communications earth & environment

Article

https://doi.org/10.1038/s43247-024-01847-0

How climate change intensified storm Boris' extreme rainfall, revealed by near-real-time storylines

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Disentangling the impact of climate change on environmental extremes is of key importance for mitigation and adaptation. Here we present an automated system that unveils the climate change signal of the day in near-real-time, employing a set of innovative storyline simulations based on a coupled climate model. Its potential to complement probabilistic assessments is showcased for storm Boris, which brought record-breaking rainfall over Central and Eastern Europe in September 2024, leading to devastating floods. Our near-real-time storylines suggest that storm Boris deposited about 9% more rain due to human-induced warming. The area impacted by the same storm's extreme rainfall (>100 mm) was 18% larger and would continue expanding in a future warmer climate. Results from our prototype storyline system are disseminated publicly via an online tool. The case of Storm Boris demonstrates the potential of near-real-time storylines for rapid evidence-based climate change communication.

At present, there is hardly any weather-related extreme event with societal impact that does not spawn public and scientific discussion about the role played by climate change. In recent years, heatwaves, droughts, and extreme rainfall events have impacted human health[1], disrupted ecosystems[2,3], caused large losses to agro-economic sectors[4,5], and induced considerable societal costs[6]. In mid-September 2024, unprecedented rainfall over Central and Eastern Europe brought by storm Boris, led to multiple casualties and infrastructure damages[7]. For such an extreme flood event as for the everyday weather, two questions arise: How much of the observed conditions is attributable to climate change? And how are they projected to unfold in an even warmer future climate?

To address the attribution and projection questions posed above, the scientific community predominantly employs probabilistic methods which rely on observational data and the use of large ensembles of climate model simulations to estimate changes in the likelihood or intensity of extremes[8]. This approach is the cornerstone of successful attribution efforts by the World Weather Attribution (WWA) group[9] which routinely quantifies the influence of climate change on high-profile extreme weather events, often within just 1 or 2 weeks. The method has recently been adopted routinely by national weather services (e.g., the German Meteorological Service). Rapid attribution is now also being carried out by ClimaMeter[10] based on circulation analogs found in the observed record.

However, finding good analogs of record-shattering events in previous observations, which usually span just the last few decades, is challenging because of these events' exceptional characteristics—as acknowledged by the ClimaMeter assessment of storm Boris[11]. This can also be an issue when using large ensembles of climate model simulations, particularly for record-breaking or unseen extremes such as the floods triggered by storm Boris'. Furthermore, answers from different models can differ substantially. Finally, the concept of probability can be challenging to convey to non-scientists.

Event-based storylines have been used increasingly to complement the probabilistic approach[12–18]. The approach followed here employs a technique called nudging[19–21] and offers relatable "what if" scenarios: First, real contemporary extreme events are reproduced in a global climate model by imposing the observed evolution of the large-scale winds in the free troposphere (i.e., the jet stream). Second, the same winds are imposed using different background climates, thereby simulating how the same events would unfold if they occurred in a colder preindustrial climate (attribution), or in a possible future warmer world (projection). By setting aside uncertain changes associated with the circulation[22–24], the approach provides climate change information with a high signal-to-noise ratio and thereby unveils how thermodynamic aspects of global warming affect the daily weather, be it extreme or not.

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So far, event-based storyline studies focused on past individual weather extremes, often a few months if not years behind real-time[22]. Here we present the prototype of an automated system that continuously provides storyline attribution and projection of the weather for any place on Earth, and only 3 days behind real-time—when events like storm Boris that just caused devastating floods in Europe are still salient.

Results

Storyline attribution and projection of storm Boris' rainfall

Our storyline simulations are based on the Alfred Wegener Institute Climate Model[25–27] (AWI-CM-1-1-MR). This model has contributed to the Coupled Model Intercomparison Project[28] and thereby to the latest IPCC Assessment Report[8]—and was shown to be one of the most realistic models[29,30]. The storyline simulations are generated by constraining (i.e., nudging) the observed large-scale free-troposphere atmospheric circulation (that is, horizontal scales larger than ~1000 km) in the climate model, in colder preindustrial, present-day, and future +4 °C warmer climates. The nudged simulations comprise 5 ensemble members for each climate storyline, shown here as ensemble mean ("Methods"). This approach has been successfully used to analyze past heatwaves on land[20] and in the ocean[21]. We now brought the storyline approach to near-real-time. As detailed in the "Methods", the storyline simulations are automatically extended every day and disseminated via an online tool. The tool is freely accessible at https://climate-storylines.awi.de and allows both scientific and non-scientific users to explore the climate change signal of the day.

The simulated version of storm Boris in present-day conditions accurately replicates the spatial extent and exceptional nature of the event. The simulated peak value near 200 mm of rain, accumulated over 12–16 September 2024, much better resembles the observed 225 mm (Fig. 1a,b) compared to that obtained from past circulation analogs[11]. A simulated area of about 150,000 km^2 experienced accumulated precipitation exceeding 100 mm.

Comparing our storyline simulations of the event in present-day and preindustrial climates reveals the thermodynamic contribution of climate change to this extreme rainfall (Fig. 1c). While rainfall is marginally reduced in the western part of the event, up to 50 mm more rain can be attributed to climate change towards the east. The area experiencing more than 100 mm of accumulated rainfall is 18% larger than in a world without climate change, with the peak intensity increasing by 8% (changes significant at the 95% confidence level, see "Methods"). Integrated over the broad event region defined in the "Methods", 9% more rain is deposited, consistent with the 7% combined estimate of the WWA assessment[31] (99% confidence level). Anthropogenic climate change has therefore substantially contributed to the intensification of this extreme precipitation event. Preliminary analysis of the factors driving this intensification reveals a large increase of about 15% in vertically integrated water vapor (Supplementary Fig. S1), which is ~10% per degree Celsius of local surface warming and thus exceeds the 7% per °C rate expected from Clausius-Clapeyron scaling[32]. This rise in available water vapor may be explained by the amplified warming by about 2 °C in the Eastern Mediterranean and Black Sea, which are important moisture source regions for Boris[31] (Supplementary Fig. S2). Finally, increases in vertical air ascent may have also contributed to the intensification of the event, indicating a positive dynamical feedback (Supplementary Fig. S3).

Projected future changes in the event's rainfall in a globally 4 °C warmer climate (2.7 °C warmer than today) are less clear-cut (Fig. 1d). We find that a future analog of the event would be partially shifted slightly to the northeast. A 14% larger area would receive over 100 mm of rain (99% confidence level), affecting regions at the event's core and eastern periphery. Future climate change may thus continue exacerbating such an extreme rainfall event, although possibly at a more moderate rate (+2% over the broader event, statistically not significant). Large increases in water vapor (Supplementary Fig. S1), amplified sea surface warming in moisture source regions (Supplementary Fig. S2), and conversion of snow to rain likely contribute to future increased rainfall and flood risks. However, projected

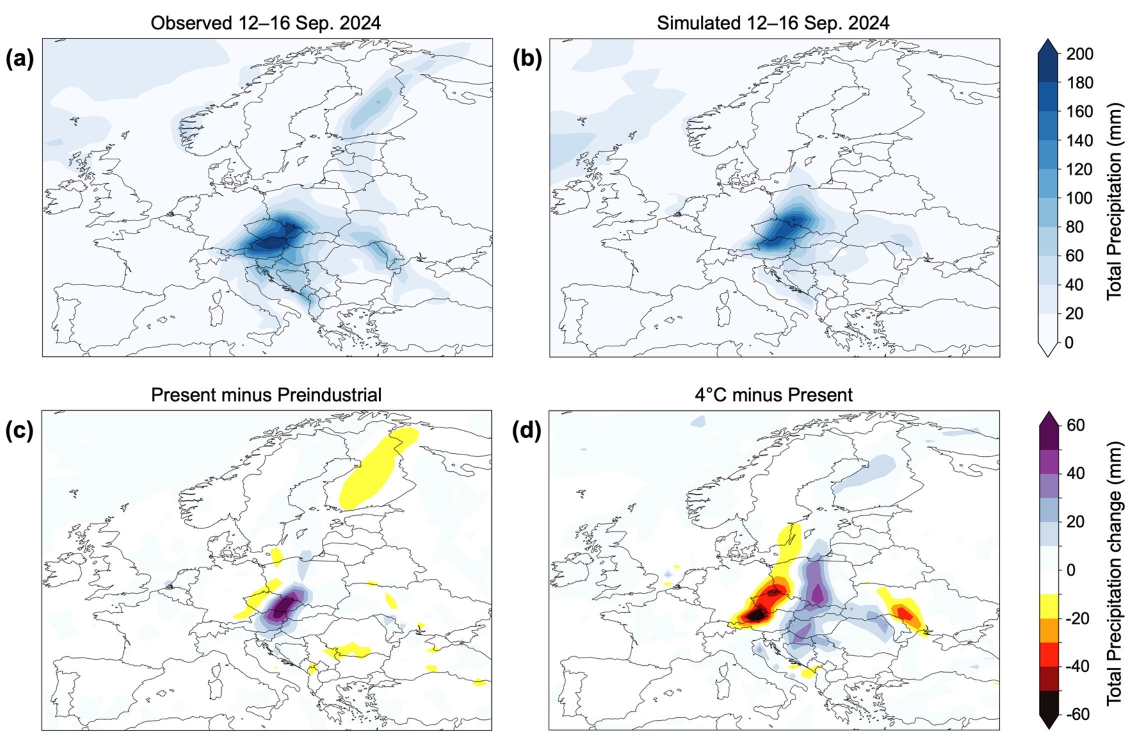

Fig. 1 | Storylines of the extreme rainfall of the September 2024 storm Boris. Total precipitation accumulated over 12–16 September 2024 (in mm), as (**a**) observed (using ERA5 reanalysis data[45] as a surrogate for observations) and (**b**) simulated in present-day conditions. **c** Simulated changes in total accumulated precipitation between the present-day event and the same extreme in a preindustrial world. This change addresses the attribution question: how much has climate change contributed to the event? **d** Simulated changes between the same extreme if it unfolded in a future 4 °C warmer world and the present-day event. This change addresses the projection question: how may future climate change impact the event? Panels are generated with the webtool https://climate-storylines.awi.de.

changes in vertical air ascent (Supplementary Fig. S3) exhibit a significant dipole pattern similar to the precipitation changes.

The shift in rainfall and air ascent likely results from a complex interplay between dynamics and thermodynamics[33], given that dynamic adjustments remain partially possible in our simulations in which only large-scale horizontal winds above 700 hPa are constrained ("Methods"). While such an interplay is challenging to disentangle and can depend on regional specificities[33] as well as the details of our nudging configuration, our results suggest that thermodynamical changes could modify the dynamical characteristics of such low-pressure systems (Supplementary Fig. S4). Increased convective available potential energy over the Eastern Mediterranean and Black Sea, important moisture source regions of this event, may also cause more upstream rainfall deposition along the advection path toward Central Europe (Supplementary Fig. S5).

Accessible and relatable climate change information

Our near-real-time storylines are disseminated through a prototype webtool (https://climate-storylines.awi.de) hosted on servers of the Alfred Wegener Institute and fed with data generated and stored at the German Climate Computing Center (DKRZ). The webtool allows the visualization of our climate storylines from 1 January 2024 and is updated every day 3 days behind real time, following the workflow detailed in Supplementary Fig. S6. Details on the data are in the "Methods". The webtool features a simple interface in which users can choose the parameter, the background climate (preindustrial, present-day, or +4 °C world), the region of interest, and the type of map or time series to visualize. The first subset of parameters available for visualization includes daily mean, minimum, and maximum 2-m air temperature, sea surface temperature, and total precipitation. Other aspects of the visualization can be adjusted by users to fit their targeted applications and analyses.

Storylines in near-real-time come with great potential for climate change communication. For example, in July 2023 the German broad-readership magazine Zeit Online featured our storyline view on the hottest day of the year in Germany, including an interactive location search to foster personal relatability, just 4 days after the event[34].

Discussion

Revealing the climate change signal of the day with global storyline simulations in near-real-time can add scientific evidence to the public debate unfolding during and right after extreme events—not only for storm Boris, but for any climate-related event happening anywhere at any time on the planet. Our prototype relies on a single coupled climate model, implying that some of our results may be model-specific. Given the growing number of groups applying wind nudging and producing climate storylines[14,20,21,35–37] we envisage an expansion to a multi-model approach also in near-real-time. Even if carried to a multi-model footing, storyline simulations do not address potential changes in the frequency of occurrence of circulation patterns. Therefore, the approach cannot replace existing probabilistic methods but rather complements those. Even if some (currently largely unknown) dynamical changes are possible, there is no evidence that existing weather patterns will completely vanish or entirely new ones will emerge[38].

Our current storylines are also limited by the coarse (~100 km) atmospheric resolution of the climate model. Km-scale storyline simulations already exist regionally without near-real-time capabilities[39], and are in development at the global scale within the Climate Adaptation Digital Twin of the Destination Earth (DestinE) Initiative[40]. They can offer local granularity, important to capture orographic effects and finer structures of precipitation patterns in particular. Km-scale simulations might also shed light on the complex interactions between thermodynamical effects and dynamic adjustments affecting precipitation extremes. Such an interplay is expected to be highly event-specific[33], implying that rainfall changes and mechanisms identified here for storm Boris may not necessarily be generalizable.

Ongoing work to include impact modeling for agricultural[41], hydrological[42] or urban storylines promises to provide further adaptation-relevant information needed to enhance societal resilience, ultimately also in near-real-time. Finally, providing simple access to storyline simulation data, such as planned in the form of data lakes and their operationalization within DestinE, will enable a broad range of applications, including those expected from the recent boost of artificial intelligence in weather and climate science[43].

Here we have showcased how a near-real-time storyline system can provide rapid, relatable climate change information for a broad-impact extreme such as the devastating European rainfall in September 2024. We envisage that this approach will become a useful tool for scientific research and an important piece of the future dissemination portfolio of climate change information.

Methods

Near-real-time storyline simulations

Our 5-member storyline simulations are performed using the global coupled climate model developed at the Alfred Wegener Institute (Germany), AWI-CM-1-1-MR[25–27]. The storyline simulations are carried out following the method first described in ref. 20, and successfully used for analyses several years behind real-time[20,21]. The observed atmospheric circulation (vorticity and divergence) is constrained (i.e., nudged) at large synoptic and planetary scales, that is, horizontal scales larger than ~1000 km. Only vertical levels between 700 hPa and 100 hPa are nudged, to leave the atmospheric planetary boundary to evolve freely. In the tropics, the performance of the approach is thus limited by the larger role of convective processes compared to horizontal large-scale advection and the presence of thermally more direct circulations such as the Walker circulation.

Here we present a prototype system for near-real-time storyline attribution and projection of the weather for any place on Earth at any time, following the workflow illustrated in Supplementary Fig. S6. Storylines are first initialized using states from our AWI-CM-1-1-MR historical and Shared Socio-economic Pathway scenario ssp370 free-running simulations to produce the different background climate conditions. Preindustrial, present-day and +4 °C conditions are obtained by branching 4-year nudged simulations off the free runs respectively on the 1st January 1851, 2017 and 2093, the latter corresponding to a +4 °C global mean surface air temperature increase compared to preindustrial in the model. Storyline simulations are then extended from these different initial states, and nudged to the global atmospheric vorticity and divergence from ERA5 starting on the 1st January 2017 until the 31st December 2023.

From the 1st January onwards, the storylines are extended daily, and utilize atmospheric vorticity and divergence from the ERA5 reanalysis initial release (ERA5T) provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) 3 days behind real-time. This daily extension workflow is illustrated by the dashed box in Supplementary Fig. S6. Storylines each comprise five ensemble members spawned from the five respective AWI-CM-1-1-MR free-running simulation ensemble members and thus starting from different initial conditions. Figures show ensemble means for each five-member storyline ensemble. All storyline simulations are generated and stored on the German Climate Computing Center (DKRZ), using 1600 node-hours (3071 cores) for a throughput of 1680 GB per simulated year.

Prototype visualization webtool

The prototype webtool disseminating our near-real-time storylines is accessible to everyone at: https://climate-storylines.awi.de. The webtool features a simple interface in which users can choose the data source (storyline simulations or ERA5 climate reanalysis data), the parameter, the background climate (preindustrial, present-day, or +4 °C world), and the type of map or time series to visualize. ERA5 reanalysis data and the simulated SST fields are interpolated to the grid of the model's atmospheric component to facilitate comparisons. The storyline data has daily resolution and is averaged over five ensemble members for each climate storyline—that is, five versions of the storyline simulation differing slightly from one another. Visualizing the ensemble average ensures that the signal of climate change of the day that may arise from our storylines is robust.

Calculating anomalies

SST anomalies shown in Supplementary Fig. S2 are derived with respect to the reference period 1985–2014. Anomalies for the ERA5 reanalysis fields are produced with respect to the ERA5 climatology. For the present-day storyline simulations, we derive the simulated climatology from the 5-member ensemble mean of our AWI-CM-1 model's free-running simulations with historical scenario, from which the storylines are branched off.

Thermodynamical changes

Changes in precipitation, air and sea surface temperature, and vertical wind velocity, are calculated as the difference between the 5-member ensemble mean storyline simulations (in preindustrial, present-day, or 4 °C warmer climates). Relative changes, given in %, are all with respect to absolute values from present-day simulations. Changes in precipitation are additionally scaled with the local 2-m air temperature changes, to compare to the expected Clausius-Clapeyron precipitation scaling.

Spatially-integrated quantities

We define a broad event region enclosed within 11–25°E, 46–54°N to quantify large-scale changes in the event's intensity. Geographic boundaries for the region are derived from the observed distribution of precipitation, following a similar approach to the WWA[31]. We additionally use a 100 mm threshold for total precipitation as an indicator of areas undergoing severe rainfall in each storyline simulation (in preindustrial, present-day, or 4 °C warmer climates). The total area experiencing more than 100 mm of rain is calculated at the sum of the grid area for each grid cell identified over the threshold. The relative changes, given in %, are all with respect to the area from present-day simulations.

Confidence level

We calculate the statistical significance of changes in our simulations with a two-sided Wilcoxon test. The test is applied to the two 5-member storyline ensembles being compared (i.e., present-day against preindustrial storylines or +4 °C against present-day storylines). For reference, a complete separation of 5-member ensembles between two climates corresponds to a p value of 0.008, i.e., a confidence level above 99%, and is therefore highly significant.

Data availability

Data from the AWI-CM-1-1-MR free runs are available in the Earth System Grid Federation (ESGF) data nodes (https://esgf-data.dkrz.de/search/cmip6-dkrz/). The nudged storyline simulations are stored in the supercomputer Levante from DKRZ and are available on Zenodo (https://doi.org/10.5281/zenodo.14034062). ERA5 reanalysis data used in this study can be accessed from the European Centre for Medium-Range Weather Forecasts (ECMWF; https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5).

Code availability

The source code for the coupled FESOM v.1.4 model that is used in AWI-CM-1-1-MR is the same as in ref. 20, 21, and available online (Zenodo, https://doi.org/10.5281/zenodo.10401309). For the source code of ECHAM6, registration on the MPI-ESM user page is required (http://www.mpimet.mpg.de/en/science/models/license/).

Received: 25 September 2024; Accepted: 25 October 2024;
Published online: 08 November 2024

References

1. Ballester, J. et al. The effect of temporal data aggregation to assess the impact of changing temperatures in Europe: an epidemiological modelling study. *Lancet Reg. Health Eur.* **36**, 100779 (2024).
2. Brown, M. V. et al. A marine heatwave drives significant shifts in pelagic microbiology. *Commun. Biol.* **7**, 125 (2024).
3. Knutzen, F. et al. Impacts and damages of the European multi-year drought and heat event 2018–2022 on forests, a review. *EGUsphere.* [preprint], https://doi.org/10.5194/egusphere-2023-1463 (2023).
4. Toreti, A. et al. Climate service driven adaptation may alleviate the impacts of climate change in agriculture. *Commun. Biol.* **5**, 1235 (2022).
5. Szuwalski, C. S., Aydin, K., Fedewa, E. J., Garber-Yonts, B. & Litzow, M. A. The collapse of eastern Bering Sea snow crab. *Science* **382**, 306–310 (2023).
6. Newman, R. & Noy, I. The global costs of extreme weather that are attributable to climate change. *Nat. Commun.* **14**, 6103 (2023).
7. Stezycki, K., Laizans, J. & Stoklasa, R. "Central European floods leave trail of devastation; new areas to evacuate". Reuters. https://www.reuters.com/world/europe/poland-fortifies-towns-deadly-floods-afflict-central-europe-2024-09-17/ (18 September 2024).
8. IPCC. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Masson-Delmotte, V. et al.) 2391 (Cambridge University Press, 2021).
9. Philip, S. et al. A protocol for probabilistic extreme event attribution analyses. *Adv. Stat. Climatol. Meteorol. Oceanogr.* **6**, 177–203 (2020).
10. Faranda, D. et al. ClimaMeter: contextualizing extreme weather in a changing climate. *Weather Clim. Dynam.* **5**, 959–983 (2024a).
11. Faranda, D., Alberti, T., Coppola, E. & Antonescu, B. Heavy Precipitations in Storm Boris exacerbated by both human-driven climate change and natural variability. ClimaMeter. https://www.climameter.org/20240913-15-storm-boris (2024b). (17 September 2024).
12. Hazeleger, W. et al. Tales of future weather. *Nat. Clim. Chang.* **5**, 107–113 (2015).
13. Shepherd, T. G. A common framework for approaches to extreme event attribution. *Curr. Clim. Chang. Rep.* **2**, 28–38 (2016).
14. Wehrli, K., Hauser, M. & Seneviratne, S. I. Storylines of the 2018 Northern Hemisphere heatwave at preindustrial and higher global warming levels. *Earth Syst. Dyn.* **11**, 855–873 (2020).
15. Hawkins, E., Compo, G. P. & Sardeshmukh, P. D. ESD ideas: translating historical extreme weather events into a warmer world. *Earth Syst. Dyn.* **14**, 1081–1084 (2023).
16. Aalbers, E. E., Van Meijgaard, E., Lenderink, G., De Vries, H. & Van Den Hurk, B. J. The 2018 west-central European drought projected in a warmer climate: how much drier can it get? *Nat. Hazards Earth Syst. Sci.* **23**, 1921–1946 (2023).
17. Ludwig, P. et al. A multi-disciplinary analysis of the exceptional flood event of July 2021 in central Europe–Part 2: historical context and relation to climate change. *Nat. Hazards Earth Syst. Sci.* **23**, 1287–1311 (2023).
18. Schär, C., Frei, C., Lüthi, D. & Davies, H. C. Surrogate climate-change scenarios for regional climate models. *Geophys. Res. Lett.* **23**, 669–672 (1996).
19. van Garderen, L. & Mindlin, J. A storyline attribution of the 2011/2012 drought in Southeastern South America. *Weather* **77**, 212–218 (2022).
20. Sánchez-Benítez, A., Goessling, H., Pithan, F., Semmler, T. & Jung, T. The July 2019 European heat wave in a warmer climate: storyline scenarios with a coupled model using spectral nudging. *J. Clim.* **35**, 2373–2390 (2022).
21. Athanase, M. et al. Projected amplification of summer marine heatwaves in a warming Northeast Pacific Ocean. *Commun. Earth Environ*. **53**, https://doi.org/10.1038/s43247-024-01212-1 (2024).
22. Shepherd, T. G. et al. Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. *Clim. Chang.* **151**, 555–571 (2018).
23. Hoskins, B. & Woollings, T. Persistent extratropical regimes and climate extremes. *Curr. Clim. Chang. Rep.* **1**, 115–124 (2015).
24. Woollings, T. et al. Blocking and its response to climate change. *Curr. Clim. Chang. Rep.* **4**, 287–300 (2018).

25. Sidorenko, D. et al. Towards multi-resolution global climate modeling with ECHAM6–FESOM. Part I: model formulation and mean climate. *Clim. Dyn.* **44**, 757–780 (2015).
26. Rackow, T. et al. Towards multi-resolution global climate modeling with ECHAM6-FESOM. Part II: climate variability. *Clim. Dyn.* **50**, 2369–2394 (2018).
27. Semmler, T. et al. Simulations for CMIP6 with the AWI climate model AWI-CM-1-1. *J. Adv. Model. Earth Syst.* **12**, e2019MS002009 (2020).
28. Eyring, V. et al. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.* **9**, 1937–1958 (2016).
29. Lee, J. et al. Systematic and objective evaluation of Earth system models: PCMDI Metrics Package (PMP) version 3. *Geosci. Model Dev.* **17**, 3919–3948 (2024).
30. Merrifield, A. L., Brunner, L., Lorenz, R., Humphrey, V. & Knutti, R. Climate model selection by independence, performance, and spread (ClimSIPS v1.0.1) for regional applications. *Geosci. Model Dev.* **16**, 4715–4747 (2023).
31. Kimutai, J. et al. Climate change and high exposure increased costs and disruption to lives and livelihoods from flooding associated with exceptionally heavy rainfall in Central Europe. https://doi.org/10.25561/114694 (2024).
32. Lenderink, G. & van Meijgaard, E. Increase in hourly precipitation extremes beyond expectations from temperature changes. *Nat. Geosci.* **1**, 511–514 (2008).
33. Pfahl, S., O'Gorman, P. & Fischer, E. Understanding the regional pattern of projected future changes in extreme precipitation. *Nat. Clim. Chang.* **7**, 423–427 (2017).
34. Blickle, P., Erdmann, E., Tröger, J. & Zehr, B. "So viel heißer wäre die aktuelle Hitze in Zukunft". *Zeit Online* **13**, https://www.zeit.de/wissen/umwelt/2023-07/klimakrise-erderwaermung-hitzewelle-extremwetter-zukunft (2023).
35. van Garderen, L., Feser, F. & Shepherd, T. G. A methodology for attributing the role of climate change in extreme events: a global spectrally nudged storyline. *Nat. Hazards Earth Syst. Sci.* **21**, 171–186 (2021).
36. Roach, L. A. et al. Winds and meltwater together lead to Southern Ocean surface cooling and sea ice expansion. *Geophys. Res. Lett.* **50**, e2023GL105948 (2023).
37. Blanchard-Wrigglesworth, E. et al. Model biases in simulating extreme sea ice loss associated with the record January 2022 Arctic cyclone. *J. Geophys. Res. Oceans* **129**, e2024JC021127 (2024).
38. Palmer, T. N. A nonlinear dynamical perspective on climate prediction. *J. Clim.* **12**, 575–591 (1999).
39. Klimiuk, T. et al. The European summer heatwave 2019—a regional storyline perspective. *Earth Syst. Dynam*. Discuss. [preprint], https://doi.org/10.5194/esd-2024-16, in review, (2024).
40. Hoffmann, J. et al. Destination Earth–A digital twin in support of climate services. *Clim. Serv*. **30**, 100394 (2023).
41. Martin, L. et al. *Assessing the Vulnerability of Agricultural Areas under Climate Change in Europe through a Heat Stress Index Approach (No. EGU24-15603)*. Copernicus Meetings (2024).
42. Rakovec, O., Sanchez Benitez, A., Gößling, H. & Samaniego, L. The recent European droughts within the nudged storyline context. In *EGU General Assembly Conference Abstracts* 12331 (2024).
43. Koldunov, N. & Jung, T. Local climate services for all, courtesy of large language models. *Commun. Earth Environ.* **5**, 13 (2024).
44. Barbi, D. et al. ESM-Tools version 5.0: a modular infrastructure for stand-alone and coupled Earth system modelling (ESM). *Geosci. Model Dev.* **14**, 4051–4067 (2021).
45. Hersbach, H. et al. The ERA5 global reanalysis. *Q. J. R. Meteorol. Soc.* **146**, 1999–2049 (2020).

Acknowledgements
This work was supported by the Helmholtz Research Field Earth & Environment for the Innovation Pool Project SCENIC. All simulations were performed at the German Climate Computing Center (DKRZ) using ESM Tools[44] and resources from the ba1264 and bk1099 projects. We thank Stefan Pinkernell for the assistance with the webtool (https://climate-storylines.awi.de), and Angelika Heil for making the ERA5 initial release data available at DKRZ.

Author contributions
M.A., A.S.B., H.F.G., and T.J. conceptualized the study. M.A. designed the prototype system. A.S.B. conducted the data analysis. E.M. implemented the webtool. M.A., A.S.B., and H.F.G. wrote the initial study, and all authors edited the manuscript.

Funding
Open Access funding enabled and organized by Projekt DEAL.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-024-01847-0.

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Peer review information *Communications Earth & Environment* thanks Damián Insua-Costa and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Heike Langenberg. A peer review file is available.