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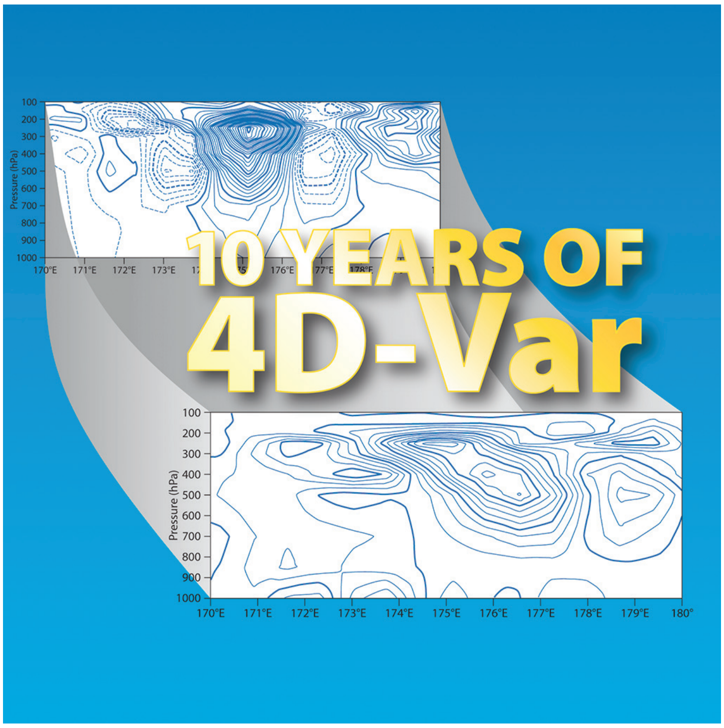
Merging VarEPS with the monthly forecasting system: a first step towards seamless prediction



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Merging VarEPS with the monthly forecasting system: a first step towards seamless prediction

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An integrated medium-range and monthly forecasting system became operational at ECMWF on 11 March 2008. This merges the Variable Resolution Ensemble Prediction System (VarEPS) with the monthly forecasting system. The new system is referred to as VarEPS-Monthly.

An ensemble monthly forecasting system has been operational at ECMWF since October 2004 (*Vitart,* 2005). This system was run separately from the medium-range ensemble prediction system (EPS): for example, it had a lower resolution but used a coupled ocean-atmosphere model instead of just an atmosphere model. When the monthly forecasting system was set up, it was too costly to extend the EPS integrations to the monthly time-scale and to produce the re-forecasts that are necessary to calibrate those forecasts.

In November 2006, the EPS was upgraded to the 15-day Variable Resolution Ensemble Prediction System (VarEPS, see *Buizza et al.,* 2007). The VarEPS approach allows changes to be made to the atmospheric horizontal resolution during the model integration, and since its implementation it has been running with the following configuration:

- From day 0 to day 10: T399L62 resolution, uncoupled (hereafter referred as leg 1)
- From day 10 to day 15: T255L62 resolution, uncoupled (hereafter referred as leg 2)

Built upon the variable-resolution approach used with the 15-day VarEPS, the extension of the EPS integration to the monthly time-scale becomes feasible at a reasonable cost. Merging monthly forecasting with the 15-day VarEPS has several advantages:

- Resources are saved by not having to run separately the first 15 days of the monthly forecasting system.
- The re-forecasts produced to calibrate the monthly forecasting system will be available to calibrate medium-range forecasts.
- The monthly forecasting skill may benefit from the higher resolution in the first 10 days of the forecasts.
- User's access/retrieval to the ECMWF forecasts is simplified.

The only drawback of the merging is that the combined 32-day VarEPS-Monthly ensemble system will be uncoupled from day 0 to day 10, as will be discussed in more details in the next section.

In this article, the merged 32-day VarEPS-Monthly ensemble system will be referred to as VarEPS-Monthly and the previous monthly forecasting system will be referred to as MOFC.

The rest of this article will contain sections dealing with the following.

- Description of the merged VarEPS-Monthly forecasting system along with a comparison with the current monthly forecasting system.
- Comparison of the probabilistic scores obtained over a large number of cases with VarEPS-Monthly and MOFC.
- Comparison of the performance of VarEPS-Monthly and MOFC for some cases of extreme weather.
- Explanation of the rationale behind the coupling of the atmospheric model to an ocean model during the VarEPS-Monthly integrations.

The article will end with a summary of the benefits of the new system.

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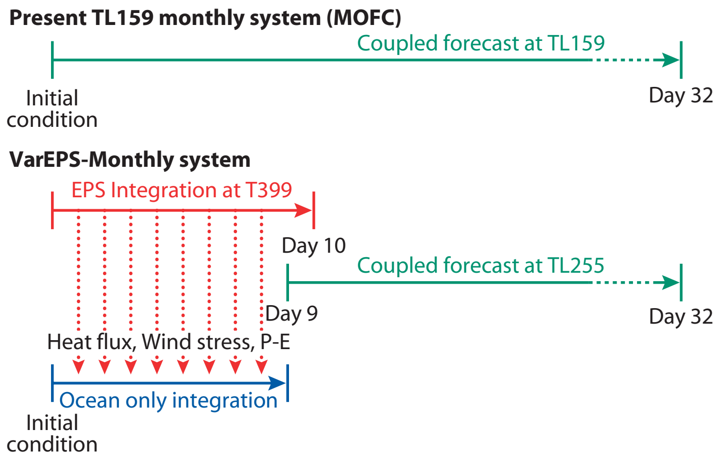

Figure 1 Description of MOFC and the new VarEPS-Monthly forecasting system. VarEPS-Monthly has a higher horizontal resolution than the old system, but the 10 first days of the integrations are uncoupled unlike in MOFC where the ocean-atmosphere coupling starts at day 0. The coupled integrations start at day 9 instead of day 10 in order to reduce the shock of the change of model resolution from T399 to T255 (see *Buizza et al.,* 2007 for more details).

Description of the VarEPS-Monthly ensemble system

Figure 1 gives a description of MOFC and the new VarEPS-Monthly forecasting system.

VarEPS-Monthly is an extension of VarEPS to 32 days once a week (every Thursday at 00 UTC). The atmospheric resolution will be higher than in MOFC:

- Day 0 to 10 (leg 1): T399L62
- Day 10 to 32 (leg 2): T255L62

Ideally, the atmospheric model should be coupled to the ocean from days 0 to 32, but for technical reasons the T399 atmospheric and the ocean models cannot be coupled during the first 10 days. Therefore the coupled ocean-atmosphere integrations will start at the same time as the T255 integrations at day 9 (there is an overlap of one day between the two legs to reduce the impact of the change of resolution on the fields that are more sensitive to the truncation from the high to the low resolution). Coupling from day 0 will be possible when the next version of the ocean system (NEMO) is implemented in the near future.

The first leg of the VarEPS-Monthly forecasting system will therefore be uncoupled for the time being. However, the atmospheric model will be forced by *persisted SST anomalies* from day 0 to day 10 in the new configuration instead of *persisted SSTs.* The advantage of using persisted SST anomalies is discussed later.

In addition to the merging with the monthly forecasting system, the following changes will be introduced to VarEPS:

- All the VarEPS forecasts starting at 00 UTC (including those who are not extended to 32 days) will be coupled after day 10.
- All the VarEPS forecasts starting at 12 UTC will remain uncoupled after day 10, but forced by persisted SST anomalies instead of persisted SSTs as in the first leg.

The VarEPS system will introduce an additional difference between the 00 UTC and 12 UTC integrations since the ocean-atmosphere coupling is only applied to the 00 UTC runs. Ideally the coupling at day 10 should be also applied to the 12 UTC integrations, since it is beneficial in the tropics (see below). However, for technical reasons, this would be difficult to implement with the current ocean model. It will be implemented when the new ocean model is operational.

The ocean component is the same as the one used for seasonal forecasting and MOFC – the Hamburg Ocean Primitive Equation (HOPE) model. This ocean model has lower horizontal resolution in the extratropics, but higher resolution in the equatorial region in order to resolve ocean baroclinic waves and processes that are tightly trapped in the equator. The ocean model has 29 vertical levels, and the ocean and atmosphere communicate through the Ocean Atmosphere Sea Ice Soil (OASIS) coupler. The coupling frequency is 3 hourly whereas it was hourly in the previous system. This is because in the previous system both oceanic and atmospheric models had a 1 hour time step. Now the T255 integrations have a time step of 45 minutes, which means that the oceanic and atmospheric models are in phase every 3 hours.

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The ocean initial conditions come from the Near Real Time (NRT) component of the operational ocean analysis system (*Balmaseda et al.,* 2007). During the first leg, the ocean model is forced by the fluxes provided by each atmosphere-only integration, but the atmosphere is not sensitive to the ocean model state. The persisted anomaly SST product used to force the atmosphere is also used to constrain the SST of the ocean model.

VarEPS-Monthly consists of 51 forecasts run from slightly different initial conditions. The 50 perturbed forecasts are generated by perturbing both the atmosphere and ocean initial conditions. The atmospheric perturbations are the same as those applied to the medium-range ensemble forecasts: singular vectors to perturb the atmospheric initial conditions and stochastic perturbations during the model integrations. The oceanic initial conditions include a control and four perturbed ocean analyses: the perturbed ocean analyses are produced by adding randomly chosen patterns (computed by taking the difference between different wind analyses) to the wind forcing as in MOFC. However, unlike MOFC, perturbations in the initial conditions of SSTs are not applied since the ocean model is integrated for the first nine days in uncoupled mode, forced by the fluxes produced by each ensemble member. Since the total ensemble size is 51, each of 5 ocean assimilations is used as the initial condition of 10 or 11 (for the control assimilation) ensemble members.

A problem with long-term integrations is that the model mean climate begins to be different from the analysis climate. As for MOFC and seasonal forecasting, the effect of the drift on the model calculations is estimated from integrations of the model in previous years (the re-forecasts). The drift is removed from the model solution during the post-processing. In MOFC, the re-forecasts consist of a five-member ensemble of 32-day coupled integrations, starting on the same day and month as the real-time forecast for each of the past 12 years. For instance, re-forecasts corresponding to 3 January 2008 consist of five-ensemble member integrations starting on 3 January 1996, 3 January 1997.... 3 January 2007 with the same resolution and model cycle as the real-time forecasts. In VarEPS-Monthly, the set of re-forecasts has been extended to 18 years. The ensemble size remains at five.

As for MOFC, the monthly forecasting products from VarEPS-Monthly are mainly based on weekly mean anomalies, since the monthly forecasting system does not have much skill to predict daily variability beyond day 10. The 7-day periods correspond to days 5–11, days 12–18, days 19–25 and days 26–32. They have been chosen so that they correspond to Monday to Sunday calendar weeks (the 32-day integrations start on Thursdays at 00 UTC).

The MARS archiving of the 32-day forecasts has been revised and the VarEPS-Monthly archiving is consistent with the VarEPS archiving. This should make the access and retrievals of ECMWF data simpler. A description of the MARS archiving of this new system can be found at: www.ecmwf.int/research/monthly_forecasting/mofc-mars_veps.html

Current users of the monthly forecasting system are advised to view the differences between the old and new MARS retrieval commands at: www.ecmwf.int/research/monthly_forecasting/differences.html

Table 1 summarizes the key differences between the old and the new systems.

Initial time	Forecast days	Old	New
00 UTC	0–10	Leg1	Leg1–SST
	10–15	Leg2	Leg2–coupled
	0–32 (only Thu)	Monthly	—
	15–32 (only Thu)	—	Leg2–coupled
12 UTC	0–10	Leg1	Leg1–SST
	10–15	Leg2	Leg2–SST
Leg1	T399L62 with persisted SST		
Leg2	T255L62 with persisted SST		
Monthly	T159L62 with coupled ocean model		
Leg1–SST	T399L62 with persisted SST anomalies		
Leg2–SST	T255L62 with persisted SST anomalies		
Leg2–coupled	T255L62 with coupled ocean model		

Table 1 Key characteristics of the old and the new ensemble systems.

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Comparison of the general performances of VarEPS-Monthly and MOFC

VarEPS-Monthly has been tested in research mode to compare its skill to MOFC. The general comparison is based on five-member ensembles run of VarEPS-Monthly and MOFC with IFS cycle 31r2 (hereafter referred to as Cy31r2) starting on 1 January, 1 April, 1 June and 1 October for 1991 to 2003 (52 cases in total). With this experimental setting, the model biases with both configurations can be compared along with the probabilistic scores calculated in cross-validations. A relatively small ensemble size (5 members as opposed to the 51 used for the real-time forecasts) means that some of the probabilistic scores are lower than in the real-time forecasts. However the goal here is to compare VarEPS- Monthly with MOFC. The overall skill of the 51-member ensemble MOFC real-time forecasts is documented in Vitart (2004).

Model Bias

The mean annual bias has been computed from the 52 realizations of five-member ensemble integrations for VarEPS-Monthly and MOFC. Figures 2 and 3 show the biases in geopotential height at 500 hPa and precipitation for days 26–32 (last week of the forecast). The biases of precipitation look quite similar, but the biases in geopotential height at 500 hPa are reduced in VarEPS-Monthly, although the patterns remain broadly the same.

Probabilistic Scores

Figure 4 shows the ROC (Relative Operating Characteristic) diagrams of the probability that 2-metre temperature is in the upper tercile for days 5–11, 12–18 and 19–32. The ROC Scores obtained with VarEPS-Monthly are slightly increased with respect to those obtained with MOFC.

- For days 5–11, the ROC Score is 0.81 with VarEPS-Monthly instead of 0.80 with MOFC.
- For days 12–18, the ROC Score is 0.63 with VarEPS-Monthly instead of 0.61 with MOFC.
- For days 19–32, the ROC Score is 0.57 with VarEPS-Monthly instead of 0.55 with MOFC.

Similar improvements can be seen when looking at reliability diagrams and the Brier Skill Scores (not shown).

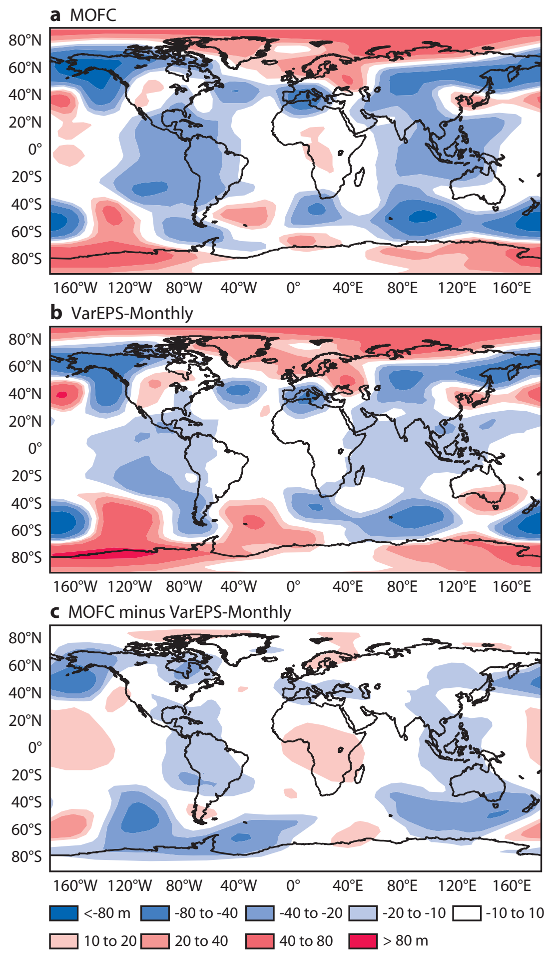

Figure 2 Bias in geopotential height at 500 hPa relative to ERA-40 calculated for (a) MOFC and (b) VarEPS-Monthly. (c) The difference of bias between MOFC and VarEPS-Monthly.

The improvements in ROC Score and Brier Skill Score translate into a higher potential economic value with VarEPS-Monthly than with MOFC. Figure 5(a) shows the Economic Value as a function of the Cost/Loss Ratio for the northern extratropics for days 12–18. According to the Wilcoxon-Mann-Whitney test, the difference is statistically significant within the 10% level of confidence for days 5–11 and days 12–18.

Overall, results indicate that the increase of atmospheric horizontal resolution from MOFC to VarEPS-Monthly slightly improves the performances of VarEPS-Monthly at all time ranges over the northern extratropics. The same conclusion is valid for the probability of 2-metre temperature in the lower tercile, and for other variables such as precipitation, surface temperature or mean sea level pressure. Similar results are also obtained over the southern extratropics.

Unlike in the extratropics, the probabilistic scores tend to be slightly higher with MOFC than with VarEPS-Monthly in the tropics. This is illustrated by the Economic Value as a function of the Cost/Loss Ratio shown in Figure 5(b). A possible explanation is that in the tropics the ocean-atmosphere coupling may play a more important role than the increase of resolution. The penultimate section will show that this is at least the case for the Madden-Julian Oscillation (MJO). It is expected, therefore, that the quality exhibited by MOFC will be regained when the new ocean model allows coupling from the start of the VarEPS-Monthly forecasts.

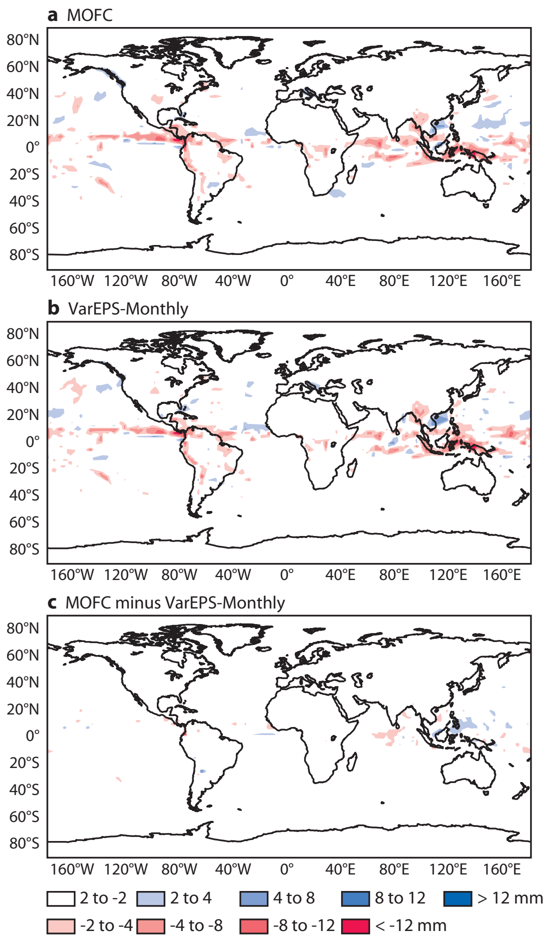

Figure 3 As Figure 1 but for total precipitation.

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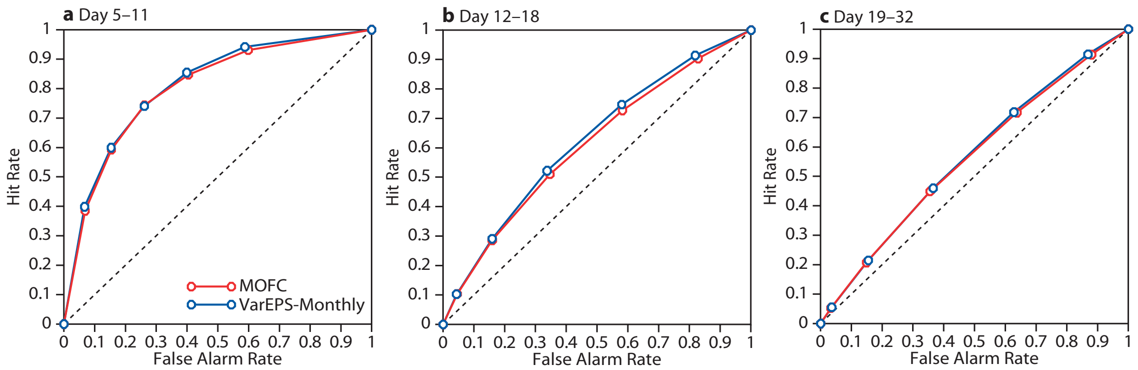

Figure 4 ROC diagram of the probability that 2-metre temperature averaged over (a) days 5–11, (b) days 12–18 and (c) days 19–32 is in the upper tercile over the northern extratropics for MOFC and VarEPS. Only land points are scored.

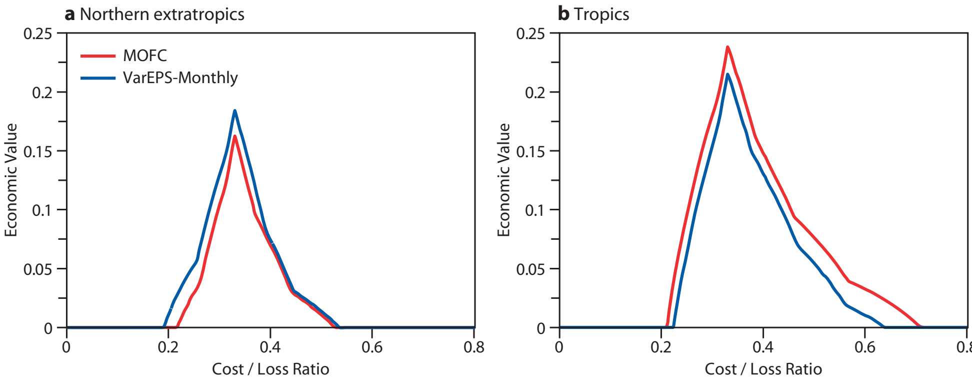

Figure 5 Potential economic value of the probability that 2-metre temperature averaged over days 12–18 is in the upper tercile over (a) northern extratropics and (b) tropics for MOFC and VarEPS-Monthly.

A few case studies of extreme events

The previous section showed that VarEPS-Monthly displays slightly better scores overall in the extratropics than MOFC. However, the sharp increase in resolution from MOFC to VarEPS-Monthly is expected to be beneficial mostly for the prediction of extreme events. We now discuss two specific cases of extreme events over Europe: the heat wave over Europe in summer 2003 and the unusually wet summer 2007 over England.

The heat wave over Europe in summer 2003

The heat wave in summer 2003 killed about 35,000 people in Europe, and is therefore a particularly important case for monthly forecasting. Here we will focus on the calendar week 2–9 August, when the 2-metre temperature anomalies were the highest, with weekly mean 2-metre temperature anomalies exceeding 6°C over some areas (Figure 6(a)).

The MOFC system, which was not operational, was running routinely at that time. Its performance in predicting the 2003 heat wave is discussed in *Vitart* (2005). Overall the ensemble mean anomalies for 2–9 August were above normal up to three weeks in advance. Figure 6(b) shows the ensemble mean anomalies of the 2-metre temperature for days 12–18 of the MOFC forecast starting on 23 July 2003 and verifying on 3–9 August. At this time range the model predicted a significant shift in the ensemble distribution, and the ensemble mean displays an anomaly larger than 2°C over most of France and Germany. Although a few ensemble members displayed a 2-metre temperature anomaly larger than 4°C, none of them produced a heat wave as intense as that observed.

Would the VarEPS-Monthly system have produced a better warning for this extreme event than the MOFC system? To answer this question, a 51-member ensemble of VarEPS-Monthly integrations with IFS Cy31r2 was run from 23 July 2003 with the same atmospheric and oceanic initial conditions as the pre-operational MOFC system, along with a five-member ensemble starting on 23 July 1991 to 2002. The re-forecasts from 1991 to 2002 are used to calibrate the 2003 forecasts and compute the 2-metre temperature anomalies. Since the model is not the same as in 2003, the same experiment was repeated but with MOFC and IFS Cy31r2.

The 2-metre temperature anomalies of MOFC and VarEPS-Monthly with IFS Cy31r2 are shown in Figures 6(c) and 6(d). Figure 6(d) indicates that the 2-metre temperature anomalies produced by VarEPS-Monthly are significantly larger than those produced by the monthly forecast in 2003 (Figure 6(b)), with anomalies of the ensemble mean exceeding 4°C over a large portion of western Europe. However, VarEPS-Monthly does not seem to predict the heat wave over Portugal, but this was also the case with the pre-operational monthly forecast (Figure 6(b)) and MOFC at Cy31r2 (Figure 6(c)). Comparing Figure 6(c) with Figure 6(d) indicates that most of the improvement is not due to the changes in model physics, but rather to the increased horizontal resolution in VarEPS-Monthly. Those results suggest that VarEPS-Monthly could be a useful tool for early warnings of this type of extreme heat wave over Europe.

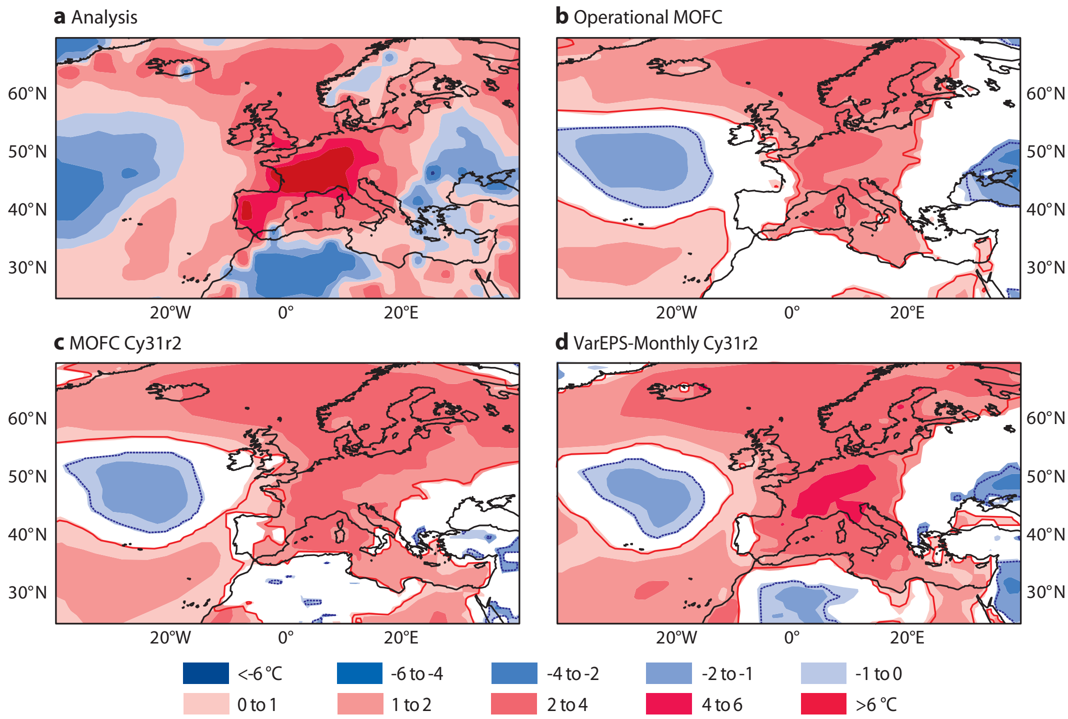

Figure 6 2-metre temperature anomaly relative to the past 12-year climate for 3–9 August 2003. Red colours indicate positive anomalies and blue colours represent negative anomalies. (a) The anomaly from the operational analysis/ERA-40. (b) The pre-operational monthly forecast of days 12 to 18 issued in 2003. (c) Re-forecast using a recent version of the monthly forecasting system with IFS Cy31r2. (d) Re-forecast with VarEPS-Monthly and IFS Cy31r2.

Wet summer over England in 2007

The summer 2007 over England was exceptionally wet with record precipitation which led to significant flooding over Southwest England, particularly during the week of 16 to 22 July 2007. We will focus on that specific week, where a heat wave also took place in Southeast Europe. Consider the precipitation anomalies (Figure 7(a)) and 2-metre temperature anomalies (Figure 7(b)) that are observed along with those predicted by MOFC and VarEPS/Monthly. The left panels in Figure 7 show the anomalies computed from the ECMWF operational analysis and ERA-40. A VarEPS-Monthly test suite was running routinely last summer with the same ensemble size and model cycle than MOFC. Comparison of the forecasts with the analysis shows that the VarEPS-Monthly test-suite (right panels) appears to better capture the anomalous precipitation over England than MOFC (middle panels) at the time range of 12 to 18 days. Furthermore, the heat wave over Southeast Europe is significantly stronger in VarEPS-Monthly than in MOFC, in agreement with observations.

The heavy precipitation over England was associated with a persistent low pressure system centred over England (Figure 8(a)). This low is also better predicted by VarEPS-Monthly (Figure 8(c)) than by MOFC (Figure 8(b)), along with the wave train across the Atlantic. For longer time ranges, beyond day 18, both VarEPS-Monthly and MOFC forecasts did not predict a particularly high risk of heavy precipitation over England, but the heat wave over Southeast Europe was still stronger in VarEPS-Monthly than in MOFC.

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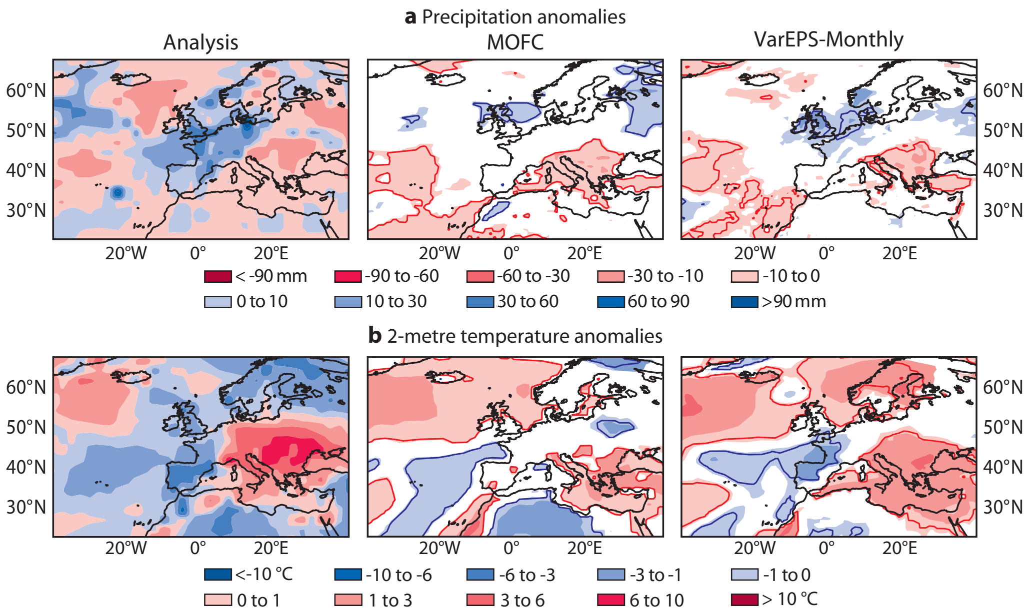

Figure 7 Anomalies averaged over the 16–22 July 2007 for (a) precipitation and (b) 2-metre temperature. The anomalies are computed relative to the past 12-year climate. Left panels: the ensemble mean anomalies computed from ECMWF operational analysis and ERA-40 for the 12-year climate. Middle panels: the operational MOFC forecasts starting on 5 July 2007. Right panels: the VarEPS-Monthly forecasts starting on 5 July 2007. For each model the anomalies are computed relative to the model climate.

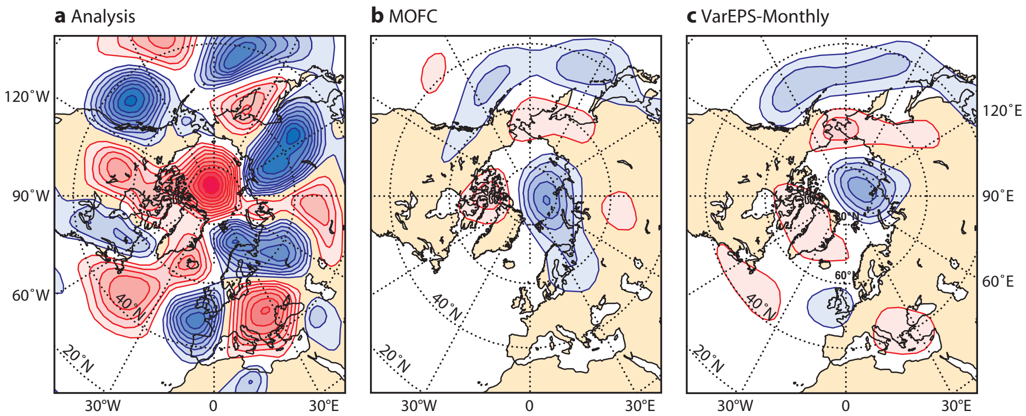

Figure 8 Geopotential at 500 hPa anomalies relative to the past 12-year climate and averaged over the week 16–22 July 2007 for (a) ECMWF analysis and ERA-40, (b) MOFC for the forecast starting on 5 July 2007 (time range days 12–18) and (c) VarEPS-Monthly for the forecast starting on 5 July 2007. The fields are displayed using a contour with intervals of 2 dam between 2 dam and 40 dam (red), and –40 dam –2 dam (blue).

Impact of persisted SST anomalies and of ocean coupling

As described earlier, VarEPS-Monthly consists of 10 days of atmosphere-only integrations followed by 22 days of ocean-coupled integrations. During the first 10 days of integrations, the atmospheric model is forced by persisted SST anomalies instead of persisted SSTs as in the previous VarEPS systems. The reason for using persisted SST anomalies is that for a long-range integration the seasonal cycle starts to have a significant impact on the amplitude of SSTs. In the context of VarEPS-Monthly, persisted SST anomalies provide more realistic initial conditions for the coupled integrations at day 10 than persisted SSTs (Figure 9). This has little impact on the atmospheric scores of medium-range forecasts over land, but the ROC diagram in Figure10 shows that using persisted SST anomalies instead of persisted SSTs has a positive impact on the probabilistic scores beyond day 10.

One justification for including an interactive ocean below the atmospheric model is the impact of the ocean-atmosphere interactions on the propagation of the Madden-Julian Oscillation (MJO) which is a main source of predictability in the tropics on the sub-seasonal time scale. In order to assess the impact of ocean-atmosphere coupling in the VarEPS-Monthly configuration, a five-member ensemble of 32-day integrations of VarEPS- Monthly was performed each day from 15 December 1992 until 31 January 1993, when a strong MJO event took place. The same experiment was repeated, but with persisted SST anomalies through the 32-day integrations instead of coupling the atmosphere to the ocean model after day 10. The MJO is diagnosed by projecting each ensemble member into the two leading combined Empirical Orthogonal Functions (EOFs) of velocity potential at 200 hPa, zonal wind at 850 hPa and outgoing long-wave radiation (OLR) computed from ERA-40 (see *Woolnough et al.,* 2006 or *Vitart et al.,* 2007 for more details). The skill of the monthly forecasting system is then estimated by computing the anomaly correlations of principal components 1 and 2 (PC1 and PC2) predicted by the model with the PC1 and PC2 computed from the analysis (in this case ECMWF's reanalysis dataset, ERA-40).

Figure 11 shows the time evolution of the mean of the correlations obtained with PC1 and PC2. During the first 10 days, the scores are identical since the experiment setting is identical in both experiments. However when the coupled ocean-atmosphere integrations start, at day 10, the VarEPS-Monthly integrations display higher correlations with analysis than those obtained with 32 days of persisted SST anomalies. This shows that the ocean-atmosphere coupling is important at this time range, and therefore supports the introduction of the ocean in the context of VarEPS-Monthly.

Note that the scores displayed in Figure 11 for the two VarEPS-Monthly experiments are lower than those obtained with MOFC. This is due to MOFC being coupled from day 0 instead of day 10 for VarEPS-Monthly; the ocean-atmosphere coupling seems to have more impact on the MJO propagation than an increase in horizontal resolution (*Vitart et al.,* 2006).

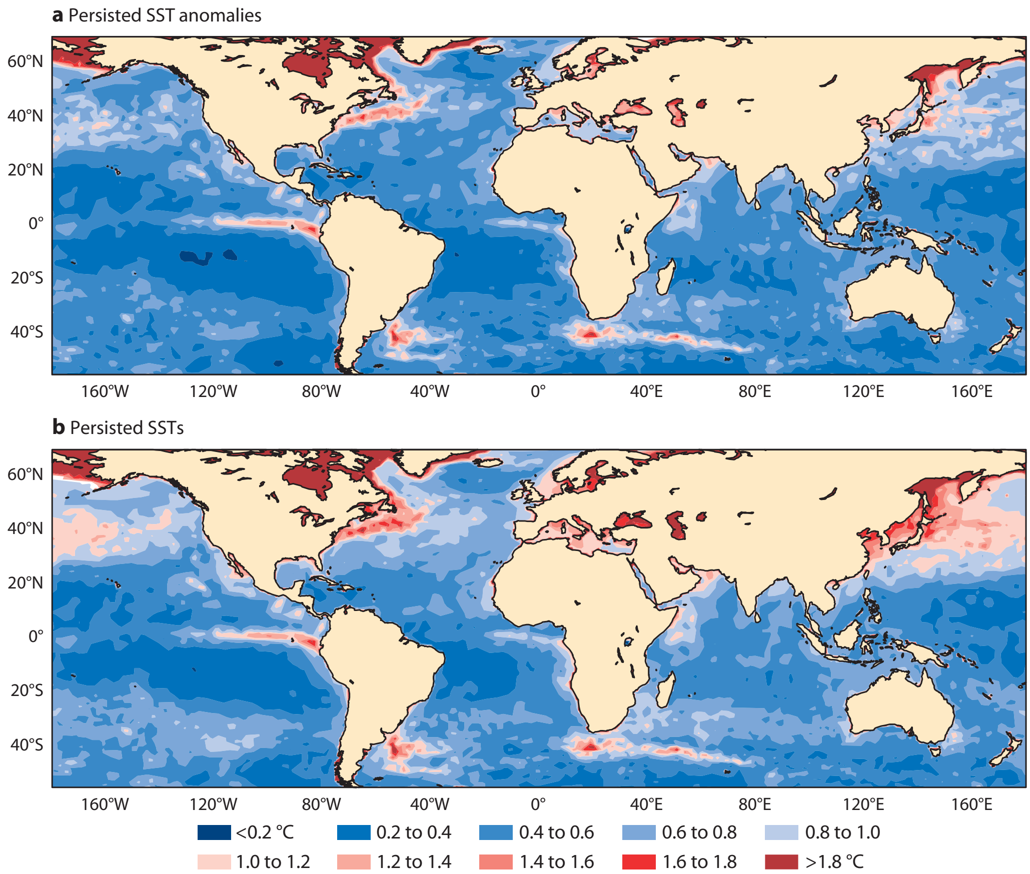

Figure 9 RMS error of sea surface temperatures at day 10 from 52 five-member ensemble cases (four starting dates over 13 years) with (a) persisted SST anomalies and (b) persisted SSTs. The RMS error is significantly lower, particularly in the extratropics, with persisted SST anomalies than with persisted SSTs.

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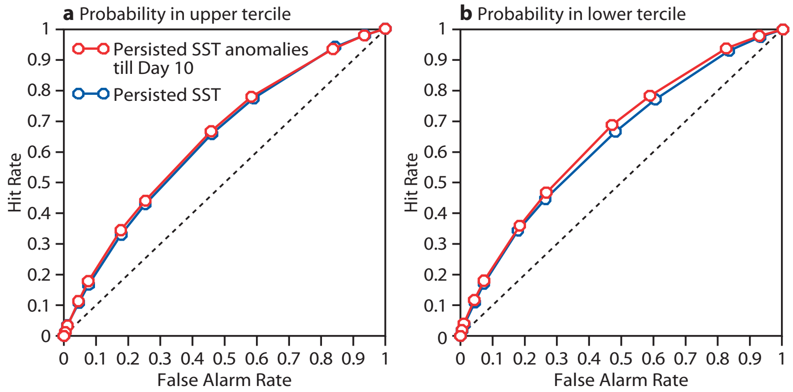

Figure 10 ROC diagrams indicating that the probability of 2-metre temperature averaged over the land points in the northern extratropics for days 12–18 is in (a) the upper tercile and (b) the lower tercile for *persisted SST anomalies* till day 10 and *persisted SSTs.* 52 cases were used in the computation of the ROC areas.

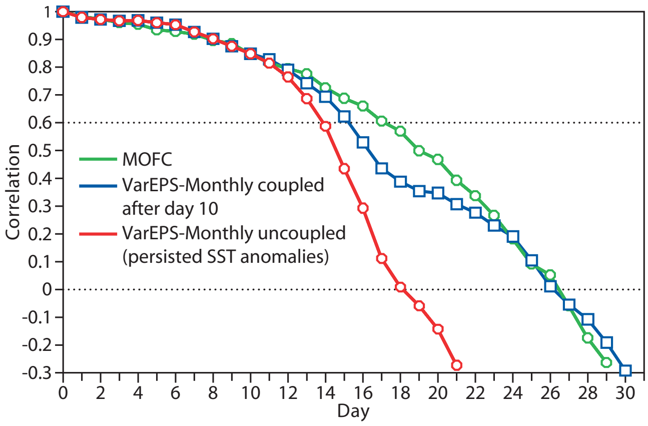

Figure 11 The time evolution of the mean of the correlations obtained with PC1 and PC2 (the individual correlations of PC1 and PC2 look similar) for VarEPS-Monthly uncoupled (*persisted SST anomalies*), VarEPS- Monthly coupled after day 10 and MOFC. The MJO is diagnosed by projecting each ensemble member into the two leading combined EOFs of velocity potential at 200 hPa, zonal wind at 850 hPa and outgoing long-wave radiation computed using ERA-40. The skill is estimated by computing the anomaly correlations of principal components 1 and 2 (PC1 and PC2) predicted by the model with the PC1 and PC2 computed from the analysis (in this case ERA-40).

Benefits of the new system

The ECMWF monthly forecasting system was developed and run separately from the EPS system. Now both systems have been merged into a unified forecasting system. The synergy will provide users with an easier access to ensemble forecasts from day 0 to day 32, and will give users of monthly forecasts more skilful predictions.

First of all, the change will make the retrieval of data much easier for users. This will also help to build forecasting products across the different time ranges. For instance, EPSgrams could be presented with daily values till day 12 and then weekly mean values afterwards. Some probabilistic products from the EPS (e.g. the Extreme Forecast Index, EFI) can also be applied to the extended forecast range. Another big advantage of this new system is that EPS and monthly forecasting can share the same re-forecast system.

Secondly, as results presented here have shown, monthly forecasts will benefit from the increased horizontal resolution of the atmospheric model. The scores in the extratropics are overall higher at all time ranges, and most particularly the prediction of extreme events seems to benefit from the higher horizontal atmospheric resolution. Furthermore, the case studies discussed in this article have shown that the new merged VarEPS-Monthly system is capable to provide useful warnings of extreme weather events beyond forecast day 15.

The only drawback of the new merged system is the negative impact on the scores of the monthly predictions in the tropical regions caused by running the atmospheric model forced by persisted SST anomalies till day 10 rather than coupling at day 0. Results have indicated that this has a negative impact on MJO predictions. Work is progressing towards the development of a new ocean model that will allow coupling of the merged VarEPS-Monthly system from day 0, and thus this weakness will be addressed.

Further Reading

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