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METEOROLOGY

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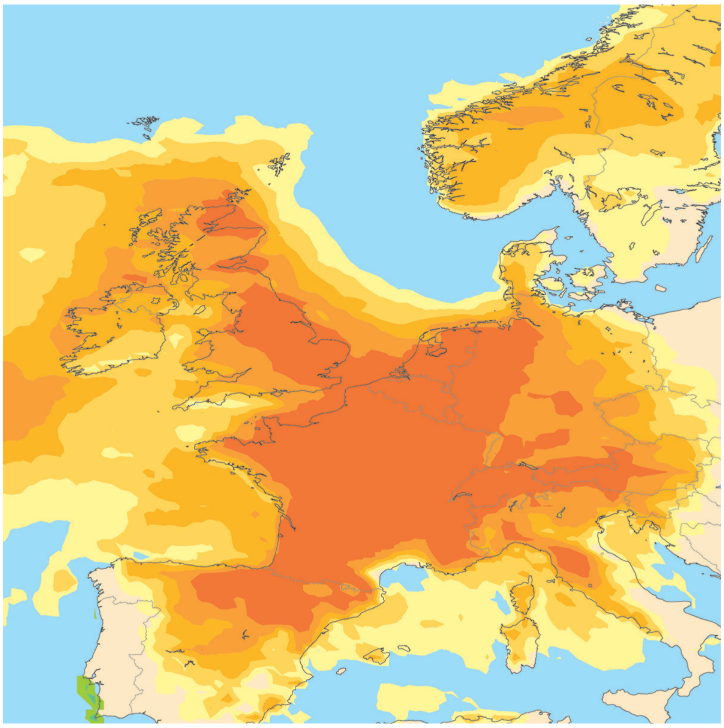

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Use of ERA5 reanalysis to initialise re-forecasts proves beneficial

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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 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:

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- 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.

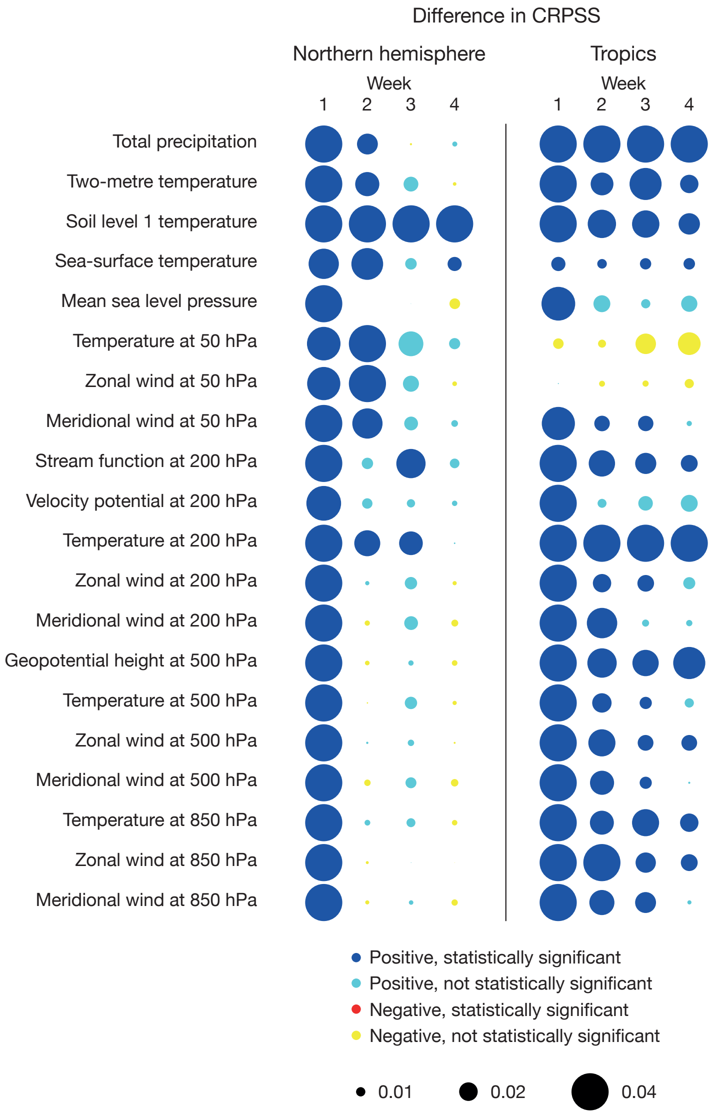

Figure 1 Scorecard of the difference in continuous ranked probability skill scores (CRPSS) between the experiment initialised with ERA5 and the control experiment over the northern extratropics (left-hand columns) and the tropics (right-hand columns) for weeks 1 to 4. The size of the dots is proportional 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).

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

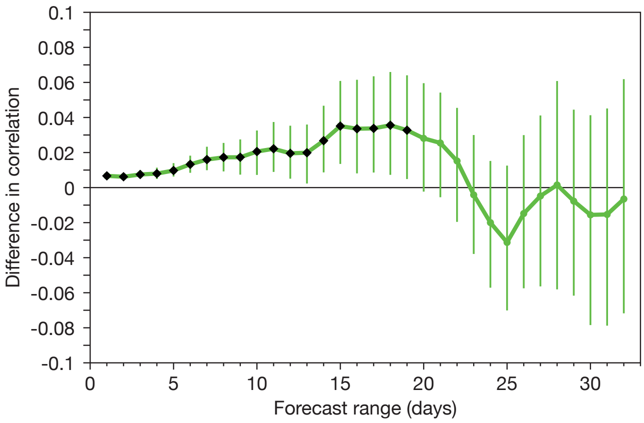

Figure 2 Difference in MJO bivariate correlation as a function of forecast lead time between the experiment initialised from ERA5 and the control experiment. The black diamonds indicate statistical significance at the 99% confidence level.

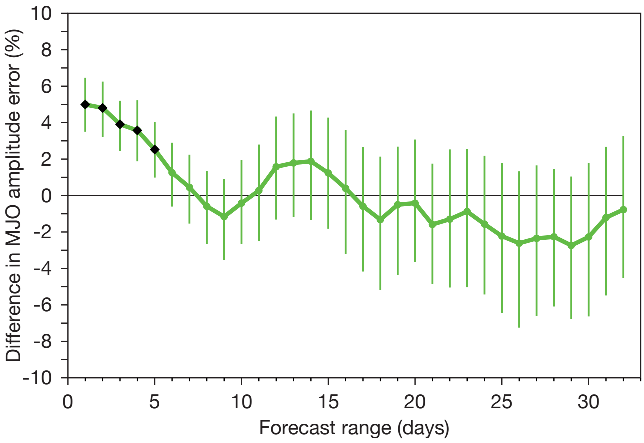

Figure 3 Difference in MJO amplitude error between the ERA5 experiment and the control experiment relative to the MJO amplitude in ERA-Interim. The black diamonds indicate statistical significance at the 99% confidence level. Positive values mean that the amplitude error is bigger in the control experiment.

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.

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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 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.

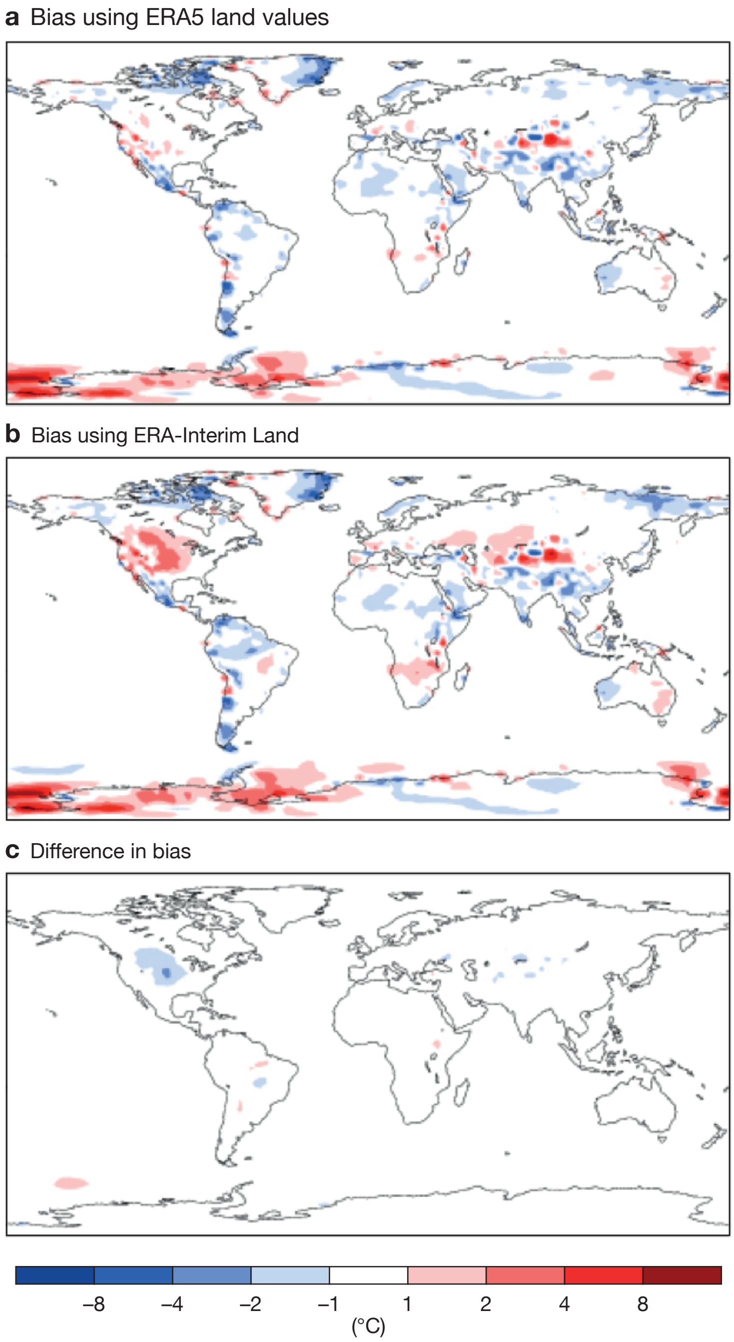

Figure 4 Two-metre temperature mean biases computed for forecast days 5–11 of re-forecasts between 2000 and 2016 relative to ERA5, showing (a) biases for re-forecasts initialised using ERA5 for the atmosphere and the land surface, (b) biases for re-forecasts initialised using ERA5 for the atmosphere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

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).

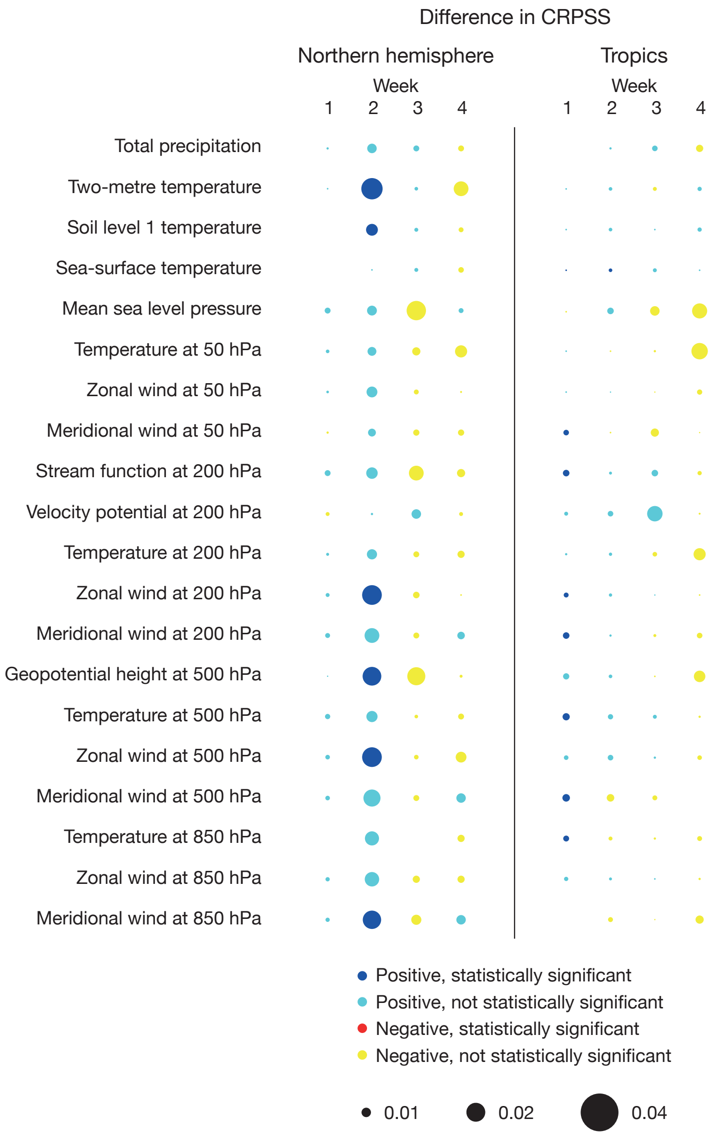

Figure 5 Same as Figure 1, but this time the difference is between an experiment initialised from ERA5 and using the ERA5 EDA to provide initial condition perturbations, and a second experiment initialised from ERA5 but using the same initial condition perturbations as in the IFS Cycle 45r1 operational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

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

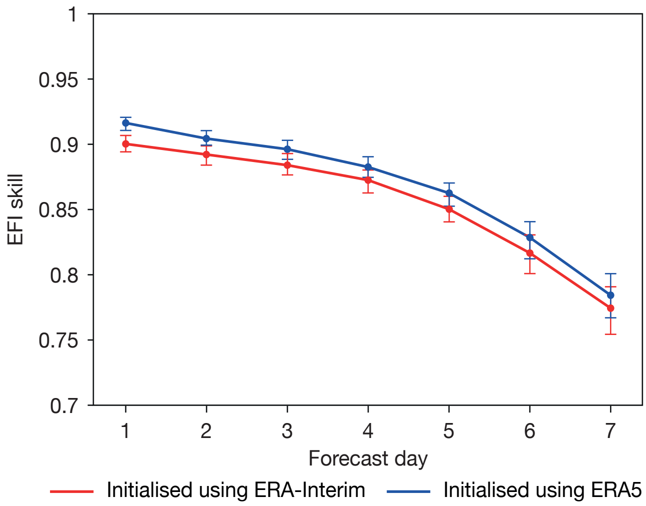

Figure 6 EFI skill of re-forecasts between 2000 and 2016 as a function of forecast lead time for global 2-metre temperature. Skill is here measured by a ROC area score (2 x ROC area – 1) so that '1' corresponds to a perfect forecast and '0' to 'no skill'. The vertical bars show 95% confidence intervals.

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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 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.

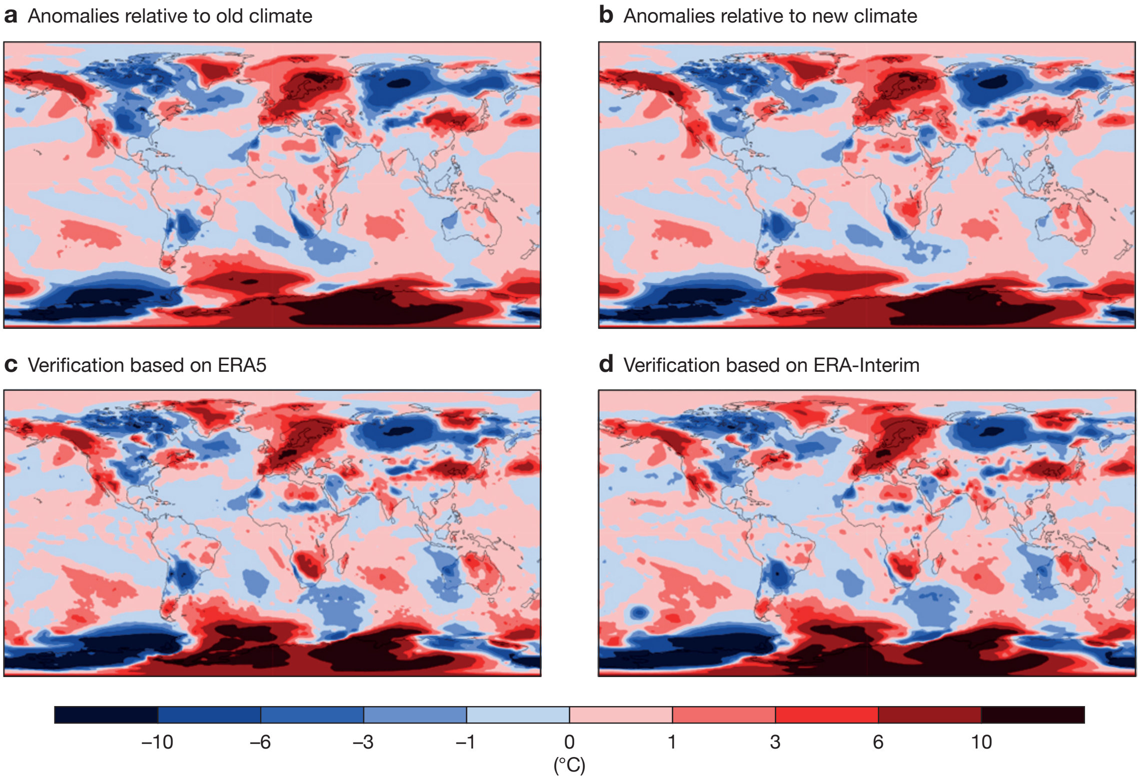

Figure 7 Two-metre temperature anomaly charts for (a) 5 to 11 day forecasts starting on 26 July 2018 using ERA-Interim-initialised re-forecasts to construct the model climate, (b) the same forecasts but using ERA5-initialised re-forecasts to construct the model climate, (c) the verifying anomalies based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

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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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