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 The ECMWF Newsletter is not peer-reviewed.

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Value to society

At ECMWF, we pride ourselves on pushing the boundaries of weather science to produce forecasts of ever higher quality. It is important to remember that this is not an end in itself. The ultimate test for the progress we make is its usefulness to society. Severe weather and the impact it can have on people and economies are stark reminders of the value of timely and accurate weather forecasts. Tropical cyclone Idai, which hit Mozambique in March 2019, is an example of a storm that brought multiple hazards, from high winds and a storm surge to extreme rainfall causing widespread flooding. As described in this Newsletter, ECMWF worked with partners at the Universities of Reading and Bristol and the UK Government to support the humanitarian response to the disaster. Briefings drew on flood forecasts from the Global Flood Awareness System, which is part of the EU-funded Copernicus Emergency Management Service and uses rainfall from our ensemble forecasts as input.

Our rules allow us to provide a full set of relevant data to any Member of the World Meteorological Organization (WMO) facing severe weather. But weather forecasts are of great value in other ways too: they routinely support planning and decision-making in many sectors of the economy as well as the day-to-day lives of citizens. Our forecasts are made available in full to our Member and Co-operating States as well as to a wide range of other users, and a significant subset is freely available to all WMO Members. The wide use of our forecasts means that the substantial progress made in the June upgrade of ECMWF's Integrated Forecasting System (IFS) matters. The scorecards for IFS Cycle 46r1 presented in this Newsletter speak for themselves: significant improvements have been achieved across regions and parameters, in both our ensemble forecasts and our high-resolution deterministic forecasts. The upgrade also makes new output parameters available, including extended-range products for 2-metre temperature and total precipitation to provide earlier indications of severe weather.

Making our data useful requires more than the production of timely, high-quality forecasts. The data need to be handled, stored and disseminated efficiently. Improving the systems that do this is a major, continuous stream of work. A lot of it takes place outside the limelight. Progress reported in this Newsletter includes a major upgrade of ECMWF's Fields Database software library, which makes the short-term storage of meteorological fields much more resilient and flexible. This will help to ensure the timely dissemination of forecasts. A new, more efficient and modern product generation software package has also been implemented. Other user-oriented developments include a new distribution channel for ECMWF software and the development of a user forum for the EU-funded Copernicus Climate Change Service implemented by ECMWF. It is only by continuously updating and improving all our systems that we can maximise the usefulness of our data to society.

Florence Rabier
Director-General

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Editor Georg Lentze • **Typesetting & Graphics** Anabel Bowen

ECMWF works with universities to support response to tropical cyclone Idai

Linus Magnusson, Ervin Zsoter, Christel Prudhomme, Calum Baugh, Shaun Harrigan (all ECMWF),
Andrea Ficchì, Rebecca Emerton, Hannah Cloke, Liz Stephens, Linda Speight (all University of Reading, UK)

The tropical cyclone season of 2019 in the southern Indian Ocean was one of the most active on record, with 15 tropical storms. On 15 March, tropical cyclone Idai made landfall in Mozambique, causing around a thousand fatalities. This made Idai the deadliest cyclone in the southern Indian Ocean for more than 100 years. ECMWF's forecasts predicted the landfall location and extreme precipitation and winds with high confidence about 5 days ahead of landfall. At the same time range, flood forecasts based on ECMWF's precipitation forecasts indicated a moderate risk of severe flooding, rising to a very high risk after landfall. ECMWF worked with partners at the Universities of Reading and Bristol and the UK Government to support the humanitarian response to the disaster.

Meteorology

On 4 March, a tropical depression made landfall on the coast of Mozambique and propagated northwest. The depression brought anomalous rainfall and led to deadly floods across central Mozambique and southern Malawi from 5 March. On 8 March, the depression turned eastward, and on 9 March it moved back over the ocean. On 10 March, the depression intensified and became a tropical cyclone. A few days later, it started to propagate southwest and intensified further. The cyclone made landfall near Beira on 15 March and later moved further inland bringing heavy rainfall also to Zimbabwe. When Idai reached the coast of Mozambique, it brought winds of up to 170 km/h and a significant storm surge of about 4.5 m around Beira. According to NASA-GPM data, rainfall totals between 3 and 17 March reached 400–600 mm over much of the Sofala and Manica provinces of Mozambique, between Beira and Chimoio. These extreme rainfall amounts caused widespread flooding around most rivers in the region, including the Pungwe, Save, Buzi, Revue and Shire Rivers. According to the United Nations, an estimated 1.85 million people were affected by Cyclone Idai in Mozambique and required humanitarian assistance.

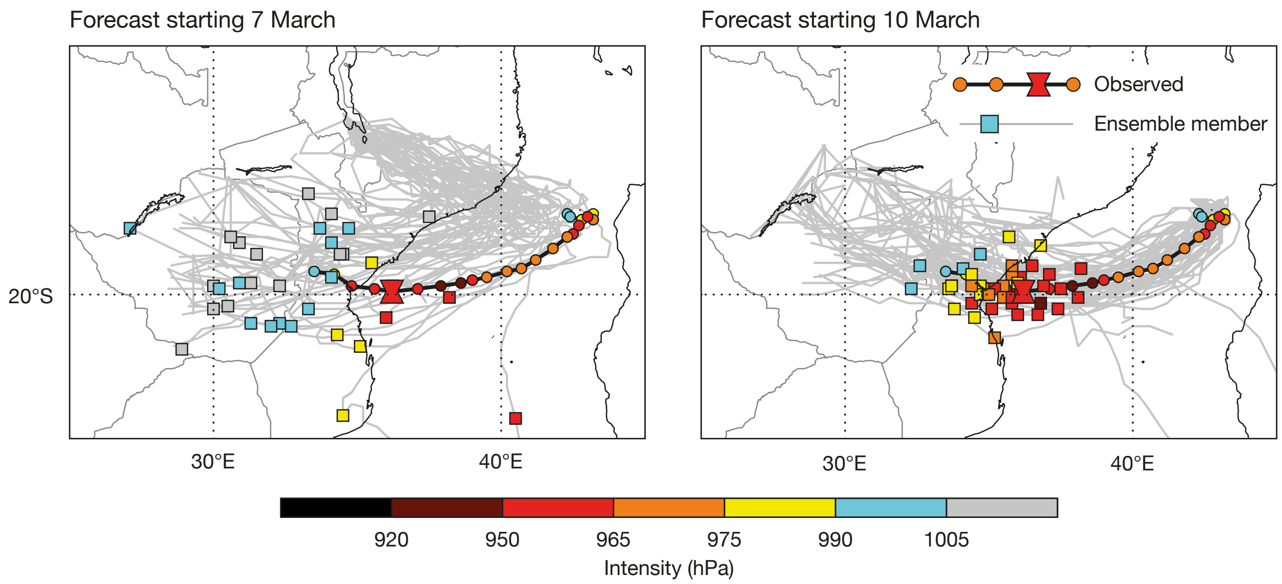
ECMWF's forecasts

ECMWF's ensemble forecasts (ENS) from 4 March signalled an increased probability of a tropical cyclone between mainland Africa and Madagascar for the following week. This coincides with the first appearance of the depression. In the forecast from 7 March, many ensemble members captured the depression's reappearance over sea and subsequent intensification. There was, however, large uncertainty in the track forecast, and the predicted turning point was too far to the west, leading to a predicted landfall location too far north.

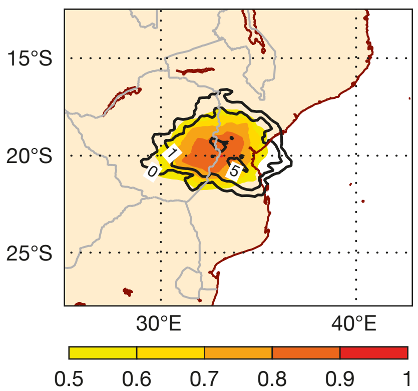
On 10 March, when the depression intensified, the forecast became much more confident on the landfall location. From this point on, the ensemble forecasts predicted extreme rainfall in southern/central Mozambique and also the severe winds over Beira with high confidence.

GloFAS flood forecasts

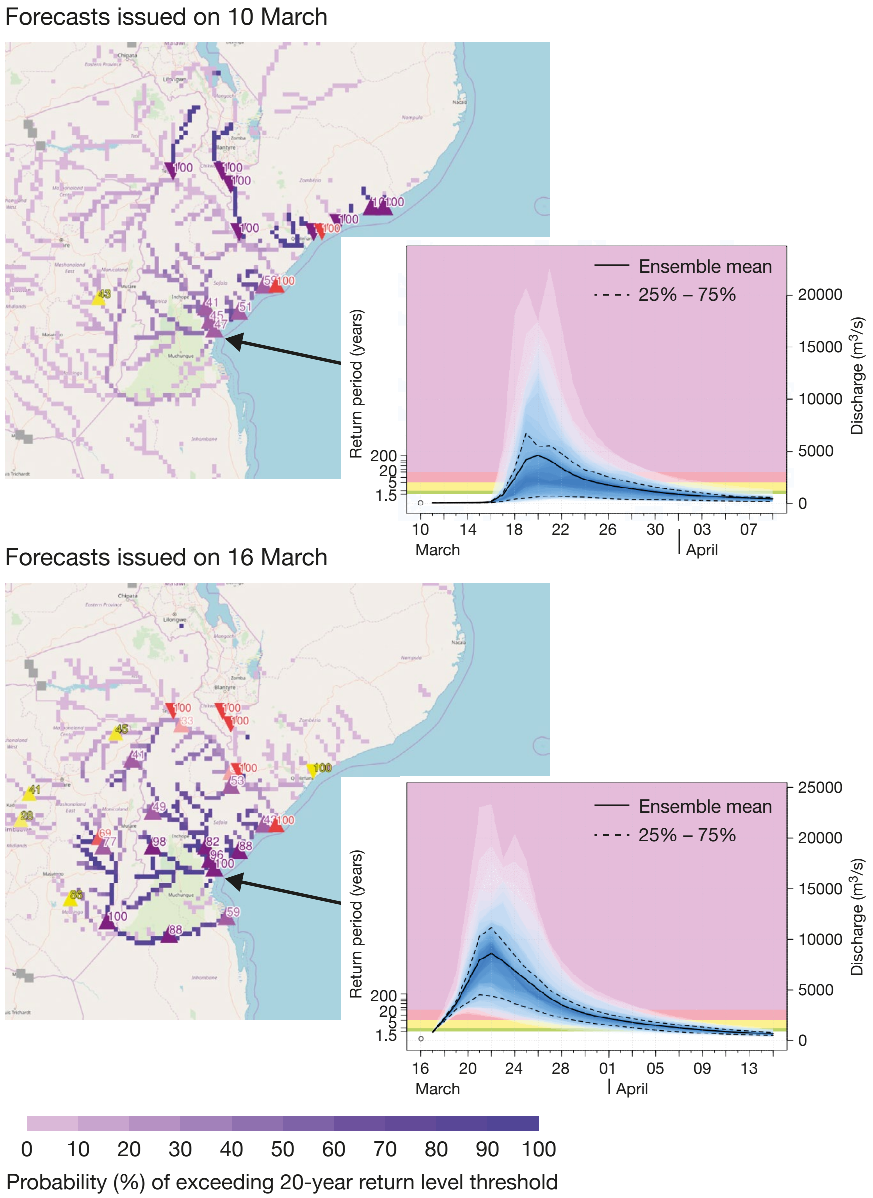
Forecasts from the Global Flood



ECMWF's track, position and intensity forecasts for Idai. The plots show forecasts starting at 00 UTC on 7 March 2019 (left) and 00 UTC on 10 March 2019 (right). The squares indicate position and intensity forecasts for 12 UTC on 14 March. The black line shows the observed track ('Best Track' estimate), while the observed position and intensity at 12 UTC on 14 March is indicated by the hourglass symbol.



Extreme Forecast Index (EFI) and Shift of Tails (SOT) for precipitation. There was a clear signal in the EFI (shading) and SOT (contours) for total precipitation on 15 March in the area affected by Cyclone Idai in the forecast from 00 UTC on 10 March.



GloFAS flood risk forecasts. The shading of the rivers in the maps shows the predicted probability (in %) of the streamflow exceeding the severe flood alert threshold (20-year return period) over the next 30 days in forecasts starting on 10 March (top) and 16 March (bottom). The triangles denote so-called reporting points, where the predicted evolution of the ensemble discharge, with the probability of exceeding different thresholds, is available on the GloFAS website. Upward pointing triangles indicate rising flow, downward pointing triangles indicate receding flow. The inset charts show the discharge evolution for the reporting point location indicated in the map (the Pungwe River at Beira, 19.65°S and 34.65°E).

Awareness System (GloFAS, www.globalfloods.eu), which is part of the EU-funded Copernicus Emergency Management Service (CEMS), use rainfall from ENS as input. From 10 March, as forecasts of the landfall location of Cyclone Idai became more certain, GloFAS forecasts showed moderate probabilities (> 40%) of severe flooding around Beira and for the most affected rivers in Mozambique (Pungwe, Buzi, Revue and Save). These probabilities did not increase but fluctuated in the following days, in line with the precipitation forecasts, until landfall on 15 March. On 12 March, severe flooding for the Pungwe River at Beira was predicted with a probability of more than 50%, while lower probabilities of severe flooding were indicated for the other main rivers. Only once Idai had made landfall and large rainfall amounts were observed or predicted by short-range forecasts (from 16 March), probabilities of severe flooding became very high (> 90%) across the whole region. At that point water levels were still increasing and flood peaks were consistently predicted to happen 3 to 7 days ahead.

Response

In the immediate aftermath of the landfall of Cyclone Idai, the CEMS-Floods team at ECMWF worked with the University of Reading, the University of Bristol, and the UK Government (Department for International Development, DFID) to provide humanitarian agencies involved in the response to Cyclone Idai with scientific information on flood hazard and population exposure.

Forecasts from GloFAS were used in combination with satellite imagery from Copernicus and flood extent maps from the University of Bristol to identify where, when and for how long flooding may occur, as well as where people may be impacted. Every two days, a flood emergency briefing was sent to DFID and shared with partners, including the United Nations Office for the Coordination of Humanitarian Affairs (UN OCHA), to help them plan their humanitarian actions.

UN OCHA and DFID subsequently asked ECMWF and the Universities of Reading and Bristol to provide flood briefings for Cyclone Kenneth from 24 April 2019, ahead of its landfall in northern Mozambique on the evening of 25 April. DIFD told the team that the briefings had been “well received” and that “UN humanitarian response actors stated that the reports produced were tremendously helpful”.

The Extreme Forecast Index for water vapour flux

David Lavers, Ivan Tsonevsky, David Richardson, Florian Pappenberger

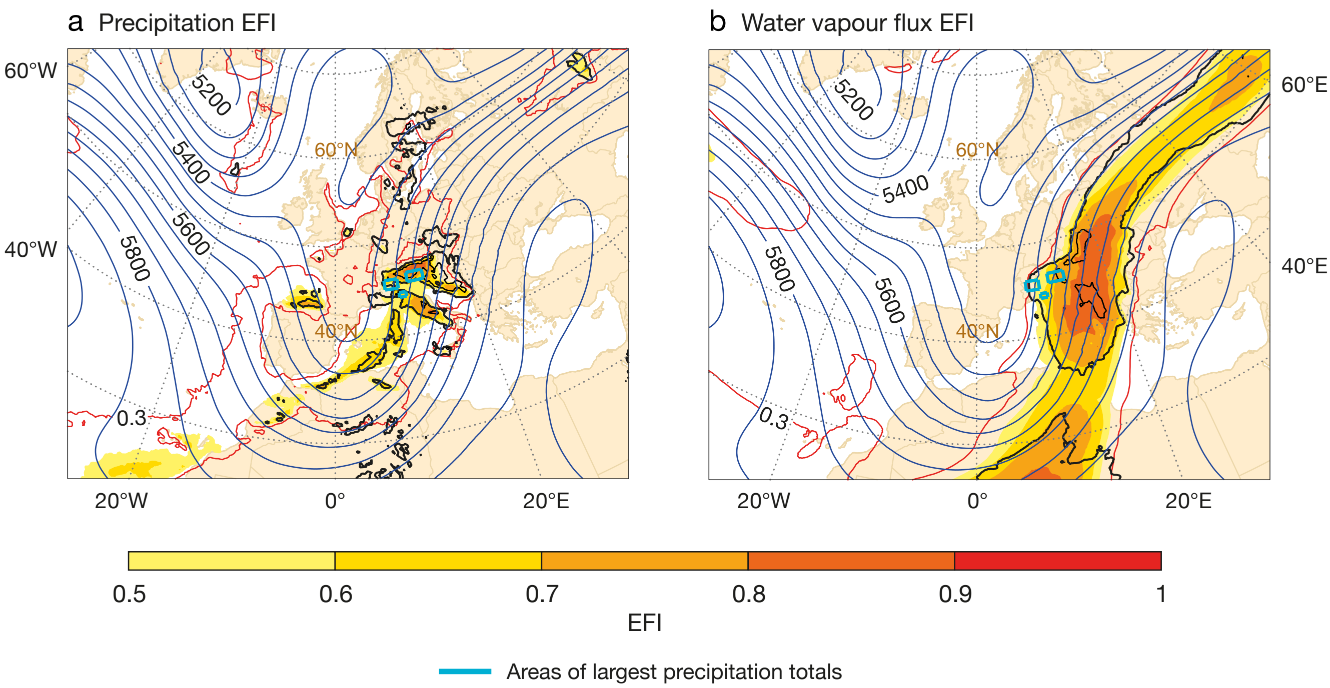
In the upgrade of ECMWF's Integrated Forecasting System to IFS Cycle 46r1, implemented in June 2019, the Extreme Forecast Index (EFI) for water vapour flux became operational. This new EFI parameter can provide an improved understanding of the synoptic-scale processes behind an extreme hydro-meteorological event. In addition, in some cases it can enable earlier awareness of extreme precipitation on the west coasts of mid-latitude continents than the EFI for precipitation.

Following evaluation of the precipitation and water vapour flux EFI across western Europe and western North America, the water vapour flux EFI was found to complement the precipitation EFI by highlighting large-scale water vapour transport in the atmosphere. It was also shown to better identify extreme precipitation in the late medium-range forecast horizon. This is because of its large-scale characteristics and hence higher predictability, which leads to flux predictions being more skilful at these lead times. Conversely, precipitation is linked to smaller-scale processes, such as the cloud microphysics and processes linked with the land surface topography. Precipitation forecasts are therefore less skilful in identifying extremes at these longer lead times. During winter 2018/19, these EFI maps were run in experimental mode and evaluated by users, including the Flood Forecasting Centre based at the UK Met Office and the Atmospheric Rivers Reconnaissance field campaign, following which the EFI for water vapour flux was made operational.

An example in Italy

From 27 to 30 October 2018, northern Italy experienced multiple weather hazards including extreme precipitation and flooding. A few stations reported more than 300 mm in 24 hours. This was the result of a large-scale trough over the western Mediterranean, from which a deep cyclone developed and moved from Sardinia to the north. More details on this event can be found in an article by Linus Magnusson and Luigi Cavaleri (Institute of Marine Science, Italy) in ECMWF Newsletter No. 158. In the figure, the EFI maps shown for precipitation and water vapour flux are centred on the event on forecast days 7 to 9. In this case, the precipitation forecast is able to identify the location of the event, as shown by the co-location of high EFI values and the areas with the highest precipitation totals, while the water vapour flux EFI highlights the large-scale nature and atmospheric structure and thus provides a synoptic context for forecast users.

An article by David Lavers et al. published in *Weather and Forecasting* (doi: 10.1175/WAF-D-17-0073.1) gives more details on the evaluation of the precipitation and water vapour flux EFI across western Europe and western North America.



Extreme Forecast Index and Shift of Tails for precipitation and water vapour flux. EFI (shading) and SOT (black contours) in the forecast from 00 UTC on Monday, 22 October 2018 for 72-hour total precipitation and water vapour flux valid from 00 UTC on 28 October to 00 UTC on 31 October 2018. The blue contours show the 500 hPa geopotential at T+180 hours valid at 12 UTC on 29 October 2018. The cyan lines indicate the areas affected by the largest precipitation totals.

Upgrade makes Fields Database more resilient

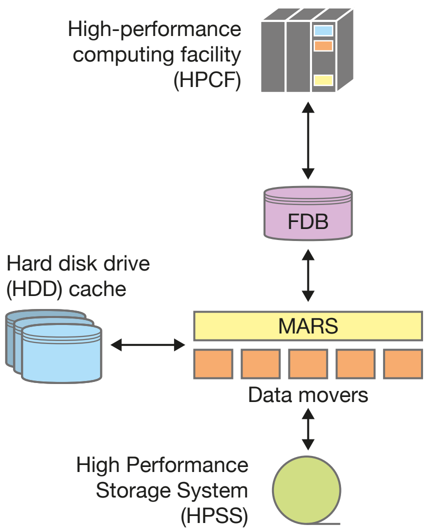
Tiago Quintino, Simon Smart, Baudouin Raoult, Manuel Fuentes, Matthias Zink, Sebastien Villaume, John Hodkinson, Anna Mueller-Quintino, Axel Bonet-Cassagneau, Oliver Treiber, Christian Weihrauch

A major upgrade of ECMWF's Fields Database (FDB) software library makes the short-term storage of meteorological fields much more resilient and flexible, thus minimising delays in the dissemination of forecasts. The change to the new version (FDB5) for time-critical operations was implemented as part of the upgrade of the Integrated Forecasting System to IFS Cycle 46r1, described in this Newsletter. The FDB is an internally provided service, used as part of ECMWF's weather forecasting software stack. It operates as a domain-specific object store, designed to store, index and serve meteorological fields produced by the IFS. It acts as the first level of storage for recently created objects, efficiently receiving all model output and derived post-processing fields and making them available to the post-processing tasks in the forecast pipeline, as well as to users.

The FDB serves as a 'hot-object' cache inside the high-performance computing facility (HPCF) for the Meteorological Archival and Retrieval System (MARS). MARS makes many decades of meteorological observations and forecasts available to a wide range of end users and operational systems. Around 80% of MARS requests are served from the FDB directly, typically for very recently produced data. A subset of this data is later re-aggregated and archived into the permanent archive for long-term availability.

Every day, more than 200 TiB of data is written to and 370 TiB is read from the FDB, including both core operations and research activities. More than 100 TiB of this data is then moved to MARS for archiving. At any given time, the total content of the operational FDB is estimated to be between 4 and 5 PiB.

The fourth version of the FDB (FDB4) was one of the most venerable pieces of software still in operations, with code containing references to the original Cray machine from more than 20 years ago! As such, it had quirks that showed its age and restricted the operational forecast system. For example, FDB4 did not handle some error conditions



The place of the FDB in ECMWF's supercomputing and data handling infrastructure. The FDB works as a data cache layer between the HPCF and MARS. Most data requests are handled from the FDB, with only a few passing through to the MARS disk cache (HDD cache) and HPSS tape system.

well, which could lead to corruption of indexing information or the data. Furthermore, only one forecast component could write to each database within FDB4 at any one time without risking index corruption, which placed severe constraints on the design of the forecast pipeline and suites.

Main benefits

To address these deficiencies, development of FDB5 began in 2015. This version brings several improvements:

1. Most importantly, FDB5 is now a transactional store designed in line with ACID (Atomicity, Consistency, Isolation, Durability) database principles. This means it is robust and resilient to failures. A model or system failure does not corrupt existing data, and the model is able to restart where it stopped. This saves critical minutes in the event of a catastrophic model crash and restart, minimising forecast delivery delays.
2. By improving the consistency semantics, some restrictions on ECMWF's workflows have been lifted, enabling more flexible suite design. For example, FDB5 is no longer restricted to a single serial writer per database.
3. FDB5 supports direct-to-MARS archiving, which will reduce overall congestion of the HPCF storage system by avoiding the creation of intermediate files when archiving to MARS. Moreover, FDB5 has stronger verification of the data and disallows fields which are not recognised by MARS.
4. FDB5 separates access via a configurable front-end API from storage back-ends. This creates a great deal of flexibility to develop and configure the system to make use of new storage technologies and paradigms without having to explicitly modify the forecasting workflow.
5. FDB5 should have slightly better performance for the same hardware thanks to an improved indexing scheme for data retrievals, although this improvement is likely to be noticeable for very large datasets only, such as ECMWF's operational forecasts.
6. FDB5 makes the I/O software stack more flexible and adaptable to new technologies, such as object-stores and non-volatile storage class memories (NVRAM).

Bringing the newly developed FDB5 into operational use took some time. Existing components of the forecast pipeline depended on and were hard-wired to use FDB4. In particular, the previous Product Generation software (ProdGen) needed to be retired and replaced with a newer system (pgen) before FDB5 could be brought into time-critical operations. Although improved performance was not necessarily the main goal of the development, the adoption of FDB5 into time-critical operations, along with corresponding changes to the software pipeline, have saved 50% of the time spent in product generation I/O.

OpenIFS user meeting held at the University of Reading

Marcus Köhler, Gabriella Szépszó, Glenn Carver (all ECMWF),
Suzanne Gray, Robert Plant (both University of Reading)

The fifth OpenIFS user workshop was held from 17 to 21 June 2019 at the Department of Meteorology, University of Reading, on 'The Impact of Moist Processes on Weather Forecasts'. The meeting attracted 60 scientists from institutes in Europe and further afield. It was organised around case-study-based exercises using OpenIFS run on ECMWF's high-performance computing facility.

The OpenIFS activity at ECMWF (https://confluence.ecmwf.int/oifs/) provides a supported version of the operational Integrated Forecasting System (IFS) model for research and education. User workshops are an opportunity for scientists to interact, present their work with OpenIFS and learn more about ECMWF. Each meeting focuses on an active research area at ECMWF with invited and contributing presenters.

Training and research

In response to feedback from previous workshops, this year the first day of the workshop was dedicated to lectures and exercises designed to teach participants more about the model itself. Several ECMWF scientists gave lectures on the spectral method, the semi-Lagrangian dynamical core, the radiation scheme and lake modelling parametrization. The latter two talks highlighted new aspects of the new release of OpenIFS based on IFS Cycle 43r3. The practical exercises on that day were designed for participants who were new to OpenIFS or had very limited user experience.

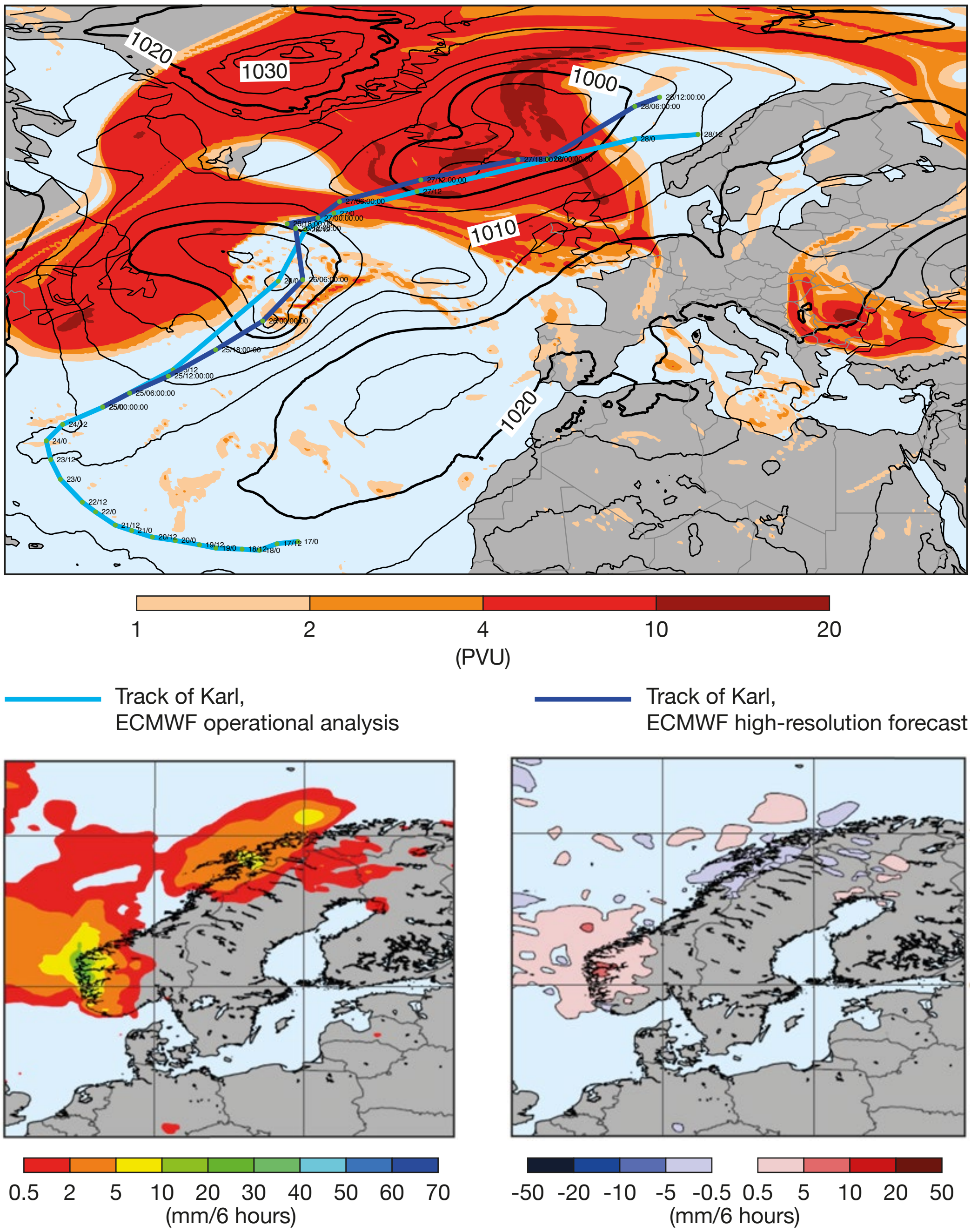
The scientific programme began on 18 June and was opened by Paul Williams from the Department of Meteorology, University of Reading, and Andy Brown, Director of Research at ECMWF, who gave overviews of research under way at both institutes. Each morning featured a combination of invited and contributed presentations. The high-quality talks by nine invited speakers and ten contributing speakers and the 14 poster presentations provided examples of the diverse activities under way with the OpenIFS models. The launch event for the new 'OpenIFS@Home' facility also took place at the workshop. David Wallom, of the Oxford e-Science Centre, described how OpenIFS can now be run on volunteers' personal computers to generate ensembles with many thousands of members for new research possibilities. As a demonstration, during the workshop a 2,000-member ensemble was distributed to public volunteers, and preliminary results were shown on the final day of the workshop.

The afternoons were devoted to running OpenIFS using a forecast case study taken from the NAWDEX field campaign (the North Atlantic Waveguide and Downstream impact Experiment, https://www.pa.op.dlr.de/nawdex/index.html). The campaign followed the development of tropical storm Karl as it transitioned to an extratropical system. To explore the role of physical processes, the model was modified to allow the definition of a three-dimensional 'box' in which the impact of radiation, cloud and convection processes could be increased or decreased. Participants worked in teams with guidance from experienced researchers and devised experiments to understand the role of these processes in the model forecasts of the resulting extreme precipitation over Scotland and Norway.

Outcomes

The workshop made the user community aware of many improvements and new features in the soon-to-be-released OpenIFS 43r3 version. The exercises provided an opportunity for training and first-hand experience with the new model. Beyond these developments within ECMWF, the workshop showcased external developments, for instance the use of OpenIFS as part of the forthcoming EC-Earth4 community Earth system model; coupling

Group photo in the Weather Room at ECMWF. Sixty scientists from institutes in Europe and beyond took part in the workshop.



Focus on extra-tropical transition of tropical storm Karl. The top panel shows the analysis of mean sea level pressure (contours, in hPa) and potential vorticity at the 320 K potential temperature level (shading) at 00 UTC on 26 September 2016 as well as the track of tropical storm Karl before and after extratropical transition in September 2016. Increasing the convective temperature tendencies by 50% during the first 24 hours of its extratropical phase increased the precipitation rate over parts of Norway by 5 mm/6 hours, in 66-hour forecasts valid at 18 UTC on 27 September 2016. The control experiment is shown in the bottom-left panel, the difference in the bottom-right panel. *Figure courtesy of Victoria Sinclair, Guokun Dai, Jian-Feng Gu, Ying Li and Jun Xu*.

OpenIFS to 3D ocean models such as FOCI-OpenIFS; and the generation of initial conditions using the AutoSubmit software tool. In oral and poster presentations, the role of diabatic processes in both mid-latitude and tropical forecasting errors was explored. The discussions continued during tea and lunch breaks, and the user community presented examples of how OpenIFS is applied as a research and teaching tool in idealised experiments and in forecasting case studies. Finally, it was shown that OpenIFS can run on a wide variety of platforms, including large numbers of volunteer PCs and even on four Raspberry Pi microcomputers! Early feedback suggests that participants appreciated the "good set of speakers at the workshop" and the "opportunity for interaction between ECMWF scientists and OpenIFS users".

The workshop was organised jointly by the Department of Meteorology at the University of Reading and ECMWF. It would not have been possible without financial support from the EU ESiWACE programme, the European Geophysical Union, the Department of Meteorology at the University of Reading, the University of Reading's Research Endowment Trust Fund, and ECMWF. The organisers would like to thank all those who helped.

SAPP Optional Programme users meet at ECMWF

Jordan Rice, Cristiano Zanna, Umberto Modigliani

The first user workshop in support of the SAPP Optional Programme was successfully held at ECMWF on 13 and 14 June. More than 25 representatives from 14 Member and Co-operating States attended the event. The participants were introduced to the SAPP system, its key features and its operational use at ECMWF. The workshop included live demonstrations of SAPP in operation. Attendees also received a tour of the recently developed online user documentation in the SAPP Confluence Space (https://confluence.ecmwf.int/display/SAPP/SAPP+Home). A discussion session enabled them to share experiences and feedback based on initial tests in their local operating environments.

At the workshop, ECMWF and the user community discussed and agreed plans for future collaborative work in support of the SAPP Optional Programme. ECMWF agreed to improve the way data extractions are modified to make it easier for users to configure SAPP to their specific requirements. For example, SAPP is currently configured to extract data every six hours, but users may require hourly extractions. ECMWF and the user community also agreed to collaborate on SAPP decoder development. The SAPP decoders are Python/FORTRAN programmes designed to convert data from one known observation type and data format (e.g. data from a buoy) to a consolidated BUFR format. Establishing channels for collaborative work such as this, with the user community at the heart of the decision making, was one of the main aims of this workshop.

Initial feedback from participants has been very positive and constructive. Such feedback is extremely valuable as it helps ECMWF to deliver excellent user support. We now look forward to holding a second workshop, which has been pencilled in for early 2020.

The workshop was recorded and live-streamed to remote attendees. All presentation material and recordings are available via the new SAPP Confluence Space. Please note that access to the SAPP Confluence Space and user support is limited to Member and Co-operating States which have chosen to participate in the SAPP Optional Programme.

What is SAPP?

The Scalable Acquisition and Pre-Processing (SAPP) system is the ECMWF operational acquisition and pre-processing system for observations and other input data. It is an essential component of ECMWF’s Integrated Forecasting System (IFS), delivering timely observational data in BUFR format to the data assimilation system.

Group photo. The first workshop was attended by more than 25 representatives from 14 Member and Co-operating States

About the SAPP Optional Programme

A couple of years ago, some Member and Co-operating States declared an interest in installing SAPP in their own operational processing environments. Following an initial trial phase, in December 2018 the ECMWF Council approved the Optional Programme supporting the provision of SAPP to participating states. This means only the Member and Co-operating States that have chosen to participate in the Optional Programme will be provided with SAPP user support, including any workshops or online documentation.

New observations since April 2019

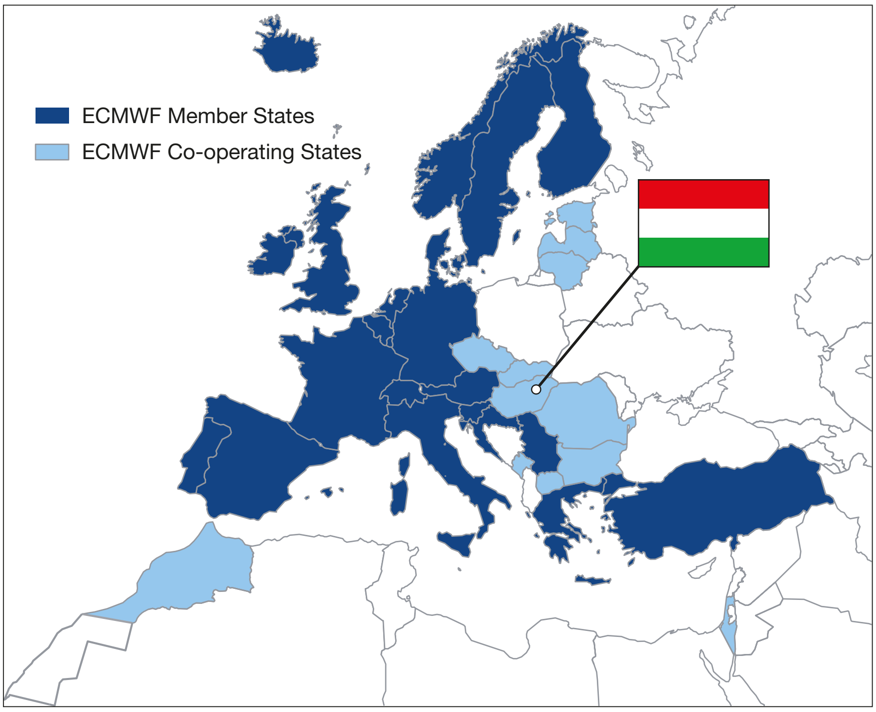
The following new observations have been activated in the operational ECMWF assimilation system since April 2019.

Observations	Main impact	Activation date
SMOS neural network soil moisture	Soil moisture	11 June 2019
Atmospheric Motion Vectors from Metop-C AVHRR imagery (single-satellite product)	Tropospheric wind	25 June 2019

25 years of cooperation between the Hungarian Meteorological Service and ECMWF

István Ihász (Hungarian Meteorological Service), Umberto Modigliani (ECMWF)

Twenty-five years ago, on 1 July 1994, the co-operation agreement between Hungary and ECMWF entered into force. Since then, it has proved very beneficial for a wide range of activities, including in terms of the contributions the Hungarian Meteorological Service (OMSZ) has made to several developments at ECMWF.



ECMWF's oldest Co-operating State. Hungary was the second country to conclude a co-operation agreement with ECMWF after Iceland, which became a Member State in 2011.

Lateral boundary conditions

At the end of the 1980s, the use of limited-area models (LAMs) became a key element in operational weather forecasting. At the time, the Swedish grid point LAM was one of the best, and OMSZ acquired it in 1988. Dezső Dévényi headed a small new team focusing on this activity. Having solved several problems, in July 1991 a version of the model with a horizontal resolution of 0.9°x0.9°covering Europe and 12 levels in the vertical became operational at OMSZ. At that time, it was not possible to obtain adequate lateral boundary conditions from the Global Telecommunication System (GTS). There was an obvious solution to this problem: to use ECMWF data as lateral boundary conditions. Among one of his first activities, Iván Mersich, the new president of OMSZ, sent an application by the Hungarian Meteorological Service to join ECMWF as a member. In the event, a co-operation agreement between ECMWF and Hungary was signed in the spring of 1994. Lateral boundary conditions then became available and were used operationally by the LAM model. This development led to significantly improved forecast quality for the rest of the life of this LAM, until 1998.

Hungary was one of the first countries to participate in the ALADIN project led by Météo-France since 1991. In 1998, the ALADIN/HU model became operational at OMSZ, on a new high-performance computing facility. In the first ten years of operations, the model was coupled to the global ARPEGE model. It was then coupled to ECMWF's deterministic global model, resulting in significant improvements in the quality of the forecasts provided by OMSZ.

Since 2009, OMSZ has been running the ALADIN model with 11 ensemble members. In 2016, ECMWF started to provide ensemble lateral boundary conditions in the framework of the Boundary Condition (BC) Optional Programme. OMSZ has been using them ever since, thus improving the quality of its probabilistic forecasts.

In the first decade of this century, the AROME non-hydrostatic model was developed in the framework of international cooperation. In 2010, the AROME model was made operational at OMSZ. This non-hydrostatic model provides very useful information, especially on extreme precipitation events in summer.

Ensemble product development

Over the last 25 years, OMSZ has worked with ECMWF in various areas of product development. They include many pioneering activities in the use of ensemble forecasts. Since 2003, ensemble clustering focusing on central European meteorological patterns has been run operationally using resources provided by ECMWF's ecgate computing cluster. This system makes available the representative ensemble member and the ensemble mean for each cluster to the General Directorate of Water Management. OMSZ has also been able to significantly improve the quality of the ensemble forecasts by means of calibration for variables such as 2-metre temperature, 10-metre wind speed, and precipitation.

Since 2011, OMSZ has developed ensemble vertical profiles. These can support decision-making for precipitation type in winter and for the intensity of convective events in summer. In 2018, ECMWF developed a similar method for the ecCharts visualisation system.

The version of ECMWF's Integrated Forecasting System introduced operationally in May 2015 (IFS Cycle 41r1) contained precipitation type as a new experimental product. At OMSZ, an ensemble precipitation type diagram was developed in autumn 2015 and this supported forecasters' decision-making during the winter season. A similar ECMWF product was created in the framework of the EU-funded ANYWHERE project inspired by the bar chart product from OMSZ, exploiting the probabilistic information provided by ECMWF ensemble forecasts.

Some other aspects

Forecasters and model developers from OMSZ regularly take part in ECMWF's educational programme (training courses, workshops, seminars). New types of training, such as webinars, eLearning materials and online training, are also very popular at OMSZ. ECMWF software packages, such as ecCodes, Magics, Metview and ecFlow, are widely used at the Hungarian Meteorological Service. Liaison visits and visits of the ECMWF User Support Contact Point are well attended and very much appreciated. OpenIFS has been used for educational purposes at the Eötvös Loránd University in Budapest. Finally, a number of former OMSZ employees are longstanding members of staff at ECMWF. Overall, the relationship between OMSZ and ECMWF has gone from strength to strength and is in excellent shape in this anniversary year.

ECMWF's user meeting focuses on ensembles

Anna Ghelli

The theme of this year's Using ECMWF's Forecasts meeting (UEF 2019), which took place in Reading from 3 to 6 June 2019, was 'The Strength of Ensembles'. The annual UEF meetings give ECMWF data users a unique opportunity to learn about the Centre's plans, new products and services. They also foster networking and experience sharing. The reason why the meeting returned to the theme of ensemble forecasts is the recognition that the information about the probabilities of different scenarios provided by such forecasts improves the ability to make decisions in situations when the weather plays a role. UEF 2019 focused on four thematic areas: processing model outputs; visualisation; verification and diagnostics; and applications and impact forecasting.

Speakers' Corner. Speakers gave a range of updates on new products, visualisations and applications.

Meeting highlights

Director of Research Andy Brown and Director of Forecasts Florian Pappenberger both addressed the meeting. Andy stressed the incredible amount of work that has gone into improving the seasonal forecast model and to move it towards a seamless system with a consistent approach to modelling from the medium to the seasonal forecast range. Another novelty, continuous data assimilation, enables the use of more up-to-date weather observations to help define the initial conditions for forecasts. This change, implemented in June this year, has significantly improved the quality of forecasts (see ECMWF Newsletter No. 158 for details).

Florian reminded his audience that the goals in ECMWF's ten-year Strategy to 2025 include the development of a 5 km ensemble. He noted that an intermediate goal to 2020 is a significant increase in our computational capacity, to be provided by the next high-performance computing facility, which will be located in Bologna. Florian added that over the next eight to ten years the number of observations used to build an analysis is expected to increase by a factor of ten; we will be producing 2,000 times more model data per day; and 100 times more data will be archived per day. As part of efforts to address this challenge, ECMWF is working with its key partners to set up a European Weather Cloud. The idea is to provide cloud services to bring users closer to our data.

Central to the UEF is also the sharing of experiences on data access and use, facilitated by a dedicated Speakers' Corner session. "ecCharts, the web application for visualising ECMWF data, has undergone changes to make it faster and easier to use," explained Cihan Sahin while demonstrating the new capabilities

Group photo. About a hundred external participants took part in the UEF 2019 meeting.

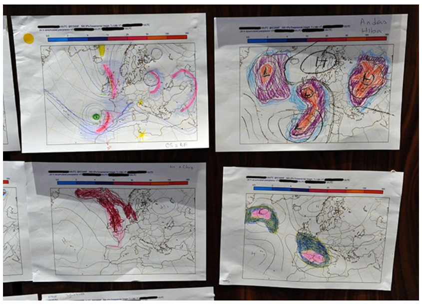
during the session. ecCharts offers around 300 layers (parameters) from medium-range atmospheric and wave model fields, extended-range forecasts up to 6 weeks ahead, re-forecasts and Copernicus Atmosphere Monitoring Service (CAMS) products. New products, such as point rainfall, have been added to ecCharts (see ECMWF Newsletter No. 159 for more details).

Several plenary session talks illustrated the use of ECMWF data in a variety of sectors and applications. Sippora Stellingwest (Weather Impact) stressed that weather information should be easy to understand, localised and customised to have impact on human activities. For example, forecasts, and information on the confidence we can have in them, help to mitigate the impact of pests on plants, as illustrated by research results presented by Ivana Aleksova (Météo-France). Marine services benefit from the probabilistic information provided by ECMWF's ensemble forecasts, as timely decisions can be taken days to weeks ahead of severe events to ensure the safety of personnel on oil rigs and to reduce economic losses.

Poster sessions have become a central part of the UEF. They offer a chance to discuss details of the piece of work presented and to seek future collaborations. Poster topics ranged from forecast performance in specific weather situations to newly developed products and the use of hourly to seasonal products in sectoral applications. An interactive poster provided feedback to ECMWF on the next dissemination schedule, which defines the way data is delivered to our data users. Currently ECMWF has a fixed dissemination schedule determining at which time individual products are released. A review of that schedule is being undertaken as part of preparations for the move of the data centre to Bologna.

Art and science

An 'art and science' challenge highlighted the usefulness of an ensemble when predictability is relatively low. Participants were divided into groups and were briefed on the current weather situation and how it might evolve. It was down to them to produce a drawing showing what the weather might look like in five days' time. The result was an artistic ensemble (58 members) which encompassed the observed outcome and some degree of uncertainty around it. Louise Arnal, the creator of the game, noted that "no team was able to capture the exact location and intensity of the event, but in combination all the drawings gave an indication of the future situation". Well done to the winners!



Art and science. A '58-member ensemble' of forecasts was created during the art and science session.

And the winners are… The Twitter engagement winner was Leonard Smith from the London School of Economics (@lynyrdsmyth), while Claudia Stoker from MeteoSwiss and Biserka Frankovic from Crocontrol Ltd, Croatia, won the art and science competition. The photo shows (left to right) UEF 2019 organisers Julia Wagemann and Anna Ghelli; Claudia Stoker; and Lovro Kallin from the Croatian Meteorological and Hydrological Service, who accepted Biserka's prize on her behalf.

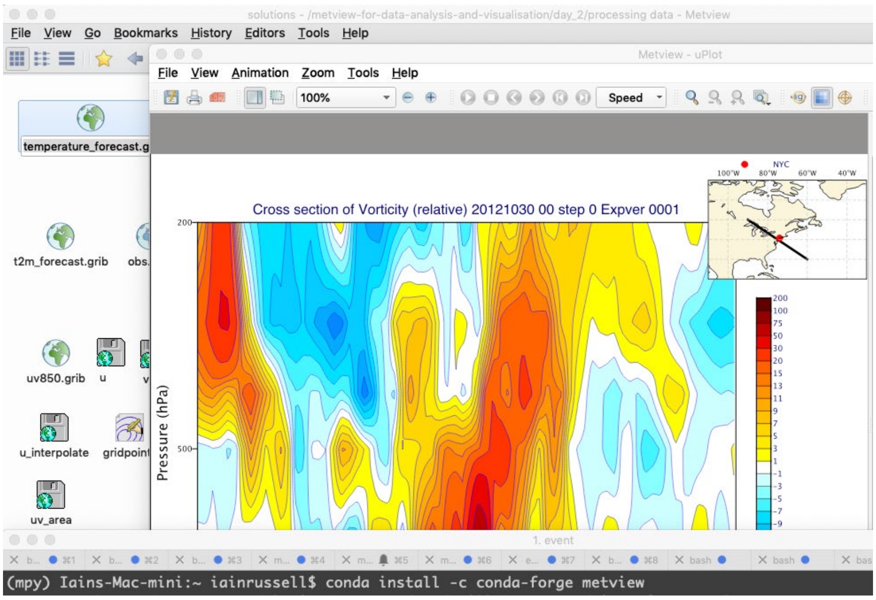
New distribution channel for ECMWF software

Stephan Siemen, Iain Russell

ECMWF has made its software packages ecCodes, Magics, Metview and CodesUI available from the conda package manager, which is popular within the Python community. With the help of the software company Old Reliable Tech, ECMWF's software packages have been added to the conda-forge channel. This development provides external users of ECMWF's software with a straightforward way of installing it on various platforms without the need to install dependencies themselves or compile code. ecCodes, Magics and CodesUI are available through conda on Linux, macOS and Windows. Metview is available on Linux and macOS. For example, to install Metview and its Python interface on their machine, a user would only need to type these commands in their conda shell:

```
conda install -c conda-forge metview
pip install metview
```

As with all new developments, ECMWF would appreciate feedback on this development and suggestions to make it easier to install its software.



Using conda. Here Metview can be seen running on macOS installed via conda.

New product generation software implemented

Umberto Modigliani

Following extensive testing, ECMWF has successfully implemented a new, more efficient and modern product generation software package called 'pgen'. The new software is now used for the generation of all tailored data products sent to Member and Co-operating States and all users. This new software has been developed over the past few years and takes full advantage of the new Meteorological Interpolation and Regridding (MIR) library, which was implemented operationally in early 2019. The new pgen software provides a scalable and more efficient way for user-tailored post-processing of Integrated Forecasting System output. It replaces a very old software package and will facilitate maintenance and development to support user requirements over the next few years. The new design is expected to provide a more robust service and reduce the number of delays in product generation. For more information on this new software, see: https://confluence.ecmwf.int/display/UDOC/New+Product+Generation+software.

The migration of several hundred users went very smoothly. ECMWF would like to thank all users for their cooperation during this migration.

> *"We transitioned back on 5 February, no code changes or impact on our end. Great work by ECMWF staff, you changed a lot and caused little to no impact."*
>
> (Matthew Rydzik, Commodity Weather Group, US)

C3S Climate Data Store user forum launched

Kevin Marsh, Xiaobo Yang, Anabelle Guillory

The Copernicus User Support team at ECMWF, which supports users of the EU-funded Copernicus Climate Change Service (C3S) and Copernicus Atmosphere Monitoring Service (CAMS), has launched the C3S Forum, which is primarily intended for users of the C3S Climate Data Store (CDS). The C3S Forum (http://copernicus-support.ecmwf.int/forum) adds to the existing Copernicus User Support ecosystem (Knowledge Base, Helpdesk) by providing a platform on which users can share their knowledge and experience with others.

CDS users form a rapidly growing new community from a diverse range of backgrounds. We anticipate that, by engaging with them early, we will help them to support each other by sharing their questions, knowledge and solutions. The forum is open for anyone to view, but users need to be registered with the ECMWF website in order to create new topics (or 'threads'), or to comment on existing threads within the forum.

Initially, four dedicated channels have been created:

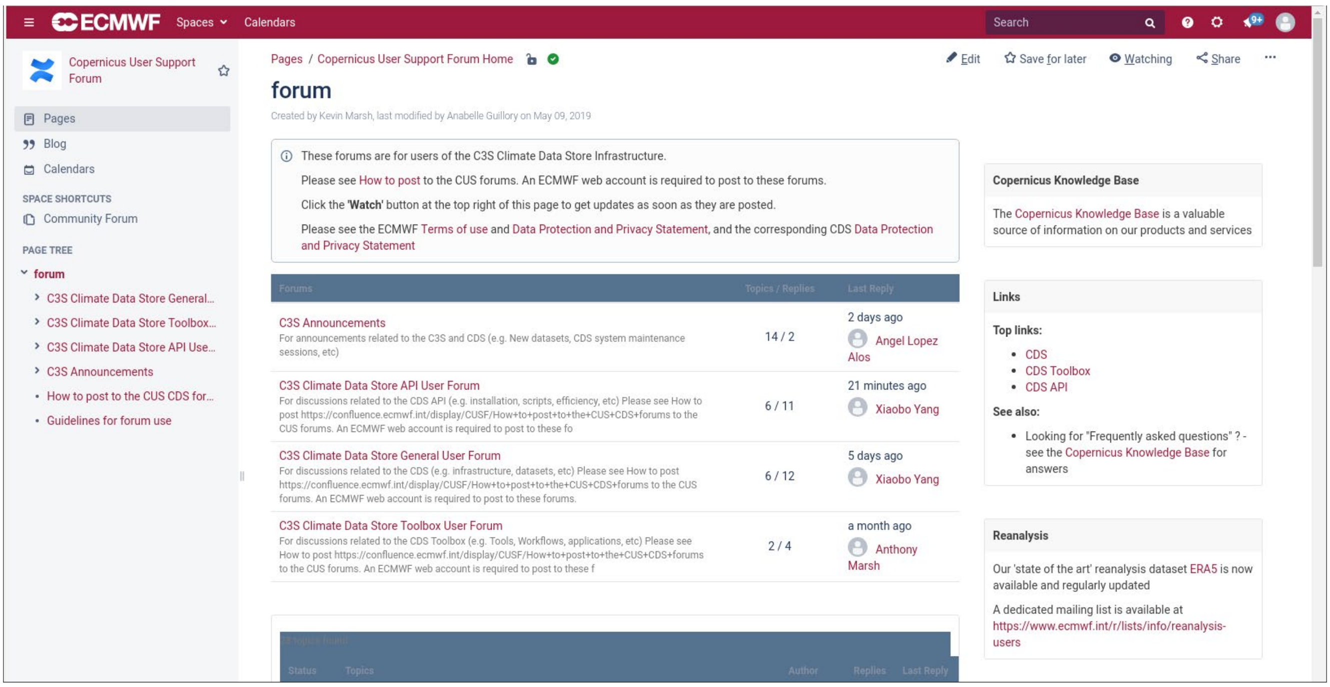
- C3S Announcements – for system maintenance sessions, new dataset releases, etc.
- CDS General – for questions on datasets, performance, etc.
- CDS API – for conversations concerning the API; syntax, queues, etc.
- CDS Toolbox – for discussions about tools, workflows and applications

Registered users can post questions, comment on existing threads (including using images and markup in their contributions), and 'like' particular content. Any thread can also be 'watched' so that the user is informed when new content is added, and a user can search across the entire forum.

As the forum uses the Confluence platform, many users will already be registered with us, and content they provide can be easily linked to Jira issues, the Copernicus Knowledge Base, etc. There are rules and policies in place informing users what content can be added, and the forum is monitored by Copernicus User Support and CDS staff to ensure that questions do not go unanswered and that conversations reach an effective conclusion.

We hope that users will find this a valuable addition to the support we provide, and one which can be used in the future to engage with other groups of ECMWF and Copernicus users. We also hope that the C3S Forum will lead to a wider use of similar forums at ECMWF/Copernicus. As well as the existing OpenIFS forum (https://confluence.ecmwf.int/display/OIFSUF/OpenIFS+User+Forums) and the C3S Forum, a new forum has recently been set up for ECMWF's operational acquisition and pre-processing system for observations and other input data, SAPP (https://confluence.ecmwf.int/display/SAPP/User+Forums).

The Copernicus User Support team is always interested to hear from our users on how we can improve further. If you have any ideas or suggestions, you can reach us at copernicus-support@ecmwf.int.



C3S Forum. The new forum currently has four dedicated channels: C3S Announcements, CDS General, CDS API and CDS Toolbox.

CAMS supports scientific aircraft campaigns

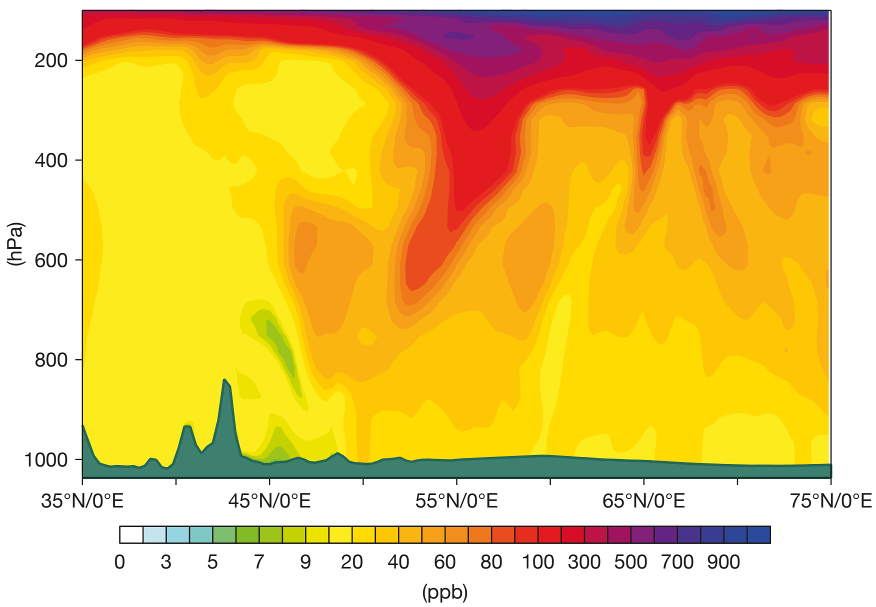
Johannes Flemming, Luke Jones (both ECMWF), Anne-Marlene Blechschmidt (Universität Bremen)

Atmospheric composition forecasts produced operationally by the Copernicus Atmosphere Monitoring Service (CAMS), which is implemented by ECMWF on behalf of the EU, can on request be provided in the form of tailor-made, detailed plots on a dedicated web page to support scientific field campaigns. ECMWF provided such a service even before CAMS was created in 2014, and to date more than 30 field campaigns have been supported in this way.

Enhancing our knowledge of trace gases and aerosols in the atmosphere is key to tackling air pollution, responding to climate change and improving the simulation of feedbacks between weather and atmospheric composition. Aircraft campaigns make an important contribution to this endeavour by observing trace gases and aerosols in situ. It is important for these campaigns to define their flight routes in a timely manner. CAMS forecasts provide valuable advance information on pollutant or desert dust plumes to support the flight route planning.

The CAMS flight campaign support service (FCSS) is a special service for the scientific community. Principal investigators of interested campaigns can request a choice of parameters, geographical areas, levels and vertical cross-section lines by filling in an online form. Each day for the duration of the campaign, the requested plots (typically several hundred) are produced and presented on the CAMS website shortly after the forecast is completed.

A further challenge such campaigns face is the timely attribution of observed concentration patterns to associated sources. To help with this, the CAMS FCSS runs an additional forecast suite that includes hypothetical tracers with a prescribed atmospheric residence time, which are injected over predefined regions to indicate the origin of observed plumes. Most commonly, anthropogenic or biomass burning emissions of carbon monoxide are used as the emissions of the hypothetical tracer. The source areas can be continental in scale, such as North America, but local hotspots such as the Ruhr area in Germany have also been requested and have proven to be valuable for campaign planning. The tracers often show the predicted transport patterns more clearly than the forecast for the actual concentration fields. Another tracer used in the CAMS system, stratospheric ozone, identifies intrusions of dry and ozone-rich air into the troposphere. If CAMS is involved in the campaign planning at an early stage, more complex tracers can be implemented. For example, a tracer to track oceanic emissions of short-lived halocarbons and a tracer of the nitrogen oxides emitted from lightning were included in the forecasts for the CAST/CONTRAST/ATTREX campaigns.



Stratospheric ozone tracer. North–south cross section of a 24-hour stratospheric ozone tracer forecast over Europe starting at 00 UTC on 26 July 2017 to support flight planning for the EMeRGe-EU campaign.

Some examples

The first time the service was provided was back in 2008 for the POLARCAT/ACTRIS campaigns, which investigated the long-range transport of pollutants into the Arctic. Several subsequent campaigns supported by the service observed the pollutant plumes resulting from biomass burning and anthropogenic emissions (e.g. SAMBA and EMeRGe).

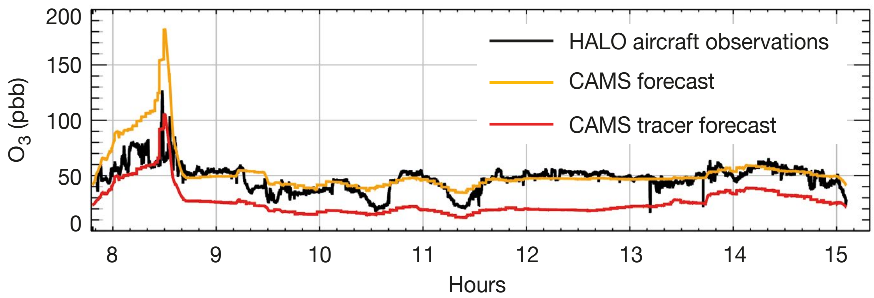
As Prof. John Burrows, principal investigator of the EMeRGe campaigns, explains: “The CAMS 5-day forecast input was used by the flight planning group to prepare the flight tracks to catch the plumes from mega-cities and biomass burning on a daily basis. Gas samples taken have shown that HALO aircraft intercepted the pollution plumes very successfully.”

Other campaigns have aimed to measure aerosol composition and its interaction with radiation and clouds (e.g. ICE-D and W-CAN). Outflow patterns of desert dust and its impact on local weather have also been studied (e.g. FENNEC and DACCIWA). Yet other campaigns (e.g. ACTRIS and HIPPO) have focused on the long-range gradient and distribution of long-lived greenhouse gases and on exchange processes between the stratosphere and the troposphere.

Mutual benefits

CAMS can in turn use the observations made during the campaigns to evaluate its forecasts and analyses. This targeted evaluation complements the routine evaluation of CAMS products. As transport processes play a big role in weather forecasts, tracer observations can also help to evaluate meteorological aspects in ECMWF's Integrated Forecasting System (IFS).

For more information on the CAMS flight campaign support service, see: https://atmosphere.copernicus.eu/scientific-field-campaign-support



Ozone forecasts and measurements. Ozone molar fraction observed by the HALO aircraft, and the corresponding CAMS forecast of ozone and of the stratospheric ozone tracer during the EMeRGe campaign over central Europe on 26 July 2017. The ozone measurements were provided by Andreas Zahn and Florian Obersteiner (Karlsruhe Institute of Technology, Institute of Meteorology and Climate Research, Germany).

Why we need to protect weather prediction from radio frequency interference

Stephen English

Numerical weather prediction (NWP) relies on observations from Earth observation satellites, radiosondes, aircraft, radar and other observing systems as inputs. In turn, these observing systems rely on the allocation of radio frequency bands both for directly observing the atmosphere and the planet and for exchanging observations through telecommunication networks. These allocations are defined in international agreements and regularly updated at an event called the World Radiocommunication Conference (WRC) in the light of new requirements. The next WRC, WRC-19, takes place this coming November. The World Meteorological Organization (WMO), with strong support from space agencies such as EUMETSAT and ESA, as well as EUMETFREQ (a EUMETNET programme), coordinates the response of the international meteorological community and represents the community at WRC-19. Their goal is to ensure that frequencies used operationally at centres like ECMWF continue to be allocated to this application area, without interference from new users. This process is increasingly challenging as many new application areas are emerging that require frequency bands, for example the next-generation mobile phone data service, 5G. In the WRC, the demands of different application areas need to be weighed up, taking into account economic and societal benefits.

A proactive approach

For the meteorological case to be fairly heard, the spectrum managers who make decisions on radio-frequency allocations need the best and most up-to-date information on the value of the bands to meteorology, in terms that can be compared to other application areas. This enables them to try to ensure continued allocation of the required frequencies to the Earth Exploration-Satellite Service (EESS), as well as protecting these frequencies from out-of-band emissions from neighbouring frequency bands. Therefore, ECMWF has been proactive in providing information and coordinating inputs from the wider meteorological community to support the WMO and the space agencies. In particular, ECMWF organised a workshop on radio frequency interference in September 2018, which was attended by representatives of many major NWP centres (*https://www.ecmwf.int/en/learning/workshops/radio-frequency-interference-rfi-workshop*). Following this, ECMWF wrote an article for the International Telecommunication Union (ITU) News Magazine, which gained prominence at the ITU headquarters. This stimulated further interest, and ECMWF has been engaging with the media to ensure a broad understanding of the meteorological use of radio frequencies, for example by contributing to an article published by *Nature News* entitled 'Global 5G wireless networks threaten weather forecasts' (*www.nature.com/articles/d41586-019-01305-4*).

doi: 10.21957/bh691senk5

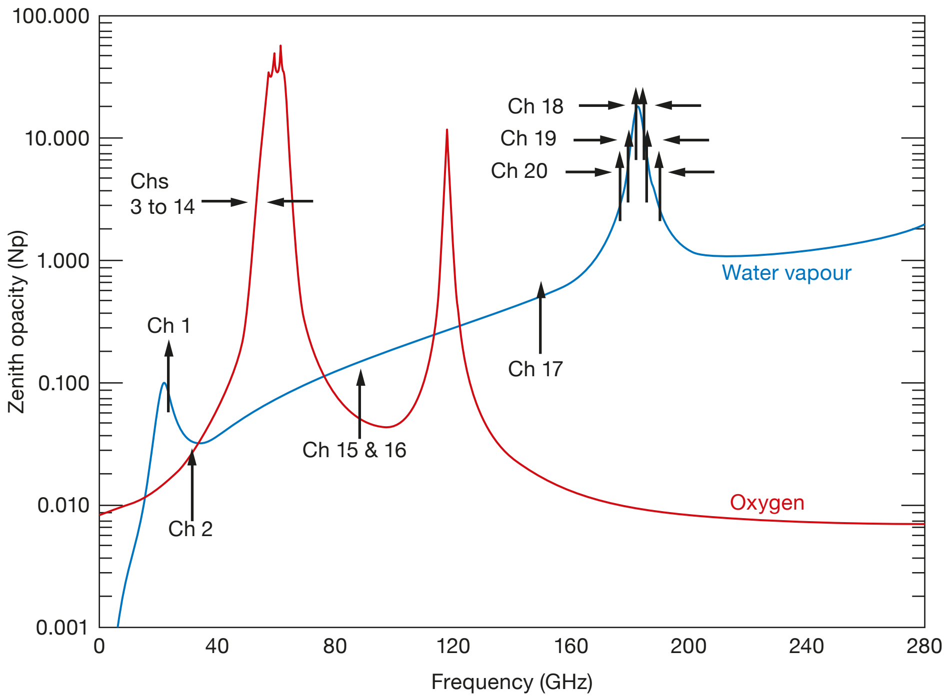
ITU NEWS MAGAZINE ARTICLE. An article by Stephen English on the issue of radio frequency interference was published in the *ITU News Magazine* 01/2019 and advertised at the ITU headquarters.

The value of passive microwave sensing

Many satellite observations for NWP use passive sensing techniques in radio frequency bands. Such passive measurements are made by very sensitive instruments that measure the very low-power microwave radiances naturally emitted from the atmosphere and the Earth's surface. These passive techniques are the most vulnerable to interference from new users of radio frequencies generating electromagnetic emissions for their own purposes. Passive sensing makes it possible to gain information on the current state of the Earth system by exploiting the absorption characteristics of the atmosphere. There are absorption peaks due to the molecular resonance of atmospheric gases, including water vapour. There is also absorption and scattering by clouds and precipitation, which increase with frequency, and a slow increase in absorption by water vapour with increasing frequency. How efficiently the Earth's surface emits and reflects microwave radiation also changes slowly with increasing frequency.

Below 10 GHz, the atmosphere is almost completely transparent, even in the presence of clouds. These low frequencies directly sense the planet's surface, providing information on sea-surface temperature (SST), soil moisture, sea ice coverage and snow. At 18 GHz, the dielectric properties of sea water are such that emission has a low sensitivity to SST, so the surface emission is primarily sensitive to the sea state and small waves. At 22–24 GHz, there is a weak water absorption line, and by measuring close to this spectral line we gain information on total column water vapour. At 31 GHz, information on the liquid water content of clouds is obtained. There is a strong oxygen absorption band at 50–60 GHz. This is a remarkable spectral feature, enabling us to gain information on the 3D structure of atmospheric temperature with little impact from clouds, especially ice clouds, and water vapour. Above 60 GHz the most important spectral feature of interest is the water vapour line at 183 GHz, which provides information on the 3D structure of water vapour. Frequencies above 200 GHz can provide very detailed information about trace gases and ice clouds. All these spectral features arise from the laws of physics and are

THE WMO INTEGRATED GLOBAL OBSERVING SYSTEM (WIGOS). Satellite observations, including those that use passive sensing techniques in radio frequency bands, are a crucial part of the WMO Integrated Global Observing System (WIGOS) used to support numerical weather prediction. (*Source: WMO*)



ATMOSPHERIC OPACITY IN THE FREQUENCY RANGE 0–280 GHZ. The chart shows frequencies used by the channels of the Advanced Microwave Sounding Unit (AMSU-A, channels 1-15, AMSU-B channels 16-20), one of the most important instruments used in NWP. It has been continuously operated since 1998 on a series of operational satellites run by NOAA and EUMETSAT. Today there are also a range of new-generation instruments that measure microwave radiances, such as China's MWTS-2 and MWHS-2, Russia's MTVZA-GY and the USA's ATMS, amongst many others. (Source: S. J. English et al., 1994, *Q.J.R. Meteorol. Soc.*, doi:10.1002/qj.49712051706.)

therefore determined by nature. They are a unique asset which cannot be substituted by other measurements. Each of these bands thus provides information essential to modern state-of-the-art weather prediction. Furthermore, there are strong interdependencies between bands: to extract the information from one band it is usually important to have two or three other bands available, for example to know the impact of clouds on a temperature sounding.

Assessments of the impact of weather observations have found that microwave observations are presently the most important satellite observing system for global NWP, typically contributing around 30–40% of the overall improvement in forecast skill arising from the use of observations. It has also been demonstrated that without microwave observations there would be a major loss of resilience to changes in the WMO Integrated Global Observing System (WIGOS): the skill of forecasts would vary more from day to day and month to month as the number of observations available fluctuates (e.g. due to satellite failures and new satellite launches). When microwave observations are not present, the degradation from any loss of hyperspectral infrared observations is several times larger than when microwave observations are present.

The use of radio frequencies in meteorology is not limited to these passive microwave observations. Systems such as weather radar also suffer from radio frequency interference. Radiosondes rely on a specific allocation for tracking and telecommunication. Command and download of data from all satellites needs specific frequency allocations. All these allocations are every bit as important as the passive allocations.

Why we need to act

NWP users are already seeing evidence of radio frequency interference in the L (~1.4 GHz), C (~6.9 GHz), X (~10.7 GHz) and K (~18.7 GHz) frequency bands, notably on the European SMOS instrument and the Japanese AMSR2 instrument. Loss of these and other bands would have a negative impact on national weather warning systems as well as our ability to monitor climate change through the Copernicus Climate Change Service (C3S), implemented by ECMWF on behalf of the EU. New applications (e.g. 5G) outside the field of meteorology are interested in higher frequencies, e.g. in bands adjacent to 24 GHz and 50 GHz, which are crucial for obtaining accurate estimates of water vapour and temperature in the analysis, from which the forecast is then run. Although the radio regulations prohibit all emissions in the passive allocations at 24 and 50 GHz, we also have to ensure protection is in place to limit the level of out-of-band emissions from active systems operating in neighbouring bands (e.g. emissions from the 5G band between 24.25 GHz and 27.5 GHz affecting the passive band 23.6–24.0 GHz).

In a world hungry for the use of radio frequencies in new applications, meteorological centres such as ECMWF need to be clear about the value of our use of such frequencies. The next key event is the World Radiocommunication Conference in November 2019. ECMWF's high level of activity this year reflects the fact that there are many questions for that meeting that will decide the future viability of many bands used for operational weather forecasting. ECMWF will continue to support the WMO and space agencies in this important activity.

IFS upgrade greatly improves forecasts

Michael Sleigh, Philip Browne, Michail Diamantakis, Thomas Haiden, David Richardson

On 11 June 2019, ECMWF implemented a substantial upgrade of its Integrated Forecasting System (IFS). IFS Cycle 46r1 includes changes in the model and in the data assimilation procedure used to generate the initial conditions for forecasts. The upgrade has had a very positive impact on the skill of medium-range and extended-range ensemble forecasts (ENS) and medium-range high-resolution deterministic forecasts (HRES). It follows the implementation of IFS Cycle 45r1 in June 2018, which brought coupling to all ECMWF forecasts, from one day to one year ahead, by including ocean and sea-ice models in the HRES configuration.

Cycle 46r1 is the culmination of the work of many across ECMWF and brings major changes in many areas, including:

- **In data assimilation:** continuous data assimilation (an extra 4D-Var outer loop, an increase from 6 to 8 hours in the early-delivery assimilation window length, and an extension in the observation cut-off time); twice the number of members in the Ensemble of Data Assimilations (EDA); weakly-coupled data assimilation for sea-surface temperature in the tropics; consistent spatial interpolation of the model to observation locations in trajectories and minimisations; use of the EDA to calculate Jacobians in the soil-moisture analysis.
- **In the use of observations:** assimilation of the SMOS neural-network soil-moisture product; assimilation of SSMIS-F17 satellite data at 150h GHz and GMI satellite data at 166 GHz; improved use of land/sea mask in the field of view for microwave imagers; introduction of inter-channel observation error correlations for ATMS and geostationary water-vapour channels; slant path calculations for geostationary radiances; usage of geostationary radiances at higher zenith angles; consistent infrared aerosol detection.
- **In the model:** improvements in the convection scheme (entrainment, CAPE closure, shallow convection); activation of long-wave scattering in the radiation scheme; 3D rather than 2D aerosol climatology; correct scaling of dry mass flux in the diffusion scheme; improvement of the tangent linear and adjoint of the semi-Lagrangian departure point scheme in the polar-cap area; new parametrization for wind input and open ocean dissipation of the wave model; increase in the frequency of the ensemble radiation time step from 3 hours to 1 hour.

Data assimilation and observations

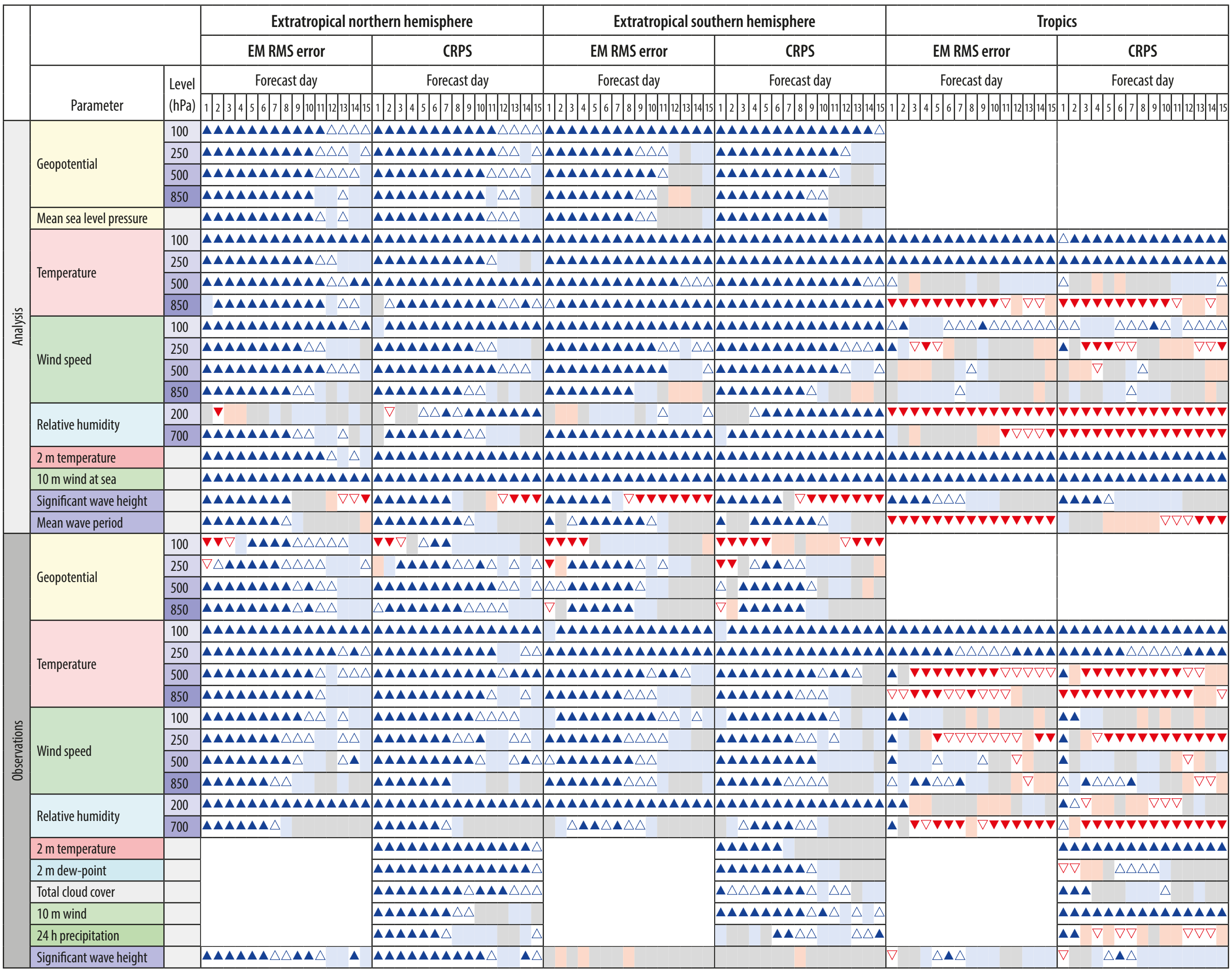
The continuous data assimilation scheme enables the use of later-arriving observations and, crucially, decouples the starting time of the assimilation calculations from the observational cut-off time. This permits the beneficial introduction of an additional outer loop without affecting delivery time. In addition, the early-delivery assimilation window length has been increased from 6 hours to 8 hours, thus ensuring that all observations that have arrived can be assimilated. For more details, see Lean et al. (2019).

The number of EDA members has increased from 25 to 50. The computational resources required are roughly the same as before as a result of efficiency improvements. The increase in the number of EDA members improves the HRES analysis by providing better background error variance and covariance estimates. Furthermore, it is now possible to assign a unique EDA perturbation to each ensemble forecast member, which makes the ensemble forecast members exchangeable. For more details, see Lang et al. (2019).

In the newly developed ocean–atmosphere weakly-coupled data assimilation, the atmospheric analysis sea-surface temperature in the tropics is taken from the ECMWF OCEAN5 near-real-time analysis, rather than from the OSTIA product directly. This results in improved forecast scores for near-surface temperature and humidity in the tropics compared to the analysis. For more details, see the article on weakly coupled data assimilation in this Newsletter.

For the surface analysis of soil moisture, the Simplified Extended Kalman Filter (SEKF) described by de Rosnay et al. (2013) has been significantly upgraded to improve computational efficiency, by computing its Jacobians directly from the EDA rather than with perturbed nonlinear trajectories. This reduces the SEKF computing cost, compared to previous IFS cycles, by more than a factor of three in the operational HRES configuration. The EDA-Jacobian approach in the SEKF also enhances the coupling between the land and atmospheric assimilation systems by ensuring more dynamic Jacobian estimates than in the previous finite-difference approach.

 doi: 10.21957/gt23msc861



Symbol legend: for a given forecast step...

- ▲ 46r1 better than 45r1 statistically significant with 99.7% confidence
- △ 46r1 better than 45r1 statistically significant with 95% confidence
- 46r1 better than 45r1 statistically significant with 68% confidence
- no significant difference between 45r1 and 46r1
- 46r1 worse than 45r1 statistically significant with 68% confidence
- ▽ 46r1 worse than 45r1 statistically significant with 95% confidence
- ▼ 46r1 worse than 45r1 statistically significant with 99.7% confidence

FIGURE 1 ENS scorecard of IFS Cycle 46r1 versus IFS Cycle 45r1 for medium-range forecasts up to forecast day 15, verified by the respective analyses and observations at 00 UTC based on 282 ENS forecast runs in the period June 2017 to June 2019.

Cycle 46r1 has introduced a package of changes to microwave all-sky assimilation. This includes the assimilation of SSMIS-F17 satellite data at 150h GHz and GMI satellite data (vertical and horizontal polarisation radiances) at 166 GHz, which bring new information on humidity and wind over tropical and subtropical oceans, as well as improving the use of the land–sea mask in the field of view for microwave imagers. Each microwave observation has a footprint depending on its frequency. We use the 10 GHz footprint for AMSR2 and GMI and the 19 GHz footprint for SSMIS-FOV to compute how the land–sea mask is affected by this footprint. This land–sea mask is more accurate than that used in Cycle 45r1, which depends on the resolution of each loop.

Inter-channel observation error correlations have been introduced for ATMS satellite data, which results in ATMS observations being assimilated, on average, with more weight. This has resulted in significant and consistent improvements in the fit of the short-range forecasts used in the data assimilation system (first-guess fit) to independent observations sensitive to temperature, humidity and wind, indicating improved forecasts of these variables.

Similarly, inter-channel observation error correlations have been introduced for geostationary satellite water vapour channels, affecting SEVIRI (Meteosat Second Generation) and AHI (Himawari) instruments, to provide the best first-guess fit to water vapour channels on other instruments, as well as impact at longer lead times.

A further upgrade to the use of geostationary radiances is to account for slanted paths within the radiative tansfer calculation. This change enables us to use data up to zenith angles of 74°, thus improving coverage at the edges of the geostationary disks. This is particularly significant in the North Atlantic, where previously a significant amount of Meteosat-10 data was not used.

In addition, the SMOS (Soil Moisture and Ocean Salinity) neural-network soil moisture satellite product is now assimilated along with the ASCAT level-2 surface soil moisture satellite product. The impact of using SMOS neural network data and the EDA Jacobians on medium-range weather forecasts is near neutral. However, there is a small but significant improvement in 2-metre temperature forecasts in the short range in the northern hemisphere.

Main modelling improvements

In Cycle 46r1, the ENS radiation time step has been reduced from 3 hours to 1 hour, as is already the case for the HRES. Forecast skill is improved almost everywhere as a result, including a substantial error reduction for 2-metre temperature forecasts. Much of the improvement can be attributed to the faster coupling of radiation, clouds and the surface. Over tropical land areas, the root-mean-square error in low clouds has been reduced by as much as 15%. More frequent radiation updates incur an overall cost increase in the operational ENS of only about 3%. This was made possible in part because the new radiation scheme introduced in IFS Cycle 43r3 (ecRad) is significantly cheaper than its predecessor.

In addition, long-wave radiation scattering has been turned on in the radiation scheme, which leads to a slight warming of the surface and a reduction in the root-mean-square error in tropospheric temperature forecasts of around 0.5%. A key innovation in the implementation is to represent longwave scattering by clouds but to neglect it for aerosols (Hogan & Bozzo, 2018). This brings virtually all the benefits whilst enabling several optimisations to be performed, such that the overall cost of the radiation scheme when longwave scattering is included is very slightly reduced.

The 2D aerosol climatology used in the radiation scheme has been replaced by a new 3D aerosol climatology. This change has some positive impacts on lower tropospheric temperature and winds, especially along coastlines affected by seasonal biomass burning interacting with boundary layer clouds. Bigger positive impacts can be seen in the stratosphere, where the root-mean-square error of the temperature field in the 50–100 hPa layer near the summer pole decreases by 10% due to a similar reduction in the temperature bias.

Changes in the convection scheme include an increase in test-parcel entrainment; a correction for the denominator in the convective available potential energy (CAPE) closure (improving the tangent-linear approximation); and, for shallow convection, a relative-humidity-dependent area fraction for evaporation (previously a constant value).

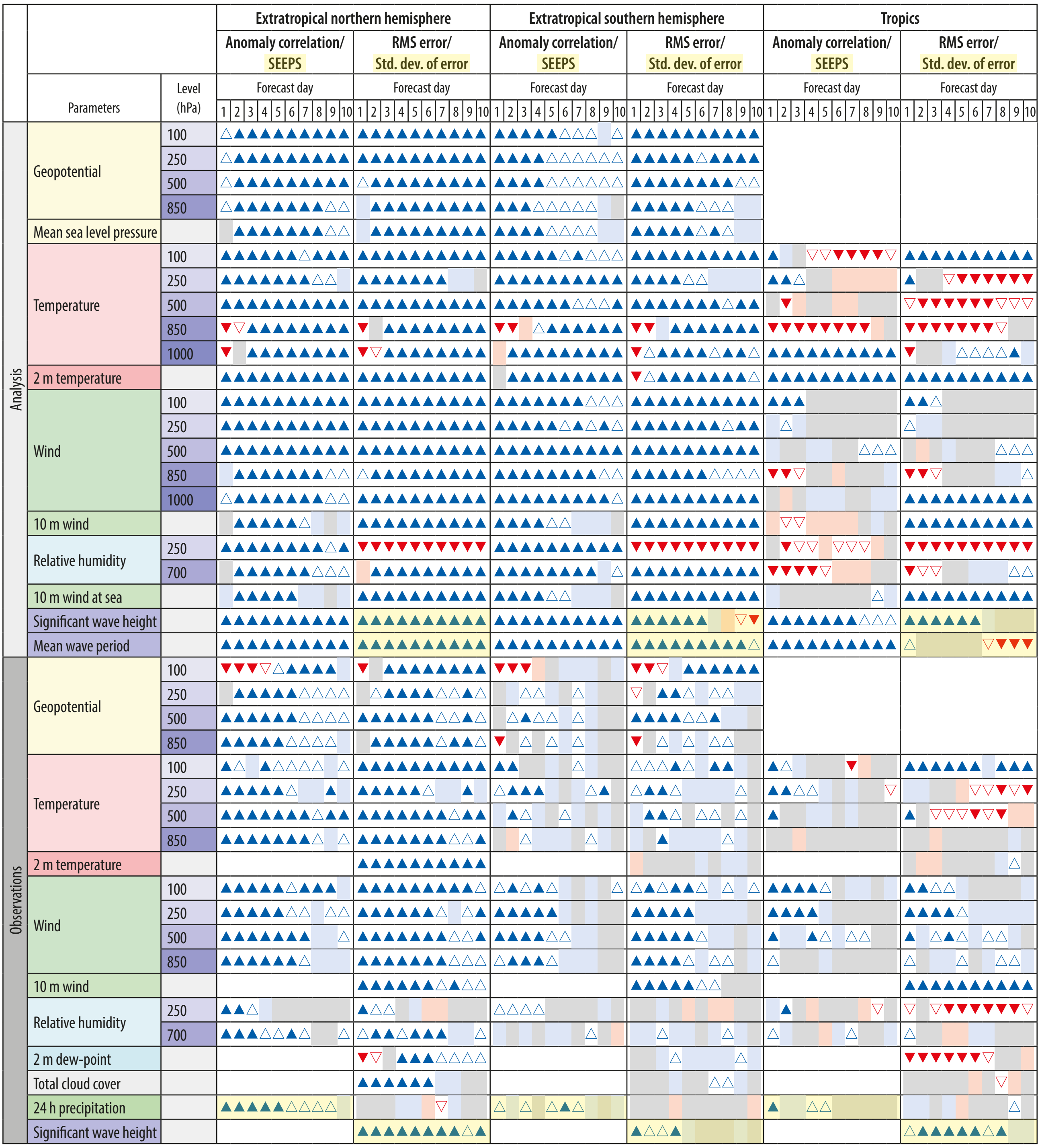
A modification in the semi-Lagrangian advection scheme in tangent linear and adjoint coding results in improving the departure-point calculation near the polar cap area. This was a long-standing problem, which has in the past occasionally given rise to instabilities.

The changes introduced in the land-surface scheme aim to minimise the occurrence of spikes in the maximum 2-metre temperature. This was done by adjusting the wet-tile skin conductivity. This modification partially solves the spike problem, lowering the frequency of its occurrence by almost half, with a slightly positive net overall impact. In Cycle 46r1, the amount of rain that can refreeze when intercepted by the snowpack has been corrected, leading to improved handling of episodic snow events. Previously, unphysical accumulations of snow in rainy conditions were locally observed during wintertime.

A new wave physics parametrization for wind input and open ocean dissipation has been implemented in Cycle 46r1. It is based on the work of Ardhuin et al. (2010) and on an initial implementation in the Météo-France version of the wave model code. Because the wave model is coupled to the atmosphere, the new configuration was set up to yield a similar level of feedback in the form of a sea-state-dependent Charnock coefficient. This yields slightly larger ocean surface roughness under typical tropical wind conditions than before. The main benefit of the changes is on the wave parameters, partly addressing the issue of overprediction of long swell energy and the small underestimation in the storm tracks. Based on new parametrizations developed by Peter Janssen (2017) and Augustus Janssen, the freak wave parameter calculation has been updated. The main impact is an enhanced probability of larger waves in shallow water compared to the old version.

Cycle 46r1 performance evaluation

IFS Cycle 46r1 brings substantial improvements in forecast skill for both ENS and HRES (Figures 1 and 2). Medium-range forecast errors in the extratropics are reduced by 1–5% for upper-air parameters and by 0.5–2% for surface parameters. Improvements of this magnitude are seen in verification against both the analysis and observations. In terms of lead time, upper-air improvements amount to a gain of around 2–3 hours. In the tropics, HRES results are predominantly positive, but there are some increases in temperature and humidity errors, mainly seen in verification against the analysis. For temperature, these are due to changes in the analysis and the introduction of the 3D



Symbol legend: for a given forecast step...

- ▲ 46r1 better than 45r1 statistically significant with 99.7% confidence
- △ 46r1 better than 45r1 statistically significant with 95% confidence
- 46r1 better than 45r1 statistically significant with 68% confidence
- no significant difference between 45r1 and 46r1
- 46r1 worse than 45r1 statistically significant with 68% confidence
- ▽ 46r1 worse than 45r1 statistically significant with 95% confidence
- ▼ 46r1 worse than 45r1 statistically significant with 99.7% confidence

FIGURE 2 HRES scorecard of IFS Cycle 46r1 versus IFS Cycle 45r1, verified by the respective analyses and observations at 00 and 12 UTC, based on 690 forecast runs in the period June 2017 to June 2019.

aerosol climatology. ENS results in the tropics are also mixed. In addition to the changes mentioned already, they are affected by a minor reduction in spread (around 1%) due to changes in the deep convection scheme. Wave parameters (significant wave height and mean wave period) in the HRES are improved substantially by 5–10% due to the upgrade in the ocean wave model. Increased wave activity leads to some degradation in wave height at longer lead times in the ENS.

Precipitation forecast skill increases in the extratropics by about 0.5% in the ENS and 1% in the HRES. Other weather parameters, such as 2-metre temperature and 2-metre dewpoint, 10-metre wind speed and total cloud cover improve by about 1% in the ENS, and by 0.5–1% in the HRES when verified against observations. In the tropics, slightly reduced spread and increased bias lead to a very small (0.1–0.2%) degradation in ENS precipitation. Scores in the tropics show strong improvements for 2-metre temperature (4–8% against the analysis both in ENS and HRES, 1–2% against observations in the ENS). Tropical cyclone forecast skill is neutral overall, with a slight reduction in track error, consistent with improved winds in the tropics.

New forecast outputs

An Extreme Forecast Index (EFI) for water vapour flux has been introduced, as well as new EFI products to highlight potential extremes in the extended range (Figure 3). Probabilities for 850 hPa temperature anomalies in terms of standard deviations from the climate average, together with additional probability thresholds for precipitation and near-surface (10 m) wind have been added to support the activities of World Meteorological Organization Members. Ocean fields, including sub-surface data such as the depth of the 20°C isotherm and the average salinity and potential temperature in the upper 300 m, are now also available.

Summary

The implementation of IFS Cycle 46r1 brings us another step closer to the implementation of ECMWF's ten-year strategy, which includes two important scientific goals to help improve medium-range forecast skill. One is a more accurate estimation of the initial state and the consistent representation of uncertainty associated with observations and the model. Progress in this direction can be seen in the package of improvements associated with continuous data assimilation; the 50-member EDA and the new consistency between EDA and ENS members; and many other changes. The second is a better representation of physical and chemical processes and of the interactions between different Earth system components. Examples of progress in this area include a faster coupling between radiation, clouds and the surface, because of the more frequent radiation updates; the improvements in the ocean wave model; and many other modelling changes.

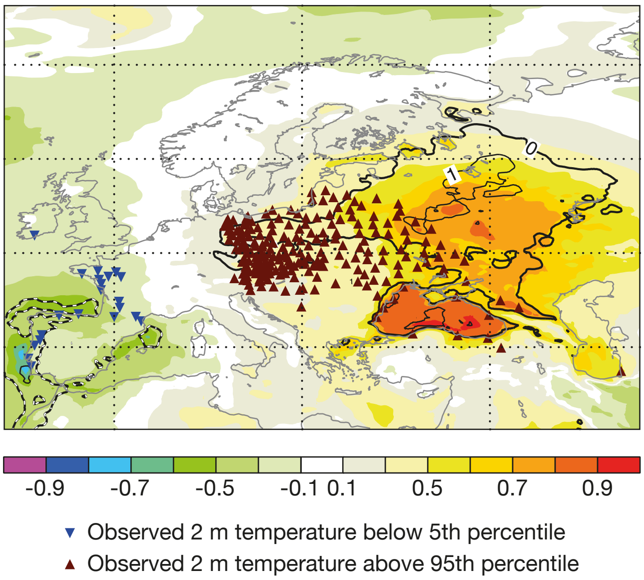


FIGURE 3 IFS Cycle 46r1 introduced a new extended-range Extreme Forecast Index (EFI) and Shift of Tails (SOT) for 2-metre temperature and total precipitation. The chart shows the EFI (shading) and SOT (contours) for 2-metre temperature from 00 UTC on 3 June 2019 for the week from 10 to 17 June together with the locations where the observed 2-metre temperature in that week was below the 5th percentile or above the 95th percentile of the observed 20-year climatology. The forecast gave an indication of the anomalously cold conditions in the west and the unusually hot conditions in eastern Europe.

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Coupled ocean–atmosphere data assimilation at ECMWF

Philip Browne, Patricia de Rosnay, Hao Zuo

For forecasts more than about three days ahead, components of the Earth system that are typically slower to change than the atmosphere become more important. This is true both in terms of their representation in the model and in terms of an accurate specification of the initial conditions on which forecasts are based. Such components include the ocean, sea ice and the land surface and how they dynamically interact with each other and the atmosphere.

One of the goals of coupled data assimilation (Box A) is to make sure that all components of an Earth system model are initialised consistently with one another. If the different components are not mutually consistent, they are sometimes referred to as unbalanced. This lack of balance can lead to fast adjustments in the system in the initial stages of the forecast in a phenomenon known as initialisation shock. Initialisation shock can be reduced by initialising the various components together via coupled data assimilation.

Another goal of coupled data assimilation is to extract as much information as possible from observations and provide it to all relevant parts of the Earth system model. This is because there are many observations that contain information useful to multiple parts of the Earth system. These include, for example, scatterometer data, which contain information on the interface between the Earth surface and the atmosphere. Another example is near-surface observations used in one component that are near a data-sparse region of another component.

Here we describe the form of weakly coupled data assimilation for the atmosphere, the ocean and sea ice implemented operationally in ECMWF's Integrated Forecasting System (IFS) in June 2018 (IFS Cycle 45r1) and June 2019 (IFS Cycle 46r1). The new system makes it possible to combine information from different Earth system components despite the fact that they have different assimilation windows. Experiments confirm that weakly coupled ocean–atmosphere data assimilation as implemented at ECMWF significantly improves the analysis of atmospheric variables such as temperature and humidity in the tropics and in the polar regions.

ECMWF's operational setup

The IFS uses models of a range of Earth system components in different combinations for different purposes. The short-range forecasts which are used in the data assimilation system to produce the atmospheric analysis use the atmospheric model, the land model, the lake model, and the wave model. ECMWF's medium-range to seasonal forecasts, on the other hand, are all produced using those models plus interactive ocean and sea ice models. The latter are the 3-dimensional community ocean model NEMO and the Louvain-la-Neuve 2 (LIM2) sea ice model developed at the Belgian Université Catholique de Louvain. The ocean temperature, salinity, and horizontal currents are initialised separately from the atmosphere using the 3D-Var First Guess at Appropriate Time (FGAT) assimilation technique. The length of the assimilation window varies from 8 to 12 days. In parallel, a sea ice concentration analysis is produced using the same 3D-Var FGAT method. This ocean and sea ice analysis system is known as OCEAN5. Since IFS Cycle 45r1, all of ECMWF's medium-range forecasts have been fully coupled to OCEAN5 in the tropics and partially coupled in the extratropics.

Observations that are currently assimilated to produce the ocean analysis are in situ profiles of temperature and salinity and satellite-derived sea level anomaly and sea ice concentration observations. For sea-surface temperature (SST), a relaxation is performed towards the OSTIA SST product from the UK Met Office. The ocean and sea ice analysis system requires forcing fields from the atmospheric analyses and forecasts. See Zuo et al. (2018) for full details.

The atmospheric analysis is produced using 4-dimensional variational data assimilation (4D-Var). The land data assimilation component is weakly coupled to the atmosphere. The various components of the land surface are initialised using different methodologies: the snow analysis is produced using a 2D-OI (optimal interpolation) technique, as is the soil temperature analysis, while soil moisture is analysed using a Simplified Extended Kalman Filter. Similar to the land analysis, the wave analysis is weakly coupled to the atmosphere and is produced using 2D-OI.

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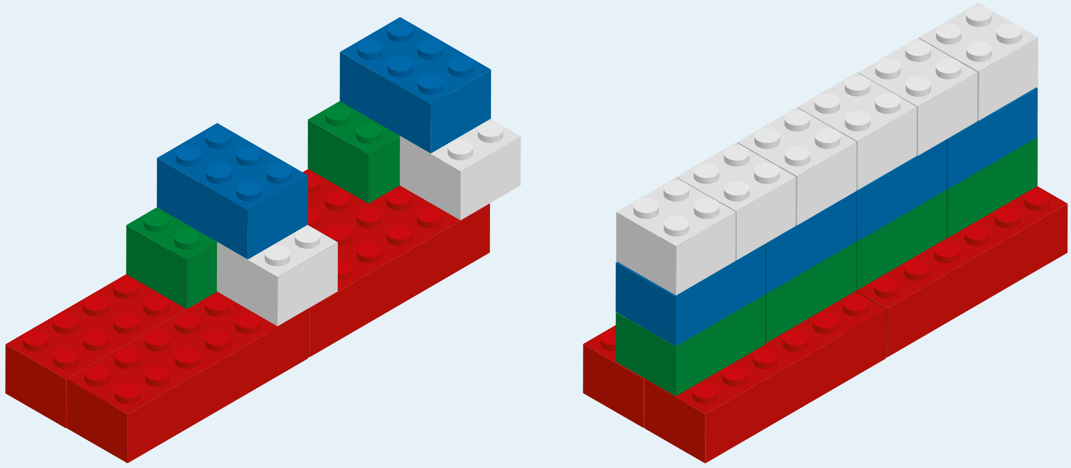
a What is coupled data assimilation?

In numerical weather prediction, data assimilation is the combination of short-range forecasts with observations to arrive at the best possible estimate of the current state of the Earth system. This estimate, called the analysis, is used to initialise forecasts. In coupled data assimilation, the observations of one Earth system component influence the analysis in other components.

There is enormous variety in the configuration of coupled data assimilation systems, for both technical and scientific reasons. The atmosphere and ocean waves typically change on much shorter timescales than, for example, the ocean subsurface or land surface variables such as soil moisture. Thus, historically, assimilation systems for slower components have been developed independently of those used for the atmosphere. They may work on different operational schedules and may have different assimilation windows (the time during which observations to be used in a data assimilation cycle are made). A further complication is that different assimilation techniques may be used for the various components. It is, however, possible to categorise coupled data assimilation systems by the timing of the influence of observations of one component on the analysis in other components. We refer to strong coupling when there is an immediate impact from observations made in one component on another. If the observation impact from one component on another is lagged, then this is referred to as weak coupling. In uncoupled data assimilation, there is no observation information exchange between different components.



Schematic representation of different configurations of a coupled data assimilation system. The different-coloured bricks represent the different Earth system components, for example red the atmospheric 4D-Var data assimilation, blue the ocean assimilation, white the sea ice assimilation, and green the land surface assimilation. The right-hand configuration, in which the components are all aligned with the atmospheric 4D-Var, represents a strongly coupled assimilation system. The left-hand configuration represents a weakly coupled assimilation system. Here the bricks are differently sized to represent different assimilation methods, and the components can overlap to reflect the lag in the observation information passing between components.

Tens of millions of observations are processed and used daily. The vast majority of these come from polar-orbiting and geostationary satellites carrying a range of instruments, such as infrared and microwave imagers, scatterometers and altimeters. In addition to satellite observations, there are in situ observations from aircraft, radiosondes and dropsondes, as well as observations from ships, buoys, land-based stations and radar.

The ocean and ice surface conditions need to be supplied to the atmospheric model to drive the 4D-Var data assimilation and the uncoupled short-range forecasts used to produce the atmospheric analysis. Until the implementation of IFS Cycle 45r1 in June 2018, level 4 (L4) gridded products (satellite observations processed to produce complete gridded fields) were used to provide global coverage of sea-surface temperatures and sea ice concentrations to the data assimilation system. The L4 product used was the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA), a 0.05° resolution dataset that does not use a dynamical model. For SST, OSTIA combines satellite data from the Group for High Resolution Sea Surface Temperature (GHRSST) and in-situ observations to produce a daily analysed field of foundation sea-surface temperature (SST at a depth of about 10 m, not sensitive to the diurnal cycle). Sea ice concentration fields in OSTIA are derived from OSI SAF L3 satellite observations of sea ice concentration.

When using an external L4 product as the lower boundary for the atmosphere, ECMWF's high-resolution data assimilation system can stand alone, independent of any information from the OCEAN5 analysis. However, OCEAN5 is a different possible source for the lower boundary ocean and ice fields that the atmospheric data assimilation system needs. If these fields are used, the atmospheric and ocean data assimilation systems are combined into a larger, weakly coupled assimilation system.

Weakly coupled data assimilation

When using an external L4 product as the lower boundary condition over the ocean, only those boundary conditions and observations in the atmosphere will influence the atmospheric analysis. This change in atmospheric analysis will lead to a change in the forcing fields by which the ocean analysis is driven. This will lead to a change in the ocean analysis. However, observations of the ocean not used by OSTIA, such as observations of currents, will not influence the atmospheric analysis as no information from the ocean model is propagated back to the atmospheric analysis. This system can be thought of as a 'one-way' coupled assimilation system.

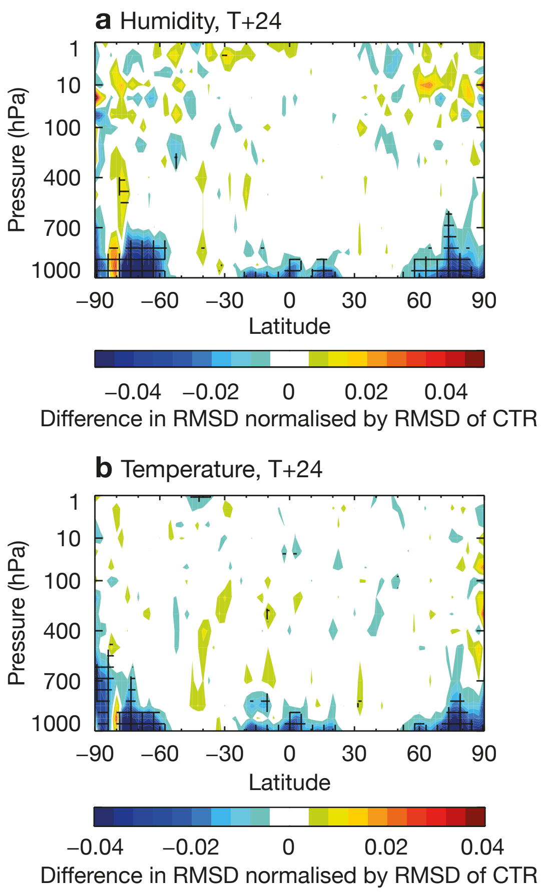


FIGURE 1 Latitude–pressure diagram of the normalised difference in root-mean-square deviations (RMSD) of forecasts from the experiment's own analysis with and without weakly coupled data assimilation (EXP minus CTR) for (a) 24-hour humidity forecasts and (b) 24-hour temperature forecasts, for the period 9 June 2017 to 21 May 2018. Blue shades mean that the differences between forecasts and the analysis are smaller when weakly coupled data assimilation is used. Hatching indicates statistically significant differences.

To form a 'two-way' weakly coupled ocean–atmosphere data assimilation system, ECMWF has begun to use fields from the OCEAN5 analysis as the lower boundary condition for sea ice (since IFS Cycle 45r1) and SST (since IFS Cycle 46r1) in the atmospheric data assimilation system. This means that observations of the ocean and the sea ice which previously only influenced the ocean analysis now also modify the atmospheric analysis via the lower boundary conditions. The effect is not immediate within a given assimilation cycle but is delayed. The reason for this is that the OCEAN5 near-real-time analysis only produces a single analysis every day. The atmospheric analysis must wait for the ocean analysis fields, valid at the end of the day, to be produced to force the next day's atmospheric analyses. Hence, we categorise this as a weakly coupled data assimilation system for the ocean, sea ice and the atmosphere.

The analysis of SST and sea ice concentration from OCEAN5 may not always be better than the OSTIA product. Indeed, there are known deficiencies in the OCEAN5 analysis that would lead to degradations in forecast performance if left unmitigated. For example, in the extratropics the position of western boundary currents such as the Gulf Stream is known to be less accurate in OCEAN5 than in OSTIA.

This problem has been addressed within the model by using a 'partial-coupling' approach, in which the tendencies (the model evolution from its initial conditions) rather than the absolute values of SST are passed to the atmosphere. Since the ocean model in OCEAN5 has greater effective resolution in the tropics than the extratropics, the partial coupling is only required at higher latitudes (> 25°), where the ocean model is unable to resolve eddies.

In IFS Cycle 46r1, the SST in the atmospheric analysis is aligned with that used to initialise the coupled forecast, which is SST from the OCEAN5 analysis in the tropics, smoothly transitioned to the OSTIA SST in the extratropics.

Evaluation

To assess the impact of the weakly coupled ocean–atmosphere configuration compared to the previous use of L4 products for the lower boundary conditions in the atmospheric data assimilation system, two experiments were conducted: a control experiment (CTR) which does not use any weakly coupled assimilation, and a second experiment (EXP) with weakly coupled assimilation in both sea ice and sea-surface temperature.

Both experiments are based on IFS Cycle 45r1 at the operational high-resolution grid spacing of 9 km (TCo1279). They cover the period 9 June 2017 to 21 May 2018. From each analysis, a coupled ocean–atmosphere forecast is produced and is compared against the respective analysis. When a coupled forecast is initialised, the atmospheric lower boundary conditions are replaced by those coming from the ocean and sea ice analysis. If, as is the case here, the ocean and sea ice analyses are similar, then weakly coupled data assimilation does not change the coupled forecasts dramatically. However, the results show that there are differences between EXP and CTR in the atmospheric analysis at the interface between the ocean/sea ice and the atmosphere, and that these propagate vertically into the troposphere. The extra information provided by the weakly coupled system thus aligns the atmospheric analysis more closely with coupled forecasts, at least in the short range.

Figure 1 shows the impact of weakly coupled data assimilation on differences between the analysis and forecasts of atmospheric humidity and temperature 24 hours ahead. There are three distinct regions where these differences are significantly reduced: the tropics and the two polar regions. This is the result of weakly coupled data assimilation relating to the treatment of tropical SST on the one hand and sea ice on the other. The hatching indicates that the differences are

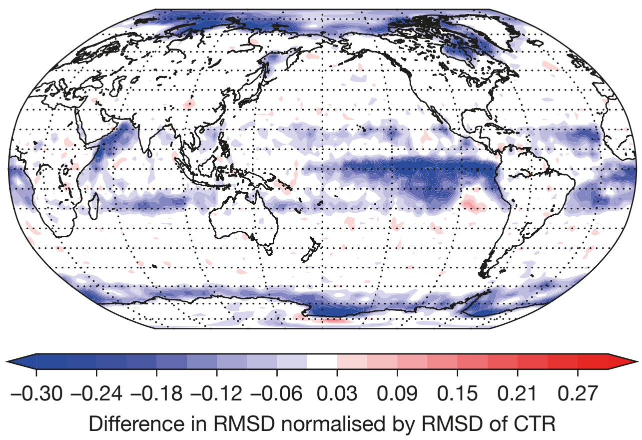


FIGURE 2 Normalised difference in root-mean-square deviation (RMSD) of forecasts from the experiment's own analysis with and without weakly coupled data assimilation (EXP minus CTR) for forecasts of temperature at 1,000 hPa 24 hours ahead, for the period 9 June 2017 to 21 May 2018. Blue shades mean that the differences between forecasts and the analysis are smaller when weakly coupled data assimilation is used.

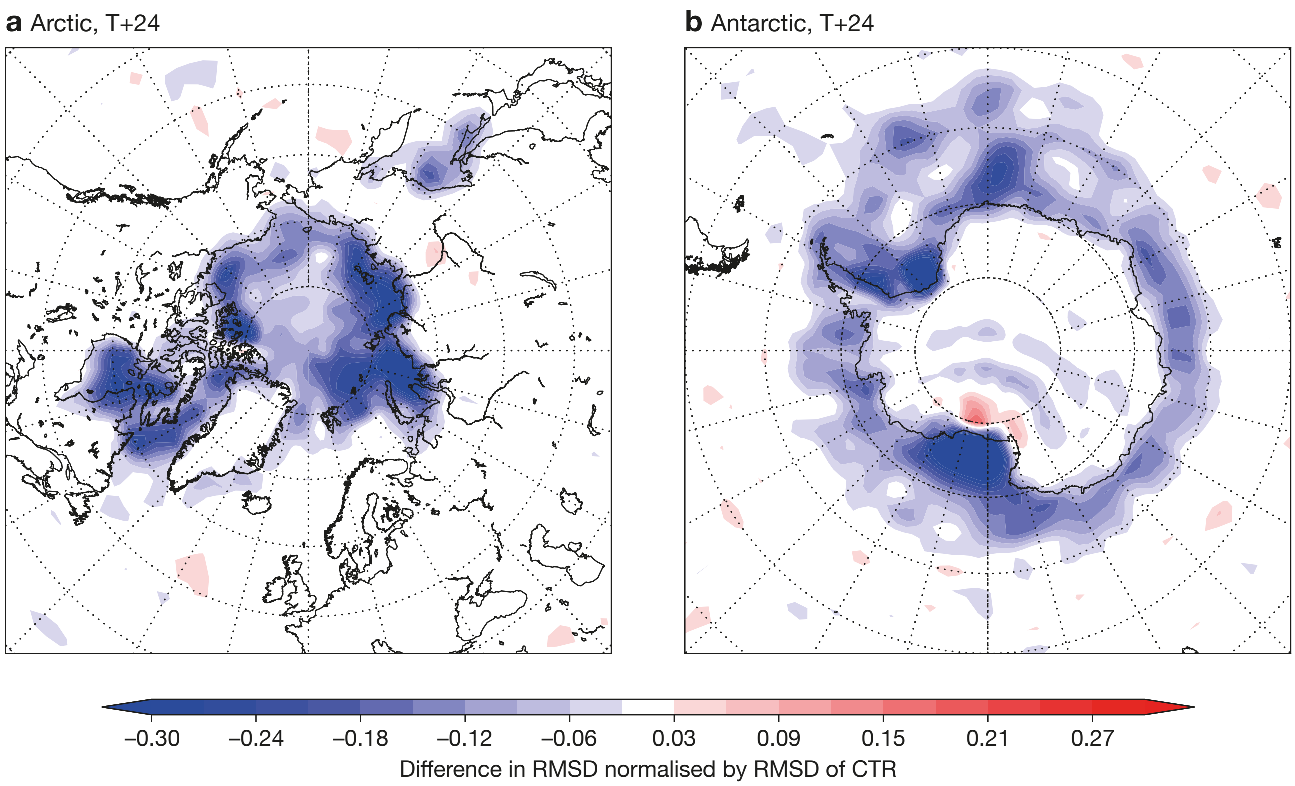


FIGURE 3 Normalised difference in root-mean-square deviation (RMSD) of forecasts from the experiment's own analysis with and without weakly coupled data assimilation (EXP minus CTR) for forecasts of 1,000 hPa temperature 24 hours ahead in (a) the Arctic and (b) the Antarctic, for the period 9 June 2017 to 21 May 2018. Blue shades mean that the differences between forecasts and the analysis are smaller when weakly coupled data assimilation is used.

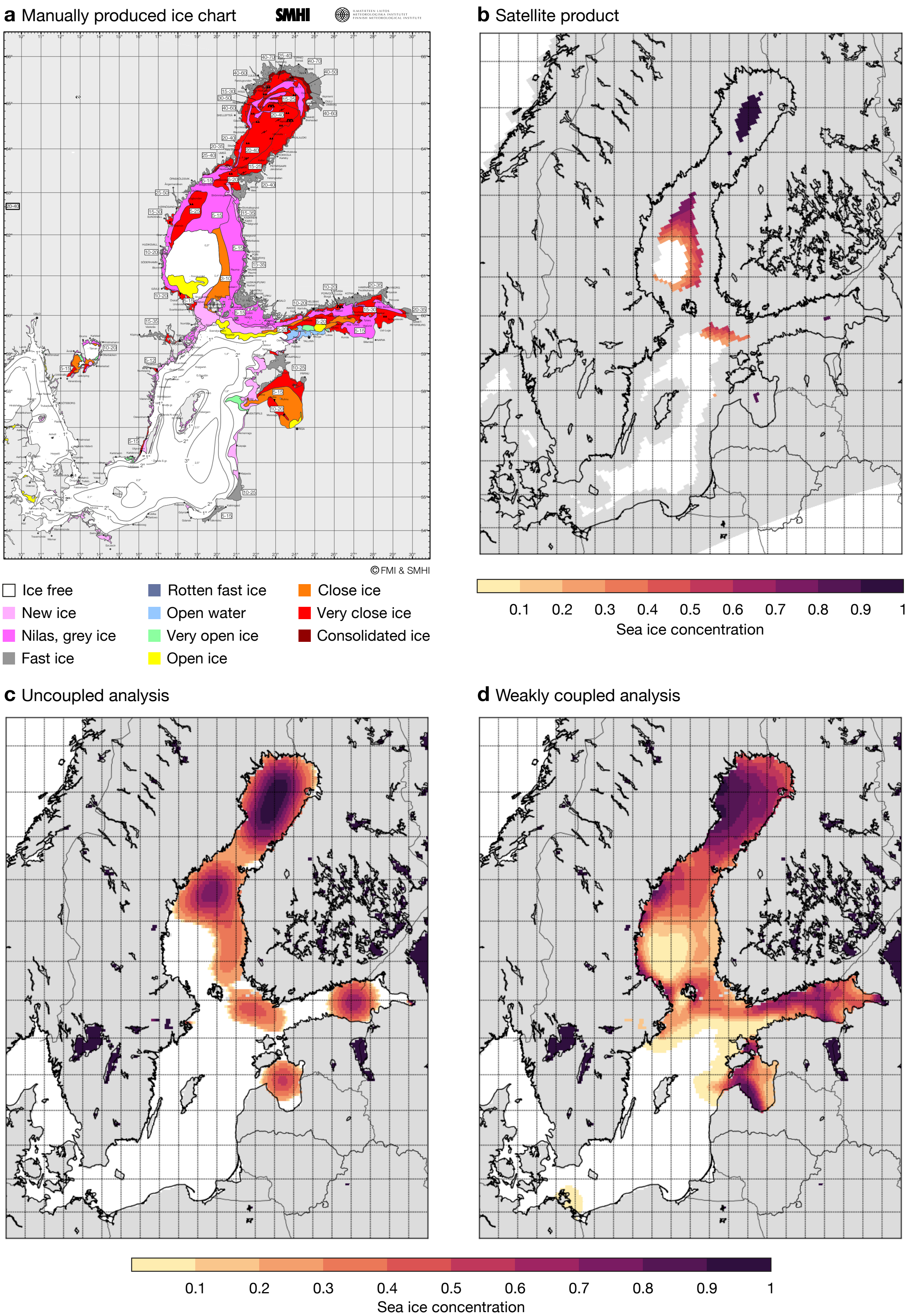


FIGURE 4 The maps show (a) a manually produced Finnish-Swedish ice chart of the Baltic Sea for 5 March 2018 (copyright FMI and SMHI, 2018), (b) the OSI SAF 401-b satellite sea ice concentration product for the same day (missing data around coastlines due to coastal contamination in satellite retrievals of sea ice concentration are shown in grey), (c) the corresponding uncoupled ECMWF sea ice concentration analysis, in which the ice field is very smooth and centred on the available OSI SAF L3 observations, and (d) the ECMWF sea ice concentration analysis using weakly coupled data assimilation. Note the much more realistic structure and the good agreement with the manual ice chart when using weakly coupled data assimilation.

statistically significant. As can be seen in Figure 1, the influence of weakly coupled data assimilation over sea ice extends up to roughly 700 hPa, which is higher than the impact related to SST in the tropics. This is likely due to a different usage of microwave satellite observations, which are strongly influenced by the presence of sea ice, in the weakly coupled atmospheric 4D-Var. Figure 1 also shows that weakly coupled data assimilation does not have much of an impact on the upper troposphere or spatial regions where weakly coupled data assimilation is not active. Beyond 48 hours, the differences between EXP and CTR are small (not shown). This is because by then forecast errors rather than different data assimilation methods are the main cause of differences between forecasts and the experiment's own analysis.

The map in Figure 2 confirms that the improvement in the analysis related to SST is restricted to the latitudinal band for which weakly coupled data assimilation is active. Within this band, there are variations in the differences between forecasts and the analysis. For instance, for temperature at 1,000 hPa, the strongest positive impacts are seen in the Arabian Sea, the eastern Atlantic and the eastern Pacific.

In the Arabian Sea, there is evidence of improvements in the analysis of other variables, such as low-level winds and significant wave height (not shown). This indicates that weakly coupled data assimilation improves the position of the summer monsoon, which is known to be difficult to predict well. The regions of positive impact in the Atlantic and the equatorial Pacific tend to have high cloud cover. This persistent cloud cover makes observing the SST from satellites difficult. The use of the ocean model within the OCEAN5 analysis system seems to be able to effectively fill the observational gap.

In the polar regions, we see significant reductions in the differences between coupled short-range forecasts and the analysis due to weakly coupled assimilation. Figure 3 shows that the improvements due to sea ice are not confined to the ice edge but encompass the entire extent of sea ice cover.

There is also evidence that the weakly coupled assimilation system improves the ocean analysis as the surface increments (the difference between the short-range forecasts used in the data assimilation system and the analysis) are reduced while maintaining the fit to observations (not shown).

A detailed look at the spatial distribution of sea ice in the Baltic Sea (Figure 4) shows that weakly coupled data assimilation captures the structures seen in the manual ice chart much better than the L4 product. Note that because of the geography and coastal contamination of satellite observations, this is a particularly challenging area for sea ice concentration analyses. The use of the background information coming from the dynamical model leads to a much more realistic spatial distribution of the ice field.

Conclusions and future plans

Weakly coupled data assimilation enables components of the Earth system with different timescales and assimilation methods to be linked together. As an alternative to using purely observation-based L4 products for the lower boundary of the atmosphere, with their associated delays, weakly coupled data assimilation enables dynamical models of the ocean and sea ice to fill in the gaps in observations and to propagate fields to the appropriate time. It improves the match between coupled forecasts and ECMWF's analysis in regions near the interface between the atmosphere and the ocean/sea ice and up to an altitude of about 700 hPa.

In the future, we will look to build on the currently operational system to couple more ocean variables to the atmospheric analysis. For example, a weakly coupled data assimilation system that has knowledge of ocean currents should be able to better make use of scatterometer data, and it should enable improvements in wave modelling.

The system described in this article represents the first steps in operational coupled ocean–atmosphere assimilation at ECMWF. It represents the baseline for further coupled ocean–atmosphere data assimilation developments, which will rely on a progressive implementation of combined weak and outer-loop coupling. In outer-loop coupling, coupled model trajectories are used within the data assimilation system whilst the linearised trajectories remain uncoupled (see Schepers et al., 2018). This will give more immediate impact across the various Earth system components for the benefit of medium-range and extended-range forecasts.

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Arctic weather forecasting – in the high Arctic

Michael Tjernström, Gunilla Svensson (both Stockholm University), Linus Magnusson (ECMWF)

In spring 2018, scientists from several nations and a number of different projects were getting instruments and systems ready for the Arctic Ocean 2018 (AO2018) expedition on the Swedish research icebreaker Oden. Oden was heading for the high Arctic during August and September. The main goal was to investigate the formation and life cycle of low-level Arctic clouds (Box A). One of the projects participating in this expedition was Arctic Climate Across Scales (ACAS), funded by the Swedish Knut and Alice Wallenberg Foundation and endorsed by the Year of Polar Prediction (YOPP). One of the aims of this project is to increase the amount of meteorological observations from the sparsely observed central Arctic Ocean (Box B). The idea is to help advance numerical weather prediction and climate modelling by developing a quasi-unattended meteorological observatory on Oden. The need for minimal human intervention stems from the fact that the primary limitation for participating in icebreaker-based research is the limited number of berths on board the icebreakers that are used as platforms. As a contribution to YOPP, and in collaboration with the EU-funded Horizon 2020 project APPLICATE, we have begun to evaluate ECMWF operational forecasts in the Arctic using these observations from ACAS. Initial findings suggest that wind forecasts are of high quality but that there are some issues with cloudiness and temperature forecasts.

Expedition trajectory

Oden left Longyearbyen on Svalbard on 1 August, reached the North Pole on 12 August and, a few days later, moored to an ice floe about 2 km^2 in size near 89.5°N and 30°E. The ship drifted with this ice floe for a month, facilitating observations on the ice in addition to those taken on board. The expedition ended back in Longyearbyen on 21 September (Figure 1).
The researchers used the almost stationary ice drift period, from 15 August to 14 September, to collect data for the forecast evaluation.

Ice conditions in early August along the northward track (Figure 1) were unexpectedly difficult. Although the ice edge was located unusually far north of Svalbard, the ice was thick and there was very little open water between ice floes once inside the pack ice. Such open water is a key factor for icebreaking. There were also a larger-than-expected number of icebergs all the way to the pole. A persistent high-pressure ridge during early August likely contributed to strong ice convergence, which created the harsh icebreaking conditions. The increased mobility of the ice probably resulted in the large number of icebergs, which must have come from land. During the ice camp, expedition members named a nearby iceberg Mt John, after the meteorological research engineer who was the first to climb it and who raised the Union Jack at its top.

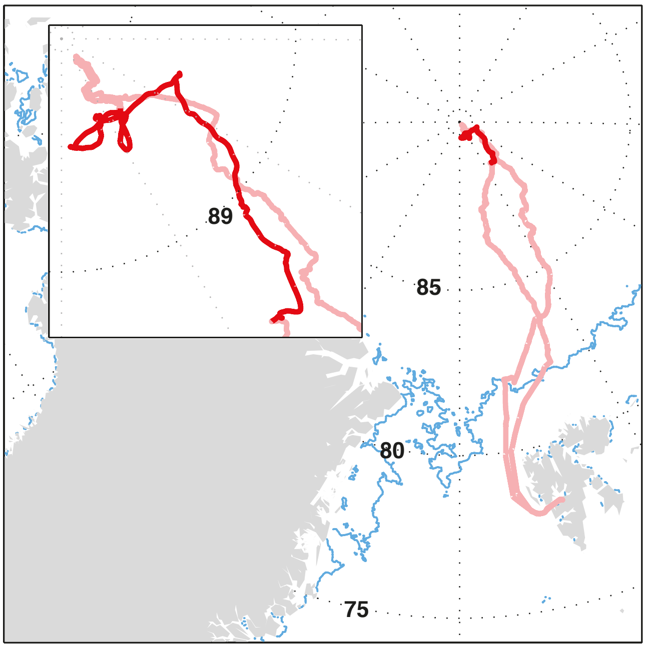

FIGURE 1 Map of the AO2018 cruise track, with the track during the ice-drift period shown in darker red. The light-blue line is the ice edge in early August.

The weather was typical for the Arctic Ocean summer, with a lot of low cloud and fog. Throughout the expedition, fog prevailed for about 25% of the time, the average cloud fraction was close to 90%, and the lowest cloud base typically around 100 m. There was melting snow on the ice almost all the time until the end of August, when the summer melt ended, ensuring a high surface albedo in spite of many melt ponds (see Figure 2). Hence, on the few occasions when the clouds broke up and the sun came out, the change in surface net shortwave radiation was unable to balance the longwave cooling, causing the temperature to drop. This special condition applies through most of the summer over sea ice in the high Arctic. Near-surface temperature

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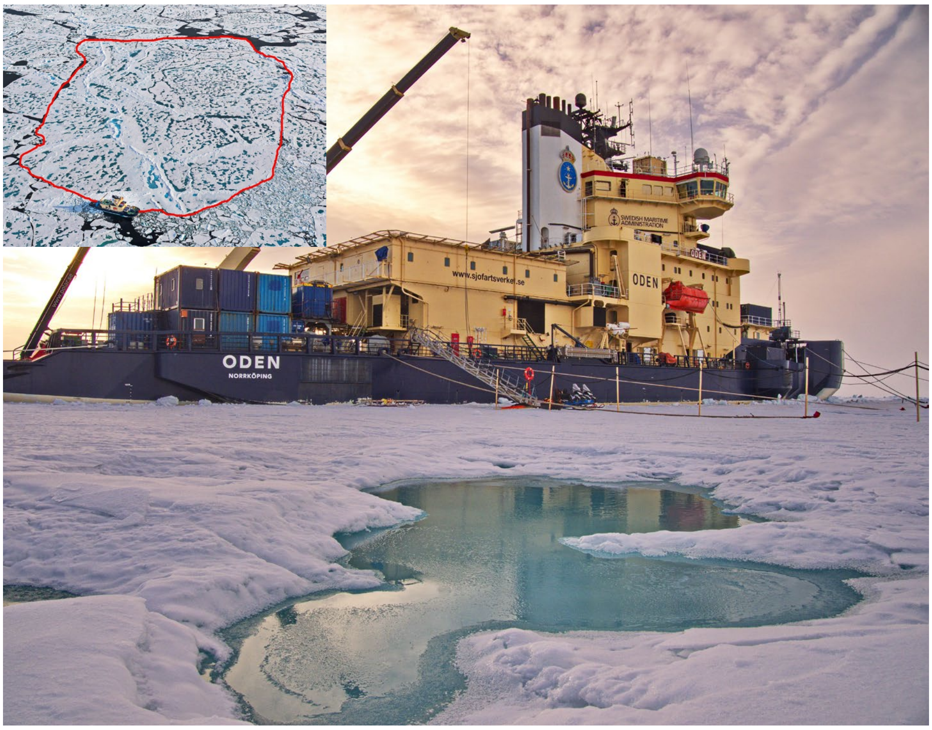

FIGURE 2 The research icebreaker Oden moored to the ice in the central Arctic on 20 August. The insert shows Oden surrounded by drift ice. The turquoise pond in the foreground of the main photo is fresh meltwater, whose colour comes from the bare ice at the bottom. The insert was taken earlier, on 14 August, and shows quite a few melt ponds of varying size. On 20 August, however, ice had started to form at the top of the melt pond. The gangway is suspended from the ship's main crane so that, when a polar bear approaches, it can be quickly lifted once everyone is on board. The posts to the right support power lines to some of the instrument systems. If the cables were allowed to rest on the surface, they would melt into the ice and become impossible to extract. The battery-powered snowmobiles parked by the gangway were the main mode of transport for heavier equipment.

rarely goes above zero while the surface is melting. When the sun comes out, people can feel its warmth due to darker-coloured clothes, but the temperature typically plummets.

On-board forecasting

The primary purpose of on-board weather forecasting was to support operational planning. In transit it was used for navigation, although the ship's track was more dependent on ice conditions. Weather forecasts are crucial for determining when certain activities can happen, such as when to fly the helicopter, start deploying instruments on the ice or start packing up. For example, the ice camp operations were ended one day earlier than originally planned, a decision based on forecasts of an approaching storm. Work on the ice must always be planned with safety as the highest priority. It becomes dangerous in stormy conditions and in dense fog, when the polar bear guards on the ship's bridge cannot see far enough to warn about approaching animals. But forecasts were also used for scientific decisions, for example on cloud top heights and wind speeds for the tethered balloon flights, or for when Oden had to be moved and rotated to keep the bow upwind to protect on-board air-pollution sensitive instruments from contamination from the ship itself.

But weather forecasting for an icebreaker expedition to the high Arctic comes with some special challenges. Probably the most substantial is the limited communications bandwidth. The Internet is not available and therefore any forecast products had to be sent to the ship in a predetermined graphical format via a satellite phone email service, each message smaller than a few hundred kilobytes. Without the possibility to download any of the extra information provided from weather services as a part of the YOPP special observations periods, only limited predetermined data was available. A second challenge is that there are very few observations in the area other than our own, and on top of this the ship is moving. Even when moored to an ice floe, it moves, albeit slowly. So, the operational forecasting relied to a great deal on the experience of the ship's forecast meteorologist, who on Oden also served as local air traffic controller for the helicopter operations, drawing on very limited numerical weather prediction output from ECMWF and real-time satellite imagery, received directly from polar-orbiting satellites. ECMWF data were used because national regional models do not cover the area in question.

ECMWF forecasts up to three days ahead were turned into tailored forecast maps at the Swedish Meteorological and Hydrological Institute (SMHI) and transferred via satellite phone link twice a day. One set of maps combined surface pressure, wind, precipitation and temperature and a second set of maps combined the 850 hPa geopotential, wind, temperature and relative humidity. The wind at about 140 m and vertically integrated lower-level precipitable water were provided on a third set of maps. APPLICATE collaborated with ACAS to provide an additional experimental forecast product for Oden's position, twice daily. This was extracted from ECMWF's operational high-resolution forecast (HRES) for a single column and was provided in the form of three graphical images, combining time–height sections of temperature and cloud water with 2-metre and skin temperature; a specific humidity time–height section with accumulated precipitation and cloud-water path; and a time–height section of wind speed with 10-metre wind speed and direction. These were too large for the satellite phone email delivery and were transferred to Oden via satellite phone FTP.

Evaluating the forecasts

Important for understanding this evaluation is that both 3-hourly SHIP observations and 6-hourly BUFR messages from Oden's soundings were assimilated in ECMWF's Integrated Forecasting System (IFS). The forecasts were first evaluated subjectively by the ACAS Principal Investigator and the ship's forecast meteorologist on the fly. The largest forecast challenge was clouds and fog, and here the IFS cloud forecasts provided little direct guidance. This was somewhat of a

a The Arctic Ocean 2018 expedition

The overarching research focus for the scientists on board Oden during the AO2018 expedition was Arctic low clouds, how they form and dissipate, and how they interact with the surface. One main outstanding question is where the cloud condensation nuclei, on which clouds form, come from, since there are so few known local sources. Are the aerosols formed locally or are they transported from far-away sources, anthropogenic or natural? How important are different aerosol sources for the formation and life time of Arctic low-level clouds compared to other processes, and how do the clouds affect the surface energy budget?

To help answer these questions, a large amount of aerosol and atmospheric chemistry instruments were deployed on Oden and on the ice. To understand the interactions with the surface, the physical, chemical and biological characteristics of sea ice and the upper ocean were also measured, mostly during the ice camp, when access to the ice was easier. Meteorological instruments were used to characterise the vertical atmospheric column from the surface through the troposphere. They included radiosondes and several instrument payloads carried by tethered balloons, a Doppler cloud radar, different lidars and micrometeorological instruments, on board and on the ice.

For operational meteorology, 3-hourly SHIP observations and 6-hourly radiosoundings were conducted and submitted to the Global Telecommunication System (GTS) through the UK Met Office. The UK National Centre for Atmospheric Science (NCAS) provided the radiosounding station and Environment and Climate Change Canada (ECCC) provided radiosondes. These observations were then available for operational assimilation at ECMWF and other weather centres.

The photo shows a view of Oden taken from the top of the 20-metre bow mast. The two rows of containers served as laboratories or workshops. Oden's permanent laboratory is located below the lowermost row of containers and some of the remote sensing instruments (microwave profiler and Doppler lidar) were installed on top of the rightmost container; the cloud radar antenna is located in front of the row of containers. More meteorological instruments were deployed on the roof of the bridge.

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problem for AO2018 since low visibility prohibited work on the ice, due to polar bear hazards, and limited the use of the helicopter. However, quite often the predicted lower-troposphere precipitable water was more useful for judging the risk of fog than the cloud forecast directly from the model. In fact, this product was quickly nicknamed ‘fog chart’ even though there is neither visibility nor cloud water on the map. The failure to correctly forecast clouds also affected the surface energy budget and therefore the temperature forecast: predicted temperatures were often too high. The IFS wind forecast, on the other hand, quickly became considered very accurate, almost surprisingly so. Especially the wind direction forecast became trusted. This was important in AO2018 to determine when the ship had to be rotated to make sure the bow kept facing the wind, to limit contamination from the ship for some of the measurements.

The objective evaluation has now started, focusing on a few variables at first. We use observations from the 7th deck weather station, about 20 m above the surface, and 6-hourly soundings launched from Oden’s helipad, 14 m above the surface. For simplicity, we have interpolated IFS model output to the resolution of the sounding data. This results in a fine-scale vertical error structure that is meaningless and needs to be disregarded; the model does not have such a high vertical resolution and so could not be expected to resolve details in the soundings. We chose this method to avoid having to predetermine an appropriate averaging scale for the observations. For the 7th deck weather station, the observations were averaged over 5 minutes centered on the forecast time. We define model bias as the median difference between the model and observations.

As mentioned above, the IFS cloud forecast was a problem. The forecasts tended to overestimate cloudiness and did not capture the few cloud-free periods. The even fewer cloud-free periods that were predicted did not materialise in reality. One effect of this is clear in Figure 3, which shows overlapping 3-day forecasts of 20-metre temperature together with observations. For example, around 17 August the clouds dissipated and the observed temperature dropped for 2 to 3 days, down to –5°C, while the forecasts maintained the clouds and hence a too high temperature. It is interesting to note that the initial temperatures during this period were often lower, showing the effect of assimilating the observed temperature. However, the forecast warm bias returns within 6 to 12 hours. The predicted near-surface temperature features a pronounced warm bias throughout, which we believe is at least partly due to the cloud forecasts. Predicted temperatures are (almost) never below the observations and sometimes, during colder periods, the model is up to 6°C too warm. Before 28 August, when the surface is still melting, the predicted near-surface temperature is near-constant at about 0.5°C. Although errors become larger later, this is an unphysical solution since the surface skin temperature of melting snow and ice cannot be above 0°C, even when the surface energy budget is constantly positive; all the surplus energy goes into melting and the temperature is stuck at the melting point. Preliminary data indicate that the net surface energy budget (not shown) is positive at about 20 W/m^2 until at least 23 August and does not go permanently below zero until around the end of August. Around 28 August, the predicted temperatures suddenly drop and then correctly stay below 0°C. While the warm bias in the forecasts actually increases when the surface energy budget becomes negative and the surface starts freezing, the forecasts faithfully

b Why we need more weather and climate data from the Arctic

Climate change is faster in the Arctic than for any other region on Earth: annual average near-surface temperatures are increasing over twice as fast as the global average. As a consequence, sea ice cover is decreasing, especially at the end of the melt season in late summer, and the ice is also thinning rapidly. Although many hypotheses have been put forward, the understanding of the underlying mechanisms behind this amplification, often referred to as ‘Arctic amplification’, is poor, but low clouds are known to be an important factor in the Arctic.

Climate and weather forecast models typically perform less well in the Arctic than for other regions, and as the Arctic warms up and the ice decreases, interest in the ability to model weather and climate here is rapidly increasing. The World Climate Research Programme (WCRP) and the World Meteorological Organization (WMO) jointly implemented the International Polar Year (IPY) in 2007 and 2008. Following on from this, the World Weather Research Programme (WWRP) initiated the Polar Prediction Project (PPP, 2013 to 2022). The PPP’s flagship activity is the Year of Polar Prediction (YOPP), whose core phase took place from May 2017 to June 2019. Within this whole time frame, the research icebreaker Oden carried substantial meteorological observation capability to the Arctic Ocean on three previous expeditions. Since there are very few conventional observations, data gathered during expeditions can help to better constrain forecasts and to improve numerical weather prediction models.

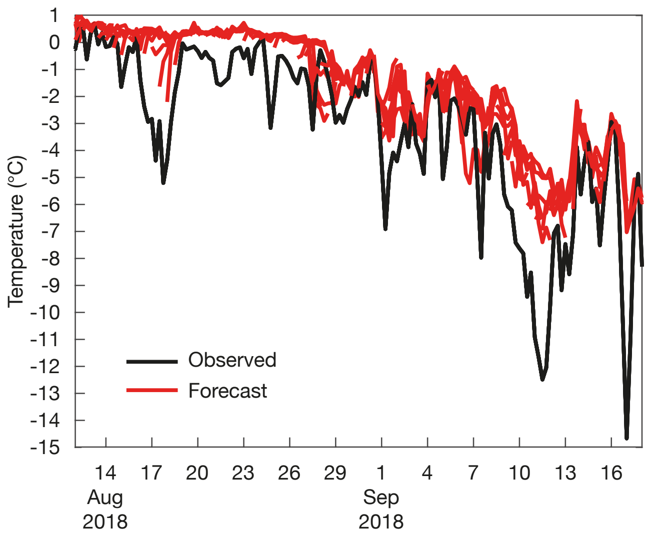

FIGURE 3 Plot of the observed and predicted 20-metre temperature. The overlapping 3-day forecasts are initiated every 12 hours while the observations are 5-minute averages around forecast times.

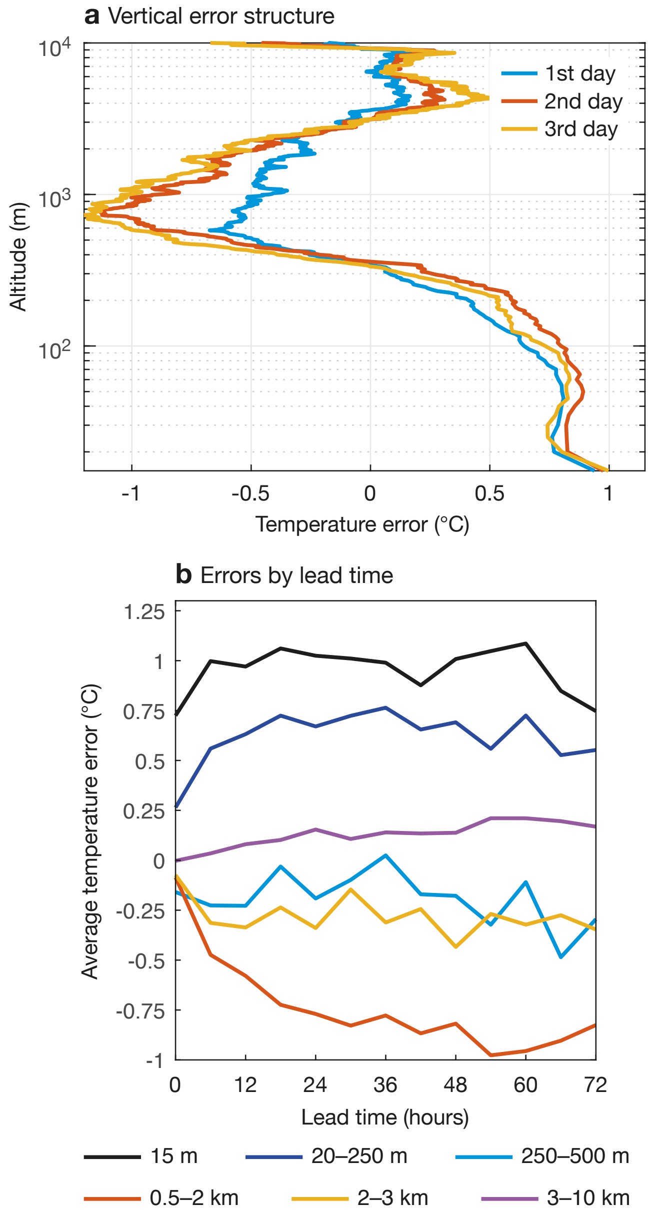

FIGURE 4 Forecast temperature errors (°C), showing the median error with respect to soundings (a) as a function of height, for three daily averages (forecast days one to three), and (b) as layer averages as a function of forecast time. Note the logarithmic height scale in (a).

capture the timing of rapid changes in temperature due to synoptic-scale weather.

Figure 4a reveals a distinct vertical structure of the bias in the temperature forecasts. It is interesting to note that, except at altitudes of about 0.5–1 km and 4–6 km, there is not much error growth with forecast length. The warm–cold–warm–cold bias structure with increasing altitude looks like a 'model climate' that the forecasts snap into very fast, even when provided with highly accurate initial conditions. Except in the boundary layer, the initial errors are small (Figure 4b). The boundary-layer error is large from the initial time and grows further over the first six hours, while in the 0.5–2 km layer a large negative bias develops, mostly over the first day. The largest errors thus appear in the layer below 2 km. The analysis so far indicates that the boundary-layer warm bias is related to the handling of the surface energy budget, which is probably also affected by cloud forecasts. The cold bias on top of the boundary layer is probably also due to errors in the prediction of clouds. Previous summer expedition data has indicated that the top of the very persistent low clouds is usually near the 1-kilometer range. In other layers of the atmosphere, error growth is small and systematic errors are within a few tenths of a degree.

Outlook

We will continue to evaluate the IFS forecasts used during the expedition by looking at more variables, such as clouds and the terms in the surface energy budget, and also explore differences between forecasts initiated at 00 UTC and 12 UTC, to further analyse several of the features discussed above. Within APPLICATE we will also perform and evaluate forecast experiments with different new formulations. Work is already ongoing to address the issue of surface skin temperatures for melting snow and ice, to improve formulations of snow on the ice and for turbulent mixing in clouds. The data and evaluation from this observation campaign are being used by ECMWF to help identify shortcomings in the model physics. Progress in addressing the issues identified is already being made. This collaborative effort between ECMWF and the ACAS project thus illustrates the benefits of observation campaigns for model development. In June 2019, ECMWF held a workshop where leading scientists discussed how to further strengthen the many potential links between observation campaigns and model development.

Towards sub-seasonal to seasonal forecasts for EFAS

Fredrik Wetterhall

ECMWF is currently developing a sub-seasonal to seasonal (S2S) hydrometeorological forecasting system for the European Flood Awareness System (EFAS) to complement the existing seasonal hydrometeorological forecasts that have been produced operationally since December 2016. The work on EFAS-S2S is part of ECMWF's role as the computational centre for EFAS, the early warning system for floods of the European Commission's Copernicus Emergency Management Service (CEMS). The new system will use ECMWF extended-range forecasts, which are issued every Monday and Thursday with a lead time of up to 46 days. As expected, tests have shown that forecast skill is comparable to that of seasonal forecasts when the forecasts are initialised at the same time. The advantage of EFAS-S2S compared to seasonal forecasts lies in the more frequent updates of the hydrological and meteorological initial conditions. The new system is planned to be made operational later this year.

The growing EFAS portfolio

EFAS (*www.efas.eu*) has been running operationally since 2012. ECMWF's responsibilities include running the hydrometeorological computations, archiving the data and disseminating the forecasts through the EFAS web interface. EFAS delivers forecasts over many time ranges, from nowcasting flash floods to probabilistic medium-range and seasonal forecasts. The medium-range forecasts are produced twice daily up to 10 days ahead, whereas the seasonal forecasts, forced with ECMWF's seasonal forecasting system SEAS5, are issued once a month and provide an outlook of up to 8 weeks ahead (Arnal et al., 2018). The main idea of the EFAS-S2S forecasts is to provide more frequent outlooks of the hydrological situation than the seasonal forecasts can provide. This would ideally provide decision-makers with more up-to-date, actionable information at the timescales they require (Wetterhall & Di Giuseppe, 2018).

In the numerical weather prediction community, there is growing interest in the sub-seasonal to seasonal range, loosely defined as the range beyond 15 days up to 2 months. This has manifested itself in many projects and initiatives, including the S2S Prediction Project launched by the World Meteorological Organization in 2013. At the S2S time range, the predictability of meteorological surface variables over Europe is in general quite low, although this depends on the spatial and temporal scales. This limits the use of S2S predictions of such variables for decision-making. However, for many catchment areas the skill of S2S hydrometeorological forecasts, e.g. of river discharge and water levels of rivers and lakes, depends to a considerable extent on hydrological initial conditions, such as snow, soil moisture and ground-water storage. Furthermore, the hydrological time of concentration, meaning the time it takes for water to flow from the most remote point in a watershed to the outlet, can be as much as weeks and months for the largest river systems. Therefore, the skill of hydrometeorological forecasts is expected to be higher compared to that of forecasts of meteorological variables for the same areas.

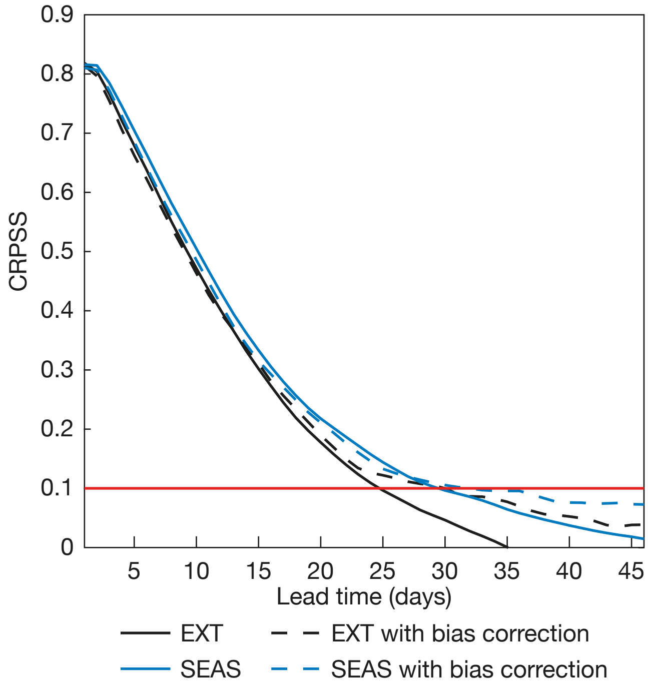

FIGURE 1 CRPSS of daily discharge as a function of lead time for EXT and SEAS forecasts for all starting months and evaluation points, with and without bias correction.

S2S experiment

To test hydrometeorological predictability at the S2S range, an experiment was set up using extended-range

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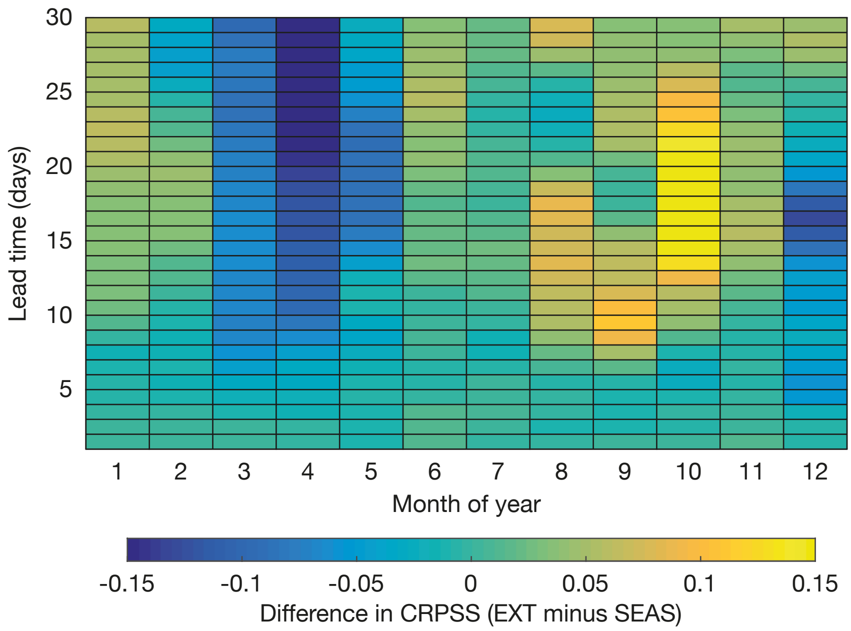

FIGURE 2 Difference in CRPSS of daily discharge of the EXT and SEAS forecasts. Positive values mean that EXT forecasts are better than SEAS forecasts.

hydrometeorological ensemble re-forecasts (hereafter referred to as EXT) covering 20 years up to June 2017. The 11-member re-forecasts were produced using the latest available operational version of ECMWF's Integrated Forecasting System (IFS Cycle 43r3) and were issued twice weekly (Mondays and Thursdays) with a lead time of 46 days. The EXT re-forecasts were compared with hydrometeorological re-forecasts forced with ECMWF SEAS5 seasonal re-forecasts and referred to hereafter as SEAS. SEAS5 meteorological re-forecasts cover 36 years (1981–2016), have 25 ensemble members and are initialised on the first of each month, but only re-forecasts from the same period as for the EXT forecasts were used in the experiment. The meteorological re-forecasts used to produce SEAS and EXT were initialised using the ERA-Interim reanalysis. For more details on the forcing data, see Table 1.

The meteorological forcing was run through the hydrological model LISFLOOD (the operational model in EFAS) across the European domain to produce the hydrometeorological re-forecasts. LISFLOOD has been calibrated and set up on a 5x5 km grid across all of mainland Europe. It includes a routing component, which translates the runoff into modelled discharge over the river network. The model also uses static maps to provide information on the soil, vegetation, elevation etc. The system used in this study is the same as in the operational EFAS.

Forcing data	Lead time	Grid spacing	IFS cycle	Ensemble members
Extended-range forecasts	15/46 days	18/36 km (TCo639/ TCo319)	IFS Cycle 43r3	11
SEAS5 forecasts	214 days	36 km (TCo319)	IFS Cycle 43r1	25

TABLE 1 Details of the meteorological data used in the experiment.

The hydrometeorological re-forecasts were compared against a hydrological reanalysis run using observed precipitation and temperature as forcing. This is referred to as 'simulations forced with observations (SFO)' and is used as a proxy for observations. Using simulated discharge as the ground truth means that EXT and SEAS forecast skill is compared without any effects caused by biases in the hydrological model. The scores used were the continuous ranked probability score (CRPS), bias and reliability for the modelled discharge over a selected number of points across the domain where the hydrological model was calibrated, hereafter referred to as 'outlet points' (see Mazzetti & Prudhomme, 2018). CRPS was adjusted to account for the difference in ensemble size between EXT and SEAS, in accordance with the method presented in Ferro et al. (2008).

A CRPS skill score (CRPSS) was calculated against a reference forecast consisting of randomly selected SFO simulations with the same start date as the forecasts but selected from all other years (hereafter referred to as CLIM). This reference forecast has no predictive skill, but it has the advantage of having perfect reliability and being unbiased. Bias was defined as the ensemble mean minus SFO, such that a positive bias means that the forecast is too wet. It is not straightforward to correct for the bias in the forecast, since discharge is quite a complex variable. Attempts to apply bias correction to the forcing meteorological variables have shown promise but are not unproblematic. In this study, forecasts are bias-corrected by multiplying the forecasts with a scaling factor as a function of lead time, month of year and location. The scaling factor was calculated by applying a smoothing filter to the relative mean error of the mean of the ensemble forecasts in comparison with the SFO.

Limit of predictability

To understand the potential for using forecasts in decision-making, it is essential to understand the limit of predictability. Figure 1 shows the CRPSS of discharge for all outlet points across Europe as a function of lead time for EXT and SEAS. Forecast skill is compared against the reference forecast, CLIM. The limit of predictability is here defined as the lead time when the CRPSS drops below 0.1. As shown in Figure 1, that time is in the region of 25 to 35 days across all locations and seasons. This is much more skilful than the skill of precipitation forecasts over the same area. Just looking at Figure 1, it might seem that SEAS performs better than EXT. However, when comparing EXT and SEAS for all starting months from January to December separately (Figure 2), the forecasts perform somewhat differently depending on the season. SEAS has higher skill in spring (March to May), whereas EXT has higher skill in late summer and autumn (August to November). These small differences in skill can be explained by the higher resolution of the first 15 days of the extended forecast, which leads to a better representation of precipitation in EXT in summer and autumn. The difference in skill in spring needs further investigation.

Bias and reliability

The relatively sharp decline in CRPSS can to some extent be explained by a bias in both EXT and SEAS forecasts. This is the result of a bias in the underlying meteorological forecast, especially over the winter months, which translates into a bias in discharge. The uncorrected forecast bias in EXT is not spatially consistent: it is negative (too dry) over the Alpine catchments and positive (too wet) in central-eastern Europe. The pattern is similar for SEAS. The dry bias over the Alpine catchments can to some extent be explained by a slight underestimation of precipitation in these areas, which then translates into an underestimation of the river flow. This also explains some of the lower skill in the winter months seen in Figure 2.

Reliability of a forecast is important in terms of its usefulness for decision-making. A reliable forecast can be trusted to predict the correct probability for different outcomes, regardless of the accuracy of the ensemble mean. A strongly unreliable forecast is in practice of no use and can lead to poor decisions. Figure 3 is a reliability diagram, which shows to what extent predicted probabilities are matched by the observed frequency of occurrence when such predictions are made. The closer the lines are to the diagonal, the more reliable the forecast is. The figure shows that both EXT and SEAS are slightly overconfident when it comes to predicting flow at or above the observed median. For example, high

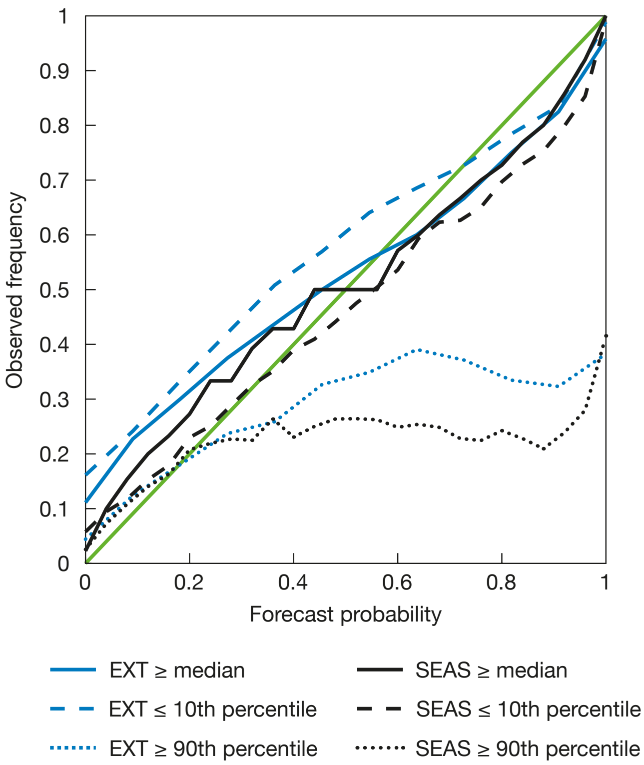

FIGURE 3 Reliability diagram for EXT and SEAS5 for week 4 for all outlet points. The solid lines indicate the reliability at or above the median of observed discharge, the dashed (dotted) lines the forecast reliability for the forecast being below (above) the 10th (90th) percentiles of observed discharge.

probabilities of such an outcome in the forecast are not quite matched by similarly high frequencies of occurrence. This can be attributed to an underestimation of the ensemble spread. The reliability regarding the prediction of low flows (dashed line, Figure 3) indicates an underprediction of low flows in EXT, which can be explained by the wet bias in the lower distribution of precipitation. SEAS performs better than EXT in this regard. High flow predictions are generally not reliable in either system, but EXT performs slightly better than SEAS.

Towards an actionable forecast

Since EXT and SEAS are comparable in performance, the main justification for the use of EXT in an operational context lies in the time gain in a response situation. More frequent forecast updates are potentially useful in decision-making. As an example, we analysed the predicted low flow for the river Rhine at a station just upstream of Cologne, Germany, during the European heatwave in the summer of 2003. This was an exceptional meteorological event, which combined significant precipitation deficits with record-breaking high temperatures. At its peak in August, extremely low discharge levels of rivers were reported in large parts of Europe. For several months, inland navigation was severely disrupted and shipping on the Danube and the Rhine came to a complete halt.

Despite the fact that, in 2003, conditions were extremely unusual from a climatological point of view, the upcoming deficit in precipitation and the high temperatures are well predicted by SEAS5 seasonal re-forecasts. The good predictability of the event is confirmed by the low discharge prediction provided by SEAS for the Rhine upstream of Cologne (Figure 4). More than 30% of the ensemble members predict extreme low-flow conditions. In fact, the observed discharge confirms that the river flow on two separate occasions, from mid- to late August (with a short interruption) and from mid- to late September, went below the 3rd percentile of the climatological distribution for the season (Figure 4). While most SEAS ensemble members predict the extreme conditions two to four weeks ahead, there is only a weak indication of the recovery period observed between the two events in the forecast starting on 1 August. A more detailed picture of this temporary recovery is conveyed by the EXT forecasts. Thanks to the more frequent updates, there are indications of a temporary increase in river flow, giving a potential advantage of two to three weeks for planning actions. SEAS does indicate the second low flow but underestimates the severity of the event. EXT gives a much more detailed forecast of the two events.

Even though this is a reasonable forecast for SEAS, the information it provides is more informative (anomaly condition) than actionable. In the above example, a decision-maker would have to make a decision based on a forecast that was issued 2.5 weeks earlier, which would inherently make the decision rather uncertain if they only had the seasonal forecast to go by. With a more frequently updated system, such as EXT, a decision-maker would gain the same early indication of a hazardous event and have the benefit of more frequent updates. In this particular case, the EXT forecast for the first event is more unstable for some ensemble members, but in general the event is well captured. The EXT is also able to give an indication of the recovery with higher water levels between the extreme low flow events. The onset of the second low period is correctly predicted by the EXT system about a week in advance, whereas this event is not well predicted by SEAS (Figure 5). Similar results are obtained when using different thresholds, for example below the 10th or 5th percentile (not shown).

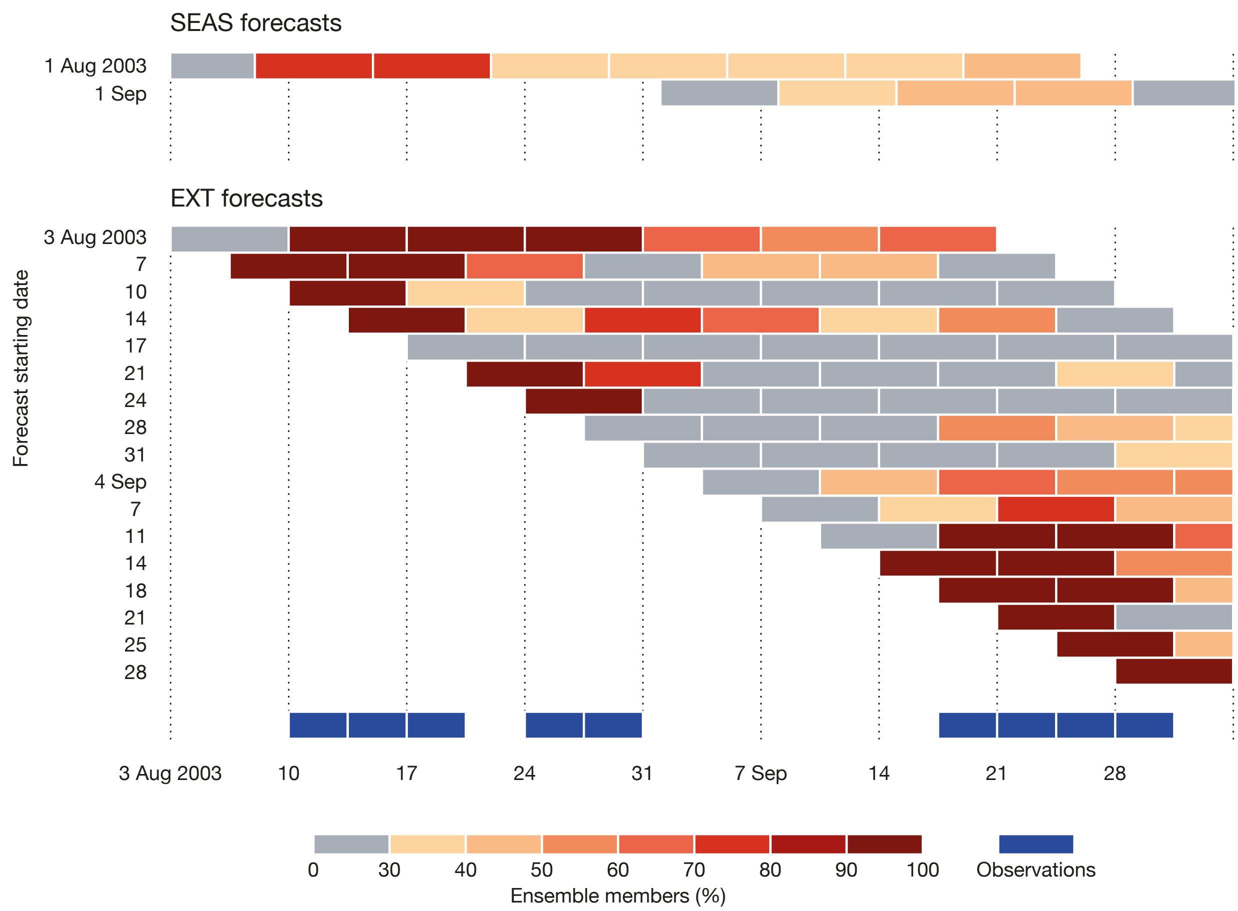

FIGURE 4 Percentage of ensemble members predicting a low river discharge anomaly (lower than the 3rd percentile of the climatological distribution) on the river Rhine at a location north of Cologne during August and September 2003 for (a) SEAS and (b) EXT, for different starting dates. River discharge below the 3rd percentile was observed during three periods in August and September 2003, as indicated.

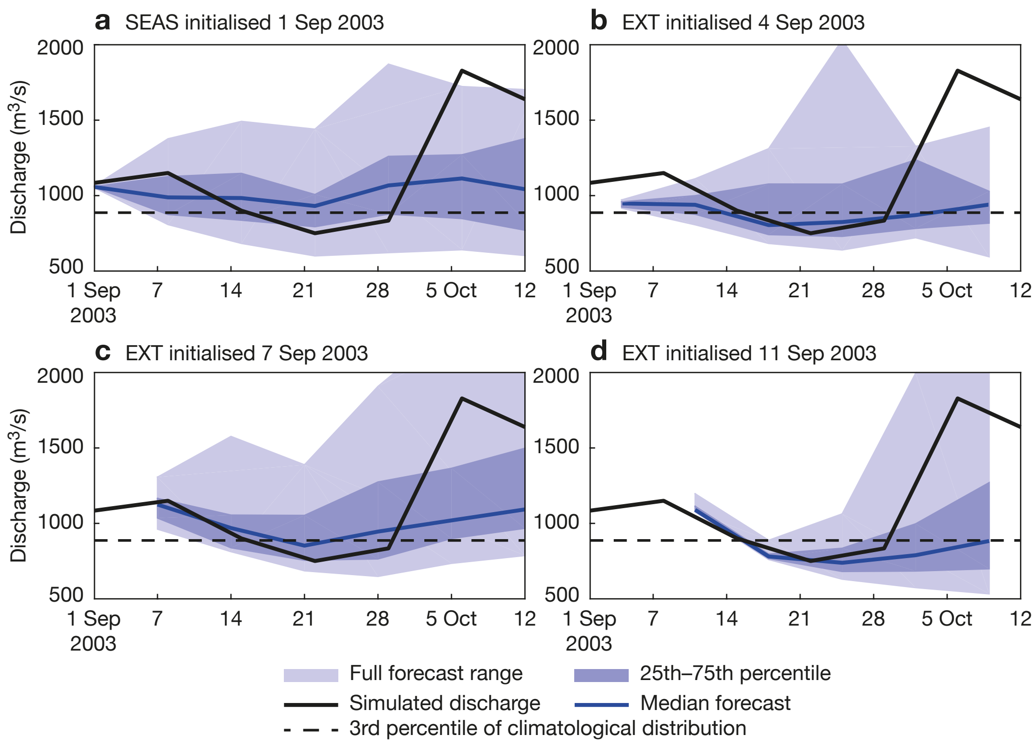

FIGURE 5 Weekly forecast plumes for the event in September 2003 by (a) SEAS initalised on 1 Sepember and (b) EXT initialised on 4 September, (c) EXT initialised on 7 September, and (d) EXT initialised on 11 September.

Going forward

The example given above highlights the potential for the use of sub-seasonal to seasonal forecasts in the case of an extreme low-flow situation on the river Rhine. The higher frequency of EXT means that these forecasts are more actionable than seasonal forecasts. However, care should be taken when using the forecasts in decision-making since their reliability over Europe is only "marginally useful" (Weisheimer & Palmer, 2014). It is therefore important to assess the reliability and skill of the forecasts at a given location and over the season of interest.

EXT and SEAS used very similar versions of the IFS, and they were both initialised using the same reanalysis. The results indicate that in these conditions they are very similar in skill despite some small differences in performance depending on the season and area. However, the system that produces ECMWF's operational ensemble forecasts is updated more frequently than the seasonal forecasting system, so it is expected that the skill of EXT will increase more quickly than that of SEAS: every new IFS upgrade can be expected to further improve EXT. Wetterhall & Di Giuseppe (2018) showed such a difference in skill when comparing System 4 (IFS Cycle 36r4) seasonal forecasts with extended-range forecasts using IFS Cycles 41r1 and 41r2.

The EFAS extended-range forecast is planned to be made available to users operationally later this year. It will show weekly anomalies against a model climatology rather than daily values of discharge. This is intended to avoid over-interpretation of the forecasts. The operational S2S forecasts will be disseminated with a disclaimer regarding their skill and reliability. Further efforts will be made to improve the bias correction of the forecasts to achieve a hydrometeorological forecast that is as reliable and skilful as possible on time ranges that are useful for decision-makers. Experiments in which the operational ensemble forecasts are merged with extended-range forecasts are also planned. This could lead to sub-seasonal hydrometeorological forecasts being issued on a daily basis.

Further reading

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ECMWF publications

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Technical Memoranda

849 **Malardel**, **S.**, **M. Diamantakis**, **A. Agusti-Panareda** & **J. Flemming**: Dry mass versus total mass conservation in the IFS. *June 2019*

848 **Barré**, **J.**, **S. Massart**, **M. Ades**, **L. Jones**, **R. Engelen** & the **CAMS team**. Emission optimisations first attempt based on the Ensemble of Data Assimilation for atmospheric composition. *June 2019*

847 **Polichtchouk**, **I.**, **T. Stockdale**, **P. Bechtold**, **M. Diamantakis**, **S. Malardel**, **I. Sandu**, **F. Váňa** & **N. Wedi**: Control on stratospheric temperature in IFS: resolution and vertical advection. *June 2019*

845 **Lawrence**, **H.**, **J. Farnan**, **I. Sandu**, **N. Bormann**, **P. Bauer** & **L. Magnusson**: An Assessment of the use of observations in the Arctic at ECMWF. *April 2019*

ECMWF Calendar 2019/20

Sep 2–5	Annual Seminar on subseasonal and seasonal forecasting: recent progress and future prospects
Sep 25–27	NEXTGenIO workshop on applications of NVRAM storage to exascale I/O
Oct 7–9	Scientific Advisory Committee
Oct 7–10	Training course: Use and interpretation of ECMWF products
Oct 10–11	Technical Advisory Committee
Oct 14–16	Workshop on building reproducible workflows for Earth sciences
Oct 21–22	ESCAPE-2: 1st dissemination workshop
Oct 28–29	Finance Committee
Oct 29	Policy Advisory Committee
Nov 18–21	Workshop on stratospheric modelling, predictability and influence on the troposphere
Nov 25–28	Satellite-inspired hydrology for an uncertain future: an H SAF and HEPEX workshop
Dec 10–11	Council
Jan 27–30	Training course: Use and interpretation of ECMWF products (for trainers)
Feb 3–6	Joint JCSDA–ECMWF workshop on assimilating satellite observations of cloud and precipitation into NWP models
Feb 11–13	Workshop on aircraft observations
Jun 1–4	Using ECMWF's Forecasts (UEF)
Jun 23–24	Council
Sep 1–4	Annual Seminar
Sep 14–18	Workshop on HPC in meteorology (Bologna)
Oct 5–8	Training course: Use and interpretation of ECMWF products
Dec 8–9	Council

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