University of Groningen

Future equivalent of 2010 Russian heatwave intensified by weakening soil moisture constraints

Rasmijn, L. M.; van der Schrier, G.; Bintanja, Richard; Barkmeijer, J.; Sterl, A.; Hazeleger, W.

Published in:
Nature climate change

DOI:
[10.1038/s41558-018-0114-0](https://doi.org/10.1038/s41558-018-0114-0)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2018

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Rasmijn, L. M., van der Schrier, G., Bintanja, R., Barkmeijer, J., Sterl, A., & Hazeleger, W. (2018). Future equivalent of 2010 Russian heatwave intensified by weakening soil moisture constraints. *Nature climate change*, 8, 381-385. <https://doi.org/10.1038/s41558-018-0114-0>

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Future equivalent of 2010 Russian heatwave intensified by weakening soil moisture constraints

L. M. Rasmijn¹, G. van der Schrier^{1*}, R. Bintanja^{1,2}, J. Barkmeijer¹, A. Sterl¹ and W. Hazeleger^{3,4}

The 2010 heatwave in eastern Europe and Russia ranks among the hottest events ever recorded in the region^{1,2}. The excessive summer warmth was related to an anomalously widespread and intense quasi-stationary anticyclonic circulation anomaly over western Russia, reinforced by depletion of spring soil moisture^{1,3–5}. At present, high soil moisture levels and strong surface evaporation generally tend to cap maximum summer temperatures^{6–8}, but these constraints may weaken under future warming^{9,10}. Here, we use a data assimilation technique in which future climate model simulations are nudged to realistically represent the persistence and strength of the 2010 blocked atmospheric flow. In the future, synoptically driven extreme warming under favourable large-scale atmospheric conditions will no longer be suppressed by abundant soil moisture, leading to a disproportional intensification of future heatwaves. This implies that future mid-latitude heatwaves analogous to the 2010 event will become even more extreme than previously thought, with temperature extremes increasing by 8.4 °C over western Russia. Thus, the socioeconomic impacts of future heatwaves will probably be amplified beyond current estimates.

Consistent with the scenario that heatwaves are predicted to become more intense, longer lasting and more frequent with increasing global mean temperatures^{1,11–13}, recent Northern Hemisphere mid-latitude summers have seen a remarkable number of record-breaking heatwaves^{1,13}. The sweltering 2010 Eurasian ‘mega’-heatwave (EHW) shattered all-time maximum temperature records in numerous locations, leaving a record-scale area of more than 2 million km² affected¹. The EHW resulted from a hemisphere-wide quasi-stationary Rossby wave train^{5,14} that culminated in a persistent blocking anticyclone centred over western Russia (Fig. 1a) where reduced cloudiness and advection of warm air, in combination with spring soil moisture deficits, amplified the hot extremes^{1,2}. With 55,000 lives lost, and more than US\$15 billion in economic losses¹, the EHW illustrated the vulnerability of society to persistent extreme weather. It is therefore vitally important¹⁵ to investigate the impact of global climate warming on the temperature extremes caused by the anomalous atmospheric circulation that led to the EHW.

At present, generating accurate information on future exceptional heatwaves is challenging, since weather and climate models generally have difficulty in representing atmospheric blocking^{16–18}. As a result, many studies addressing climatic extremes do not take the synoptic conditions leading to these extremes into account^{10,18}, which prevents one making realistic projections of extreme events in a warming world. Here we overcome this problem by consistently transposing the large-scale circulation associated with the EHW to

a future warmer climate, rendering it possible to realistically assess the impact of climate change on this extreme event.

Instead of searching for an analogue of the EHW in long climate simulations, we apply the forced sensitivity method¹⁹ to assimilate the upper-troposphere large-scale circulation associated with the EHW in the atmospheric component of a coupled global climate model, EC-Earth²⁰. Unlike traditional nudging²¹, the forced sensitivity method suppresses neither synoptic-scale variability nor planetary wave variability, but computes model tendency perturbations that optimally force the modelled summer (June–August, JJA) atmospheric circulation in the direction of the one observed during the EHW in a dynamically consistent manner. The area capturing the jet stream over the EuroAtlantic sector is used in the calculation of the tendency perturbations. Tendency perturbations are calculated only for vorticity and divergence; other prognostic variables, such as temperature, or diagnostic variables are not used. This results in a climate simulation with a realistic summer atmospheric circulation that resembles the circulation associated with the EHW (Fig. 1). The tendency perturbations are calculated and applied in simulations under present-day as well as future (2100, Representative Concentration Pathway 8.5) climatic conditions (see Methods).

Consistent with the observation, as represented by the ERA-Interim reanalysis²² (OBS), a hemisphere-wide wave train of vorticity anomalies during the summer months is simulated in the perturbed (with additional forced sensitivity forcing) runs, with a good agreement (pattern correlation of ~0.7) of the locations of the positive and negative vorticity anomalies (see Supplementary Fig. 1). The blocking index²³ based on model results (Fig. 1b) shows a similar pattern to the observations (Fig. 1a), with a blocking centred over western Russia and increased variability across southern Asia.

As occurred in the EHW, summer temperatures over eastern Europe and western Russia increase dramatically as a result of the persistent blocking. The midday 2 m temperature (T_{2m}) for the hottest days (with T_{2m} larger than the 31.5 °C threshold (Fig. 2b)), averaged over the 30 simulated summers in the present-day climate (Fig. 1e), has an amplitude within 1 °C of the OBS over the most intense period of the EHW (Fig. 1d), although the centre of the pattern is moved slightly (2.8°) to the northeast. The area enclosed by the +10 °C isotherm is within 10% of the observed value. This demonstrates that a realistic simulation of the large-scale upper-air circulation across a large area spanning Europe and Russia during the summer of 2010 is sufficient to trigger a heatwave with characteristics very close to those observed. The area (35°E–52.5°E, 50°N–60°N)-averaged summer daily temperatures in OBS (Fig. 2a) and EC-Earth present-day control simulations (Fig. 2b, blue histogram) are quite similar, with a slight cold bias²⁰ in the latter.

¹Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands. ²Energy and Sustainability Research Institute Groningen (ESRIG), University of Groningen, Groningen, The Netherlands. ³Wageningen University, Wageningen, The Netherlands. ⁴Netherlands eScience Center, Amsterdam, The Netherlands. *e-mail: schrier@knmi.nl

Fig. 1 | Anomalous five-day running-mean Tibaldi-Molteni blocking index and T_{2m} . **a**, OBS blocking index (BI) during summer (JJA) 2010. **b,c**, Blocking index averaged over all 30 perturbed summer seasons under present-day (**b**) and future (**c**) climate conditions. **d**, OBS T_{2m} (coloured shading) at 12:00 UTC and 500 hPa geopotential height (Z_{500} , blue contour lines) averaged over the heatwave period (see Methods). **e,f**, T_{2m} averaged over all simulated heatwave days under present-day (**e**) and future (**f**) climate conditions. The dots in **b,c,e,f** indicate regions where the difference between the compared quantities is insignificant ($P > 0.05$).

Fig. 2 | Histogram for daily summer T_{2m} averaged over western Eurasia. **a**, Daily OBS (1979–2014) T_{2m} . The box-and-whiskers plots indicate daily temperatures during the heatwave period. The black vertical line at 34.0 °C indicates the OBS threshold (see Methods). **b**, 30-year daily T_{2m} in the present control (blue), and perturbed (red) simulation. **c**, The same as in **b**, but for the future simulations. The black vertical lines indicate the threshold temperature at 31.5 °C (**b**) and 35.7 °C (**c**). Quantitative information on the distributions is available in the Supplementary Information.

Not only does the perturbed distribution shift to warmer (significant at the 5% level) temperatures (Fig. 2b, red histogram) under persistently blocked circulation conditions, there is also a widening (and positive skew) of the distribution, implying that the warm extremes warm more than the cold extremes; the 95th percentile warms with 6.4 °C compared to the 95th percentile of the control, whereas the 5th percentile warms only 2.0 °C. The latter demonstrates that the models' internal variability is not suppressed by the forced sensitivity forcing, as boundary conditions unfavourable for generating high temperatures are capable of inhibiting the formation of a heatwave.

In the future control simulations, the climate change signal is evident in the significant ($P < 0.01$) local mean T_{2m} increase of 3.6 ± 5.5 °C (Fig. 2b,c, blue distributions), and in the positive skew, implying that over western Eurasia, extreme summer temperatures will exhibit much stronger increases than the mean²⁴. The simulation of the future equivalent of the EHW yields a blocking centred over western Russia (Fig. 1c), spatially similar to the EHW, but stronger (Fig. 1c) and with far more excessive temperature anomalies (Fig. 1f) compared to the present-day simulations (Fig. 1b,e, respectively). In terms of daily area-averaged summer temperatures (Fig. 2c, red histogram), an even stronger shift (significant at the 5% level) towards higher temperatures is obtained compared to the present-day simulations (Fig. 2b). Averaged over the EHW

region, the shift of the mean of the distribution under future climate conditions ($+6.1 \pm 7.0^\circ\text{C}$) is 40% larger ($P < 0.01$) than that under present-day conditions ($+4.3 \pm 6.6^\circ\text{C}$). Moreover, with 54% more days in the warm tail (Fig. 2b,c, black vertical lines) of the future perturbed distribution compared to its present-day equivalent, the future 95th percentile warms by as much as 8.4°C compared to the 95th percentile of the future control. This indicates that warm extremes become more abundant and increase disproportionately under a favourable atmospheric circulation pattern.

Abundant soil moisture generally caps the daily temperature maximum during a heatwave by balancing the incoming radiation with the latent heat flux rather than the sensible heat flux²⁵. Under favourable upper-air circulation, a lack of spring soil moisture may lead to large surface air temperature anomalies, as was the case during the summer of 2010 (Fig. 3a,b, red lines). In the present-day simulations (Fig. 3c, red line), the mean surface air temperature gradually rises at the start of summer as the upper-air circulation is modified towards the persistently blocked configuration. Coinciding with the increasing summer temperatures is a negative mean soil moisture trend throughout the summer (Fig. 3d, red line). Soil moisture is computed over the top 1.0 m of the soil, as

most evaporation takes place here, and this includes the root zone. Soil moisture levels at the end of spring are negatively correlated with the maximum five-day temperature reached during the following summer for both the perturbed ($r_p = -0.44$) and the control ($r_p = -0.45$) simulations (Fig. 4a) of the present-day climate. High soil moisture levels at the end of spring suppress maximum summer temperatures, even when the blocked circulation as observed during the EHW persists.

Under future persistent summer blocking (Fig. 3e,f, red lines), however, temperature anomalies increase throughout the summer, whereas soil moisture levels (mean and 95th percentile) quickly decline after the start of summer and level-off in August. This dramatic and rapid drop in soil moisture shows that the soil will be largely depleted of moisture long before the end of summer. This feature effectively decouples spring soil moisture levels from the maximum summer temperature anomalies in the future climate, which, as a result, can reach 30% higher values under persistently blocked summer circulation (Fig. 3e, red lines). In the simulation of the EHW under future climate conditions, the correlation between spring soil moisture and maximum five-day summer temperatures is effective.

Fig. 3 | Evolution of anomalous ten-day running-mean T_{2m} and soil moisture. **a,b**, 30-year OBS T_{2m} (**a**) and soil moisture climatology (**b**) (blue line) with the year 2010 highlighted in red. **c–f**, 30-year simulations under present-day (**c,d**) and future (**e,f**) climatic conditions. The thick blue (red) lines give the median of the control (perturbed) simulation. The shading encloses the data between the 5th and 95th percentiles of OBS climatology (**a,b**), control (blue) and perturbed (red) simulations (**c–f**). P values (Wilcoxon rank-sum test) comparing the control and perturbed distributions are indicated below the figures, with the light shading indicating differences significant at the 5% level.

Fig. 4 | Dependence of maximum T_{2m} on soil moisture and large-scale circulation. **a, b**, Five-day running-mean late-spring soil moisture (average between 1 and 25 May) versus the maximum five-day running-mean T_{2m} in the control (blue) and the perturbed (red) simulations under present-day (**a**) and future (**b**) climatic conditions. **c, d**, Pattern correlation between summer 2010 Z_{500} and simulated five-day running mean Z_{500} (at the time of maximum T_{2m}) versus the maximum five-day running-mean T_{2m} under present-day (**c**) and future (**d**) climatic conditions. Pearson correlation coefficients (r_p) and P values of a linear regression are indicated in the figure. The shading indicates the 95% confidence interval.

tively zero (Fig. 4b), implying that even an above-average wet spring will no longer be able to constrain summer temperatures under a favourable circulation similar to the one observed during the EHW. As a result, the highest maximum temperatures are reached for atmospheric circulation patterns that are close to the observed blocking pattern of summer 2010, regardless of the level of spring soil moisture (Fig. 4d). Whereas spring soil moisture still plays an important role in capping temperatures (Fig. 4b, blue data) under normal flow conditions, our results demonstrate that this constraint will disappear in the future under favourable blocked circulation (Fig. 4b, red data), leaving only the persistence and pattern of atmospheric circulation as driving factors for extremely high temperature extremes (as reflected by the strong correlation of 0.65 between T_{2m} extremes and circulation, Fig. 4d, red data).

The robustness of this phenomenon for the climate model is tested by comparing the standard set-up of EC-Earth with other Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations of present-day climate (see Supplementary Information). Heatwaves in summer over western Russia, quantified by the heatwave duration index²⁶, are selected and the depletion of soil moisture during each heatwave is monitored. This shows that the EC-Earth is well within the spread of CMIP5 models and that the soils in the EC-Earth model in this area are not depleted faster than other CMIP5 models (Supplementary Fig. 1).

The driver of the increase in the ‘thirst of the atmosphere’ is the higher temperatures in the future climate (see Supplementary Information).

The model results demonstrate that the inverse relationship^{3,6,8,27} between spring soil moisture and maximum summer temperature will no longer hold for the future equivalent of the EHW. The weakening spring soil moisture–temperature coupling under future mid-latitude atmospheric blocking circulations implies that spring/

summer climate conditions that under present-day conditions would not result in extremely high surface air temperatures, will do so in the future, as heat advection and net surface radiation will govern summer temperature extremes. In other words, while under present-day conditions not all EHW-type-blocking circulations will lead to devastating ‘mega’-heatwaves such as the EHW, under future climate conditions it is likely that they all will. As a result, future mid-latitude atmospheric blocking circulations such as the EHW will lead to amplified warming—much larger than the mean climate change effect—because of the disappearance of the evaporative cooling constraint. This is vital information for many sectors in society including health, since the rising frequency, intensity and duration of temperature extremes have been projected to adversely affect human mortality and morbidity¹².

Methods

Methods, including statements of data availability and any associated accession codes and references, are available at <https://doi.org/10.1038/s41558-018-0114-0>.

Received: 2 February 2017; Accepted: 16 February 2018;
Published online: 19 March 2018

References

- Barriopedro, D., Fischer, E. M., Luterbacher, J., Trigo, R. M. & García-Herrera, R. The hot summer of 2010: redrawing the temperature record map of Europe. *Science* **332**, 220–224 (2011).
- Dole, R. et al. Was there a basis for anticipating the 2010 Russian heat wave? *Geophys. Res. Lett.* **38**, L06702 (2011).
- Hauser, M., Orth, R. & Seneviratne, S. I. Role of soil moisture versus recent climate change for the 2010 heat wave in western Russia. *Geophys. Res. Lett.* **43**, 2819–2826 (2016).
- Miralles, D. G., Teuling, A. J., van Heerwaarden, C. C. & Vilà-Guerau de Arellano, J. Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation. *Nat. Geosci.* **7**, 345–349 (2014).

5. Lau, W. K. M. & Kim, K.-M. The 2010 Pakistan flood and Russian heat wave: teleconnection of hydrometeorological extremes. *J. Hydrometeorol.* **13**, 392–403 (2012).
6. Fischer, E. M., Seneviratne, S. I., Lüthi, D. & Schär, C. Contribution of land–atmosphere coupling to recent European summer heat waves. *Geophys. Res. Lett.* **34**, 6707 (2007).
7. Vautard, R. et al. Summertime European heat and drought waves induced by wintertime Mediterranean rainfall deficit. *Geophys. Res. Lett.* **34**, L07711 (2007).
8. Seneviratne, S. I. et al. Investigating soil moisture–climate interactions in a changing climate: a review. *Earth Sci. Rev.* **99**, 125–161 (2010).
9. Lenderink, G., van Ulden, A., van den Hurk, B. & van Meijgaard, E. Summertime inter-annual temperature variability in an ensemble of regional model simulations: analysis of the surface energy budget. *Climatic Change* **81**, 233–247 (2007).
10. Fischer, E. M., Rajczak, J. & Schär, C. Changes in European summer temperature variability revisited. *Geophys. Res. Lett.* **39**, L19702 (2012).
11. Schär, C. et al. The role of increasing temperature variability in European summer heatwaves. *Nature* **427**, 332–336 (2004).
12. Meehl, G. A. & Tebaldi, C. More intense, more frequent, and longer lasting heat waves in the 21st century. *Science* **305**, 994–997 (2004).
13. Beniston, M. The 2003 heat wave in Europe: A shape of things to come? An analysis based on Swiss climatological data and model simulations. *Geophys. Res. Lett.* **31**, L02202 (2004).
14. Trenberth, K. E. & Fasullo, J. T. Climate extremes and climate change: the Russian heat wave and other climate extremes of 2010. *J. Geophys. Res.* **117**, 17103 (2012).
15. Marotzke, J. et al. Climate research must sharpen its view. *Nat. Clim. Change* **7**, 89–91 (2017).
16. Brunet, G. et al. Collaboration of the weather and climate communities to advance subseasonal-to-seasonal prediction. *Bull. Am. Meteorol. Soc.* **91**, 1397–1406 (2010).
17. Scaife, A. A., Woollings, T., Knight, J., Martin, G. & Hintn, T. Atmospheric blocking and mean biases in climate models. *J. Clim.* **23**, 6143–6152 (2010).
18. Russo, S. et al. Magnitude of extreme heat waves in present climate and their projection in a warming world. *J. Geophys. Res.* **119**, 12 (2014).
19. Barkmeijer, J., Iversen, T. & Palmer, T. N. Forcing singular vectors and other sensitive model structures. *Q. J. R. Meteorol. Soc.* **129**, 2401–2423 (2003).
20. Hazeleger, W. et al. EC-Earth V2.2: description and validation of a new seamless Earth system prediction model. *Clim. Dynam.* **39**, 2611–2629 (2012).
21. Davies, H. C. & Turner, R. E. Updating prediction models by dynamical relaxation: an examination of the technique. *Q. J. R. Meteorol. Soc.* **103**, 225–245 (1977).
22. Dee, D. P. et al. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Q. J. R. Meteorol. Soc.* **137**, 553–597 (2011).
23. Tibaldi, S. & Molteni, F. On the operational predictability of blocking. *Tellus Ser. A* **42**, 343 (1990).
24. Volodin, E. M. & Yurova, A. Y. Summer temperature standard deviation, skewness and strong positive temperature anomalies in the present day climate and under global warming conditions. *Clim. Dynam.* **40**, 1387–1398 (2013).
25. Della-Marta, P. M. et al. Summer heat waves over western Europe 1880–2003, their relationship to large-scale forcings and predictability. *Clim. Dynam.* **29**, 251–275 (2007).
26. Klein Tank, A. M. G., Zwiers, F. & Zhang, X. *Guidelines on Analysis of Extremes in a Changing Climate in Support of Informed Decisions for Adaptation* Report No. 72 (Climate Data and Monitoring Programme, WMO, 2009).
27. Mueller, B. & Seneviratne, S. I. Hot days induced by precipitation deficits at the global scale. *Proc. Natl Acad. Sci. USA* **109**, 12398–12403 (2012).

Acknowledgements

The authors would like to thank F. Selten and other colleagues at KNMI for their help and advice. H. de Vries is thanked for providing a code to compute the Tibaldi–Molteni blocking index.

Author contributions

The experiments were devised by L.M.R., G.v.d.S., J.B., A.S. and W.H. in collaboration while L.M.R. overcame the technical problems with the data assimilation, performed the simulations and prepared the figures. G.v.d.S., R.B., J.B., A.S. and W.H. contributed to the development of the analyses and figures and the discussion of results. L.M.R. wrote the paper with contributions and feedback from G.v.d.S., R.B., J.B., A.S. and W.H.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at <https://doi.org/10.1038/s41558-018-0114-0>.

Reprints and permissions information is available at www.nature.com/reprints.

Correspondence and requests for materials should be addressed to G.S.

Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Methods

Forced sensitivity method. The forced sensitivity method^{19,28} aims to optimally lead the model atmospheric circulation towards a pre-defined situation: the target pattern. In this study, we used the anomalous vorticity and divergence from the upper troposphere, averaged over the period between 20 July 2010 and 31 July 2010 (which is at the height of the EHW) as the target pattern. Modification of the model circulation is achieved by adding small perturbations to the tendencies of vorticity and divergence in the model. The tendency perturbations are constructed iteratively by minimizing a cost function that measures the offset between a forecast and the target pattern, such that they produce, after the forecast time T (about five days), a deflection of the model atmospheric state in the direction of the target pattern, leaving the synoptic-scale variability to evolve freely.

A climate simulation consists of a long series of these perturbed forecasts, each of which has its own set of time-independent tendency perturbations computed. The end of each perturbed forecast of length T projects closely onto the target pattern, drawing the mean climate state towards the pre-specified circulation. A detailed description of the forced sensitivity method and a description of its application in a climatic context is found elsewhere^{19,29,30}.

Experimental set-up. The cost function, which produces optimal tendency perturbations, is evaluated between 30°N–80°N and 50°W–150°E between model levels 20 (~200 hPa) and 35 (~500 hPa), capturing the jet stream over the EuroAtlantic sector. The model atmospheric state outside this mask does not enter the cost function and only vorticity and divergence are used; other prognostic variables, such as temperature, or diagnostic variables are not used in the assimilation. The tendency perturbations are applied only in the summer (JJA) season; the model is allowed to develop freely in the other seasons.

The experiments, both the perturbed (with tendency perturbations) and control (without additional forcing), are run for present-day climatic conditions, representative of 1970, and future climatic conditions under the Representative Concentration Pathway 8.5 scenario of around 2075 and for 30 years.

Internal variability is not suppressed, which gives a large spread in the simulated area-averaged temperature distribution. This motivates us to define heatwave days as all summer days in the 30-year daily distribution with T_{2m} equal to or larger than a threshold temperature. This threshold relates to the average T_{2m} at the height of the heatwave. It is the black vertical line in Fig. 2a. The model equivalent of this threshold, accounting for model biases, relates to the T_{2m} for which the same number of days is enclosed in the warm tail of the simulated T_{2m} distribution (taking any difference in sample size into account). Area averaging

in Figs. 2–4 is performed over the area spanned by 35°E–52.5°E, 50°N–60°N, as indicated by the black box in Fig. 1d.

A possible change in rooting depth of plants and trees under climate change, as well as a shift of vegetation zones, may lead to a situation in which plants are able to reach a larger soil moisture reservoir than what is currently the case. This may limit soaring temperatures.

Validation. Supplementary Fig. 1a shows the target pattern of relative vorticity and the resulting summer (JJA) relative vorticity anomaly (Supplementary Fig. 1b), averaged over 30 summers of the present-day simulation and relative to the control present-day control run averaged over the same period, vertically averaged between model level 20 (~200 hPa) and 35 (~512 hPa). In both panels, a wave-train-like pattern of relative vorticity perturbations is observed.

The more noisy character and high amplitude of the target pattern is due to the averaging over less than one month, while the response in the right panel is much smoother, being an average over JJA of a 30-year simulation.

The similarities are further quantified in Supplementary Fig. 1c showing the pattern correlation, computed over the entire Northern Hemisphere north of 30°N, plotted as a function of model level. The pattern correlation is ~0.7 across the target area between 200 and 512 hPa, where the cost function is minimized, and reaches its maximum value at ~0.75 around model level 10 (~100 hPa), just above the levels where the cost function is minimized.

Due to the noisier and highly nonlinear processes that are more dominant in the lower troposphere compared to the upper troposphere, a forcing in the latter is more easily recognizable than in the former.

Data availability. The data sets generated for this experiment and analysed during the current study are available from the corresponding author on reasonable request.

References

28. Palmer, T. N. Extended-range atmospheric prediction and the Lorenz model. *Bull. Am. Meteorol. Soc.* **74**, 49–66 (1993).
29. Rasmijn, L. M., van der Schrier, G., Barkmeijer, J., Sterl, A. & Hazeleger, W. On the use of the forced sensitivity method in climate studies. *Q. J. R. Meteorol. Soc.* **141**, 845–853 (2015).
30. Rasmijn, L. M., van der Schrier, G., Barkmeijer, J., Sterl, A. & Hazeleger, W. Simulating the extreme 2013/2014 winter in a future climate. *J. Geophys. Res.* **121**, 5680–5698 (2016).