On the predictability of the extreme summer 2003 over Europe

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[1] The European summer 2003 is a prominent example for an extreme hot and dry season. The main mechanisms that contributed to the growth of the heat wave are still disputed and state-of-the-art climate models have difficulty to realistically simulate the extreme conditions. Here we analyse simulations using recent versions of the European Centre for Medium-Range Weather Forecasts seasonal ensemble forecasting system and present, for the first time, retrospective forecasts which simulate accurately not only the abnormal warmth but also the observed precipitation and mid-tropospheric circulation patterns. It is found that while the land surface hydrology plays a crucial role, the successful simulations also required revised formulations of the radiative and convective parameterizations. We conclude that the predictability of the event was less due to remote teleconnections effects and more due to in situ processes which helped maintain the dry surface anomalies occurring at the beginning of the summer. **Citation:** Weisheimer, A., F. J. Doblas-Reyes, T. Jung, and T. N. Palmer (2011), On the predictability of the extreme summer 2003 over Europe, *Geophys. Res. Lett.*, *38*, L05704, doi:10.1029/2010GL046455.

1. Motivation

[2] The summer 2003 was exceptionally warm and dry over large parts of Europe with temperatures reaching record values over extended periods of time. While a number of studies have reported on the exceptional nature of the event [*Schär et al.*, 2004; *Black et al.*, 2004; *Grazinni et al.*, 2003] and its far-ranging impacts on different sectors of society [*Fink et al.*, 2004], the key physical mechanisms for the development of these extraordinary meteorological conditions are still controversial. Several studies emphasise the role of the land surface [*Ferranti and Viterbo*, 2006; *Fischer et al.*, 2007], others stress the importance of global and regional oceanic conditions [*Jung et al.*, 2006; *Black and Sutton*, 2007; *Feudale and Shukla*, 2007; *Nakamura et al.*, 2005] or dynamical mechanisms in the atmosphere [*Cassou et al.*, 2005]. However, no contemporary climate model has been able to simulate with any realisms, the circulation structures associated with the 2003 heat wave. In the following, we show simulations of the summer 2003 with the European Centre for Medium-Range Weather Forecasts (ECMWF) seasonal ensemble forecasting system and discuss the impact of the land surface, the radiation and convection parameterization schemes.

2. Skill of Retrospective Forecasts

[3] We first analyse the overall quality of seasonal retrospective forecasts (re-forecasts, simulations that are made *after* the actual forecast date but emulate real-time forecasting conditions as close as possible) based on a 46-year record of June, July and August (JJA) seasonal mean 2m temperature (T2m) averaged over southern European land areas (30°–48°N, 10°W–0°E). The re-forecasts were generated with ECMWF's forecasting system S3 (operational since 2007) [*Anderson et al.*, 2007] initialised on 1st May each year (see auxiliary material) [*Weisheimer et al.*, 2009].[1] In general, the re-forecasts follow the verifying temperature evolution closely (Figure 1a) with an anomaly correlation between the ensemble mean and the verification of 0.79 (statistically significant with $p < 0.05$). Moreover, as shown in Figure 1b, there is a very good agreement between the climatological probability density functions (pdf) of the verifying and predicted temperature anomalies, especially at the upper tail of the distribution. This indicates that the forecast model performs in an overall sense very well for extreme high temperatures. A similar conclusion holds for the probabilistic hit rate versus false alarm rate statistics, as manifest in a ROC diagram (see auxiliary material) in Figure 1c, for predicting upper tercile T2m anomalies of the climatological probability distribution. The blue curve lays well above the no-skill diagonal line with a ROC skill score of 0.76 ($p < 0.05$). In the context of seasonal forecasting of extra-tropical land temperatures, this level of skill is remarkably high.

[4] The main reason for this skill is easily explained. Southern European land temperatures have undergone a pronounced warming trend since the early 1980s that is well captured by the seasonal re-forecasts [*Doblas-Reyes et al.*, 2006] (Figure 1a) and accounts for most of the positive forecast skill. When the linear trend between 1979 and 2005 is removed from the verification and the model data, the anomaly correlation coefficient for the de-trended time series drops to 0.58 ($p < 0.05$) and the *ROC* skill score becomes 0.29 (not significant, Figure 1c, green).

3. Re-Forecasts With the Operational System S3

[5] Given the positive skill for temperature re-forecasts, it can be asked whether S3 was capable of predicting the extreme summer 2003. Surprisingly, the forecast shows no indication of an extremely hot, or even just a warm summer as the forecast distribution is only marginally shifted away from the climatological distribution towards warmer

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL046455.

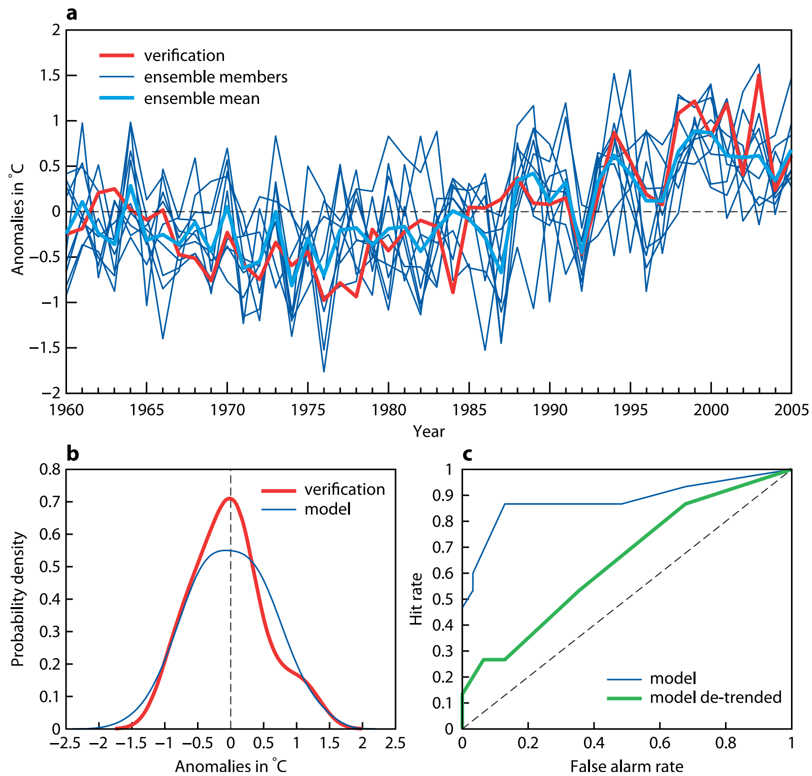

Figure 1. S3 seasonal re-forecasts of T2m in JJA over Southern Europe land areas initialised on 1st May 1960 to 2005. (a) Anomaly time series of ensemble members (blue), ensemble mean (cyan), verification (red). (b) Climatological pdf of the verification (red) and the forecast anomalies (blue). (c) ROC diagram showing probabilistic hit rate versus false alarm rate statistics for predicting upper tercile T2m anomalies. The curve in blue is based on the re-forecast data in Figure 1a; the curve in green is based on the re-forecasts where the linear trend between 1979 and 2005 has been removed. Verification data are ERA-40 reanalysis until 2001 and ECMWF's operational analysis thereafter.

temperatures (Figure 2a). According to a two-sampled Kolmogoroff-Smirnov (KS) test at $p = 0.05$, the difference between the model climate and re-forecast distributions is not statistically significant.

[6] The warmest T2m anomalies in JJA 2003 occurred over a large central and Southern European domain (Figure 3a). This warming was accompanied by a substantial negative precipitation anomaly consistent with a positive (anticyclonic) geopotential height anomaly in the mid-troposphere (Z500). By contrast, the anomaly patterns of the S3 ensemble mean re-forecast indicate neutral-to-weak warm temperature anomalies (Figure 3b). The S3 forecasts neither showed a dry signal (indeed they had a somewhat wet signal) nor the correct anticyclonic atmospheric circulation anomaly.

[7] A further set of re-forecasts using observed SSTs to replace the coupled ocean model at the lower boundary made, contrary to *Black and Sutton* [2007], no substantial difference towards simulating correctly the conditions over Europe (not shown). This finding suggests either that the model was unable to simulate properly the effect of SST anomalies, or, a rather minor role of SST anomalies in

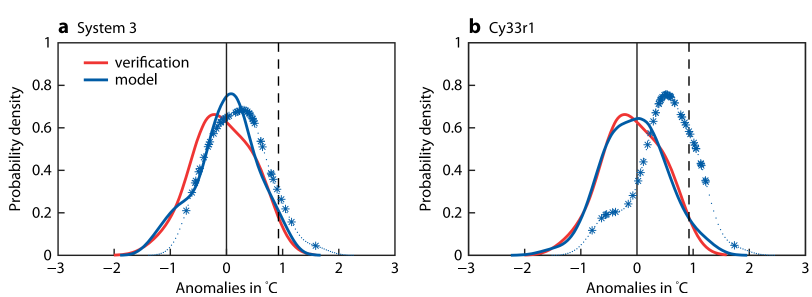

Figure 2. Summer 2003 re-forecast distribution of T2m anomalies initialised on 1st May 2003 for Southern European land areas with (a) S3 and (b) model cycle CY33R1. The red (blue) solid curve presents the climatological pdf of the verification (re-forecast) anomalies over the period 1991–2005. The dotted curve shows the re-forecast pdf for JJA 2003 based on a 50 member ensemble. Each ensemble member is indicated by an asterisk. The verifying T2m anomaly for JJA 2003 of 0.93°C is given by the dashed vertical line.

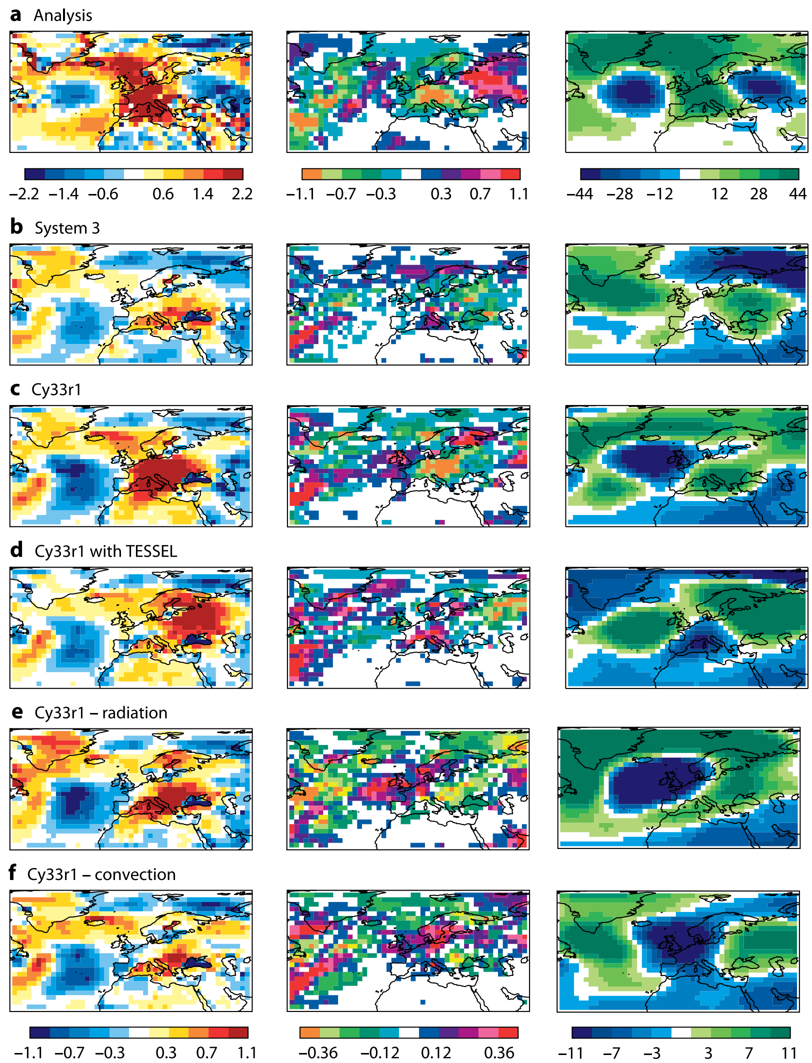

Figure 3. Anomalies of T2m, precipitation and Z500 in (a) the verification and (b–f) seasonal re-forecasts using S3 (Figure 3b), with cycle CY33R1 (Figure 3c), in CY33R1 with the old land surface scheme TESSEL (Figure 3d), in CY33R1 with the old radiation scheme (Figure 3e), and in CY33R1 with the old convection scheme (Figure 3f). Anomalies in the seasonal re-forecasts are based on the ensemble mean and are plotted with a different scale than the verifying anomalies.

accounting for the European heat wave in the ECMWF model [*Ferranti and Viterbo*, 2006; *Jung et al.*, 2006]. Further numerical experiments are in progress to distinguish between these possibilities.

4. Impact of Improved Physical Parameterizations

[8] Since the operational implementation of S3 in 2007, major upgrades in the atmospheric and land surface components led to a more recent version of the model, labelled CY33R1. The upgrades include a revised land surface hydrology component (H-TESSEL, *Balsamo et al.*, 2009) with geographically varying soil texture, infiltration and sub-grid surface runoff that leads to reduced soil moisture (SM) and T2m errors. In addition, CY33R1 has a new radiation transfer package [*Morcrette et al.*, 2008] with an improved description of land surface albedo from MODIS observations and new treatments of short-wave radiation and cloud-radiation interactions. A further major revision in CY33R1 occurred in the deep convection parameterization scheme resulting in an overall beneficial increase in model variability [*Bechtold et al.*, 2008].

[9] We now describe how this updated model performs in JJA 2003 over Europe. Figure 2b shows the pdf for T2m anomalies based on re-forecasts from 1991 to 2005. Even though CY33R1 performs rather similarly to S3 in a climatological sense, the re-forecast for summer 2003 shows a distinct and statistically significant (KS test at $p = 0.05$) shift of the forecast pdf away from the climatological distribution towards positive anomalies. The CY33R1 re-forecasts not only improve the temperature signal over S3, but importantly they now correctly show a large-scale dry precipitation anomaly for a wider European area (Figure 3c). In addition, the mid-tropospheric circulation is similar to the verification with a ridge over Europe and negative anomalies to the west and east.

[10] Because model version CY33R1 includes a range of revised parameterizations compared to S3, without further experimentation it is not clear which of the modifications

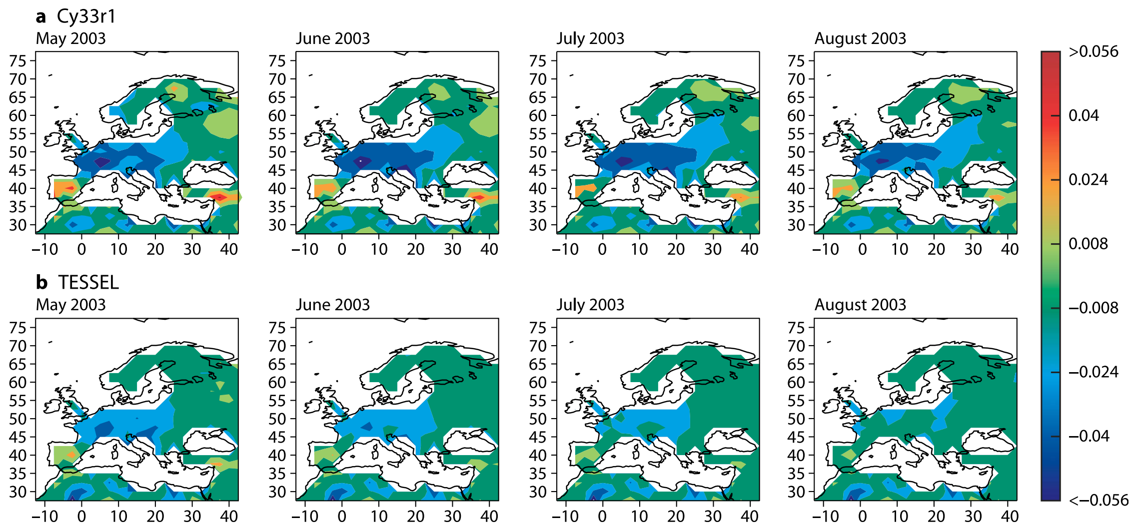

Figure 4. Monthly mean total soil moisture anomalies during May to August 2003 in cycle CY33R1 using the land-surface schemes (a) H-TESSEL and (b) TESSEL.

led to this significant gain in simulation accuracy. To test the sensitivity to these modifications, a set of three systematic seasonal re-forecast experiments over the 15-year period 1991–2005 was carried out. These experiments use CY33R1 as a base version with the following three individual modules switched back to their corresponding S3 versions: land surface, radiation and convection.

[11] While the overall impact of each of these three schemes on the T2m bias over Southern Europe is insignificant (not shown), their influence on the simulation accuracy of the extreme summer 2003 is not. The spatial structure of the T2m, precipitation and Z500 anomalies for the sensitivity experiment using the previous land-surface scheme (TESSEL) indicates that the strongest warming is erroneously shifted towards north-eastern Europe with neutral conditions over central and Southern Europe (Figure 3d). Interestingly, the dry precipitation anomaly which was correctly reproduced with H-TESSEL in CY33R1 became a wet anomaly with TESSEL and the anomalous atmospheric circulation (Z500) has a trough over Europe, the reverse of what was observed.

[12] How can improvements in the land hydrology lead to such substantial changes in the atmosphere? Heat waves like the one in 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. During summer, the large-scale westerly flow regime over Europe becomes weaker and the continental climate is potentially more influenced by processes with a relatively long memory such as SSTs and SM. The spring preceding the summer heat wave in 2003 was characterised by a deficit of precipitation over most of Europe [*Fischer et al.*, 2007; *Vautard et al.*, 2007] resulting in a pronounced depletion of SM during spring and summer. Given a strong coupling between low soil wetness and evapotranspiration (ET) [*Seneviratne et al.*, 2010], the dry SM anomaly resulted in a reduced ET with reduced latent cooling and the emission of more sensible heat. This, via local convective inhibition (see below), contributed to a temperature increase and precipitation decrease.

[13] A number of studies have demonstrated how summer drought conditions and SM-temperature interactions can amplify nonlinearly large-scale temperature anomalies through local and remote effects [*Schär et al.*, 1999; *Viterbo and Beljaars*, 2004]. Figure 4 shows the monthly evolution from May to August 2003 of total SM anomalies in the H-TESSEL and TESSEL experiments. In both cases, ERA-40 SM initialisation was used. However, for all H-TESSEL experiments a re-scaling to the soil moisture index was applied to minimise the inconsistency between the initial conditions and the forecast model, see http://www.ecmwf.int/products/changes/soil_hydrology_cy32r3/. Already in the first month, H-TESSEL simulates a stronger and more widespread dry SM anomaly than TESSEL. The initial negative anomaly was not maintained during the forecast range using TESSEL. By contrast, H-TESSEL shows a remarkable improvement simulating pronounced dry SM anomalies throughout the summer. In agreement with the persistent nature of SM anomalies, the key element of H-TESSEL is its better soil memory due to improved soil characteristics like conductivity and available water capacity [*Balsamo et al.*, 2009].

[14] However, the success of the summer 2003 re-forecast comes not only from more realistic simulations of the local land surface - atmosphere coupling. It was found that improvements in the radiation and convection schemes also contributed positively although the magnitude of their impact is smaller than for the land surface hydrology (Figures 3e–3f). For example, the divergent upper tropospheric flow over the tropical Indian Ocean and Africa in JJA 2003 is sensitive to the convection formulation used. The Sahel region experienced one of the wettest monsoon seasons of recent decades in 2003 with negative outgoing long-wave radiation (OLR) anomalies observed over the Sahel and positive OLR anomalies over Europe. While the OLR in CY33R1, in agreement with observations, indicates increased convective activity over the Sahel and compensating subsidence, and thus a warming over Europe, this signal is weakened with the old convection parameterization scheme (not shown, see also *Hohenegger et al.*, 2009). In addition, the new formulation of convective entrainment in

the modified convection parameterization implies that convective activity is more sensitive to fluctuations in environmental moisture [*Bechtold et al.*, 2008]. In turn this means that local dry conditions over Europe were maintained by stronger convective inhibition, and thus less precipitation, in the simulations with the new convection scheme.

[15] Conventionally it is believed that extratropical seasonal predictability is linked to tropically forced Rossby wave teleconnections and it was suggested that the warm summer 2003 was linked to anomalous tropical Atlantic heating due to a northward shift of the Atlantic intertropical convergence zone [*Cassou et al.*, 2005]. The diagnosis of our coupled simulations as well as further experiments using relaxation techniques [*Jung et al.*, 2010] to determine any tropical impact on the Euro-Atlantic circulation, however, do not support the hypothesis of a remote tropical diabatic forcing, rather suggesting the role of in situ processes in generating seasonal predictability.

5. Summary

[16] We have shown that the overall predictability of hot summers over Southern Europe is relatively high which is partly explained by capturing the recent warming trend in the retrospective forecasts. Yet re-forecasts from ECMWF's operational seasonal forecast system were not able to simulate the record heat summer 2003. We have demonstrated that with enhanced model physics a successful prediction of the summer 2003 extreme conditions would indeed have been possible. Our results indicate that dry soil moisture anomalies persisted through interactions with the local circulation patterns were central to understanding the predictability of this event. In order to predict it well, a climate model needs sophisticated formulations of land surface hydrology, radiation and convection. In our case, the combination of all three proved key to the successful retrospective predictions of this record breaking event.

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References

Anderson, D. L. T., T. Stockdale, M. A. Balmaseda, L. Ferranti, F. Vitart, F. Molteni, F. Doblas-Reyes, K. Mogensen, and A. Vidard (2007), Development of the ECMWF seasonal forecast System 3, *Tech. Memo*, *503*, 56 pp., Eur. Cent. for Medium-Range Weather Forecasts, Reading, U. K.

Balsamo, G., A. Beljaars, K. Scipal, P. Viterbo, B. van den Hurk, M. Hirschi, and A. Betts (2009), A revised hydrology for the ECMWF Model: Verification from field site to terrestrial water storage and impact in the integrated forecast system, *J. Hydrometeorol.*, *10*, 623–643, doi:10.1175/2008JHM1068.1.

Bechtold, P., M. Köhler, T. Jung, F. Doblas-Reyes, M. Leutbecher, M. J. Rodwell, F. Vitart, and G. Balsamo (2008), Advances in simulating atmospheric variability with the ECMWF model: From synoptic to decadal time-scales, *Q. J. R. Meteorol. Soc.*, *134*, 1337–1351, doi:10.1002/qj.289.

Black, E., and R. Sutton (2007), The influence of oceanic conditions on the hot European summer of 2003, *Clim. Dyn.*, *28*, 53–66, doi:10.1007/s00382-006-0179-8.

Black, E., M. Blackburn, G. Harrison, B. Hoskins, and J. Methven (2004), Factors contributing to the summer 2003 European heat wave, *Weather*, *59*, 217–223, doi:10.1256/wea.74.04.

Cassou, C., L. Terray, and A. S. Phillips (2005), Tropical Atlantic influence on European heat waves, *J. Clim.*, *18*, 2805–2811, doi:10.1175/JCLI3506.1.

Doblas-Reyes, F. J., R. Hagedorn, T. N. Palmer, and J.-J. Morcrette (2006), Impact of increasing greenhouse gas concentrations in seasonal ensemble forecasts, *Geophys. Res. Lett.*, *33*, L07708, doi:10.1029/2005GL025061.

Ferranti, L., and P. Viterbo (2006), The European summer of 2003: Sensitivity to soil water initial conditions, *J. Clim.*, *19*, 3659–3680, doi:10.1175/JCLI3810.1.

Feudale, L., and J. Shukla (2007), Role of Mediterranean SST in enhancing the European heat wave of summer 2003, *Geophys. Res. Lett.*, *34*, L03811, doi:10.1029/2006GL027991.

Fink, A. H., T. Brücher, G. C. Leckebusch, J. Pinto, and U. Ulbrich (2004), The 2003 European summer heat waves and drought: Synoptic diagnosis and impacts, *Weather*, *59*, 209–216, doi:10.1256/wea.73.04.

Fischer, E. M., S. I. Seneviratne, P. L. Vidale, D. Lüthi, and C. Schär (2007), Soil moisture: Atmosphere interactions during the 2003 European summer heat wave, *J. Clim.*, *20*, 5081–5099, doi:10.1175/JCLI4288.1.

Grazinni, F., L. Ferranti, F. Lalaurette, and F. Vitard (2003), The exceptional warm anomalies of summer 2003, *ECMWF Newsl.*, *99*, 2–8.

Hohenegger, C., P. Brockhaus, C. S. Bretherton, and C. Schär (2009), The soil moisture-precipitation feedback in simulations with explicit and parameterized convection, *J. Clim.*, *22*, 5003–5020, doi:10.1175/2009JCLI2604.1.

Jung, T., L. Ferranti, and A. M. Tompkins (2006), Response to the summer 2003 Mediterranean SST anomalies over Europe and Africa, *J. Clim.*, *19*, 5439–5454, doi:10.1175/JCLI3916.1.

Jung, T., M. J. Miller, and T. N. Palmer (2010), Diagnosing the origin of extended-range forecast errors, *Mon. Weather Rev.*, *138*, 2434–2446, doi:10.1175/2010MWR3255.1.

Morcrette, J.-J., H. W. Barker, J. N. S. Cole, M. J. Iacono, and R. Pincus (2008), Impact of a new radiation package, McRad, in the ECMWF integrated forecasting system, *Mon. Weather Rev.*, *136*, 4773–4798, doi:10.1175/2008MWR2363.1.

Nakamura, M., T. Enomoto, and S. Yamane (2005), A simulation study of the 2003 heat wave, *J. Earth Simulator*, *2*, 55–69.

Schär, C., D. Lüthi, and U. Beyerle (1999), The soil-precipitation feedback: A process study with a regional climate model, *J. Clim.*, *12*, 722–741, doi:10.1175/1520-0442(1999)012<0722:TSPFAP>2.0.CO;2.

Schär, C., P. L. Vidale, D. Lüthi, C. Frei, C. Häberli, M. A. Liniger, and C. Appenzeller (2004), The role of increasing temperature variability in European summer heat waves, *Nature*, *427*, 332–336, doi:10.1038/nature02300.

Seneviratne, S., T. Corti, E. L. Davin, M. Hirschi, E. B. Jaeger, I. Lehner, B. Orlowsky, and A. J. Teuling (2010), Investigating soil moisture–climate interactions in a changing climate: A review, *Earth Sci. Rev.*, *99*, 125–161, doi:10.1016/j.earscirev.2010.02.004.

Vautard, R., P. Yiou, F. D'Andrea, N. de Noblet, N. Viovy, C. Cassou, J. Polcher, P. Ciais, M. Kagayema, and Y. Fan (2007), Summertime European heat and drought waves induced by wintertime Mediterranean rainfall deficit, *Geophys. Res. Lett.*, *34*, L07711, doi:10.1029/2006GL028001.

Viterbo, P., and A. C. M. Beljaars (2004), Impact of land surface on weather, in *Vegetation, Water, Humans and the Climate: A New Perspective on the Interactive System*, edited by P. Kabat et al., pp. 52–57, Springer, Berlin.

Weisheimer, A., F. J. Doblas-Reyes, T. N. Palmer, A. Alessandri, A. Arribas, M. Deque, N. Keenlyside, M. MacVean, A. Navarra, and P. Rogel (2009), ENSEMBLES: A new multi-model ensemble for seasonal-to-annual predictions—Skill and progress beyond DEMETER in forecasting tropical Pacific SSTs, *Geophys. Res. Lett.*, *36*, L21711, doi:10.1029/2009GL040896.

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