ECMWF
European Centre for Medium-Range Weather Forecasts

Newsletter

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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The ECMWF Newsletter is not peer-reviewed.

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A time of change

This summer is a time of several important developments for ECMWF: our next high-performance computing facility (HPCF) is being installed in our newly opened data centre in Bologna, Italy; the first staff are arriving in our new office in Bonn, Germany; and we have signed contracts with the European Commission for the second phase of the two Copernicus Earth observation services run by ECMWF as well as our contribution to an additional one. All the while, our main business of global medium-range weather prediction is continuing, with an important upgrade of the forecasting system in May.

During this time of rapid change, it is important to pause for a moment to put these developments into context. The new HPCF, like others before it, will enable continued development of our Integrated Forecasting System (IFS) to the benefit of our Member States and other users. It will enable us to increase the horizontal resolution of our forecasts substantially over the next few years, in line with our Strategy. The opening of a new office in Bonn, in addition to our UK headquarters in Reading and the data centre in Bologna, is intended to consolidate our links to the EU, in particular its Copernicus programme, and to develop our research partnerships in Europe. We have run the Copernicus Climate Change Service (C3S) and the Copernicus Atmosphere Monitoring Service (CAMS) since 2014 and are delighted to have been given the go-ahead for an ambitious programme of work during the next seven years. In addition, we will continue to provide computational services for the Copernicus Emergency Management Service (CEMS).

The upgrade of ECMWF's forecasting system is part of a schedule that sees improvements about once a year, although this year another one is planned for the autumn. The May upgrade to IFS Cycle 47r2 brought two important changes: a move from double precision to single precision in high-resolution and ensemble forecasts, and an increase in the number of model levels from 91 to 137 in ensemble forecasts. The first change reduces the computational load without affecting the quality of forecasts, while the second one improves forecasts and prepares the ground for an upgrade of the horizontal resolution. The effects of these changes can be studied in this Newsletter.

More evidence of ongoing research can be seen in the articles about our participation in the EU's Horizon 2020 project APPLICATE, which stimulated efforts to tackle the challenges that limit forecast skill in the Arctic, as well as the development of a calibrated clear-air turbulence parameter for ECMWF's IFS. Additional examples of research are contained in the news section of the Newsletter. These include developing the Ensemble of Data Assimilations for the ocean, while the article on Saharan dust events shows how Copernicus results can stimulate weather prediction research. Just as a lot changes for ECMWF, we thus stay true to the principle that cutting-edge medium-range weather forecasting requires sustained research on all fronts.

Florence Rabier
Director-General

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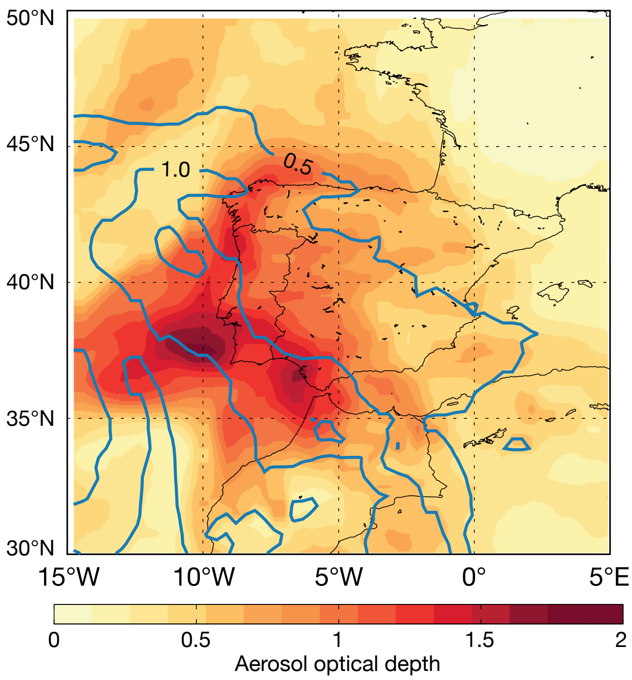
Saharan dust events in the spring of 2021

Linus Magnusson, Ivan Tsonevsky, Mark Parrington, Richard Forbes, Johannes Flemming

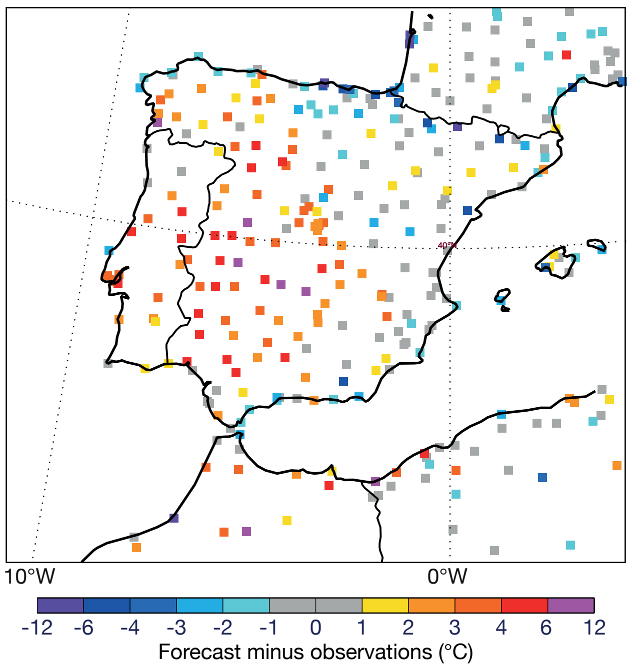
During February and March, several events of significant dust transport from the Sahara affected Europe. The most notable events were around 6–9 February, 2–4 March and 30–31 March. Such episodes can affect solar radiation in a direct way, through reflection and absorption of solar radiation, and in an indirect way, by solar absorption leading to temperature changes affecting cloud formation or by dust acting as ice nuclei. These effects can lead to cooler 2-metre temperatures and reduced solar power production. Dust particles can also have a negative impact on health. Forecasts by the EU-funded Copernicus Atmosphere Monitoring Service (CAMS) implemented by ECMWF include a prediction of dust and its radiative impacts and captured the dust events well. However, ECMWF's weather forecasts only represent dust as a seasonally varying climatology and therefore cannot yet capture the effects of specific dust events.

End of March forecasts

At the end of March, the synoptic situation over Europe was characterised by a blocking anticyclone centred over the central parts of the continent. In its western fringe, an active trough triggered an episode of intense transport of Saharan dust affecting parts of western Europe. The dust reached as far north as southern England and had a noticeable effect on the weather over the affected areas. It considerably reduced visibility in the boundary layer over southwestern parts of the Iberian Peninsula, affecting air quality, and it reduced the incoming direct solar radiation, affecting 2-metre temperature. Forecasts and analyses of aerosol optical depth (AOD) at 550 nm from CAMS clearly showed the dust plume transport along the western edge of the anticyclone, from northwestern Africa and across the Iberian Peninsula, from 29 to 31 March. The CAMS AOD forecast initialized on 27 March and valid for 30 March captured well the general transport of the dust plume across the region (see the figure on the CAMS analysis/forecast of AOD).

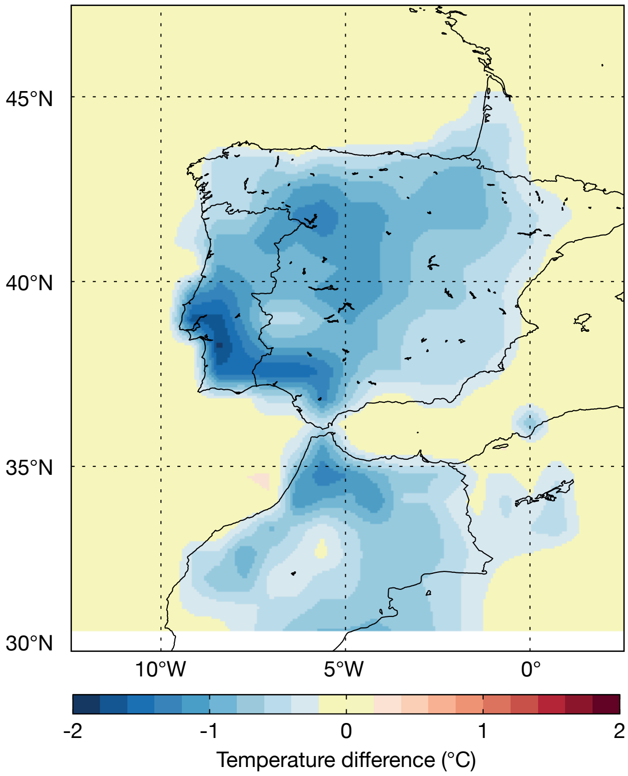


CAMS analysis and forecast of AOD. The shading shows the CAMS analysis of total aerosol optical depth (AOD) at 550 nm valid at 12 UTC on 30 March 2021. Contours show the CAMS total AOD forecast initialised on 27 March 2021 at 00 UTC and valid for 12 UTC on 30 March.



Temperature forecast errors. Two-metre temperature forecast errors (forecast minus observations) for the 12-hour HRES forecast issued on 30 March 00 UTC.

During this episode, ECMWF's high-resolution forecast (HRES) experienced large temperature errors over the dust-affected areas of the Iberian Peninsula. Even in the short-range 12-hour forecast for 2-metre temperature, the model was 2 to 7°C warmer than the observations (see the figure on temperature forecast errors). The temperature error could be due to several reasons, including a misrepresentation of dust or cloud in the model forecast. Mainly for reasons of computational cost, the HRES and the ensemble forecast (ENS) do not predict the day-to-day variation in dust or other aerosols, but instead use a seasonally varying climatology of aerosol species, based on an earlier version of the CAMS system. HRES and ENS therefore cannot capture the impact of dust episodes on the meteorology or on forecast visibility. However, the operational CAMS system does run the ECMWF Integrated Forecasting System (IFS) in a configuration for forecasting atmospheric composition and chemistry including aerosols (sources, sinks and advection of aerosol species) with direct impacts on the radiation in the model. Comparing meteorological fields from the CAMS operational output with the output from a CAMS control configuration which uses the aerosol climatology of HRES and ENS allows us to evaluate the direct radiative impact of dust plumes on parameters such as 2-metre temperatures. For the dust plume across the Iberian Peninsula on 30 March, the comparison showed a reduction in the afternoon (12:00–15:00 UTC) average 2-metre temperature of between 1.2 and 1.8°C (see the figure on the prognostic aerosol impact on 2-metre temperature).

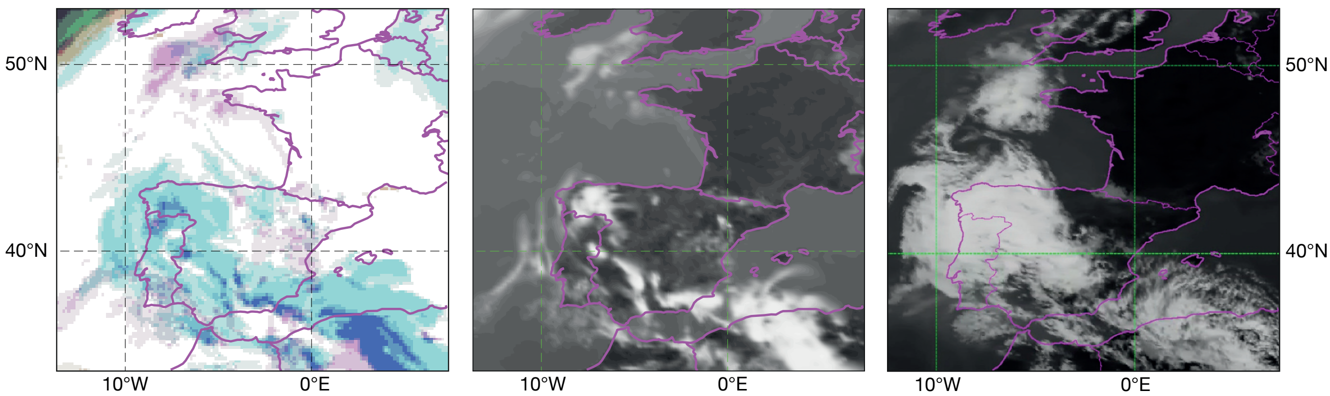


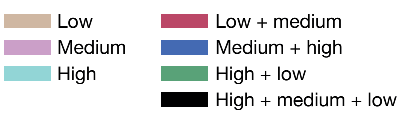
Prognostic aerosol impact on 2-metre temperature. The chart shows the 12–15 UTC mean 2-metre temperature difference between CAMS forecasts with and without prognostic aerosol–radiation interaction initialised at 00 UTC on 30 March 2021.

This result indicates that the radiative effect of a lack of dust contributed to the temperature error. However, there was also too little high cloud in HRES associated with an upper level front in the southerly air flow (see the figure on cloud cover). Although the HRES forecast high cloud cover over the region, it was too thin with insufficient ice water content, giving too weak a signal in the infrared simulated satellite image (see simulated and real satellite images). This allows too much shortwave radiation to reach the surface and therefore also contributes significantly to the warm bias in the 2-metre temperature in this case. It is not yet clear if the cloud error is related to errors in vertical motions in the upper level frontal zone, or a too dry upper troposphere, or whether missing aerosol interactions in the model play a role. Too little radiative impact of the upper level cloud field has also been observed in other similar southerly flow situations, and an investigation over a larger set of cases is needed to further understand any systematic cloud errors in these conditions.

Conclusion

Users of ECMWF forecasts (HRES and ENS) need to be aware of the use of a dust climatology in the forecasts and therefore of the lack of impact on shortwave radiation reaching the surface, 2-metre temperature and visibility during significant dust events. CAMS forecasts allow us to assess the impact of dust events like this one and demonstrates the potential for including prognostic aerosols in the IFS. Doing so in a cost-efficient way is being considered as a future development.





Cloud forecast, simulated satellite image, and real satellite image. The image shows the cloud forecast (left) and the simulated infrared image (middle) from a 12-hour HRES forecast issued at 00 UTC on 30 March, and a real image from Meteosat valid at the same time (right).

Testing the Reading–Bologna site-to-site connectivity

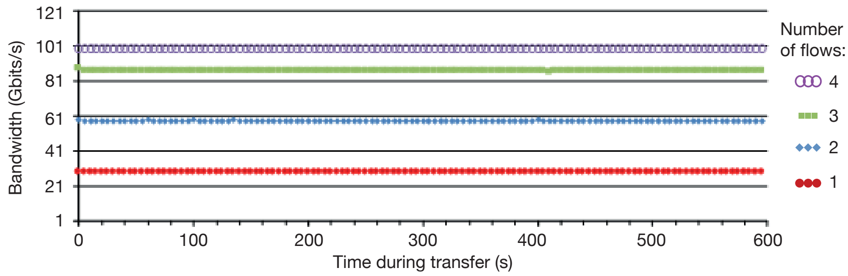
Ahmed Benallegue, Stanislav Burlakov, Lennart Sorth

ECMWF's next-generation high-performance computing facility is being installed in its new Bologna data centre, and other production services will be migrated there shortly after. This presents new challenges as during the transition period the forecast data will have to be copied between the Reading (UK) and Bologna (Italy) data centres, using 100 Gbit connections to the public Internet. It was therefore imperative to better understand the issues related to long-distance data transfers so that they can be mitigated.

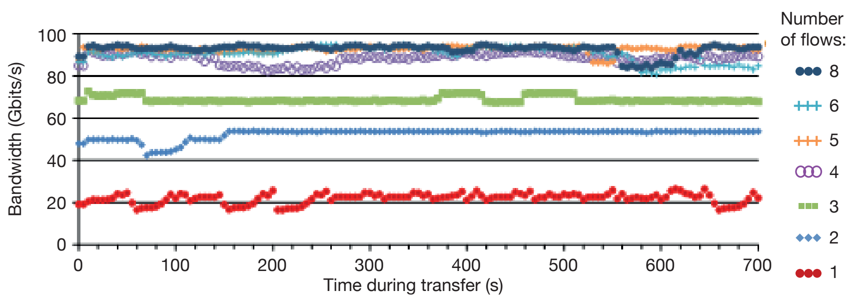
The importance of testing

Data transfers over long distances and Wide Area Networks (WANs) are inherently less predictable than data transfers over Local Area Networks (LANs). This is primarily because the data must pass through many devices that are administered by multiple third parties, and issues cannot be easily diagnosed and fixed without their involvement. Physics also plays a part as longer transfer distances introduce a substantial latency – for example, there is around 40 ms latency between Reading and Bologna compared with less than 1 ms on a local network. Finally, Internet protocol limitations and envisaged transfer methods also need to be considered.

Therefore, testing is a vital stage in the solution delivery process, as it provides an empirical way to determine that the solution meets its feature and performance targets. Early testing is particularly beneficial in projects which are complex, or involve factors that are outside of organisational control, in this instance use of the Internet as a medium for long-distance data transfers. All-in-all, ensuring that long-distance data transfers perform well is a science that combines many elements of physics, system performance tuning and application design. For this reason, simulation and testing are essential for understanding what performance can be expected and finding the best parameters for system and application tuning.



Baseline lab test. The throughput for each set of simultaneous flows between the two nodes at Reading connected back-to-back as a function of time during the flow. The maximum speed of 100 Gbps is obtained with four simultaneous data flows or more.



Real-life test. Total throughput for each set of simultaneous flows between Reading and Bologna as a function of time during the flow. The maximum speed of around 90 Gbps is obtained with five simultaneous data flows or more. As expected, the achieved throughput is not as clean as the Baseline lab-test above. The variability is caused by the nature of the Internet: contention at different points on the route, buffers filling up due to the latency, and possibly the odd packet dropped. However, the overall picture is encouraging.

Testing long-distance data transfers

A multi-stage approach to testing was applied, with the initial tests being based on 'synthetic' benchmarks rather than real-life performance. From February 2020 to March 2021, tests were carried out using two 100-Gbit-capable test servers.

In order to progress at the right pace and increase the knowledge on these matters, ECMWF enlisted the help of a long-distance bandwidth testing expert from the Gigabit European Academic Network Technology (GÉANT), the pan-European data and communication network for Europe's education and research community. Dr Richard Hughes-Jones advised on how to best configure the test servers and carried out the bulk of the tests along with ECMWF's Networks and Security and Data Handling System teams.

Test results

The initial tests were carried out from February to October 2020 with two servers connected directly to each other. This established a baseline against which the performance of real WAN connections could be measured. Some tests were also made against GÉANT test servers, first in London and then in Paris. These were useful as they made it possible to estimate how increasing latency (ca. 9 ms London, ca. 16 ms Paris) affects performance.

All these tests enabled the best tuning parameters to be used, enabling a quick and efficient running of the final tests between Reading and Bologna once the Bologna Internet circuits went live in November 2020.

As a single high-bandwidth data flow is more susceptible to protocol limitations/performance issues from packet loss than multiple low-bandwidth data flows, it is common practice to initiate several data flows simultaneously over a significant period (600 seconds or more) to ascertain the overall performance of a link. The number of flows is not relevant as the end goal is to measure the highest speed that could be obtained, although it is provided for information in the graphs.

The graphs summarise the data transfer speeds obtained during the tests. The speed variation shown for the real-life test is due to: (a) the uncertain state of the Internet according to the time of day at which the flows take place; (b) outages affecting the networks at any given time; and (c) the level of usage of the networks of the many Internet Service Providers (ISPs) involved in the end-to-end transfers.

Conclusion

As shown in this article, a well-thought-out testing strategy plays a crucial part in successful project delivery.

The test results gathered suggest that 25 Gbps for a single data flow and 90 Gbps for multiple flows should be achievable over Reading–Bologna site-to-site links. Despite problems associated with using the public Internet, this compares very well to the baseline results of 30 Gbps and 100 Gbps respectively that we obtained when test systems were directly connected.

This article has presented the results of network-level tests. The next stage will be to see how real-world applications behave when real transfers start to happen over the coming months, and what effect the ever-changing nature of the Internet has on the speed and reliability of these transfers over medium to long time frames.

‘I used ECMWF data to be fast and stay safe’

The Vendée Globe is a non-stop, unassisted, single-handed round-the-world yacht race starting from Les Sables-d’Olonne in France. Described as the Holy Grail for solo sailors, it has taken place every four years since 1992. Weather forecasting plays an important role, and in 2020/21 ECMWF forecasts were made available to the sailors by different forecast providers. Here Giancarlo Pedote, who came in eighth out of a field of 33 who started the race, describes the importance of accurate weather forecasts.

What made you want to take part in the Vendée Globe?

I have taken part in other regattas, but not around the world. This is the most interesting regatta, however, what you could call the ‘Everest’ of the seas.

How come you asked for ECMWF data?

ECMWF data is of course very good and very interesting. I looked at the different forecasts produced every day and checked how the weather evolved in 3-hour intervals. I primarily consulted wind and sea-state data but also looked at weather charts.

What did you use the data for?

I used them to assess the general situation: to find the best passage and to be fast and stay safe. The forecast was sometimes good and sometimes reality was a bit different: wind speed, wind direction, the arrival of high pressure. It would be good to have hourly forecasts and information on the real-time situation. The regatta directorate also looked at the forecast and told us if the zone of safe sailing was changing, for example if a big depression was coming.

How important was weather information to you?

The course sailors took was key to the race. Therefore, the precision of the data was very important, as well as your interpretation of it.

What would improve the forecast information you used?

Information on local showers would be good to have. Big clouds that produce more than 30 knots medium wind speed can cause trouble. In showers, wind speeds could rise to 35 knots. This can bring risks. More precise information enabling you to stay away from high pressure zones would also be good.

Will you take part in another global race?

I hope to take part in another Vendée Globe event.

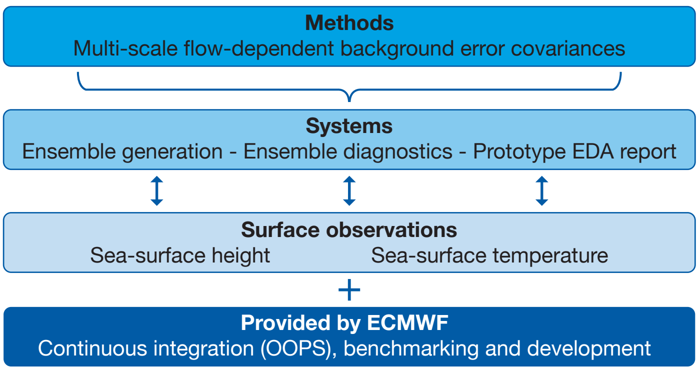
On board the Prysmian Group. Giancarlo Pedote adjusts the sails on his boat in the Vendée Globe in 2020/21. (*Photo: Jean Marie LIOT/Alea*)

Ensemble of Data Assimilations in the ocean for better exploitation of surface observations

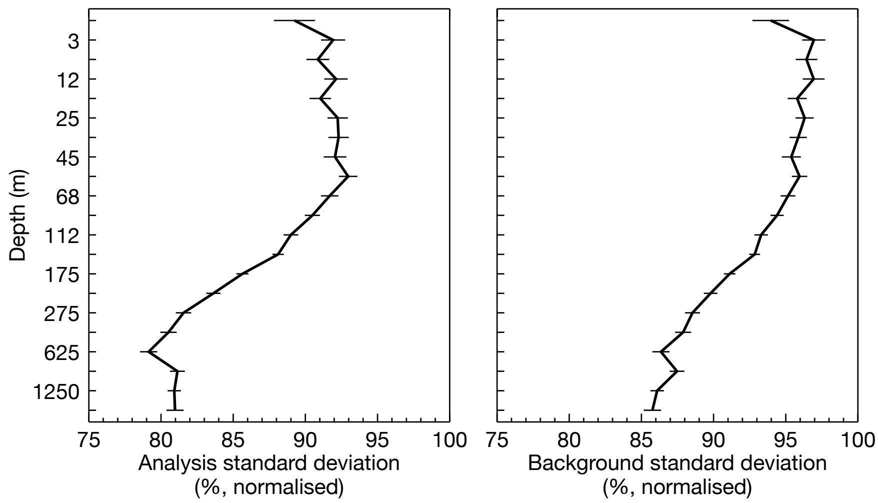
Marcin Chrust, Magdalena A. Balmaseda, Philip Browne (all ECMWF), Matthew Martin (Met Office, UK), Andrea Storto (CMRE, Italy), Arthur Vidard (INRIA, France), Anthony Weaver (CERFACS, France), Hao Zuo (ECMWF)

Since February 2019, experts from Member State institutes have been working alongside ECMWF scientists to improve ocean model initialisation for the EU-funded Copernicus Climate Change Service (C3S). The Ensemble of data assimilations (EDA) for the Reanalysis of the Global Ocean (ERGO) project, ending in July 2021, has brought a step improvement to the ocean data assimilation capabilities at ECMWF. The EDA was originally developed by Météo-France and ECMWF for the atmospheric data assimilation system. It is used to supply information about the statistics of background errors for the initialisation of the operational ensemble and for reanalysis. Introducing the same technology for the ocean helps the assimilation of surface observations, aids reanalysis in dealing with changes in observing networks and paves the way for the development of a coupled EDA system in the future.

The ERGO project had three distinct components (see the figure showing the schematic diagram of the work performed): advancing data assimilation methodology by developing efficient ensemble-based background error covariance models; improving the assimilation of sea-surface height (SSH) and sea-surface temperature (SST) observations; and overarching system developments focusing on ensemble generation, statistics and diagnostics. The developments have been continuously integrated into the ECMWF repository.



Work performed. Schematic diagram of the work carried out under the C3S ERGO contract.

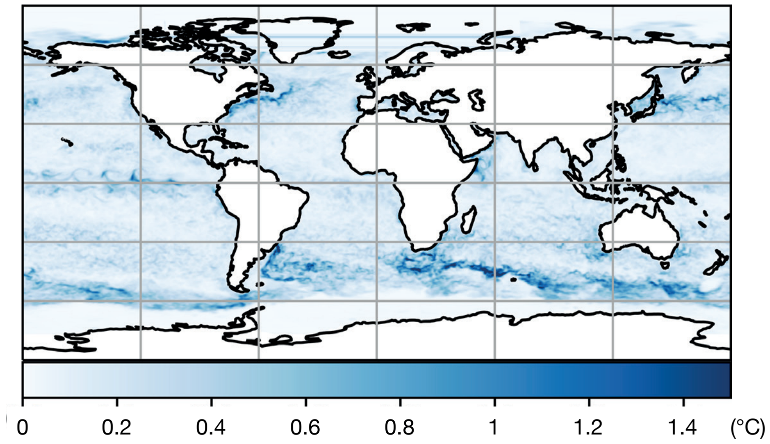


Climatological background error covariance. A significant reduction in the standard deviation of the background temperature fit to observations is obtained when using the new seasonal climatology of background errors computed from the ORAS5 ensemble. The plots concern the period of 1 January 2010 to 31 December 2013. Similar improvements were obtained for salinity and sea-surface height (not shown).

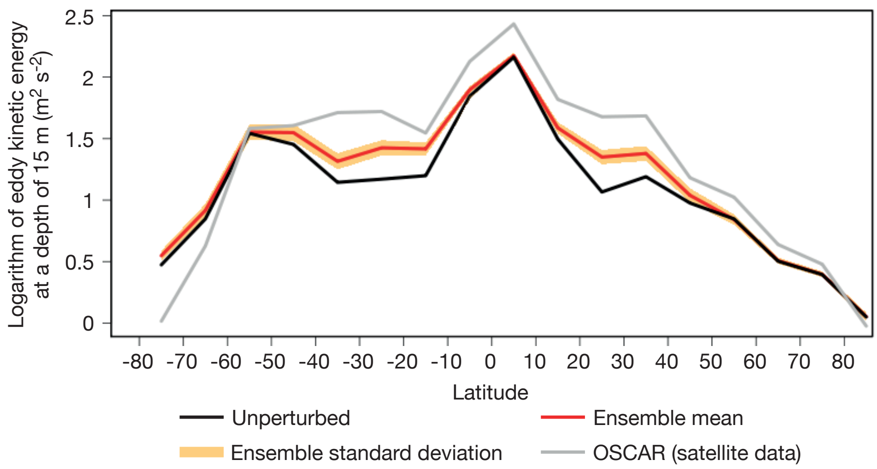
Flow-dependent background error covariance modelling

Scientists from the Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (CERFACS, France) and their ECMWF colleagues have developed two different approaches for extracting information from ensembles to capture 'errors of the day' in the specification of the background error covariances. In the first approach, an innovative estimation and filtering methodology has been developed to derive background error variances and correlation length scales from ensembles. This methodology was first applied to compute a seasonal climatology of background error statistics which, after appropriate tuning, resulted in a significant improvement of the performance of the system even without errors of the day (see the figure on climatological background error covariance). Work is ongoing to combine errors of the day with the seasonal climatology (see the figure on the EDA temperature spread) to provide more robust estimates.
A new method has been developed to compute normalisation factors to ensure that the correlation operator within the background error model has an amplitude approximately equal to one. The new method is affordable and sufficiently accurate to allow the vertical correlation length scales to be varied from cycle to cycle. This development is particularly important for the assimilation of sea-surface observations, such as SST, explored in the project.

A second approach was to use the ensemble perturbations to construct a localised sampled background error covariance matrix to account for more complex covariance structures than can be achieved with existing methods. Localisation is essential to remove spurious long-distance correlations resulting from sampling errors, but it is a costly operation. Experts from the National Institute for Research in Digital Science and Technology (Inria, France) have developed a capability to use multiple grid resolutions, allowing the localisation operator to be applied on a coarser grid and thus at a much lower cost. While the second approach still needs to mature, at some point it will complement the modelled covariance matrix with climatological parameters to provide a rich and robust representation of the background error covariances. The multi-grid capabilities are also crucial for implementation of future high-resolution EDA configurations by allowing, similarly to our atmospheric system, the minimisation to be performed at a reduced resolution compared to the forecast model.



EDA temperature spread. Ocean temperature spread at the surface from an Ensemble of Ocean Data Assimilations. The highest background errors are in western boundary current and Antarctic Circumpolar Current regions. This shows more details than without errors of the day, including a more detailed structure of sub-mesoscale eddies with much sharper fronts, and a hint of tropical instability waves in the tropical Pacific Ocean.



Stochastic physics. The new ocean stochastic physics schemes enhance the eddy kinetic energy at mid-latitudes in the NEMO simulations at 1/4° spatial resolution, due to the inclusion of stochastic kinetic energy backscatter. The experiments concern the period of 2010 to 2015.

Sea-surface observations

Researchers from the Met Office (UK) have developed a capability to assimilate level 2 SST observations in the ECMWF system, which will allow us to progressively move away from our current nudging approach. The work included implementation of a variational bias correction scheme and explored issues related to the vertical projection of the SST information into the mixed layer. Assimilation of altimeter SSH observations has also been revisited. A variational bias correction approach has been implemented for the online estimation of the mean-dynamic topography (MDT), which is needed as part of the observation operator for the assimilation of SSH. Such an approach has an advantage over current methodology in that it relies on an error-free prescribed MDT.

Ensemble generation

The quality of the estimates of the background error statistics from the ensemble crucially depends on its reliability. Our current ocean ensemble is generated by sampling the uncertainties in the observations and surface forcing fields according to their assumed error characteristics. To improve the reliability of the ensemble, the crucial sources of uncertainty arising from ocean model inaccuracies, approximations and limited spatial resolution need to be accounted for. This was achieved thanks to the work of scientists from the Centre for Maritime Research and Experimentation (CMRE, Italy) who have implemented stochastic physics parametrization schemes in the NEMO ocean model: SPP (stochastically perturbed parameters), SPPT (stochastically perturbed parametrization tendencies) and SKEB (stochastic kinetic energy backscatter). The three schemes work together to provide a larger and more realistic ensemble spread in global ocean ensemble simulations and to enhance mesoscale activity at mid-latitudes (see the figure on stochastic physics). They are now embedded in EDA experiments.

Contribution to service evolution

The developments carried out in the ERGO project will enhance the quality of service of C3S products and ECMWF operations. They will be the basis for the ocean data assimilation used in OCEAN6 and ERA6, the next generation of ocean and coupled reanalysis. OCEAN6 will be used to initialise the operational ECMWF seamless forecasts, including the future SEAS6 seasonal system, the ECMWF contribution to the C3S seasonal multi-model.

Contributions from Anass El Aouni, Gabriel Jonville, Daniel Lea, Benjamin Ménétrier, Andrea Piacentini and James While were crucial to the success of the ERGO project and are kindly acknowledged.

A new web portal for OpenIFS initial experiment data

Marcus Köhler, Paul Burton, Glenn Carver, Sylvie Lamy-Thépaut, Eduard Rosert, Krzysztof Ściubisz, Carlos Valiente, Milana Vučković

OpenIFS model users will soon have the possibility to create initial experiment data for their own forecast experiments. A new web application is being developed which will allow users to specify the requirements for their experiment and generate the model's initial data with a few clicks of the mouse.

New portal

For approximately ten years, the OpenIFS activity at ECMWF has provided a portable version of the Integrated Forecasting System (IFS) operational model to ECMWF Member State users and beyond. The OpenIFS model is used by licensed institutions for a wide range of research and training purposes. To carry out a forecast experiment, the OpenIFS model requires data for the initial conditions from which the experiment commences. Until now, this data has usually been created from the ERA reanalysis products, but it can also be based on operational analyses.

Producing such initial data on request for the model's user community is one of the routine tasks for the OpenIFS team at ECMWF. Due to the success of OpenIFS, its user community has continually expanded over the years with currently over 80 institutions holding an OpenIFS licence. The number of requests for initial experiment data has increased correspondingly.

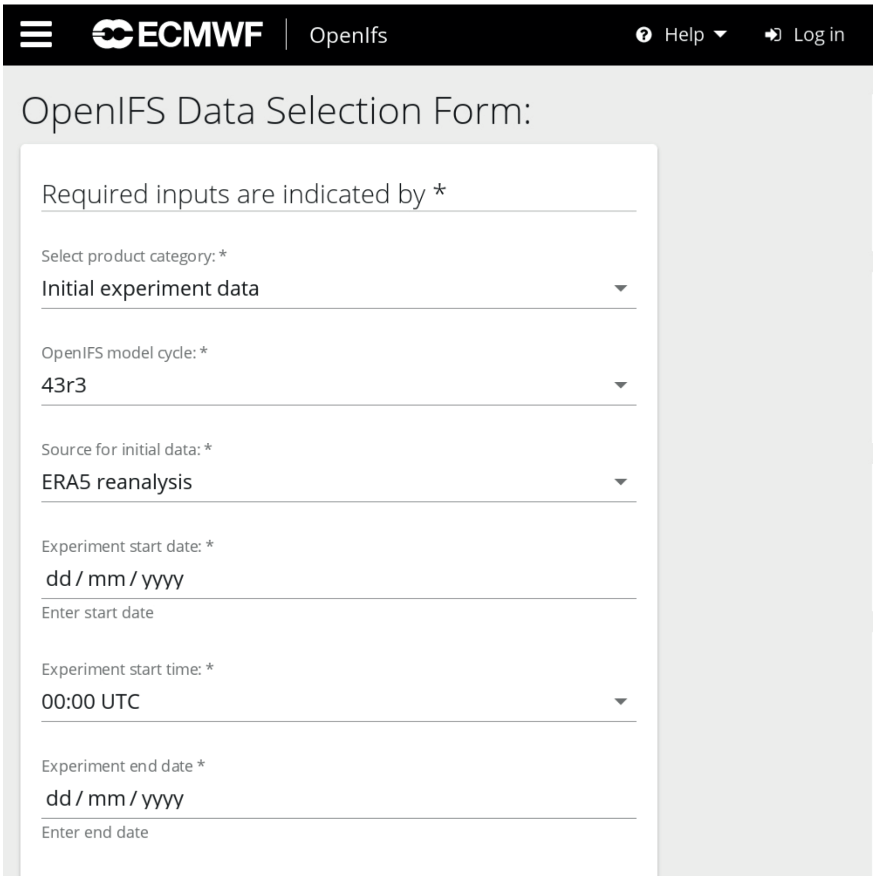
The new web application puts the user in the driving seat and will remove the need to contact OpenIFS support with a request for initial data. ECMWF scientists from the IFS section and the web development team are developing the new facility. It produces the initial data at the user's request from an easy-to-use web-based data request form. Once the data has been generated, the user will be informed via email and provided with a download web link.

In its first release, the web portal will be able to generate initial data for deterministic forecasts, for single and multiple start dates, for OpenIFS 43r3 only. When new OpenIFS versions are released, the portal will be updated to support them. Initial data is based on the ERA5 reanalysis. It can be requested for either linear reduced or cubic octahedral model grids at all spectral resolutions that are supported by the corresponding IFS cycle, up to the operational resolution. Ensemble initial data (using the Ensemble of Data Assimilations) will not be available initially. At its release, the system will be operational on the ECMWF high-performance computing facility in Reading but will later be moved to the new data centre in Bologna with minimal interruption to the user.

Benefits

This new facility provides a consistent and traceable method to produce accurate initial experiment data in the same way ECMWF prepares experiment data for internal IFS forecasts. As an automated system, it will be available 24/7 (subject to maintenance). It also frees up time for the OpenIFS team to deal with other user support queries. It has been designed with expandability in mind, towards building an OpenIFS data web site. This will allow users to easily find and access data for tutorials, exercises, case studies, relaxation files for nudged experiments, and other OpenIFS-related data products from the single site.

We expect the capability to generate initial experiment data to become publicly available to OpenIFS users before the end of 2021.

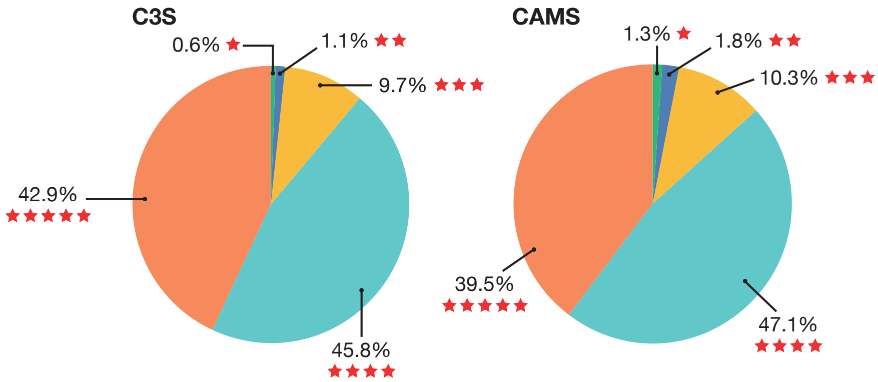


Data selection form. An early preview of some of the web interface for OpenIFS initial data requests.

Copernicus services again rated highly by users

Kevin Marsh, Anabelle Guillory, Michela Giusti, Xiaobo Yang

The 2020 user satisfaction surveys for the two EU-funded Copernicus services implemented by ECMWF show that the vast majority of users remain highly satisfied. Survey results for the Copernicus Climate Change Service (C3S) and the Copernicus Atmosphere Monitoring Service (CAMS) reflect the continued use of the services both in the EU and the rest of the world. The survey participants also made a number of useful suggestions for improvements to these services. The new approach implemented for the running of the 2020 surveys also yielded a significant increase in the number of responses and user engagement with the process.



C3S and CAMS overall satisfaction ratings 2020. Respondents to the C3S and CAMS user satisfaction surveys rated the services highly, with 89% awarding C3S four or five stars and 87% awarding CAMS four or five stars.

C3S

The 3,777 users who participated in the C3S survey gave the service an overall satisfaction rating of 4.3 out of 5 stars (see the figure). Around two thirds of survey participants were based outside the EU. As with the 2019 survey results, 70% were academics and researchers. A comparison of usage patterns from 2017 to 2020 shows that uptake in the private and public sectors has been maintained.

Climate reanalysis data (mainly ERA5 datasets) continue to be the most popular with users across the board and received the highest satisfaction ratings. Other C3S products and services, such as seasonal forecast datasets, have continued to increase in popularity. Users also appreciated the help of the User Support service; the Climate Data Store (CDS) API, which enabled scriptable access to data; and the extensive documentation of the Copernicus Knowledge Base and Copernicus User Support Forum.

Many suggestions for improvements were made by the survey participants. The CDS Toolbox was thought to benefit from additional development. The survey results indicated that the Forum should be used to further strengthen communication with users and to help the C3S user community to evolve. This is in line with the User Support vision of developing the 'self-service' user support journey, which now includes a 'Virtual Assistant' for the CDS.

> Sample of user comments on C3S
>
> *"It is one of the most user-friendly data portals to use."*
>
> *"This service is excellent for the whole community of Weather and Climate."*
>
> *"The C3S service is exceptional, and the data and knowledge it provides is paramount to the community's efforts to advance science and its application to real-world problems."*
>
> *"Improve the efficiency and waiting time of dataset ingestion in the CDS."*
>
> Sample of user comments on CAMS
>
> *"Overall CAMS is a very good and very useful service. Keep doing this!"*
>
> *"I would like to congratulate CAMS and all the staff to enable the public and stakeholders to make use of these reliable forecast data."*
>
> *"Feedback from user support is SUPERB, I really don't know how they manage."*
>
> *"I would like access to full chemical species for the regional CAMS data."*

CAMS

The number of users who participated in the CAMS survey (709) was a significant improvement on the previous year (114) and a clear endorsement of the new approach to how the survey was run. The users gave the service a satisfaction rating of 4.2 out of 5 stars (see the figure). Around 47% of participants were based in the EU, and around 47% of them worked in academia/research, while 30% were based in the business sector. As with C3S, there is a continuing interest in CAMS from the commercial sector, particularly from within the EU.

The launch of the Atmosphere Data Store (ADS) had a beneficial impact on data access for users and is expected to become ever more important in the future. The most popular CAMS services remain information on global atmospheric composition and global reanalysis. Users were satisfied with supporting services, such as data access mechanisms, validation reports and product documentation. Several areas for improvement identified by users include data access tailored to users' specifications and more detailed scientific documentation.

Further information

Full 2020 C3S and CAMS user satisfaction survey reports are available from https://climate.copernicus.eu/help-and-support and https://atmosphere.copernicus.eu/user-support, respectively.

UEF2021: A special event in an extraordinary year

Becky Hemingway

Using ECMWF's Forecasts (UEF2021) was held virtually from 1 to 4 June 2021. The second fully virtual UEF event attracted people from all over the world to discuss and provide feedback on ECMWF products and services.

The theme of UEF2021, 'Weather in extraordinary circumstances', aimed to encompass not only the extraordinary circumstances of 2020/21 and their impact but other extraordinary events which impact forecasting, modelling, users and the public. Four thematic areas were covered: 'Severe weather and hazard forecasting'; 'Forecasting in extraordinary circumstances'; 'Unforeseen impacts of extraordinary circumstances', and 'Extraordinary collaborations'. There was also a special session run by Nuno Moreira from IPMA (Instituto Português do Mar e da Atmosfera) on 'Recent developments in assessing societal impacts of extreme meteorological events at a national level'.

In addition to oral presentations on the thematic areas and updates from ECMWF, UEF2021 featured a number of new elements, including the first 'Copernicus Day' focused on the EU's Copernicus services linked to ECMWF, five-minute 'lightning talks' on a variety of topics, and a Science and Art event. Networking opportunities and interactive events were enhanced using the gather.town platform. The User Voice Corner, poster sessions, networking breaks, a social event and feedback and discussion sessions were all held in the platform.

Meeting highlights

ECMWF Director of Forecasts Florian Pappenberger presented the ECMWF Strategy 2021–2030 (https://www.ecmwf.int/en/about/what-we-do/strategy), which sets out a number of exciting projects. These include machine learning, the European Weather Cloud, Destination Earth, Copernicus services, Open Data, Bologna Our New Datacentre (BOND), and Bonn hosting the new ECMWF facility. Richard Forbes (ECMWF) presented the changes to be implemented in the next model cycle (47r3), including improved visibility forecasts and new products for Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN). Thomas Haiden (ECMWF) showed improved verification scores due to recent model upgrades, including the highest ever ensemble skill in the upper-air and highest skill so far for the 5-day Extreme Forecast Index (EFI).

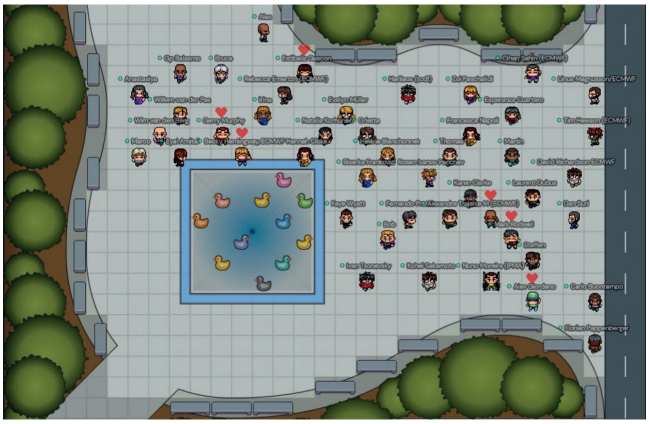
As part of the thematic presentations, authors presented on a range of activities and tools which help users and forecasters better understand and forecast extreme weather and its impacts. Natalia Korhonen (Finnish Meteorological Institute) showed that ECMWF temperature re-forecasts were the most skilful in predicting the life cycle of a heatwave. Parmoita Chakraborty from the National Centre for Medium Range Weather Forecasting (NCMRWF), India, showed an interesting comparison of ECMWF, NCMRWF and US Global Ensemble Forecast System (GEFS) models for tropical cyclone Amphan. Anastasita Stycheva's (National Institute of Meteorology and Hydrology, Bulgaria) poster discussed intense dust events in Bulgaria and how ECMWF products can be used to forecast these.

With impact-based forecasting becoming more prevalent, Joanne Robbins (UK Met Office) discussed how impact data is collected and the difficulties in processing it to make it useable for forecast evaluation. The presentation sparked a lively discussion between attendees during the special session. Min-Jeong Youn's (Korean Meteorological Agency/UK Met Office) poster complemented this by demonstrating how impact-based forecasting can be used to forecast heatwave impacts in South Korea.

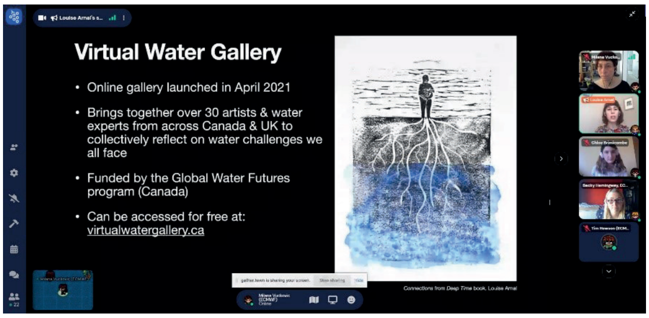
Effects of COVID-19 on the meteorological community also featured. Bruce Ingleby (ECMWF) presented an unforeseen impact of COVID-19: reduced aircraft observation data due to a drop in aircraft numbers resulting in large impacts on wind forecasts. However, model verification scores did not appear to be affected and alternative data sources were discussed. Marc Guevara (Barcelona Supercomputing Center) showed emissions from different sectors and how they changed during the COVID-19 pandemic to quantify the impact of lockdown policies.

Copernicus Day was dedicated to showcasing the variety of products and services of the Copernicus Atmosphere Monitoring Service (CAMS) and the Copernicus Climate Change Service (C3S), which are run by ECMWF, as well as the Copernicus

UEF2021 virtual group photo. Attendees were invited to submit photos of themselves for the UEF2021 group photo instead of the usual photo around the ECMWF fountain.



UEF2021 gather.town avatar group photo. All those in gather.town were invited to come together for a virtual 'group photo' with their avatar character around the ECMWF duck fountain in the virtual ECMWF office environment.



Science and Art Event at UEF2021: Artwork by Louise Arnal as part of the Virtual Water Gallery.

Emergency Management Service (CEMS), to which ECMWF contributes. Stylianos Kotsopoulos (AGROAPPS P.C.) demonstrated a tool which uses Climate Data Service (CDS) data to aid the agriculture sector with cultivation planning. The final part of the day focused on the forecast–predictions–projections nexus, with presentations demonstrating how sub-seasonal to seasonal predictions can aid shorter lead-time forecasting by utilising sources of predictability.

The five-minute 'lightning talks' were well received, covering topics such as the ECMWF unified support portal, ECMWF Summer Weather of Code (EWSoC) 2021, user-orientated forecast system development, the Severe Event Catalogue and ECMWF Learning Resources.

One lightning talk launched the Forecast User Forum (https://confluence.ecmwf.int/display/FUF/Forecast+User+Forum). The forum offers a platform for users of ECMWF forecasts around the world to discuss current and recent weather and forecasts. It widens the opportunities to provide feedback to ECMWF beyond events like the UEF.

User survey results

Prior to UEF2021, users were asked to complete two surveys: the annual User Voice Corner survey, and an ECMWF's extended-range graphical products survey. Tim Hewson (ECMWF) presented the results of both surveys during UEF2021.

The User Voice Corner survey's outcomes showed that satisfaction with ECMWF forecasts and products is generally very high, with short-range to seasonal forecasts all heavily utilised and a number of notably good forecasts cited. Issues with certain forecast fields, e.g. precipitation, in particular geographic areas were highlighted by users. Awareness of user-orientated documentation was shown to be generally very good.

The ECMWF extended-range graphical products survey showed users regularly use a range of extended-range products, particularly maps of ensemble mean anomalies, the extended-range Extreme Forecast Index (EFI), and meteograms. However, many users would like to understand products better. The survey results will be used to inform a major update to extended-range forecasting.

Interaction in Gather.town

The gather.town platform was used to provide all interactive activities at UEF2021 and to facilitate networking opportunities for attendees. It was the first time the platform had been used at a UEF event, and positive feedback was received. Participants liked how they could easily interact with other attendees by avatars getting close to each other. Audio and video were then connected, facilitating a conversation.

Attendees provided positive feedback on the event: "Well done on organizing and facilitating an excellent and informative meeting. I really enjoyed it."; "Thank you so much for the huge amount of products which are the result of the great work of the ECMWF people. Thank you for organizing UEF 2021!"; and "UEF meetings are a very good concept and the UEF 2021 was an excellent meeting. It was well organized, interactive, positive and informative."

All the presentations, posters and session recordings are available on the ECMWF website at: https://events.ecmwf.int/event/220/.

Science and Art event

Science and art are two things not usually seen as closely associated. The Science and Art event at UEF2021 wanted to dispel this by showcasing science-inspired artwork. Art can also be used to display one's own work in order to engage audiences on platforms used to promote science. Louise Arnal (University of Saskatchewan) and Chloe Brimicombe (ECMWF) presented their artwork and their scientific influences. Their presentations provided fascinating insights into why art and science should be interconnected.

The event was held in a gather.town art exhibition space, with artwork also contributed by Milana Vučković (ECMWF) and Loriano Pagni (ECMWF). It followed on from a successful Science and Art Exhibition at ECMWF in 2020. ECMWF hopes to continue these events in the future.

Making training mobile

Sarah Keeley, Xavier Abellan, Glenn Carver, Marcus Köhler, Sándor Kertész, Iain Russell

The numerical weather prediction (NWP) training courses run by ECMWF faced a new challenge this year as we embarked on another period of online training events. The question was how to try and replicate the classroom practical learning experience, especially when we did not want to postpone our new, OpenIFS-based hands-on Introduction to NWP for another year. A fundamental component of meeting the challenge is the European Weather Cloud. Cloud technologies allow us to provide each course participant with convenient and easy access to the same computing environment, a training lab, no matter what their local machine is. Each individual training lab instance can be provisioned on demand and tailored for each particular course.

The European Weather Cloud, whose main purpose is to deliver data access and cloud-based processing capabilities for the European Meteorological Infrastructure (EMI) and its users, was the perfect fit for this activity. With this solution, each participant could have enough compute power to run a six-day forecast at T_L255, which is the resolution of the seasonal forecast, in under 30 minutes.

What is a JupyterLab?

JupyterLab is a popular web-based user interface to your underlying computing platform that enables you to work with documents and activities such as Jupyter notebooks, text editors, terminals and many other features. You can arrange multiple documents and activities side by side in the work area using tabs and splitters, all without leaving your web browser. The notebooks running in the lab allow for users to interact with instructor-developed notebooks to play with code and visualise data.

Web-based courses

The decision was taken early on that for the new hands-on course the participants should only need to have access to a web browser to interact with all the training material. This meant developing all our training, including running OpenIFS and visualising it with Metview, within the JupyterLab environment (see box for more details). A new set of high-level Metview Python functions were created to aid data exploration and will shortly be released publicly. This new development can utilise the Jupyter environment and provides OpenIFS users with an easy way to visualise experiments with suitable visualisation styles for each meteorological variable, including animations, differences and ensemble plotting.

The other challenge was to create a classroom in which instructors and participants could interact with each other in a similar way as when seated side by side, working in teams or being instructed or discussing things as a group. For this we used a piece of proximity video chat software called Gather. This allows interactions over video, audio and screen shares when participants' avatars are physically

Gather screenshot. Instruction in the class with the main lecturer speaking and class members grouped around tables. The shared screen could be maximised by users to interact with the lecture material.

close in the virtual world. Participants sat in our virtual classroom in groups and worked together; instructors could walk round the virtual world seeing how people were getting on as well as talking to the whole class (see screenshot). Training videos about how to use each piece of technology were created, making sure that each participant could have a positive virtual classroom experience.

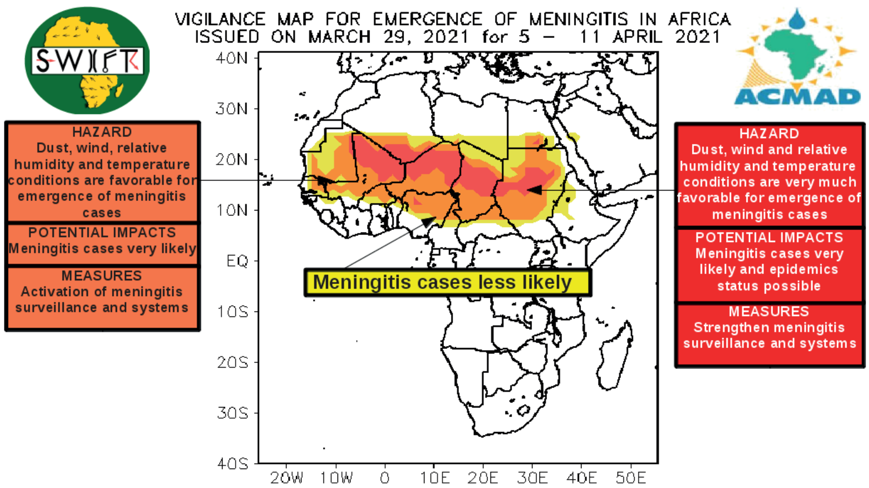
Looking to the future

The cloud technology was used for all the NWP courses this year, and over 130 participants were taught in the virtual classroom. The opportunity to have a practical element to the course was appreciated by participants to help them engage with and consolidate the training material. Nevertheless, many survey respondents strongly favoured the return to face-to-face training as soon as possible. Participants missed the informal networking and the time and space to focus solely on the training event by being at ECMWF. Going forward we will need to determine the most optimal way to deliver high-quality training events while maintaining accessibility. Whatever the coming years bring, the work to move our practical training to be deployed on the European Weather Cloud means that we can take our training to any of our sites and know that our practical sessions will run. This gives us the flexibility to tailor each course, picking from our library of material that has been prepared for the cloud and delivering the course material through whichever form is most appropriate.

Real-time access to sub-seasonal forecasts in Africa

Linda Hirons, Elisabeth Thompson, Felipe de Andrade, Steve Woolnough (all NCAS, University of Reading, UK), Joshua Talib (UKCEH, UK), Cheikh Dione (ACMAD, Niger)

Having real-time access to sub-seasonal forecast data from ECMWF has been transformational for African meteorological agencies. It has enabled the co-production of new bespoke forecast products with users to support their decision-making in a variety of sectors. They range from health metrics – combining temperature, relative humidity and wind to support predictions of meningitis outbreaks across the Sahel – to precipitation forecasts supporting hydropower planning – leading to reduced use of diesel and uninterrupted energy production in Kenya. Providing these forecast tools, tailored to the decision-making context of users, has supported preparedness action in areas where peoples' lives and livelihoods are particularly vulnerable to weather-related extremes.



Vigilance map of meningitis cases. This weekly vigilance map shows meningitis cases expected during the week from 5 to 11 April 2021, using forecasts initialised on 29 March 2021. Weekly mean surface dust concentrations during the past week (based on a product from the Barcelona Supercomputer Center) are combined with 1,000 hPa atmospheric fields (temperature, relative humidity and meridional wind) extracted from the S2S forecast database of ECMWF data (1.5° x 1.5°, weekly mean, bias-corrected using the ERA5 reanalysis) to generate the three vigilance levels (yellow, orange, and red).

Recent advances in the understanding of sources of sub-seasonal predictability (e.g. the Madden–Julian Oscillation), and their predictive skill across Africa, have the potential to improve preparedness action and early warning of high-impact weather. However, across much of sub-Saharan Africa forecast information on these timescales is either unavailable or existing tools are inappropriate for effective action-based forecasting.

Sub-seasonal forecasting testbed

The African SWIFT (Science for Weather Information and Forecasting Techniques; https://africanswift.org) project is running a two-year (2020–2021) forecasting testbed as part of the sub-seasonal to seasonal (S2S) Real-Time Pilot Initiative. The project was authorised by ECMWF's Council in support of the World Meteorological Organization's WWRP (World Weather Research Programme) and WCRP (World Climate Research Programme). The testbed combines knowledge from researchers, forecast producers and forecast users to co-produce and evaluate sub-seasonal forecast products tailored to the decision-making context of users in sectors such as agriculture, health, food security, energy and disaster risk reduction.

The testbed supports the provision of real-time sub-seasonal ECMWF data (1–4 weeks ahead) to African meteorological agencies in four SWIFT partner countries: Ghana, Kenya, Nigeria and Senegal, as well as two (regional and pan-African) climate centres. Weekly forecast initialisations are downloaded, and SWIFT partners access the data directly to co-produce forecast products with their users. At the outset, each of these six operational groups identified a key user who had weather-related decisions to make on sub-seasonal timescales. In Ghana and Nigeria, the focus has been the provision of precipitation information (e.g. weekly anomalies) to inform agricultural decisions. In Kenya key users are an energy company using precipitation forecasts for hydropower planning and a dairy farm utilising extreme temperature forecasts for production decisions. ICPAC, the regional climate centre in East Africa, has been using precipitation, temperature and soil moisture to inform food security decisions in the region. Access to the real-time data has enabled the African Centre of Meteorological Application for Development (ACMAD) to add forecast information, combining temperature, relative humidity and wind, to its existing meningitis outlooks and improve the early warning of potential outbreaks (see the figure).

Using this co-production approach shifts the emphasis away from a supply-driven forecast product to a demand-led process, which seeks to better understand and incorporate knowledge from users. Having direct access to the raw data during this forecasting testbed has enabled user-directed iterations to forecast products to make them more actionable. For example:

- Multi-variable metrics: using multiple forecast variables to create new combined metrics for specific applications. For example, temperature, relative humidity and wind forecasts are combined for application in the health sector to predict the prevalence of meningitis across the Sahel (see the figure).
- Data manipulation: directly manipulating the data to provide more user-relevant products. This includes applying different spatial and temporal averaging; the application of appropriate user-defined thresholds; and forecast calibration to enable the provision of user-relevant total values rather than anomalies. For example, the temporal averaging is changed to be consistent with existing forecasting tools (Central Africa).
- Product visualisation: co-developing how the forecast data is presented to ensure all the information is clear, correctly interpreted and relevant for its intended application. This includes tailoring colour scales to match existing products; showing smaller regions; changing the format; and combining forecast data with local monitoring data. An example is the combination of recent rainfall observations with model climatology and forecast data on one plot for improved user application (Kenya).

This sub-seasonal forecasting testbed has successfully piloted the provision of data directly to meteorological agencies and regional climate centres in Africa. Co-producing bespoke forecast products in this way has the potential to increase their uptake and thereby more effectively translate advances in predictability into real benefits for societies and economies. However, it comes with challenges. Firstly, accessing and manipulating raw forecast data to provide tailored products requires capacity building within institutions. Secondly, tailoring forecast products for specific users is time-consuming and will require considerable resource investment to ensure the sustainability of project-initiated services. Thirdly, these forecast products are only useful if the information within them is reliable. Therefore, emphasis needs to be given to the ongoing evaluation of forecast products, both in terms of meteorological and user verification.

Outlook

This short pilot project has demonstrated huge potential for improving the use of sub-seasonal forecast data to support decision-making in Africa. However, its continued progress relies on national and regional met services having direct access to the real-time sub-seasonal forecast data to develop and provide bespoke forecast products.

A new way of displaying ECMWF training resources

Becky Hemingway, Esperanza Cuartero

ECMWF offers a wide range of learning resources on its products and services. They range from in-person and online training courses to e-learning lessons and webinars, and they also include articles on topics related to forecasting, research, and computing. A new ECMWF learning public page has been developed as a signpost to the learning resources ECMWF has to offer (https://learning.ecmwf.int/web/guest/public-channel).

The aim of the public page is to make ECMWF learning resources easy to find and access without the need for a login. The page pulls together and displays content which already exists on the ECMWF website but is disseminated across different locations.

Learning resources page

Each resource presented on the public page has been categorised as ‘Forecasting’, ‘Research’ or ‘Data, Software and Computing’. This means users do not have to scroll through learning resources which are irrelevant to them. Instead, resources can be easily found and discovered based on user interests.

The public page contains a variety of learning resources that ECMWF provides to reinforce knowledge on forecasting, research, and computing. It includes:

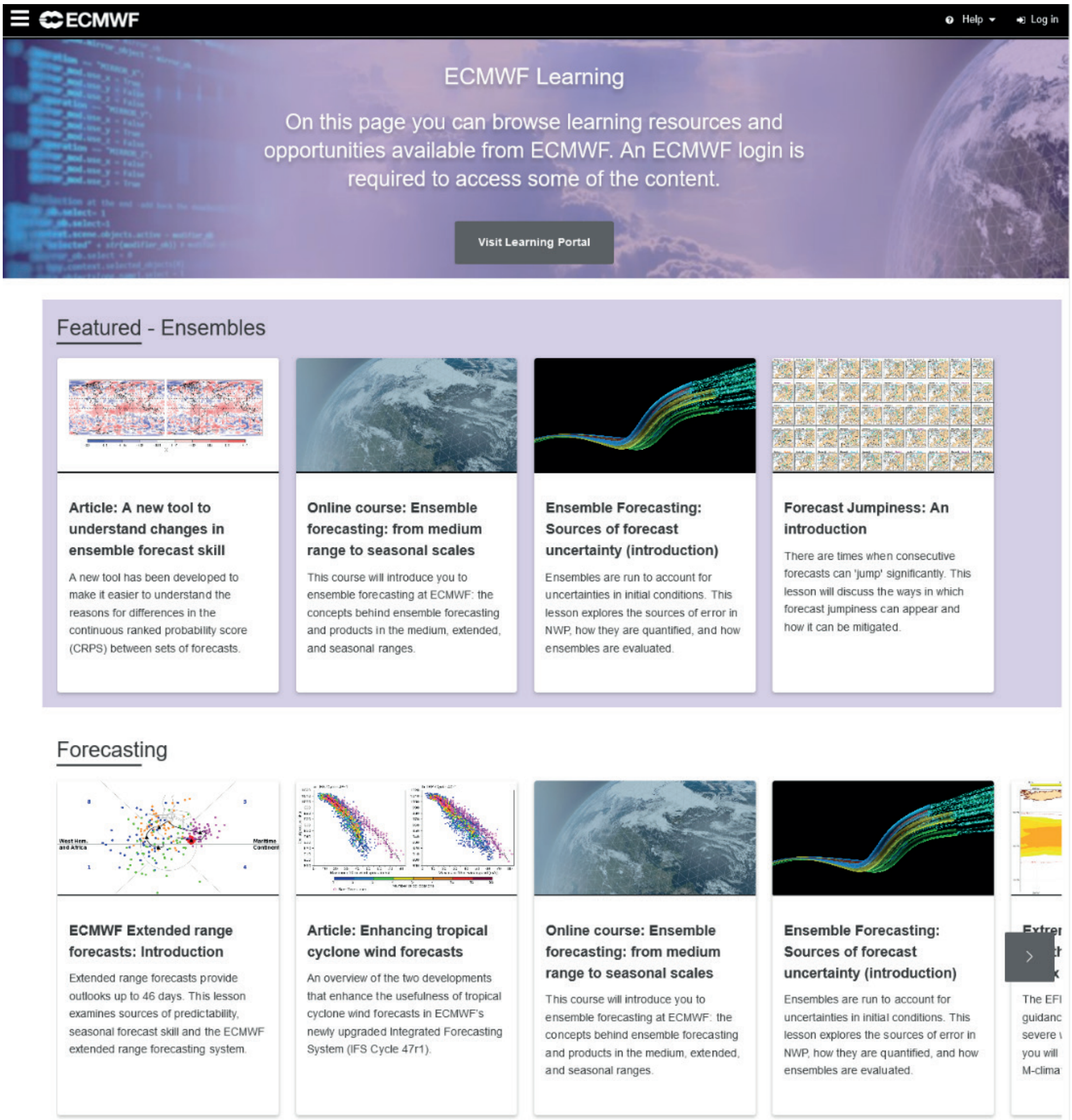
- **E-learning lessons** - these online lessons take less than an hour to complete and are available for a large variety of topics. They encourage self-study on a specific topic and require an ECMWF login to access.

- **Training courses** - these are hybrid events with a face-to-face element, held in person or virtually, as well as online pre-course learning requirements. They require pre-registration and take place at set times in the year.
- **Online training courses** - these take place fully in the virtual environment and are done at the user's own pace. They require an ECMWF login to access.
- **Articles** - including Newsletter articles and other news pieces. These cover the latest advances and ECMWF's involvement. They enhance user knowledge and understanding, ensuring they are on the cutting edge of developments in the field. These are freely accessible to all.
- **Webinars and events** - including upcoming and past ones. These are webinars and events which users may find useful to attend or watch to learn more about ECMWF products and services, including how to use them. Attending events and webinars live provides users with the opportunity to ask questions and provide feedback directly to ECMWF experts. Some may require registration to access.

If a learning resource which requires a login is chosen, the user is taken to the ECMWF login page, where they can log in or freely register to access the content. Users can access and see their progress with e-learning lessons and online training courses directly using the Learning Portal (https://learning.ecmwf.int/group/guest/dashboard).

A fresh and dynamic page

The categorisation of the public page, based on the target audience and content type, is simple and intuitive. It allows trainers within organisations, forecasters, researchers and those using ECMWF's computing facilities to



Excerpt from new public page for ECMWF learning resources. A new public page has been developed to make ECMWF learning resources easier to find and access.

easily explore resources on topics of their interest.

The selection of publications listed in the ‘Articles’ section covers the latest advances, news, approaches and expertise, focused on different aspects of a field. These articles have been chosen to provide a fresh look at ECMWF products and services and related topics, with new articles being added regularly.

At the top of the public page, the ‘Featured’ section highlights four learning resources on a particular topic. This area is dynamic, with a monthly theme changing the featured resources. The aim of the section is to quickly showcase resources to users which they otherwise may not discover. The monthly themes will be chosen based on time of year, e.g. winter weather in winter months, upcoming events such as Using ECMWF’s Forecasts or hot topics in the news. The featured learning resources will be accompanied with tweets on Twitter to further promote the variety of learning available at ECMWF using #learningofthemonth.

More information on the public page can be found by watching the recording of a recent webinar entitled ‘Learning Resources at ECMWF: Forecasting, Research and Computing’ (https://events.ecmwf.int/event/252/).

Outcomes of ECMWF/OceanPredict event on ocean data assimilation

Magdalena A. Balmaseda (ECMWF), Andrew Moore (University of California, Santa Cruz), Matthew Martin (UK Met Office)

More than 170 scientists from around the world discussed recent progress and challenges ahead in ocean data assimilation in a virtual event from 17 to 20 May 2021. The workshop was organised jointly by ECMWF and OceanPredict, a science programme for the coordination and improvement of global and regional ocean analysis and forecasting systems. It was designed to meet the ever-increasing requirements of marine, weather, environmental and climate services. It was very timely since 2021 marks the beginning of the UN Decade of Ocean Science for Sustainable Development.

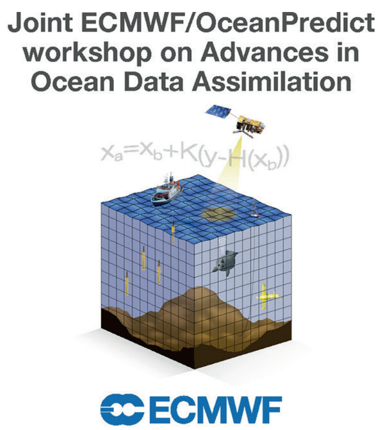
During this event, experts from different domains addressed the multidisciplinary science underpinning climate and environmental monitoring and predictions, the exploitation of novel observations, and interactions in the ocean–atmosphere–sea-ice–biogeochemistry system at global and regional scales.

A combination of 36 plenary talks, 29 poster presentations, four working group discussions and several informal virtual breaks facilitated the exchange of information and seeding of new ideas. The working group discussions addressed questions common to all applications, including treatment of model error, the specification of short-range forecast and observation errors, the balancing of resolution and ensemble configurations, and the exploitation of machine learning. The discussions also covered the infrastructure needed to share developments among different domains, and between operations and research.

Progress

In the past few years, operational ocean activities have consolidated in different centres, and the number of ocean specialists has increased. There is now a critical mass to spark productive collaborations. Availability of a wider range of ocean observations greatly facilitates development efforts. It has given rise to activities on observing system impact and design as well as observation operators and treatment of observation error. Oral and poster sessions presented progress on variational and ensemble methodology and algorithms, opportunities for data assimilation arising from machine learning, theoretical considerations on the validity of the various assimilation methods for systems with different degrees of non-linearity, and practical considerations on balancing the competing demands of higher resolution and larger ensembles.

The workshop also touched on



common developments for sharing data assimilation infrastructure, with major initiatives such as JEDI (Joint Effort on Data Assimilation Integration) and PDAF (Parallel Data Assimilation Framework) being presented.

More details on the workshop can be found here: https://events.ecmwf.int/event/199/. A brief summary of the recommendations is presented below.

Overarching recommendations

Coupled data assimilation: Recommendations concern advancing the scientific foundations underpinning the coupling among Earth system components, which will require the productive engagement of all domain scientists. They also suggest exploring machine learning solutions and the use of targeted observations.

Resolution: Models should have sufficient resolution to resolve the relevant physical processes. Approaches for affordable solutions should be explored. Emerging observations with the ability to sample the ocean at finer spatial/temporal scales may become more useful. Observations that sample coarser scales might need different treatment in a high-resolution data assimilation system than before.

Methodology: Further development of methods for representing multi-scale flow-dependent background errors, which include the time dimension, and for balancing resolution/ensemble needs is recommended.
The exploration of machine learning solutions for different aspects of data assimilation is encouraged. Efforts to develop methods targeting coupled data assimilation, treatment of model error and parameter estimation should continue and strengthen.

Ensembles: In principle, the quality of the background error statistics diagnosed from ensembles will improve with an increasing number of ensemble members. In practice, computational resources constrain the ensemble size, and it is important to invest in enhanced ensemble generation strategies to improve the reliability of the ensemble and control sampling issues.

Observing System (Simulation) Evaluation experiments (OSEs/ OSSEs): Comparison studies of coordinated OSSEs and OSEs will be helpful to learn from different systems. It is recommended to involve the observational community in the design of observation impact experiments, and to share the OSSE/OSE outputs with the wider community. Specific activities contributing to the UN decade of Ocean Science are encouraged.

Evaluation: As well as standardised metrics of fit to the assimilated observations, evaluation against independent data and error growth diagnostics are important.
The reliability of the ensemble and the temporal consistency of the estimation should be considered.

Treatment of observations: Progress should be made to develop efficient methods to model observation error correlations in data assimilation systems. There is a need for developing and sharing methods for automatic quality control and observation bias correction. Historical observation repositories should be updated regularly and as promptly as possible.

Infrastructure developments: Modular and open source software infrastructure that facilitates exchange of developments and their application to different models are welcome and encouraged. Management of the complexity of the data assimilation infrastructure is crucial to facilitate its uptake. The need for data-sharing infrastructure to facilitate collaborations was also identified.

Links with the modelling community: Stronger links between the data assimilation and modelling communities will benefit the scientific and infrastructure developments in both domains. The capability to compare model fields with observations, the information from analysis increments, and the possibility of using data assimilation for parameter tuning are important assets for model development.

Training and recruitment: Investment in training of the next generation of data assimilation scientists is identified as critical. This should include specific training on the use of modern software development/collaboration techniques. Beyond training, sustained funding for data assimilation in the research community is required to maintain a sufficient pool of expertise to exploit new computer architectures and observing systems.

Next steps

The recommendations of the working groups will be used to inform the plans for ocean and coupled data assimilation developments at ECMWF and other forecasting centres around the world. They will also inform work within the Data Assimilation Task team of OceanPredict and will help to improve collaborative efforts being planned under the UN Decade of Ocean Science for Sustainable Development.

The full workshop report can be found here: **https://events.ecmwf.int/event/199/attachments/1000/2308/Workshop_report.pdf**

This article was written on behalf of the workshop's organising committee, working group chairs and rapporteurs.

New observations since April 2021

The following new observations have been activated in the operational ECMWF assimilation system since April 2021.

Observations	Main impact	Activation date
GOES-17 Clear-Sky Radiances (replacing GOES-15, which has been excluded since 27 February 2020)	Tropospheric humidity and wind	18 May 2021
Scatterometer winds from HY-2B	Near-surface winds over ocean	23 June 2021

IFS upgrade provides more skilful ensemble forecasts

Mark Rodwell, Michail Diamantakis, Peter Düben, Martin Janoušek, Simon Lang, Inna Polichtchouk, Fernando Prates, Chris Roberts, Filip Váňa

On 11 May 2021, ECMWF implemented a substantial upgrade of its Integrated Forecasting System (IFS). As with almost all upgrades, this involved contributions from many teams within the Centre. IFS Cycle 47r2 includes changes to the forecast model, but not to the data assimilation system. The upgrade is neutral for the medium-range deterministic high-resolution (HRES) forecast but brings benefits to the medium- and extended-range ensemble forecasts (ENS). Cycle 47r2 is the culmination of two strands of work:

- A change from double precision to single precision in HRES and ENS forecasts
- An increase in the number of model levels from 91 to 137 in ENS forecasts

Forecast model

Previous versions of the IFS have used 'double precision', where each number is stored using 64 bits of memory. This is often more accurate than required when we consider observational errors and model approximations. Single precision, in which each number is stored with 32 bits of memory, offers the prospect of freeing up memory and, importantly, increasing processing speeds. Single precision of the IFS started as a research project in collaboration with the University of Oxford and as part of the OpenIFS effort. Similar lines of research were pursued in the COSMO (Consortium for Small-scale Modelling) model. It then became a collaborative project across many ECMWF teams. With more people working on the project, forecast skill became increasingly neutral over time with respect to double precision, up to a point where it could be incorporated into our operational forecasts. This allows computational savings to be made which can be used to achieve skill improvements. Figure 1 shows the computational changes to the ensemble forecast. Faster core processing (green circles) of single-precision data permits a 50% increase in ENS model levels from 91 to 137. Even with this increase in levels, data transferred (red arrows) between the memory on each node (yellow boxes) is reduced because it is now in single precision.

Double precision is still used throughout the data assimilation process, and some calculations in the forecast do still require double precision. The most expensive of those, such as the calculation of the associated Legendre polynomials and the finite-element integral operators of the vertical discretisation, are only done once and are not repeated during time-stepping. Hence, there is minimal impact on computational efficiency. Further detailed experimentation helped us to identify a few other

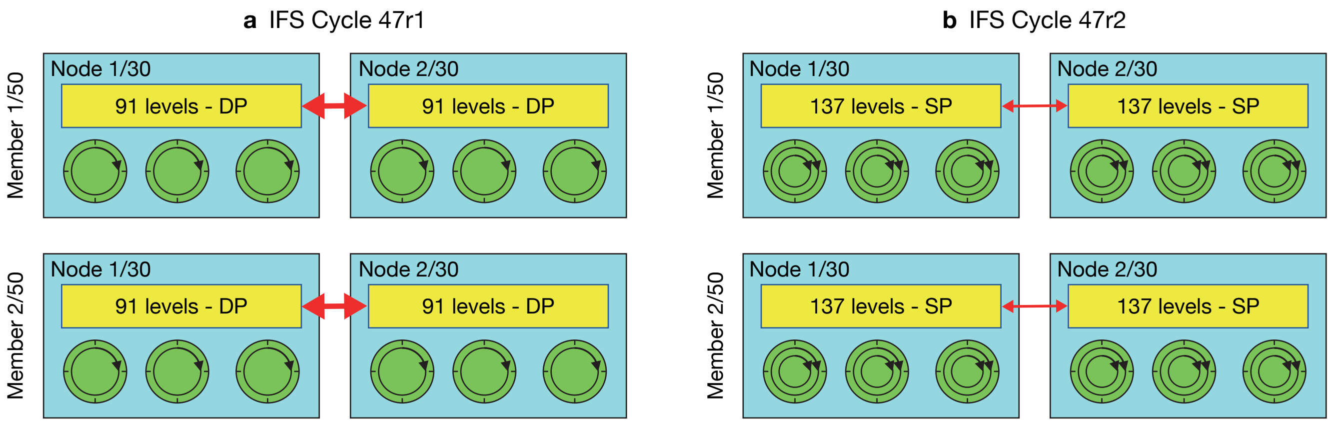


FIGURE 1 The computational change from (a) IFS Cycle 47r1 with double precision (DP) and 91 levels in the ensemble forecast to (b) IFS Cycle 47r2 with single precision (SP) and 137 levels in the ensemble forecast allows faster core processing (green circles) and reduced data transfer (red arrows) between the memory on each node (yellow boxes).

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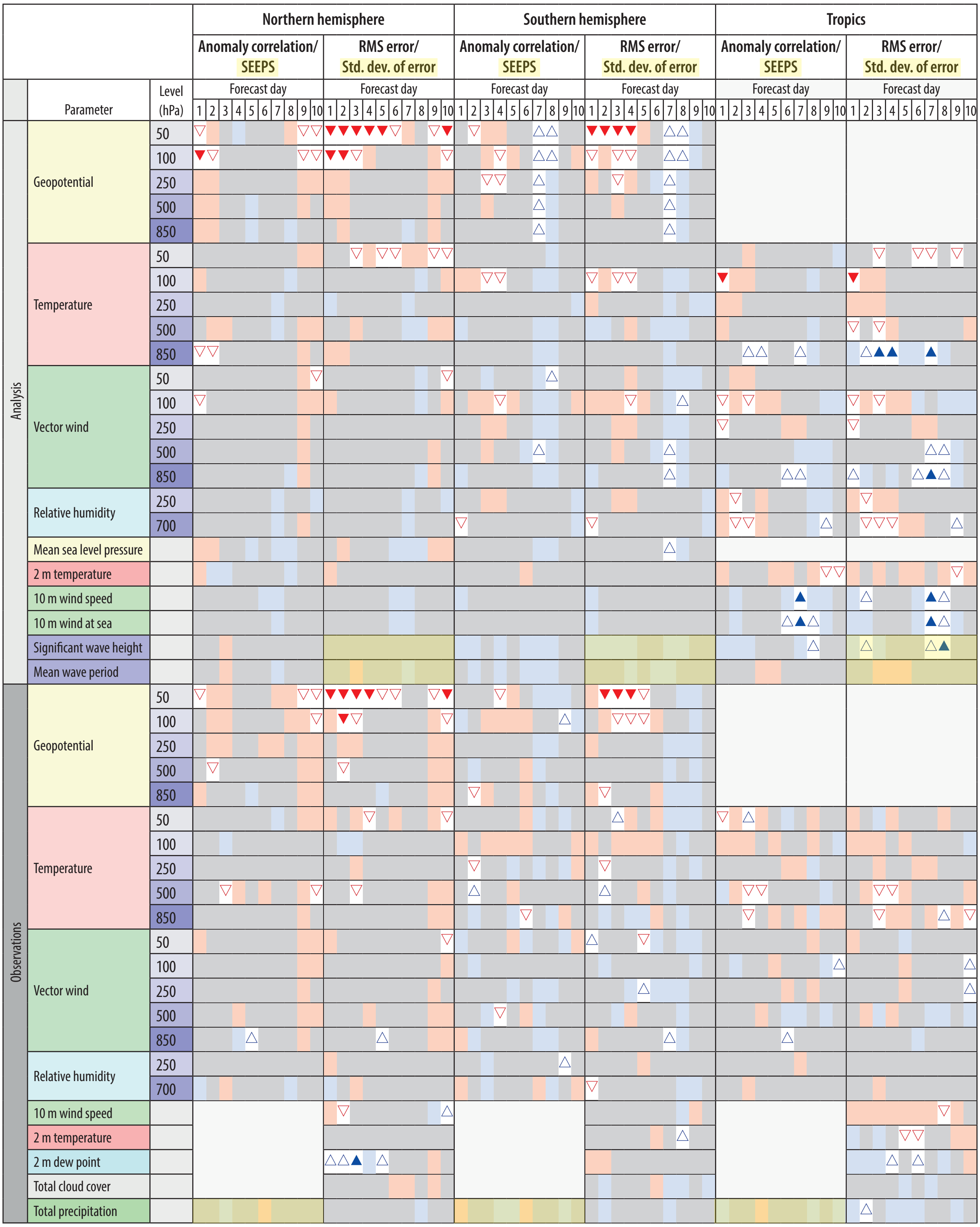
47r2 HRES scorecard



Symbol legend: for a given forecast step...

- ▲ 47r2 better than 47r1 statistically significant with 99.7% confidence
- △ 47r2 better than 47r1 statistically significant with 95% confidence
- 47r2 better than 47r1 statistically significant with 68% confidence
- no significant difference between 47r1 and 47r2
- 47r2 worse than 47r1 statistically significant with 68% confidence
- ▽ 47r2 worse than 47r1 statistically significant with 95% confidence
- ▼ 47r2 worse than 47r1 statistically significant with 99.7% confidence

FIGURE 2 HRES scorecard of IFS Cycle 47r2 versus IFS Cycle 47r1, verified by the respective analyses and observations at 00 and 12 UTC, based on 619 forecast runs in the period May 2020 to April 2021. The HRES is run at TCo1279 resolution, corresponding to a horizontal grid spacing of about 9 km.

calculations in parts of dynamics and physics and the stochastic physics perturbations that need to be secured with double precision. However, those also represent a very small part of the total computational load. Note also that GRIB encoding is unchanged, so archived files remain the same size.

The change to 137 levels brings us one step closer to a more seamless ensemble data assimilation and forecasting system. The need for vertical interpolation when generating ensemble initial conditions is now greatly reduced as the ensemble of data assimilations (EDA) is already run with 137 levels. The consistency with the HRES vertical resolution should also aid the evaluation process of future cycles. Technical changes to the ensemble include the calculation of singular vector perturbations with 137 levels.

Impact on medium- and extended-range forecasts

The goal for the implementation of single precision was neutrality in HRES scores, together with major computational cost savings. Neutrality would be demonstrated in an HRES scorecard (Figure 2) with approximately a third of the boxes being grey, a third red and a third blue, and with little more than 5% of the red and blue boxes being statistically significant at the 5% significance level (indicated by triangles). As can be seen in Figure 2, this has largely been achieved. A possible exception is a degradation (typically less than 1%) in stratospheric extratropical geopotential height scores.

The neutrality for the HRES is illustrated in Figure 3 by track forecasts of Hurricane Laura. While agreement cannot be perfect for a chaotic system, the medium-range track differences between single and double precision are much smaller than the spread of the ensemble, which represents the impacts of initial and model uncertainty. More generally, the impact of single precision on HRES tropical cyclone track and intensity scores is neutral.

The increase in vertical resolution from 91 to 137 levels has been introduced to all ENS forecasts in the medium to the extended range. The ENS scorecard is shown in Figure 4. The change leads to statistically significant improvements to many ENS scores of about 0.5–2% throughout most of the free atmosphere. Stratospheric temperature scores are greatly improved, typically by 5–20%. This is, among other things, due to a weaker growth of temperature biases because the ENS can better resolve gravity waves in the vertical. Figure 5 shows this improvement at day 10, but it persists into the extended range. The mean cooling difference below 600 hPa (Figure 5 bottom panel) acts to decrease the warm bias around 850 hPa. It improves tropical medium-range scores at that level by over 6%. It does also slightly increase the tropical near-surface cool bias, and this is reflected in the 2-metre temperature scores in Figure 4, which are degraded by up to 1% by day 14. Ten-metre wind scores are also slightly degraded by 0.1–0.3%.

The extra levels mean that sharper inversions can be resolved. For example, the ensemble vertical profile product now uses 34 model levels below 700 hPa instead of the previous 22. The Cycle 47r2 test profile in Figure 6, which uses the new mapping of model levels, shows a slightly sharper thermal inversion at around

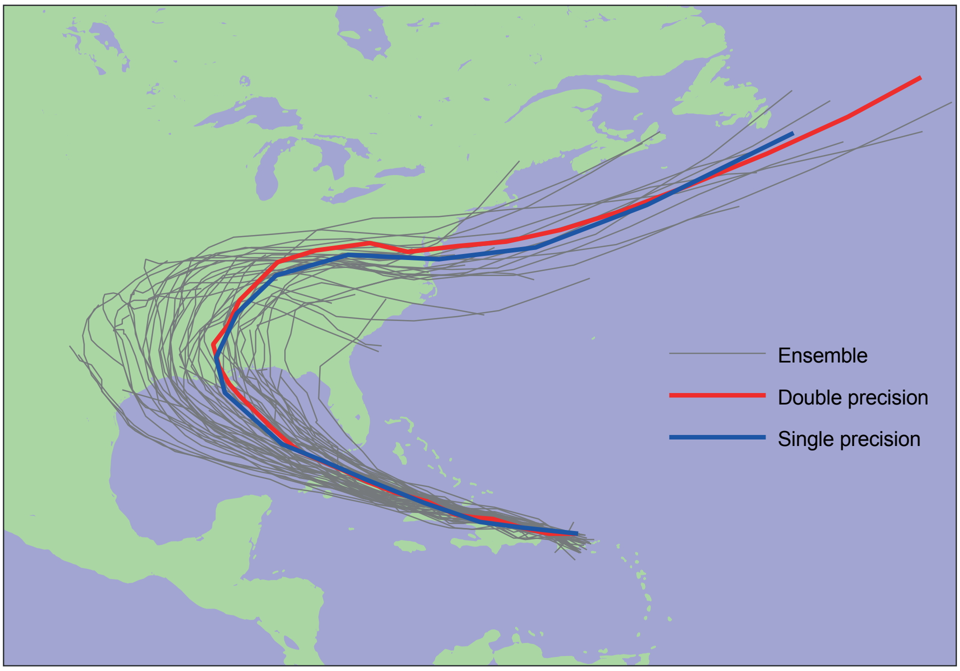
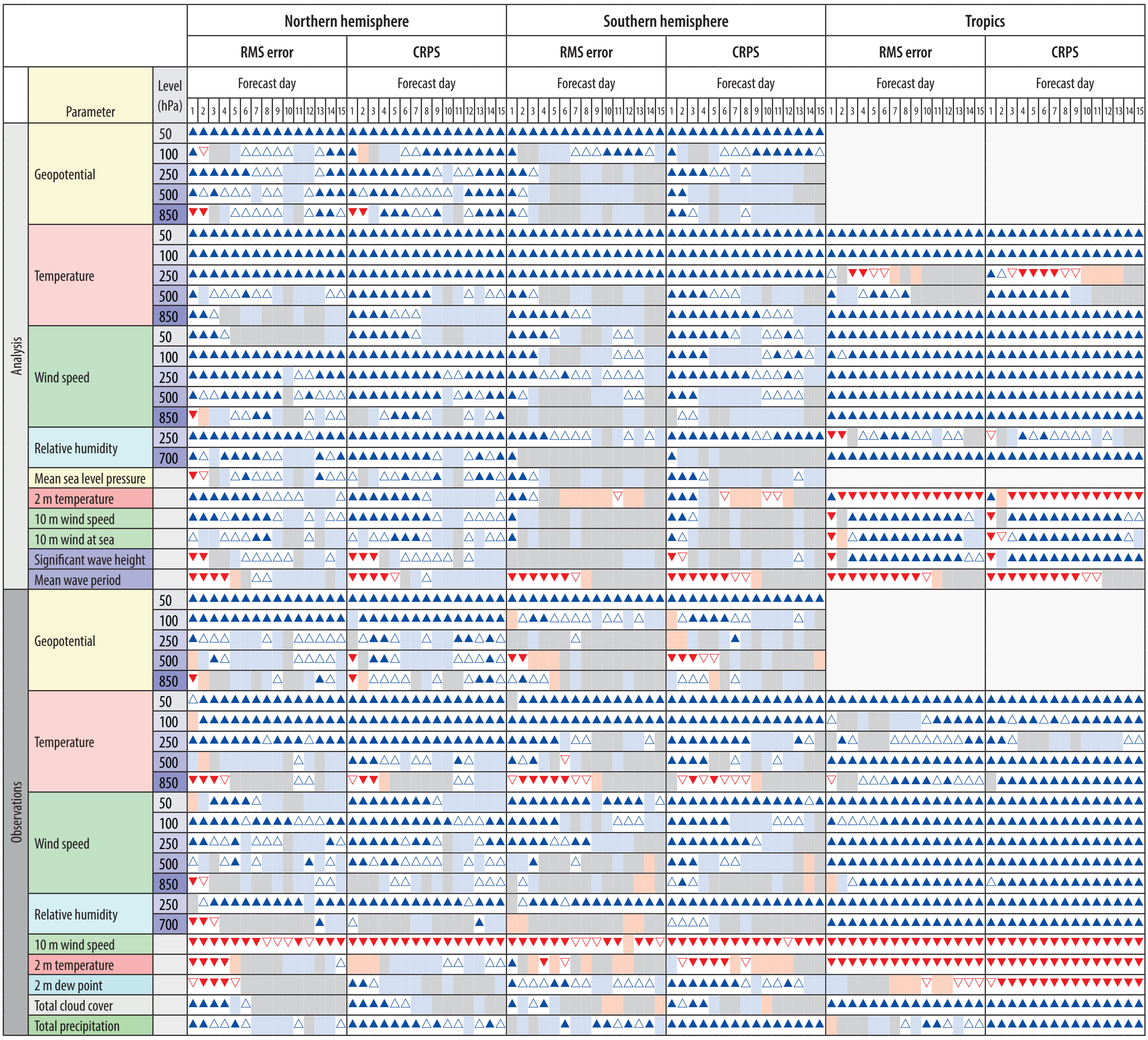


FIGURE 3 Eight-day tracks of Hurricane Laura from 12 UTC on 22 August 2020 in high-resolution deterministic forecasts with double precision (red) and single precision (blue) along with those from the operational ensemble at the time (grey).

47r2 ENS scorecard



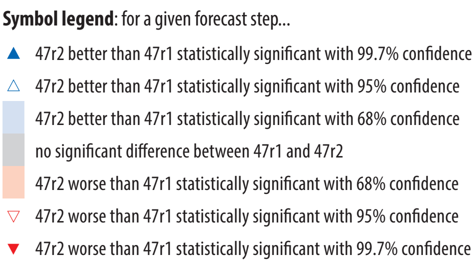


FIGURE 4 ENS scorecard of IFS Cycle 47r2 versus IFS Cycle 47r1 for medium-range forecasts up to forecast day 15, verified by the respective analyses and observations at 00 UTC based on 408 ENS forecast runs in the period November 2019 to April 2021. The ENS is run at TCo639, corresponding to a horizontal grid spacing of about 18 km.

850 hPa than the Cycle 47r1 profile. Users will need to ensure that they extract the correct model levels when creating their own forecast products.

Tropical cyclones show reduced intensity errors (see Figure 7a). This is largely associated with reduced bias. There is a mean reduction of about 2 hPa in central pressure in the medium range, increased spread, and improved reliability as measured by the spread-error agreement. The cycle is neutral in terms of track errors (Figure 7b). Along with the increased tropical cyclone intensity, other tropical activity is increased: calculating anomalies from the operational extended-range re-forecasts may be advisable.

A key source of sub-seasonal predictability is the Madden–Julian Oscillation (MJO). Out to the extended range, the amplitude of the MJO is better sustained:

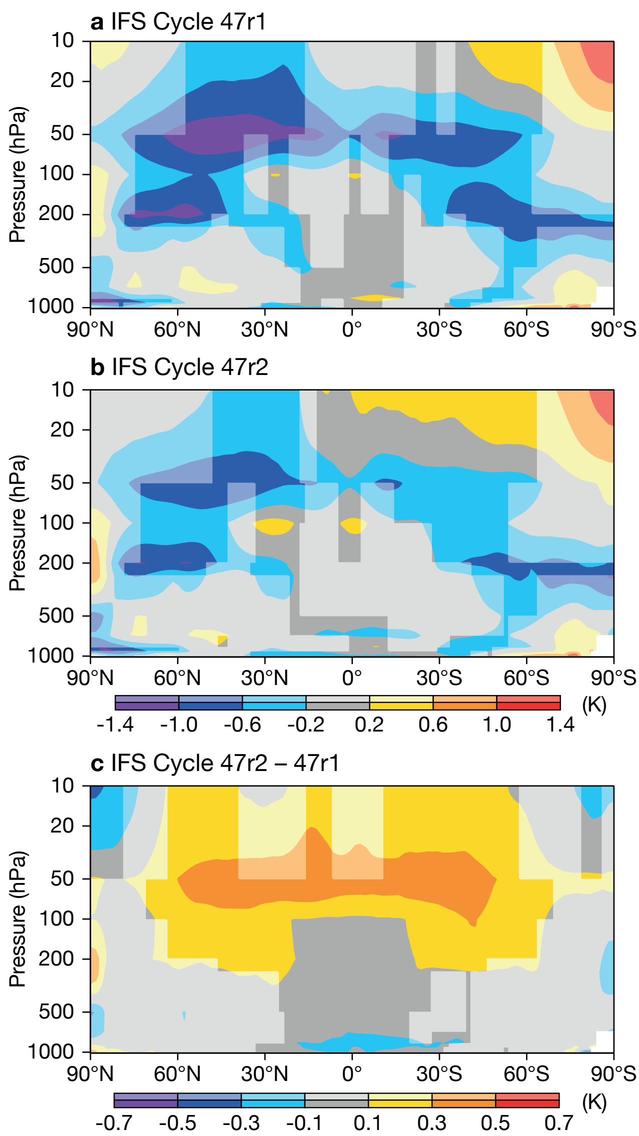


FIGURE 5 Zonal means of mean temperature errors at a lead time of 10 days in the ensemble control forecast for (a) IFS Cycle 47r1, (b) IFS Cycle 47r2, and (c) the difference between IFS Cycles 47r2 and 47r1. More saturated colours indicate statistical significance at the 5% level using a t-test accounting for temporal correlation. Evaluated over all forecasts between 25 November 2019 and 28 February 2020 as well as 10 May 2020 and 7 November 2020.

the amplitude loss by day 15 is now about 15% rather than the previous value of about 20% (Figure 8). There is also an increase in MJO spread, improved reliability and better scores. Changes come mostly from improvements in tropical zonal winds at 200 hPa.

Forecast outputs

More frequent tropical cyclone track updates are now available with the inclusion of forecasts from 6 and 18 UTC initial times, alongside those of the 0 and 12 UTC forecasts. More snowfall Extreme Forecast Index (EFI) and Shift of Tails (SOT) products are now available with the inclusion of 3-, 5-, 10- and 15-day accumulation periods, in addition to the previous 1-day accumulations. A selection of new specialist climatological model parameters includes some which describe the characteristics of topographic features smaller than the model grid box, some which are used within radiation calculations, and the 'Logarithm of surface roughness length for heat'.

Summary

The change to single precision in forecast mode for the HRES and ENS systems has freed up computing resources to be used to enhance forecast skill. In IFS

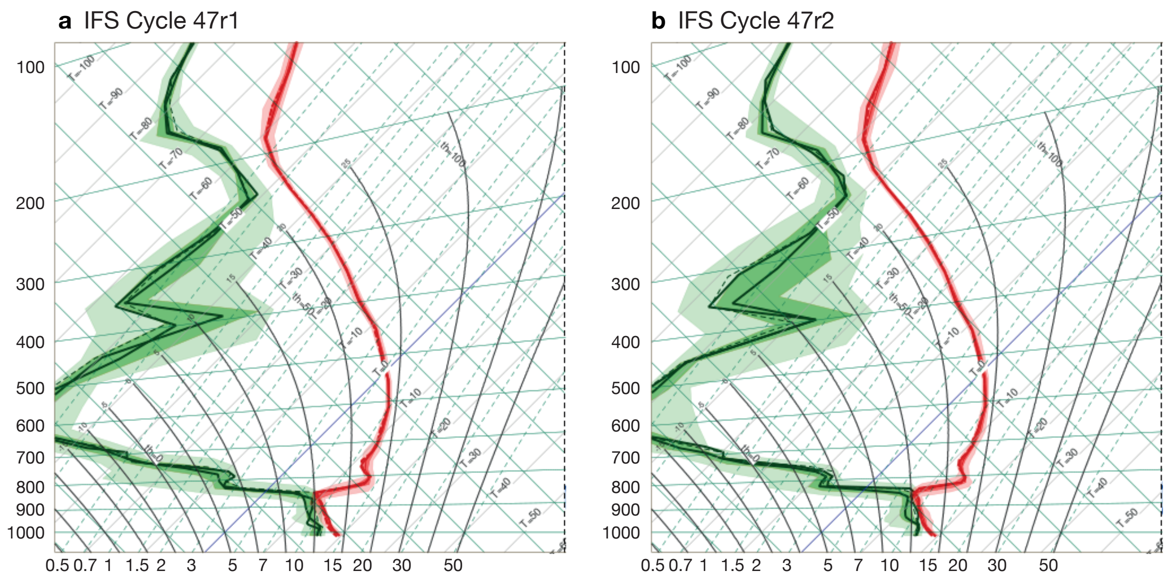


FIGURE 6 The vertical structure of temperature (red) and moisture (dewpoint, green) in tephigram format in (a) IFS Cycle 47r1 in a 60-hour forecast from 21 January 2021 00 UTC at 20.03°S 90°W and (b) the same forecast in IFS Cycle 47r2. Shaded bands denote the minimum, 25th and 75th percentiles and maximum for temperature and dewpoint ENS distributions at each level. The median dewpoint value is shown by the solid line within the dark green shading. The other solid line represents HRES and a thick dashed line represents the Control forecast.

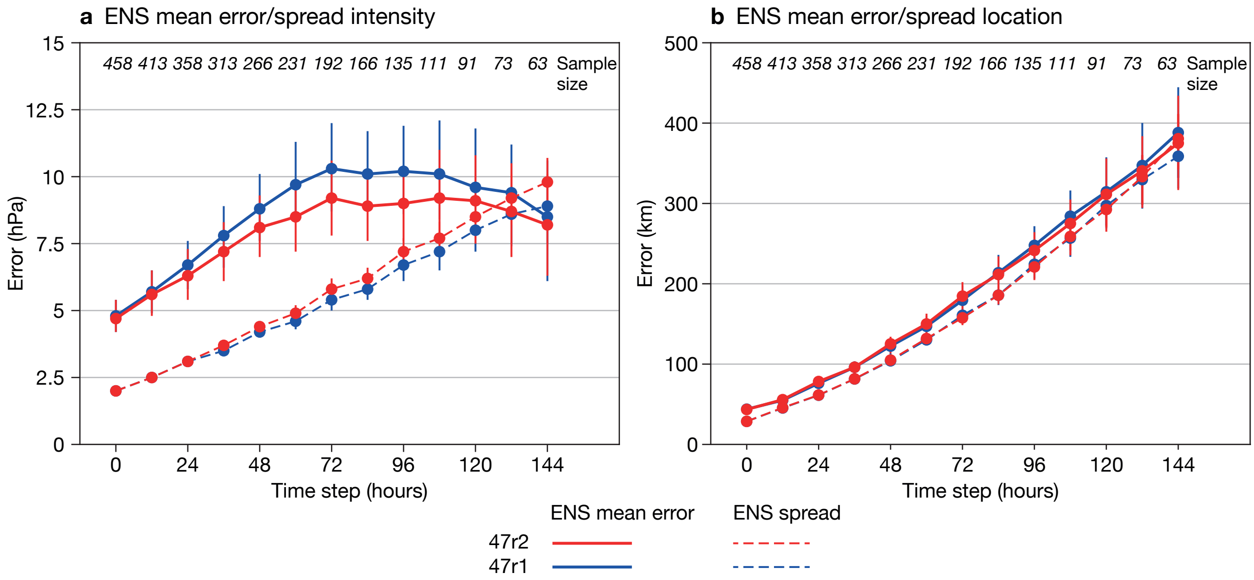


FIGURE 7 Root-mean-square errors (RMSE) in the ensemble mean of (a) tropical cyclone (TC) intensities along with the standard deviation (spread) among ensemble members and (b) tropical cyclone locations along with the standard deviation (spread) among ensemble members. Results are based on all TC basins for the periods 25 November 2019 to 28 February 2020 and 10 May 2020 to 30 November 2020. The numbers at the top of the panels indicate the number of TCs which could be evaluated at each lead time. The bars indicate 95% confidence intervals.

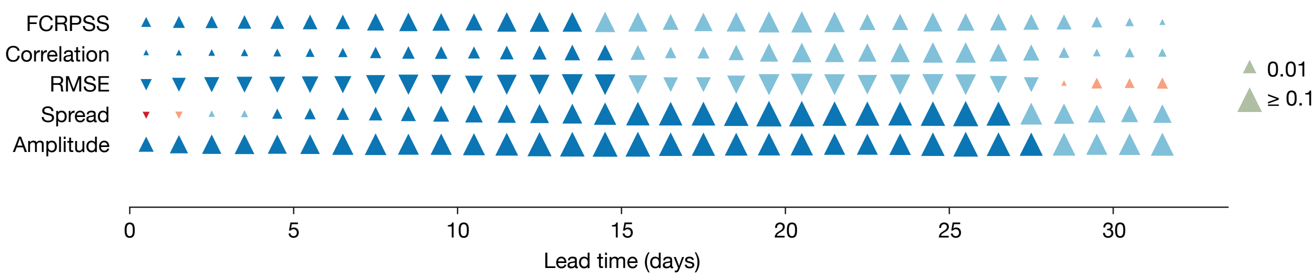


FIGURE 8 Score differences (Cycle 47r2 with 137 levels minus Cycle 47r2 with 91 levels) for the bivariate real-time multivariate Madden–Julian Oscillation (RMM) index based on re-forecasts initialised at the start of each month for the period 1989–2016. The differences shown are for (i) the fair version of the continuous rank probability skill score (FCRPSS), (ii) the bivariate anomaly correlation, (iii) the bivariate root-mean-square error (RMSE), (iv) the bivariate spread of the ensemble with respect to ensemble mean, and (v) the amplitude of the RMM index. Bivariate scores are calculated and verified against the RMM index constructed from the ERA5 reanalysis. Triangles indicate increased (pointing up) and decreased (pointing down) values, which are significant at the 1% level when the shading is more saturated.

Cycle 47r2, the choice has been made to use these resources to make the model levels used in the ENS match those of the EDA and HRES systems. This represents an important step within ECMWF's ten-year Strategy 2021–2030, which highlights "work towards a seamless integration from the ensemble of data assimilations to the ensemble forecast system". The fact that the ENS and HRES now have the same model levels should also facilitate future cycle development. The new cycle increases ENS forecast skill by typically 0.5–2% in the free atmosphere, but by 5–20% for stratospheric temperatures at 50 hPa and by 6% in the tropical troposphere. It also intensifies tropical cyclones, thus reducing intensity errors and improving reliability, and it helps to better sustain the amplitude of the Madden–Julian Oscillation into the extended range.

Further reading

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Polichtchouk, **I.**, **T. Stockdale**, **P. Bechtold**, **M. Diamantakis**, **S. Malardel**, **I. Sandu et al.**: 2019. Control on stratospheric temperature in IFS: resolution and vertical advection. *ECMWF Technical Memorandum* **No. 847**.

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How APPLICATE contributed to ECMWF core activities

Irina Sandu, Gabriele Arduini, Jonathan Day, Linus Magnusson, Heather Lawrence, Niels Bormann, Peter Bauer, Sarah Keeley, Gianpaolo Balsamo, Thomas Haiden

ECMWF's main goal is to continuously improve medium-range forecast skill for the benefit of its Member and Co-operating States. In recent decades, predictive skill has steadily increased in the ECMWF Integrated Forecasting System (IFS) from the tropics to polar regions. Predictive skill in the Arctic remains lower, however, than in the northern hemisphere mid-latitudes (Figure 1). ECMWF's participation in the EU's Horizon 2020 project APPLICATE stimulated a concerted effort across ECMWF to examine in more detail the challenges that limit forecast skill in Arctic regions, and to identify ways to overcome them. It also fostered close interactions between ECMWF scientists and many colleagues in national meteorological services, universities and research institutes in the Member and Co-operating States and beyond, in particular at the Alfred Wegener Institute (Germany), Stockholm University (Sweden), MET Norway, the German National Meteorological Service (DWD), the UK Met Office, and Environment and Climate Change Canada (ECCC). Moreover, it supported ECMWF's contribution to the World Meteorological Organization's Year of Polar Prediction (YOPP).

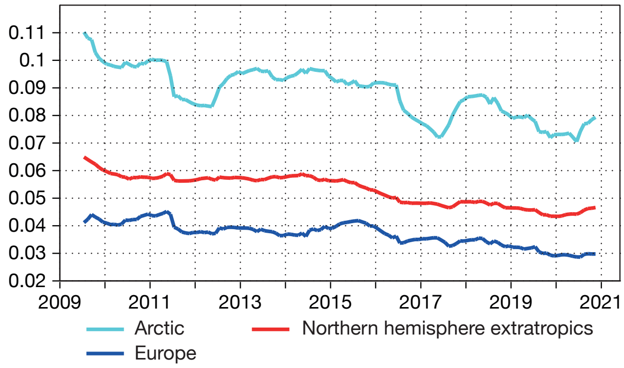

FIGURE 1 Fraction of large 2-metre temperature errors in the ECMWF operational ensemble forecasts (with CRPS values larger than 5 K) at day 5 for the Arctic, the northern hemisphere extratropics and Europe.

This article summarises the advances made at ECMWF in the framework of APPLICATE in the key ingredients for improving weather forecasts in the Arctic and beyond (see Box a): coupled modelling and process-

a **Key ingredients for accurate weather forecasts**

The accuracy of weather forecasts depends on the quality of the forecast model and on the initial conditions. The quality of the forecast model is key both for ensuring that the forecast errors are the smallest possible, and for an effective use of observations in data assimilation when creating the initial conditions. The initial conditions are produced with comprehensive data assimilation systems, which cover a time window (12 hours for the operational ECMWF system) in which they optimally combine the available observations with short-range forecasts to produce a best estimate of the state of the atmosphere, land and ocean including sea ice. This is called the analysis.

Observations are thus used to correct forecast errors, leading to increments in state variables such as temperature, wind, humidity and geopotential height. This process relies on the observations and their usage, including how model variables like temperature are transformed in satellite radiances and an observation bias removal or correction. It also relies on weighting the observations and short-range forecasts (or background) by the respective observation and background error covariance matrices. In the ECMWF system, this weighting depends in part on the flow-dependent background errors, which are described using the spread of a 50-member Ensemble of Data Assimilations (EDA). The EDA is an ensemble of independent 4D-Var data assimilations, in which the main analysis error sources (observation errors, model errors, and boundary condition errors) are represented by perturbing the related quantities (observations, model, sea-surface temperature, etc.). To provide reliable background errors, the spread of the EDA needs to capture both the magnitude and the variation of the errors in the short-range, as well as the correlations of these errors (Lang et al., 2019).

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based diagnostics, effective use of observations, and data assimilation and ensemble techniques.

Challenges limiting predictive skill in Arctic regions

The work done within APPLICATE allowed us to better examine the specific challenges posed by Arctic regions and identify ways forward.

In terms of coupled modelling and diagnostics, the key challenges in the Arctic are related to the representation of stable boundary layers and strong near-surface temperature inversions, mixed-phase clouds, snow and sea ice, plus the coupling between these different elements of the Earth system. Work done in APPLICATE at ECMWF showed for example that fluxes of heat, momentum and radiation at the interfaces can be erroneously represented, particularly in very cold conditions (Day et al., 2020).

There are also challenges related to the use of observations at high latitudes when creating the initial conditions of weather forecasts. There are far fewer conventional observations (radiosondes, buoys) than in other regions (Figure 2a), and it is harder to assimilate them than at lower latitudes due to a variety of reasons (e.g. larger model errors, larger representativeness errors). The Arctic is well observed by polar-orbiting satellites because of their high revisit time over polar areas. An analysis of the use of Arctic observations in the IFS performed within APPLICATE, based on diagnostics from the ECMWF data assimilation system, has however shown that satellite sounding observations are particularly difficult to use in numerical weather prediction (NWP) systems over sea ice and snow covered surfaces and in the shallow polar atmosphere (again due to a variety of reasons detailed in Lawrence et al., 2019a). Figures 2b,c illustrate that the number of assimilated observations from microwave sounding channels peaking in the lower troposphere is indeed much lower during winter than during summer, in particular in regions covered by snow and sea ice.

Finally, there are challenges in data assimilation methodologies. These are related, for example, to how much weight is given to observations versus the model in the data assimilation process, and how bias correction is dealt with. Work within APPLICATE has also shown that the spread of the Ensemble of Data Assimilations (EDA) is underestimated in the lower troposphere and in the upper troposphere/lower stratosphere in polar regions (Lawrence et al., 2019a). This means that the adjustments observations make to the short-range forecasts in the Arctic in these regions during the assimilation are probably too small.

The issues highlighted above all require detailed evaluation to guide progress. For this purpose, it is useful to complement the forecast evaluation against analysis, reanalysis or regular observation networks with evaluation against observations from field campaigns and supersites. A considerable effort in APPLICATE consisted in more systematically using such comprehensive suites of observations of the coupled Earth system to investigate model errors by applying newly developed process-oriented diagnostics.

Coupled modelling and novel process-based diagnostics

In terms of coupled modelling, the APPLICATE focus at ECMWF was on the representation of snow and the coupling of the atmosphere, ocean, snow and sea ice. Advances on these aspects, the representation of which currently limits forecast skill, were facilitated by the

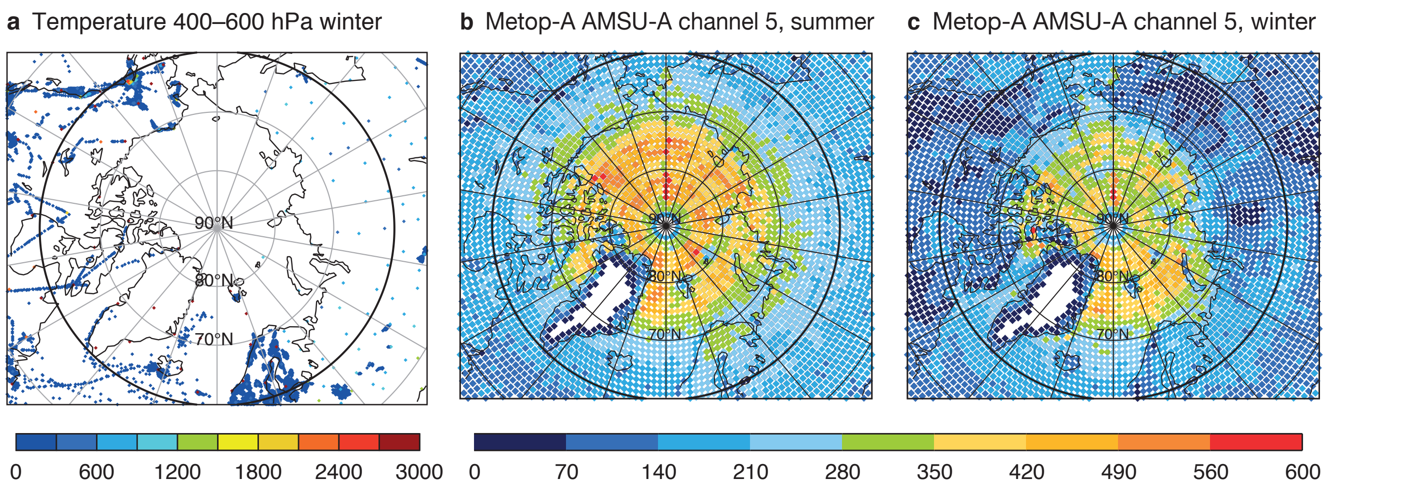

FIGURE 2 Number of observations assimilated in the ECMWF operational system from (a) temperature (radiosonde and aircraft) observations between 400 and 600 hPa for the period December 2017 to March 2018; (b) Metop-A AMSU-A channel 5 (peaking around 650 hPa) for June–September 2016 and (c) the same as (b) but for December 2017 to March 2018. Figure from Lawrence et al. (2019b), CC BY 4.0 (*https://creativecommons.org/licenses/by/4.0/*).

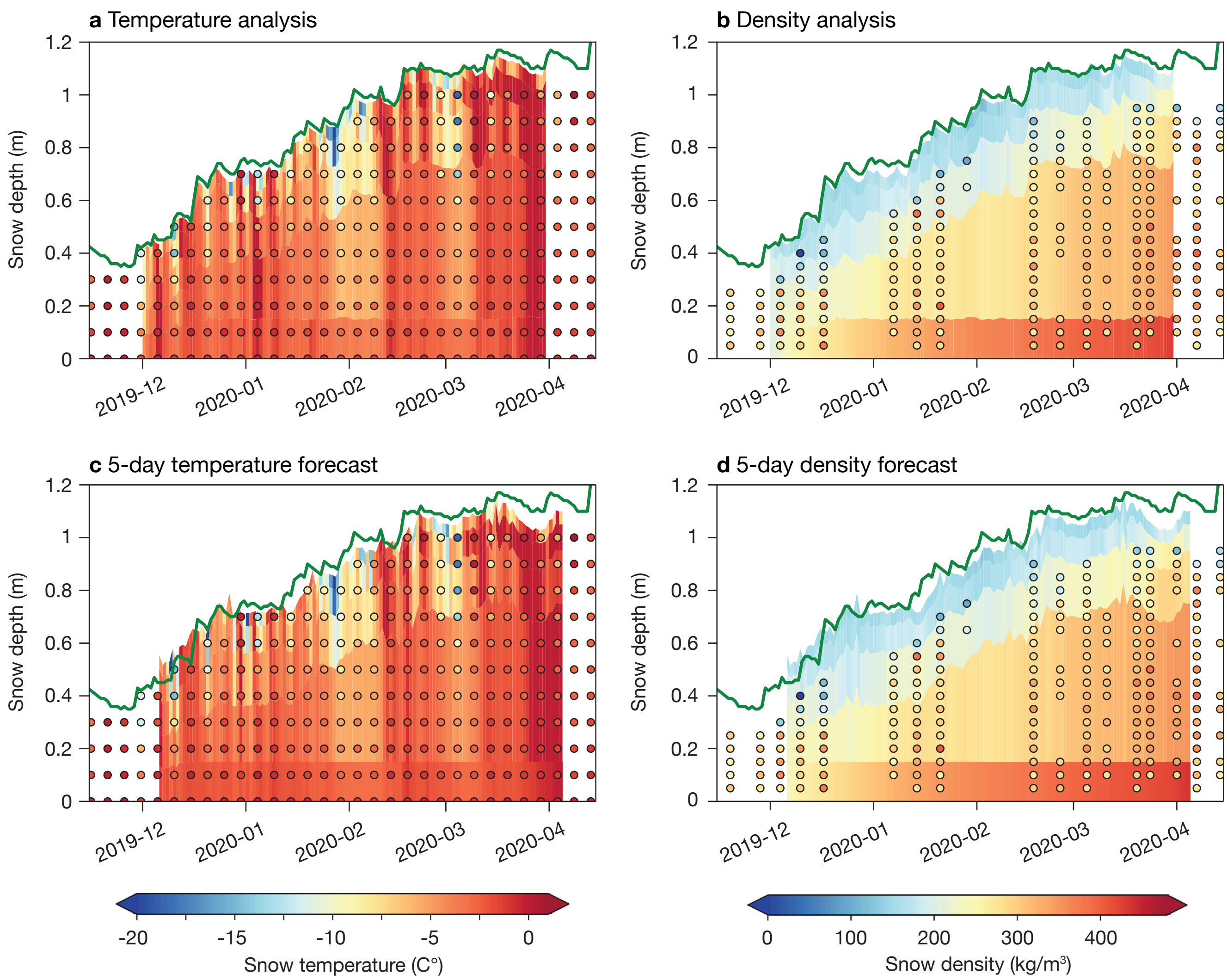

FIGURE 3 Time-height plots showing the analyses of (a) snow temperature and (b) snow density at Sodankylä, and 5-day forecasts of (c) snow temperature and (d) snow density, all with the multi-layer snow model (background colours) and observations (coloured dots) for the 2019/2020 season. The snow depth from observations is superimposed (green line). Observational data are courtesy of Anna Kontu (Finnish Meteorological Institute).

development and application of novel process-based diagnostics. Targeted diagnostics and observational verification are key for pinpointing sources of systematic model error, and for ensuring that changes to the forecasting system lead to forecast improvements for the right reasons and do not introduce compensating errors. A novel aspect within APPLICATE was to make more regular and extensive use of observations from so-called observational supersites, which include a variety of observations spanning the snow–atmosphere and sea-ice–atmosphere interfaces (Day et al., 2020).

Snow modelling

One of the main sources of forecast errors over snow-covered surfaces is the use of a bulk snow scheme in the current version of the IFS. Representing the snowpack with a single layer of snow leads to an overestimation of the thermal inertia of the snowpack, particularly for deep snowpacks. For such snowpacks, the temperature variations near the snow surface are much larger than at the base (Figure 3), and therefore a single-layer snow model overestimates the strength of the snow–atmosphere coupling. This leads to forecast biases in terms of snow depth, snow temperature and near-surface air temperature. Generally, the snow depth is too large, the near-surface air temperature too high, and its diurnal cycle is underestimated. To address these systematic errors, a multi-layer snow scheme was further developed in APPLICATE. This scheme, which builds on Dutra et al. (2012), represents the snowpack with several (up to five) layers. It also brings improvements in terms of the representation of certain physical processes, e.g. considering the penetration of solar radiation in the snowpack and a prognostic liquid water content.

The multi-layer (ML) snow scheme was first evaluated in offline integrations and coupled deterministic medium-range forecasts starting from the operational analysis.

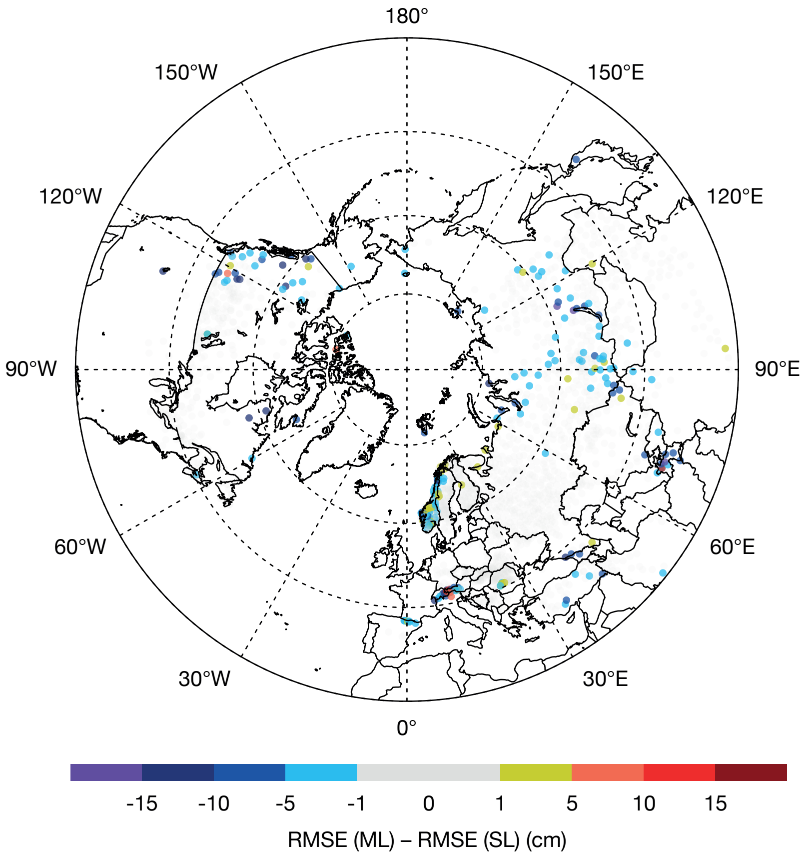

FIGURE 4 Difference between the root-mean-square error (RMSE) of snow depth between coupled forecasts at a lead time of t+12 hours using the multi-layer (ML) and single-layer (SL) snow schemes and initialised from a consistent analysis using a multi-layer and single-layer snow scheme, respectively, from December 2019 to January 2020.

A description of changes to the snow representation and this initial evaluation can be found in Arduini et al. (2019). More recently, complex code changes were made to be able to use the ML scheme in the data assimilation cycles, and to run the IFS in an operational-like configuration, which is used to produce operational analyses and forecasts. These included developments in the 4D-Var data assimilation system and in the snow optimum-interpolation analysis.

As the ML scheme is planned for operational implementation in IFS Cycle 48r1 in 2022/23, its performance was evaluated across the range of configurations used for operational forecasts: analysis and coupled medium-range deterministic and ensemble forecasts, monthly and seasonal forecasts. It was also assessed in the context of snow-impacted hydrology observations. Figure 4 illustrates improvements to the snow depth from pilot data assimilation experiments, in which the ML scheme is used both in the coupled ten-day forecasts and in the 4D-Var and snow optimum-interpolation analysis. The root mean square error of the forecasts of snow depth at 12 hours is reduced in the ML compared to the single-layer (SL) data assimilation experiments. This suggests that the first-guess snow depth, which is cycled from one analysis cycle to the next, is of better quality in the ML experiment.

The benefits seen in snow depth using the ML scheme are related to an increased realism in the representation of snow properties. This can be shown by using observations of internal snow temperature and density collected routinely at snow supersites like Sodankylä (Finland). The snow temperature from the analysis shows good agreement with the observations, in particular in representing the alternance of episodes of cooling and warming of the snowpack, e.g. during December 2019 (Figure 3a). The snow density is in good agreement with the observations in the upper part of the snowpack, but it is overestimated in the bottom layer (Figure 3b). This can be due to challenges in the representation of upward water vapor fluxes in the presence of large vertical temperature gradients in snowpack models. The forecasts at t+120 hours show a slight degradation compared to the analysis, in particular in the topmost layer, which can be partly associated with errors in the atmospheric forcing at this lead time (Figure 3c,d).

The impact of the ML snow scheme in these pilot data assimilation experiments on near-surface meteorological variables is evaluated using 2-metre temperature (T2m) observations from the SYNOP network. The T2m biases over Eurasia are reduced by about 1 K compared to SL experiments, confirming the results presented in Arduini et al. (2019). The root-mean-square error (RMSE) of T2m increases in the ML experiments over certain regions, for instance in Alaska and West Scandinavia (not shown). This can be partly due to an increase in variability associated with errors in other variables and processes, like cloud cover and/or cloud microphysics, to which the new scheme is more exposed, as described in Arduini et al. (2019).

The increase in forecast variability can have a positive effect in an ensemble framework through an increase in spread. Figure 5 shows that using the ML snow scheme in ensemble forecasts generally improves the continuous ranked probability score (CRPS) of 2-metre temperature over the northern hemisphere, with some negative impact located over northwest America, the Alps, and east Asia.

Coupled sea-ice–atmosphere modelling

Ocean and sea-ice models are still a fairly recent addition to NWP systems, while they have been an integral component of climate models for some time. Until recently it was assumed that sea-ice–ocean fields change so slowly that it is acceptable to keep them fixed, or to use climatological anomalies, for the period covered by global medium-range forecasts. However, coupled systems have been found to improve forecast skill in the tropics, and in certain situations errors in the position of the sea ice can lead to degradations in the skill of atmospheric forecasts. For example, during marine cold-air outbreaks, the geometry and position of the sea-ice edge exerts a strong control on turbulent exchange and can strongly influence boundary layer development hundreds of kilometres downstream of the sea ice. It can thus influence the track and intensity of hazardous polar lows on short and medium-range forecast timescales.

ECMWF's ensemble forecasts have been coupled with the ocean since 2013 and with sea ice since 2016, and ECMWF's deterministic high-resolution forecasts became coupled during the APPLICATE project (July 2018). This means that the NEMO and LIM2 ocean and sea-ice models are now used in all forecasts to evolve the ocean and sea-ice properties (Keeley & Mogensen, 2018). During APPLICATE, it was shown that a warm bias in atmospheric boundary layer temperature, downstream of the sea-ice edge during marine cold-air outbreaks, was corrected when using an interactive sea-ice model. This is because the sea-ice model accounts for the southward expansion of the sea ice in those situations. Such an expansion in sea ice can be seen in the case shown in Figure 6.

Improved use of observations and data assimilation

Given how crucial the accuracy of the initial conditions is for the quality of weather forecasts, and how expensive it is to ensure the monitoring of the Earth system both from ground-based observing networks

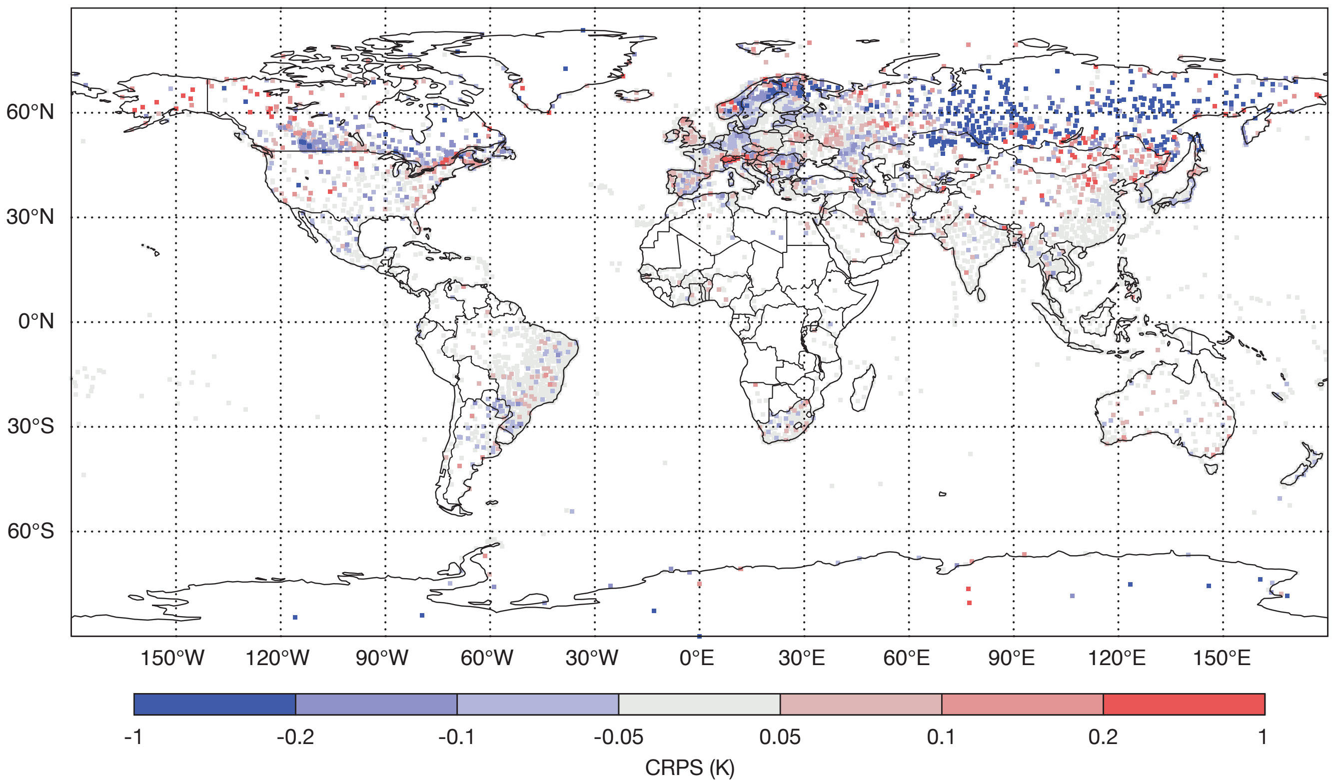

FIGURE 5 Difference between the continuous ranked probability score (CRPS) of 2-metre temperature of ensemble forecasts at a lead time of t+120 hours using the multi-layer (ML) and single-layer (SL) snow schemes and initialised from a consistent analysis using a multi-layer and single-layer snow scheme, respectively, from December 2019 to February 2020. Each ensemble consists of eight perturbed members. The differences are generally small in the southern hemisphere.

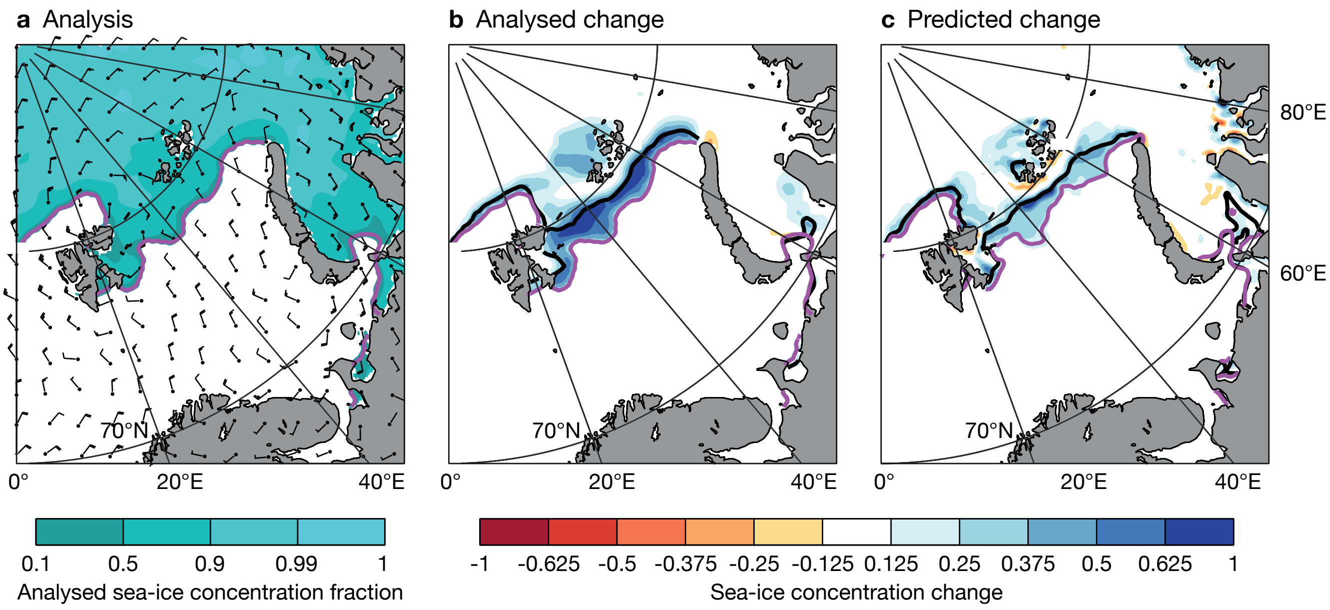

FIGURE 6 The plots show (a) the analysed sea-ice concentration and 10-metre wind on 28 December 2017, (b) 3-day change in analysed sea-ice concentration and the sea-ice edge between 25 December 2017 (black) and 28 December 2017 (pink), and (c) 3-day change in sea-ice concentration and the sea-ice edge in the first 3 days of an HRES forecast initialised on 25 December 2017.

and from space, it is important to regularly assess the value extracted from current observing systems. This is even more important for the Arctic, given that the harsh meteorological conditions in this region make the maintenance of observing networks more difficult and costly than in other parts of the globe.

The value of Arctic observations

A novel aspect of APPLICATE, in which ECMWF took a leading role, consisted in examining for the first time the impact of current atmospheric Arctic observing systems on predictive skill. This was done by performing observing system experiments, in which different observing systems were removed from the data assimilation system when creating the initial conditions of weather forecasts. This type of numerical experimentation is regularly done at weather centres on a global scale to quantify the value of observations for short- and medium-range weather forecasts. The novelty in APPLICATE was to do this exercise with a particular focus on Arctic observations, and to do it in coordination with other weather centres in the framework of both APPLICATE and YOPP. Coordinated experiments were thus performed at ECMWF, ECCC and DWD with their global forecasting systems, and at Met Norway with the regional forecasting system AROME Arctic. Different types of atmospheric observations, from conventional networks (such as radiosondes, buoys, SYNOP observations) and from satellites (microwave and infrared sounders, atmospheric motion vectors and radio occultation) were removed north of 60°N for different winter and summer periods.

It was demonstrated that all Arctic observing systems have complementary positive impacts on the skill of ECMWF forecasts, both in the Arctic and in the mid-latitudes (Lawrence et al., 2019b). The impact in the mid-latitudes was shown to be primarily associated with certain flow regimes which favour the propagation of air masses from the Arctic towards the mid-latitudes. For example, removing Arctic in-situ or satellite observations during winter leads to a deterioration in forecast skill in the medium range over northern Asia during Scandinavian blocking episodes (Day et al., 2019). This is due to the fact that during such blocking episodes (a) error growth is enhanced in the European Arctic, as a result of increased baroclinicity in the region, and (b) high-amplitude planetary waves allow errors to propagate efficiently from the Arctic into the mid-latitudes.

The observing system experiments performed at ECMWF showed that conventional in-situ observations play the most important role during winter, emphasizing the need to maintain and further develop conventional observational networks, which are sparse and costly to maintain in polar regions (Figure 7a). These experiments have also shown that satellite microwave observations play the most important role during summer (Figure 7b), while for winter the use of these observations is not found to be optimal due to issues with their assimilation, in particular over snow and sea ice.

Enhancing the uptake of microwave observations

The strong positive impact of microwave observations on predictive skill in summer suggests that improving their use over snow and sea ice, which is currently not optimal, is likely to further improve forecasts in the Arctic and mid-latitudes. For this to be achieved, investments are needed in all key components of NWP systems, i.e. coupled modelling, ensemble and data assimilation techniques and use of observations.

As discussed by Lawrence et al. (2019b), the uptake of microwave radiances over snow and sea ice can be enhanced through better modelling of snow, sea ice, mixed-phase clouds and shallow stable boundary layers. It can also be enhanced through a better representation of surface characteristics over sea ice and snow in the forward modelling, i.e. the radiative transfer computations used to project model variables into satellite observation space (radiances). For the forward modelling of surface-sensitive microwave radiances, improvements to the representation of surface emission/reflection are expected to be made for some instruments in IFS Cycle 48r1. In addition, the representation of skin temperature currently neglects surface penetration effects, which can be significant over snow and sea ice at microwave frequencies. This practice also contributes to systematic errors in the forward modelling. Methods for an enhanced treatment of skin temperature during the assimilation are currently being tested.

Moreover, the assumed background error covariances are important for the use of all observations, since they determine the weight given to them in the analysis, but they also play a particular role for satellite radiances. This is because they affect the vertical structure of the increments as well as the separation of radiance signals into different geophysical variables. This is particularly important where the vertical structure may not be well captured by the background. It would be interesting to further investigate how to improve the spread of the EDA in the lower troposphere, where it is currently underestimated, and to see how this may lead to a larger impact of the observations. This could be done, for example, in the context of planned developments of model uncertainty representation and ensemble resolution increases.

Outlook

In summary, the work done in APPLICATE at ECMWF, in collaboration with many colleagues from Member and Co-operating States and beyond, has enabled progress on many aspects which are central to ECMWF's core activities and strategy for the next decade. Advances have been made in terms of coupled modelling, the use of observations and novel diagnostics, which are all key for further improving the quality of ECMWF forecasts. Avenues for further progress in these directions were also identified.

Coupled modelling: Systematic errors in the Arctic can be further reduced by taking into account snow over sea ice and by improving the thermodynamical coupling between snow, sea ice and atmosphere. Preliminary experiments indicated that accounting for snow over sea ice can improve the forecasting of strong radiative cooling events during clear skies. They also highlighted the impact of compensating errors among snow and

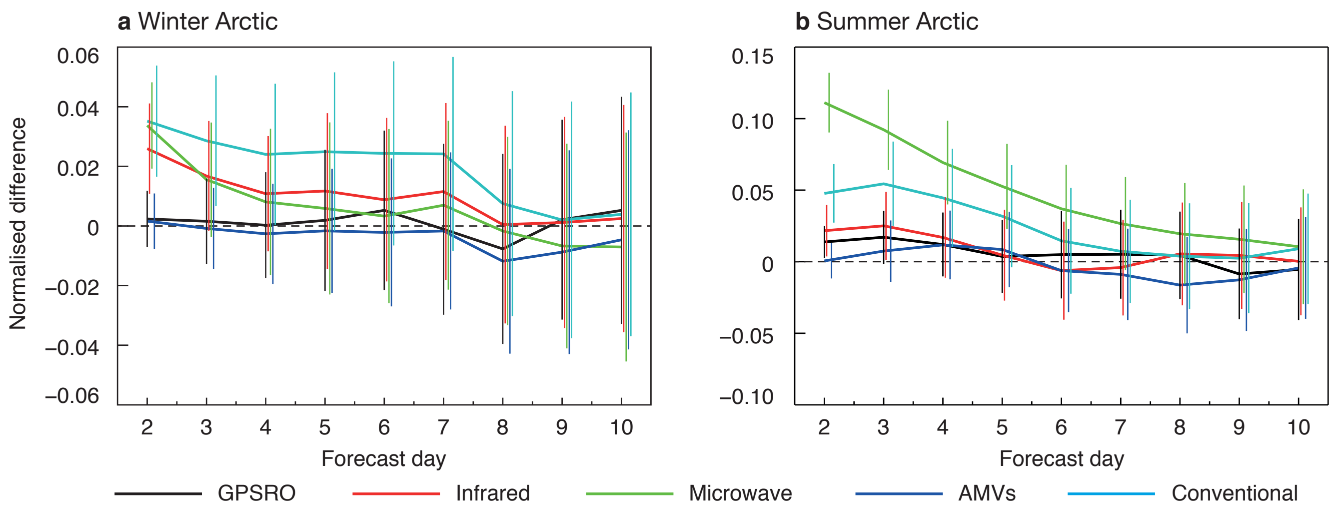

FIGURE 7 Normalised change in the standard deviation of forecast error for geopotential height at 500 hPa over the Arctic region (north of 60°N) during (a) winter and (b) summer. Different lines give results from observing system experiments in which certain observation types are removed when creating the initial conditions for the forecasts, with the observing systems indicated in the legend (GPSRO: bending angles from radio occultation; Infrared: radiances from hyperspectral infrared sensors; Microwave: radiances from passive microwave instruments; AMVs: Atmospheric Motion Vectors; Conventional: all in-situ observations, such as radiosondes, SYNOP observations, aircraft data, etc.). Note that forecast errors are verified against the ECMWF high-resolution operational analysis. Values are given as fractions. The intervals show a 95% confidence level. Figure from Lawrence et al. (2019b), CC BY 4.0 (*https://creativecommons.org/licenses/by/4.0/*).

cloud processes on the Arctic surface energy balance and the need to further improve the representation of mixed phase clouds. The research done in APPLICATE indicated that a more holistic approach, considering improvements in snow processes, mixed-phase clouds representation and turbulent mixing in stably stratified conditions, is required in the future to further improve the representation of the Arctic boundary layer in NWP systems.

Use of observations: APPLICATE further demonstrated the need to improve the uptake of microwave radiances from polar satellites over snow and sea ice. This should lead to better forecasts and also to better reanalyses, such as those produced by the EU-funded Copernicus Climate Change Service provided by ECMWF. Given that microwave sounding observations are one of the most important observation types for the quality of the initial conditions, this finding triggered a lot of interest both from the NWP community and satellite agencies. Increasing the uptake of satellite data over all surfaces (as well as in all-sky conditions) in the Integrated Forecasting System is identified as one of the priorities highlighted in the ECMWF Strategy for 2021–2030. Enhancing the uptake of satellite observations at high latitudes was recently discussed in a workshop organised by EUMETSAT and during the ESA European Polar Science week in 2020.

Novel diagnostics: Such a holistic approach to the development of coupled models requires further development in techniques to diagnose the causes of error in coupled systems which take into account the additional degrees of freedom in the coupled system. Such work will continue at ECMWF as part of the INTERACTIII project, which will utilise Arctic research station data for this purpose, and in ECMWF's ongoing contribution to YOPP.

Another important ECMWF contribution to YOPP in the framework of APPLICATE is the ECMWF YOPP dataset (Bauer et al., 2020). This freely available dataset covers the period from mid-2017 until the end of the MOSAiC field campaign in autumn 2020. This dataset also includes tendencies from model dynamics and individual physical processes, which are essential for characterising the contribution of individual processes to model state evolution and, hence, for diagnosing sources of model error. It opens thus many research opportunities with colleagues in ECMWF Member and Co-operating States and beyond.

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This is a contribution to the Year of Polar Prediction (YOPP), a flagship activity of the Polar Prediction Project (PPP), initiated by the World Weather Research Programme (WWRP) of the World Meteorological Organization (WMO). We acknowledge the WMO WWRP for its role in coordinating this international research activity.

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Forecasting clear-air turbulence

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Forecasting severe turbulence in the free troposphere and stratosphere is challenging. The turbulence is generated by processes such as shear instabilities (Kelvin–Helmholtz instabilities), upper-level fronto-genesis, large-amplitude mountain waves and breaking of convectively generated gravity waves (Ellrod & Knapp, 1992). In particular, turbulent eddies and waves with length scales of a hundred metres to several kilometres pose an important hazard to civil aviation. There is thus a great demand in aviation forecasting for reliable turbulence estimates (Sharman et al., 2014). The eddy dissipation rate (EDR), which is the cube root of the dissipation rate of turbulent kinetic energy, and hence has units of $m^{2/3}$ s^{-1}, has become the International Civil Aviation Organization (ICAO) standard for aircraft reporting and therefore the standard measure for clear-air turbulence (CAT).

A recent survey among the ECMWF forecast user community has revealed that a CAT parameter has a high priority on the user wish list, just below convection. Furthermore, we expect that an observable measure of turbulence intensity computed in the forecast will be beneficial for research purposes, in particular the development of turbulence parametrizations in the free troposphere and stratosphere. Our objective was therefore to develop a calibrated CAT parameter for the ECMWF Integrated Forecasting System (IFS) that serves the purpose of aviation forecasting as well as research in turbulence. The adopted solution was developed in a strong and useful collaboration with scientists from the German Aerospace Center (DLR). It is planned to become available later this year in IFS Cycle 47r3.

Method

We essentially follow the method presented in Sharman & Pearson (2017). This means that a certain number of turbulence predictors are projected onto the observed climatological distribution of the EDR, and then a suitable CAT parameter is defined. The method has the advantage that it can be applied to widely used predictors of CAT in aviation forecasting and to the output of the turbulence scheme of the IFS. As the IFS currently does not use a prognostic turbulence scheme for the turbulent kinetic energy, the EDR is not directly available from the IFS. The following three predictors have been included to obtain a measure of the EDR:

- **Ellrod1** The positive definite Ellrod1 index has been developed by Ellrod & Knapp (1992). It is the product of the vertical wind shear with the total deformation. The deformation terms, involving horizontal gradients, are still small at 9 km resolution compared to the vertical gradients. However, using their product with the vertical shear term has been shown to improve the correlations compared to using the vertical shear term only (Ellrod & Knapp, 1992). The Ellrod1 index provides highly valued guidance in aviation forecasting and was also shown to be the best performing index in Sharman & Pearson (2017).
- **GWD** While the Ellrod1 accounts for resolved flow features only, we also include a subgrid contribution from the drag by breaking convectively generated gravity waves. A simple approach is to scale the dissipation rate from the non-orographic gravity wave scheme (assuming a globally uniform departure wave spectrum) with the normalised vertically integrated convective heating between 500 hPa and the cloud top. The cube root of the dissipation is then in units of the EDR.
- **DISS** The total turbulent dissipation rate of the IFS in units of EDR is derived from the model's physical tendencies for horizontal momentum. It includes tendency contributions from the vertical diffusion scheme and the convective momentum transport. The largest contribution to the total turbulent dissipation is from the vertical diffusion scheme that includes dissipation due to turbulent mixing, orographic wave drag and orographic blocking (Beljaars et al., 2004).

The numerical expressions for Ellrod1, GWD and DISS are presented in detail in Bechtold et al. (2021). The computation of the Ellrod1 index increases the numerical cost of an IFS forecast by 4–5% as it requires additional inverse spectral transforms of the vorticity and the divergence fields to compute the required horizontal wind gradients.

Figure 1 shows the climatological distributions of the natural logarithm of Ellrod1, GWD and DISS as obtained from daily 24-hour hindcasts with the IFS during the first half of 2019. The distributions are valid for the 4.5–15 km atmospheric layer. Also included in

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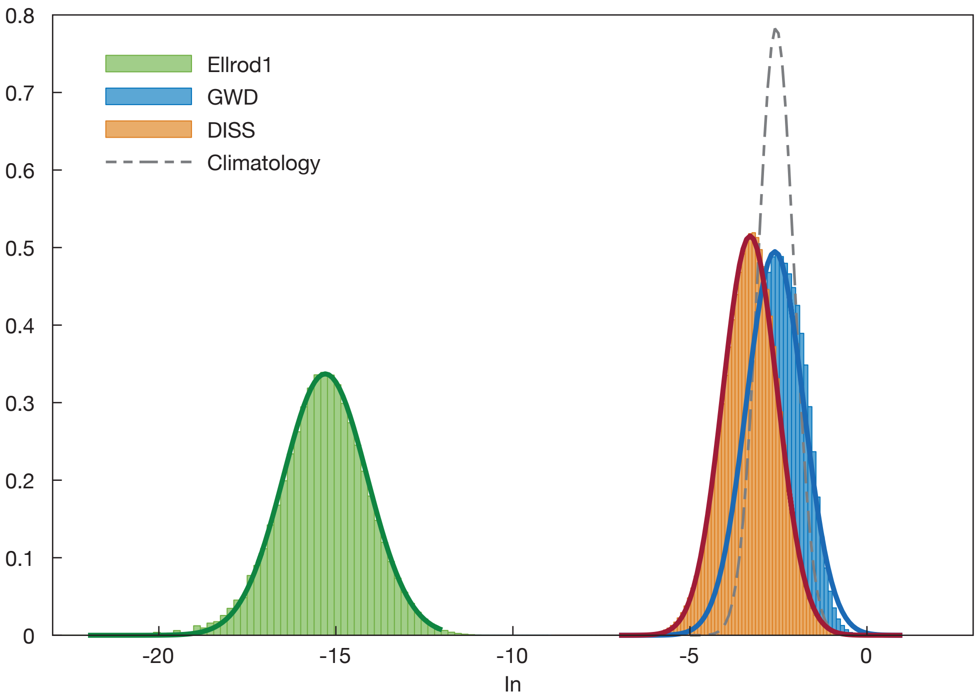

FIGURE 1 Probability density distributions of the natural logarithm of the Ellrod1 index, gravity wave drag (GWD) and turbulent dissipation (DISS) for the atmospheric layer between 600 and 150 hPa (4.5–15 km) as obtained from six months of IFS simulations for 2019 at the TCo1279 resolution (about 9 km horizontal grid spacing). The solid lines show the fitted log-normal distributions. The climatological EDR distribution is denoted by the dashed grey curve.

Figure 1 (solid lines) are the log-normal fits to the individual distributions, as well as the climatological distribution of the EDR derived from aircraft data by Sharman & Pearson (2017). We note that all parameters closely follow a log-normal law and that the distributions of GWD and DISS, which naturally have units of the EDR, are reasonably close to the climatological distribution of the EDR.

The aim of the extensive pre-computations in Figure 1 is to fit log-normal distributions for each index in order to be able to project indices on the climatological EDR. This computation has only to be done once. Then, the final step and actual forecasting of the EDR consists in computing in each forecast Ellrod1, GWD and DISS and projecting the values on the climatological EDR. The simple projection procedure, together with a table of the fitting parameters (the mean and variance of the distributions as used in Figure 1), is given in Bechtold et al. (2021).

Observations

It can be difficult to obtain calibrated EDR measurements onboard civil aircraft as the data is generally the property of the airline. We have retrieved ‘max EDR’, that is the peak EDR of 12 individual EDR measurements over a one-minute interval, from the US National Oceanic and Atmospheric Administration (NOAA) Meteorological Assimilation Data Ingest System (MADIS) public archive for aircraft data. The dataset and algorithm onboard civil aircraft to compute the EDR is thoroughly described in Sharman et al. (2014). In summary, the aircraft response to turbulent eddies with wavelengths of 10 m to 1 km is felt as bumpiness. The aircraft is more sensitive to vertical gusts than to lateral gusts, i.e. the steering is more sensitive in the vertical as aircraft are built to be stable in the lateral axis. The EDR is proportional to the root-mean-square vertical acceleration experienced by an aircraft under specific flight conditions. The EDR algorithm uses either the measured vertical accelerations or the aircraft vertical winds that are determined using the aircraft’s angles of attack and cruising speed. A Fourier transform is performed on the 8 Hz sampled vertical velocity time series (with a cruise speed of 250 m s^{-1}, this retains eddies of 30 m that can significantly affect the aircraft wings), and a von Kármán spectrum is fitted to the retrieved vertical velocity spectrum in the inertial turbulent subrange. When the algorithm detects a turbulent event, a report is generated and downlinked at a 1 min (~15 km) interval. Follow-up reports are then also generated.

In order to compare the IFS with observations, we have performed daily 24-hour forecasts for January to March 2019 and used hourly model output on the full vertical model resolution of 137 levels, but on a reduced horizontal grid of 0.3° × 0.3° to make the data volume more manageable. The comparison focuses on the height range 5–12 km, i.e. the cruising altitude, where the IFS vertical resolution is roughly 300 m. The projection of the forecasts onto the observations is done by retaining all observations 15 minutes before and after the full hour and allowing a maximum height difference between observations and model data of 160 m.

We had to account for the fact that, out of the more than

4 million observations onto which the IFS data has been projected, a large majority has zero value, while the model is producing a quasi-continuous field. We therefore included an EDR threshold of 0.005 $m^{2/3}$ s^{-1} for the observations. We were thus able to retain only 197,000 observations for the statistics. The statistics are robust, however, even for a single month.

Definitions of CAT

We have defined CAT parameters/products based on the EDR projections of the three indices, Ellrod1, GWD and DISS, as follows:

CAT1 = 0.7 x Ellrod1* + GWD*

CAT2 = 0.66 x DISS* + GWD*

CAT12 = 0.5 x (CAT1 + CAT2)

where the asterisk denotes the value of the index after the EDR projection. In addition, scaling factors have been added to better fit the aircraft observations we have used during the 3-month evaluation period. While CAT1 is essentially based on the Ellrod1 index (GWD* is relatively small), CAT2 represents the total dissipation rate of the IFS, and CAT12 is the arithmetic mean of CAT1 and CAT2.

Figure 2 shows, for the whole 3-month period, the probability distribution functions of the observations and the corresponding projected IFS data for the different EDR estimates. Both CAT1 and CAT2 underestimate the relative occurrence of weak turbulence intensities with EDR < 0.05 $m^{2/3}$ s^{-1} compared to the observations, which deviate from the log-normal law for small values. CAT2 overestimates the observed distribution for medium to strong turbulence, while CAT1 underestimates the occurrence of strong to severe turbulence with EDR > 0.3 $m^{2/3}$ s^{-1}. The best overall match with the observed distribution is obtained by a linear combination of CAT1 and CAT2.

Case study 2 March 2019

Figure 3 shows global maps of two EDR-based diagnostics for CAT on 2 March 2019 as obtained from a 0–24 h forecast with a horizontal resolution of about 9 km. The values represent averages over the whole day and the 10–12 km atmospheric layer. To illustrate the role of wind shear, isotachs of the 250 hPa wind speed have also been included in Figure 3. We notice that the global distributions of EDR are very similar between the independent products CAT1 and CAT2. Maximum daily and layer mean values of between 0.1 and 0.18 are present near the flanks of the subtropical jets and in the storm tracks, but also over orography such as the Rocky Mountains and the Himalayas. We also notice significant EDR in tropical regions,

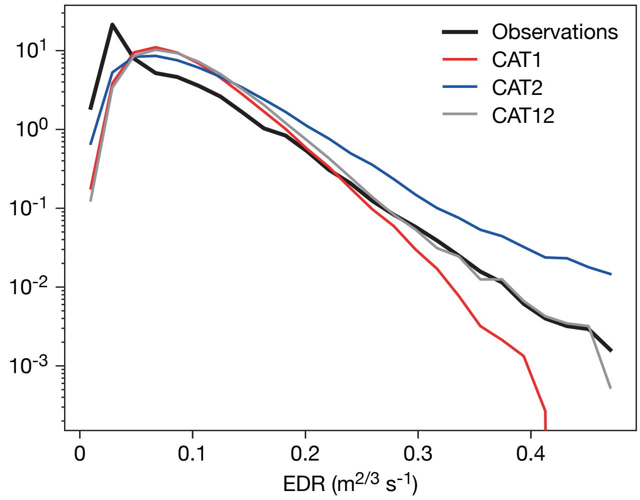

FIGURE 2 Probability density distributions of the EDR for the period January to March 2019 and for heights between 5 and 12 km, as obtained from the NOAA/MADIS observational dataset (black) and from daily 0 to 24-hour IFS forecasts projected onto the observation locations, where CAT1, CAT2 and CAT12 are as defined in the text.

especially near the equator and in convective regions over land. The convective contribution to CAT1 stems from the convective gravity wave drag, while for CAT2 it also includes a contribution from convective momentum transport.

A comparison with all non-zero EDR aircraft reports between 5 and 12 km altitude for 2 March 2019 is presented in Figure 4. The different CAT products predict the turbulence regions over the southern Rockies and northern Florida, and also the observed elevated turbulence over the central US, southern Greenland and the north-eastern Atlantic. However, while CAT1 tends to underpredict the high turbulence regions with observed EDR above 0.3 $m^{2/3}$ s^{-1}, CAT2 tends to overestimate the horizontal extension of high turbulence regions. The linear combination of CAT1 and CAT2 seems to perform best. This is also consistent with the probability density functions in Figure 2. The representativity of the observations has to be treated with some caution, however, as aircraft try to avoid and/or rapidly quit regions with strong turbulence.

Need for ensembles

We have verified the daily high-resolution forecasts of CAT during the January to March 2019 test period. However, turbulence is inherently intermittent and reliable estimates of turbulence require an ensemble approach. Therefore, we have also evaluated ensemble forecasts (ENS) of CAT, comprising a 15-member ensemble at a resolution of about 18 km that was run daily during the first two weeks of January 2019.

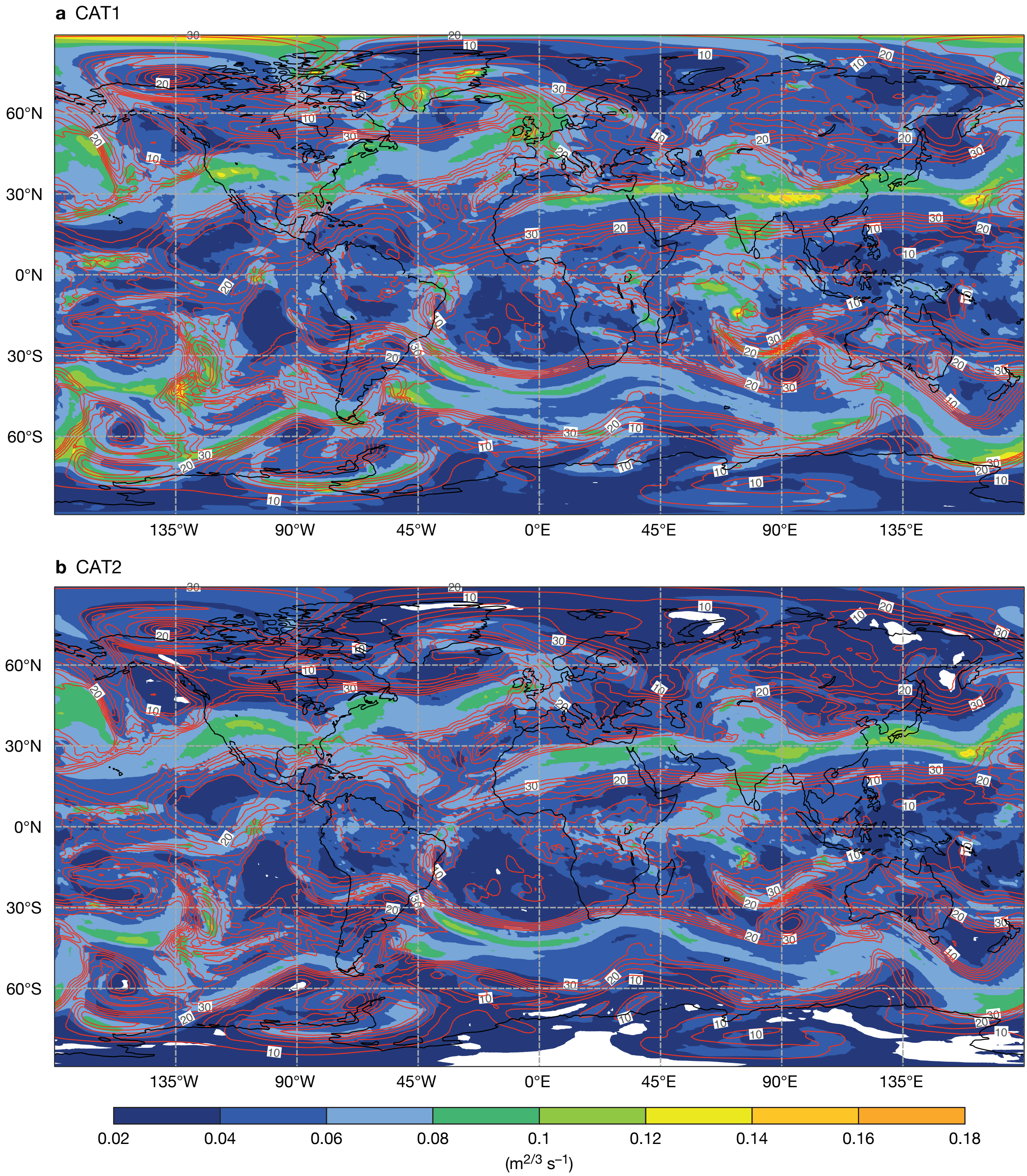

FIGURE 3 Global daily mean distributions of CAT1 and CAT2 for 2 March 2019 averaged over the 10–12 km layer from a 24-hour IFS hindcast at the TCo1279 resolution (about 9 km horizontal grid spacing). The isotachs of 250 hPa wind speed (m/s) are overlaid by red contours.

Table 1 shows the point correlations and mean absolute error (MAE) against the observations of the high-resolution forecasts for January to March 2019. For the period 1–14 January 2019, which comprises 19,600 observations, we compare the high-resolution forecasts to the ensemble forecasts. The latter are evaluated using the ensemble mean correlation and the continuous ranked probability score (CRPS). The CRPS of the ensemble against observations directly compares to the MAE of the high-resolution forecasts. All data has been reduced to a 0.3°×0.3° output grid on model levels.

The 3-month average point correlations from the high-resolution forecasts with the observations is

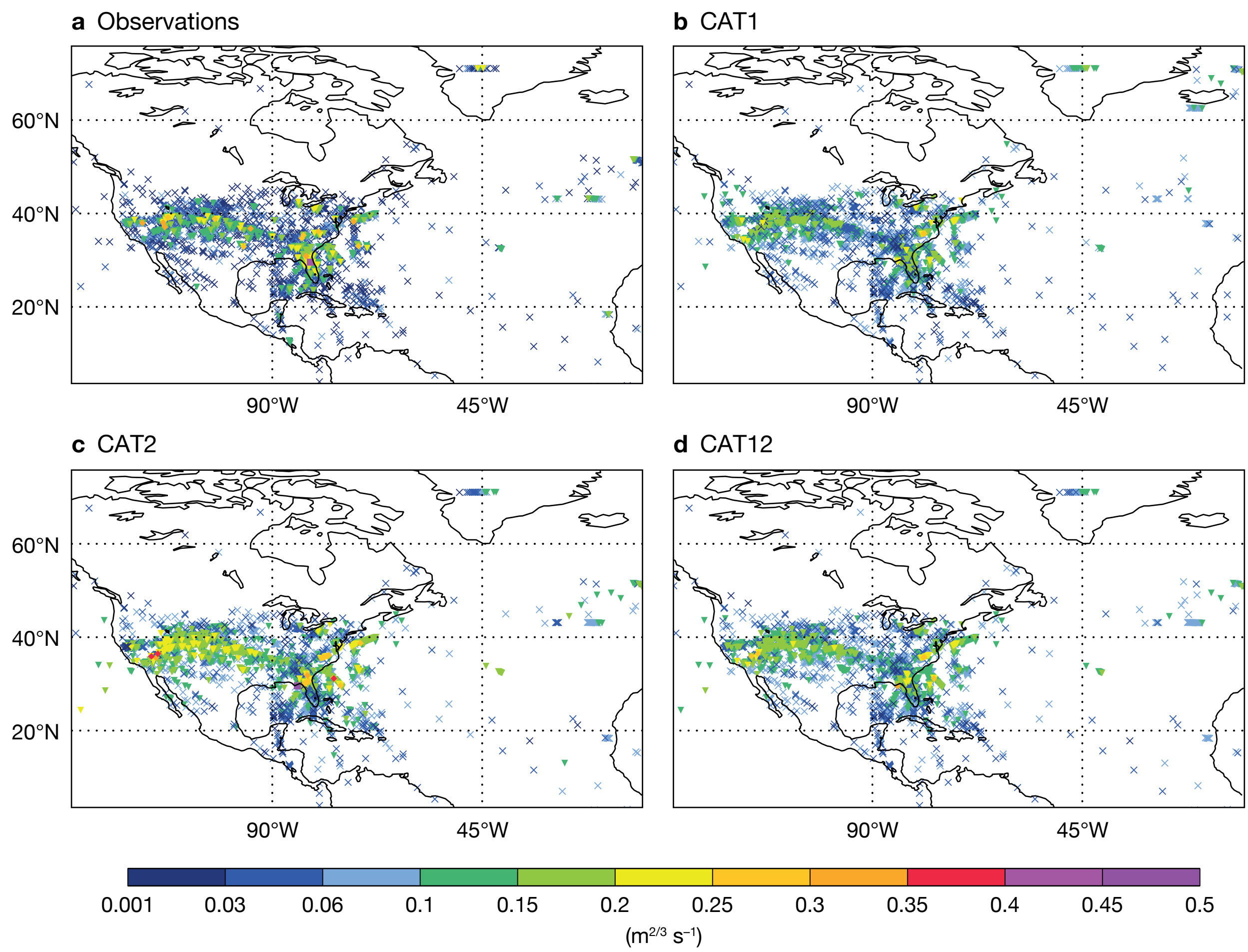

FIGURE 4 EDR for 2 March 2019 including (a) all available observations between 5 and 12 km, (b) CAT1, (c) CAT2 and (d) a linear combination of CAT1 and CAT2 as defined in the text. The CAT values are taken from a 0 to 24-hour hindcast at the TCo1279 resolution (about 9 km horizontal grid spacing). Colours (see legend) and symbols are used to denote the strength of the EDR, with different symbols for each 0.1 $m^{2/3}$ s^{-1} EDR interval.

0.33 for CAT1, 0.30 for CAT2 and 0.35 for CAT12, while the MAE is around 0.05 $m^{2/3}$ s^{-1}. The errors are slightly higher for CAT2 compared to CAT1, which is expected, as CAT2 is based on model tendencies and therefore more variable than CAT1, which is based on state variables. For the shorter January test period, the correlations attain values between 0.32 for CAT2 and 0.36 for CAT12, while the MAE remains around 0.05 $m^{2/3}$ s^{-1}. Comparing these values to the ensemble, we see that the ensemble performs significantly better, with ensemble mean correlations attaining 0.37 for CAT2 and up to 0.40 for the combined product CAT12, while the CRPS is around 0.03 $m^{2/3}$ s^{-1}. We therefore think that the ensemble forecasts are of reasonable reliability, given that turbulence intensity is typically classified in EDR intervals of 0.1 $m^{2/3}$ s^{-1}. The obtained point correlations might still appear relatively low, but they have to be put into perspective with point correlations of around 0.53 obtained for 10-metre wind speed forecasts over land, and point correlations of 0.2–0.4 obtained

EDR parameter	Corr HRES Jan–Mar	MAE HRES Jan–Mar	Corr HRES 1–14 Jan	Corr ENS 1–14 Jan	MAE HRES 1–14 Jan	CRPS ENS 1–14 Jan
CAT1	0.33	0.050	0.33	0.38	0.049	0.030
CAT2	0.30	0.057	0.32	0.37	0.054	0.034
CAT12	0.35	0.045	0.36	0.40	0.049	0.029

TABLE 1 Verification of different EDR parameters against observations for the high-resolution forecasts (HRES - grid spacing of about 9 km) for January–March 2019 and for HRES and the ensemble forecasts (ENS - grid spacing of about 18 km) for the period 1–14 January 2019. Verification statistics are correlation (Corr), mean absolute error (MAE) and continuous ranked probability score (CRPS).

when verifying forecasts of daily rainfall accumulations over tropical land against synoptic observations.

Outlook

We think there is now sufficient evidence that a clear-air turbulence (CAT) diagnostic based on the eddy dissipation rate (EDR) will be a useful addition to the standard IFS output for both forecasters and research in turbulence, particularly when used in the context of ensembles. Such a turbulence diagnostic will also be interesting for the next climate reanalysis, ERA6.

We have put CAT based on the total dissipation rate (referred to as CAT2 in the article) into IFS Cycle 47r3, which is expected to become operational in the autumn of 2021. The diagnostic will be available on model levels for the high-resolution forecast and the ensemble, therefore roughly satisfying the 0.1° horizontal and 300 feet vertical resolution requirements of the turbulence guidance product that is in development for the International Civil Aviation Organization by 2030 (Kim et al., 2018). In the future we might also access real-time EDR data as provided by the International Air Transport Association (IATA) for forecast verification and possibly data assimilation.

The total dissipation rate is a more useful CAT predictor in the planetary boundary layer than the Ellrod1 index. It also avoids the increased computational burden of 4% that is associated with the computation of the horizontal gradients in the latter. However, both CAT1 and CAT12 can be computed online by internal users of the IFS from Cycle 47r3 onward under optional computational flags and may be turned on operationally as part of a later upgrade. Finally, the detailed information provided in the Technical Memorandum by Bechtold et al. (2021) should enable users to also compute offline an additional CAT product based on Ellrod1 and enable advanced postprocessing using non-linear regression and/or machine learning.

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ESA Contract Reports

Weston, P., P. de Rosnay & **S. English**: GRDS test-bed plan. *Nov 2020*

Weston, P. & **P. de Rosnay**: Quarter 1 2021: Operations Service Report. *April 2021*

Weston, P., P. de Rosnay & **S. English**: GRDS test-bed report. *May 2021*

Weston, P. & **P. de Rosnay**: Quarter 2 2021: Operations Service Report. *July 2021*

EUMETSAT/ECMWF Fellowship Programme Research Reports

56 **Lean, K.** & **N. Bormann**: Using model cloud information to reassign low level AMVs for NWP. *June 2021*

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Sep 13–17	Annual Seminar 2021
Sep 20–24	19th Workshop on high-performance computing in meteorology
Oct 4–6	Scientific Advisory Committee
Oct 4–7	Training course: Use and interpretation of ECMWF products
Oct 6	Advisory Committee of Co-operating States
Oct 27–28	Finance Committee
Oct 28	Policy Advisory Committee
Nov 4	Extraordinary session of Council
Nov 15-18	ESA-ECMWF workshop on machine learning for Earth system observation and prediction
Dec 2–3	Council

2022 dates	
Feb 14–18	Radio Frequency Interference 2022 workshop
Apr 11–13	Advisory Committee for Data Policy
Apr 26–27	Finance Committee
Apr 27	Policy Advisory Committee
May 9–13	Workshop on model uncertainties
Jun 7–11	Using ECMWF's forecasts (UEF2022)
Jun 28–29	Council
Oct 31 – Nov 4	Sixth WGNE workshop on systematic errors in weather and climate models

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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.

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