The contribution of the land surface to predictability in the ECMWF seasonal prediction system: The European summer 2003 case

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1. Introduction

The summer 2003 was a very unusual summer in large parts of continental Europe with temperatures reaching record high values over an extended period of time from May to August and pronounced dry conditions starting in early spring and lasting until late summer. A number of studies have reported on the extremeness of the event (*Schär et al., 2004; Black et al., 2004; Grazzini et al., 2003*). Heat waves like the one of summer 2003 are generally linked to quasi-stationary anticyclonic circulation patterns with associated subsidence, clear-sky- conditions, advection of warm air and prolonged hot surface temperatures.

Figure 1 shows near-surface (2m) temperature, precipitation and 500 hPa geopotential height anomalies for June-August (JJA) 2003 as diagnosed from the ERA-40 reanalysis/operational analysis and the GPCP data set over the period 1991-2005. The 15-year period was chosen because the seasonal hindcast experiments for this study were carried out over this period. The maximum warming occurred over France and Switzerland with a large domain of positive temperature deviations from the climatological mean reaching from the North Sea to the Mediterranean Sea and from the Atlantic coast of France to approx. 15º E (Fig 1a). A negative precipitation anomaly was observed at almost the same position, mainly over land areas (Fig 1b). The warm and dry conditions were accompanied by a heat low near the surface (not shown) and a positive (anticyclonic) geopotential height (Z500) anomaly in the mid-tropospheric circulation at 500 hPa (Fig 1c) with an equivalent barotropic vertical structure.

The occurrence of the European summer 2003 meteorological conditions was statistically extremely unlikely (*Schär et al., 2004*) and understanding key physical processes and their contributions to the extreme summer 2003 clearly is of vital importance. Due to the far-ranging impacts of the extreme summer on different sectors like human health, energy, agriculture and forestry (see e.g. *Fink et al., 2004*), it is of direct interest to analyse to what extent the signal was predictable in advance. How well could a state-of-the-art dynamical long-range forecasting system have predicted such an extreme season? Which physical processes had an impact on its predictability?

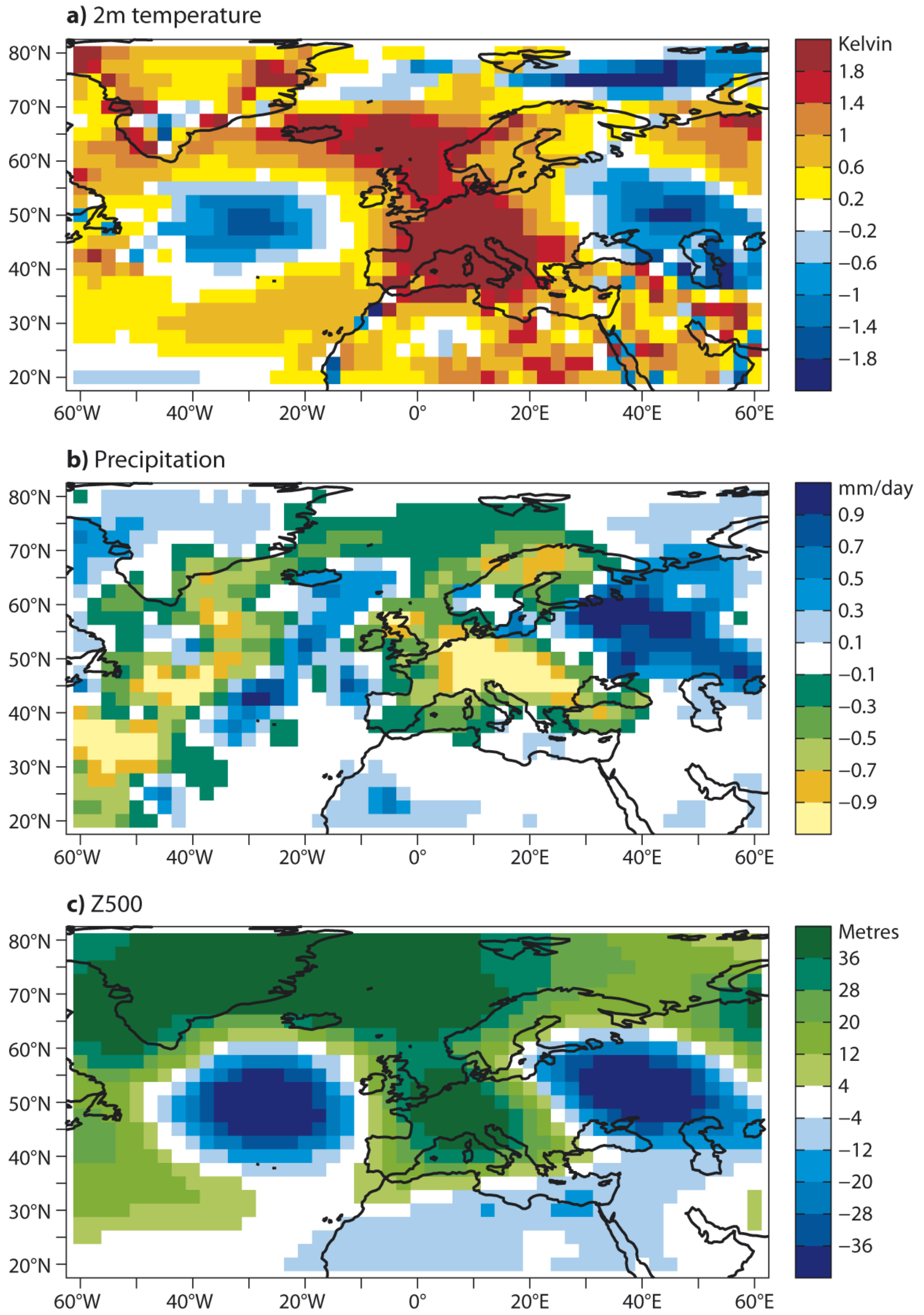

Figure 1: JJA 2003 anomalies of a) 2m temperature (T2m) in the ERA-40/operational analysis, b) precipitation in the GPCP data and c) geopotential height at 500 hPa (Z500) in the ERA-40/operational analysis. Anomalies were computed with respect to the 1991-2005 reference period by leaving the target year 2003 out in the computation of the climatological mean.

The spring 2003 over Europe preceding the summer heat wave was characterised by a deficit of precipitation over most of Europe (*Fischer et al., 2007*) resulting in a dry soil moisture anomaly. A number of studies have shown how summer drought conditions are capable to nonlinearly amplify large-scale temperature anomalies (e.g., *Schär et al., 1999; Viterbo and Beljaars, 2004*). As soil moisture varies slowly on time scales of weeks to months, feedbacks between precipitation and evaporation can persist the initial precipitation signal a season or so ahead. The lack of rainfall in spring 2003 and the consequent soil moisture depletion led to reduced latent cooling and the emission of more sensible heat which, via local convective inhibition, contributed to a temperature increase. Sensitivity studies using observational data *(Zaitchik et al., 2006*) and regional models (*Fischer et al., 2007)* emphasised the importance of the coupling between the land and the atmosphere and demonstrated how soil-moisture-temperature interactions amplified the evolution of heat waves through local and remote effects. *Vautard et al. (2007)* showed how winter rainfall deficits over Southern Europe effected the 10 hottest summers between 1948 and 2005 and that the rainfall frequency in the Mediterranean region during the previous winter and early spring is correlated with summer temperature in central continental Europe. *Della-Marta et al. (2007)* suggested Mediterranean precipitation from January to May as a predictor for statistical seasonal summer forecasts.

This paper is a summary of a presentation given at the ECMWF/GLASS Workshop on Land Surface Modelling, Data Assimilation and the implications for Predictability held in November 2009. We try to address the above questions using ECMWF's seasonal forecasting system. Global forecasts up to seven months ahead using a coupled atmosphere-ocean circulation model are nowadays issued routinely at ECMWF and other centres around the world (*Anderson et al., 2007*). The scientific basis for seasonal forecasts mainly stems from the relatively slowly evolving components of the climate system, like the ocean or land-surface that present boundary conditions for the more chaotic atmosphere with its shorter characteristic time scales. It will be demonstrated that with the recent atmospheric cycle 33R1 of the IFS in the coupled model, a successful prediction of the summer 2003 extraordinary warm and dry conditions over Europe would have been possible. The new land surface hydrology scheme H-TESSEL had, among other factors, a remarkable positive impact on correctly simulating the anomalous meteorological conditions of extremely warm temperatures, the precipitation deficit and an anticyclonic pressure structure in the free atmosphere. Evidence will be presented to show that a lack of soil moisture throughout the summer might have contributed to enhancing and maintaining the local heating in the simulations.

2. Seasonal hindcasts with the operational forecasting system S3

2.1. Skill of the ECMWF seasonal forecasts

The seasonal forecast System 3 (S3, see *Anderson et al., 2007*) has been in operational use since 2007. It basically consists of the ECMWF atmospheric model IFS coupled to the HOPE ocean model. The version of the atmospheric IFS model used in S3 is cycle 31R1, a cycle that was operational in medium-range weather forecasting in 2006. The only change to the IFS model in seasonal forecasting compared to the medium-range forecasts concerns its reduced resolution: S3 runs the IFS with 62 vertical levels and in spectral horizontal resolution T159. The forecasts are initialised in the atmosphere with the ERA-40 re-analysis/operational analysis and in the ocean with the ORA-S3 re-analysis. All simulations analysed for this study are retrospective forecasts (re-forecasts or hindcasts) for the boreal summer season (JJA) initialised on 1st May of each year. They consist of an ensemble of nine members generated by sampling uncertainties in the initial conditions and model error of the atmosphere and ocean.

Figure 2a shows time series of summer JJA 2m temperature hindcasts over Southern European land areas from 1960 to 2005. The hindcasts were performed as part of the ENSEMBLES project stream 2 simulations (*Weisheimer et al., 2009*) and use exactly the same configuration as S3 but with nine ensemble members. We chose Southern Europe (30º-48ºN, 10ºW-40ºE) because it is one of the standard global land regions for verification where most of the extreme temperatures occurred. As can be seen, the temperature anomaly in 2003 of 1.50 ºC (0.93 ºC with respect to the 1991-2005 reference period) was the highest over the 46-year period in the analysis. The System 3 hindcasts follow, in general, the observed temperature evolution well. The anomaly correlation of the ensemble mean with the analysis is 0.79 (highly significant). For the period 1991-2005 the correlation is even higher with 0.84. The anomalies of the analysis and the model were calculated with respect to their individual climate mean states during the given reference periods.

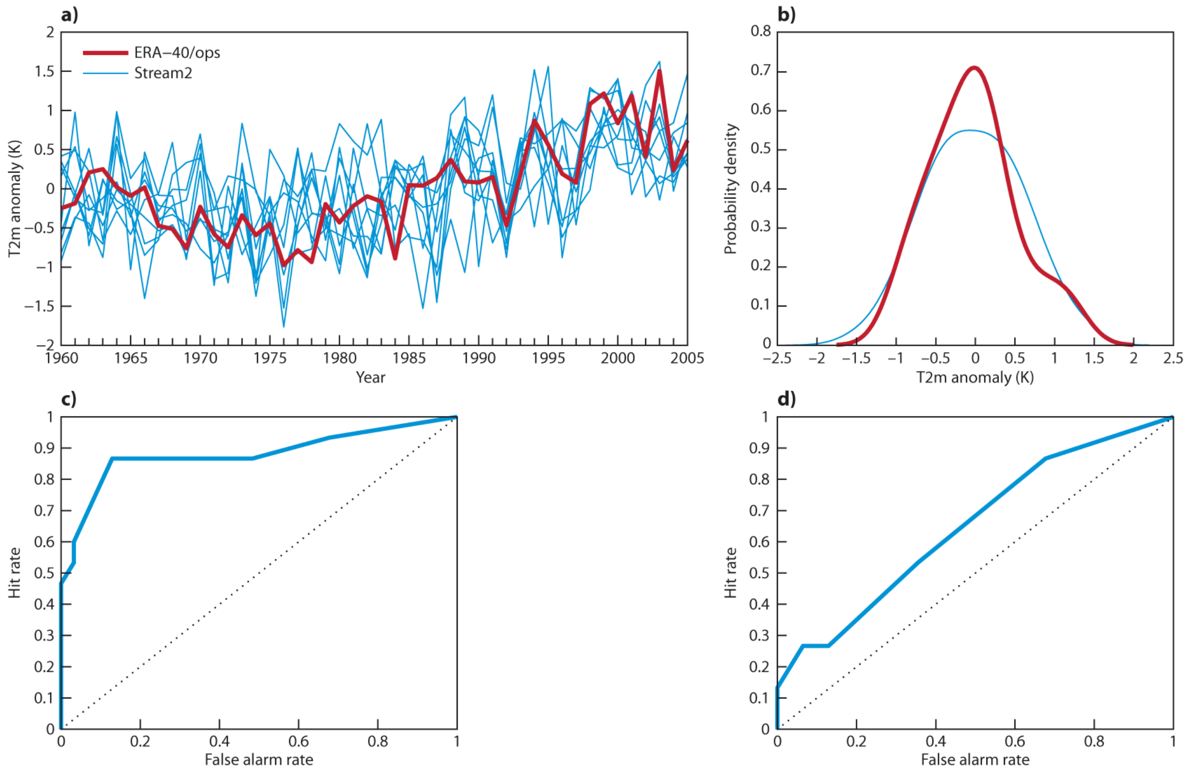

Figure 2: Seasonal hindcasts of T2m anomalies in JJA over Southern European land areas with the operational seasonal forecasting system S3 for the ENSEMBLES stream 2 hindcast period 1960-2005. The anomalies have been computed with respect to the model and analysis climatology over the 46-year hindcast period. The hindcasts were initialised on 1st May of each year. a) Time series of seasonal hindcast temperature anomalies (nine ensemble members in blue; analysis in red). b) Probability density distributions (pdf) of the analysis climate (red) and the model climate (blue). The pdfs were estimated using a Gaussian kernel estimator. c) ROC diagram for the hindcast events "temperature anomaly in the upper tercile". d) as in c) but for the "detrended" hindcasts, i.e., the linear trend between 1979 and 2005 in a) had been removed.

The climatological distribution of the analysis and the model re-forecast anomalies over the 46-year hindcast period is shown as probability density functions (pdfs) in Fig 2b. There appears to be a very good agreement between the analysis and model especially at the tails of the distribution indicating that the model performs, in a statistical sense, well for extreme temperatures. A similar conclusion can be drawn from analysing the hit-rate vs false alarm rate statistics, displayed in form of a ROC diagram in Fig 2c, for predicting temperature anomalies in the upper third of the distribution. The ROC curve lays well above the no-skill diagonal line with the ROC skill score ROCSS

$$\begin{aligned} ROCSS &= 2 * A_{ROC} - 1 \\ &= 0.76 \end{aligned}$$

being statistically significantly different from zero (no skill). Here, A_{ROC} indicates the area below the ROC curve. For seasonal forecasts of extratropical temperature over land this amount of skill is relatively high. For comparison, the corresponding ROCSSs for Northern European land areas and North America are 0.26 and 0.25, respectively.

From the time series in Fig 2a it can be seen that the Southern European land temperatures have undergone a pronounced warming trend since the early 1980s. This warming trend is well captured by the seasonal hindcasts and can be demonstrated to explain most of the positive hindcast skill. Fig 2d shows the ROC diagram based on a similar time series as in Fig 2a but where the linear trend between 1979 and 2005 has been removed from the analysis and model. The anomaly correlation coefficient for the detrended time series drops to 0.58 (highly significant) and the ROCSS has been estimated to be 0.29 (not significant). While hypotheses about the anthropogenic origin of the recent warming trend during summer remain speculative (*Philipona et al., 2009*), *Schär et al. (2004)* suggest that the temperatures experienced across Europe in summer 2003 could be considered “normal” by the end of the 21st Century under a high greenhouse-gas emission scenario.

2.2. Re-forcasting the summer 2003

In the light of these encouraging positive hindcast skill results for predicting warm summers over Southern Europe, how well would System 3 have forecasted the meteorological conditions in 2003? Figure 3a shows the temperature forecast pdf for JJA 2003 (dotted curve with asterisks) together with the pdfs of the analysis and model climate over the 1991-2005 hindcast period (solid curves). The re-forecasts for the year 2003 have been re-run with a larger ensemble of 50 members to obtain a better estimate of the forecast pdf. For comparison, the observed temperature anomaly of 0.93 ºC is indicated by the vertical dashed line. As can be seen, the forecast pdf of System 3 is very similar to the model climate pdf showing only very little evidence for warmer-than-normal conditions in 2003. Note that the analysis and model climate statistics in Fig 3a were computed excluding the target year of 2003 in order not to blur the forecast signal.

The maps in Fig 3b show the spatial distribution of the ensemble mean forecast anomalies for JJA 2003 in terms of 2m temperature, precipitation and Z500. In contrast to the observed conditions (Fig 1), the strongest warming over Europe is simulated over south-eastern Europe. Not only is the location of the warming at the wrong position, also the warming is linked to an anomalous wet summer season in the model instead of extremely dry conditions in reality. The circulation in the mid-troposphere appears to be shifted by half a wave length with a trough now situated over central Europe.

During summer the large-scale westerly flow regime over Europe becomes weaker and the continental climate is potentially more influenced by processes with a longer memory than a few days. The two most obvious candidates for such a long memory are sea-surface temperature (SST) and soil moisture. In a study using a previous version of the IFS *Ferranti and Viterbo (2006)* concluded that the response of large dry soil anomalies greatly exceeds the impact of the ocean boundary forcing. However, neither the very dry initial soil moisture conditions nor using prescribed observed SSTs helped predicting the hot summer signal using the S3 seasonal forecasting system. These results are broadly similar to the equally poor real-time seasonal forecasts for JJA 2003 with the then-operational system, System 2 (*Ferranti and Viterbo, 2006*).

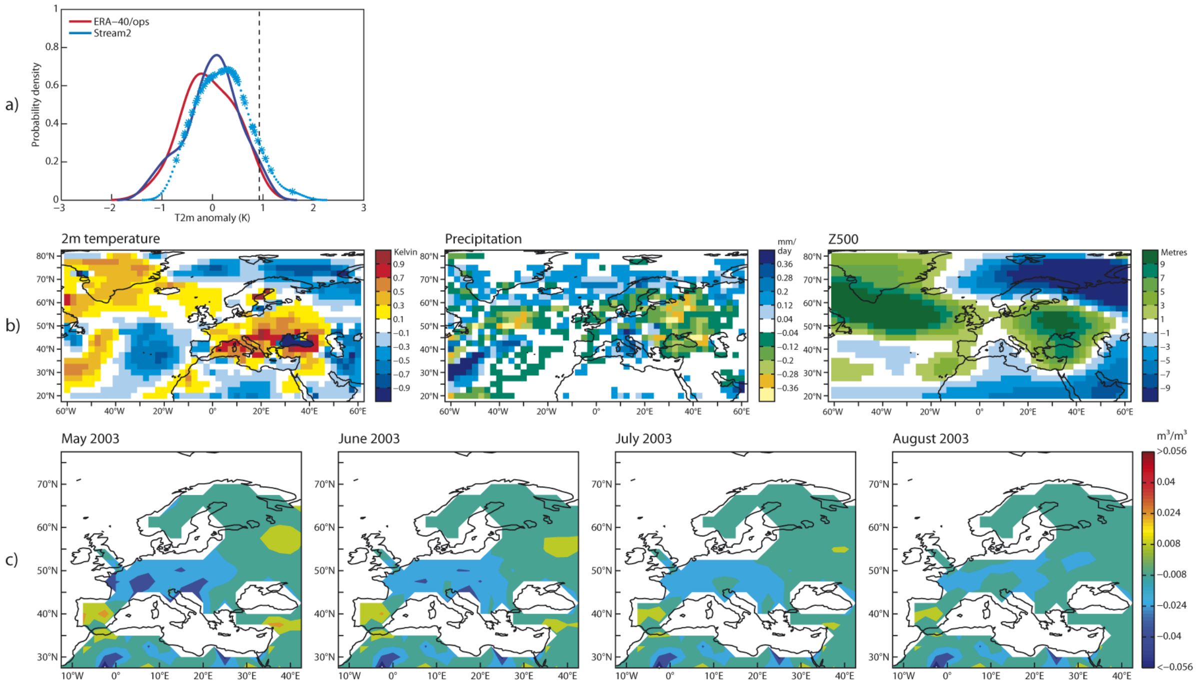

Figure 3: Seasonal hindcasts of JJA 2003 with the operational seasonal forecasting system S3. All anomalies are computed with respect to the 1991-2005 reference period of the model but leaving the target year 2003 out (see Fig 1). a) pdfs of T2m for the model and analysis climate (blue and red solid lines, respectively) and the JJA 2003 re-forecast (dotted line; each of the 50 ensemble members is denoted by an asterisks) for Southern European land areas. The analysed temperature anomaly of 0.93 ºC during JJA 2003 is indicated by the dashed black vertical line. b) Ensemble mean of the hindcast anomalies for T2m, precipitation and Z500. c) Monthly mean total soil moisture hindcast anomalies during May - August 2003.

As mentioned in the introduction, already the spring season in 2003 was characterised by a deficit in soil moisture over wide parts of Europe. Figure 3c shows total soil moisture forecast anomalies for the first four months of the summer 2003 seasonal forecasts. Here, the forecast anomalies were calculated with respect to the model soil moisture climatology. Observed soil moisture anomalies are not shown due to the lack of long-term continental-scale observations, although *Ferranti and Viterbo (2006)* demonstrate a clear negative soil moisture index anomaly throughout the summer based on ERA-40 and operational analysis data. Whereas the anomalously negative soil moisture structure is clearly visible in May during the first month of the forecast, it was not maintained, quickly disappeared and got almost completely damped out by August.

System 3-like atmosphere-only hindcasts using observed sea surface temperatures at the lower boundary show no improvement in forecasting correctly the extreme summer 2003 conditions over Europe (not shown). This is in agreement with precious findings (*Grazzini et al., 2003; Jung et al., 2006; Ferranti and Viterbo, 2006*).

3. Seasonal hindcasts with an improved cycle of the atmospheric model - impact of physical parameterization schemes

3.1. The IFS cycle 33R1

In this section, we discuss the impact of a newer than System 3 version of the IFS model on forecasting the summer 2003 conditions. Cycle 33R1 was introduced at ECMWF as the operational cycle for the medium-range forecasts in June 2008. It contained a number of major changes to different physical parameterization schemes compared with cycle 31R1 used in System 3.

The land-surface scheme TESSEL (Tiled ECMWF Scheme for Surface Exchanges over Land) had been revised by introducing the new land surface hydrology H-TESSEL (*Balsamo et al., 2009*). H-TESSEL contains new infiltration and sub-grid surface runoff schemes depending on geographically varying soil texture and orography; it led to reduced soil moisture and 2m temperature errors.

Additionally, the new radiation package McRad was implemented (*Morcrette et al., 2008*). It includes an improved description of the land surface albedo from MODIS observations and new treatments of short-wave radiation and cloud-radiation interactions.

Another significant change related to the convection scheme with a new formulation of the convective entrainment and reduced vertical diffusion above the planetary boundary layer (PBL) (*Bechtold et al., 2008*). These changes resulted in an overall beneficial increase in model activity, especially in the tropics.

Coupled seasonal hindcasts for the boreal summer season over the period 1991-2005 were carried out similar to those for System 3. In terms of model climatology and systematic errors the new cycle 33R1 performed rather similar to the System 3 cycle 31R1. For example, in Fig 4a the climatological pdf of 2m temperature anomalies in 33R1 differs only very little from that in 31R1 (Fig 3a). Again, a very good agreement with the estimated pdf of the analysis can be found. However, in contrast to the System 3 forecast pdf for JJA 2003, the new cycle indicated a significant shift of the forecast from the model climatology towards warmer temperature anomalies.

The corresponding ensemble mean patterns of temperature, precipitation and Z500 are shown in Fig 4b. The strong warm signal over large parts of central Europe resembles very well the observed temperature anomaly structure in summer 2003 (Fig 1a). In contrast to the System 3 forecast of anomalous wet conditions, the new IFS model cycle now correctly simulates dry conditions over the regions of the strongest warming. At the same time the circulation in the middle troposphere has also improved with a large-scale Z500 ridge over the European continent. The warm and dry atmospheric conditions were accompanied by anomalously negative soil moisture (Fig 4c).The initial dry anomaly in May is well persisted, or maintained, into the summer months through to August.

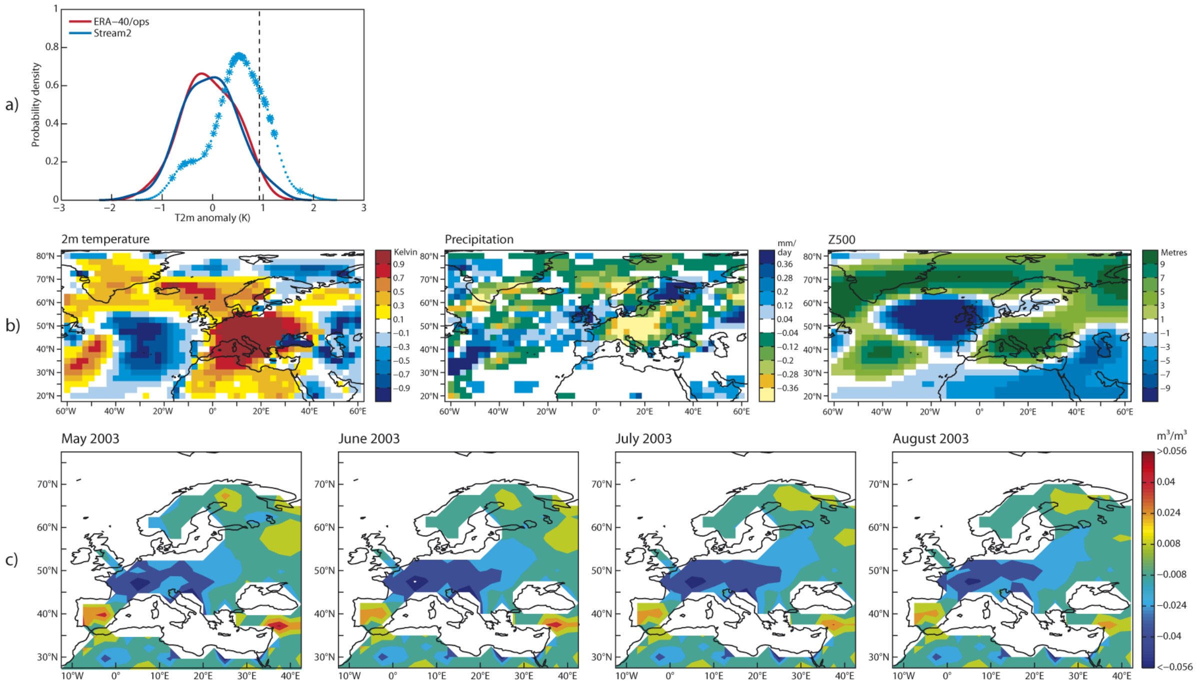

Figure 4: Seasonal hindcasts of JJA 2003 with the new atmospheric model cycle CY33R1. All anomalies are computed with respect to the 1991-2005 reference period of the model. a) - c) as in Fig. 3.

3.2. Impact of physical parameterization schemes

Given the positive seasonal re-forecast of summer 2003 using the IFS model version 33R1 but the somewhat disappointing results from cycle 31R1, one might ask where the gain in predictability between these two model cycles came from. Can it be attributed to any of the discussed changes to the physical parameterisation schemes in cycle 33R1? In order to test the sensitivity and impact that the introduced modifications to the land-surface, radiation, convection and PBL schemes had on the JJA 2003 hindcasts, a set of systematic seasonal hindcast experiments was carried out by switching back individual physics schemes in cycle 33R1 to their cycle 31R1 versions. For example, in one experiment the new land-surface hydrology scheme H-TESSEL was switched back to TESSEL while the radiation, convection and PBL changes from cycle 33R1 were all retained. Another 33R1 experiment was carried out using H-TESSEL but the old 31R1 radiation package and another one by replacing the old convection scheme but keeping the cycle 33R1 versions of all other parameterizations. All sensitivity runs were done for the 1991-2005 common hindcast period using 9 ensemble members. The year 2003 re-forecasts were extended to a total of 50 ensemble members.

Results of the impact of the new land-surface scheme H-TESSEL on the summer 2003 re-forecast are shown in Figures 5 and 6. While the climatological pdf of the simulation with TESSEL remains almost unchanged and thus close to the analysis pdf (Fig 5a), the predicted warming for Southern European land areas is less pronounced than it was using H-TESSEL.

The spatial structure of the corresponding JJA 2003 anomalies (Fig 5b) indicate, however, that the strongest warming was misplaced over North-Eastern Europe with neutral conditions in Central Europe. The negative precipitation anomaly, which was successfully reproduced in cycle 33R1, reversed to a positive anomaly in the seasonal re-forecast using the previous land-surface scheme TESSEL. Similarly, the circulation in the middle troposphere was affected by these changes and an unrealistic negative anomaly developed.

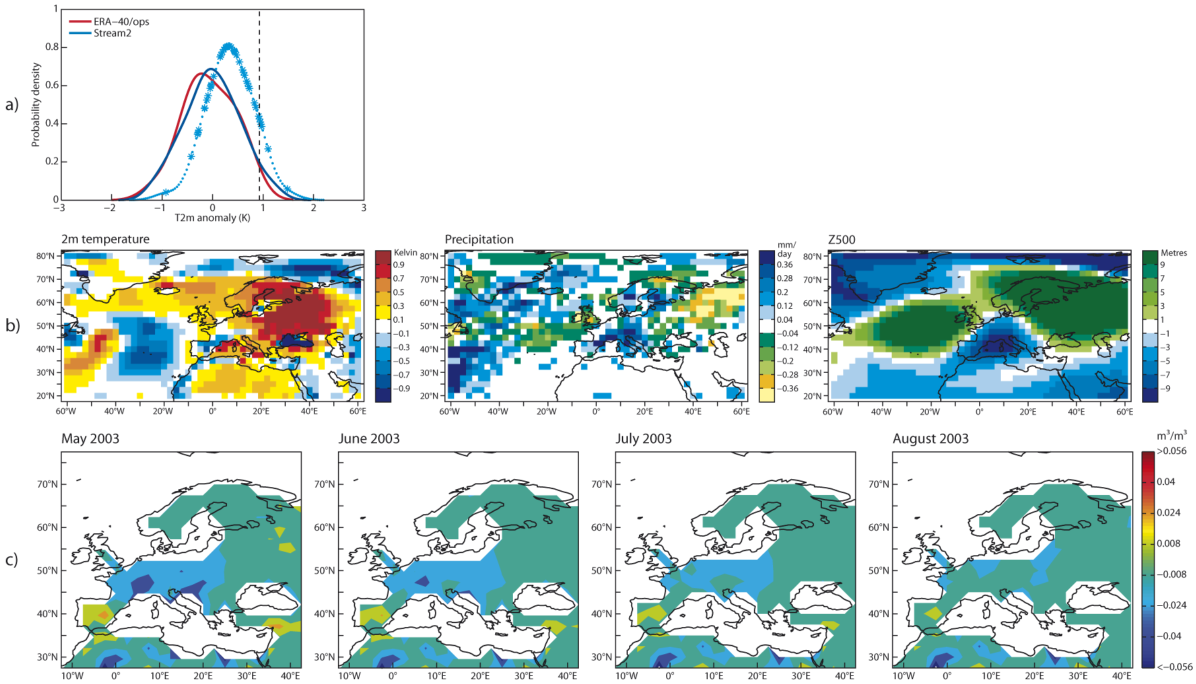

Figure 5: Seasonal hindcasts of JJA 2003 with the atmospheric model cycle CY33R1 but replacing the new land-surface scheme H-TESSEL with the old scheme TESSEL (used in S3). All anomalies are computed with respect to the 1991-2005 reference period of the model. a) - c) as in Fig. 3.

As discussed in Section 2, land-surface processes can, via exchanges of latent and sensible heat fluxes, locally interact with and feedback on the atmospheric conditions above. In summer 2003, extreme dry soil moisture conditions already in spring and which persisted into the summer season contributed via reduced evaporation processes to a positive feedback between soil moisture and temperature-precipitation anomalies. Fig 5c shows the monthly evolution of soil moisture anomalies from May to August 2003 in the re-forecast using TESSEL. Compared to the anomalies developing in H-TESSEL, already in the first month of the integration using TESSEL the negative anomaly is relatively small and diminished further during the summer months. The absence of a clear dry soil moisture anomaly in summer might have hindered the development of an anomalously dry precipitation field in the atmosphere.

In Figure 6 model anomalies of the short-wave and long-wave surface radiation components for May and JJA 2003 are shown for the re-forecasts using cycle 33R1 (H-TESSEL) and TESSEL. In accordance with observations (*Black et al., 2004; Ferranti and Viterbo, 2006*), a pronounced positive (downward) anomaly in the solar component of the radiation budget was found for both simulations during the first month of the hindcasts. While the model configuration with H-TESSEL correctly persisted the initial anomaly into the summer months (Fig 6a), the TESSEL land-surface scheme integrations lost the signal during summer, or rather had it replaced further to the northeast where the maximum warming occurred in the model (Fig 6b).

An analysis of the thermal, or long-wave surface radiation component in both model integrations demonstrates that, similar to the short-wave results the new cycle 33R1 with the revised land-surface processes is able to persist the negative radiation anomaly for up to 4 months (Fig 6c), whereas the model using TESSEL loses the initial radiation signal quickly during the summer season (Fig 6d).

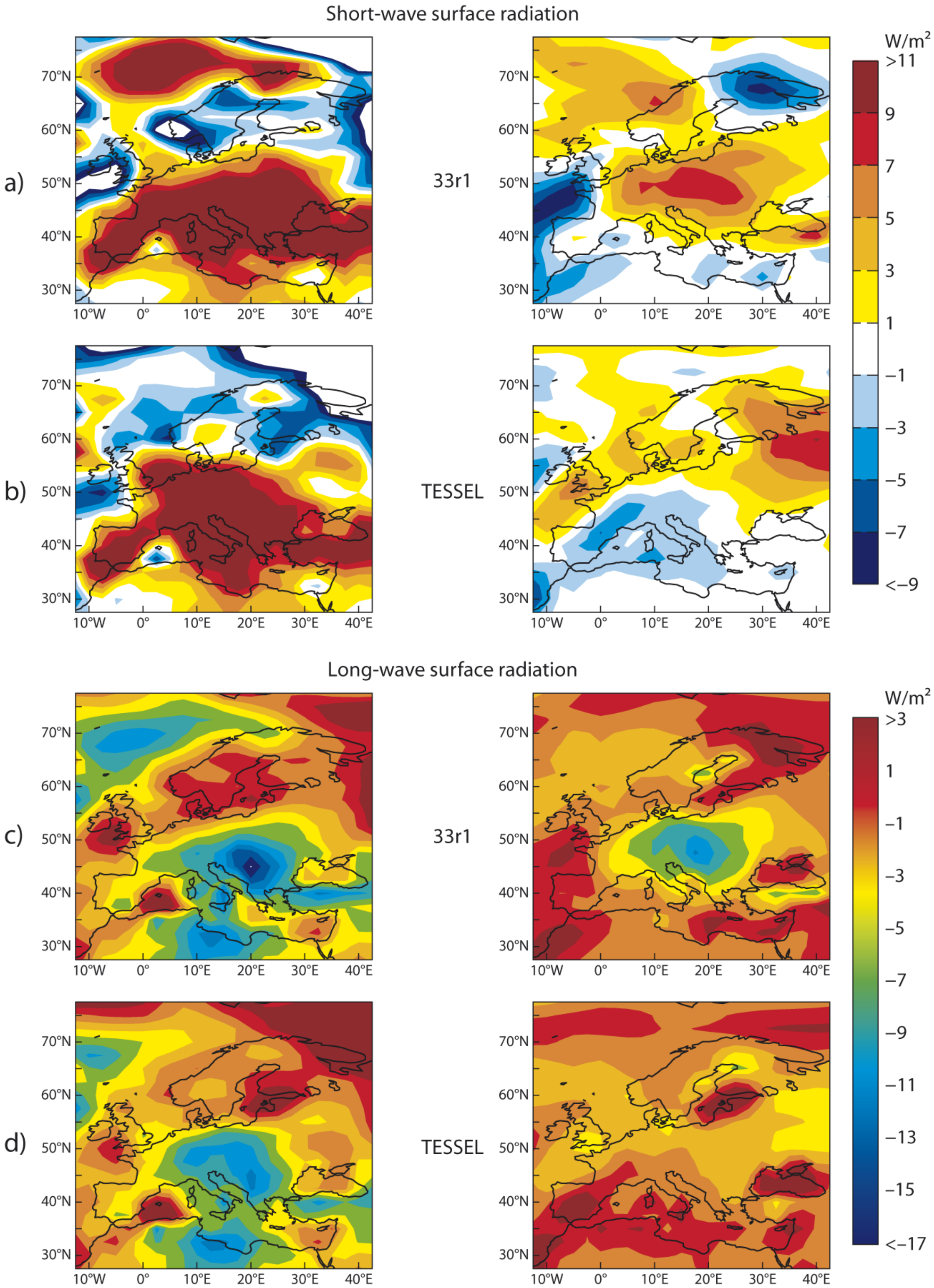

Figure 6: Surface radiation in the first month (May 2003) and seasonal means for JJA 2003 with the atmospheric model cycle CY33R1 using H-TESSEL and TESSEL. All anomalies are computed with respect to the 1991-2005 reference period of the models. a) Short-wave surface radiation anomalies using H-TESSEL. b) Short-wave surface radiation anomalies using TESSEL. c) Long-wave surface radiation anomalies using H-TESSEL. d) Long-wave surface radiation anomalies using TESSEL.

The success of the summer 2003 re-forecast with the IFS cycle 33R1 not only comes from the more realistic simulations of the local coupling and feedback processes between the land surface and the atmosphere. By analysing sensitivity experiments to the formulation of the radiation, convection and vertical diffusion parametrisation schemes, it was found that non-local improvements in the convection and radiation schemes also contributed positively to the successful re-forecast with cycle 33R1 (not shown). However, no specific factor could be singled out to explain solely the positive forecasts. For example, a version of the IFS that uses all the new cycle 33R1 parameterizations (including H-TESSEL) except for convection, failed in reproducing the correct signal. Thus. only the interplay of a good land surface hydrology, radiation and convective parameterization models have, in hindsight, led to a successful prediction of the record-breaking summer. As the focus of this paper, and indeed the workshop, was on the land surface, details of the sensitivities of the predictability of the summer 2003 to other physical parameterization schemes will be left to discuss elsewhere (*Weisheimer et al., 2010*).

4. Summary and outlook

It has been demonstrated that the predictive hindcast skill for near-surface temperature in summer over Southern Europe in ECMWF’s operational seasonal forecast system based on the coupled IFS/HOPE model is, in general, relatively high. A large part of the positive skill can be explained by the correct simulation of the observed warming trend over the last 30 years. However, despite of the good overall performance of the seasonal forecast system in predicting warm summers, the seasonal re-forecasts for the extreme JJA 2003 using the currently operational System 3 showed no sign of an unusually warm summer. A number of recently revised physical parameterization schemes developed for NWP had a remarkably positive impact on the predictability of summer 2003. Not only were the extreme temperature and precipitation anomalies over Central Europe correctly simulated, but also the large-scale circulation in the troposphere had improved. The new land surface hydrology Scheme H-TESSEL played an important role in these improvements by successfully persisting the dry soil moisture anomaly from the spring into the summer. Improvements to the radiation and convection schemes were also found to be beneficial. However, it is only the interplay of local land surface hydrological (precipitation - evaporation feedback) and large-scale radiative and convective processes that has, in hindsight, led to the successful prediction of the record-breaking summer 2003.

Very recently a numerical bug in the short-wave radiation calculation of the new McRad radiation scheme in the IFS cycle 33R1 was discovered. So far evidence for a major impact on this case study has been very small.

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