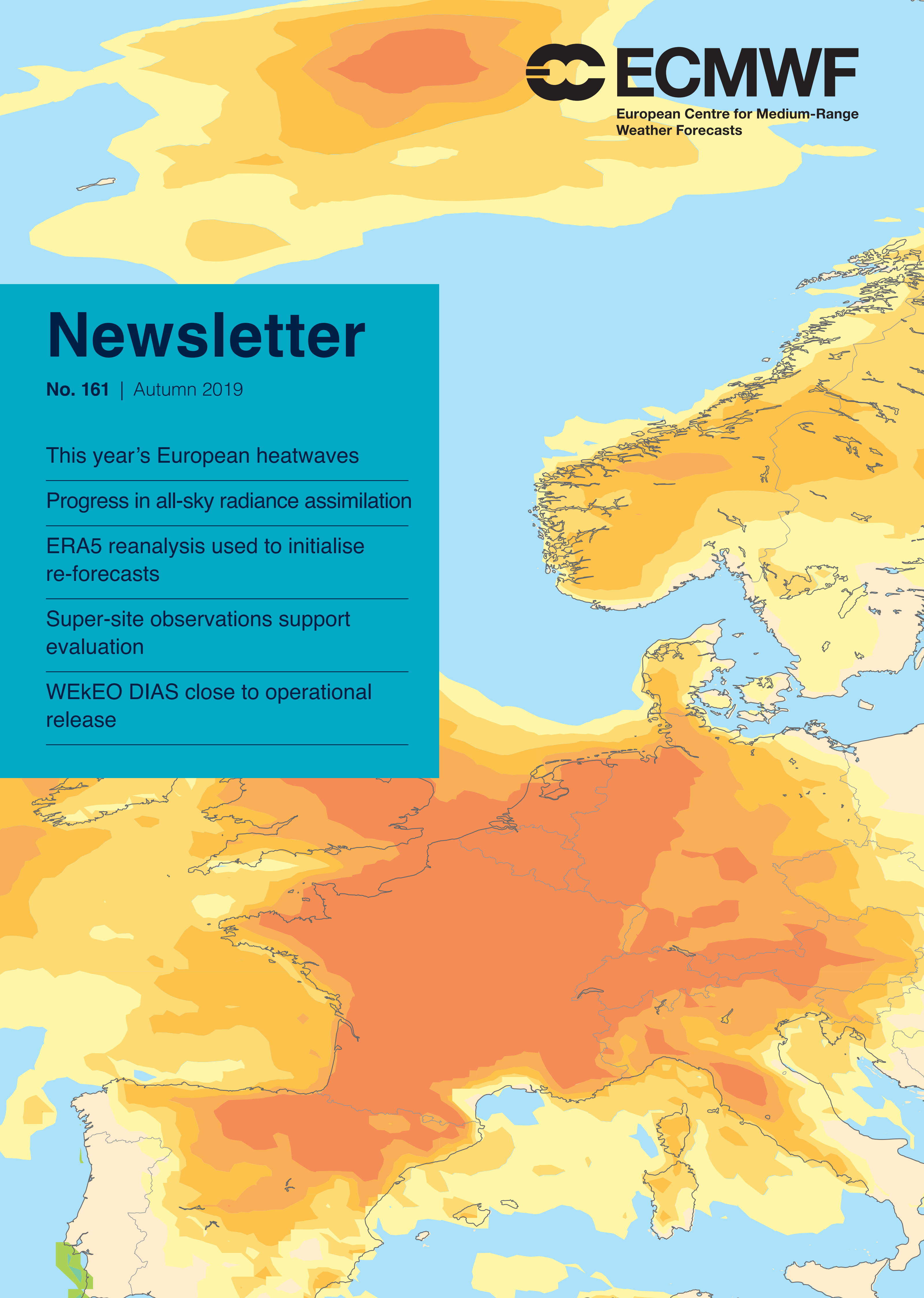

ECMWF
European Centre for Medium-Range Weather Forecasts

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 The ECMWF Newsletter is not peer-reviewed.

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

Guidance about submitting an article is available at *www.ecmwf.int/en/about/media-centre/media-resources*

Field campaigns

This summer, 70 scientists came together at ECMWF to review and strengthen the synergies between observational field campaigns and numerical weather prediction. There were lively discussions and broad agreement that collaboration between observationalists and modellers should be intensified. The meeting served as a reminder that prediction centres need Earth system observations not just to help initialise weather forecasts. They also need them to better understand and model Earth system processes that are relevant to weather forecasting.

One of the areas where modellers would benefit from targeted field campaigns is the interactions of the lower atmosphere with the underlying surface. How strongly do conditions in the soil influence near-surface weather? What is the impact of heterogeneity in the land surface on surface fluxes? How do ocean currents, waves and the atmosphere interact? Better understanding these processes, and others listed in this Newsletter, will help us to improve their representation in our Integrated Forecasting System. In many cases, it will be important for measurements to be made through the atmosphere–surface interface, or along a path that crosses different types of surfaces.

An example of the successful use of observations to support model evaluation and development is presented in this Newsletter: 'super-sites' in our Member States, such as Falkenberg in Germany, Cabauw in the Netherlands and Sodankyla in Finland, are providing us with detailed data on the lowest part of the atmosphere as well as the soil and snow at those sites. These data are enabling new insights into possible causes of biases in forecasts of near-surface variables, such as temperature. But they need to be complemented by studies into the effects of local differences in vegetation, land use or soil properties to better understand the complicated patterns of temperature forecast biases.

An important source of information to support the modelling of clouds and precipitation is satellite data. An article in this Newsletter sets out recent progress in the all-sky assimilation of satellite radiances at ECMWF. Together with the use of ground-based observing systems, progress in interpreting satellite radiances in all-sky conditions and over land is bringing us close to 'microphysical closure': the point at which the sources of forecast errors related to clouds and precipitation can be identified through the overlapping sensitivities of different types of instrument.

There is a vital ingredient in all these efforts: collaboration. Collaboration between different teams at ECMWF; collaboration between ECMWF and its Member and Co-operating States; and collaboration between ECMWF scientists and the global observational and modelling communities. Two articles in this Newsletter illustrate how much progress has been made in numerical weather prediction over the last 40 years. Many pieces of the puzzle had to come together to get to this point. It is only by working together that we can continue to improve our forecasts for the benefit of society.

Florence Rabier
Director-General

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The 2019 western European heatwaves

Linus Magnusson

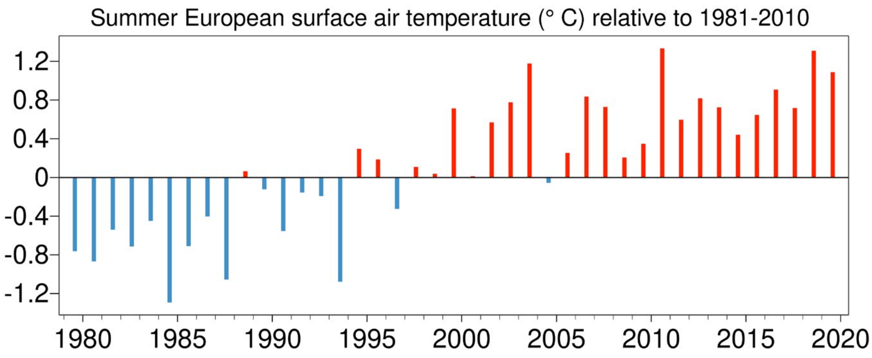
The European summers of 2018 and 2019 were both record breaking, but in different ways. While the summer of 2018 broke the record for the highest seasonal average temperature in many places, in 2019 national all-time maximum temperature records tumbled in Belgium, France, Germany, Luxembourg, the Netherlands and the UK. The national records were broken during two relatively short but extreme episodes of heat that hit western Europe at the end of June and the end of July 2019. Both episodes were relatively well predicted although inaccuracies in the prediction of a Rossby wave over the US hampered the June forecasts.

For the first episode, we focus on 26–28 June and for the second on 23–25 July. The two episodes had a similar geographical structure, apart from the fact that the July heatwave extended further to the north, including the British Isles, as seen in the panels showing predictions of the Extreme Forecast Index (EFI) for average temperature 1–3 days ahead. Regarding medium-range predictability, the geographical extent of both episodes was well captured a week in advance, as illustrated in the panels showing EFI predictions 7–9 days ahead.

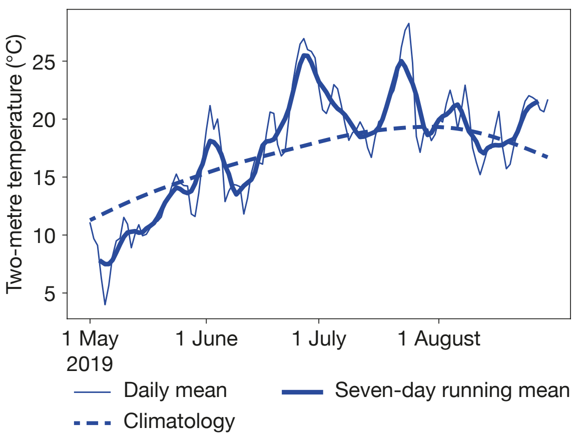
In the medium range, the ensemble was more confident about the extreme heat for the first episode. Looking at the evolution of ensemble distributions for 3-day average temperature in a 6x6 degree box over western-central Europe (44°N–50°N and 2°E–8°E), we find a very different evolution of predictions for the two heatwaves. For the July episode, a warm anomaly was present in forecasts issued as early as two weeks in advance. Later on, the ensemble distribution continued to smoothly shift to more and more extreme temperatures, but with a large ensemble spread.

For the June episode, 10–15 days before the event most ensemble members actually predicted a cold anomaly. The last cold forecast was issued 8 days before the start of the verifying period. However, the forecast drastically changed between 18 and 19 June, with the latter one clearly predicting the heatwave. We have therefore tried to trace the difference between these ensemble forecasts to the beginning of the forecast range. We found a short-range (2-day) forecast difference concerning an eastwardly propagating Rossby wave packet west of the Rocky Mountains. In the coming days, the difference amplified over North America and the Atlantic, with an underestimation of the wave amplitude in the forecast from 18 June. Finally, this forecast missed the wave-breaking over the eastern Atlantic and the resulting cut-off low east of the Iberian Peninsula, which pushed the heat northward over western Europe. On average, the presence of Rossby wave packets helps to enhance predictability, but occasionally they are responsible for error propagation, as in this case.

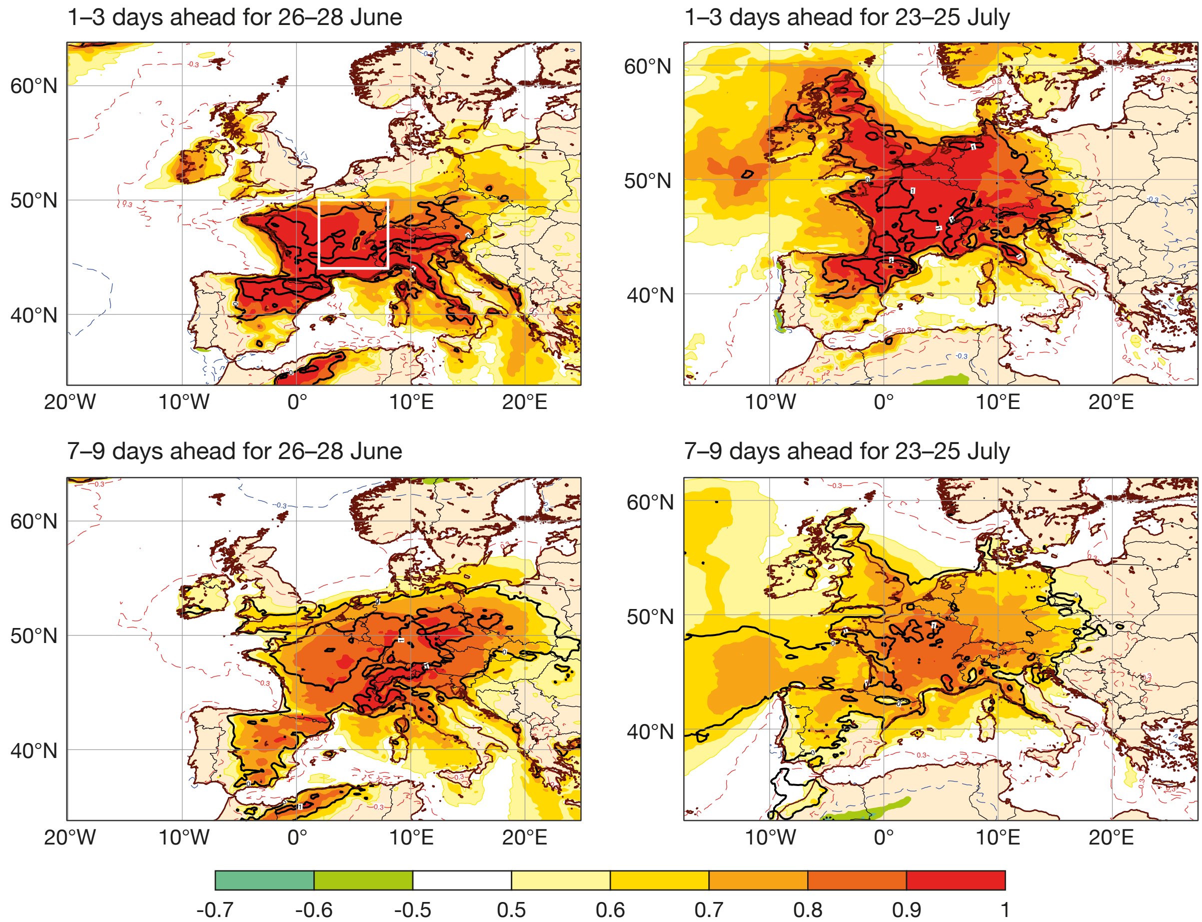
Overall, both episodes were relatively well predicted, with a warm signal early on, especially in forecasts of the July event, and a relatively rapid and consistent convergence on the analysed average temperature, especially in forecasts of the June event.



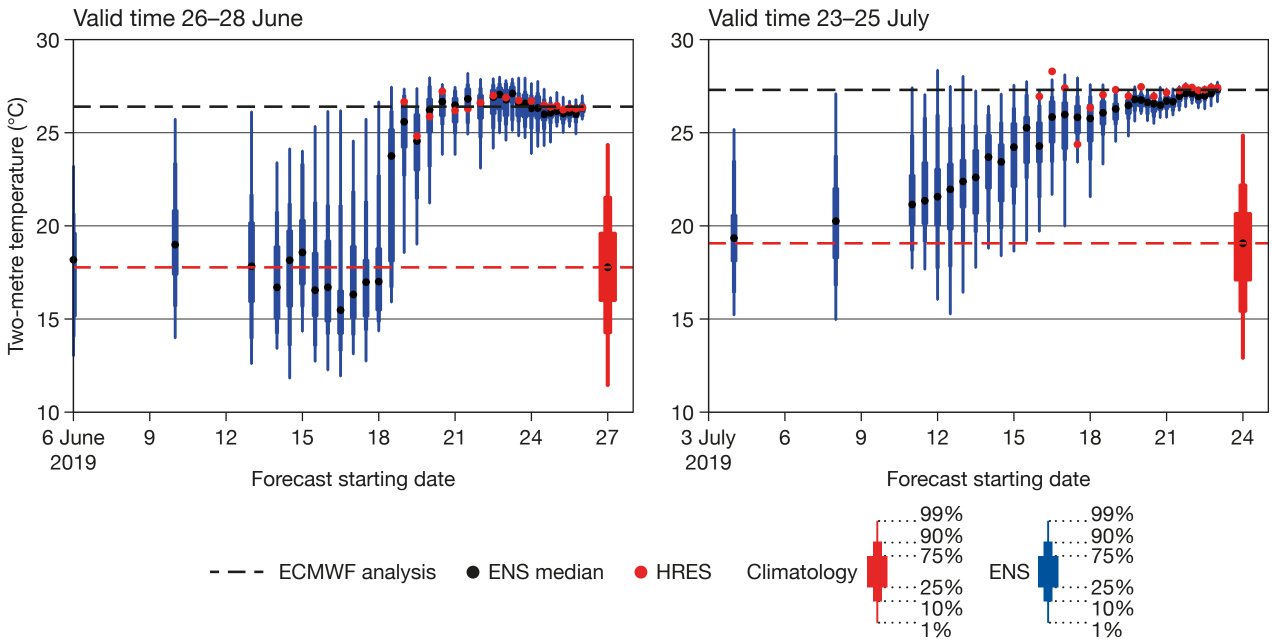
Two warm summers. Across Europe, average temperatures this summer were the fourth warmest on record, while those in 2018 were the second warmest, just behind 2010. The chart shows temperature anomalies compared to the 1981–2010 average, based on ERA5 reanalysis data provided by the EU-funded Copernicus Climate Change Service implemented by ECMWF.



Two-peak temperature structure in 2019. The summer of 2019 in western-central Europe was marked by two short episodes of extreme heat, as shown in this chart of daily mean 2-metre temperature from ECMWF analyses in a box covering some of the area (44°N–50°N and 2°E–8°E) from 1 May to 1 September 2019.



Extreme Forecast Index (EFI) and Shift of Tails (SOT) forecasts. The charts show the EFI (shading) and SOT (contours) for maximum temperature in forecasts from 00 UTC on 26 June for 26–28 June (top left); from 00 UTC on 23 July for 23–25 July (top right); from 00 UTC on 20 June for 26–28 June (bottom left); and from 00 UTC on 17 July for 23–25 July (bottom right). The white square in the top-left panel shows the area of 44°N–50°N and 2°E–8°E referred to in the text.

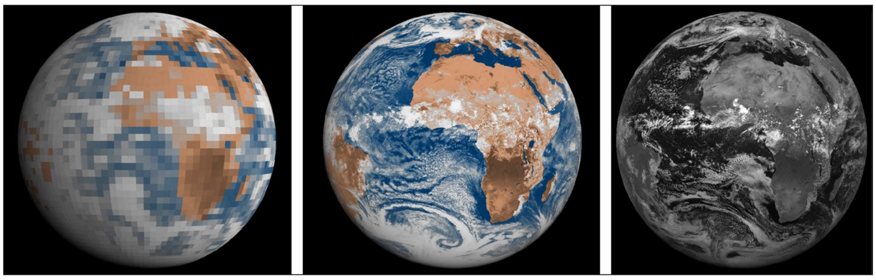


Ensemble temperature forecasts. The charts show the evolution of forecasts for 3-day average 2-metre temperature in western-central Europe (44°N–50°N and 2°E–8°E) valid on 26–28 June (left) and 23-25 July (right). The blue box-and-whisker symbols show ensemble forecasts for different starting dates. The red dots indicate ECMWF's deterministic high-resolution forecasts (HRES).

Forty years of medium-range forecasting

Philippe Lopez, Mark Rodwell

On 1 August 1979, ECMWF produced its first operational medium-range forecast for Member States. This major achievement marked the first milestone on the road towards producing useful weather forecasts beyond two to three days. It was achieved less than four years after the Convention creating ECMWF was signed on 1 November 1975.



Simulated satellite images then and now. The left-hand panel shows a simulated satellite image based on 12-hour-averaged solar fluxes from a 72-hour forecast from the original 1985 operational archive from 1 August 1985 at 12 UTC (200 km grid spacing); the middle panel shows a corresponding re-forecast using today's IFS, initialised from the ERA5 reanalysis, based on 1-hour-averaged solar fluxes (9 km grid spacing); and the right-hand panels shows a corresponding Meteosat-2 satellite visible image (copyright: EUMETSAT).

The first forecasts

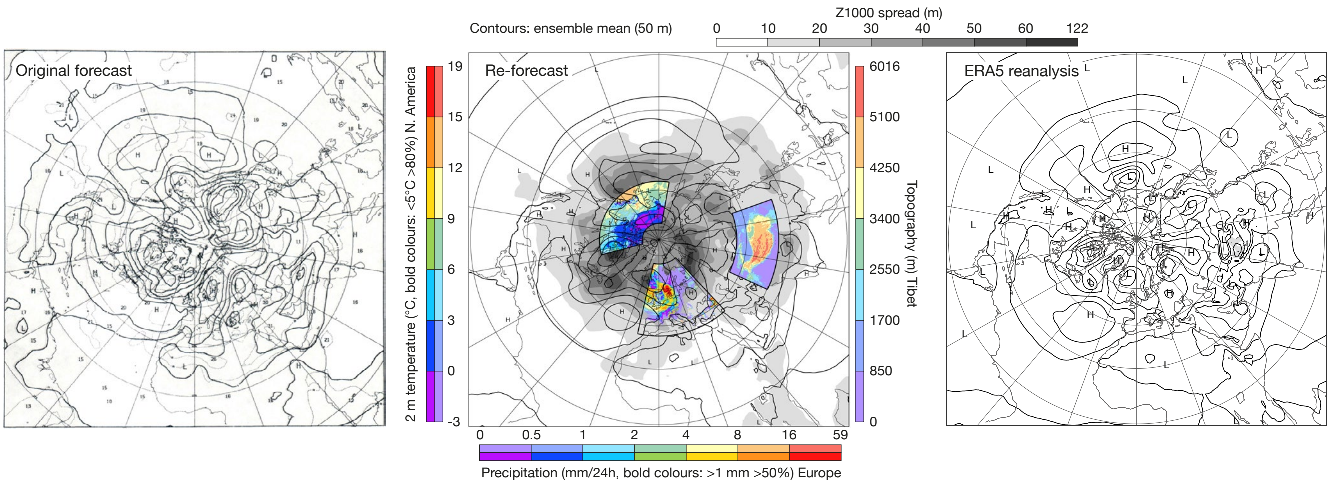
ECMWF's first operational medium-range forecasts were produced to ten days ahead, five days a week, but only the first seven days were disseminated to Member States. The model had a horizontal grid spacing of 210 km with 15 vertical levels. Four decades later, improvements in modelling and data assimilation, coupled with vastly greater computing power and observational coverage, have led to much better forecasts as well as a wide range of forecast products and applications.

A notable development was the introduction of ensemble forecasts in 1992, following years of research and development. For the first time, these forecasts presented the range of future weather possibilities and their likelihood of occurrence. For example, the grey shading in the 1 August 1979 re-forecast plot shows the ensemble spread, which indicates substantial uncertainty in some areas. The operational forecast made in 1979 did not come with any quantification of uncertainty. Comparison against the verifying ERA5 reanalysis of 1,000 hPa geopotential on 8 August 1979 illustrates the better performance of the modern re-forecast, with better predicted features such as the Azores anticyclone and the Icelandic Low.

Views from space

To illustrate the huge progress made over the last few decades in the prediction of cloud systems in the Integrated Forecasting System (IFS), we have created simulated visible images of our planet as seen from a geostationary satellite. The simulated images are based on predicted solar fluxes at the top of the atmosphere from 72-hour forecasts using the 1985 and 2019 forecasting systems, respectively. The forecasts were initiated on 1 August 1985 at 12 UTC as forecast and satellite data from earlier years are not available in ECMWF's archive.

For more details, read our web article published on 31 July 2019: **https://www.ecmwf.int/en/about/media-centre/news/2019/ecmwf-celebrates-40-years-operational-medium-range-forecasting**.

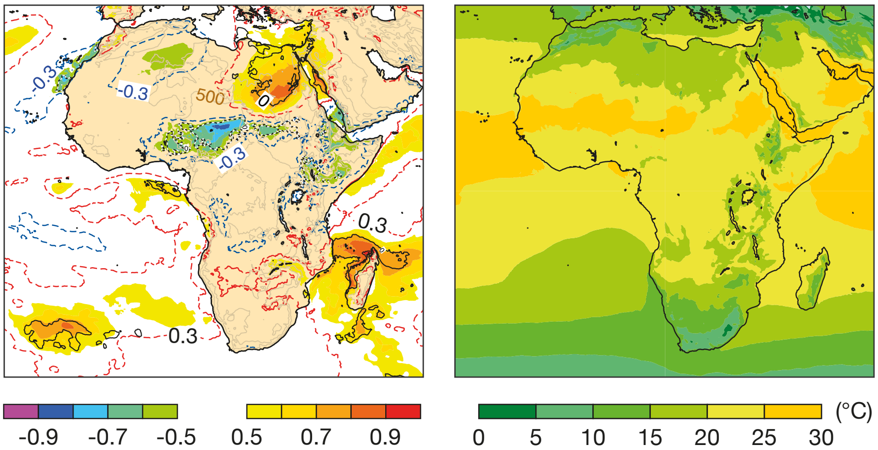


Original forecast, re-forecast and verification. The first operational ECMWF forecast was a 7-day forecast from 12 UTC on 1 August 1979. The plot (left) shows predicted 1,000 hPa geopotential height in solid contours. The corresponding modern re-forecast (centre) is a 50-member ensemble forecast. The verifying ERA5 reanalysis, including uncertainty, is shown on the right. Initial conditions for the re-forecast are derived from ERA5. The re-forecast uses the current operational model (IFS Cycle 46r1). Contours show the ensemble-mean 1,000 hPa height field. Grey shading shows the ensemble standard deviation. The coloured regions highlight different details and ensemble information available in present-day forecasts.

ECMWF makes more products freely available to WMO Members

Umberto Modigliani, Emma Pidduck

ECMWF has substantially increased the amount of weather prediction products it makes available free of charge to Members of the World Meteorological Organization (WMO). All the static web charts and the Ensemble Meteogram on the ECMWF website are now available free of charge to all WMO Members. The additional products enable a much more comprehensive view than before of atmospheric conditions as predicted by ECMWF, including near-surface weather conditions. This will help users to make better assessments of weather-related risks. Registered national meteorological and hydrological services (NMHSs) have been able to access the new data since 24 July 2019. Products are available for both probabilistic and deterministic forecasts. These changes help to provide forecasters in the NMHSs of WMO Members with the information they need to carry out their operational activities.



Extreme Forecast Index for temperature. Additional products available to WMO Members include static charts such as the Extreme Forecast Index (EFI) for 2 m temperature. The left-hand panel shows the EFI (shading and dashed contours) and the Shift of Tails (SOT) (solid contours) from 00 UTC on 2 October 2019 for 72-hour 2 m mean temperature valid from 8 to 11 October 2019. The right-hand panel shows the 99th percentile of the corresponding model climate for those days (i.e. on 1 in 100 occasions the 2 m mean temperature is less than the value shown).

ECMWF has also reduced the cost of the NMHS web non-commercial licence, which gives access to the ecCharts service, from €3,500 to €1,000 per year. In addition, as an alternative to the fixed-price NMHS 'full' non-commercial licence (€44,400 per year), ECMWF has introduced a cheaper 'standard' licence which provides access to a fixed dataset of the licensee's specification for a reduced fee.

All these changes will allow WMO Members to access a much wider range of ECMWF products. The changes were approved by the ECMWF Council at its June 2019 session and are part of the Centre's efforts to serve WMO Members.

For information about the licences available from ECMWF, see: https://www.ecmwf.int/en/forecasts/accessing-forecasts/licences-available.

New Director of Copernicus Services

Jean-Noël Thépaut took up his position as ECMWF's Director of Copernicus Services on 1 October 2019, succeeding Juan Garces de Marcilla. ECMWF is implementing two Copernicus Earth observation services on behalf of the EU: the Copernicus Climate Change Service (C3S) and the Copernicus Atmosphere Monitoring Service (CAMS). Jean-Noël was previously the Head of C3S. Before that, he was the Head of the Data Division and Deputy Director of the Research Department at ECMWF, where he oversaw the development of world-class data assimilation algorithms for numerical weather prediction, the exploitation of satellite observations from operational and research Earth observation platforms, and the development and production of state-of-the-art climate reanalyses. Jean-Noël has served on several international committees and is currently co-chair of the World Climate Research Programme Data Advisory Council.

Experts review synergies between observational campaigns and weather forecasting

Linus Magnusson, Irina Sandu

From 11 to 13 June 2019, 70 scientists gathered at ECMWF to review the impact of field campaigns on numerical model development and to discuss how to strengthen the interactions between numerical weather prediction (NWP) centres and observation programmes. These interactions already take place, as processes that are not well understood and that cause large forecast errors often motivate field campaigns. NWP analyses and forecasts provide guidance on field campaign setup, the location of stations and research ships, and aircraft route planning. In return, many campaigns provide real-time observations that can be assimilated directly into forecasting systems. After completion of the campaigns, the observations are often used to comprehensively evaluate the forecasts and to better understand physical processes and improve their representation in models. Conversely, NWP analyses provide crucial context for interpreting the field observations. Further strengthening the links between observationalists and modellers can help maximise the benefits of observational campaigns for weather forecasting and vice versa.

Types of observational campaigns

Observational campaigns and field programmes cover different timescales, from long-term process monitoring at intensive meteorological observing sites or super-sites to gathering specialised observations over short periods. Observational campaigns differ in their aims. Most campaigns are designed to further understand physical processes and their interactions in the Earth system with a view to improving their representation in weather and climate models. Others investigate the impact of added observations on the initial conditions of forecasts, or they provide airborne and ground-based validation for novel remote sensing instruments deployed on satellites such as Aeolus.

Past and future campaigns

The workshop opened with overview talks on lessons learned from organising past field campaigns and on how observations from campaigns have been used to improve models at different NWP centres, e.g. in terms of the representation of cloud water-content and the partition between liquid and ice phase in clouds over the Southern Ocean. The sessions that followed were dedicated to campaigns targeted at cloud and boundary-layer processes, tropical cyclones, atmospheric rivers, mid-latitude dynamics and polar processes. Common to most campaigns is that, regardless of objective, location and period, they typically include standard observations from radiosondes and dropsondes that can be directly used in NWP data assimilation systems and thus provide swift feedback on model performance. Talks were also given on future observation platforms, such as stratospheric balloons and saildrones. A special talk was given by US Air Force Hurricane Hunters, documenting their reconnaissance flights around and into the centres of tropical cyclones.

Hurricane Hunters. US Air Force Hurricane Hunters (pictured 2nd and 4th from right, with some of the workshop organisers) gave a talk about their reconnaissance flights around and into the centres of tropical cyclones. From left to right: Linus Magnusson, David Lavers, Emma Pidduck, Ryan Rickert, Florian Pappenberger, Jeremy de Hart and Irina Sandu. The balloon featured logos of campaigns in which participants and their organisations have been involved.

The way forward

The workshop participants appreciated this rare opportunity to bring together observationalists and modellers and expressed their gratitude for ECMWF's support of campaigns with forecast data. Part of the workshop was devoted to discussions on how the interactions between field campaigns, modelling and operational prediction centres could be further strengthened. The discussions were chaired by James Doyle (US Naval Research Laboratory), Chris Bretherton (University of Washington) and Gunilla Svensson (Stockholm University).

During these discussions, it was suggested that highlighting past success stories, in which observational campaign data were used to improve processes in models, would be valuable. Workshop participants also recommended that ECMWF (and other centres) produce a report on key processes and systematic errors for which the model development process would benefit from observational programmes. This could be a follow-on to the recent World Meteorological Organization (WMO) Working Group on Numerical Experimentation (WGNE) survey on systematic model bias (wgne.meteoinfo.ru/the-wgne-systematic-error-survey-is-published/). It was noted that this survey provides insights into the systematic errors that modellers care most about, but it does not focus on relevant processes or on how insights gained from observational programmes can help improve their representation in models. Discussions on this topic have recently started at ECMWF and the conclusions reached (see Box) were shared with other centres at the WGNE meeting held in Germany at the end of September.

Discussions during the workshop also touched on developing and sharing data analysis tools and defining a best practice catalogue for field campaigns to facilitate data access and exchange. To increase the discoverability of the data, the principal investigators (PIs) of campaigns were encouraged to publish the datasets in data journals. Another suggestion was to establish a calendar on the ECMWF website where researchers planning to use ECMWF data can share information on planned and upcoming field campaigns. It would also be valuable to gather information in a central repository for flight campaign tools, such as mission support systems, flight trajectories and corresponding model diagnostics. The observationalists also requested access to monitoring statistics of daily assimilated observations to verify whether campaign observations have been assimilated and to assess model–observation differences.

Workshop participants. The workshop brought together observationalists and modellers.

Presentations and recordings are available on the workshop web page at https://www.ecmwf.int/en/learning/workshops/workshop-observational-campaigns-better-weather-forecasts.

Poster session. Participants had the opportunity to present and discuss their work.

Possible field campaign targets

Consensus was achieved that future observational campaigns, or better exploitation of existing datasets, could help to improve the representation of several important processes in ECMWF's Integrated Forecasting System over the coming years:

- **The coupling of the lower atmosphere with the underlying surface**, which is key for the prediction of near-surface weather. Specific issues need to be tackled over land, ocean and snow/sea-ice, e.g. the strength of land–atmosphere coupling, the impact of land heterogeneity on surface fluxes, the partition between latent and sensible heat flux over bare soil and vegetated areas, the thermodynamic coupling over sea ice, the coupling of ocean currents, waves and the atmosphere, and atmosphere–ocean coupling over boundary currents (e.g. the Gulf Stream). Efforts to improve the coupling of the lower atmosphere with the underlying surface would benefit from gathering collocated observations through the atmosphere–surface interface (e.g. in the atmosphere, at the surface, and in the ocean mixed layer/soil/snow) during future observational campaigns as well as from observations along a path across various surfaces ('observational transects'), e.g. across the snow line, from bare soil to vegetated areas, and from flat terrain to mountain ridges.
- **Low-level clouds, in particular maritime stratocumulus and low-level mixed-phase clouds at high latitudes.** As the resolution of global models increases towards resolutions at which deep convection becomes resolved, the need for observational constraints for microphysical processes will increase as these processes will play an increasingly important role.
- **Momentum transport and wind profiles in the boundary layer.** A better representation of boundary-layer winds is key for predictions of near-surface and wind turbine height winds and of heat, momentum and moisture exchange at the interface between the atmosphere, ocean, land and ice. It is also important for the large-scale circulation forecast skill, which crucially depends on surface friction (or drag).
- **Temperature, moisture and trace gases (ozone) in the stratosphere**, for which very few independent observations with high vertical resolution exist.
- **Temporal and spatial variability.** As the resolution of global NWP models increases, it is becoming important to deploy observations with high temporal and spatial frequency to be able to verify the ability of NWP models to represent mesoscale variability in both the atmosphere and the ocean and particularly over boundary currents.

Re-forecasts simulate 1979 Fastnet tragedy storm

Reinhard Strüfing (ex-DWD), Tobias Schaaf (DWD), Ray McGrath (University College Dublin)

Re-forecasts of weather conditions during the Fastnet sailing race in August 1979 show that modern forecasting systems would have enabled much earlier warnings of a storm that claimed the lives of 15 sailors and 4 members of rescue teams. The re-forecasts were produced using the global ICON model of the German national meteorological service (DWD) and the US Weather Research and Forecasting (WRF) limited-area model. ECMWF's new ERA5 reanalysis provided the initial conditions and boundary conditions, respectively.

What happened

The Fastnet Race is a famous yachting race held in August every other year. Many hundreds of yachts, among them the sailing elite, sail from Cowes on the Isle of Wight along the southern coast of England and across the Celtic Sea up to the Fastnet Rock just southwest of Ireland, and then back to Plymouth. They cover 608 nautical miles in around three days, depending on weather conditions.

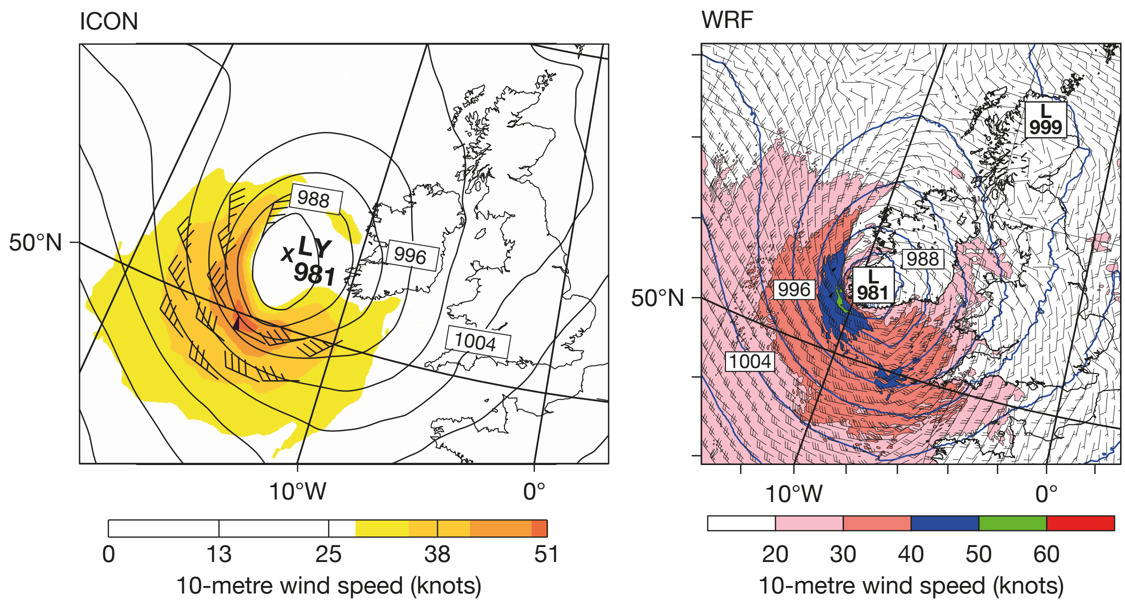
In 1979, this race resulted in the worst tragedy ever in the sport of sailing when, during the night of 13/14 August in the area south of Ireland, the yachts encountered an extremely violent storm. Two hundred yachts got into distress, five sank, 24 teams abandoned their vessels, and only 85 of the 303 yachts that started the race made it back to Plymouth. The rescue operation was one of the biggest since World War II, but the final toll was devastating: 15 sailors and 4 members of the many rescue teams died.

This disaster could be attributed to a number of causes, but one of the factors generally cited is a lack of early severe weather warnings. Forecast models at the time underpredicted the storm, which moved very quickly across the Atlantic as a shallow low but deepened almost explosively near Ireland, just as the yachts approached the Fastnet Rock. The sailors experienced gusts up to hurricane force that whipped up 10 to 15-metre seas. On top of this, wind shifts associated with the passage of the system caused freak waves.

Accurately forecasting the Fastnet storm in 1979 was impossible. Very few satellite data were available, ship observations were partially contradictory, while the resolution of the forecast models used (the UK Met Office global model with a 300 km grid spacing and 10 vertical layers and its limited-area model with a 100 km grid spacing) was insufficient to cope with this unusual weather event. Furthermore, computer problems hampered the forecasting process. When the first observations showed the full extent of the storm, the participants could not be contacted immediately because the BBC Shipping Forecast, their main source of information, had just been transmitted. The fleet was thus engulfed by this disastrous storm when they had been expecting winds of Force 4, increasing 6 to 7, locally gale 8.

Two re-forecasts

A group of meteorologists at DWD took the opportunity of the 40th anniversary of this tragedy to run a re-forecast in order to investigate how a modern numerical forecasting system would deal with this unprecedented summer storm. The aim was to present an example of improvements in weather modelling during the last 40 years and to answer



Two re-forecasts. The left-hand panel shows an ICON 72-hour re-forecast of mean sea level pressure (contours) and 10-metre winds (barbs and shading) starting at 00 UTC on 11 August 1979. The right-hand panel shows a WRF 75-hour re-forecast of mean sea level pressure (contours) and 10-metre winds (barbs and shading) also starting at 00 UTC on 11 August 1979.

the question to what extent modern forecasting can enable earlier warnings of weather events such as the Fastnet Race storm.

We started from the new ERA5 reanalysis dataset from ECMWF and used the currently operational version of the ICON model, which has a grid spacing of 13 km and 90 vertical layers. In order to illustrate whether a current forecasting system would have given the race office good guidance on cancelling or delaying the event, we ran a 72-hour re-forecast from 00 UTC on 11 August 1979, the day the race started.

The left-hand panel shows this re-forecast. It shows an extreme, fully developed storm close to the southwestern tip of Ireland with 50-knot winds, exactly as observed. The model even predicts the correct minimum pressure. However, the predicted low is slightly displaced to the north compared to the observed position, and it is 3 to 6 hours behind the observed arrival time – very small differences for a 72-hour forecast of this summer storm. Given the comparatively small observational base in 1979, this is a remarkable illustration of the improvements in weather forecasting since that time. Had such information been available in 1979, the race office would almost certainly have reacted, perhaps as they did in 2007, when the Fastnet Race was postponed by 25 hours due to the adverse weather outlook.

By coincidence, University College Dublin and the Irish Centre for High-End Computing (ICHEC) independently revisited the storm with a view to confirming its intensity – some of the race participants felt the winds were stronger than suggested by the official analysis detailed in the Fastnet Race Inquiry report (1979) – and to see how modern forecasts would perform. The WRF model version 4 was used with two domains, with a 2 km grid spacing for the inner domain and 60 vertical levels. Lateral boundary conditions were provided by ERA5 data. 3D-Var data assimilation was used to reanalyse the storm, based on conventional observations complemented with pressure observations from some of the yachts. This confirmed that winds reached violent storm force 11 on the Beaufort scale. Like the DWD re-forecast, the 75-hour WRF re-forecast shown in the right-hand panel, valid for 03 UTC on 14 August, captured the essential details of the storm. This is a remarkable achievement indicative of the progress made in numerical weather prediction since 1979. The two simulations described here also highlight the usefulness of reanalysis datasets such as ERA5, which provided the 'guiding hands' for these re-forecasts.

The Fastnet disaster of 1979 contributed to the reputation of the race as difficult and sometimes very demanding. In spite of this, the registration of yachts for the 340 places available in the 2019 race took just a few minutes.

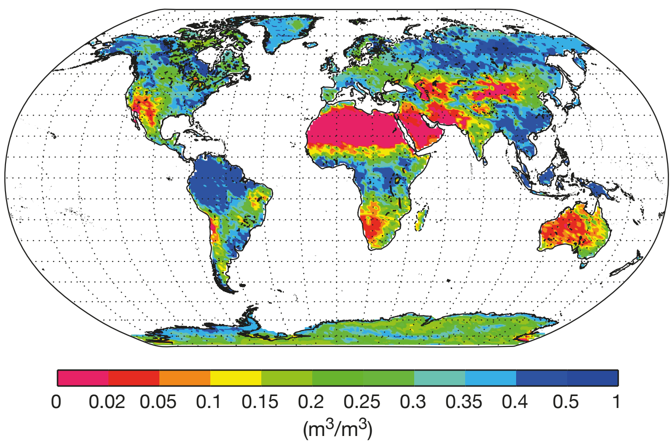
C3S releases first part of ERA5-Land dataset

Joaquín Muñoz Sabater

The EU-funded Copernicus Climate Change Service (C3S) implemented by ECMWF has made the first subset of its new high-resolution ERA5-Land dataset available through the Climate Data Store for the benefit of policymakers, businesses, scientists and land users, in particular.

Compared to the land component of the recently released ERA5 climate dataset, ERA5-Land brings several improvements that will benefit applications in areas such as agriculture, water resources management and drought prediction. An important enhancement is that ERA5-Land has a grid spacing of 9 km compared to 31 km for ERA5.

ERA5-Land is the first of its kind, providing global, hourly, high-resolution information for a more accurate representation of the water and energy cycles than ERA5 can currently offer. Initially covering the period 2001–2018, ERA5-Land makes it possible, for instance, to reveal much greater detail in the soil temperature structure, or to better resolve the lower temperatures of the peaks of alpine regions by providing more accurate data.



ERA5-Land soil moisture data. The chart shows mean soil moisture for May 2018 from ERA5-Land.

The new dataset is now available both in the Climate Data Store (CDS) and through the CDS Application Program Interface (CDS-API). The next subset of ERA5-Land will cover the period 1981–2000 and is expected to be released by early 2020. Production of the final instalment, extending back to 1950, will start later this year and its release is planned for the second quarter of 2020. For more details on ERA5-Land, see ECMWF Newsletter No. 159.

ECMWF tests new numerical scheme for vertical grid

Filip Váňa, Michail Diamantakis

ECMWF has worked with experts in its Member States to test a new numerical scheme for calculations over the vertical grid used in its Integrated Forecasting System (IFS). The results are very encouraging. The IFS employs a spectral method to solve the equations describing atmospheric dynamics in the horizontal and a finite element method to solve them in the vertical. The spherical harmonics of the spectral method cannot easily be used in the vertical due to a lack of periodicity and the use of irregularly spaced levels, varying from tens of metres near the ground to several kilometres near the model top. Instead, the vertical discretisation makes use of piecewise continuous functions as base functions. This method, known as finite element discretisation (hereafter VFE for vertical finite element) was implemented in the IFS in 2002.

Motivation for a new scheme

The IFS currently uses a hydrostatic model, which means that it implicitly assumes the upward-directed pressure gradient force (the decrease of pressure with height) is balanced by the (nearly) downward-directed gravitational pull of the Earth. This works well at the resolutions used operationally in the IFS for both forecasting and data assimilation. If in the future the IFS is to run at higher resolutions, it may become necessary to use the more general nonhydrostatic (NH) dynamics, and this, among other aspects, requires the existing VFE used in the IFS to be modified. One of the requirements for a new vertical scheme is that it is sufficiently similar in the hydrostatic and NH version of the model so that the existing hydrostatic data assimilation system can easily be used to derive initial conditions for the NH model formulation. Other reasons for a new scheme are the need to enhance flexibility in the chosen accuracy in the vertical and robustness with reduced precision.

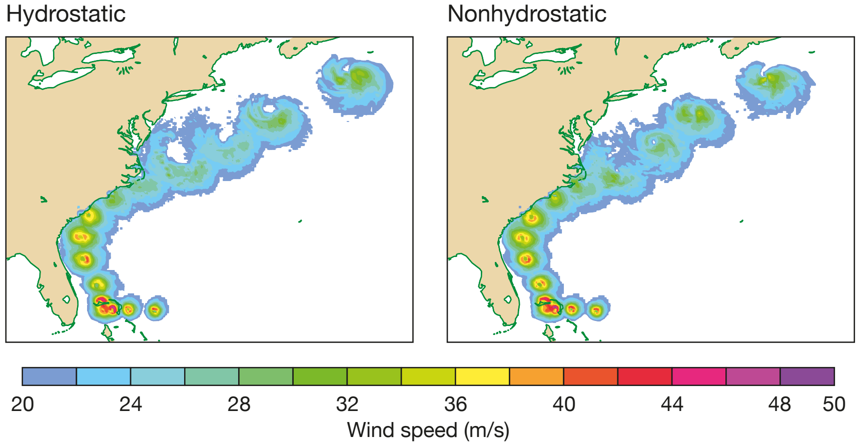
Successful collaboration

A team of scientists in ECMWF's Member States, led by Jozef Vivoda from the Slovak Hydrometeorological Institute (SHMI) and Petra Smolíková from the Czech Hydrometeorological Institute (CHMI), have developed a new formulation of the VFE scheme which works equally well with hydrostatic and NH dynamics in a stable and robust manner. ECMWF was keen to follow up on this exciting new development as soon as the new code became available from its European partners from the limited-area community and Météo-France. The leading VFE developer, Jozef Vivoda, visited ECMWF for two months earlier this year to adapt the new version of VFE and to ensure that it works successfully in the IFS. During the visit, it was shown that the new scheme offers several benefits for the IFS at the same computational cost. First, it makes it possible to increase the order of the base functions, implying higher accuracy in the vertical discretisation. Second, the new VFE is less sensitive to the model's vertical resolution and numerical precision. This makes the scheme more robust for the use of single precision calculations in the IFS. A third benefit is that NH dynamics can be modelled using the same vertical discretisation as in the modelling of hydrostatic dynamics. This means that any differences in results from NH simulations can be attributed more directly to the switch from the hydrostatic approximation to the more general NH approach rather than to differences in the numerical discretisation.

We have recently run a 10-day forecast at a grid spacing of 5 km with the new NH-VFE for Hurricane Dorian and compared it with the equivalent hydrostatic forecast using the new VFE. As the figure shows, the forecasts are remarkably similar. They also agree very well with the observed hurricane track, indeed better than the equivalent HRES forecast.

Outlook

Based on very encouraging results in first tests, it is anticipated that the new VFE will replace the existing scheme once it has been extended to and carefully tested for all configurations used at ECMWF. Research visits are a great way to continue the successful research cooperation with the (nonhydrostatic) limited-area model community, and we encourage applications as part of ECMWF's short-term visitor programme.



Forecasts using the new VFE. The charts show maximum 10 m wind speed for a 10-day forecast of Hurricane Dorian, starting from 12 UTC on 31 August 2019, at a grid spacing of 5 km, for every 12 hours starting 12 hours into the forecast. The left-hand panel shows the forecast using the hydrostatic IFS with the new VFE and the right-hand panel the forecast using the NH-IFS with the new VFE. Both forecasts were run in single precision, using the same time step of 240 s and, where applicable, identical settings for model dynamics.

Use of saildrone observations at ECMWF

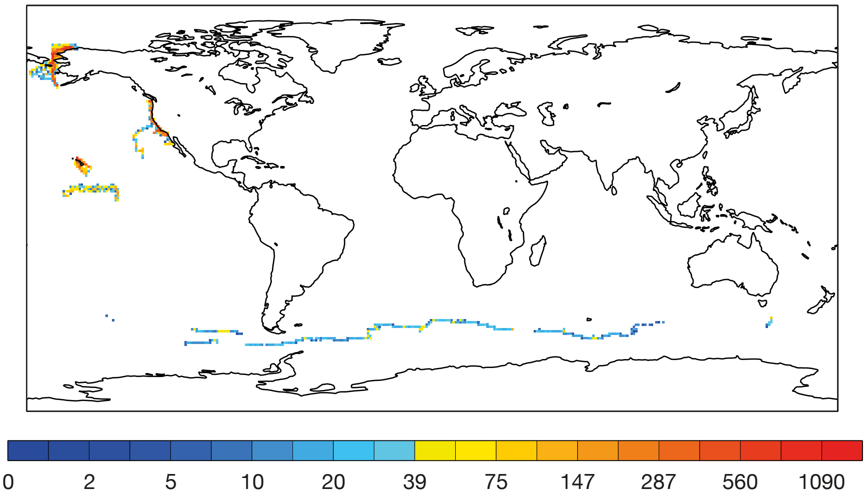
Mohamed Dahoui, Emma Pidduck, Bruce Ingleby, Lars Isaksen (all ECMWF), Sébastien de Halleux (Saildrone)

ECMWF has started assimilating data from wind-powered ocean drones, called saildrones, that have the potential to improve Earth system observation coverage in remote areas. Despite the rapid growth of satellite observations, in-situ data remain vital to numerical weather prediction. Direct measurements of key atmospheric parameters often provide useful adjustments to the analysis in sensitive areas. The impact of such observations is larger in less-observed regions. An article in the spring 2019 issue of the ECMWF Newsletter described the successful launch of 32 drifting buoys with pressure sensors in the northeast Pacific. Saildrone technology is another emerging platform well positioned to improve the coverage in remote areas and to perform targeted observation campaigns in regions of interest.

The saildrones operated by Saildrone, Inc. are unmanned, autonomous long-range observing platforms powered by wind and solar energy and equipped with a wide range of sensors measuring meteorological, oceanic and environmental parameters (for more details about the Saildrone technology, see https://www.saildrone.com/technology). Saildrones can survive severe meteorological conditions, allowing continuous all-weather reporting over extended periods of time. Over the past few years, Saildrone has successfully conducted missions to remote areas such as Antarctica. The future planned expansion of the network could reduce forecast errors in remote regions if the data are made available in near-real time.

In collaboration with the National Data Buoy Center (NDBC, US), Saildrone has started encoding and distributing data using the World Meteorological Organization (WMO) buoy reporting code form. Since 2017 a subset of the data has been made available in the WMO Global Telecommunication System (GTS) in near-real time. ECMWF has successfully received and assimilated the saildrone reports shown in the figure. The data are treated as drifting buoy data and, therefore, the same observation errors are applied and only surface pressure is used. No quality issues have been identified. Two methods are used to estimate the impact of observations: data denial experiments (running the model without the data in question) and Forecast Sensitivity Observation Impact (FSOI) diagnostics operated by ECMWF. Data denial experiments are not appropriate given the small number of observations (it is difficult for a handful of observations to make statistically significant changes affecting the large scale). FSOI diagnostics indicate a generally positive impact of saildrone data, although their collective impact is small because of the small number of reports. That said, drifting buoys and saildrone data might have a decisive role if they are near active systems where other direct measurements are absent.

Currently only a subset of saildrone data is made available to the community in near-real time. The expected evolution of the network will help fill the gaps of in-situ data availability in remote oceanic areas from which forecast errors grow fast to affect downstream areas. The encoding of saildrone data using the buoy template was a sensible choice to quickly make the data available to users, but in the long term it would be good to have a WMO template dedicated to saildrone data. This will make the quality control, data usage, monitoring and impact assessment easier. Currently the only saildrone data used at ECMWF is for surface pressure. In the future other atmospheric and oceanic parameters might be exploited for ocean assimilation and/or verification purposes.



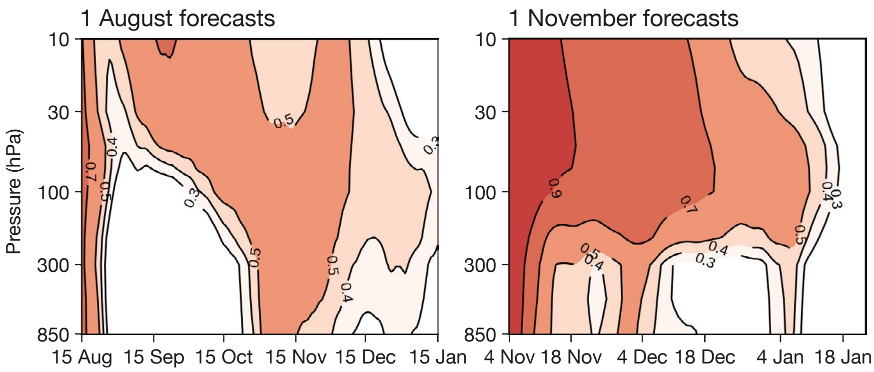
Data coverage. Coverage of saildrone reports received by ECMWF in 2018 and 2019. The shading reflects the number of observations per 1°x1° box.

Saildrone observing platform. Saildrones carry a wide range of sensors measuring meteorological, oceanic and environmental parameters. (*Photo: Saildrone, Inc.*)

Study probes impact of stratosphere on forecasts

Nick Byrne, Inna Polichtchouk (both ECMWF), Ted Shepherd (University of Reading)

To what extent does correctly predicting conditions in the stratosphere enhance sub-seasonal to seasonal forecast skill in the troposphere? And do seasonal forecasts underestimate the predictability of the real world? A new study explores these issues by analysing the performance of ECMWF seasonal forecasts in the southern hemisphere (SH) extratropics. It finds that, during certain ‘windows of opportunity’, the stratosphere can act as an important source of predictability for the troposphere. Moreover, the study finds no evidence for the underestimation of tropospheric predictability in seasonal forecasts.



Forecast skill by lead time and pressure level. The left-hand panel shows the correlation between 31-day mean ensemble mean winds in the east–west direction from 55°S to 65°S and corresponding values in ERA-Interim as a function of calendar day and pressure level for forecasts starting on 1 August. Values on the x-axis represent the central date of the 31-day mean. The right-hand panel shows the same but for 7-day means for forecasts starting on 1 November. In both panels, shaded contour regions are statistically significant at the 95% level.

The role of the stratosphere

The variability of the extra-tropical stratosphere is strongly constrained by the seasonal cycle, with the winter and spring seasons exhibiting the most activity by far. During these seasons, there is generally a band of westerly winds present over the poles, commonly referred to as the stratospheric polar vortex. In the SH, the stratospheric polar vortex gradually descends in altitude as the calendar year progresses, before eventually dissipating with the onset of summer. This dissipation is indicated by a reversal of winds from westerly to easterly and is referred to as the stratospheric polar vortex breakdown event. The descent and the breakdown of the stratospheric polar vortex are of interest to the sub-seasonal to seasonal forecasting community as both events are thought to influence shifts of the tropospheric jet stream to the north or to the south. In particular, in years with an anomalously strong vortex and/or anomalously late polar vortex breakdown, the seasonal equatorward transition of the tropospheric jet stream is delayed, with the opposite behaviour in years with an anomalously weak vortex. Thus, skilful forecasts of these stratospheric events can also make forecasts of the troposphere more skilful.

This hypothesis was explored with the ECMWF System 4 seasonal forecast ensemble, the operational seasonal forecast system at ECMWF when this study was initiated. The ERA-Interim reanalysis was used for validation. Two forecast start dates were considered (1 August and 1 November), which were chosen to roughly coincide with the descent and breakdown events in the SH stratosphere. Forecast skill of the monthly- and weekly-mean tropospheric jet stream (averaged in the east–west direction) was then assessed for these start dates. A subset of the results is shown in the figure. Perhaps most striking is the re-emergence of monthly-mean forecast skill in the troposphere for forecasts initialised on 1 August. This re-emergence of skill is consistent with an influence from the polar vortex descent on the latitude of the tropospheric jet stream. The results suggest that approximately 20–30% of monthly tropospheric jet stream variability at lead times of 3–4 months is predictable based on knowledge of the stratospheric state. Similarly, the 1 November forecasts show results consistent with an influence from the polar vortex breakdown event on the tropospheric jet stream. They suggest that approximately 20–30% of weekly tropospheric jet-stream variability at week 3 and week 4 is predictable based on knowledge of the stratospheric state.

The study also found that our knowledge of the stratosphere plays a role in correctly predicting the impact of the El-Niño–Southern Oscillation, marked by anomalously high or low sea-surface temperatures in the equatorial Pacific, on the tropospheric jet stream in the SH.

Do forecasts underestimate tropospheric predictability?

The large ensemble size in ECMWF’s System 4 (50+1 members) provides an opportunity to determine whether seasonal forecasts underestimate tropospheric predictability, i.e. to determine whether the seasonal forecasts are better at forecasting variability in the reanalysis than their relatively weak signal and high levels of noise (large spread) would suggest. This issue – referred to as the ‘signal-to-noise’ paradox – has received much attention in the seasonal forecast community in recent years. The term derives from the apparent mismatch between anomaly correlation values with the reanalysis and the ensemble’s own signal-to-noise ratio. This issue was investigated extensively for the SH extratropics in ECMWF System 4, but no statistically significant mismatch between anomaly correlation and the signal-to-noise ratio was found. Thus, there is no evidence to suggest that System 4 underestimates the predictability of SH tropospheric jet stream shifts.

Further information can be found in an article by the authors in *JGR Atmospheres*, doi:10.1029/2018JD030173.

WMO Lead Centre for Wave Forecast Verification established at ECMWF

Thomas Haiden, Zied Ben Bouallègue, Richard Mládek, Jean-Raymond Bidlot

In 2016, the World Meteorological Organization (WMO) Commission for Basic Systems recommended that ECMWF become the Lead Centre for Wave Forecast Verification (LC-WFV). With more than 20 years' experience in wave forecast verification and wave model intercomparison (see ECMWF Newsletter No. 150, winter 2016/17), ECMWF was ideally placed to formally take on this role. Three years later, the LC-WFV has reached a stage where most centres contributing to the original intercomparison are providing data to the new system, and where verification results are published regularly on the LC-WFV web page at https://confluence.ecmwf.int/display/WLW. The role of Lead Centre enables ECMWF to immediately identify weaknesses in its wave forecasts compared to others, which helps to inform further improvements to the wave model. Model intercomparison is based on the exchange of forecast fields rather than scores, making it more sustainable in the longer term and providing the necessary flexibility for introducing new scores and observation datasets in the future.

Acronym	Centre	Country
BoM	Bureau of Meteorology	Australia
DMI	Danmarks Meteorologiske Institut	Denmark
DWD	Deutscher Wetterdienst	Germany
ECCC	Environment and Climate Change Canada	Canada
ECMWF	European Centre for Medium-Range Weather Forecasts	Europe
FNMOC *	Fleet Numerical Meteorology and Oceanography Center	USA
JMA	Japan Meteorological Agency	Japan
KMA	Korea Meteorological Administration	Korea
LOPS *	Laboratoire D'Océanographie Physique et Spatiale	France
METEOAM	Servizio Meteorologico dell'Aeronautica Militare	Italy
METNO *	Norwegian Meteorological Institute	Norway
METFR	Météo-France	France
NCEP	National Centers for Environmental Prediction	USA
NIWA	National Institute of Water & Atmospheric Research	New Zealand
NZMS *	New Zealand MetService	New Zealand
PRTOS	Puertos del Estado	Spain
SHNSM	Department of Meteorology of the Naval Hydrographic Service	Argentina
UKMO	UK Met Office	UK

Contributing Centres. As of October 2019, 14 wave forecast centres regularly provide model fields to the Lead Centre. Data from another four centres, marked by an asterisk, are in preparation.

Collecting and archiving forecast data

ECMWF gathers and archives a set of selected model fields relevant to wave forecasting activities under an agreed format. The data are produced by operational global or regional forecasting systems. The following parameters are exchanged:

Atmospheric forcing

- 10 m wind speed U and V components

Wave fields

- Significant wave height
- Peak period
- Mean wave period based on the second moment of the frequency spectrum
- Mean wave direction

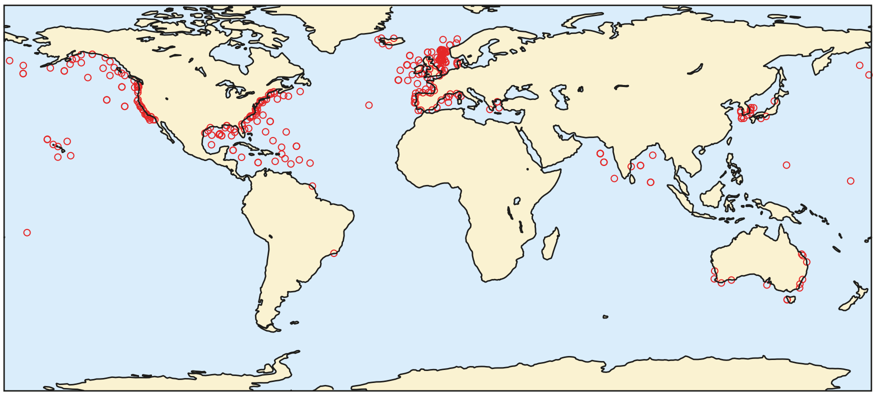
The fields are provided on a regular latitude-longitude grid at the resolution that best matches the native resolution of each contributing model. The data are encoded in GRIB format using WMO-compliant templates. During the development phase, ECMWF assisted contributing centres in the conversion to GRIB. Participants are committed to guaranteeing the steady and reliable provision of their data and are asked to communicate any relevant changes in their systems as close to real time as possible.

Observations

Forecasts of the above parameters are evaluated against quality-controlled in-situ observations from about 400 buoys and platforms available to ECMWF. Most of these are located in the coastal areas of North America, Europe, Brazil, Japan, Korea, India and Australia. Others are part of different tropical buoy networks (TAO, TRITON, PIRATA, RAMA) or of the OceanSITES network. It is anticipated that more in-situ observations will become available over time. They will be added following careful selection and quality control. Participants are strongly encouraged to promote the exchange of in-situ wind and wave observations. Other verifying data available to ECMWF, such as altimeter wave heights, will also be considered in the future.

Scores

Scores computed on a regular basis include mean error (ME), root mean square error (RMSE), error standard deviation (SDEV), scatter index



Locations of selected buoys providing wave height data for verification. The map shows the distribution of locations for which measurements of significant wave height were available during summer 2019 (June–July–August).

(normalised standard deviation of error), symmetric slope (variance ratio), and quantile-quantile (Q-Q) plots. These metrics have proven useful in previous ECMWF-led wave model intercomparison activities. Aggregated scores are generated for a wide range of domains, from global down to regional ones (e.g. the Mediterranean, or the North Sea). All results are shown on the Lead Centre's web page, together with maps of data availability.

Contributing centres

As of October 2019, 14 wave forecast centres regularly provide model fields to the Lead Centre (see table). Four centres (marked by *) are in the process of setting up the data provision. Depending on the centre, the data are sent up to four times per day (from 00/06/12/18 UTC model runs). The lead time range varies between +72 and +288 hours with time steps from one- to six-hourly. More details about each contribution can be found on the LC-WFV web page.

Technical aspects

The agreed data format is WMO-compliant GRIB edition 2. The ECMWF data acquisition system (ECPDS) is used for data exchange. The data processing before the actual verification consists of acquisition, validation (encoding and basic data quality checks), and archiving in MARS. It follows well-established workflows as used by other projects, such as TIGGE for medium-range weather forecasts or S2S for sub-seasonal to seasonal forecasts. This makes it possible to run the processing smoothly and in a flexible way using parallel processing and back archiving. Nevertheless, about 10 to 15 data issues need to be resolved on average every month to keep the archive in order and eliminate any data gaps. The most frequent issue is the transfer of incomplete or corrupted data, usually as a result of problems or technical changes in the processing chain on the provider side. In order for the Lead Centre to be able to sustain its activities in the longer term, it will be important to reduce the number of such incidents.

Outlook

Once the initial setup of the Lead Centre has been completed, ECMWF will explore possible extensions of the verification, for example the use of observations from drifting buoys, which has become possible now that fields rather than scores are exchanged. ECMWF would also like to take this opportunity to thank the contributing wave forecast centres for their efforts in implementing the data exchange and for their continued support for the Lead Centre's activities.

ECMWF upgrades OGC membership

Stephan Siemen

ECMWF has upgraded its membership of the Open Geospatial Consortium (OGC) from Associate to Technical membership. The move means that ECMWF will be able to vote and actively drive work at OGC. Over the past few months, ECMWF has already taken part in various votes, requests for comments, and a hackathon.

ECMWF joined OGC as an associate member in 2010. Together with several national weather services, it has been active in OGC's MetOcean Domain Working Group since its inception to represent the needs of our community and provide input on new standards and best practice documents. OGC sets standards for the provision of geospatial data, such as weather information and environmental data, through web services. Following these standards enables interoperability between the different services and client applications users might use. This is especially important for the two EU-funded Copernicus services implemented by ECMWF when providing services for

What is the Open Geospatial Consortium?

The Open Geospatial Consortium is an international consortium of more than 530 businesses, government agencies, research organizations, and universities driven to make geospatial information and services FAIR - Findable, Accessible, Interoperable, and Reusable. OGC's members create free geospatial standards. OGC also actively analyses emerging tech trends, and runs an agile, collaborative Research and Development lab that builds and tests innovative solutions to members' use cases. For more information, visit: *www.ogc.org*.

partners and users who are not familiar with the standards of the meteorological community. Using OGC web standards ensures they can easily integrate these services into their applications. OGC and the World Meteorological Organization (WMO) have signed a memorandum of understanding to ensure that these two standards bodies work closely together.

Marie-Françoise Voidrot, Director of the Innovation Program at OGC, welcomed the membership upgrade. She said: “As an OGC Innovation Director, and also as a meteorologist, I welcome ECMWF’s decision to upgrade to the Technical level. The Centre’s experience in Earth observation, forecasting, and operational product delivery will be valuable across all OGC programmes and committees. ECMWF’s two EU-funded Copernicus services, delivered using OGC Standards, have broadly improved the accessibility of valuable data and products. OGC looks forward to working with ECMWF to advance open, interoperable, and efficient Earth science capabilities for a sustainable future.”

ECMWF co-organises hydro-met session at EMS

Fatima Pillosu, Tim Hewson (both ECMWF), Conor Murphy (Mynooth University, Ireland)

ECMWF scientists helped to organise a hydro-met session on ‘Exploring the interfaces between meteorology and hydrology’ at the 2019 Annual Meeting of the European Meteorological Society (EMS) in September in Copenhagen. The initial goal was to create an all-embracing hydro-meteorological forum where experts from both disciplines could join forces to accelerate the integration of the two fields. The longer-term aim, to be pursued in future sessions, is to build a larger and influential hydro-met voice within the EMS community. Scientifically, the justification is that meteorology and hydrology act in tandem across the interface between the Earth’s atmosphere and its land surface, and as our understanding and predictive capabilities grow, this interface becomes increasingly important.

The session was very well received in terms of both abstracts submitted (19 talks and 6 posters) and attendance, which peaked at around 100 during the morning session. Topics covered were very wide ranging and included lake temperature prediction; snowmelt impacts; spatio-temporal statistics of rainfall extremes; the use of rescued data for drought and flood reconstruction; impacts of meteorological and hydrological models on predictive skill for flash floods; atmospheric rivers; monthly and seasonal hydrological predictions; and groundwater modelling in an Earth system model framework.

Session conveners and participants. The session conveners were (from left to right) Tim Hewson (ECMWF), Fatima Pillosu (ECMWF and the University of Reading) and Conor Murphy (Mynooth University, Ireland). The right-hand photo shows the session in progress.

Like the conveners, the EMS Programme and Scientific Committee were very happy with the submission level and turnout for the session, so we will work hard to build on this success in the coming years. We invite all those interested to submit abstracts for next year’s conference. To facilitate networking, we organised a joint dinner for participants in our session and a companion hydro-met session on precipitation monitoring; the canal boat venue chosen for this purpose proved very popular.

New observations since July 2019

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

Observations	Main impact	Activation date
Bending angles from KOMPSAT-5’s radio occultation instrument	Temperature in upper troposphere/ lower stratosphere	24 July 2019
High-resolution dropsondes	More observations near tropical cyclones, with dropsonde drift accounted for	4 September 2019
Radiances from IASI on Metop-C	Temperature, humidity, ozone, dynamics	25 September 2019

ECMWF's second Summer of Weather Code

Esperanza Cuartero, Julia Wagemann, Anna Ghelli, Claudia Vitolo

Faithful to its spirit of innovation, the second ECMWF Summer of Weather Code (ESoWC) programme invited proposals for up to twelve open-source projects that address weather-related software challenges. Developers from around the world submitted their proposals and eight were selected for coding. From May to the end of August, ECMWF mentors and participants joined forces to work on projects related to machine learning, data visualisation, software development, Jupyter notebooks and functionalities of open source Geographical Information Systems. Seven teams successfully completed the coding challenge.

On 20 September 2019, during the ESoWC 2019 showcase day, the seven teams presented an impressive set of results at ECMWF's headquarters.

Outcomes

All teams used the online software development platform GitHub to track the progress of the projects and share their knowledge with the larger open source community. The seven successful projects were:

1) **Obtaining online aircraft metadata.** AMDAR aircraft meteorological reports do not provide the aircraft type, which can be a vital piece of information to be able to evaluate temperature biases and wind errors. This ESoWC project developed Python code to compare AMDAR flights with those from internet sources, such as flightaware.com and flightradar24.com, to match aircraft types.

2) **New calibration software: ecPoint-Calibrate.** The new software uses conditional verification concepts to compare numerical weather prediction output with point observations in different weather situations, in order to take into account sub-grid variability and grid-scale bias. ecPoint-Calibrate provides a dynamic, user-friendly environment for post-processing model parameters to deliver better probabilistic forecasts for point locations.

3) **Jupyter notebook for OpenIFS.** This project aimed to develop an interactive Jupyter environment for OpenIFS, an easy-to-use version of ECMWF's Integrated Forecasting System (IFS) for external users. The outcome is a simple and modern Jupyter notebook which is compatible with the Fortran interface of the IFS and enhances scientific productivity when using OpenIFS.

4) **Blender Visualization Toolkit.** The challenge was to develop a set of scripts that can be used to generate Earth animations to help the general public interpret the data produced by ECMWF. The solution uses the Blender Visualization Toolkit (BVTK), an add-on for the Blender 3D graphics software package, to make it possible to use the VTK visualisation library inside Blender through a graphical interface, based on node trees.

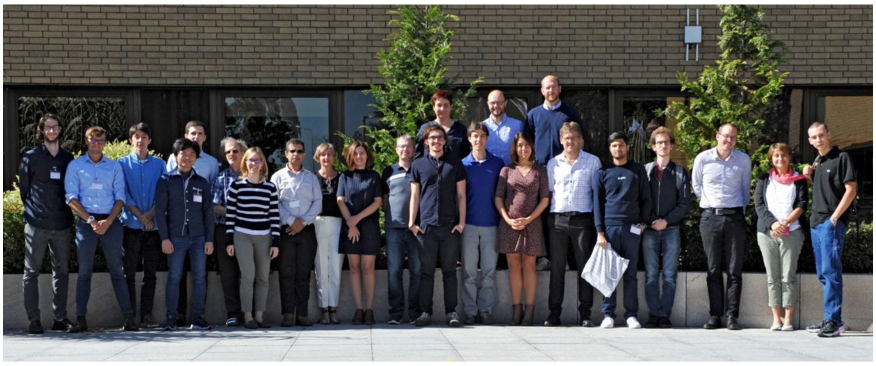
5) **Geographical Information System tools.** This project addressed workflow problems within EFAS (European Flood Awareness System) when a new partner is added to the EFAS domain. The tools developed automate the process of adding a new partner region; updating river basins with new partner region IDs; and updating grid points in river basins with new partner region IDs.

6) **Machine Learning (ML) to better predict and understand drought.** The goal was to predict pixel-wise values of vegetation health in Kenya using ML techniques. The project developed a pipeline of different processing components, written in Python, that can be used to apply the implemented approach to a variety of datasets and regions.

7) **MAchine learning TEchniques for High-Impact Weather (MATEHIW).** The goal was a comparison of different ML techniques applied to the prediction of floods, based on ERA5 data and GloFAS (Global Flood Awareness System) river discharge data. The project developed a machine learning model architecture that splits the flood forecast model into two parts: a transport model that accounts for advection of water from upstream river to downstream river grid points; and a local model, that accounts for the difference to observed values.

The two explorative projects applying machine-learning algorithms were supported by the two EU-funded Copernicus services implemented by ECMWF: the Copernicus Climate Change Service (C3S) and the Copernicus Atmosphere Monitoring Service (CAMS). They have prepared the ground for further research in this field.

For more details on the open source projects, visit the ECMWF Summer of Weather Code website: https://www.ecmwf.int/en/learning/workshops/ecmwf-summer-weather-code-2019, and the ESoWC GitHub space: https://github.com/esowc.



Seven project teams. The ESoWC coding teams and their ECMWF mentors came together at the Centre on 20 September.

ECMWF adopts new application platform

Andrew Brady

ECMWF is starting to provide some of its web and data services based on applications deployed on a new IT platform. For the migration of ECMWF's data centre to Bologna, we are transforming several applications to run as Docker containers on Kubernetes-managed platforms. This article explains what Docker/Kubernetes are, why they are increasingly being used at ECMWF, and what this means to users.

Reasons for the change

Developing IT-based applications historically means having to know a lot about the technical environment. Software code can be developed and run perfectly in a limited environment (like a laptop, desktop or workstation) but it can then be hard to transition, maintain and run in other environments. The traditional approach is to develop services and applications based on common shared code/libraries which are deployed onto dedicated infrastructure to ensure that the applications get the IT environment and resources they need to run. This approach is not sustainable as services grow and does not scale in terms of infrastructure or effort. Looking for alternatives, ECMWF web application analysts became aware of two new technologies: Docker and Kubernetes.

What are Docker and Kubernetes?

Docker is a generic environment for running software without having to know details about the infrastructure. Docker uses operating system virtualisation to enable development and delivery of software applications consistently in runnable packages called containers. Kubernetes is a tool for managing Docker applications that are running on clusters of infrastructure. Kubernetes solves the problem of scaling and operating services composed of containers. General market adoption of Docker and Kubernetes, for application development, has been substantial, supporting accelerated development, rapid release of updates to production and efficient scaling. They are key technologies for development. ECMWF has aligned itself with these technologies, realising that they are beneficial for our services.

What does it mean for users?

ECMWF is currently using Docker and/or Kubernetes successfully to provide several services, including Atlassian, EFAS-IS, GloFAS, the RMDCN website, FTP, the Data Services Costing Application, Accounts and Nexus. There are other services in the pipeline for deployment on Kubernetes in Bologna, including the www.ecmwf.int website, ecCharts, and webapi.

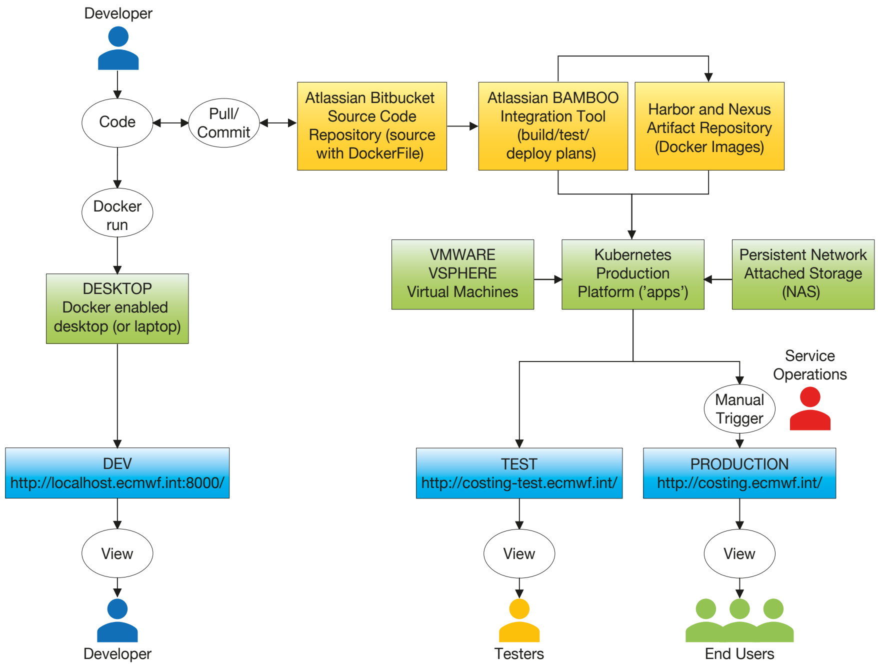
The key improvements users of these services should see as ECMWF adopts Docker and Kubernetes are:

- improved turnaround time for fixes/updates/improvements
- more robust services as applications are even more comprehensively tested during their development.

As illustrated in the diagram, the use of Docker/Kubernetes also improves our workflows as development can be undertaken in relative independence. In addition, the transition of applications to production is facilitated as application containers do not need to be changed for operations.

The current setup

Our current Kubernetes Cluster consists of virtual machines (VMs) from our VMWARE VSPHERE and Network Attached Storage for data persistence. The infrastructure can be scaled transparently by adding new VMs and/or bigger VMs using Kubernetes to orchestrate containers across VMs. In production, the cluster also provides many operations-ready functions by default and using it significantly reduces the effort needed to implement commodity application



Example of Continuous Integration workflow. The workflow shown here enables the developer to make code changes safely in isolation and test their work on their desktop. When they are satisfied, they commit changes, and this triggers the workflow that generates a Docker container and, if successful, deploys it automatically. This then becomes available as a generally accessible test service. If the testers are satisfied, service operations manually trigger the update to production, possibly in a scheduled session. The entire workflow is traceable from source code change to deployment to production.

components, such as web servers, application servers or databases.

It is important to realise that Docker and Kubernetes are not the only technologies used. To efficiently and robustly deploy applications, we have implemented Continuous Integration/Continuous Deployment (CI/CD) tooling. We use Atlassian Bitbucket, Harbor, Nexus and Atlassian BAMBOO. With these tools, we have a pipeline system that enables rapid and robust development, with a light touch, through to operations. We have also integrated automated functionality to test and ensure the quality of code and the security of underlying platforms.

If you are interested in learning more, please feel free to get in touch with Andrew Brady (andrew.brady@ecmwf.int).

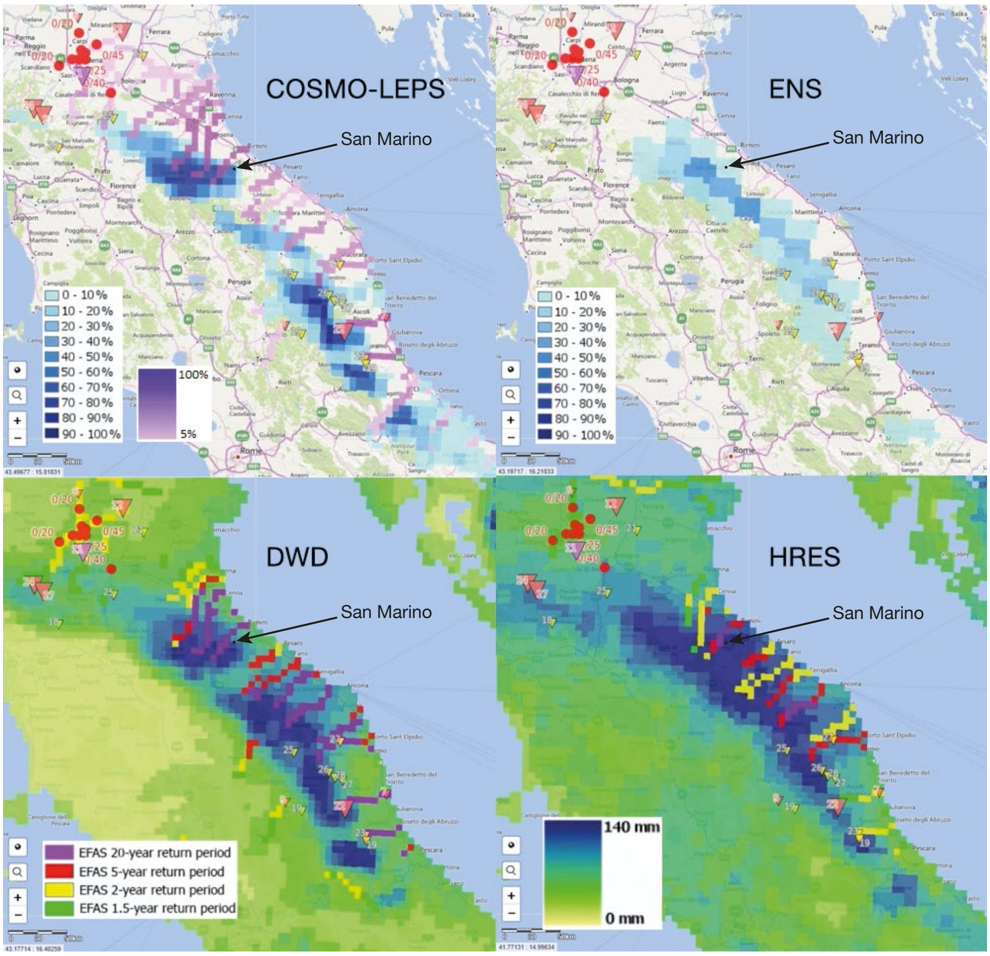
Italian floods in May 2019 proved hard to predict

Ervin Zsoter, Christel Prudhomme, Corentin Carton De Wiart

According to ECMWF's ERA5 reanalysis, in May 2019 parts of Italy experienced at least two to three times the average rainfall for that month. There were severe flash floods and riverine floods in many areas, associated with an increased landslide risk in some places. One of the worst-hit areas was the Emilia-Romagna region, which experienced severe floods around 13 May. In the upstream areas of the Savio and Marecchia rivers near San Marino, in two days up to 200 mm of rain was observed. Forecasts issued by the European Flood Awareness System (EFAS) for this short-lived event involving relatively small catchments proved challenging in the medium range, and even short-range forecasts were of uneven quality. EFAS is a component of the Copernicus Emergency Management Service for which ECMWF is the computational centre. As requested by the EFAS partners, work is under way to improve flood forecast performance for similar events.

Forecasts of the event

EFAS forecasts showed little sign of a risk of substantial floods near San Marino in the medium range. This began to change a few days ahead of the event, and by one day before there was a strong signal in three of the four hydro-meteorological forecast chains used in EFAS. As shown in the figure, forecasts driven by the COSMO-LEPS limited-area model, the German DWD model and ECMWF's deterministic high-resolution forecast (HRES) showed a



EFAS forecasts starting at 00 UTC on 12 May 2019. The top-left panel shows the COSMO-LEPS forecast of the probability of total precipitation over 5 days exceeding 150 mm and the probability of river discharge exceeding the 20-year return period level. The top-right panel shows the corresponding ENS forecasts but for 10-day precipitation totals. The bottom left panel shows the DWD total precipitation forecast (7 days) and predicted return periods. The bottom-right panel shows the corresponding HRES forecasts but for 10-day precipitation totals. Red dots and yellow triangles denote five- and two-year return period river flood reporting points, respectively. Larger triangles show flash flood reporting points.

strong hydrological signal for the worst-impacted area west and northwest of San Marino. This can be attributed to good precipitation forecasts and the associated river response in EFAS. Higher resolution seems to have helped in this case as forecasts driven by ECMWF's lower-resolution ensemble forecast (ENS) did not show the same severity in the flood signal despite indicating a probability of up to 40% of 10-day precipitation exceeding 150 mm in the area.

Redefining reporting points

When EFAS detects a consistently high flood risk based on a combination of the information provided by the different forecast chains, it defines reporting points where flood forecasters can investigate in detail the shape of the flood hydrograph. One of the issues with this event was that no reporting point was shown in the worst-hit area. There are several reasons for this: high uncertainty in the meteorological forcing; a large variation in forecasts from one forecast run to the next; and the short duration of the event. In addition, rules to identify reporting points are currently slightly less restrictive for river points where partners provide data, which is the case in some of the areas where reporting points are shown in the figure, but not in the San Marino area. The introduction of fixed reporting points for certain river basins, where flood hydrographs are always produced with available hydrological data, should help in the future with cases such as the San Marino floods. Such an upgrade was tested in EFAS during the summer of 2019 and was implemented on 8 October. The way reporting points are identified and shown could also be revised, for example with more flexible rules regarding forecast uncertainties. However, the multiplication of reporting points associated with lower probabilities of flooding might make the interpretation of the forecasts more difficult.

Improved time stepping and resolution

The fact that ENS-based flood forecasts use a daily time step with daily meteorological forcing leads to a smoothing of flood peaks in small, fast-responding catchments, such as in this event. Furthermore, due to the spatial resolution of the hydrological model in EFAS (25 km^2 per pixel), forecast skill tends to be lower for small catchments, such as the Savio and Marecchia catchments (approximately 1,000 km^2). There are plans to switch the ENS-driven EFAS forecasts to a 6-hourly time step. To this end, a hydrological model calibration using a 6-hourly time step is currently being developed and will be released in spring 2020. This is expected to improve forecast skill for fast-responding catchments. Finally, preparations have begun to increase the spatial resolution of the hydrological model to enable the production of higher-resolution EFAS forecasts in the coming years.

Save the date!

Every second year, ECMWF hosts a workshop on the use of high-performance computing in meteorology. ECMWF's new high-performance computing facility will be installed at the Tecnopolo di Bologna in 2020. For the first time, ECMWF's data centre will be separated from its headquarters and the Centre will function as a multi-site organisation. To mark this occasion, the 19th workshop on high-performance computing in meteorology will take place in Bologna. The workshop programme will include a visit to the new data centre.

For more information, visit: https://www.ecmwf.int/en/learning/workshops/19th-workshop-high-performance-computing-meteorology
Contact: events@ecmwf.int

Recent progress in all-sky radiance assimilation

Alan Geer, Niels Bormann, Katrin Lonitz, Peter Weston, Richard Forbes, Stephen English

Satellite observations make a major contribution to the Earth system data which are routinely assimilated into models to determine the initial conditions for weather forecasts. Since the beginning of satellite data assimilation in the 1980s, most cloud-affected observations have been rejected following the 'clear-sky' approach. This is because, in areas of cloud and precipitation, neither model forecasts nor the conversion of model values into satellite observation equivalents (observation operators) have been accurate enough. The machinery for using cloud and precipitation in data assimilation has needed decades of development, but the work is starting to pay off. A decade ago, ECMWF introduced direct 'all-sky' assimilation of satellite radiances in the presence of cloud and precipitation. The aim was to extract more information in sensitive and under-observed areas, particularly in midlatitude fronts. We saw that four-dimensional variational data assimilation (4D-Var) was able to infer updates to winds, temperatures and pressures from the location of cloud and precipitation in the observations, resulting in improved medium-range forecast quality in ECMWF's Integrated Forecasting System (IFS). Recent progress in exploring the full potential of assimilating observations of cloud and precipitation has been substantial. In one stream of work, we have expanded the coverage of all-sky assimilation from a handful of microwave sensors with limited impact to now nine sensors that are a major part of the observing system. We aim to expand all-sky assimilation to the rest of the operational microwave and infrared sensors over the next few years, and we hope to add entirely new types of sensors aimed primarily at cloud and precipitation, such as the upcoming Ice Cloud Imager on EUMETSAT's next generation of polar satellites. Progress has also been made in properly representing observation error correlations; using more observations over land surfaces; and exploiting the information provided by cloud and precipitation-affected radiances to further develop the modelling of moist processes in the atmosphere.

Increasing use of all-sky data

The first instruments to receive the 'all-sky' treatment were microwave imagers, but this has been extended to currently nine humidity, cloud and precipitation-sensitive microwave sensors. These give around 15% of all observational impact, which is comparable with other influential components of the observing system (see Box A). Despite some scepticism in past decades, it is now clear that all-sky assimilation of microwave humidity-sensitive radiances is beneficial – indeed it can roughly double the impact of a satellite instrument compared to the clear-sky approach.

We have recently explored how far we can take the all-sky approach. Infrared radiances are not yet operationally assimilated in all-sky conditions, partly due to concerns about their more nonlinear sensitivity to cloud, particularly to its vertical overlap and sub-grid variability. We have now experimentally demonstrated a small benefit from moving infrared humidity sounding channels into the all-sky approach, meaning that it would be feasible to start doing some level of all-sky infrared assimilation in the operational system. As for temperature-sounding satellite data in both the microwave and infrared, the concern has been that cloud-related errors could adversely affect the temperature fields and destroy the analysis. If there are location errors in the cloud field of the short-range forecasts used in data assimilation (the background), then data assimilation should try to correct them by adding cloud at the observed location. However, it could also erroneously try to fit the observations by changing the temperature and moisture profile of the atmosphere. To prevent this occurring requires strong physical constraints in the data assimilation as well as background errors that are appropriately set. However, this may be difficult to achieve since cloud-related errors can be as large as 100 K when measured in terms of brightness temperature, whereas background temperature errors translate to around 0.1 K variations in observed brightness temperature.

Nevertheless, we have demonstrated an all-sky assimilation of Advanced Microwave Sounder – A (AMSU-A) data that gives around the same impact as clear-sky assimilation (Figure 1). We hope that with additional development it could become operationally viable in the next few years. Since all-sky assimilation

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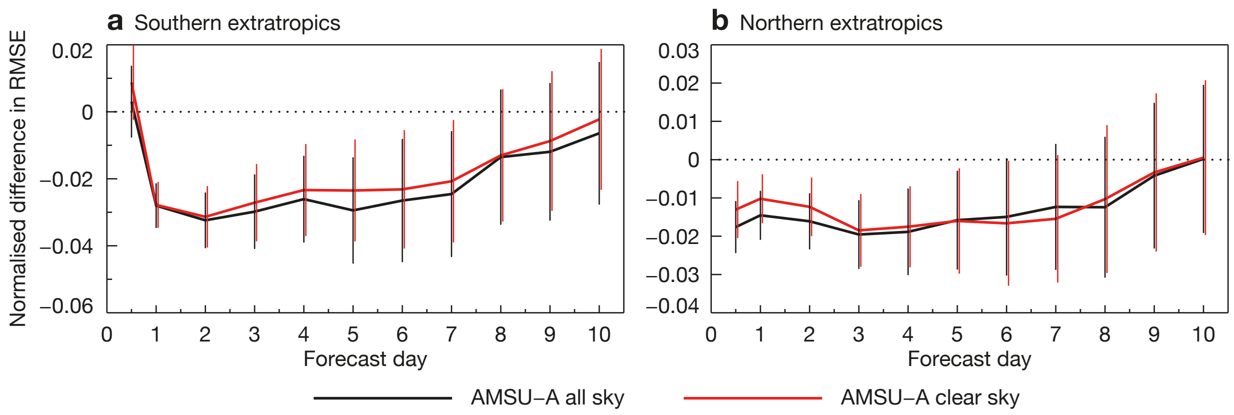


FIGURE 1 Impact of AMSU-A assimilation (from 6 sensors) compared to an experiment in which no AMSU-A data are assimilated. Results are given for (a) the southern extratropics (20°S to 90°S) and (b) the northern extratropics (20°N to 90°N). The figure shows the normalised change in root-mean-square error (RMSE) in 500 hPa geopotential, with negative values indicating error reductions with AMSU-A assimilation. See Weston et al. (2019) for more details.

runs in a separate framework to the old clear-sky approach, some of the biggest issues for AMSU-A have been to do with replicating some apparently minor aspects of the clear-sky framework, such as the exact data thinning pattern and the geophysical quality control. These aspects have been finely tuned over decades and, with the number of AMSU-A sensors being assimilated and their substantial influence on forecast quality, even apparently minor details can have an impact.

For the future, any new microwave sensors that are added to our system will be implemented directly in the all-sky framework. For example, we expect to use all-sky assimilation for all three microwave and sub-millimetre sensors to be flown on EUMETSAT Polar System – Second Generation (EPS-SG) satellites from 2022 onwards. Over the next decade, we should be able to start using all remaining satellite radiance data in cloudy and precipitating conditions. This will both benefit the forecasts and help rationalise our system so that a common all-sky approach can be used throughout. In future, in the all-sky framework we will also add completely new types of sensors whose atmospheric information content is dominated by clouds, such as imagers working at solar frequencies. Our development of all-sky assimilation for passive satellite sensors goes in parallel with our developing ability to use active sensors, such as cloud radar and lidar, which will be reported separately.

Overcoming barriers to progress

Further progress will come from observation scientists adding more sensors and continuing to improve the accuracy and physical realism of the observation operator. For example, we are improving our microphysical representation of snow and graupel particles in the microwave scattering observation operator, and we hope to better represent the effects of preferential particle orientation, three-dimensional cloud and precipitation structures, and horizontal inhomogeneity. These improvements will enable us to have greater confidence in the observations, leading to the use of smaller observation errors or a reduced need for quality control.

Overcoming two further significant barriers could produce even more benefit from satellite radiance data. First, we need to use more observations over land and sea-ice surfaces, particularly over ice, snow and desert surfaces. The techniques that have worked for all-sky assimilation – fast approximate observation operators and observation errors that inflate in difficult situations – should also help over land surfaces. Second, we need to use more of the data at higher spatial resolution. At present, we have to thin most satellite data down to around 100 km scales because spatial observation error correlations are not yet modelled in the data assimilation. To improve, we need to start modelling spatially correlated observation errors in the data assimilation process.

All-sky data over land surfaces

Currently only the 183 GHz and 118 GHz humidity- and temperature-sounding channels are assimilated in all-sky conditions over land, taking advantage of their generally small sensitivity to the surface. These channels provide information on mid- and upper-tropospheric humidity and on snow and ice particles in the atmosphere. Many other microwave imager channels have sensitivities to low-level rain and water cloud. They thus have the potential to provide information that is almost unique in land areas that are poorly covered by ground-based sensors. However, these channels are currently discarded due to their high sensitivity to the surface. The difficulty is the poor accuracy in the simulated brightness temperatures due to uncertainties in the emissivity and skin temperature over land. All-sky assimilation adds the difficulty of separating errors in cloud and precipitation from those in the description of the surface. Currently, surface emissivity is retrieved from the observations themselves as part of the data assimilation process. This estimate is only accurate enough when clouds are semi-transparent to microwave radiation. In situations of heavy precipitation, the surface is not visible and emissivity values from an emissivity atlas are taken instead. To provide more accurate estimates, a 'constrained emissivity retrieval' is being tested. In this method, the emissivity retrieval at a low frequency (where the sensitivity to clouds and precipitation is minimal) is extrapolated to other channels, using the frequency-dependence recorded in the atlas.

Figure 2 illustrates the additional information we could gain over land surfaces. Based on the same profile of humidity and temperature, we have simulated the brightness temperature change due to adding a liquid water cloud over a grass surface and over an ocean surface. Over the ocean, because of the relatively cold radiating temperature of a water surface, liquid clouds have an impact of over 40 K at 89 GHz in horizontally polarised channels. Over land, for the same channel the effect of the same water cloud is just 4 K. Hence over land we have a smaller signal to work with and bigger errors in the surface emissivity to contend with. Nevertheless, information on water cloud over land surfaces from other sources is extremely limited, and getting it right is important to the surface radiation budget and to near-surface temperature forecasts. Hence, there is strong motivation for improving our representation of the surface characteristics to be able to use the information on water clouds and liquid precipitation available from microwave observations. Beyond this, microwave observations, particularly at lower frequencies, are crucial parts of the observing system for soil moisture, vegetation and snow cover. If the atmospheric sensitivities of microwave observations have been well represented, that should make it easier to simultaneously infer information on the surface characteristics. Hence the ultimate goal is to use our land surface model to drive a physical land emissivity model, but it will take some development work before its accuracy can beat the emissivity retrieval approach.

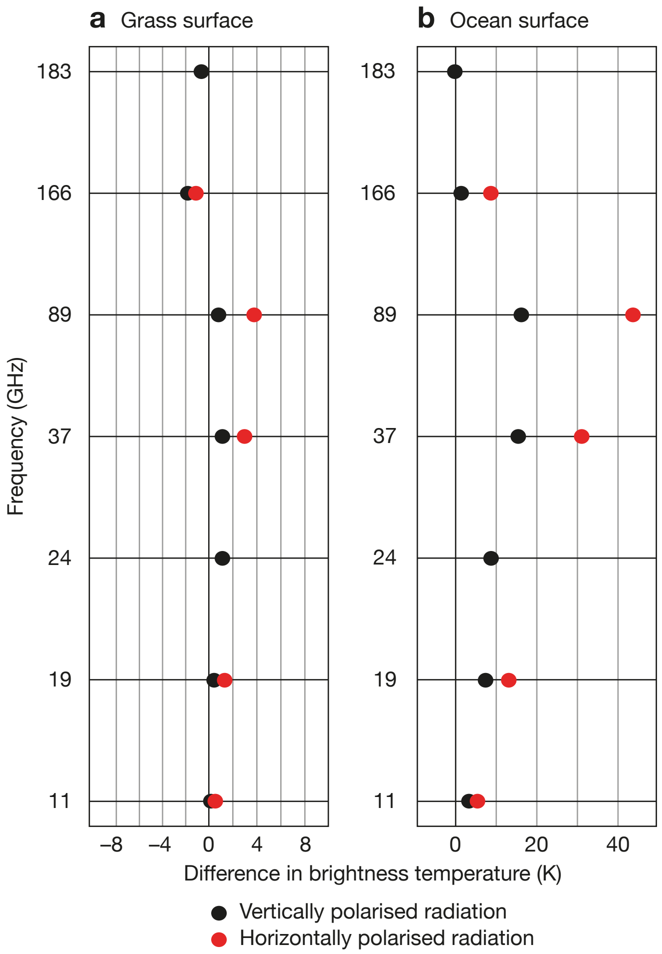


FIGURE 2 Differences in brightness temperature between a profile containing a liquid water cloud and the same profile without cloud for (a) a grass surface and (b) an ocean surface. Horizontally and vertically polarised radiation is shown separately because it is typically measured on microwave imagers using separately polarised channels.

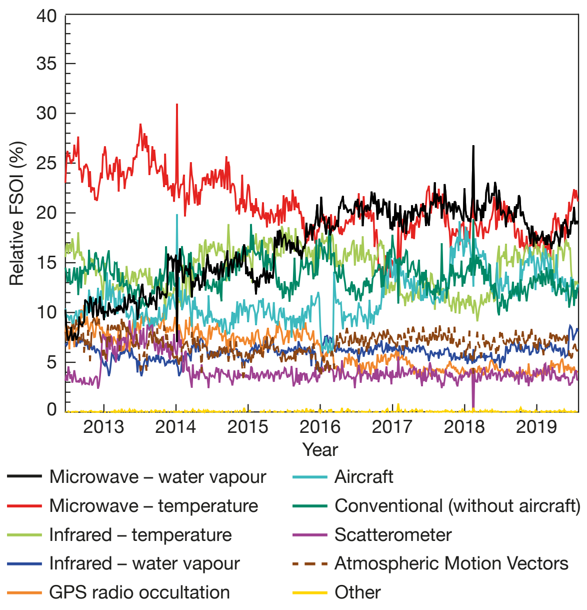
Representing observation error correlations

The modelling of observation error correlations has already benefitted the assimilation of clear-sky observations. For example, the move to inter-channel error correlations for hyperspectral sounders provided significant benefit to forecast scores. The operational all-sky approach does not yet represent observation error correlations, but the presence of cloud and precipitation has a substantial impact on them, for example increasing the correlations between channels. Further, the presence of cloud affects spatial correlations, but its exact effect is still unclear. On the one hand, it could shorten the distances over which these errors are correlated down to the scales of the cloud or precipitation features themselves. On the other hand, the distances over which these error correlations are important could also become longer where there are systematic errors or biases in particular cloud regimes.

To demonstrate all-sky infrared assimilation of hyperspectral water vapour sounding channels, an error correlation model was successfully devised. It includes careful filtering of the error covariance matrix. This was needed to prevent the amplification of subtle inter-channel bias signals and gravity waves with relatively short vertical periodicity. Both effects can degrade the analysis, through changes in the model climate and/or through the introduction of additional gravity wave activity in the model propagating into the stratosphere.

a Impact on forecasts

The impact of observations on the operational forecast is monitored by the ‘Forecast Sensitivity to Observation Impact’ (FSOI) diagnostic, which estimates the impact of each observation on a measure of global forecast errors at 24 hours lead time. The diagnostic requires computations in the short range but has been found to be broadly indicative of observation impact in the medium range. The FSOI diagnostic has been estimated operationally since 2012. It has recorded, among other things, the rising importance of microwave water-vapour sensitive data, most of which is assimilated with the all-sky technique. The figure shows the relative impact of different subsets of the global observing system, normalised so that the impact at every analysis cycle adds up to 100%, irrespective of long-term changes in the overall quality of forecasts. The relative impact of any one type of observation changes as techniques evolve and satellites are added to the system, or are lost to old age. For predominantly northern hemisphere data, such as aircraft, the impact varies with the seasons because the measure of global forecast error is dominated by the winter hemisphere. Occasional spikes are likely due to numerical instabilities in the FSOI calculations during sudden stratospheric warmings. The ‘microwave water vapour’ category contains the all-sky microwave data plus three similar sensors that have not yet been converted to all-sky assimilation. This category has comparable impact on forecast quality to the other main categories, such as microwave and infrared observations sensitive to temperature, aircraft observations and the rest of the conventional observing system (radiosondes, surface stations, ships and buoys). The relative impacts of different classes of observation, as seen in the FSOI, is broadly backed up by observing system experiments (OSEs), which measure the importance of observations by removing them from the system.



Relative sensitivity of the operational 24-hour forecast quality to various components of the observing system since 2013.

The development of interchannel error correlation models for the all-sky microwave imagers is proceeding, but with some difficulty, possibly partly due to changes in the analysed climate when correlations are represented. It is likely that observation error modelling will continue to require significant research and development effort in the future, particularly when it comes to all-sky assimilation.

Evaluating systematic errors in the forecast model

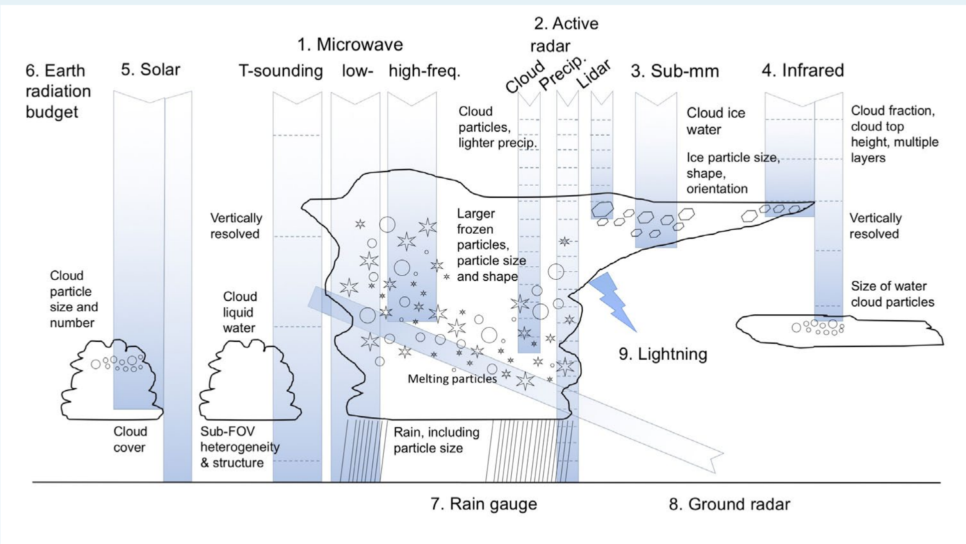
Progress in all-sky assimilation can help to improve not just the initial conditions but also the forecast model. For example, combining satellite radiances from many different frequencies should extract more information on microphysical details like the shapes and sizes of cloud and precipitation particles. Combining that with information from active sensors and ground instruments, we could reach a point of ‘microphysical closure’ (Box B).

In a previous Newsletter article (Forbes et al., 2016), we showed how a combination of all-sky microwave imagers, lidar cloud retrievals (from CALIPSO) and broadband radiation budget measurements (from CERES) helped to identify a lack of supercooled liquid water in convective cold-air outbreaks at high latitudes over the ocean. Potential solutions were tested and a series of changes made to the cloud and convection processes in recent IFS upgrades to significantly reduce mean top-of-the-atmosphere shortwave radiation errors, particularly since June 2019 with the implementation of IFS Cycle 46r1. However, a re-evaluation of microwave brightness temperature departures with the latest IFS cycle shows there is some compensation of errors with still too little supercooled liquid water in much of the cold-air outbreak region where the cloud is deeper, but now too much supercooled liquid water in the shallower boundary layer cloud regime. Hence, the all-sky evaluation within the data assimilation system is showing the need for further improvement of the supercooled cloud processes.

With increasing use of all-sky observations, including for a wider range of frequencies, we hope to shed light on other aspects of the model representation of cloud and precipitation. This should make it possible to further increase the realism of the model. One new example is an apparent lack of coverage of convective cloud over land surfaces in the model revealed by experimental all-sky infrared assimilation. This is shown in Figure 3 for three different channels representing different altitudes. Over the central US, southern parts of South America, northern India and much of the equatorial areas of Africa, blue colours indicate a substantial mean bias between the model and observations suggesting the model is lacking convective cloud. This is supported by the all-sky microwave observations over land at 183 GHz, sensitive to precipitation-sized ice particles, which also suggests a lack of frozen precipitation in these regions (not shown). Currently the observation operator for this channel needs to artificially boost the effect of model precipitation over land surfaces, for better agreement with observations and to permit assimilation of the data. This could be removed if the model cloud and precipitation representation were

b Microphysical closure

By the end of the next decade, we could be assimilating a huge amount of satellite and ground data sensitive to cloud and precipitation. In-situ measurements of cloud and precipitation are not possible on a global scale, so almost everything is a remote measurement of some form or other. The bulk of cloud and precipitation information comes from 'passive' satellite measurements of the upwelling electromagnetic radiation from the Earth. Because of the way radiation interacts with particles, the greatest sensitivity to the microphysical details of cloud and rain in the atmosphere occurs when the wavelength of the radiation is close to the size of the particles. For example, microwave wavelengths are from around 30 cm to 1 mm giving, as the wavelength decreases, increasing sensitivity to microphysical details (size, shape, and orientation) of first raindrops, then snow and hail. As the wavelength decreases, the frequency increases, so often the microwave region is roughly split, as in the diagram, into 'low-' and 'high-'frequency regions, based on whether the primary sensitivity is to the liquid or ice phase. Sub-mm wavelengths have sensitivity to smaller cloud ice particles, whereas infrared and visible wavelengths cover down to around 0.4 microns, with increasing sensitivity to the number concentration (and hence size) of cloud water droplets. Passive measurements tend to see the integrated contribution from many levels of the atmosphere or they may just see the top of a cloud. 'Active' instruments measure the backscatter from particles and are able to provide profiles through the depth of a cloud. At microwave wavelengths, the active approach is known as radar, with sensitivity to precipitation and cloud; at visible wavelengths, the approach is known as lidar and is mainly aimed at cloud particles. In addition, we can use ground radar and rain gauges, and lightning measurements from satellites. Although our original focus has been on improving initial conditions for forecasting, such a range of microphysical sensitivities available from the global observing system can also support efforts to improve the forecast model, to reach a point of 'microphysical closure' where the source of errors in the forecast model is made obvious through the overlapping sensitivities of different observation types.



The main measurement techniques for cloud and precipitation available in the global observing system and the micro- and macrophysical aspects to which they are most sensitive.

improved in these regions. Figure 3 also shows differences between the model and the all-sky infrared observations elsewhere, suggesting other possible issues with IFS cloud forecasts, but more work is needed to draw firm conclusions.

We aim to continue to improve the representation of cloud and precipitation in the IFS through close cooperation between observation and model experts, which is essential for interpretation and drawing firm conclusions on present shortcomings. Even then, it can be a challenge to improve the model physics to remedy the problem without degrading other aspects of forecast performance. For the future, there are opportunities to re-examine the model development process, taking inspiration from recent successes with machine learning, but likely working within the data assimilation framework so as to constrain updates based on prior knowledge and to weigh that against the errors in the new information coming from observations.

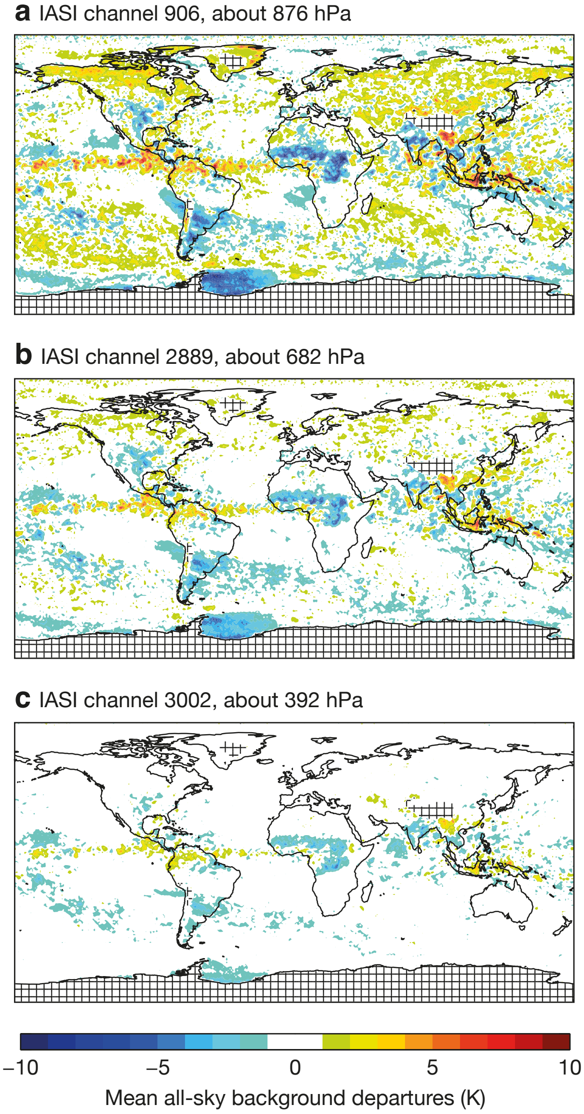


FIGURE 3 Mean all-sky background departures (the difference between the all-sky observations and the short-range forecast used in the data assimilation system, called the background) in brightness temperature from Metop-A (using operational bias correction) for three IASI instrument channels sensitive to pressure levels centred on (a) 876 hPa, (b) 682 hPa and (c) 392 hPa. The sampling period was 1 to 20 June 2017. Cross-hatching indicates areas where observations are excluded due to poor quality of the conversion of model values into satellite observation equivalents.

Next steps

We aim to work towards a complete all-sky, all-surface assimilation that benefits from different cloud and precipitation sensitivities across the electromagnetic spectrum and from active and passive sensors. Observations of cloud and precipitation are coming in ever greater numbers and variety, but because they are indirect measurements in terms of radiance or reflectivity, they need a high-quality data assimilation system to make use of them. We need to make much better use of information that is currently discarded, with continuing efforts to improve observation operators and observation error modelling, as well as improvements to the forecast model. To achieve this, observation, data assimilation and modelling experts will have to work together to make the best use of observations of cloud and precipitation. Over the next decade this should bring us to a point where our forecasting system can make full and automatic use of cloud and precipitation observations both to inform the initial conditions and to develop the model itself.

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Use of ERA5 reanalysis to initialise re-forecasts proves beneficial

Frédéric Vitart, Gianpaolo Balsamo, Jean-Raymond Bidlot, Simon Lang, Ivan Tsonevsky, David Richardson, Magdalena Balmaseda

Reanalysis, in other words the combination of observations with model information to reconstruct past weather and climate, plays an important role in numerical weather prediction. An example of this is the use of reanalysis to initialise re-forecasts. Re-forecasts are forecasts produced at the current time but starting from some point in the past. They are used to estimate a forecast model climate, which is needed to calibrate forecast products. Like all forecasts, re-forecasts require a set of initial conditions, which reanalysis can readily supply. ECMWF uses 11-member operational ensemble re-forecasts initialised every Monday and Thursday and covering the past 20 years to construct an extended-range model climate as a function of forecast lead time. This is in turn used to calculate extended-range forecast anomalies, e.g. weekly mean departures of predicted variables, such as 2-metre temperature or precipitation, from the model climate. A similar model climate is used to produce the Extreme Forecast Index (EFI) and the Shift of Tails (SOT) based on medium-range forecasts. Re-forecasts also serve to assess extended-range forecast skill and the evolution of forecast skill from year to year. Many years of re-forecasts are needed to accurately evaluate extended-range forecast skill. In the upgrade of ECMWF's Integrated Forecasting System to IFS Cycle 46r1 in June 2019, ECMWF's new ERA5 reanalysis replaced the older ERA-Interim to initialise re-forecasts. The change has resulted in better re-forecasts, better EFI skill scores and improvements in the prediction of extended-range anomalies.

From ERA-Interim to ERA5

Before the operational implementation of IFS Cycle 46r1, ensemble re-forecasts were initialised from the ERA-Interim reanalysis for atmospheric and ocean wave fields. Land initial conditions (soil and snow) were provided by ERA-Interim Land, which is an offline land surface model simulation driven by ERA-Interim surface fluxes. The main reason a land surface model simulation was used for soil initialisation was the inconsistency between the TESSEL land surface scheme in ERA-Interim, which is more than 12 years old, and the HTESSEL scheme used in the operational analysis. The ensemble generation for re-forecasts is similar to the one used for real-time forecasts. Singular vectors and an Ensemble of Data Assimilations (EDA) are used to perturb the re-forecast initial conditions. Since ERA-Interim does not include an EDA, the re-forecast initial conditions were perturbed using the latest operational EDA available at the time of production of the re-forecasts. Hence, the EDA initial perturbations were identical for all re-forecast years and were not flow dependent.

Production of ERA-Interim stopped in August 2019. The Centre's latest reanalysis is ERA5, which is produced operationally by the EU-funded Copernicus Climate Change Service (C3S) implemented by ECMWF. Compared to ERA-Interim, ERA5 benefits from a decade of developments in model physics, core dynamics and data assimilation. It makes better use of the modern observing system, and it has a significantly enhanced horizontal resolution, with a 31 km grid spacing compared to 79 km for ERA-Interim. For more details on ERA5, see Hersbach et al. (2019). The implementation of IFS Cycle 46r1 was an opportunity to introduce the following important changes to the initialisation of re-forecasts:

- use of ERA5 instead of ERA-Interim to initialise atmospheric parameters
- use of ERA5 to initialise the land surface, instead of using an offline land surface model simulation
- use of the ERA5 EDA to perturb re-forecast initial conditions, instead of using the EDA of the real-time forecasts.

The next three sections will discuss these changes and their impact on extended-range re-forecast skill as well as on the consistency between real-time ensemble forecasts (ENS) and re-forecasts.

Use of ERA5 to initialise atmospheric fields

To assess the impact of initialising the atmospheric fields with ERA5, two re-forecast experiments were run: a control experiment in which ERA-Interim provided atmospheric initial conditions, and an experiment in which ERA5 provided those conditions. ERA5 was also

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used to initialise the land surface in the ERA5 experiment, while an offline land model simulation forced by ERA-Interim (ERA-Interim Land) was used to initialise the land surface in the control experiment. The experimental setup was as follows:

- A 5-member ensemble starting on the first day of each month
- Re-forecast period: 2000 to 2016
- Resolution: TCo319L91 (about 36 km grid spacing, 91 vertical levels) and 0.25°x0.25° for the ocean (the same resolution as the extension of ENS beyond 15 days)
- IFS Cycle 45r1

The ERA5 experiment uses the same initial ensemble perturbation methodology as the control experiment. Therefore, the ERA5 experiment does not use the EDA ensemble from ERA5 but the operational EDA from 2018. Figure 1 shows a scorecard of the difference in continuous ranked probability skill scores (CRPSS) between the two experiments, with re-forecasts verified by the respective reanalysis used to initialise them. It shows that the skill scores are significantly improved when using ERA5 as initial conditions up to week 3 in the extratropics and week 4 in the tropics, except for zonal (east–west) wind and temperature at 50 hPa in the tropics, which is slightly degraded, although the difference is not statistically significant. These results suggest that the impact of ERA5 on extended-range forecasts is large and extends well beyond the first few days of the re-forecasts. They highlight the importance of high-quality atmospheric initial conditions for obtaining high-quality extended-range forecasts.

Verifying both experiments against ERA-Interim also indicates that the ERA5 experiment generally outperforms the control experiment, except for zonal wind at 50 hPa in the tropics and northern extratropical sea-surface temperatures in week 1 (not shown). This confirms that the increased skill shown in Figure 1 is not simply due to the choice of verification data.

The Madden–Julian Oscillation (MJO), a wave of tropical convection which is a major source of

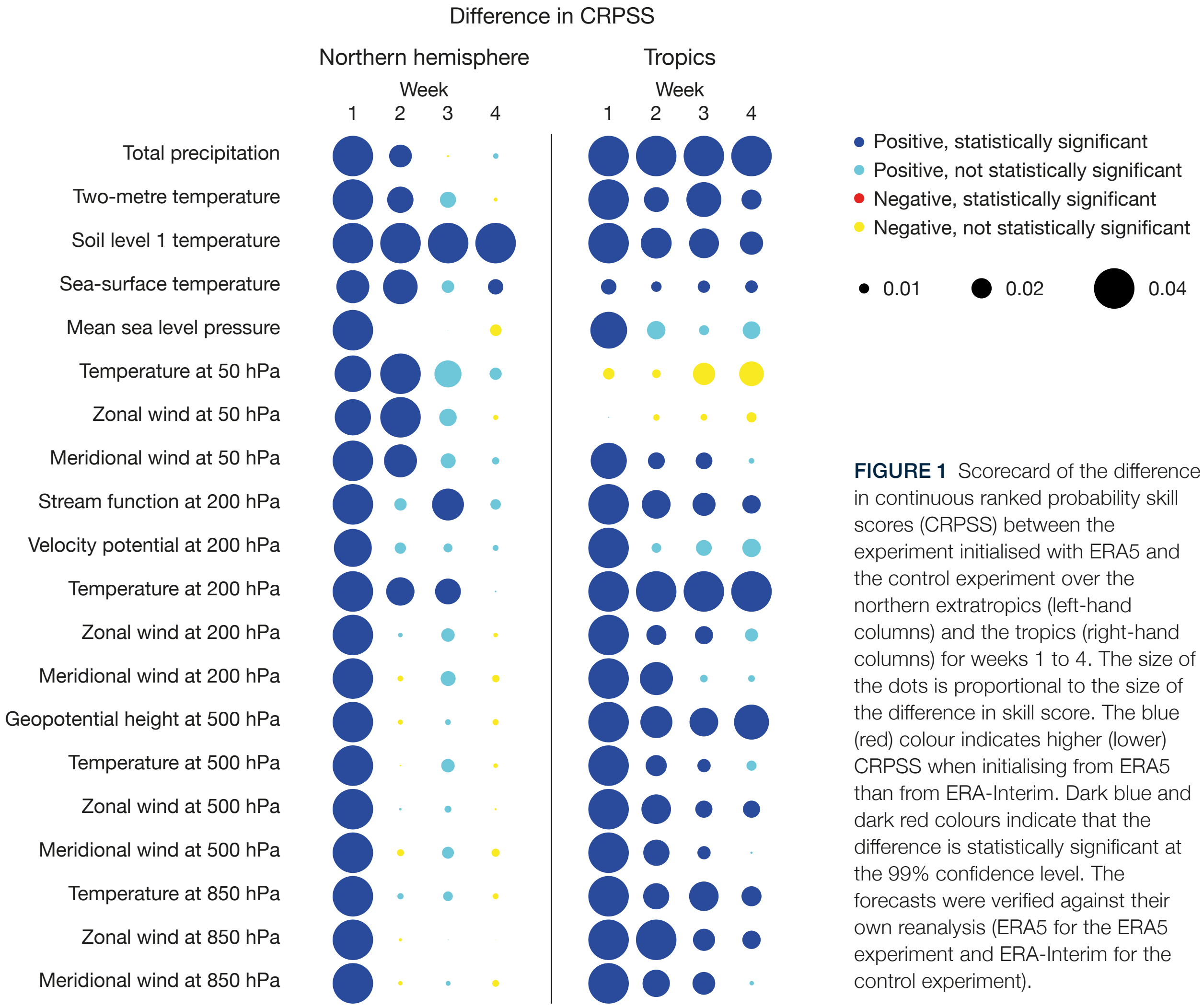

FIGURE 1 Scorecard of the difference in continuous ranked probability skill scores (CRPSS) between the experiment initialised with ERA5 and the control experiment over the northern extratropics (left-hand columns) and the tropics (right-hand columns) for weeks 1 to 4. The size of the dots is proportional to the size of the difference in skill score. The blue (red) colour indicates higher (lower) CRPSS when initialising from ERA5 than from ERA-Interim. Dark blue and dark red colours indicate that the difference is statistically significant at the 99% confidence level. The forecasts were verified against their own reanalysis (ERA5 for the ERA5 experiment and ERA-Interim for the control experiment).

sub-seasonal predictability, has been diagnosed in both experiments using the MJO index described by Wheeler & Hendon (2004). The re-forecast skill scores have been computed using a bivariate correlation, as described in Rashid et al. (2011), between the ensemble mean forecast and each experiment's own reanalysis. According to Figure 2, the MJO skill scores are statistically significantly improved during the first 20 days of the re-forecasts when initialising from ERA5 instead of ERA-Interim. The amplitude error of the MJO is also smaller in the ERA5 experiment during the first few forecast days, by 3–5% compared to the control experiment (Figure 3). After six days, the difference in MJO amplitude errors is no longer statistically significant.

Use of ERA5 to initialise land-surface fields

The results presented so far were produced with ERA5 used to initialise the land surface in the ERA5 experiment, while ERA-Interim Land was used to initialise the land surface in the control experiment. There are pros and cons to initialising the land surface with ERA5 in the ERA5 experiment. On the one hand, using ERA5 land fields has the advantage of ensuring consistency between the initial conditions for the land surface and upper-level fields. On the other, ERA5 has a coarser resolution than ENS up to day 15. As a result, the land surface initial conditions from ERA5 need interpolating, which can generate spurious anomalies. This is not the case if ERA-Interim Land is used, since it has the same resolution (TCo639, corresponding to a grid spacing of about 18 km) as ENS up to day 15. However, there were inconsistencies between ERA-Interim Land and the operational land analysis, which led to spurious 2-metre temperature anomalies over some regions, especially the Great Plains of North America (spurious cold anomalies in summer). This is probably due to the lack of data assimilation in ERA-Interim Land.

Tests show that, overall, it is better to initialise the land surface from ERA5 instead of using a different dataset. For example, Figure 4 shows that 2-metre temperature biases of re-forecasts are reduced over North America when initialising the land surface from ERA5 instead of ERA-Interim Land. Initialising the land surface from ERA5 has thus helped to remove spurious temperature anomalies in the Great Plains by generating a model climate that is more consistent with real-time forecasts. Re-forecast skill scores have also been compared between an experiment initialised from ERA5 for atmospheric and land-surface fields and an experiment initialised from ERA5 for the atmosphere and an offline land surface reanalysis forced by ERA5, similar to ERA5 Land but at a lower resolution (not shown). Verification was performed relative to ERA5, so it is unsurprising

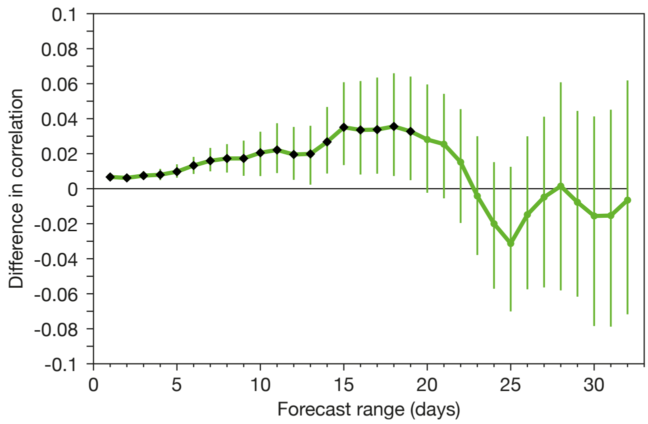

FIGURE 2 Difference in MJO bivariate correlation as a function of forecast lead time between the experiment initialised from ERA5 and the control experiment. The black diamonds indicate statistical significance at the 99% confidence level.

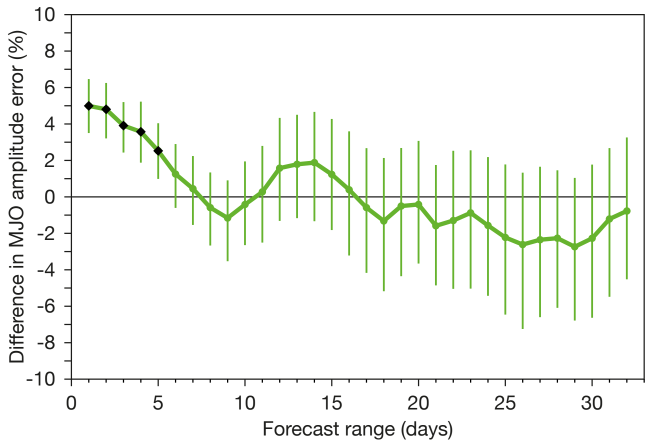

FIGURE 3 Difference in MJO amplitude error between the ERA5 experiment and the control experiment relative to the MJO amplitude in ERA-Interim. The black diamonds indicate statistical significance at the 99% confidence level. Positive values mean that the amplitude error is bigger in the control experiment.

that surface temperature skill scores are significantly degraded when using the offline land simulation instead of ERA5. For upper-level fields, there are no statistically significant differences in forecast skill scores. However, biases in temperature at 850 hPa relative to ERA5 in winter over north India are reduced when using land initial conditions from ERA5 directly. This difference in biases is robust and consistent across all winter months. Using the ERA5 land fields also reduces the warm biases over the Great Plains of North America, which were also present in the previous system.

Based on these results, there was no clear reason for using an offline land surface model simulation with ERA5, at least for IFS Cycle 46r1, for which ERA5 and the operational land surface analysis are still sufficiently consistent. Therefore, in 46r1 re-forecasts, the land surface is initialised directly from ERA5, which results in a simpler setup. The option of using a standalone land simulation or reanalysis may become useful when new changes to the land surface model (e.g. 5-layer snow, 9-layer soil, new lake mapping, ...) are introduced operationally.

Use of the ERA5 EDA

An additional set of re-forecasts has been run using ERA5 for initialisation and also to generate the initial perturbations, in other words using the ERA5 EDA instead of the operational EDA from recent years. An important advantage of this change is that the ERA5 EDA provides flow-dependent EDA initial perturbations across the re-forecast years instead of the non-flow-dependent perturbations provided by the current operational setup. The amplitude of the singular vector initial perturbations is flow dependent because it is linked to the EDA analysis uncertainty estimates of the day. The scaling of the singular vector initial perturbations is controlled by the EDA ensemble standard deviation and a scaling factor. The scaling factor is chosen such that on average there is a good match between the ensemble standard deviation and the ensemble mean root-mean-square error (RMSE). Using the ERA5 EDA to provide the initial condition perturbations for ensemble re-forecasts has a statistically significant positive impact in week 1 in the tropics and week 2 in the extratropics. No statistically significant impact is detected after week 2 (Figure 5). The impact on MJO skill scores is neutral (not shown).

Wave initialisation

IFS Cycle 46r1 introduced a new wave model parametrization for wind input and open ocean dissipation. This change has resulted in a systematic change in certain aspects of the wave model climatology. However, experiments suggested that initialising wave re-forecasts directly from ERA5, instead of using data from an offline simulation closer to the operational model physics, does not significantly impact re-forecast skill scores. This is to be expected since the influence of the wave model initial conditions on forecasts quickly tails off within the first seven days and within an even shorter period for the model's feedback to the atmosphere or the oceans. Moreover, EFI products for waves computed with IFS Cycle 46r1 did not show any spurious anomalies when initialising the wave model directly from ERA5. For these reasons, in 46r1 the wave model is initialised directly from ERA5.

EFI calculations

Ensemble re-forecasts are also used for the calculation of the EFI. Inconsistencies between the model climate and real-time forecasts are liable to produce spurious EFI signals. In order to test the impact on the EFI when ERA5 is used to initialise re-forecasts, a test suite was

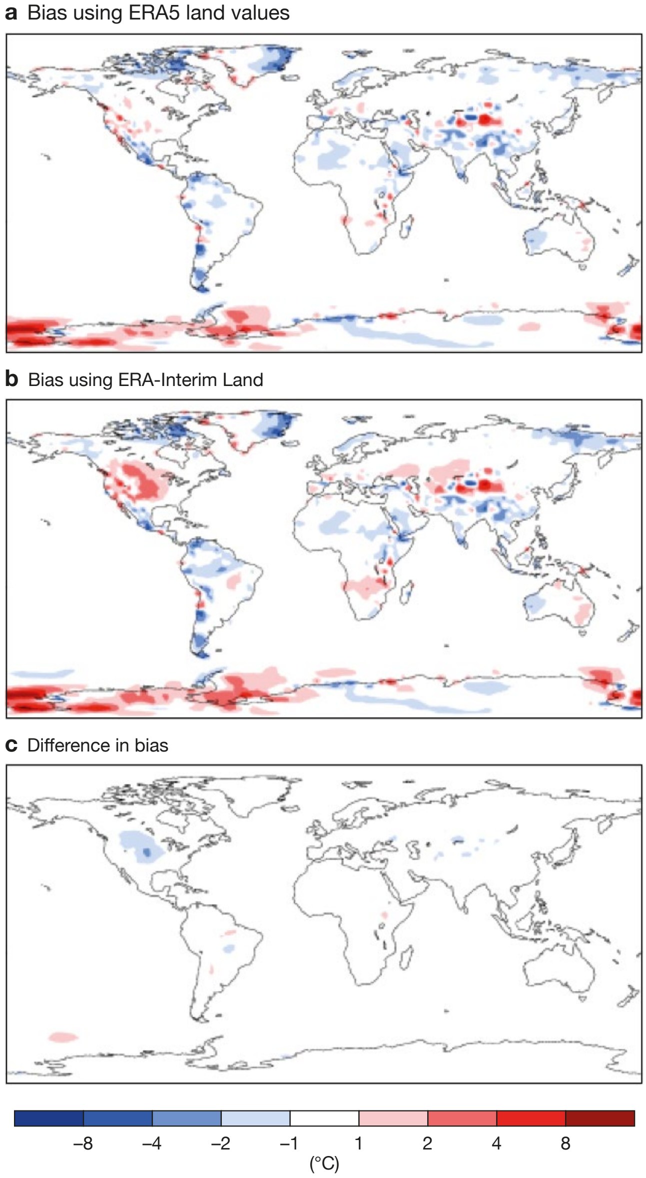

FIGURE 4 Two-metre temperature mean biases computed for forecast days 5–11 of re-forecasts between 2000 and 2016 relative to ERA5, showing (a) biases for re-forecasts initialised using ERA5 for the atmosphere and the land surface, (b) biases for re-forecasts initialised using ERA5 for the atmosphere and ERA-Interim Land for the land surface, and (c) the difference in biases between (a) and (b).

run in parallel to the operational re-forecast suite from June to September 2018. The only difference between the two suites was the use of ERA5 for the initialisation of the land and the atmosphere and initial perturbations. To reduce the cost of this experiment, the test suite was run with a re-forecast ensemble size of 5, instead of 11 in operations, and once a week only, instead of twice a week. Figure 6 shows the results for the EFI calculated for summer 2018 using the same re-forecast sample from operations as in the test suite (2000–2016, 5 members, once a week). The summer 2018 real-time data used for the EFI calculations is the same in both cases. The impact on the EFI for total precipitation is neutral (not shown) and there is a small but statistically

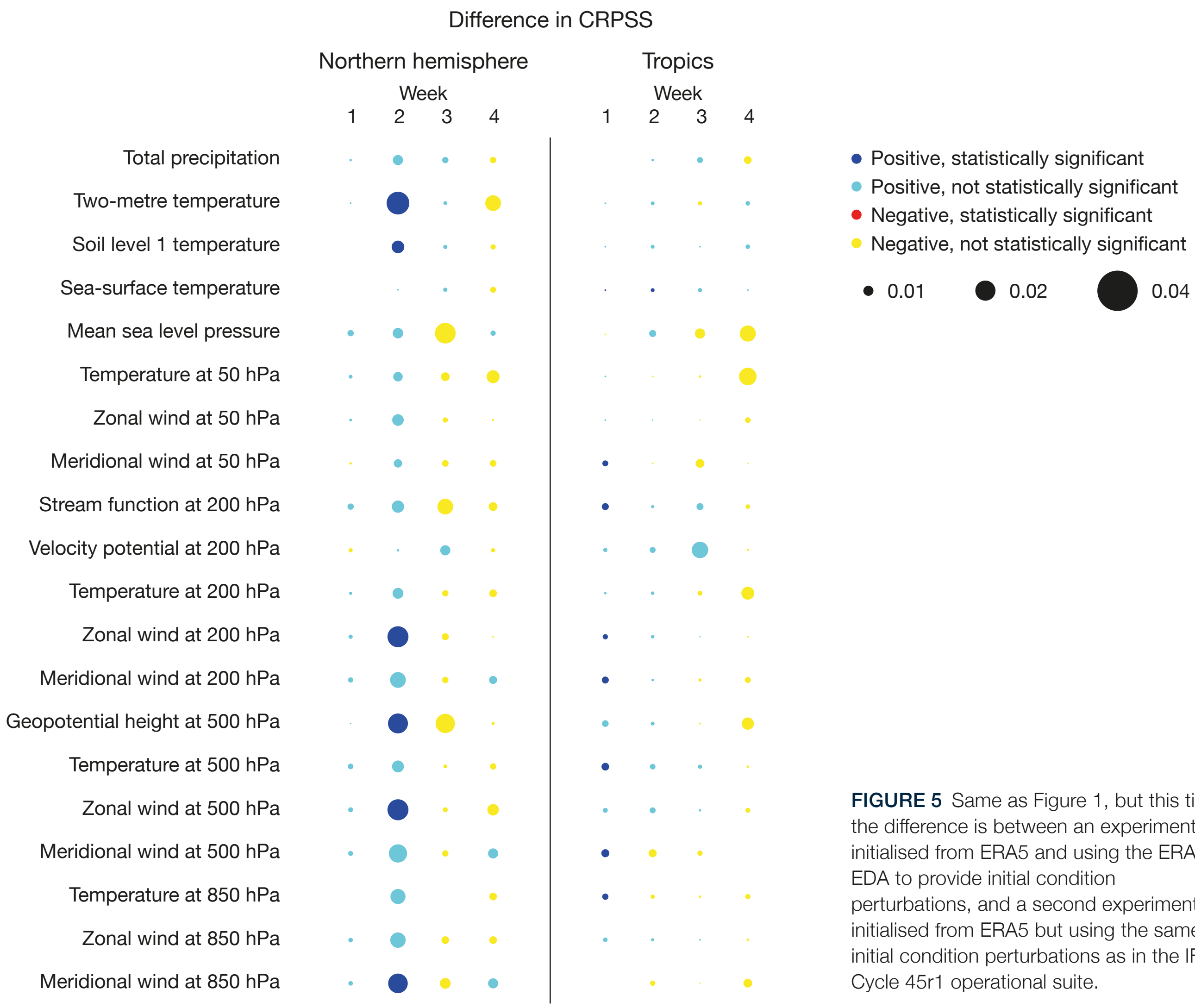

FIGURE 5 Same as Figure 1, but this time the difference is between an experiment initialised from ERA5 and using the ERA5 EDA to provide initial condition perturbations, and a second experiment initialised from ERA5 but using the same initial condition perturbations as in the IFS Cycle 45r1 operational suite.

significant positive impact on the 2-metre temperature EFI globally (Figure 6).

Extended-range forecast charts

In the summer of 2018, a re-forecast test suite using all the changes described above was run in parallel to the operational re-forecast suite. Extended-range forecast charts were produced using the test suite model climate to calculate anomalies. These were compared with charts in which operational re-forecasts of the same frequency, ensemble size and re-forecast period as in the test suite were used to construct the model climate. In this comparison, the real-time forecasts are thus the same, the only difference lies in the model climate used to calculate anomalies. In general, the anomaly forecasts look similar, but the slight differences in the model climate can generate some regional differences. Figure 7 shows an example of weekly mean anomaly charts with and without the changes: the week 1 (days 5 to 11) anomaly of 2-metre temperature from the

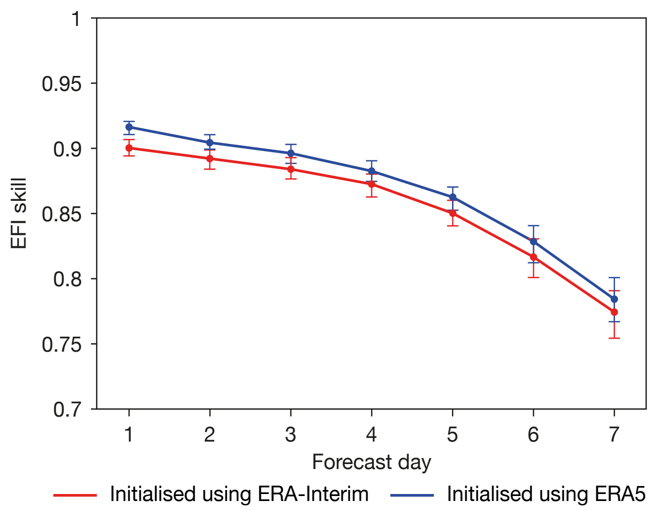

FIGURE 6 EFI skill, for re-forecasts between 2000 and 2016, as a function of forecast lead time for global 2-metre temperature. Skill is here measured by a ROC area score (2 x ROC area – 1) so that '1' corresponds to a perfect forecast and '0' to 'no skill'. The vertical bars show 95% confidence intervals.

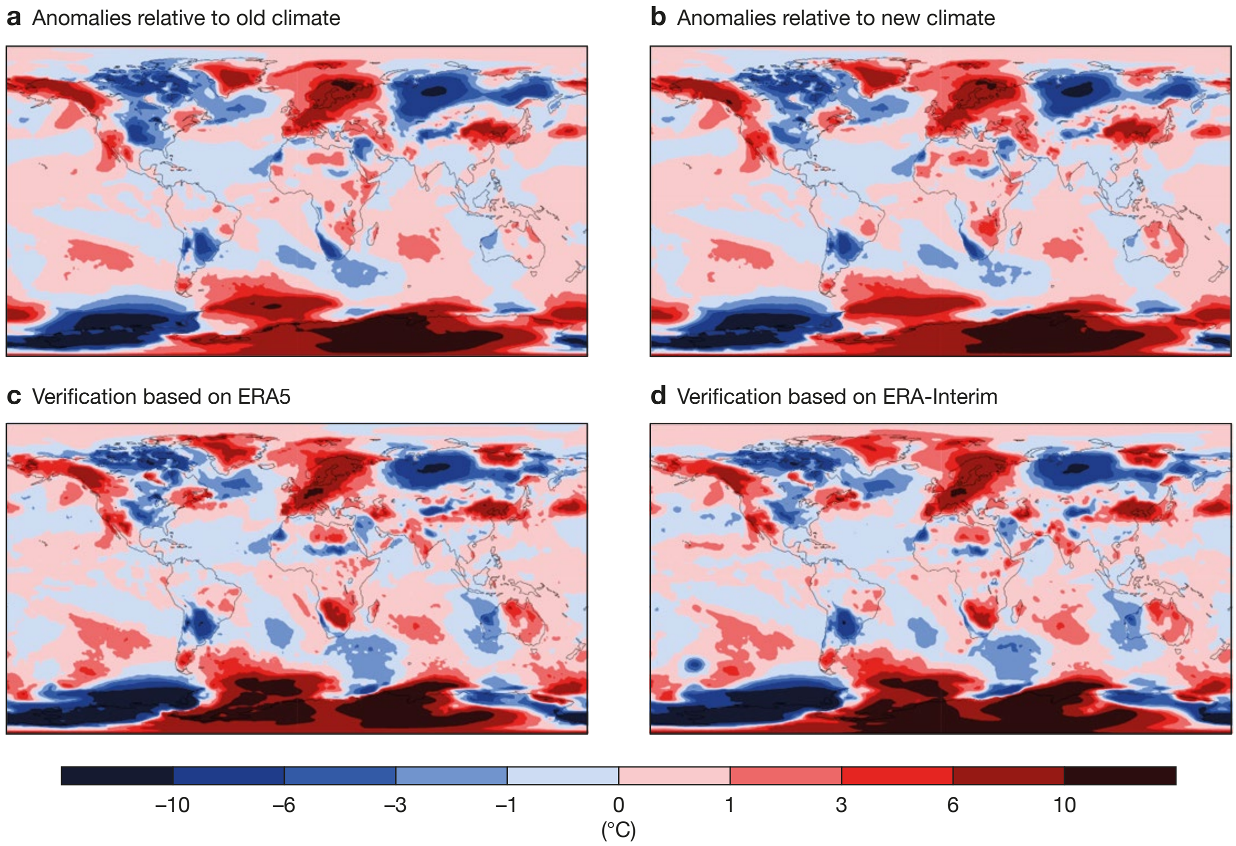

FIGURE 7 Two-metre temperature anomaly charts for (a) 5 to 11 day forecasts starting on 26 July 2018 using ERA-Interim-initialised re-forecasts to construct the model climate, (b) the same forecasts but using ERA5-initialised re-forecasts to construct the model climate, (c) the verifying anomalies based on ERA5 and (d) the verifying anomalies based on ERA-Interim.

ensemble forecast starting on 26 July 2018. Globally the charts look similar, but the use of the new re-forecasts produces weaker cold anomalies over the central US and stronger warm anomalies over Australia and South Africa. These anomalies produced using the new re-forecasts are more consistent with verification based on ERA5 or ERA-Interim.

Conclusions and discussion

Using ERA5 instead of ERA-Interim to initialise operational re-forecasts improves re-forecast skill and the quality of ECMWF extended-range forecasts and of the EFI. Re-forecast skill is improved up to at least week 3, and the model climate is more consistent with real-time forecasts, which removes some known issues in the previous operational system. The impact on EFI skill scores is neutral to positive. On this basis, it was decided to use ERA5 to provide the initial conditions for re-forecasts in IFS Cycle 46r1. All the changes described here have since been tested directly with IFS Cycle 46r1, with similar results. In addition, since ERA5 is closer to the operational model than ERA-Interim, comparing ERA5 re-forecast scores instead of ERA-Interim scores with real-time forecast scores is likely to provide a better estimation of the evolution of the skill of real-time forecasts.

Since the implementation of IFS Cycle 46r1, ERA5 has also been used to help generate some operational extended-range products, such as MJO forecast products, as well as for the verification of extended-range forecasts. Future plans include using the ERA5 EDA as the verification uncertainty in the calculation of probabilistic skill scores, such as the CRPSS.

Further reading

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Use of super-site observations to evaluate near-surface temperature forecasts

Polly Schmederer, Irina Sandu, Thomas Haiden, Anton Beljaars, Martin Leutbecher (all ECMWF), Claudia Becker (DWD, Germany)

Systematic forecast errors in temperature and humidity near the surface can be better understood by also examining errors higher up in the atmospheric boundary layer and in the soil. Meteorological observatories, also known as super-sites, provide long-term observational records of such vertical profiles and of surface energy budget components, such as surface radiative fluxes. Those datasets thus constitute an invaluable resource for ECMWF's efforts to further reduce forecast errors in near-surface weather parameters. Initial findings for 2-metre temperature errors in ECMWF forecasts at two European super-sites suggest that the errors are partly the result of the model exchanging too much energy between the atmosphere and the land. However, the influence of other factors, such as errors resulting from the representation of vegetation in semi-arid areas and from small-scale variations in vegetation and soil type near measurement stations, mean that it is difficult to adjust the energy exchange in a way which leads to an overall error reduction on the European scale.

Increasing use of super-sites

ECMWF verifies forecasts of 2-metre temperature (T2m) and 2-metre dew point (D2m) against observations from SYNOP weather stations on a routine basis. These evaluations reveal that forecast biases undergo annual and diurnal variations and exhibit large-scale geographical patterns. Biases in T2m and D2m can be due to a multitude of factors, such as the representation of the surface physiography (including vegetation, soil type, soil texture), soil temperature, soil moisture, atmospheric mixing, strength of land–atmospheric coupling, cloud cover, cloud properties and wind speed.

The routine verification against SYNOP observations does not provide information about forecast errors within the lower atmosphere, in the soil or at their interface. In a recent project focused on 'Understanding uncertainties in surface–atmosphere exchange' (USURF), ECMWF started to use data from super-sites such as Falkenberg (Germany, associated with Meteorologisches Observatorium Lindenberg – Richard-Aßmann-Observatorium), Cabauw (the Netherlands) and Sodankyla (Finland) more systematically than before to evaluate the quality of forecasts in the lowest part of the atmosphere (up to 100 m) and in the soil/snow, in an attempt to disentangle sources of forecast error in near-surface weather parameters. Such observations have been used previously at ECMWF to investigate wind errors (see Sandu et al., 2014).

Systematic errors in near-surface temperature

The focus of this article is on the use of super-site observations from Falkenberg and Cabauw (Box A) to evaluate ECMWF high-resolution deterministic (HRES) and ensemble (ENS) forecasts for the 12-month period from June 2017 to May 2018. The super-sites are in regions without complex topography. Unlike Cabauw, Falkenberg has the additional advantage of being situated inland, so that coastal effects play no role. Such conditions are ideal for capturing large-scale error patterns instead of local meteorological effects. This is why the analysis presented here largely focuses on Falkenberg. The German National Meteorological Service (DWD) kindly provides the observational data on a daily basis in near-real time. It has also provided forecasts from their global Icosahedral Nonhydrostatic Model (ICON) for a selected period. The Royal Netherlands Meteorological Institute (KNMI) kindly provides the observations at Cabauw.

Within the June 2017 to May 2018 period, we focus here on the summer months (June, July and August) since in this season the amplitude of the diurnal cycle of T2m is substantially underestimated in ECMWF forecasts (see Haiden et al., 2018). The night-time minimum temperature (Tmin) is typically 1–2 K too high in HRES forecasts and the day-time maximum temperature (Tmax) 1–2 K too low. This issue is present in the land areas of the extratropics for Tmin and in land areas across the globe for Tmax (Figure 1) and its causes need to be better understood. The mean error (bias) shown in Figure 1 is based on a subset of SYNOP stations. It includes only stations where the model orography differs by no more than 100 m from the actual terrain elevation, and where at least three of the four nearest grid points are land points. This is to exclude locations where the model cannot be expected to

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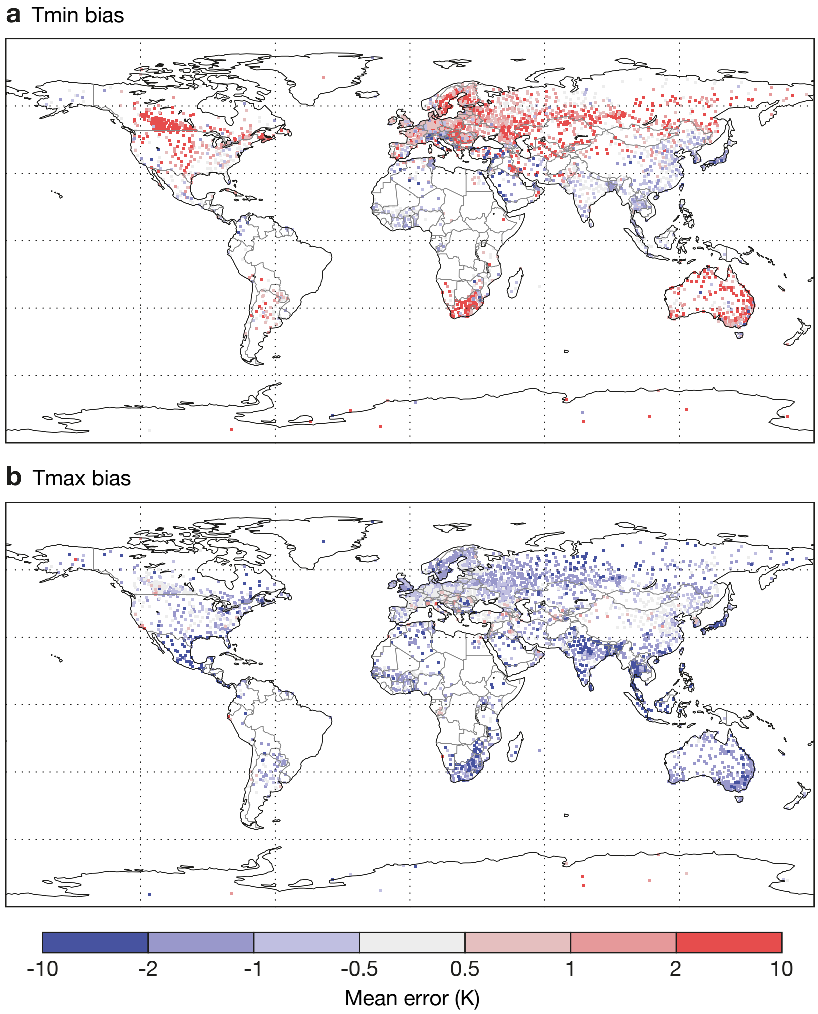


FIGURE 1 Mean error (bias) of (a) daily minimum T2m (Tmin) and (b) daily maximum T2m (Tmax) for a forecast range of 72 to 96 hours in summer 2017 (June, July and August). Verification is against SYNOP observations. Stations for which the model elevation differs by more than 100 m from the true elevation and stations where the nearest grid point is a sea point were not included.

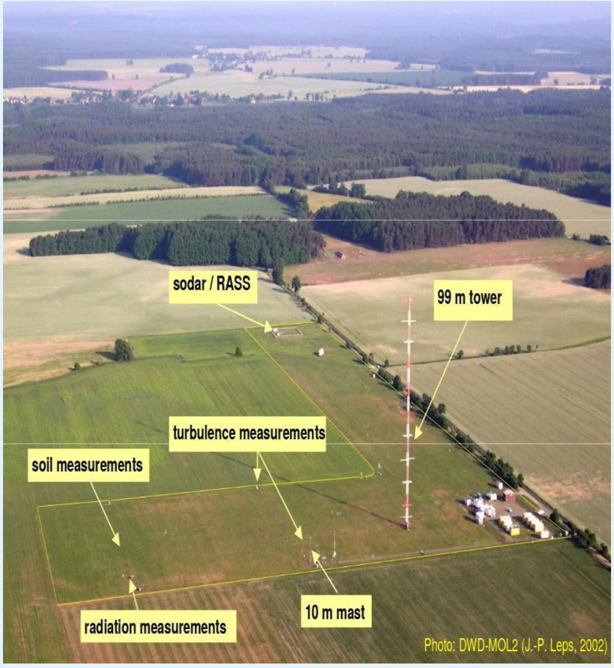
provide bias-free forecasts simply due to limitations imposed by horizontal resolution. The purpose of this filtering is the same as the selection of the super-sites: to capture mainly large-scale bias patterns and reduce the impact of local effects on evaluation results.

T2m is a diagnostic variable in ECMWF's Integrated Forecasting System (IFS), which means that it is not predicted directly by the model but is derived from other variables. Specifically, it is computed through vertical interpolation between the temperature at the lowest model level (about 10 m above the surface) and the surface (or skin) temperature. Biases can stem from biases in skin or air temperature or they can be due to the profile function used to derive the T2m diagnostic. To better understand and identify the sources of the errors, it is useful to look at the observed and predicted profiles of temperature in the atmosphere and soil at Falkenberg. Figure 2 shows such profiles for 4-day HRES, ENS mean and ICON forecasts and for observations. It shows that, at 00 UTC, the HRES is too warm not only at 2 m but also at the surface and in the lowest part of the atmosphere up to 20 m. Above 35 m, the HRES is too cold since here the night-time inversion (warmer temperatures at greater heights) is not sufficiently pronounced. In the soil, the HRES is too cold at all depths. The fact that the biases are not confined to 2 m suggests that they are due not only to the computation of the T2m diagnostic but also to the representation of the prognostic (i.e. directly predicted) temperatures at the surface, within the atmosphere or in the soil. DWD's ICON is also too warm at, and close to, the surface, but above 60 m it matches observations well for the selected period. In the soil, ICON is too cold in the first soil layer and matches observations well in deeper soil layers.

Systematic errors of medium-range ensemble forecasts were examined too. The ensemble mean behaves similarly to the HRES, being too warm at 2 m and at the surface, and too cold in the soil (Figure 2). For the study period, only the surface parameters were available for the ensemble forecasts, since model level data are not operationally archived. Recently we started to extract data on model levels at the super-sites from the ensemble forecasts for the Boundary Conditions programme, which stores the whole profile of the ensemble forecasts for a limited period of time. In the future, this will make it possible to also assess

a The Falkenberg and Cabauw super-sites

Falkenberg



- Coordinates: 52.17°N, 14.12°E at an elevation of 73 m above mean sea level.
- Observations include surface, soil, atmospheric and flux measurements every 10 minutes.
- The tower has a height of 98 m. Soil measurements are made to a depth of 1.5 m.
- The super-site is located in a rural area with open fields close to the site and patches of forest nearby.
- The ground consists of sandy soils on top of a layer of loam, which is typically at a depth of 50–80 cm.

For more information, visit: *http://srnwp.cosmo-model.org/support/Lindenberg/stationInfo.pdf*

Cabauw

- Coordinates: 51.971°N, 4.927°E at an elevation of 0.7 m below mean sea level.
- The North Sea is at a distance of 50 km to the west-northwest.
- Observations include surface, soil, atmospheric and flux measurements every 10 minutes.
- The tower has a height of 217 m. Soil measurements are made to a depth of 0.5 m.
- The super-site is located in agricultural grassland with open land to the west, windbreaks to the east, and mixed land (pastures and some windbreaks) to the north and south.
- The ground consists of 0.6 m of river clay above a thick layer of peat.

For more information, visit: *http://www.cesar-observatory.nl/*

ensemble forecast errors in the lower atmosphere at the super-sites.

To get a better idea of the temporal evolution of the forecast biases at Falkenberg, monthly averaged diurnal cycles of temperature at different heights in the atmosphere (surface, 2 m, 10 m, 98 m), and different depths in the soil (5 cm, 20 cm, 60 cm) are shown in Figure 3. Both in HRES and ICON, the amplitude of the diurnal cycle is underestimated in the atmosphere, with larger biases close to the surface. During the night, in both models the temperatures are about 1–2 K too warm at 2 m and about 2 K too warm at the surface. HRES slightly overestimates the diurnal cycle of the soil temperature in the first soil layer, being up to 2 K too cold at night. In all other soil layers, the HRES is too cold at all times. ICON is warmer than the IFS in all soil layers during the day, and slightly colder during the night, which leads to a slightly stronger overestimation of the diurnal cycle. The ensemble mean behaves similarly to the HRES and therefore has the same systematic error.

Too much heat transfer?

The results shown in Figures 2 and 3 suggest that ICON and the IFS have similar systematic errors in the atmosphere and in the soil close to the surface but exhibit different behaviour in the deeper soil. The main conclusion from the diurnal cycle evaluation for the summer period is that probably too much energy is exchanged between the atmosphere and the land, especially for the IFS. This means, for example, that during the night too much energy is extracted from the soil and transferred to the atmosphere. This results in soil temperatures that are too cold and skin temperatures and T2m that are too warm. The same qualitative behaviour can be observed at Cabauw (not shown).

The parameter that controls the heat transfer between the vegetation layer and the soil is the skin layer conductivity $\lambda skin$. In the IFS, the values of this parameter were reduced for some vegetation types in the upgrade to IFS Cycle 43r1 implemented in November 2016. This led to a slight improvement in T2m forecasts. The Falkenberg evaluation suggests, however, that these values are perhaps still too high.

A sensitivity experiment (EXP) has been performed to test this hypothesis. It has been carried out for the short range only (up to 48 h) to minimize feedback effects from the large-scale flow and isolate the direct impact of the physics changes. $\lambda skin$ was further reduced from 10 to 5 W m^{-2} K^{-1} for the vegetation types 'crops' (low

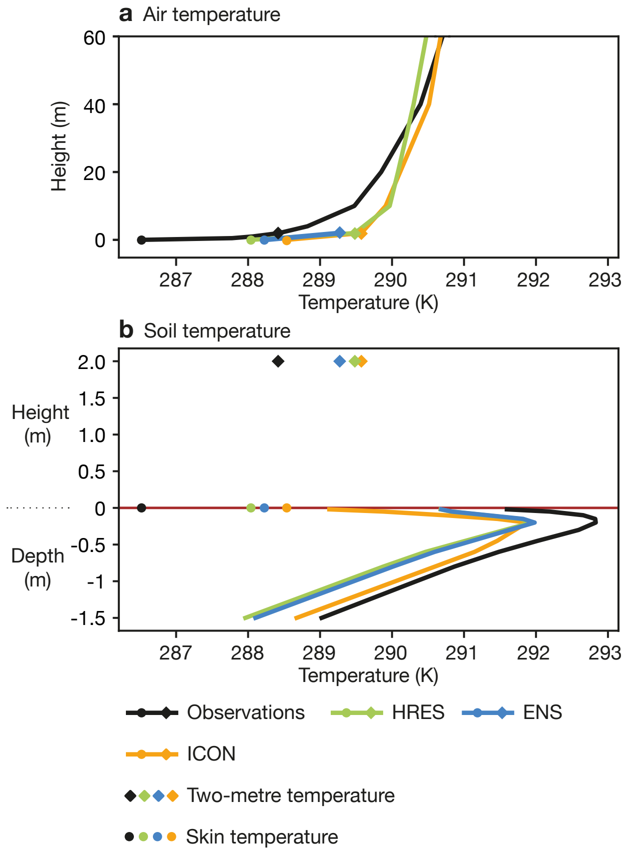


FIGURE 2 Observed and predicted profiles of (a) air temperature and (b) soil temperature at Falkenberg. The forecasts are for day 4 at 00 UTC and are averaged over the summer 2017 (June, July and August).

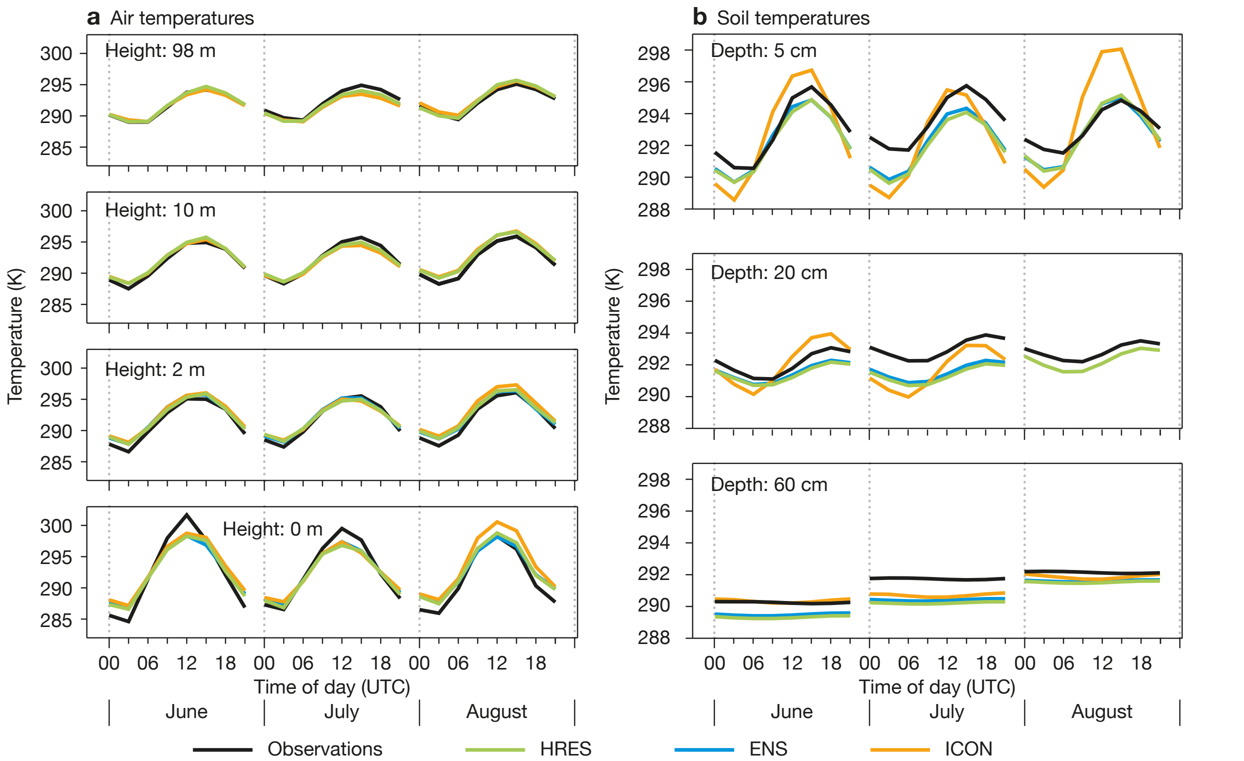


FIGURE 3 Monthly averaged diurnal cycles of temperatures at (a) different heights in the air and (b) different depths in the soil at Falkenberg at forecast day 4 for the months of June, July and August 2017.

vegetation) and ‘interrupted forest’ (high vegetation), which are the dominant vegetation types in the IFS in the Falkenberg area, as well as in Europe in general. As expected, this adjustment compared to the operational setup (CTR) reduced the night-time T2m and skin temperature at Falkenberg and Cabauw on average by about 1 K and 0.5 K, respectively. It also cooled the temperature in the first soil layer at day-time by 1 K and 0.5 K in Falkenberg and Cabauw, respectively (not shown), but had little response at night-time in the soil. The T2m biases were thus almost halved at Falkenberg and almost entirely removed on average over the 3-month summer period at Cabauw, where the biases are smaller. On the European scale, the impact of this reduction in thermal coupling varies. At day-time, the effect is small and there is almost no change in bias (Figure 4a,c). At night-time, in the continental region over eastern Europe, characterised by a big systematic warm bias at night, the reduction in thermal coupling reduces the T2m error (Figure 4b,d). In parts of western Europe where the bias is smaller and more variable, e.g. over Germany and the Iberian Peninsula, the change seems to be too big and results in a predominantly cold bias (Figure 4d). On average, reducing *λskin* does not have a positive effect on T2m forecast performance on the European scale, leading to smaller biases at some stations, but larger biases at others. This is very likely due to the fact that these biases are partly due to other factors than the thermal land–atmosphere coupling. One of these other factors is likely the representation of vegetation in semi-arid areas, where low vegetation potentially dies in summer. The model does not capture this effect, and water from the low vegetation keeps evaporating, which cools the surface during the day. During the night, the model vegetation insulates the soil more effectively than the vegetation does in reality, which may contribute to the night-time warm bias. Another potential issue is heterogeneity. The model assumes homogeneity in regions where in reality vegetation and soil types vary on small scales or the dominant soil and vegetation type are not representative for the measurement station.

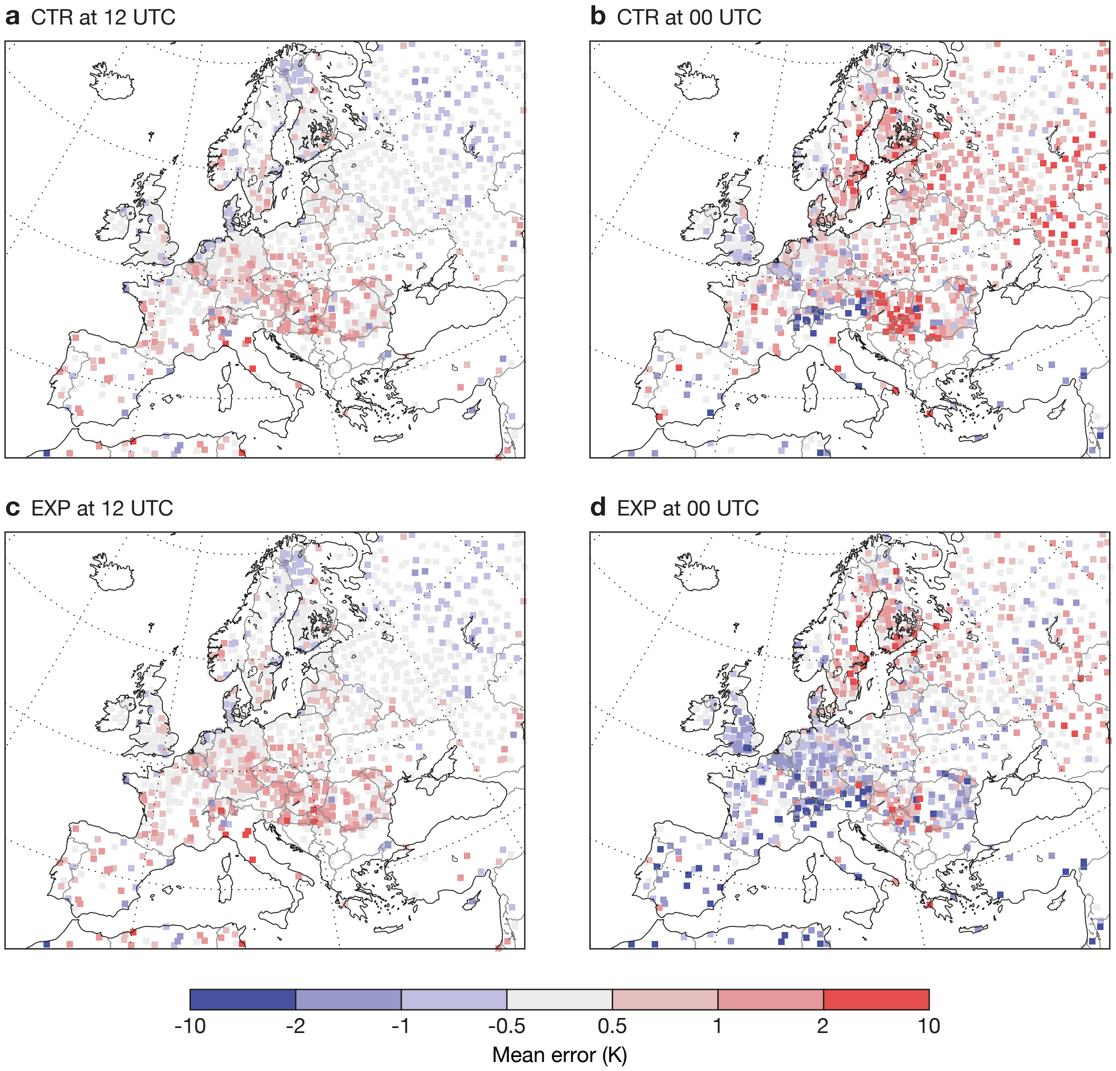


FIGURE 4 Mean error of T2m at forecast day 2 at (a) 12 UTC with operational land–atmosphere coupling (CTR), (b) 00 UTC with operational land–atmosphere coupling (CTR), (c) 12 UTC with decreased land–atmosphere coupling (EXP), and (d) 00 UTC with decreased land–atmosphere coupling (EXP). Verification was performed against the same subset of SYNOP observations as in Figure 1.

Reliability of ensemble forecasts

The ensemble provides flow-dependent estimates of forecast uncertainty. One interesting question is how reliably the ensemble spread reflects the magnitude of the error of the ensemble mean. Following the approach described by Yamaguchi et al. (2016), the reliability of the ensemble spread was examined by sorting the forecast–observation pairs by increasing ensemble variance into five equally populated classes. Variations in the expected magnitude of the random error are captured rather well by the ensemble for T2m forecasts at day 4 at Falkenberg. Figure 5 shows the relationship between the variance and the mean squared error of the ensemble mean for forecast day 4. Even the raw data are a good fit to the diagonal that represents a perfectly reliable ensemble. Removing the systematic error from the ensemble mean (bias correction) improves the fit. When verifying with observations, the observation uncertainty needs to be accounted for by adding an estimate of the observation error variance to the ensemble variance. We use a value of 1 K^2 as an estimate for the T2m observation error variance. This value is similar to the estimate used in the data assimilation system for radiosonde temperature observations in the lower troposphere. Accounting for the observation error variance has an even bigger positive effect than correcting for the systematic bias. Combining both corrections yields an almost perfect relationship for T2m in summer. Therefore, there is no evidence of an underdispersion of the ensemble. We conclude that the systematic error (Figure 3) is the main issue for T2m in the medium-range forecast of the ensemble in Falkenberg at day 4. Further investigations are ongoing to analyse different lead times and locations as well as the profile of the lower atmosphere and the soil for a deeper understanding of T2m forecast errors.

Spatial representativeness

When point observations are used for verification, the question of representativeness arises. Even in the absence of significant topography, the Earth's surface exhibits substantial inhomogeneities due to variations in vegetation cover and soil type. Thus, an assessment is required of how representative the results of the super-site evaluation are at grid-box scale and beyond. The 'representativeness error' can be defined as the difference between a 'grid-box mean' observed value and the point observations. The true grid-box mean observed value is not known but we can obtain an estimate by upscaling T2m observations (i.e. averaging over SYNOP stations within a certain area). Differences in elevation between stations are taken into account using the standard 0.0065K/m temperature gradient. Figure 6 shows such an estimation of representativeness errors for central Europe for 20 km grid boxes in terms of the absolute value of the mean difference (|BIAS|) and the root-mean-square difference (RMSD). As expected, representativeness errors are generally larger at night, and the bias makes a

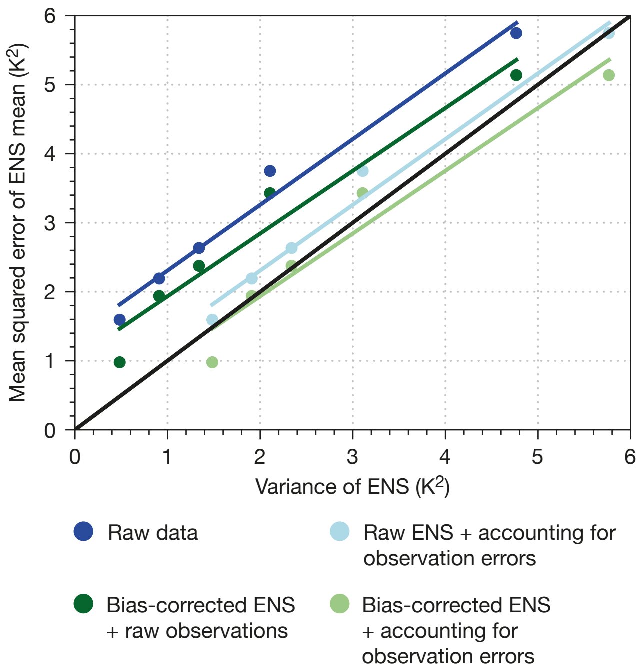


FIGURE 5 Reliability diagrams for ENS 2-metre temperature forecasts for Falkenberg at forecast day 4 in June, July and August 2017. To create the charts, three-hourly data were grouped into five equally populated classes of increasing ensemble variance. The mean ensemble variance and the mean squared ensemble mean error were then computed for each class (i) with the raw data; (ii) with raw ensemble data but accounting for observation errors; (iii) with bias-corrected ensemble data but raw observations; and (iv) with bias-corrected ensemble data and accounting for observation errors.

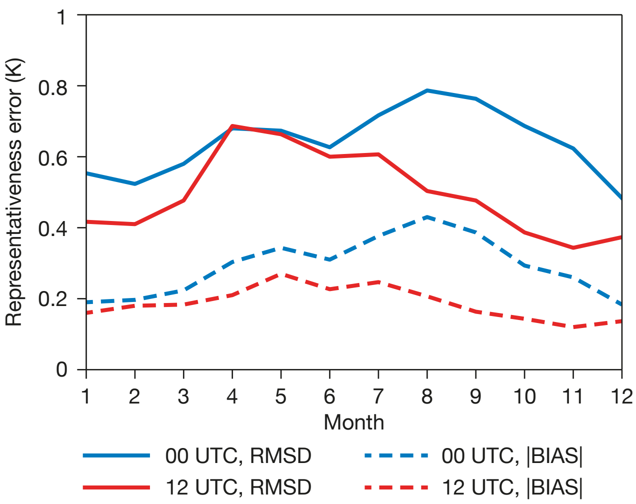


FIGURE 6 Estimation of T2m representativeness error at 00 UTC and 12 UTC based on SYNOP observations in central Europe (48–55°N, 6–15°E) in the period 2016–2018. The chart shows the absolute value of the bias (|BIAS|) and the root-mean-square difference (RMSD) between the point observations and the mean observed value within 20x20 km boxes.

substantial contribution to the RMSD. Somewhat surprisingly, representativeness errors are smallest in winter. This appears to be due to the (on average) higher wind speeds in that season, which reduce small-scale inhomogeneities in the temperature field other than those connected to elevation. Results like those shown in Figure 6 provide a benchmark for the IFS, indicating the minimum level of forecast error that can be expected at the given horizontal resolution.

Outlook

Super-site observations have become a valuable additional resource for further developing parametrizations of boundary-layer processes and of surface–atmosphere exchange. They make it possible to gain deeper insights into possible causes of biases in near-surface weather parameters. However, when used for evaluation studies, their limitations in terms of horizontal representativeness must be kept in mind. The complicated patterns of cold/warm biases both at global and European scale, as for example illustrated by Figure 4a, are not fully understood and need to be further investigated. It would be interesting to explore whether more up-to-date mapping of the vegetation, land use, or soil properties could help to address some of these errors in near-surface temperature or humidity. Other possible areas of investigation are how these errors are affected by the modelling of mixing within the atmospheric boundary layer or of heat transfer within the soil. For example, the choice of soil vertical discretisation and the total depth of soil represented in the IFS (currently 2.89 m) can affect the thermal diffusivity (rate of heat transfer) with an impact on deep soil temperature biases. Preliminary investigations suggest that the thermal diffusivity in the model is fairly similar at Falkenberg and Cabauw, while that derived from observations, using a method similar to that described by Verhoef et al. (1996), is quite different. One reason for this could be that the soil types at the two sites are quite different, with sandy soil at Falkenberg, and river clay at Cabauw. Overall, further reductions in near-surface biases in the IFS appear possible but will require both systematic modelling efforts and a quantitative assessment of the representativeness of observations at the locations of SYNOP stations and super-sites.

Further reading

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Yamaguchi, **M.**, **S.T.K. Lang**, **M. Leutbecher**, **M. J. Rodwell**, **G. Radnoti** & **N. Bormann**, 2016: Observation-based evaluation of ensemble reliability. *Q. J. R. Meteorol. Soc.*, **142**, 506–514.

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WEkEO DIAS moves towards operational release

Baudouin Raoult, Lawrence Albinson, Ricardo Correa (all ECMWF), Guillermo Grau, Laia Romero (both Mercator Ocean), Michael Schick (EUMETSAT)

As part of the EU's Copernicus Earth observation programme, ECMWF, EUMETSAT and Mercator Ocean have joined forces to implement a Data and Information Access Service (DIAS) platform called WEkEO (Box A). The European Commission's vision is to facilitate the use of the vast amount of Copernicus Earth observation (EO) data by a wide range of users, including institutional bodies, the private sector, scientists and civil society. The idea is also for WEkEO to enable third parties to develop their own value-added products and services. ECMWF, EUMETSAT and Mercator Ocean are key players in the Copernicus programme: ECMWF operates the Copernicus Climate Change Service (C3S) and the Copernicus Atmosphere Monitoring Service (CAMS); EUMETSAT provides data services from the Copernicus Sentinel satellites it operates (Sentinel-3 Marine Mission, Sentinel-4, Sentinel-5 and Sentinel-6), complemented by EUMETSAT data and data from third parties, with a focus on the atmosphere, the ocean and climate monitoring; and Mercator Ocean operates the

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Copernicus Marine Environment Monitoring Service (CMEMS). WEkEO will work hand in hand with existing services for the provision of Copernicus data, such as the C3S Climate Data Store (Box B). Following a proof-of-concept phase, an operational version of WEkEO is currently being built. This includes a new web portal to be released by the end of this year.

WEkEO's offering

WEkEO consists of cloud-based services that make all Copernicus data and information available to its users. It also provides tools and processing capabilities for data and information processing, including big-data analysis tools. Data is spread across a wide geographical area, and the data volume is very large – certainly too large to replicate to many locations on a continuous basis. Accordingly, WEkEO hides the physical location of the data.

In the crowded arena of EO platforms, which includes generic clouds, thematic/regional EO frameworks and wide-scoped EO platforms like WEkEO and the four DIASes operated by the European Space Agency (ESA), WEkEO puts the emphasis on:

- providing harmonised, performant access to the full range of Copernicus data and Copernicus services
- ensuring up-to-date data by accessing its original source and avoiding replication
- offering a broad spectrum of processing tools running on modern infrastructure
- focusing on an excellent user experience, including first-class user support drawing on the years of experience accumulated by the three WEkEO partners.

Most importantly, WEkEO differentiates itself from other platforms by being built around the idea of federation: data federation, with new data providers being able to join; infrastructure federation, with contributions by the three partners, industrial contractors and other interested parties; and user support federation, with distributed experts in IT and EO products and services.

WEkEO currently offers two packages designed to appeal to a wide range of users. The Essential Plan provides free and open access to all of its data holdings, as well as Jupyter Notebooks. The Advanced Plan additionally includes cloud-based processing and tools, for a flat rate depending on the allocated resources and with an initial free trial period.

From proof-of-concept to operations

The concepts behind the WEkEO platform have been demonstrated during a proof-of-concept phase

a What's in a name?

The name WEkEO, pronounced 'wikio', alludes to the idea of a collaborative platform, as in Wikipedia, and comprises three distinct elements:

- 'WE', as in the first person plural pronoun, refers to the three centres involved (EUMETSAT, ECMWF and Mercator Ocean) together with all WEkEO users
- 'k' stands for 'knowledge'
- 'EO' stands for 'Earth Observation' and 'Environment Observatory'

(known as WEkEO-V0). During this pre-operational period, which began in June 2018, organisations and individuals were invited to try out WEkEO. Valuable feedback has been received from many of these pilot users and has been taken into consideration for new releases of the system. Gauging the demand for such services and getting to know potential users better has also been an important part of the process. Moving forward, the WEkEO partners are currently building the operational version (WEkEO-V1) of the platform. To this end, they have put out to tender the various components of the platform in line with each partner's respective responsibilities, as illustrated in Figure 1.

ECMWF is responsible for the procurement of the software to implement data access services, processing and tools. An invitation to tender was published in July 2018. In November that year, the contract was awarded to a consortium comprising GMV Aerospace and Defence, MEEO, The Server Labs, B-Open

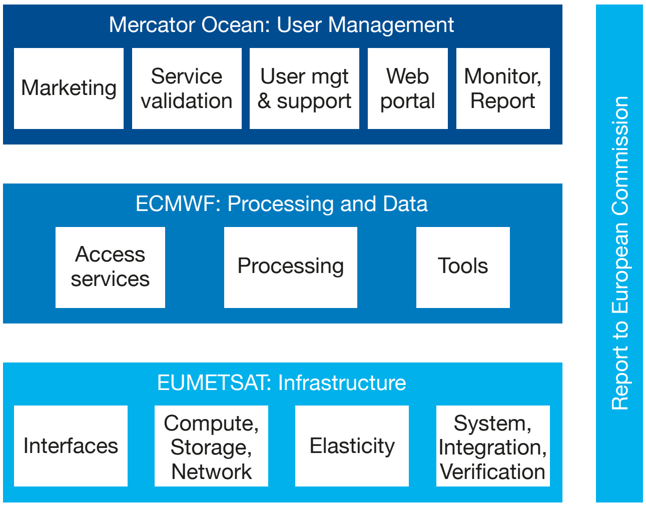


FIGURE 1 Distribution of responsibilities between the WEkEO partners.

Solutions and Sinergise, which delivered the required software components in June 2019.

The consortium demonstrated to ECMWF a Harmonised Data Access (HDA) API, allowing registered users to access all available data in a transparent and consistent way, independent of the underlying access methods and physical data location. They also presented the creation of virtual machines based on images (i.e. templates) that were preloaded with scientific software (data analytics, plotting, etc.). Users are able to install other packages on top of that. The virtual machines also contained the necessary software to use the HDA interface. Furthermore, they showed that users could use predefined 'blueprints' to create, with a few clicks, clusters of inter-connected virtual machines to process big data, using the cluster computing framework Apache Spark, as well as a machine learning cluster based on Google's TensorFlow software. Using Jupyter Notebook, a demonstration was made of training the cluster using limited examples of data.

For Apache Spark, a WEkEO extension has been built that will make the ingestion of big datasets into the cluster much more user-friendly. The new component extends the standard Spark Data Source API to make it possible to download data directly into Spark via the WEkEO HDA interface. A number of satellite image visualisation tools will be available to users either as part of their virtual machine images, such as SNAP from ESA, or as part of additional services, such as Sentinel Hub from Sinergise.

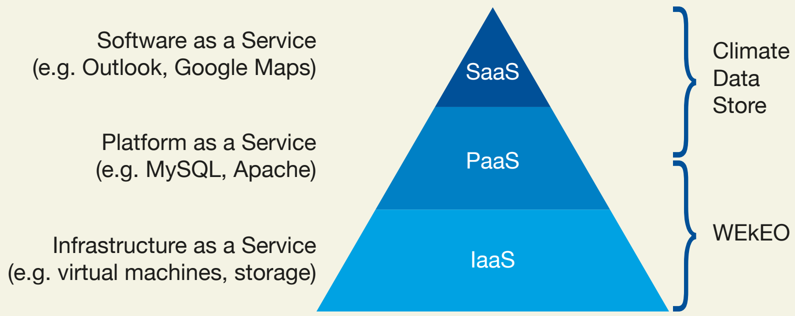
Outlook

All delivered software has now been handed over for operational deployment to the industrial partner responsible for the WEkEO Services and Operations contract, managed by EUMETSAT. In parallel, several projects related to user management are at various stages of execution by Mercator Ocean. Work is already under way on a new WEkEO web portal which integrates all products and services, and whose first release is expected by the end of this year. A centralised monitoring and reporting facility is also envisaged, as well as a revamped user support service. With a solid team across ECMWF, EUMETSAT and Mercator Ocean and their respective industrial partners, a well-differentiated technical and user-oriented approach, and the valuable experience gained from WEkEO-V0, WEkEO is shaping up to become a valuable platform for the EO community in the near future. For more information, visit: *https://wekeo.eu*.

b WEkEO and the Climate Data Store

ECMWF is already operating the Climate Data Store (CDS), a cloud-based service for the provision of C3S data and tools and, in the future, CAMS data and tools. The CDS and WEkEO are complementary since they serve different purposes.

Cloud services are traditionally split into three categories: infrastructure as a service (IaaS), platform as a service (PaaS) and software as a service (SaaS). Although the CDS uses cloud technologies for its implementation, users are unaware of this, as are users of Google Maps, for example; the CDS and its toolbox are therefore considered primarily as software as a service (SaaS). WEkEO, on the other hand, will give users access to computing resources (virtual machines, virtual disks, virtual networks, etc.) and therefore primarily provides infrastructure as a service (IaaS). WEkEO users will be able to run their own software and models on that infrastructure.
The CDS, on the other hand, offers functionality tailored to the processing of C3S and CAMS data through a dedicated toolbox implementing authoritative algorithms. The need for synergies between the two systems is driving the development of both platforms.



ECMWF publications

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

Technical Memoranda

850 **Prates**, **C.**, **E. Andersson** & **T. Haiden**: WIGOS Data Quality Monitoring System at ECMWF. *July 2019*

851 **Magnusson**, **L.**: ECMWF severe event catalogue for evaluation of multi-scale prediction of extreme weather. *October 2019*

EUMETSAT/ECMWF Fellowship Programme Research Reports

50 **Weston**, **P.**, **A. Geer** & **N. Bormann**: Investigations into the assimilation of AMSU-A in the presence of cloud and precipitation. *September 2019*

51 **Burrows**, **C.**: Assimilation of radiance observations from geostationary satellites: second-year report. *October 2019*

ECMWF Calendar 2019/20

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 12–13	Workshop on aircraft weather observations and their use
Feb 24–28	Training course: Data assimilation
Mar 2–6	Training course: EUMETSAT/ECMWF satellite data assimilation
Mar 9–13	Training course: Advanced numerical methods for Earth system modelling
Mar 10–12	Workshop on the challenge of warm conveyor belts
Mar 16–19	Training course: A hands-on introduction to numerical weather prediction models: understanding and experimenting
Mar 23–27	Training course: Predictability and ensemble forecast systems
Mar 30 – Apr 3	Training course: Parametrization of subgrid physical processes
May 12	Online training: Data manipulation and visualisation – processing and visualising ECMWF ensemble data
May 14	Online training: Data manipulation and visualisation – interactive analysis of ECMWF data
Jun 1–4	Using ECMWF's Forecasts (UEF)
Jun 23–24	Council
Sep 1–4	Annual Seminar: Numerical methods for atmospheric and oceanic modelling – recent advances and future prospects
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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