used to test the S3D measurements is shown in Figure 2. When a measurement is assimilated, we need to reproduce it by simulation – or 'forward modelling' – using information provided by the forecasting system. This is because we compute the differences between the measured and simulated values during the assimilation process, in order to update the forecast given the new observations and produce an improved estimate of the state (the 'analysis').

As described above, by construction S3D = ZTD – SSH, so both atmospheric and ocean state information must be available when simulating – or 'forward modelling' – the S3D values within the DA system. Computing the ZTD part is relatively straightforward because we already have this forward model available for the ground-based GNSS assimilation. The use of SSH, and making it available within the ground-based GNSS system, exploits more recent developments in coupled DA.

As shown in Figure 2, the ocean DA system, NEMOVAR, is run in parallel (outer-loop coupling) with the atmospheric 4D-Var DA system. NEMOVAR assimilates all the available SLA information and other sea-surface temperature and salinity observations for this period in the standard way. It provides a short-range forecast of the two-dimensional SSH field (or 'absolute dynamic topography', ADT) that is passed to the atmospheric 4D-Var system, using the extended control variable (XCV) framework.

Briefly, the XCV is an important generalisation of 4D-Var because it enables additional parameters to be appended to the normal, atmospheric state vector

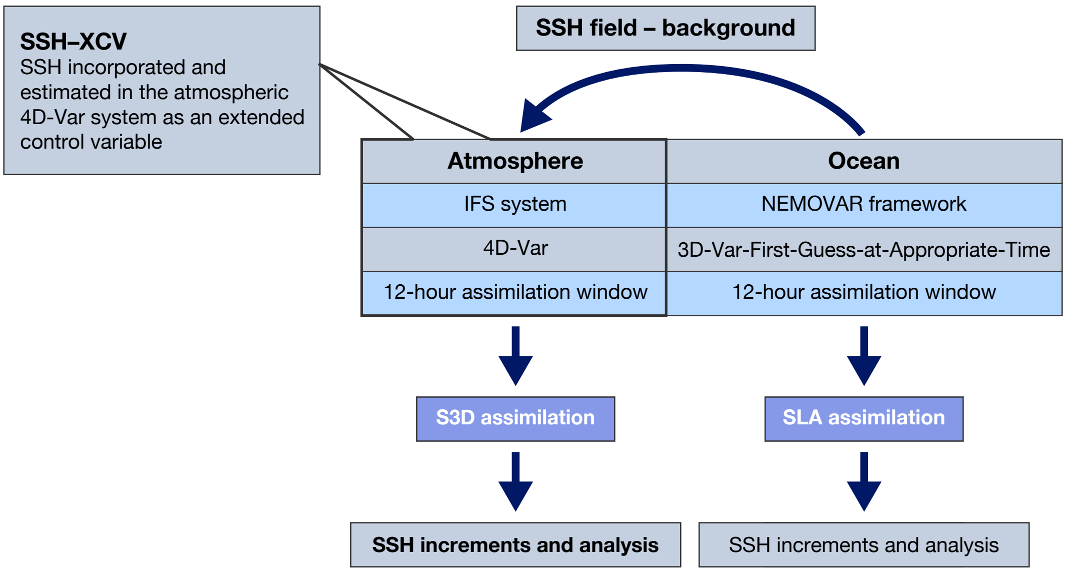

FIGURE 2 A schematic of the coupled DA system used in the S3D assimilation experiments. The cycling ocean DA system, NEMOVAR, provides a short-range forecast of the SSH field for use in the atmospheric 4D-Var system. The SSH information is appended to the normal 4D-Var state vector using the XCV framework.

(Massart et al., 2021). This generalisation means we are able to adjust both the atmospheric state and the SSH values stored in the XCV when producing the 4D-Var analysis. Note that the SSH analysis in the XCV is not 'cycling', so an estimate of the SSH in the XCV at a given time does not influence the XCV SSH at a later time.

Experiments

The proof-of-concept assimilation experiments with the new Sentinel-3A and -3B S3D information cover the period of 7 June to 30 August 2020. The S3D values are thinned to 28 km horizontal separation, and they are only used in the latitude range between 60° north and 60° south. The assumed observation uncertainty of the S3D values is 3 cm, and the assumed standard deviation of the XCV background error of the SSH from the NEMOVAR forecast is 4 cm. The XCV background error correlation matrix assumes an exponential decay with a separation distance, assuming a 50 km horizontal scale length. These uncertainty specifications are a reasonable first step, but they can probably be improved in future work.

Figure 3 illustrates the typical S3D coverage for a 12-hour assimilation window on June 7, 2020, with the colour shading illustrating the increments in S3D space for the observation tracks. More generally, Figure 4 shows the spatial map of the S3D observation minus background (o–b) and observation minus analysis (o–a) root-mean-square (RMS) departure statistics averaged over the three-month period. The spatially averaged RMS value of (o–b) is 5.7 cm, but this is reduced to 3.2 cm for the (o–a) statistics. This indicates that the assimilation system is able to move the combined ocean/atmosphere state estimate towards the observations quite effectively. It is interesting to compare the values of these departure statistics with those typically found for ground-based GNSS ZTD observations. In the northern and southern hemispheres, there are clear seasonal variations, with larger values in summer than winter, but the RMS value of (o–b) is typically around 0.8–1.2 cm. It is larger in the tropics, with a value around 1.8 cm. The S3D (o–b) departure statistics are poorer because they combine both SSH and ZTD short-range forecast errors, with SSH errors clearly making the larger contribution.

To date, we have not been able to demonstrate a clear positive impact on tropospheric humidity. For example, Figure 5 shows the changes in RMS forecast error statistics for TCWV with and without the S3D observations being assimilated. Overall, the TCWV impact is neutral. One possible reason is that the volume of S3D data is not particularly high in this testing, and we need more observations before a clear impact is seen. To that end, we have started work with Sentinel-6A data, but bias characteristics of these S3D data differ from Sentinel-3A and -3B, and the cause of this difference requires further investigation. Another reason relates to the current specification and partitioning of the background uncertainty.
The background SSH uncertainty assumed in the XCV is currently set to 4 cm, whereas the background ZTD uncertainty used in the atmospheric 4D-Var will be around 1 cm (but it is not defined explicitly). This means that the S3D departures will primarily increment the SSH field rather than the atmospheric state when trying to fit the observed values.

The system used to test the S3D assimilation (Figure 2 schematic) produces two SSH analyses: the new SSH analyses in the XCV determined by combining the NEMO forecasts and the S3D observations in 4D-Var; and the SSH analysis produced by the cycling NEMOVAR system, assimilating SLA and other routinely used observation information. These two sets

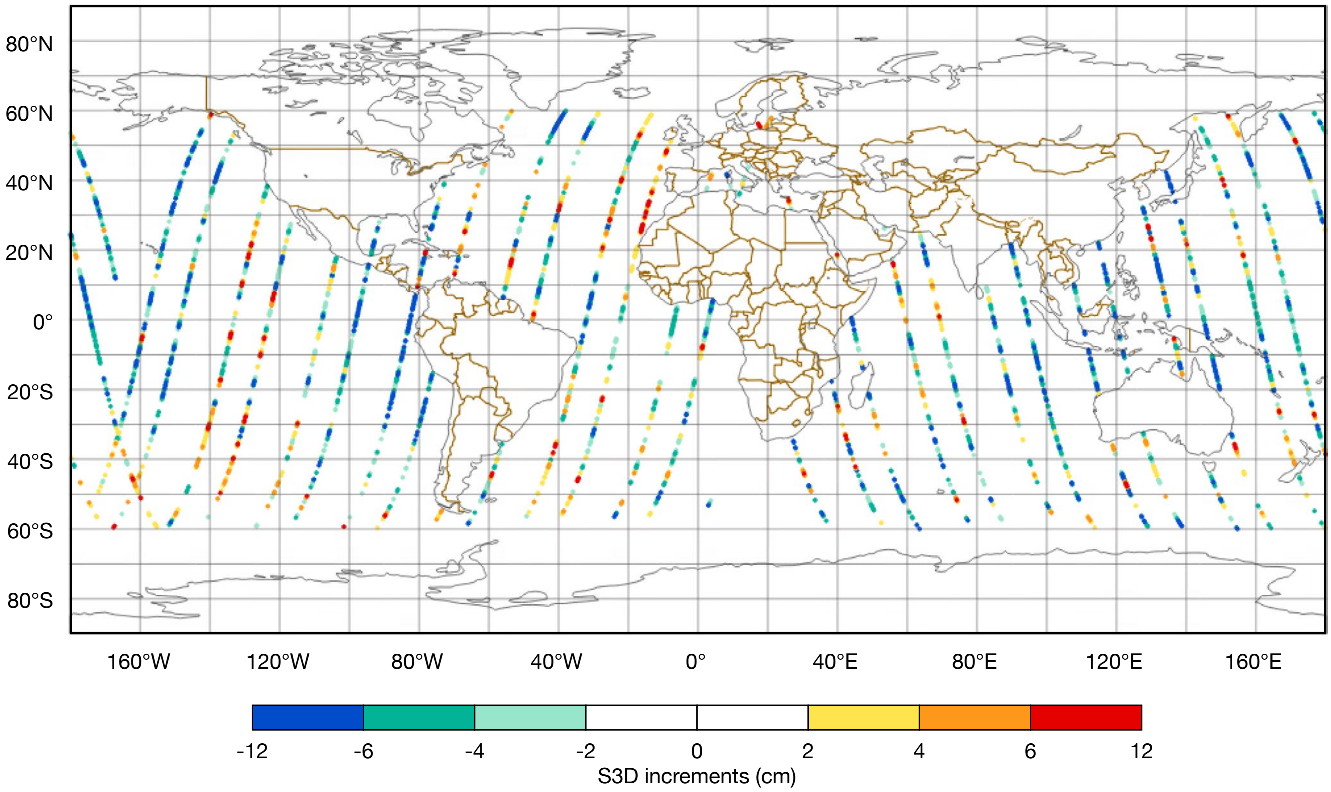

FIGURE 3 The combined Sentinel-3A and Sentinel-3B S3D observation coverage used in a 12-hour assimilation window on 7 June 2020. The colour range shows the S3D increments (analysis minus background) in cm.

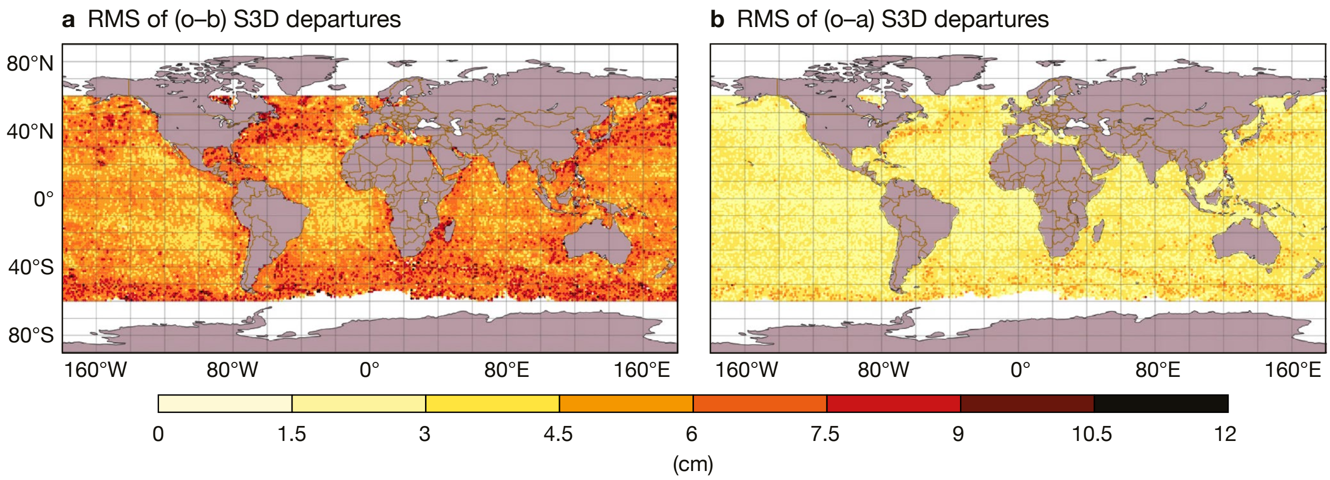

FIGURE 4 The RMS of (a) the (o–b) S3D departures and (b) the (o–a) S3D departures. The spatially averaged RMS departure is reduced from 5.7 cm to 3.2 cm, showing how the combined atmospheric plus SSH analysis is able to improve the fit to observations.

of analyses have been compared with the independent Copernicus Marine Environment Monitoring Service (CMEMS) gridded daily level-4 SSH analysis for the experimental period to investigate whether the SSH analyses are reasonable.

Figure 6 shows the improvement in RMS difference, when comparing the analyses and short-term (background) forecasts against the CMEMS SSH analysis for both the XCV approach (left) and NEMOVAR analyses (right). The negative values (green/ blue colours) indicate where the XCV and NEMOVAR analyses are closer to the CMEMS analysis than the forecasts. Conversely, orange/red indicates that the analyses move away from CMEMS.

In general, the S3D observations are moving the NEMOVAR forecasts towards the CMEMS analyses and improving the consistency between these two SSH estimates, which is very encouraging. There are clear spatial differences in the XCV and NEMOVAR agreement with CMEMS. NEMOVAR is clearly doing a much better job in the important, eddy active regions, where the SSH forecast errors are known to be larger (Southern Atlantic, Indian Ocean, North Atlantic, North Pacific). It assimilates more altimeters (Jason-3, CrysoSAT-2, AltiKa) and the SSH field also benefits from sea-surface temperature and salinity observations via balance relationships in the well-tuned, flow-dependent background error covariance matrix. We also find that the S3D data is rejected more frequently in these higher forecast error regions as a result of stricter quality control (QC) in 4D-Var. This is because the QC does not account for spatial variations in the forecast uncertainty of the SSH, and large (o–b) departures caused by the large forecast errors we want to correct are more likely to be rejected. However, it is also noticeable that S3D appears more consistent with CMEMS off the west coast of South America, Africa and India, which is promising.

Summary and further work

In this work, we have assimilated altimeter observations that normally provide sea-surface height information for ocean applications into the atmospheric 4D-Var system, by exploiting recent developments in coupled data assimilation at ECMWF. The work is motivated by many NWP centres routinely assimilating ground-based GNSS observations over land. The neutral atmosphere propagation corrections applied in altimeter SSH processing are essentially equivalent to these ground-based GNSS observations.

This novel use of altimeter information represents a potential new source of humidity information over the ocean, based on an accurate measurement of a time delay. Experiments assimilating Sentinel-3A and -3B delays have been performed for June to August 2020. We have not yet seen a strong impact on the humidity field, but we have demonstrated that this new Earth system approach is now technically feasible.

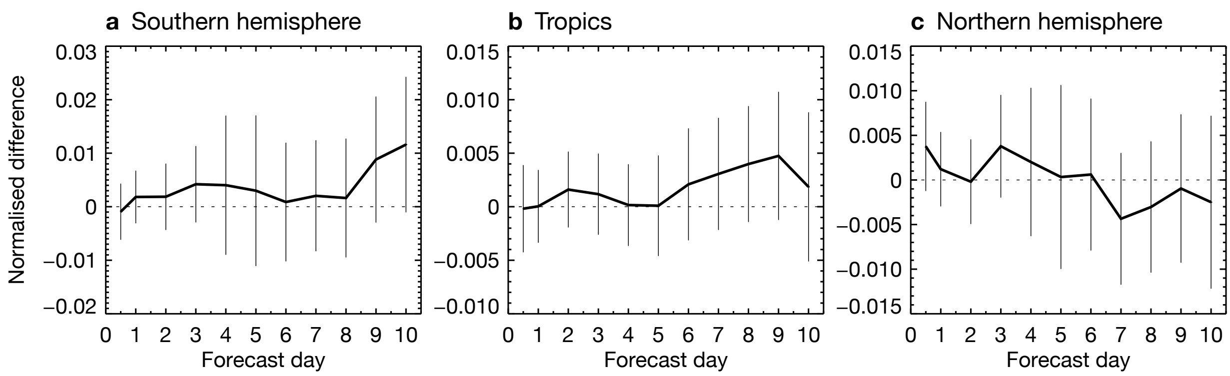

FIGURE 5 The change in RMS TCWV forecast error as a function of forecast range for (a) the southern hemisphere (–90° to –20°), (b) the tropics (–20° to 20°), and (c) the northern hemisphere (20° to 90°). Values above 0 indicate that the S3D values are degrading the forecasts. The error bars show the 95% confidence interval, and the forecasts are verified against their own analysis.

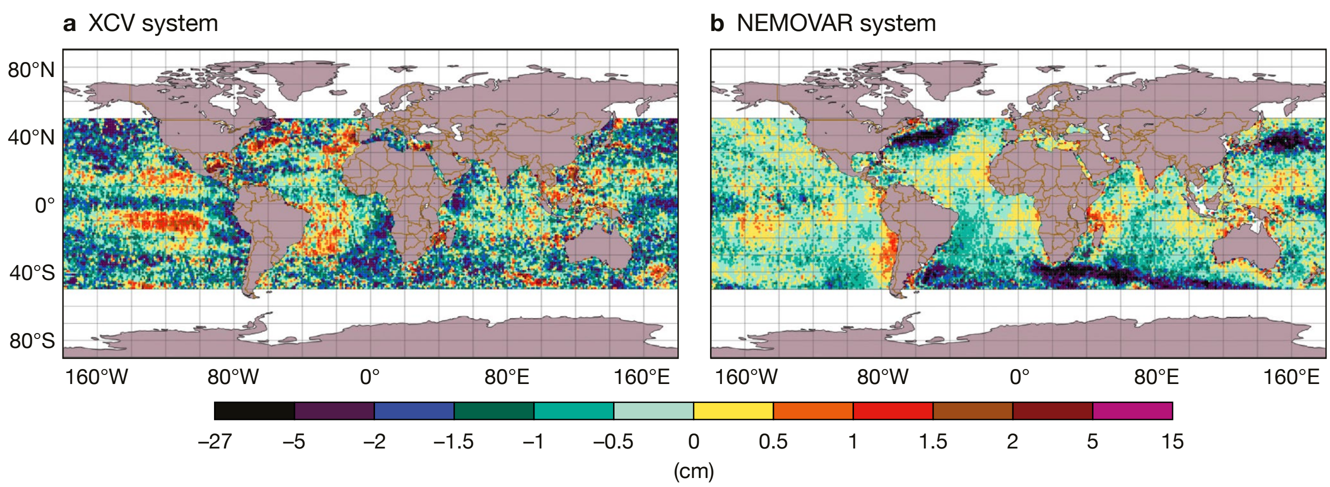

FIGURE 6 The change in 'RMS (analysis – CMEMS) minus RMS (forecast – CMEMS)', for (a) the XCV system and (b) the NEMOVAR system. Values below 0 indicate that the analyses are more consistent with CMEMS than the background forecasts. The statistics are computed for the period 7 June to 31 August 2020.

The SSH analyses produced by 4D-Var assimilating the S3D observations move the SSH forecasts towards the independent, CMEMS level-4 gridded daily analyses, which is very encouraging. In particular, the XCV system appears to perform slightly better than NEMOVAR off the west coast of, for example, South America, Africa and India.

However, the XCV SSH analyses are not as accurate as the NEMOVAR system where the SSH forecast errors are known to be large. This is because NEMOVAR uses more observation data, it benefits from a more sophisticated formulation of the background error covariance matrix, and it uses more appropriate quality control in regions where the SSH forecast errors are large.

This novel use of altimeter measurements is still in its early stages, and there are a number of areas for possible future work. Firstly, we can try to improve the humidity impact by increasing the number of S3D values by adding new altimeters. In preliminary work, the application to Sentinel-6A data highlighted S3D bias differences compared to Sentinel-3A and -3B, which requires further investigation. We can also look at how to couple the S3D information more closely with NEMOVAR. For example, instead of assimilating both S3D and the SLA information in the 4D-Var and NEMOVAR systems, respectively, we could just assimilate the S3D information in the 4D-Var and pass departures to NEMOVAR. However, this would require revising the 4D-Var QC approach to increase S3D usage in the regions of large SSH errors.

Finally, the assimilation methods described here may have relevance to the use of data from a new generation of wide-swath satellite altimeters, such as the Surface Wave Ocean Topography (SWOT) mission. Recent work (Hay et al., 2025) has indicated that humidity structures with horizontal scales less than 80 km can be difficult to correct with a radiometer-based wet tropospheric correction. As a consequence, residual wet delay errors may alias into the SSH estimate. Using the S3D assimilation system – following the example set by Bevis et al. in the 1990s – we could potentially investigate whether wide-swath altimeters are a useful source of humidity information.

Further reading

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National Collaboration Programmes strengthen engagement through Copernicus

Stijn Vermoote, Cristina Ananasso, Samuel Almond

ECMWF has a longstanding tradition of working closely with its Member and Co-operating States to promote the effective use of its data and services. Through structured training, user feedback mechanisms such as the Green Book surveys as well as liaison visits to Member and Co-operating States, and initiatives like Using ECMWF's Forecasts (UEF) events, the Centre maintains a vibrant dialogue with national meteorological and hydrological services (NMHSs) and other users. With the advent of the Copernicus Programme, the Earth observation component of the EU's space programme, this engagement has deepened and expanded. The Copernicus Atmosphere Monitoring Service (CAMS) and the Copernicus Climate Change Service (C3S), both implemented by ECMWF, have ushered in a new era of co-development, both through applications and targeted user uptake activities.
A milestone in this evolution was the launch of the CAMS National Collaboration Programme (NCP) at the end of 2021, an initiative that reaffirms ECMWF's user-oriented approach and its commitment to working with and for countries. By supporting countries in implementing Copernicus data within their national contexts, NCPs foster long-term partnerships, accelerate data-driven decision-making, ensure that the benefits of Copernicus reach national policy users, and support related domain specialists across Europe.

The vision behind NCPs

NCPs aim to enhance the operational use and integration of Copernicus data and services across EU Member States and other participating countries, including Norway, Iceland, the United Kingdom, and more recently also Ukraine. ECMWF pioneered the concept of NCPs, initially through CAMS. Today, NCPs are a core element of the European Commission's Copernicus user uptake strategy and are integrated across almost all Copernicus Services, including C3S. While tailored differently for CAMS and C3S, reflecting differences in strategic focus and national policy contexts, the NCPs share a common foundation based on five core principles, as presented in Box A.

CAMS NCP: air quality and beyond

The CAMS NCP, launched at the end of 2021, supports national and regional authorities in integrating CAMS data into areas such as air quality assessments, greenhouse gas monitoring, energy applications and

a Core principles

The following are core principles of the CAMS and C3S NCPs as they stand today.

1. Fostering meaningful dialogue: Sustained engagement with national representatives builds mutual trust and ensures that the unique capacities and needs of each country are recognised and addressed. Dialogues, recognising the diversity between countries, serve as the foundation for successful cooperation.

2. Enabling co-design: NCPs are conceived as collaborative frameworks and function as a two-way process. ECMWF implements Copernicus funding and provides technical expertise and coordination on CAMS and C3S data and services, while national partners define how Copernicus products can serve their specific policies and operational mandates.

3. Preparing for 'the last mile': Acknowledging the importance of the roles of different entities in the data value chains, ECMWF works to ensure that Copernicus products are operationally usable, enabling downstream national institutions and experts to develop and enhance services such as downscaling, integration with national datasets and the development of value-added solutions.

4. Enhancing user intelligence: Understanding the practical needs and experiences of national users helps ECMWF to continually refine its services, ensuring they remain fit-for-purpose in evolving national contexts.

5. Extending reach: Countries contribute by translating materials and promoting CAMS and C3S in national languages, inspiring new users and expanding awareness through outreach, and by investing in training activities that transfer knowledge to broader user communities.

doi: 10.21957/s76spe39xv

public health services (*https://atmosphere.copernicus.eu/cams-national-collaboration-programme*). Several of these are closely linked to requirements as driven by the European Commission.

The programme is modular in design: each participating country selects from a suite of predefined modules based on national relevance. Upon an initial pilot phase, these now include:

- support for air quality data reporting
- direct use of CAMS products at national level
- downscaling of CAMS air quality products
- emissions modelling
- support for in-situ monitoring networks
- communication and user outreach
- training
- development of demonstrators for the energy and/or health sectors.

To date, ECMWF has active agreements with 26 countries (see Figure 1). The most widely adopted modules are 'direct use' (86%) and 'downscaling' (80%), followed by 'support for in-situ networks' and the 'development of demonstrators'.
The 'communication and outreach' module is mandatory across all contracts.

Engagement is further strengthened through twice-yearly Atmosphere User Forums (*https://atmosphere.copernicus.eu/4th-atmosphere-user-forum*), which gather over 100 participants for discussion of experiences on ongoing activities and for ECMWF to share information on new developments and plans. Dedicated technical workshops allow countries working on similar modules to collaborate, discuss challenges, and learn from each other. Box B presents two user testimonials for the CAMS NCP.

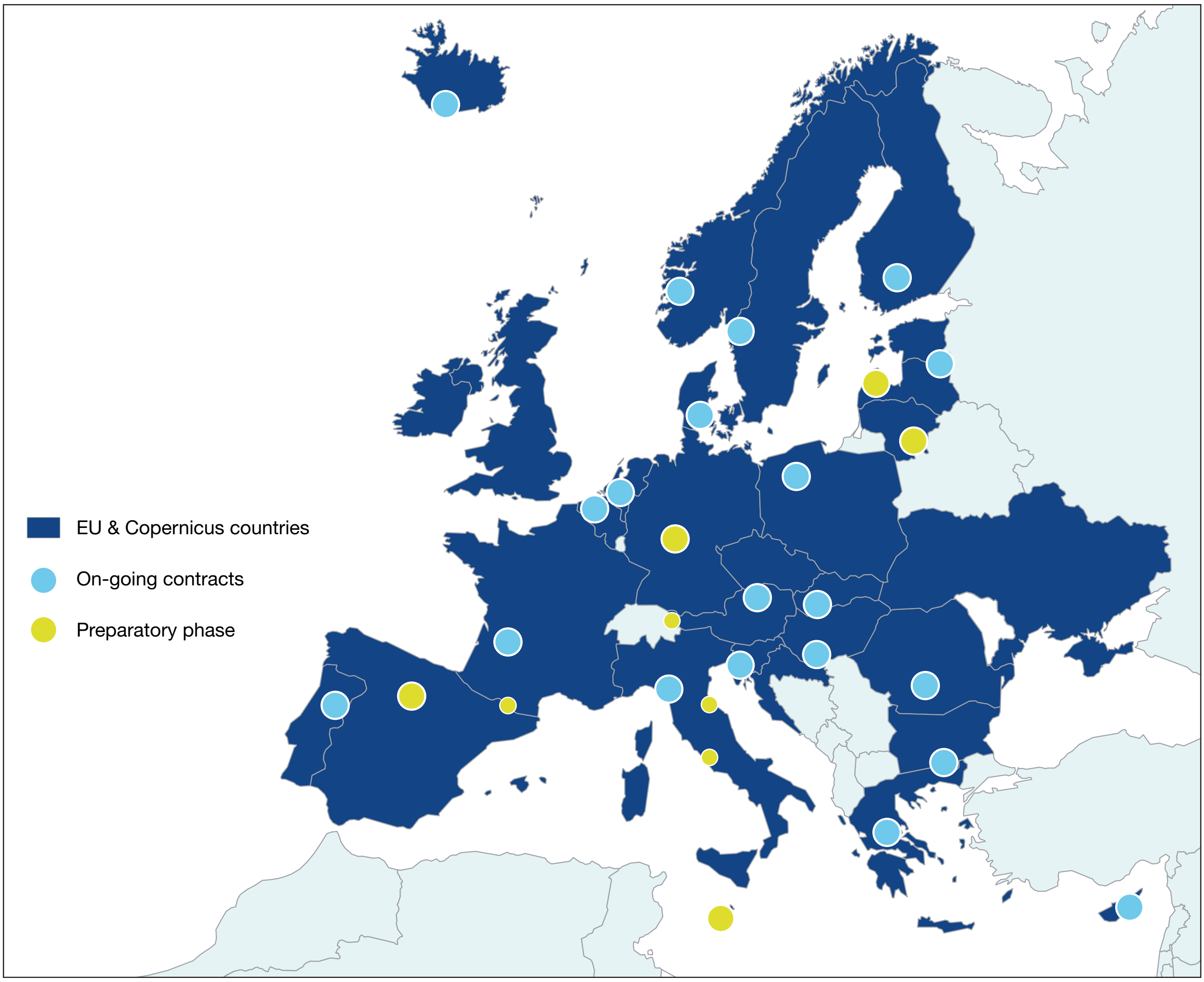


FIGURE 1 Overview of countries engaged in the CAMS NCP (May 2025).

b **User testimonials 1–2**

User testimonial 1 – Agricultural University of Iceland (AUI):

"CAMS NCP helped fill important gaps in our understanding of air quality challenges in Iceland and made significant steps towards data accessibility. Our activities have raised awareness among the public and local authorities about air pollution and its impacts, contributing to the establishment of science-backed actions to protect people's health."

User testimonial 2 – Italian Institute for Environmental Protection and Research (ISPRA):

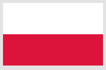
"The expansion of the NCP partnership aims to enhance the use of CAMS products to improve air quality in Italy at both national and local levels. Key activities include assessing pollution events, quantifying the desert dust contribution to PM10, developing ensemble forecasting models and innovative pollen monitoring tools, as well as training and awareness initiatives."

C3S NCP: climate action in partnership

Launched in 2023, the C3S NCP fosters the integration of C3S data and services into national climate policy and planning (*https://climate.copernicus.eu/c3s-national-collaboration-programme*). Using C3S data and services as a base, it supports countries in:

- co-developing tailored climate services to address national policy needs
- strengthening data accessibility and usability, aligned with national priorities
- complementing existing national data services and operational systems and supporting the integration of C3S data and services where requested
- enhancing communication and outreach around climate risks
- facilitating capacity building, training and knowledge exchange.

The programme operates via 'Calls for Action', which are competitive funding opportunities for which the actions are designed based on inputs from consultations with national stakeholders. The first call in 2024 led to nine funded projects (see

Lead	Country	C3S products	Priority areas
Spanish National Research Council (CSIC)		Seasonal forecast	Fire and drought management
Polish Institute of Environmental Protection – National Research Institute (EIP–NRI)		Seasonal forecast & reanalysis	Policy & adaptation planning
Portuguese Institute for Sea and Atmosphere (IPMA)		Reanalysis, seasonal and projections	Multi-sector risk assessment
Italian Institute for Environmental Protection and Research (ISPRA)		GHG emissions, reanalysis, seasonal and projections	Multi-domain climate risk assessment & adaptation
Meteo Romania		Seasonal and decadal predictions	Agriculture
National Observatory of Athens (NOA)		Seasonal and decadal predictions	Renewable energy
Swedish Meteorological and Hydrological Institute (SMHI)		Climate monitoring and awareness	Climate monitoring and communication
Flemish Institute for Technological Research (VITO)/ Royal Meteorological Institute (RMI) of Belgium/Belgian Climate Centre (BCC)		Reanalysis/observations	Health/data rescue & standardisation

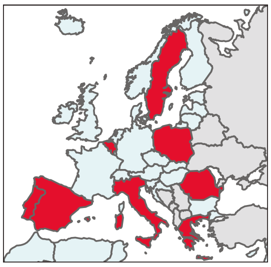


FIGURE 2 Overview of countries engaged in the 2024 C3S NCP Call for Actions.

C **User testimonials 3–4**

User testimonial 3 – Royal Meteorological Institute of Belgium (RMI)/Belgian Climate Centre (BCC):

"A very important aspect is that the NCP allows the promotion and the use of national climate observation records. This is particularly true for in-situ (station) observations, which are sometimes poorly visible and accessible in national archives while essential for climate monitoring."

User testimonial 4 – Spanish National Research Council (CSIC)/Spanish National Meteorological Service (AEMET):

"[The C3S NCP] plays a vital role in enhancing climate resilience by integrating advanced C3S datasets into national climate services, directly supporting the country's efforts to address increasing risks, especially from drought and fires. [... It] contributes to ongoing initiatives for the development of new regionalised climate services, providing improved seasonal forecasts and tailored climate information to support decision-making, emergency planning, and adaptation strategies."

Figure 2). The 2025 C3S NCP Call for Actions is about to be published over the summer months and is designed to significantly increase the reach and further enhance the impacts of the programme.

To coordinate and streamline engagement, ECMWF established the C3S NCP Joint Coordination Office in 2024 (*https://climate.copernicus.eu/joint-coordination-office*). The Office facilitates structured engagement with public administrations and fosters a vibrant community of national climate service practitioners through forums and expert exchanges. Box C presents two user testimonials for the C3S NCP, and Figure 3 shows a panel discussion on the C3S NCP at the C3S General Assembly in June 2025.

Looking ahead

In 2025, the NCPs of both CAMS and C3S will continue to evolve, focusing on deeper collaboration, regional partnerships and enhanced sustainability of

FIGURE 3 A panel discussion on the C3S NCP took place at the C3S General Assembly in Valencia, Spain, in June 2025, involving (from left to right) Delphine Deryng (ECMWF), Carlo Buontempo (ECMWF), Mark Payne (Danish Meteorological Institute), Stergios Kartsios (National Observatory of Athens), and Maialen Iturbide (Instituto de Física de Cantabria).

the targeted impacts. Key developments include:

- **Clustered country engagements:** New calls addressing transboundary environmental and climate challenges, such as air pollution transport or regional climate risks, are being planned, and entitites in neighbouring countries are invited to join forces. Twinning projects under the C3S NCP will encourage more experienced countries to support emerging national climate services.
- **Enhanced feedback loops:** ECMWF will place greater emphasis on collecting and acting upon user feedback from countries, with dedicated user interaction sessions and workshops informing future service development.
- **On-demand applications:** Through the NCP, C3S will allow countries to identify priority application areas, offering the opportunity to develop tailor-made applications that utilise C3S data to support national policy and climate service needs.
- **Cross-fertilisation with other ECMWF user engagement activities:** Established dialogues, gained user intelligence and training practices feed other user engagement activities at ECMWF in support of our Member and Co-operating States.
- **New funding mechanism, grants:** In addition to procurements, ECMWF will begin using grants to fund NCP activities. This change encourages national ownership and ensures sustainability of uptake beyond the funding period.

New grant-based funding opportunities for CAMS and C3S NCPs will be published between June and September 2025. Interested national entities are encouraged to visit the ECMWF grants web page for more information: *https://www.ecmwf.int/en/about/grants*.

ECMWF's improving data services in the era of cloud computing and machine learning

Stephan Siemen, Umberto Modigliani

For decades, ECMWF has played a pivotal role in providing comprehensive and reliable meteorological and climate data to its Member States and the broader global community. From offering real-time and historical weather forecasts to delivering sophisticated model outputs and observations, ECMWF has supported a wide array of applications, ranging from everyday weather prediction to advanced research and disaster risk management. These services, accessible through diverse platforms and APIs (Application Programming Interfaces), have empowered users to obtain precise and tailored datasets, thereby bolstering research and services across numerous sectors.

From its inception, ECMWF's core mission, as enshrined in its Convention, included the "collection and storage of appropriate meteorological data" and ensuring that these data were "available to the meteorological offices of the Member States". Consequently, the development, maintenance, and operation of data provision services has been fundamental to ECMWF's identity since its creation.

However, the landscape of data services is constantly evolving. ECMWF has witnessed a substantial surge in data volumes, driven by advances in weather forecasting technology and an escalating demand for more accurate and granular predictions. The introduction of higher-resolution models and the integration of more observational data from diverse sources, such as satellites and radars, has led to an exponential increase in the data processed and stored by ECMWF. Simultaneously, the number of users who integrate forecast data into their systems and services has expanded, placing greater demands on the services delivering this data. The variety of datasets handled by ECMWF has also grown, thanks to numerous collaborations that integrate data from other centres.

This article will explore the evolution of ECMWF's data provisioning services in response to these growing demands, the increasing variety of data sources, and the potential offered by the introduction of cloud computing and machine learning (ML). It will also present the various ways in which these developments aim to serve Member States and the wider community, highlighting the positive impact of ECMWF’s many collaboration activities on these developments.

The continuous growth of data volumes

The exponential growth of data volumes at ECMWF presents significant challenges. The organisation must manage the logistical and computational demands of processing, storing, and disseminating vast amounts of information in an effective way. Robust data management processes, including data modelling and the management of data holding catalogues, are essential. This necessitates continuous upgrades to computing capabilities and the optimisation of data handling strategies to ensure the timely and reliable delivery of forecasts. The increase in data volumes is both a driver of progress and a challenge that demands continuous innovation and investment.

ECMWF's day-to-day data volumes have grown dramatically over the years. The increasing availability of satellite data has been a key driver on the observation side. For forecast data, increases in resolution, frequency of runs, the number of ensemble members, and the number of parameters created have all contributed to a steady increase in volume. While the majority of data represents forecast and reanalysis data from operational or research and collaboration activities, observations collected across the globe are a vital component and are essential for many research activities at ECMWF and its Member States.

ECMWF has undertaken various efforts to mitigate the growth of its data archive, including stricter governance and deletion of obsolete research data, as well as the implementation of better compression and efficient storage techniques. These activities have significantly influenced the growth curve, damping the exponential trend it represents (see Figure 1).

Currently, ECMWF's overall production corresponds to 360 TB of forecast data per day. Projections indicate that this daily production will exceed 1 PB by 2027. This remarkable amount highlights a growing gap between what is produced and what can be effectively handled by users. While it is challenging for users to handle the increasing volume of data, ECMWF is actively working to offer solutions that enable users to realise more of the benefits that fully utilising this data can bring.

Embracing open data

ECMWF forecasts have always been provided at no extra charge to our Member and Co-operating States, and provisions under the umbrella of the World Meteorological

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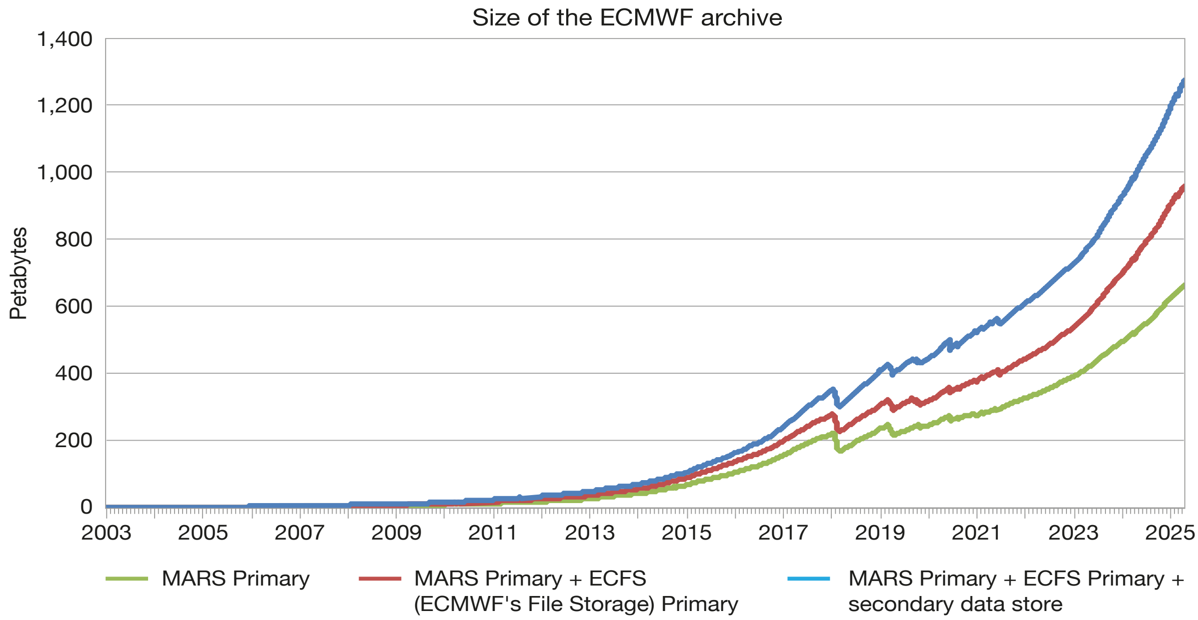

FIGURE 1 ECMWF's archive has substantially grown over the last two decades despite some reductions, and further growth is projected.

Organization (WMO) were in place to support national meteorological and hydrological services (NMHSs) and international collaborations worldwide. Fees for other users were set in coordination with Member States.

In December 2020, the ECMWF Council unanimously adopted a move towards a more open data policy. This decision aimed to make some of ECMWF's model output available under an open data licence. During this transition, a tiered approach has been designed to provide balanced services for all users. The free and open data tier provides a subset of the full ECMWF Catalogue, available with no charges under the CC-BY-4 open licence.

The implementation period, which ends in the autumn of 2025, has enabled ECMWF to prepare for the change. While the provision of open data will offer many benefits and opportunities, it will also present some challenges to implementing good and efficient management of user demand. When users take up certain services, they need to be encouraged to use relatively tailored and small requests rather than large-scale ones, which can stress the system.

As the open data offering expands, ECMWF will also remove barriers for WMO members by removing all data and service charges for full-resolution data in support of UN initiatives such as Early Warnings for All (EW4ALL). Between now and 2027, the quality and accessibility of data will be improved for all WMO members, first focusing on less developed nations in the WMO's Regional Association for Europe (WMO-RAVI) and the countries supported by the Systematic Observations Financing Facility (SOFF) initiative. SOFF aims to support some countries in generating and exchanging data compliant with the Global Basic Observing Network (GBON), which is critical for improved weather forecasts and climate services.

ECMWF's data provision services

Data provision by ECMWF takes place through two avenues: the operational dissemination system and the Meteorological Archival and Retrieval System.

Dissemination system

ECMWF's most mature and time-critical method of data provision is the operational dissemination system, which is part of the ECMWF Production Data Store (ECPDS). This advanced platform is designed to efficiently collect and distribute vast amounts of meteorological data to users, including Member States, research institutions, and commercial entities. The ECPDS is also part of a collaborative effort with Member and Co-operating States through an Optional Programme (see Gougeon, 2019).

Meteorological Archival and Retrieval System

The Meteorological Archival and Retrieval System (MARS) is the backbone of ECMWF's data services, providing a centralised repository for a vast collection of meteorological data. MARS allows users to retrieve specific datasets based on various criteria, such as time, location, and parameters.

Over time, ECMWF has continuously evolved data access methods to improve the user experience and cater to diverse needs:

- **Web-based access to data and APIs**: ECMWF has developed web-based interfaces and APIs that allow users to access data programmatically. These tools provide a user-friendly way to explore the data holdings and retrieve the desired information.

- **ecCharts**: ecCharts serves as a ‘window’ to ECMWF's forecasts, providing interactive visualisations and analysis tools. This platform allows users to explore forecast data in a graphical format, enabling them to quickly identify trends and patterns.
- **OGC standards**: ECMWF has adopted Open Geospatial Consortium (OGC) standards to ensure interoperability and compatibility with other geospatial data systems. This allows users to seamlessly integrate ECMWF data into their existing workflows and applications.

All these developments were conducted in parallel with new services across ECMWF, such as the Copernicus Climate Change and Atmosphere Data Stores, which ensured harmonisation and benefited from each other's experiences.

Processing close to the data: the emergence of cloud services

The increasing volume of data and the growing demand for customised processing have led to the emergence of cloud-based services. These services bring the processing capabilities closer to the data, reducing the need for users to download large datasets and enabling them to perform complex analyses in a scalable and efficient manner.

- **The European Weather Cloud (EWC)**: The EWC is a collaborative initiative with the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), aimed at providing a cloud-based platform for meteorological research and development. It enables users to access ECMWF data and computing resources in a secure and scalable environment, fostering collaboration and innovation (Figure 2). The EWC was able to benefit from the experiences gained from building the cloud-based EU Copernicus reference service WEkEO.
- **Interactive compute platforms – Jupyter notebooks**: ECMWF has embraced Jupyter notebooks as an interactive compute platform, allowing users to explore and analyse data using popular programming languages like Python. Jupyter notebooks provide a flexible and reproducible environment for data analysis, making it easier for users to share their work and collaborate with others.

New opportunities and challenges through machine learning

Machine learning (ML) is revolutionising many fields, and meteorology is no exception. ECMWF recognises the immense potential of ML to improve weather forecasting, climate modelling, and data analysis. The organisation is actively exploring ways to integrate

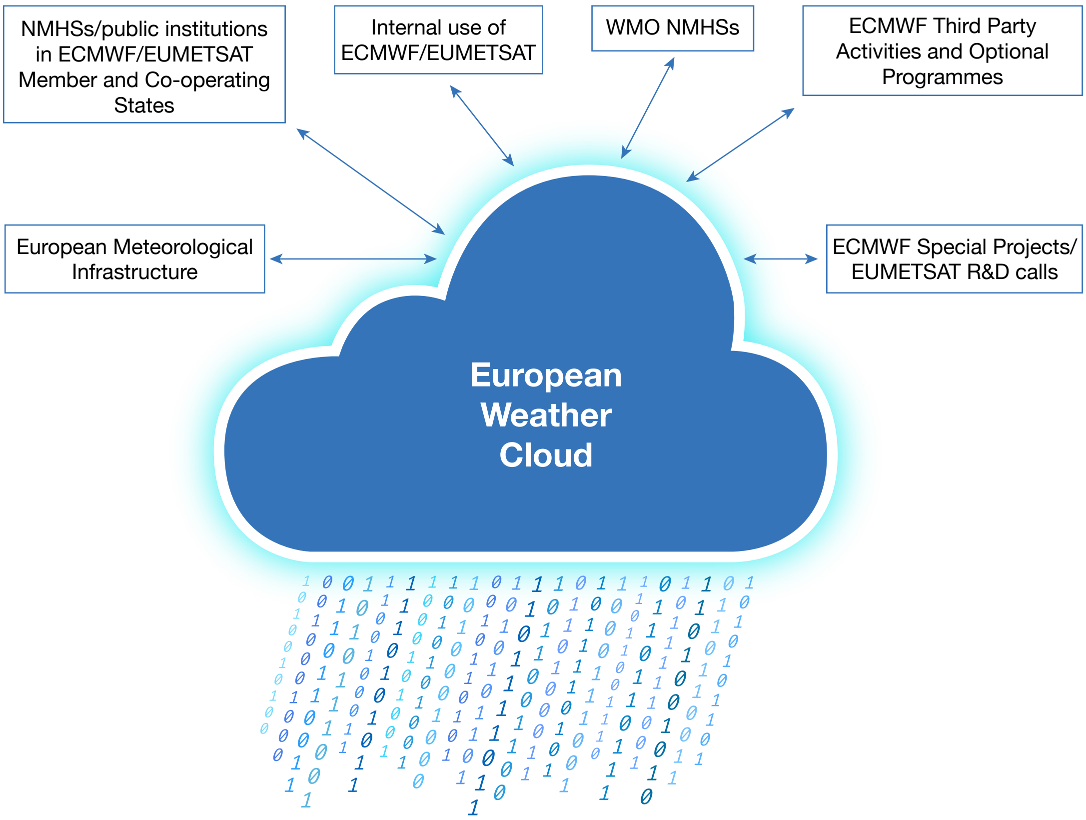

FIGURE 2 The EWC has a range of users, including European public institutions and NMHSs that are members of the WMO.

ML into its data services, offering new opportunities for users to leverage this powerful technology. ECMWF successfully operationalised its Artificial Intelligence Forecasting System (AIFS) in February and July 2025.

ECMWF is experimenting with chatbots as a new way of interacting with forecasts. These chatbots can provide users with quick and easy access to information, answering questions about weather conditions, forecast accuracy, and other topics.

ML can also be used to support the intercomparison and verification of different weather models. By training ML algorithms on historical data, it is possible to identify biases and errors in different models, leading to improved forecast accuracy.

ECMWF's data holdings, especially in the MARS archive, are an invaluable source for many ML applications, and a concentrated effort with Member States is under way to make this data accessible within popular ML frameworks. This work will open ECMWF's data to an even wider and faster-developing user community, benefiting all users overall.

Supporting the community

ECMWF is committed to supporting its user community by providing comprehensive resources and tools.

- **User support:** ECMWF offers dedicated user support to assist users with any questions or issues they may encounter. The user support team provides guidance on data access, software tools, and other topics.
- **Tools and software:** ECMWF develops and maintains a range of software tools to facilitate data processing and analysis. These tools are freely available to users and are designed to be user friendly and efficient.
- **Supporting community projects:** ECMWF actively supports community projects aimed at advancing meteorological research and development. This support includes providing data access, computing resources, and technical expertise.

The need for data spaces

European data spaces have attracted increasing attention since their inception in 2020 by the European Commission. A data space is an evolution from traditional data services and cloud systems to offer a decentralised infrastructure for trustworthy data sharing and exchange in data ecosystems, based on commonly agreed principles. It brings together relevant data infrastructures and governance frameworks to facilitate data pooling and sharing needed for new challenges, such as cross-discipline ML.

These data spaces aim to create a single European market for data, enhancing competitiveness and data sovereignty. They have progressed from conceptual frameworks to operational systems, and a common access layer, called SIMPL, is being developed. For the weather community, these data spaces present a unique opportunity to integrate meteorological data with other sectors, such as agriculture, energy, and mobility. This integration could lead to more uptake and impact of our community's data, and enhanced decision-making for weather-dependent industries, ultimately contributing to the goals of the European Green Deal. The European Open Science Cloud (EOSC) emerged as one of the first data spaces focusing on supporting the research community, and it would benefit from weather and climate data. Other sectorial data spaces, such as the Green Deal and Health ones, will also require access to substantial amounts of weather and climate data. In parallel, the EU's Copernicus Programme has started its own data space for Earth observation data, which could incorporate the Atmosphere Data Store and the Climate Data Store run by ECMWF. With these data spaces developing, ECMWF is working with its Member States and partners, EUMETSAT and EUMETNET, to form a community-wide approach to connect all these data spaces in a coordinated and harmonised way. This work has started with a series of workshops, with the latest in June 2025 bringing together key stakeholders at a side event to a meeting of the RODEO project (*https://rodeo-project.eu/*), which aims to make meteorological high-value datasets easily available. ECMWF is contributing its wide-reaching experience in providing data services for forecast data. It works with the community to develop a roadmap for a common approach.

Conclusion

ECMWF's data provision services have undergone a remarkable evolution, driven by the increasing volume and variety of data, the emergence of cloud computing, and the transformative potential of ML. By embracing these advances, ECMWF is empowering its Member States and the wider community to make better use of meteorological data, leading to improved weather forecasts, climate models, and decision-making across a wide range of sectors. ECMWF remains committed to continuous innovation and collaboration, ensuring that its data services continue to meet the evolving needs of its users in the years to come.

Further reading

Gougeon, L., 2019: The ECMWF Production Data Store. *ECMWF Newsletter* **No. 159**, 35–40. *https://doi.org/10.21957/83deq5lgc0*

ECMWF publications

(see *www.ecmwf.int/en/research/publications*)

Technical Memoranda

928 **de Elia**, **R.**, **T. Haiden**, **C. Matsudo**, **F. Otero**, **E. Gascon**, **L. Castro et al.**: Verification of global and regional NWP models over South America. *June 2025*

927 **Bonavita**, **M.** & **A. Geer**: Forecast verification using Information and Noise. *May 2025*

926 **Ingleby**, **B.**: Diagnostics of radiosonde uncertainties. *May 2025*

ESA or EUMETSAT Contract Reports

Weston, **P.**, **K. Salonen** & **P. de Rosnay**: Quarter 1 2025: Operations Service Report. *April 2025*

Lean, **K.** & **N. Bormann**: Evaluation of Hyperspectral MW for NWP: Simulation framework consolidation. *May 2025*

ECMWF Calendar 2025/26

2025	
Sep 3–5	9th CAMS General Assembly
Sep 8–9	DestinE supporting European Climate Risk Assessments
Sep 15–19	**ECMWF's 50th anniversary events in Bologna, Italy**
	Sep 15–18 Using ECMWF's Forecasts (UEF2025)
	Sep 15–19 21st workshop on high-performance computing in meteorology
	Sep 16–17 ECMWF DestinE Annual Meeting
	Sep 18 European Weather Cloud (EWC) User Workshop 2025
Sep 25	Code for Earth 2025
Oct 6–8	Scientific Advisory Committee
Oct 6–9	Training course: Use and interpretation of ECMWF products
Oct 13–17	Online training course: Introduction to ECMWF computing services (including MARS)
Oct 20–21	Technical Advisory Committee (virtual)
Oct 27–31	Training course: Machine learning for weather prediction
Oct 28	Finance Committee (virtual)
Oct 27	Policy Advisory Committee (virtual)
Nov 10–14	Training course: A hands-on introduction to Numerical Weather Prediction Models: Understanding and Experimenting
Dec 1–3	**ECMWF's 50th anniversary events in Reading, UK**
	Dec 1–2 Member States machine learning pilot project workshop
	Dec 3 European showcase on machine learning
	Dec 3 50th anniversary symposium
Dec 4–5	Council
Dec 18	AI Weather Quest SON Awards Webinar

2026	
Apr 13–17	5th ECMWF–ESA Machine Learning Workshop
Apr 29	Policy Advisory Committee (virtual)
Apr 30	Finance Committee (virtual)
Jun 16–17	Council
Oct 5–7	Scientific Advisory Committee
Oct 8–9	Technical Advisory Committee
Oct 20–21	Finance Committee
Oct 21	Policy Advisory Committee
Dec 8–9	Council

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For any query, issue or feedback, please contact ECMWF's Service Desk at *servicedesk@ecmwf.int*. Please specify whether your query is related to forecast products, computing and archiving services, the installation of a software package, access to ECMWF data, or any other issue. The more precise you are, the more quickly we will be able to deal with your query.

Newsletter | **No. 184** | Summer 2025
European Centre for Medium-Range Weather Forecasts
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