Supplemental Material

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The Summer Heatwave 2022 over Western Europe: An Attribution to Anthropogenic Climate Change
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Supplementary for 'The summer heatwave 2022 over Western Europe: An attribution to anthropogenic climate change'

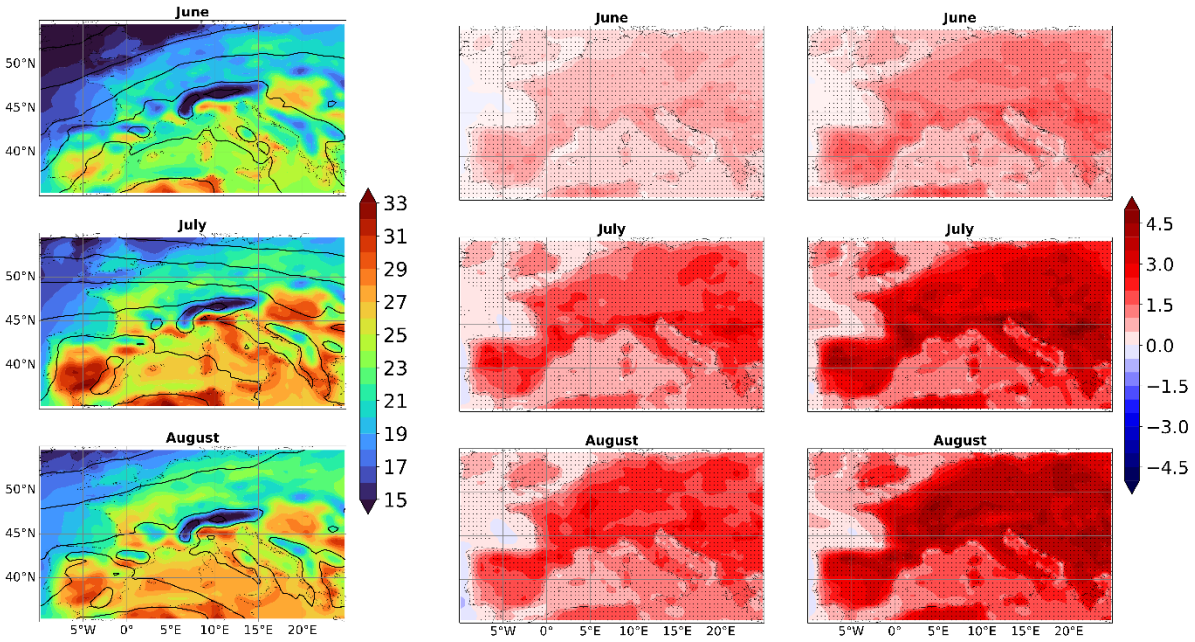

Figure 1s

The left column shows the 2m temperatures [°C] (shaded) and present-time geopotential height at 500hPa [m] (black contour lines) of the European heatwave 2022 for JJA. The middle column shows the differences in 2m temperature [°C] between the present-time and preindustrial simulations and the right column the differences between +2°C and preindustrial simulations as shaded fields. Stippling indicates where all present-time or +2°C members are > 0.1°C above all preindustrial members for that grid point.

Spectrally nudged storylines

The aim of this article is to find the effect of anthropogenic climate change on a specific weather event, the 2022 European heatwave. To do so we need a method that can provide viable knowledge on such a narrow time scale. The commonly applied statistical approaches (also known as the frequentist approach) cannot provide this, since they need a large number of events to produce any answers of statistical meaning. In the frequentist approach, the events in free running simulations are selected based on roughly the same location and, in the case of a heatwave, the temperature averaged over space and time (e.g. duration of heatwave) and are grouped to an event class. The technique is thus used to attribute an event type instead of a specific event (Watanabe et al. 2013). Also, attributing the

atmospheric dynamics of an extreme event comes with large uncertainties, not rarely larger than a random attribution (Shepherd 2014). Interpreting such highly uncertain results is difficult. Nonetheless, understanding the changing probabilities of extreme weather is crucial information for e.g. risk assessment and policy making, and therefore the statistical methods are much needed and important.

However, probabilities are not the focus of this study. Instead, it is meant to answer the question 'How much did the intensity of this extreme event change due to anthropogenic climate change?' To do so, we use the spectrally nudged storyline approach as described in van Garderen (2022). In this approach the dynamical situation of the specific extreme weather event is re-simulated with different climatological background, either with less than, equal to or more than present day levels of global warming. Doing so the effect of climate change on a specific extreme weather event can be quantified based on known thermodynamic aspects. The results presented in this study are thus a conditional attribution, since the dynamic situation is nudged towards observed weather patterns which occurred at the time of the heatwave. This provides insight into the thermodynamic climate change signal that otherwise might have been lost in the uncertainty noise of the dynamic signal. Moreover, it enables a quantitative attribution of a specific extreme weather event. Differences between the frequentist and storyline approach are summarized in Table 1s, please note that the table is not meant to be an exhaustive overview.

Spectrally Nudged Storylines Approach	**Frequentist Approach**
Specific extreme event	Extreme event class
Quantitative results	Probabilistic results
Conditional	Unconditional
Uncertainty based on thermodynamics	Uncertainty based on dynamics
Requires limited number of conditioned (spectrally nudged) simulations	Requires large number of free running model simulations

Table 1s

Comparison of extreme event attribution based on the spectrally nudged storyline approach and the frequentist approach.

SST warming pattern

To compute the changes in sea surface temperature (SSTs) for the preindustrial and +2°C storylines, SST warming patterns were computed. For the preindustrial simulations, this pattern is constructed based on 2015-2024 Max Planck Institute Earth System Model MPI-ESM1.2-HR (Müller et al. 2018) SSP370 scenario data minus preindustrial PiControl simulations from 2015-2024. This warming pattern is then subtracted from the NCEP SSTs. This way the reanalyzed SST pattern, reduced by the warming pattern, is still generally existent and it is possible to simulate weather patterns, which are close to reality. The greenhouse gas (GHG) levels were set to preindustrial values. For the +2°C simulations the difference between CMIP6 MPI-ESM1.2-HR (Müller et al. 2018) SSP585 scenario members for the averaged period 2045-2054 and the averaged historical reference period 1850 to 1920 was computed, which resulted in a +2°C warmer world. This warming pattern was then added to the NCEP SSTs. The GHG levels were accordingly selected for the 2045-2054 period. The spectrally nudged storylines were then computed with ECHAM6 using NCEP SSTs and GHG levels for the present time and using the changed SSTs and GHG levels for the preindustrial and +2°C warmer world.

Simulated Annealing and Diversified Randomization (SANDRA)

SANDRA (Philipp et al. 2007) is a non-hierarchical clustering technique based on conventional k-means clustering. In this study, SANDRA is used on temperature anomaly fields with negative anomalies being omitted, so that the focus of the clustering is purely on heatwaves. SANDRA attempts to group the input fields into a predefined number of clusters, such that the differences between fields in one cluster (intra-cluster variability) are minimized, and the differences between different clusters (inter-cluster variability) are maximized. Differences are measured by the Euclidean distances between the fields. The specific number of clusters chosen in this study shows a good balance between the intra- and inter-cluster variability.

In the process of assigning fields to clusters, the process of simulated annealing that is implemented in SANDRA allows the overall data partitioning quality to be temporarily decreased, but in the final partitioning, the clusters are closer to the 'global optimum' than, e.g., in standard k-means clustering. SANDRA has been developed for clustering atmospheric circulation fields (e.g. sea level pressure or geopotential height) and has shown good or even superior performance compared with other clustering methods for various applications, also in terms of computational effort. To our knowledge, the application of SANDRA to the context of heatwaves is novel.

In the resulting set of heatwave clusters, the dominant one (i.e., the one with most members) is the non-heatwave cluster (value of zero basically all over the domain; not shown). This is consistent with our understanding of heatwaves being extreme events, i.e. being exceptions from the climatological state.

The basic set of heatwave clusters for this study is computed from ERA5 reanalysis data following the procedure outlined above. For a comparison with the longer paleo-climate period, we assign each field (positive temperature anomalies as for ERA5) from the long MPI-ESM past2k simulation to the clusters obtained from ERA5: for each of the model fields, the difference to each of the ERA5 heatwave clusters is measured by the Euclidean distance between the cluster and the field. The respective day is then assigned to the cluster with the smallest distance.

MPI-ESM_past2k simulation

The paleo simulation employed in this study uses the Max Planck Institute Earth System Model (MPI-ESM) in the configuration for paleo-applications (MPIESM-P) according to the Paleoclimate Modelling Intercomparison Project, phase 3 (PMIP3) protocol (Jungclaus et al. 2014). The atmosphere model ECHAM6 is run at a horizontal resolution of spectral truncation T63 (1.875) with 47 vertical levels. The ocean/sea-ice model MPIOM features a conformal mapping grid with nominal 1.5 resolution and 40 vertical levels (GR1.5L40) (Jungclaus et al. 2014).

The paleo simulation for the years 1 to 2014 was used in order to analyze the very long time span of the last about 2000 years to achieve more reliable statistics on how exceptional the European summer heatwave 2022 was in a historical context. Generally, the past2k simulation should show more decadal or centennial variability than a preindustrial control run as it has more complex forcings (changing land use, volcanic activity, orbital, solar and GHG forcings). The paleo run is therefore supposedly closer to reality for the preindustrial period than a control run with less forcings.

Literature:

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