

Assessing the plausibility of unprecedented events: A process-based approach applied to month-long heatwaves in Western Europe

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Abstract. Climate model based storylines of individual climate and weather events are increasingly used to quantify impacts, vulnerability, or stress-test infrastructure to inform adaptation decisions. Here, we present an approach to test the plausibility of unprecedented climate storylines based on physical conformity, internal consistency, and historical precedent. We apply this approach to assess the plausibility of month-long heatwaves in Western Europe that would exceed existing record temperatures by around more than 5 K. These heatwaves are based on model simulations using ensemble boosting, a computationally efficient method to simulate unprecedented events. We compare these unprecedented heatwaves with historical heatwaves in a reanalysis data set, using standardised anomalies relative to a time-evolving climatology of relevant physical variables such as temperature, 500 geopotential height, surface solar radiation, and soil moisture. We show that these unprecedented heatwaves are associated with physical drivers well-known physical drivers that are similar to historical heatwaves, with anomalies that including strong anticyclones and low soil moisture. The anomalies of these drivers are more intense in magnitude but very, but similar in their temporal substructure. We also demonstrate that the relationships between different physical variables are internally consistent and exhibit many similarities with historical precedents. In this way, we show that these unprecedented spatial patterns and in their relationships with each other. However, we also reveal substantial discrepancies between historical and unprecedented heatwaves, which are related to atmospheric blocking, land-atmosphere interactions, and their temporal persistence. Despite these discrepancies, we conclude that these long-lasting heatwaves cannot, unprecedented heatwaves should not be ruled out as implausible, and thus highlight the need to anticipate such events when planning adaptation measures. Similar approaches can be used to assess the plausibility of unprecedented events in other variables other types of extreme events.

1 Introduction

Unprecedented events represent a particularly difficult challenge for extreme event research: It is essential to study them for disaster preparedness, but their rare occurrence in observational absence from reanalysis records limits our ability to make robust statements regarding about their potential magnitude and characteristics (Fischbacher-Smith, 2010; Kelder et al., 2025). Unprecedented events can be simulated in climate models, but the lack of historical analogues of comparable magnitude comparable historical analogues leads to the fundamental question whether these simulated events are plausible to occur in the real world. This question is particularly pressing following the record-shattering The importance of anticipating future unprecedented events has been further highlighted by recent extreme events such as the 2021 Pacific North West heatwave that

, which broke previous temperature records by almost 5 K ~~–which has highlighted the importance of anticipating future unprecedented events~~ (Bartusek et al., 2022; White et al., 2023; Fleishman et al., 2025). Here we assess the plausibility of simulated month-long heatwaves in Western Europe that would exceed existing records by similar margins (Lüthi et al., 2024).

Future record-breaking events can be studied using climate storylines, which provide physically self-consistent unfoldings of plausible future events, making it possible to study their characteristics and underlying physical processes (Hazeleger et al., 2015; Shepherd et al., 2018; Sillmann et al., 2021; Baulenas et al., 2023; van den Hurk et al., 2023; Baldissera Pacchetti et al., 2024). Among other approaches, such unfoldings ~~of future events~~ can be selected from single-model initial-condition large ensembles (~~SMILEs~~) of climate models (Bador et al., 2017; van der Wiel et al., 2021; Suarez-Gutierrez et al., 2020; Fischer et al., 2021) or from ensembles of weather prediction models (UNSEEN approach, van den Brink et al., 2005; Thompson et al., 2017). Furthermore, model ensembles can be optimised to simulate more frequent and intense extreme events by using rare event algorithms such as the GKTL algorithm (Giardina et al., 2011; Ragone et al., 2018; Ragone and Bouchet, 2021; Yiou et al., 2023; Noyelle et al., 2025a, b), ensemble boosting (Gessner et al., 2021; Fischer et al., 2023; Lüthi et al., 2024; Suarez-Gutierrez et al., 2025), or based on adaptive multilevel splitting (Finkel and O’Gorman, 2024, 2026). In recent years, similar approaches have been used to create extreme event storylines using machine learning (Mahesh et al., 2025a, b; Whittaker and Di Luca, 2026). However, ~~for all of these approaches, an important question remains: How~~ how can we test whether simulated unprecedented events are plausible to occur in the real world?

Assessing the plausibility of unprecedented events is essential because it informs us about the potential intensity of events that society needs to prepare for (Nordmann, 2013). This makes plausibility an essential criterion for decision making, such as for natural disaster preparations (van der Helm, 2006; Shepherd et al., 2018; Sillmann et al., 2021) ~~–Located between the and~~ is useful in a wide range of fields, ranging from epidemiology to economics (Derbyshire, 2022; Goodwin and Wright, 2010). This is because studying extreme events that are considered plausible — irrespective of their probability of occurrence — allows for the exploration of future scenarios while embracing inherent uncertainties (Selin and Guimarães Pereira, 2013). Therefore, studying plausible future extremes is essential for providing tangible what-if scenarios that are needed to inform disaster preparation.

But what does plausible mean? Located between possible (without contradiction) and ~~the~~ probable (likely to occur), ~~the~~ plausible is associated with being credible, trustworthy, and reasonable (Amara, 1991; Wilson, 1998; Selin, 2006; van der Helm, 2006; Nordmann, 2013; Urueña, 2019). However, the concept of plausibility is based on subjective judgement, and thus there are no universal criteria (Selin and Guimarães Pereira, 2013). In this work, we base our assessment of plausibility on tangible criteria ~~that are suitable to evaluate suitable for~~ climate storylines: conformity with physical principles, internal consistency, and historical precedent ~~(Amara, 1991; Nordmann, 2013).~~ (Amara, 1991; Nordmann, 2013; Shepherd et al., 2018). These criteria can be used to either affirm or question the plausibility, depending on whether the underlying physical processes are internally consistent with process understanding and externally supported by historical events. Fundamentally, it is not possible to conclusively prove that a given event is plausible; the only feasible approach is to perform a series of tests in which the confidence increases with the number of distinct tests performed.

60 There are a number of different ways to translate plausibility criteria into concrete analysis steps. Most commonly, the plausibility of simulated extremes is statistically analysed through extreme value theory and model fidelity tests, [for example, by comparing statistical distributions and moments of model output with observations or reanalysis](#) (Thompson et al., 2017, 2019; Vautard et al., 2019; Philip et al., 2020; Kelder et al., 2022a, b). In contrast, only few studies assess the plausibility of simulated extreme events by analysing the physical processes that drive them (~~Vautard et al., 2019; Kelder et al., 2022b~~), [for example, by studying the temporal evolution of variables and the correlations between them](#) (Vautard et al., 2019; Kelder et al., 2022b) or [the dynamic and thermodynamic precursors of the events](#) (Klif et al., 2026). An important part of this assessment involves comparisons with historical events; however, there are inherent limitations of this approach when analysing unprecedented extremes in a transient climate. This is particularly obvious for extreme events that are directly affected by global and regional warming trends; for example, heatwaves that reach previously impossible temperatures are becoming possible in a warming climate (Fischer et al., 2025). To account for this, we propose a process-based approach centred around standardised anomalies with respect to a time-evolving climatology, that is, we quantify how extreme an event is relative to the background climate (mean and variability) in which it occurs. ~~Expanding on existing process-based studies, this~~ [This](#) allows us to directly and systematically compare anomalies in a wide range of physical drivers during simulated unprecedented events with anomalies during historical ~~heatwaves events~~ and to evaluate their consistency with current process understanding. [In this way, we expand on existing process-based studies and offer an additional layer of evidence to complement statistical approaches.](#)

75 To demonstrate our approach, we focus on heatwaves in Western Europe. This is motivated by the fact that both mean summer temperatures and extreme heat in Western Europe are increasing faster than in almost any other region, caused by a combination of ~~global anthropogenic climate change, anthropogenic global warming, regional~~ reductions in aerosol emissions, and changes in circulation (Singh et al., 2023; Vautard et al., 2023; Schumacher et al., 2024; World Meteorological Organization et al., 2025). As a consequence, Western Europe has been a hotspot for record-breaking heat extremes: Since the turn of the 21st century, Western Europe experienced record-breaking heat extremes in 2003, 2006, 2015, 2018, 2019, 2022, [2025](#), and most recently in [2025](#) (~~Rebetez et al., 2009; García-Herrera et al., 2010; Russo et al., 2015; Kornhuber et al., 2019; Sánchez-Benítez et al., 2022; Feser et al., 2026~~ (Rebetez et al., 2009; García-Herrera et al., 2010; Russo et al., 2015; Kornhuber et al., 2019; Sánchez-Benítez et al., 2022; Feser et al., 2026). Given current global warming trends, the likelihood of record-breaking heatwaves is expected to increase further in the future (Fischer et al., 2025), with parts of Western and Central Europe among the most at-risk regions for such ~~events~~ [heatwaves](#) (Thompson et al., 2023).

The processes that govern heatwaves occur on a wide range of spatial and temporal scales and include interactions between the atmosphere, ocean, cryosphere, land surface, and biosphere (Barriopedro et al., 2023; Domeisen et al., 2023). In mid-latitudes, heatwaves are often caused by quasi-stationary Rossby wave packets that lead to persistent anticyclones (Röthlisberger et al., 2019). These anticyclones can disrupt the zonal atmospheric circulation leading to atmospheric blocking (Drouard and Woollings, 2018; Röthlisberger and Martius, 2019; Kautz et al., 2022). In summer, this can favour heat extremes through horizontal temperature advection, vertical adiabatic subsidence, and diabatic heating at the surface through solar radiation and turbulent fluxes ~~, which~~ [\(Zschenderlein et al., 2019; Barriopedro et al., 2023; Röthlisberger et al., 2026\)](#). [These surface fluxes](#) are often amplified by land-atmosphere feedbacks (~~Fischer et al., 2007; Seneviratne et al., 2010; Zschenderlein et al., 2019; Barriopedro et al., 2023~~).

95 [\(Fischer et al., 2007; Seneviratne et al., 2010\)](#), particularly during persistent heatwaves that last multiple weeks [\(Tuel and Martius, 2023; Pa](#)
 . These generally well-understood physical drivers provide the foundation for our process-based approach to assess plausibility.
 Heatwaves have severe impacts on human health, ecosystems, and infrastructure (Easterling et al., 2000; Zuo et al., 2015),
 and these impacts can be particularly severe during ~~persistent heatwaves lasting multiple weeks (D’Ippoliti et al., 2010; Anderson and Bell,~~
~~Compared with short-lived heatwaves, long-lasting heatwaves in Western Europe tend to be associated with particularly~~
 100 ~~strong low-wavenumber Rossby wave trains and land-atmosphere feedbacks (Tuel and Martius, 2023; Pappert et al., 2025).~~
~~long-lasting heatwaves (D’Ippoliti et al., 2010; Anderson and Bell, 2011; Polt et al., 2023).~~ Prominent examples of long-lasting
 heatwaves include the Eastern European heatwave of 2010 (Barriopedro et al., 2011; Dole et al., 2011) as well as the Western
 European heatwaves of 1976 ~~(Green, 1977; Rodda and Marsh, 2011; Kendon et al., 2024)~~ [\(Green, 1977; Kendon et al., 2024\)](#)
 and 2003 (Black et al., 2004; García-Herrera et al., 2010), which resulted in thousands of excess deaths (Le Tertre et al., 2006;
 105 Robine et al., 2007).

Recent model experiments based on ensemble boosting suggest that persistent, month-long heatwaves that would break
~~observational reanalysis~~ records by more than 5 K in Western Europe are possible in the near future, which would have severe
 effects on heat-related mortality (Lüthi et al., 2024). Given the unprecedented nature of these month-long heat extremes, here
 we address the pressing question whether they are plausible to occur in the real world.

110 2 Methods

2.1 Climate model and reanalysis data

~~The We create~~ unprecedented heatwave storylines ~~are created~~ using ensemble boosting ~~, a computationally efficient method~~
~~to simulate record-breaking extremes using the simulations in~~ CESM2 climate model (Gessner et al., 2021). It consists of
 re-initialising a model run a few weeks before an extreme event and creating new ensembles based on round-off sized
 115 ~~perturbations in the humidity field. The simulations used here are based on a 35-member CESM2 ensemble running from~~
~~2005 to 2035 under the historical (2005–2014) and SSP3-7.0 (2015–2035) scenarios (Fischer et al., 2023; Lüthi et al., 2024).~~
~~From this ensemble, the five most extreme 14-day heat extremes in Switzerland (“parents”) were selected, occurring in the~~
~~model years 2015, 2028, 2028, 2030, and 2031 in different ensemble members. For each parent, 100 ensemble members per~~
~~day start 14–25 before the peak of the parent event and subsequently run for 50, yielding a total of 1100 alternative realisations~~
 120 ~~of each parent heatwave. These simulations were already used and described by Lüthi et al. (2024).~~

~~with daily model output (see Appendix A).~~ As a climatological reference ~~for these boosting simulations,~~ we use ~~daily output~~
~~of~~ the 100-member CESM2 large ensemble (LE) that ~~runs from 1850 to 2100 under~~ ~~follows the~~ historical (1850–2014) and
 SSP3-7.0 (2015–2100) scenarios (Danabasoglu et al., 2020; Rodgers et al., 2021). ~~We use a number of~~ ~~Most of the~~ atmospheric
 and surface variables ~~, most of which are directly that we use are~~ available as model output (see Tab. 1). ~~The exceptions~~
 125 ~~are~~ ~~Exceptions are the diurnal temperature range (DTR, the difference between daily maximum temperature TX and daily~~
~~minimum temperature TN), total precipitation (PREC), which is calculated as,~~ the sum of convective ~~precipitation (PRECC)~~

Table 1. Heatwave characteristics and drivers analysed in this study.

TM	daily mean temperature
TX	daily maximum temperature
TN	daily minimum temperature
<u>DTR</u>	<u>diurnal temperature range</u>
Z500	500 hPa geopotential height
U500	500 hPa zonal wind (positive eastwards)
V500	500 hPa meridional wind (positive northwards)
ω 500	500 hPa vertical wind (positive downwards)
SSR	surface downwelling solar flux (positive downwards)
PREC	total precipitation
SM	top-layer soil moisture
LHF	surface latent heat flux (positive upwards)
SHF	surface sensible heat flux (positive upwards)
EF	surface evaporative fraction

and large-scale precipitation(~~PRECL~~), and the evaporative fraction (EF)~~, which is calculated from surface latent (LHF) ,~~
calculated from the surface fluxes of latent heat LHF and sensible heat fluxes (SHF) SHF as $EF = LHF / (LHF + SHF)$.

To compare with historical heatwaves, we use daily output of the ERA5 reanalysis for ~~the years 1950–2024~~ 1950–2025
130 (Hersbach et al., 2020) for all variables in Tab. 1 except for SM, for which we use ERA5-Land instead (Muñoz-Sabater et al.,
2021). In addition to these quality-checked final products, we use preliminary ERA5 and ERA5-Land data for the month-long
heatwave in Western Europe from 2026-06-17 to 2026-07-16 (Hersbach et al., 2020; World Meteorological Organization, 2026)

For the temperature budget analysis, we additionally use daily model output on the 850 hPa level from the boosting
135 simulations and from ERA5 for the temperature (T850), zonal wind (U850), meridional wind (V850), and vertical wind
(ω 850), as well as the temperature tendency due to physical parametrisations. In CESM2, this is available as the PTTEND
variable, in ERA5 we use the avg_ttpm variable which is only available from the deterministic forecast model.

For SM, the top-layer of the soil differs between CLM, CESM2’s land model (top 10 cm) and ERA5-Land (top 7 cm). To ~~test~~
~~the impact of this difference and the choice to focus on the top-layer only, we also perform our~~ compare the absolute values of
140 SM, the ERA5 values (volumetric soil water in m^3/m^3) are converted to CESM2 units (soil water mass in kg/m^2). Performing
the same analysis for the top 1 m of the soil ~~.This slightly changes some of our results quantitatively but~~ does not alter ~~any~~
~~of our conclusions .In the following, we therefore focus only on the soil moisture of the top-layer (SM~~ our conclusions (not
shown).

~~In our analysis, we~~ We focus on a box in Western Europe (WE) where the boosting simulations ~~described above detect~~
145 ~~potential heatwaves that would exceed existing observational~~ detect heatwaves that exceed historical records by particularly

large margins (0–10°E, 46–51°N; ~~covering North-Eastern France, South-Western Germany, Switzerland, Belgium, Luxemburg, and Liechtenstein; referred to as WE in the following~~). All CESM2 and ERA5 variables are averaged over this domain before we calculate standardised anomalies (see below). To study large-scale conditions, we further use the full horizontal fields of all variables analysed in Europe (12°W – 42° E, 35°N – 72°N). For this analysis, we remap the horizontal ERA5 fields to the CESM2 grid using first order conservative remapping (Schulzweida, 2023). Unless stated otherwise, all of our analysis is performed for the summer months of June, July, and August (JJA).

2.2 Standardised anomalies

~~To allow for~~ To enable a meaningful comparison between the ~~simulated unprecedented heatwaves from the CESM2 boosting simulations unprecedented heatwave storylines~~ and historical heatwaves ~~from ERA5~~, we express every variable x ~~in terms of~~ standardised anomalies as standardised anomaly z_x (in the following ~~referred to as “anomalies” for brevity~~ simply “anomaly”):

$$z_x(r, y, s) = \frac{x(r, y, s) - \bar{x}(r, y \pm 15 \text{ yr}, s \pm 2 \text{ d})}{x'(r, y \pm 15 \text{ yr}, s \pm 2 \text{ d})}. \quad (1)$$

Here, the region r refers to an individual grid cell ~~(after remapping) of the CESM2 grid~~ or the box-average over WE, y refers to the year, s refers to the day of the summer season (JJA), and $\bar{x}$ and x' refer to the mean and standard deviation of x , respectively, calculated over a centred 31-year window in time and a centred 5-day window over the seasonal cycle.

For the boosting simulations, $\bar{x}$ and x' are derived ~~from the~~ using the full 100-member CESM2-LE, using all 100 ensemble members for the 31-year period centred on each heatwave. The only exception is the SM variable ~~except for SM~~, which is available for only 90 members ~~of the ensemble. For the~~ For CESM2-LE itself, the standardisation is performed for the period 2005–2035 (the same period as the 35-member CESM2 ensemble on which the boosting simulations are based), ~~using model output from the period 1990–2050~~. For ERA5, the standardisation is limited to the period ~~1965–2009~~ 1965–2010, where a centred 31-year reference period can be constructed based on the data record available at the time of the analysis ~~(1950–2024)~~. When LHF and SHF are of opposite sign but similar magnitude, this can lead to very large absolute values in EF locally, particularly over ocean. Thus, only grid cells with ~~an EF value between 0 and 1~~ $0 < \text{EF} < 1$ are used to calculate EF anomalies.

The standardisation is performed separately for daily values and a 30-day running mean. The 30-day running mean is assigned to the “central day”, the ~~15th day within the~~ 15th day within a given 30-day period. We consider all 30-day periods whose central day lies in JJA, including ~~those periods~~ that start in May or end in September. To calculate the 30-day running mean of the box-mean over WE, we require data points on all ~~30 days~~ 30 days within a given window; for the running mean of individual grid points, this is relaxed to at least 25 data points within a 30-day window in order to reduce the effect of individual missing values in EF (see above).

2.3 ~~Event~~ Heatwave selection

~~Based on the~~ Based on anomalies in the 30-day running mean of TM in WE, we select ~~the ten most extreme 30-day heatwaves in WE in all 20 heatwaves in~~ our boosting simulations that exceed the most extreme heatwave in ERA5 (“unprecedented” heatwaves ~~U1–U10~~ U1–U20, Tab. B1) ~~as well as in~~ From ERA5 ~~(, we select all 30-day periods whose TM anomalies in WE~~

exceed the 95th percentile of all JJA 30-day means in the reanalysis record, yielding a total of 11 “historical” heatwaves H1–H10, (Tab. B2). In order to only select non-overlapping time periods, in the boosting simulations, we Our anomaly-based approach limits the reanalysis record to 1965–2010, which excludes many of the most extreme heatwaves that occurred in the last 15 years. Thus, we also perform the same analysis for the absolute TM values in WE in 2011–2026, which yields 10 “recent” historical 30-day heatwaves (in 2013, 2015, 2018, 2019, 2020, 2022, 2023, 2024, 2025, and 2026).

To avoid selecting temporally overlapping heatwaves, we only consider the maximum-largest 30-day anomaly of each boosting run; in ERA5, we, and only consider the maximum-largest 30-day anomalies within ± 30 days in ERA5, allowing more than one heatwave per year to be selected. In this way, we select the 30-day periods that feature the most anomalously high temperatures with respect to the background climate and the timing within the summer season in which they occur. Of the ten selected unprecedented heatwaves, eight come from the same parent heatwave ensemble in model year 2015 (P1), and the other two (U4 and U8) come from a second parent heatwave ensemble in model year 2031 (P2). Nevertheless, they are still quite distinct in terms of their TM time series (Fig. B1) and their physical drivers (Sect. 3.2).

To directly compare the historical heatwaves to CESM2 heatwaves of similar magnitude, we additionally select “moderate” heatwaves in CESM2. For each historical heatwave (H1–H10), we select the 20 heatwaves in the CESM2-LE with the most similar 30-day TM anomaly over WE. In this way, we select a total of 200 moderate for each historical heatwave, separately for two different periods (the historical period 1965–2010 and the period of the boosting simulations 2005–2035). In total, we thus select 220 “moderate” CESM2 heatwaves for each climate period, whose TM anomalies differ from the respective historical heatwave by at most $\pm 0.1\sigma$ (Fig. 1a).

2.4 Return periods

To estimate the return periods of the unprecedented heatwaves from the ensemble boosting simulations, we use a method that was specifically developed for this purpose and is described in detail by Bloin-Wibe et al. (2025). In short, this method uses the shared antecedent conditions between a boosted simulation and its parents to derive conditional probabilities of exceeding a threshold TM_{ref} and uses bootstrapping to derive the 95-confidence interval of the estimated return period. It provides an unbiased estimate of return periods and offers clear improvements over approaches based on fitting extreme value distributions.

When applying this method to our simulations, it should be noted that the parent heatwaves were selected based on the 14-day absolute TM in Switzerland, while our study considers the Of the 20 unprecedented heatwaves in our simulations, 15 originate from the same parent ensemble P1 (model year 2015), and the other five come from a second parent ensemble P2 (model year 2031). Unprecedented heatwaves from the same parent feature quite similar SM anomalies, but are still distinct in their atmospheric conditions (Fig. B1) and in the relative importance of relevant physical drivers (Fig. B2b). Nevertheless, to increase the independence and representativeness of the analysed heatwaves, we also include in our analysis the most extreme 30-day TM anomaly in WE. As a consequence, the five selected parent heatwaves are not among heatwaves of the three other parent ensembles P3–P5 (model years 2030, 2028, and 2028). However, because their 30-day TM anomalies are smaller than the most extreme heatwaves in the ensemble; rather historical heatwave, they are ranked 16th, 23rd, 133rd, 265th, and 294th

in terms of their 30-day TM anomaly in WE (out of the 35 ensemble members—31 ensemble years = 1085 simulated years; see Fig. 1b). Thus, setting TM_{ref} equal to the least extreme parent run, the antecedent conditions are sampled less efficiently than is theoretically possible, but, importantly, this does not affect the quality of the return period estimator. Return periods of heatwaves in the 35-member ensemble (including parent heatwaves) are estimated using an empirical frequency estimator based on the occurrence within the ensemble (Bloin-Wibe et al., 2025) not considered “unprecedented” heatwaves and instead analysed separately.

2.4 Temperature budget analysis

Following Tyrlis et al. (2013) and Garfinkel et al. (2024), the Eulerian temperature budget can be written as

$$\underbrace{\frac{\partial T}{\partial t}}_{\text{local}} = - \underbrace{\frac{u}{r \cos(\phi)} \frac{\partial T}{\partial \lambda}}_{\text{zonal}} - \underbrace{\frac{v}{r} \frac{\partial T}{\partial \phi}}_{\text{meridional}} - \underbrace{\frac{T}{\theta} \frac{\partial \theta}{\partial p} \omega}_{\text{adiabatic}} + \underbrace{\frac{J}{C_p}}_{\text{diabatic}} + \text{residual}, \quad (2)$$

where T is the temperature, t is the time, u , v , and ω are the zonal, meridional, and vertical wind components, θ is the potential temperature, p is pressure, ϕ is latitude, λ is longitude, r is the radius of Earth, J is the diabatic heating rate, and C_p is the heat capacity of air at constant p . In this way, the local temperature tendency is decomposed into four terms: zonal temperature advection, meridional temperature advection, adiabatic changes resulting from vertical temperature advection, and diabatic sources and sinks (such as radiation, evaporation/condensation, and surface exchanges), as well as a residual term.

The ten selected unprecedented heatwaves are from ensemble members that are re-initialised 11–20 For historical and recent heatwaves in ERA5 (except 2026), and for preceded and unprecedented heatwaves in CESM2, we evaluate Eq. (2). To reduce the effects of topography, we focus on the 850 before the peak of the 30-day TM anomaly in WE in the parent run and thus we use all ensemble members with lead times of 11–20 to estimate conditional probabilities. Note that these lead times do not correspond directly to the lead times defined with respect to the 14-day TM in Switzerland in Sect. 2.1. All days of the ten most extreme 30-day periods (U1–U10) occur after the re-initialisation, hPa level (Tyrlis et al., 2013; Garfinkel et al., 2024). We calculate the zonal, meridional, and adiabatic terms from second order centred differences of daily model output on the native grids of ERA5 and thus do not include any simulated days from the respective parent simulation.

2.5 Temporal substructure

To compare the temporal substructures of U1–U10 with H1–H10, we use daily anomalies of the variables listed in Tab. 1. For each variable, these daily anomalies within each 30-day period are ranked from highest to lowest, similar to the approach used by Röthlisberger et al. (2020). To evaluate systematic differences, the ranked anomalies CESM2, but the results are not sensitive to spatial remapping. For the diabatic term, we use the daily mean temperature tendency due to physical parametrisations. The resulting values are averaged over the ten historical and ten unprecedented heatwaves, as well as the selected moderate heatwaves from the CESM2-LE, respectively WE, and separately averaged over days with positive and negative local T tendencies during each event.

We evaluate the persistence of TM, Z500

2.5 Persistence

To analyse temporal persistence, U500, and SM by calculating we calculate the number of consecutive days in which the on
245 which daily anomalies are greater than $+1\sigma$ $\geq +1\sigma$ (for TM and Z500) or less than -1σ (for U500 and $\leq -1\sigma$ (for SM).
For ERA5 and the CESM2-LE, we consider periods count the occurrences of consecutive days whose end date lies in JJA ;
including periods that start in preceding months, and divide their occurrences and divide this count by 92 (the number of days
in JJA) to yield their to yield the frequency per summer season. For the simulated preceded and unprecedented heatwaves,
we take use the longest persistence period duration that ends in the 50-day period of each respective boosting run, including
250 periods that start in their respective the parent run. Thus, persistence periods durations from all sources can include days from
in months preceding JJA.

We analogously evaluate the persistence of atmospheric blocking using a simple blocking index (Tibaldi and Molteni, 1990)
, setting the northern and southern latitudes to the edges of our European domain ($35^\circ\text{N} - 72^\circ\text{N}$). A day counts as blocked, if
Z500 satisfies both blocking criteria of Tibaldi and Molteni (1990) for at least one longitude within our WE domain ($0-10^\circ\text{E}$).
255 All calculations are performed on the CESM2 grid, but spatial mapping has only a negligible effect.

2.6 Multivariate linear model

To test the plausibility of U1–U10 from a multivariate perspective, we construct a simple

2.6 Multilinear model

We construct a multilinear statistical model based on a multivariate ordinary least-squares regression. For simplicity, we focus
260 on a set of five predictors (Z500, U500, V500, SM, SSR) and apply it separately for three different prognostic variables
(TM, TX, and TN). For each prognostic variable separately, the model is fitted to the maxima of 30-day z_{TM} of each summer
season(JJA), with separate versions trained on ERA5 and the CESM2-LE. This gives six different model versions which are
used we use to infer anomalies in the prognostic variable during the unprecedented heatwaves based on the simulated anomalies
of the five predictors as

$$265 \quad z_{x,\text{inf}}(d) = \sum_p \beta_p z_p. \quad (3)$$

Here, $x \in [\text{TM}, \text{TX}, \text{TN}]$ is the prognostic variable, $p \in [\text{Z500}, \text{U500}, \text{V500}, \text{SM}, \text{SSR}]$ are the predictors, $d \in [\text{CESM2-LE}, \text{ERA5}]$ are the data sources on which the model is trained, and β_p are the coefficients of the model.

The predictors were chosen as a compromise between model simplicity and capturing the the simplicity of the model and the
inclusion of the most important processes governing the ten unprecedented heatwaves analysed: that govern the unprecedented
270 heatwaves. Z500 is the most obvious choice given the chosen due to the importance of anticyclones for mid-latitude heatwaves.
Because our model is based on region-average anomalies, the Z500 anomaly WE-mean anomalies, it does not contain any
information on the position of the anticyclone relative to WE, for which we include U500 and V500 as predictors. In addition,

SM is included to capture the important role of low soil moisture during heatwaves. ~~Finally, and~~ SSR is included to account for the diabatic contribution of radiation. ~~This~~

275 The model is meant to be a simplified representation of the relevant physical processes that drive month-long temperature extremes in Western Europe. Inherently, it cannot capture processes involving variables not included in the model, or non-linear relationships, including, but not limited to, land-atmosphere feedbacks between soil moisture and temperature. To further investigate this, we employ a modified version of the model to infer anomalies in SHF, LHF, and EF. As predictors, we chose TM, SM and SSR, which are the variables most directly linked to the variables inferred in the absence of atmospheric humidity
280 or near-surface wind in our analysis set of variables.

3 Results

~~The ten unprecedented heatwaves in our boosting simulations (U1–U10) exceed the~~ To evaluate plausibility, we focus on storylines of unprecedented month-long heatwaves, defined as periods during which the 30-day running mean TM anomaly in WE surpasses the most extreme historical heatwaves (H1–H10), ~~not only in terms of absolute temperatures, but also when compared to their respective background climate. The anomalies of the unprecedented heatwaves range from 3.7σ (U10) to 4.3σ (U1), compared with 3.6σ for the most~~ extreme historical heatwave in June/July 1976 (3.6σ , the only historical ~~heatwave to exceed an anomaly of event exceeding 3σ (Figs. see Tab. B2). In our CESM2 boosting simulations, we identify 20 such~~ unprecedented heatwaves (labelled U1–U20), with anomalies between 3.6σ and 4.3σ (purple circles in Fig. 1a, ~~Tabs. B2 and B1). This is also reflected in the return periods Tab. B1, Sect. 2.3). The return period estimates of these unprecedented~~ heatwaves ~~, with best estimates between around 600~~ range from around 300 years ~~for U10 and to more than 6000 years for U1. The, with 95 % confidence intervals of these estimates have lower bounds of roughly 400–2000~~ 200–2000 years ~~and upper bounds of roughly 1500 (lower bounds) to 500 years– ∞ (upper bounds), with infinite upper bounds for U1–U3 the three most extreme heatwaves (Fig. 1b); see Sect. ?? for details on the calculation of return periods.; see Appendix A). By centring our assessment on the most extreme heatwaves in our simulations, we target the events that are most likely to be influenced by~~ limitations in the applicability of CESM2. However, this approach also comes with some drawbacks. In addition to the limited sample size of unprecedented heatwaves in our simulations ($n = 20$), they originate from only two different parent ensembles, leading to similar preconditions in slow components such as the land surface (Sect. 2.3, Fig. B1c).

We address this challenge in two ways: (1) We increase the representativeness of our analysis by additionally including the most extreme heatwaves of the three other parent ensembles in our simulations for some of our assessments. Because their anomalies are smaller than the most extreme historical heatwave, we refer to them as “precedented” heatwaves (Sect. 2.3, pink circles in Fig. 1). (2) Using large-deviation theory, it has been shown that the typicality of heatwaves tends to increase with their magnitude, that is, more extreme heatwaves tend to become more similar in their physical pathways, as they require a “perfect storm” of strong contributions by most relevant heatwave drivers to occur (Lucarini et al., 2023; Noyelle et al., 2024). For this reason, we expect many of our findings to also apply to other unprecedented heatwaves as well as to less extreme heatwaves

305 that might only exhibit a subset of these heatwave drivers. Furthermore, if even the most extreme heatwaves simulated by CESM2 are considered plausible, this ultimate test also improves confidence in CESM2 to simulate less extreme heatwaves.

Given that the central return period estimates for ~~these unprecedented heatwaves~~ the unprecedented heatwaves analysed here are finite but much longer than a human lifetime, they appear statistically possible but ~~(by definition)~~ not probable.

~~Contextualisation of selected unprecedented month-long heatwaves in Western Europe. (a) 30-day TM anomalies of the ten most extreme historical heatwaves in WE (H1–H10, yellow circles), 200 moderate extremes in the CESM2-LE with the same TM anomaly (blue circles), and the ten unprecedented heatwaves from ensemble boosting (U1–U10, red circles). They are compared to kernel density estimates of 30-day TM anomalies during the summer season (JJA) in ERA5 (1965–2009, yellow line) and the CESM2-LE (2005–2035, blue dashed line), using a Gaussian kernel with a bandwidth of 0.2σ , truncated at the data limits. (b) Return period estimates of 30-day TM anomalies from boosting simulations (red dots), including U1–U10 (red circles), and their 95 confidence interval (CI), as well as return period estimates of heatwaves in 35-member CESM2 ensemble (cyan dots), including the selected parent events (cyan diamonds).~~

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In the following, we address the less straight-forward question of whether these unprecedented heatwaves are plausible by assessing their physical conformity, internal consistency, and historical precedent. In practice, our assessments of these characterisations naturally overlap, but generally fall into two categories: (1) By comparing the unprecedented heatwaves from CESM2 ensemble boosting simulations to less extreme heatwaves in ~~the~~ CESM2-LE, we assess ~~whether they are internally consistent; by their internal consistency within the CESM2 model. This allows us to test whether the processes present during these unprecedented heatwaves are similar to those simulated during less extreme heatwaves in CESM2.~~ (2) By comparing them to historical heatwaves, we assess whether — despite their by definition unprecedented magnitude — these heatwaves ~~are externally consistent with~~ have external empirical support from historical precedents. This allows us to test whether the processes present during these unprecedented heatwaves are similar to heatwaves in the reanalysis record.

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The conformity to physical principles represents the foundation of most of our assessment procedure; we test it by comparing the underlying physical processes in these unprecedented heatwaves both internally (within CESM2) and externally (with ~~respect to~~ ERA5). In this way, we test the ability of CESM2 to realistically simulate extreme heatwaves with intensities beyond those found in the reanalysis record. The overall result of our assessment — whether the evidence supports or questions

330 plausibility — depends on the combined results of several analysis criteria, which we present in the following.

3.1 ~~Historical analogues~~

~~As a first test~~

3.1 Spatial fields

We start by exploring the large-scale spatial behaviour of unprecedented heatwaves over Europe. For this, we compare the composite spatial fields of plausibility, we search for multivariate historical analogues for the unprecedented heatwaves. For each unprecedented heatwave, we calculate the Euclidean distance between the anomalies of 30-day mean horizontal fields over Europe (12°W — 42°E , 35°N — 72°N) between the respective unprecedented heatwave and ERA5 (1965–2009), respectively.

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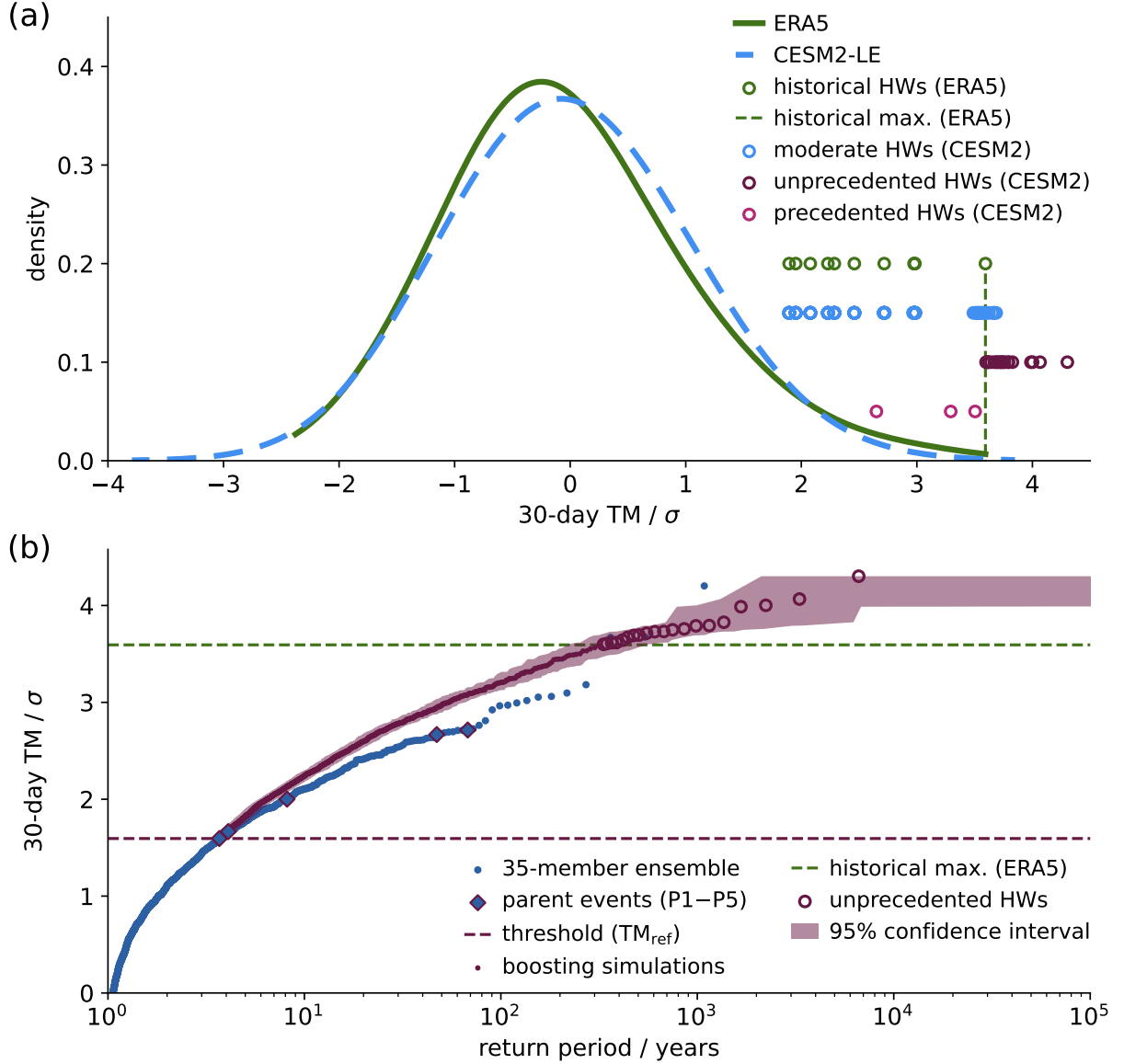


Figure 1. Unprecedented month-long heatwave storylines in Western Europe. (a) 30-day TM anomalies of the most extreme historical heatwaves (green circles), moderate heatwaves in CESM2-LE with the same TM anomalies (light blue circles), preceded (pink circles) and unprecedented heatwaves (purple circles) from ensemble boosting. Kernel density estimates of 30-day TM anomalies during JJA in ERA5 (1965–2010, green line) and CESM2-LE (2005–2035, light blue line), using a Gaussian kernel with a bandwidth of 0.5σ , truncated at the data limits. (b) Return period estimates of 30-day TM anomalies from boosting simulations (purple dots), including the selected unprecedented heatwaves (purple circles), and their 95 % confidence interval, as well as return period estimates of heatwaves in 35-member CESM2 ensemble (dark blue dots), including the selected parent heatwaves (dark blue diamonds). The thresholds for the return period calculation (TM_{ref} , dashed purple) and for the selection as unprecedented heatwave (historical maximum, dashed green) are also shown.

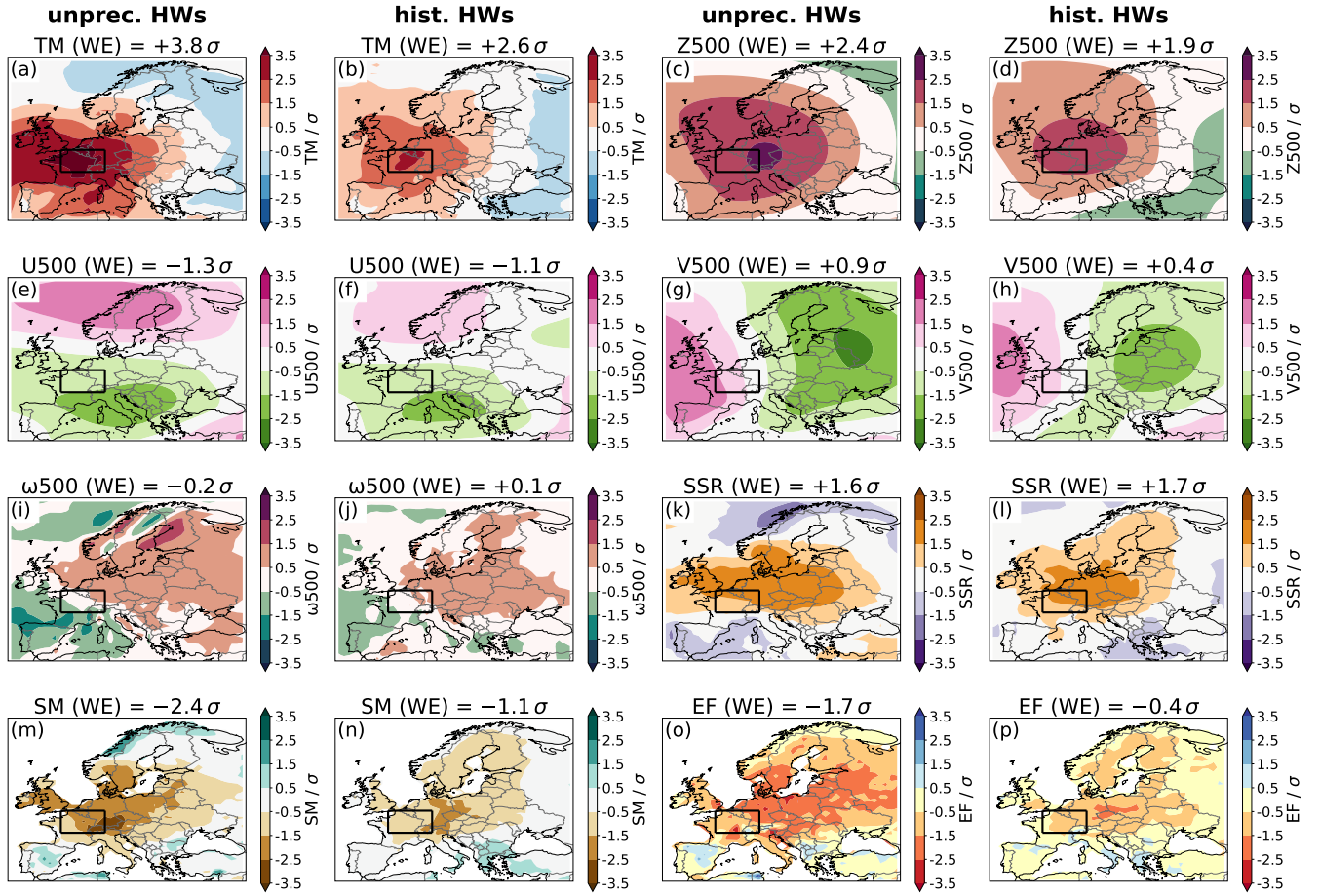


Figure 2. Spatial composites of anomalies in selected variables during unprecedented heatwaves (first and third columns) and during historical heatwaves (second and fourth columns). The surface variables SM and EF are only plotted over land.

The best multivariate analogue for each unprecedented heatwave (listed in Tab. ??) is defined as the historical 30-day period that minimises the sum over the Euclidean distances of all 13 variables (TM, TX, TN, anomalies during unprecedented and historical heatwaves for relevant heatwave variables (Fig. 2). In this context, it would support plausibility if TM anomalies arise from similar atmospheric and land-surface conditions over Europe in unprecedented and historical heatwaves. Conversely, it would not support plausibility if substantially different large-scale conditions happen to produce similar anomalies over WE.

First, the TM anomalies feature similar spatial distributions, extending slightly further west during unprecedented heatwaves (Fig. 2a,b). Similarly, the anomaly fields of the dynamical variables (Z500, U500, V500, and ω 500, SSR, PREC, SM, LHF, SHF, and EF; see Tab. 1). In the following, we present two contrasting examples of multivariate analogues for unprecedented heatwaves that highlight both the power and limitations of this approach.

The first example is the most extreme heatwave in our simulations (U1), whose best multivariate analogue is the historical heatwave in June/July 1976 (Fig. ??). Note that while this multivariate analogue overlaps with the most extreme historical 30-day TM anomaly (H1), the two periods are shifted by approximately two weeks (Tabs. B2 and ??). Both U1 and its analogue feature very similar geographic distributions of TM anomalies, with particularly extreme anomalies over Great Britain and Northern France. Although in WE, the best analogue is still about 1σ less extreme than U1, it is among the most extreme.) are also very similar between unprecedented and historical heatwaves, with very similarly located anticyclones over Central Europe that disturb the zonal flow over Central and Southern Europe, and lead to Southerly wind anomalies over Western Europe and above-average vertical subsidence over much of Central and Eastern Europe (Fig. 2c–j). The magnitudes of the anomalies are greater during unprecedented heatwaves, which is discussed in more detail in Sect. 3.2. The largest SSR anomalies are found in areas of vertical subsidence and are very similar in magnitude during historical and unprecedented heatwaves (Fig. 2k,l).

The fields of SM and EF feature substantially more negative anomalies in large parts of Central and Eastern Europe during unprecedented heatwaves (Fig. 2m–p; see also Sect. 3.2). Despite these differences in magnitude, the spatial distributions are still similar, with the most negative values of both SM and EF occurring to the east of WE, consistent with previous findings (Noyelle et al., 2025b). Overall, the large-scale conditions during unprecedented heatwaves in WE thus appear to be remarkably consistent, both externally with historical heatwaves and exhibits many similarities to U1. The Z500 anomaly, although weaker and smaller, is located in a very similar region, as are the anomalies in U500 and V500, which are quite similar in magnitude in the vicinity of WE. Both U1 and its analogue feature relatively weak anomalies in ω 500 and PREC over WE and similar distributions over most of Europe. For SSR, while the anomalies differ in WE, internally by conforming to well-understood physical processes. However, this good agreement in standardised anomalies does not necessarily extend to the case of the underlying absolute values, which can be subject to model biases in the overall spatial pattern still looks remarkably similar. The largest discrepancies are found in SM, SHF, and EF, where the 1976 analogue features much more extreme anomalies and thus appears to be much more diabatically driven than U1. This stronger diabatic contribution appears to be partly pre-conditioned: The precipitation anomalies in the months preceding the 1976 analogue are substantially lower than in the months preceding the U1 heatwave (Fig. ??). This indicates that U1 could have been even more extreme if it had occurred on top of a similarly severe drought as the one that occurred in 1976. mean and variability of heatwave variables.

The second example is the U4 heatwave, the Therefore, to complement our anomaly-based analysis, we also analyse the spatial fields of absolute values during unprecedented heatwaves. For this, we compare them with “recent” heatwaves that have occurred during 2011–2026 and are not included in our anomaly time series due to their incomplete centred 31-year climatology. These heatwaves are among the most extreme unprecedented heatwave found outside the ensemble of the P1 parent heatwave. The best multivariate analogue we find for this heatwave is the historical heatwave of July 2006, which largely overlaps with H6, but is shifted by four days heatwaves in terms of absolute TM and occur in a very similar background climate as most of our unprecedented heatwaves (Fig. 3; see Sect. 2.3). As mentioned above, the unprecedented heatwaves are on average almost 5 K warmer than most recent heatwaves (Fig. ??, Tabs. B2 and ??). Compared to most of the other unprecedented heatwaves analysed, its most extreme TM anomalies are located further east over the Benelux region and North-Western Germany. In WE, the 2006 analogue is almost 3a,b). However, the 2026 heatwave exceeded the previous 30-day

Horizontal fields in Europe of analysed variables during U1 heatwave (first and third columns) compared with the best historical analogue in July 1976 (second and fourth columns). The surface variables SM, EF, SHF, and LHF are only plotted over

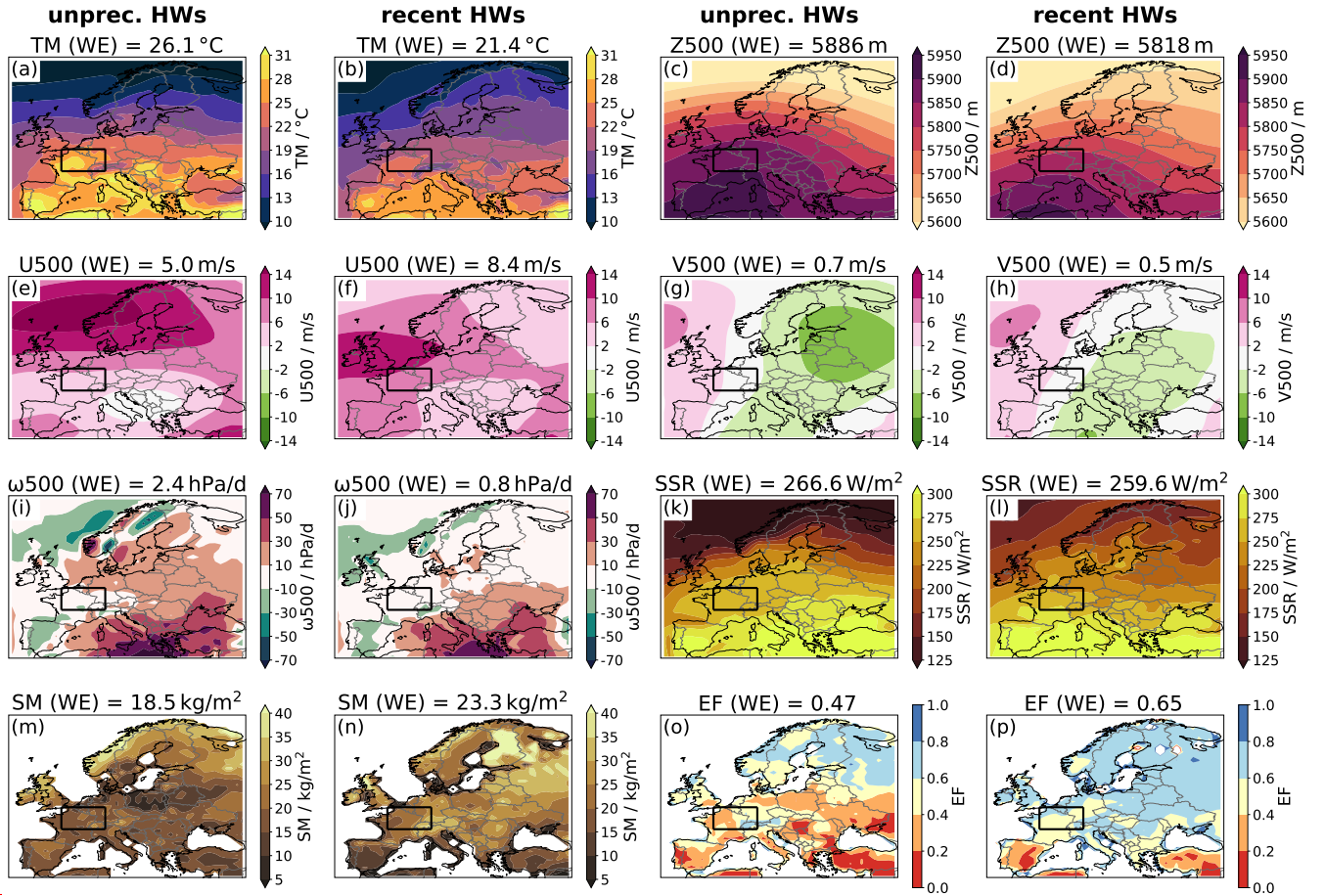


Figure 3. As Fig. 2, but for absolute values during unprecedented and recent heatwaves.

TM record by approximately 2σ weaker than U4, and substantial discrepancies exist for many other variables as well: While the magnitude of the anticyclone is similar to U4, it is shifted to the South-East in the 2006 analogue, along with the anomaly in U500 K, and was almost as extreme in 30-day TX as some unprecedented heatwaves (see Appendix B and Fig. B3).

385 Apart from more extreme TM, unprecedented heatwaves are also associated with stronger anticyclones than recent heatwaves, but they are located in very similar positions (Fig. U4 has a very pronounced spatial pattern in ω 500, with sinking motion over the North and Baltic seas, near-zero vertical motion over WE 3c,d). During unprecedented heatwaves, and rising motion over Northern Africa and the Western Mediterranean. This rising motion coincides with positive anomalies in V500, PREC, and SM and negative anomalies in SSR which exhibit characteristics of warm conveyor belts (Eckhardt et al., 2004) and atmospheric
390 deserts, air masses originating from hot and dry boundary layers (Fix-Hewitt et al., 2026). In contrast, the 2006 analogue does not exhibit any of these features but instead features substantial subsidence over WE. Finally, the 2006 analogue does not capture

the substantial anomalies in anticyclones extend further northward, which can also be seen in the location of the strongest zonal winds (Fig. 3e,f), while the positions of the strongest meridional winds are more similar (Fig. 3g,h). Both historical and unprecedented heatwaves feature the strongest vertical subsidence over South-East Europe and the Mediterranean, with much smaller values over WE (Fig. 3i,j). The northward shift of the strongest westerlies in the unprecedented heatwaves relative to the historical heatwaves can also be seen in the SSR, where the unprecedented heatwaves feature much lower values over Northern Europe (Fig. 3k,l). Some of the largest discrepancies are again visible in the surface variables SM and EF during U4, highlighting yet another reason why the TM anomalies of these two heatwaves differ so substantially, whose absolute values are substantially lower across most of Europe during unprecedented heatwaves and which (in the case of SM) also exhibit different spatial patterns (Fig. 3m-p). However, it should be noted that these surface variables are associated with substantial uncertainties in both climate models and reanalysis, and thus absolute values in particular should be compared with caution (see Sect. 4).

In summary, absolute values during unprecedented heatwaves are much more extreme than recent heatwaves, not only in TM, but also in Z500, SM, and EF. Our analysis based on absolute values thus reveals similar differences between unprecedented and (recent) historical heatwaves as our anomaly-based framework. In addition, it also highlights differences in the meridional extent of the blocking anticyclone, which is greater in the unprecedented heatwaves. This indicates that CESM2 can simulate stronger blocking anticyclones than seen in the reanalysis record (see Sect. 3.1.3 for a more detailed discussion).

Horizontal fields in Europe of analysed variables during U4 heatwave (first and third columns) compared with the best historical analogue in July 2006 (second and fourth columns). The surface variables SM, EF, SHF, and LHF are only plotted over land. To conclude this section, the spatial fields of unprecedented heatwaves are very similar to those of historical heatwaves in anomaly space but, unsurprisingly, exhibit more discrepancies compared to recent heatwaves in their absolute values. This shows that unprecedented heatwaves appear to exhibit physically plausible large-scale conditions of heatwave driver anomalies, while the absolute values of these drivers should be interpreted with caution. In other words, plausibility in anomalies does not imply plausibility in absolute values, highlighting the importance of performing bias correction when using model output for impact assessment (Lüthi et al., 2024).

In conclusion, we find a remarkably similar multivariate historical analogue for the U1 heatwave centred over Great Britain and France, supporting the plausibility of this unprecedented heatwave. In contrast, we only find a much weaker and less similar historical analogue for the U4 heatwave centred over the Benelux region and Germany. Given that the existence of a similar historical analogue is not a necessary condition for plausibility, this does not imply that U4 is implausible; rather, it is consistent with the finding that Central Europe might have been lucky to not experience a more extreme heatwave so far (Thompson et al., 2023). Part of this limitation of the historical analogue method might be overcome by choosing a longer reanalysis data set, such as the Twentieth Century Reanalysis (Compo et al., 2011). However, by their very nature, unprecedented heatwaves often do not have comparable precedents in the observational record, but might still be plausible to occur in the future. In the following sections, we therefore perform more systematic and quantitative analyses that compare the simulated unprecedented heatwaves to a larger set of historical and simulated heatwaves of less extreme magnitudes.

3.2 Monthly Regional anomalies in heatwave drivers

Next As a next step, we analyse the anomalies in different physical variables during the monthly-mean anomalies in relevant heatwave variables during unprecedented heatwaves and compare them with the most extreme historical heatwaves (Tab. 1, Fig. 4). For this, we first focus on the 30-day anomalies of these variables averaged over WE. As expected, all unprecedented heatwaves have positive anomalies in Z500, ranging from about 1.5σ to 3.0σ . Most of these Z500 anomalies, including the most extreme U1 heatwave, are comparable in magnitude to the historical heatwave with the highest Z500 anomaly (H7, 2.6σ). The anticyclones causing these positive Z500 anomalies also strongly disturb the zonal flow, which is seen by negative U500 anomalies in all unprecedented heatwaves. These anomalies are also mostly similar in magnitude to the most extreme historical heatwave (H6, -1.7σ) with the notable exception of U1, which reaches -2.5σ . In this analysis, results that would indicate plausibility include (1) similar dominant drivers during historical and unprecedented heatwaves and (2) temperature anomalies whose magnitudes are consistent with the magnitudes of relevant drivers (for example, large temperature anomalies being associated with large anomalies in key drivers). In contrast, the anomalies in SSR tend to be weaker in the unprecedented heatwaves compared to the historical heatwaves, in particular when comparing the five most extreme heatwaves; respectively findings that would question the plausibility of these unprecedented heatwaves include (1) systematically different dominant drivers in historical and unprecedented heatwaves and (2) temperature anomalies whose magnitudes are decoupled from the magnitudes of relevant drivers (for example, large temperature anomalies being associated with only small anomalies in key drivers).

The SM anomalies during the unprecedented heatwaves are much more negative than those of most historical heatwaves. However, the H2 and H1 heatwaves match and even exceed the magnitude of these negative simulated SM anomalies, respectively. This applies similarly to anomalies in EF, where only U8 slightly exceeds the negative anomaly of EF during H1. During historical heatwaves, large negative EF anomalies (H1 & H2) are mainly caused by Overall, historical and unprecedented heatwaves are governed by quite similar dominant drivers, with large positive anomalies in SHF with negligible LHF anomalies; during unprecedented heatwaves with large negative EF anomalies Z500 and SSR and substantial negative anomalies in U500, PREC, and SM. In contrast, anomalies in SHF, $\omega 500$ (U4 & U8), the negative LHF anomalies are substantially larger in magnitude than the positive SHF anomalies. A possible explanation for this discrepancy is related to the projected long-term decrease in SM in Western Europe. Despite similar anomalies in SM, the absolute values of SM are around 15–20 lower in U4 and U8 (model year 2031) than in the other unprecedented events (model year 2015). As a consequence, the same SM anomaly can imply that land-atmosphere fluxes are energy-limited during historical heatwaves, but moisture-limited (or transitional) in future heatwaves (Seneviratne et al., 2010). This is also consistent with the fact that historical heatwaves with less extreme SM anomalies tend to feature substantial positive LHF anomalies.

Other potential atmospheric drivers appear to play only a minor role during most of the analysed heatwaves. For V500, which we use as a proxy for mid-tropospheric temperature advection, only two unprecedented heatwaves (U8 & U9) and one historical heatwave (H5) have anomalies greater than $+1\sigma$. Similarly, for $\omega 500$, adiabatic warming) and V500 (which we use as a proxy for adiabatic warming, only one simulated heatwave (U3) and one historical heatwave (H1) have anomalies greater than

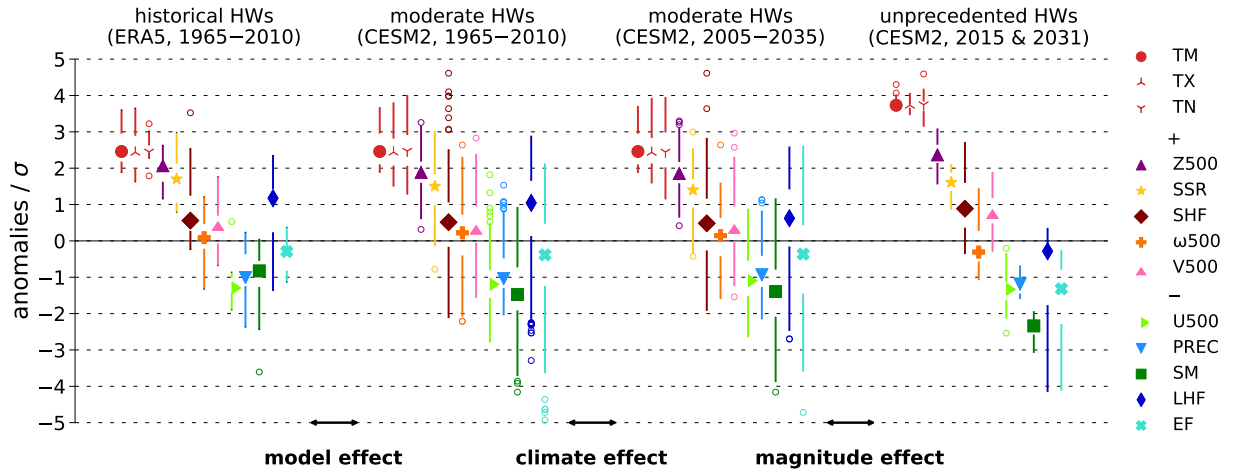


Figure 4. Anomalies of monthly mean heatwave characteristics and drivers variables in WE (see Tab. 1). (a) Ten most extreme historical month-long heatwaves in ERA5 (H1–H10). (b) Ten most extreme unprecedented month-long heatwaves in CESM2 ensemble boosting simulations (U1–U10). (c) Box plots of anomalies in heatwave variables during historical heatwaves (H1–H10 HWs), moderate heatwaves (HWs) from two different background climates, and unprecedented heatwaves (U1–U10): Median (filled symbols), inter-quartile range IQR (IQR, empty space), whiskers (1.5 IQR, solid lines) and outliers (empty circles). Shown are We further indicate below the isolated effects of varying model, climate, and magnitude of heatwaves, respectively. For clarity of visualization, we broadly distinguish temperature variables (red), and variables with expected positive (“+”) and negative (“−”) anomalies during heatwaves. This separation is a simplification primarily adopted for ease of visualization; several variables feature substantial anomalies of both signs during heatwaves.

460 +1σ mid-tropospheric temperature advection) appear to play a secondary role in both historical and unprecedented heatwaves. This relatively minor role for advective and adiabatic processes might be affected by our simplified methodology is partly caused by our focus on monthly-mean regional anomalies in this section, which can obscure short-term anomalies in these drivers (see Sect. 3.1.2). To disentangle and quantify the effects of different processes on air masses, Lagrangian approaches, for example based on back-trajectories, deliver more detailed results (?) these processes more explicitly, we also perform a
465 temperature budget analysis (Sect. 3.1.1).

The main differences between historical and unprecedented heatwaves can be seen in variables related to land-atmosphere exchanges. In relative terms, SM and EF appear to play a substantially more important role during the unprecedented heatwaves than during the historical heatwaves. Furthermore, the averaging period of 30 can obscure more short-term anomalies in these drivers (see discussion in Sect. 3.1). Nevertheless, our analysis demonstrates that the simulated unprecedented heatwaves
470 behave quite similarly to historical heatwaves when analysed from a Eulerian perspective.

To analyse the differences in physical drivers more systematically, we compare the distributions of their anomalies during historical and unprecedented heatwaves, as well as during moderate heatwaves in the CESM2-LE anomalies in LHF are generally positive in historical heatwaves but mostly negative in unprecedented heatwaves. So what exactly explains these differences?

475 The unprecedented heatwaves structurally differ from the historical heatwaves in three main ways: They originate from a climate model rather than reanalysis, occur in a different background climate, and are more extreme in magnitude. To disentangle these effects on the anomalies of heatwave drivers, we additionally analyse “moderate” heatwaves simulated by CESM2 that have the same ~~TM-anomalies as the historical heatwaves~~ (magnitude as historical heatwaves and are selected separately for two different climate periods (“historical” 1965–2010 and “present” 2005–2035; see Sect. ?? for details). We

480 find that when comparing heatwaves of the same magnitudes (historical and moderate 2.3). This allows us to distinguish between the three main effects at play:

(1) The “model effect”: Most physical drivers have similar anomalies during ERA5 and CESM2 heatwaves), most physical drivers feature very similar anomalies. The moderate heatwaves from the same climate. The CESM2 heatwaves tend to have slightly less positive anomalies in Z500, SSR, SHF, and LHF and slightly more negative SM anomalies more negative anomalies in SM, but only the difference in SSR exceeds latter difference exceeds $\pm 0.5 \sigma$. This suggests that, when comparing heatwaves of the same magnitude from the same background climate, CESM2 can accurately capture generally captures the physical drivers present during heatwaves in ERA5 when comparing heatwaves of similar magnitude. Compared to moderate well. However, it also shows that CESM2 heatwaves, the unprecedented heatwaves have more positive Z500 and SHF anomalies, and substantially more negative U500, SM, LHF and EF anomalies, while the median anomalies in SSR, $\omega 500$, V500 and PREC are virtually identical. The only physical driver whose sign of the median anomaly changes is LHF; overestimates the role of drying soils during heatwaves. This finding is consistent with the hypothesis outlined above. This suggests that unprecedented heatwaves in CESM2 are produced by “extreme anomalies of common drivers” (Fischer et al., 2021) literature (Vogel et al., 2018; Röthlisberger et al., 2026) and will be a theme throughout this work (see Sect. 3.1).

In conclusion, although the temperature anomalies during the simulated unprecedented heatwaves are, by definition, unprecedented,

495 the anomalies of most analysed physical drivers have precedents in the historical record. However, compared to any single historical heatwave, each unprecedented heatwave exceeds the anomaly in at least one analysed driver. Furthermore, most drivers show larger median anomalies in the unprecedented heatwaves compared to more moderate heatwaves in the CESM2-LE. We therefore preliminarily conclude that the combination of simultaneously extreme anomalies in several drivers, rather than an extreme anomaly in a single driver, appears to be responsible for the magnitude of most of these unprecedented heatwaves.

500 **3.3 Temporal substructure**

As a next step, we analyse the temporal substructure of the analysed heatwaves in terms of their daily anomalies. For historical, moderate, and unprecedented heatwaves, we rank the daily anomalies of the variables analysed above from highest to lowest within the respective 30-day period (Fig. 9), similar to the approach of Röthlisberger et al. (2020). Similarly to the 30-day anomalies analysed in the preceding section, the temporal substructure of these variables is very similar in the historical and

505 moderate (2) The “climate effect”: Almost all physical drivers feature very similar anomalies during moderate CESM2 heatwaves, with less positive anomalies in SSR, SHF, and LHF and more negative SM anomalies during the moderate heatwaves.

Ranked daily anomalies of heatwave characteristics and drivers during historical heatwaves (yellow), moderate heatwaves (blue), and unprecedented heatwaves (red). Shown are the temperature variables (a–c), and variables with generally positive (d–h) and generally negative (i–m) anomalies during heatwaves. Variables are sorted from highest to lowest anomalies, meaning that the most favourable conditions for heatwaves can be found at low ranked days panels (a)–(h), but at high ranked days for panels (i)–(m).

Unsurprisingly, the unprecedented heatwaves feature substantially larger daily TM anomalies throughout the 30-day period; this difference is greatest for the most extreme 15–20 from the historical and present climates, respectively. The only noticeable difference concerns LHF which exhibits anomalies of both signs in both background climates, but is shifted towards fewer positive and more negative anomalies in the present climate. Notably, this shift is not accompanied by a shift towards more negative SM anomalies, which might be expected from physical process understanding. However, the median of absolute SM values during moderate heatwaves is around 10, a feature that is even more pronounced for TN, but slightly less pronounced for TX. The largest differences in physical drivers between the historical and the unprecedented heatwaves can be found in variables related to land-atmosphere exchanges. Compared with historical heatwaves, the unprecedented heatwaves have substantially weaker PREC on days with the highest PREC (ranked days 1–10), indicating more persistent meteorological droughts. A similar picture can be observed for SM, % lower in the present climate than in the historical climate (not shown). This is consistent with the projected long-term decrease in SM in Western Europe (Seneviratne et al., 2010), which is generally much lower in the unprecedented heatwaves, but particularly for the days with higher (less extreme) SM, indicating more persistent agricultural droughts. This also leads to unprecedented negative anomalies in LHF, whereas the ranked anomalies of PREC, SM, and EF in the unprecedented heatwaves are matched or even exceeded by the historical HI heatwave, not visible in the anomalies due to our use of a time-evolving climatology. This means that the same SM anomaly can imply that land-atmosphere fluxes are energy-limited during historical heatwaves (causing more positive LHF anomalies), but transitional or even moisture-limited in present or future heatwaves (causing less positive LHF anomalies; Seneviratne et al., 2010). Between the historical and present climates compared here, this effect is still small, but it might become more substantial for future climates that see even stronger soil drying.

Most other physical drivers feature very similar temporal substructures during the unprecedented heatwaves and the historical heatwaves, particularly SHF, ω_{500} (3). The “magnitude effect”: The TM anomalies are $> 1\sigma$ more extreme in the unprecedented heatwaves compared to the moderate heatwaves. As expected, this is accompanied by more extreme anomalies in most relevant drivers (Z500, SHF, V500, but also to a lesser extent Z500, U500, PREC, SM, and EF); only SSR and SSR. These temporal substructures also reveal that the small 30-day mean anomalies in V500 and ω_{500} are partially due to the long averaging period: Short-term periods of southerly wind or vertical sinking are largely cancelled out by periods of negative anomalies as the anticyclone itself moves (Fig. 9g,h). For Z500 and U500, the unprecedented heatwaves exhibit a small and fairly uniform shift of the ranked anomalies towards more extreme values compared to historical heatwaves (more positive for Z500, more negative for U500). This indicates slightly stronger and slightly more persistent anticyclones that perturb the zonal flow more strongly throughout the 30-day periods. As already mentioned above, the unprecedented heatwaves exhibit less extreme SSR anomalies compared to historical heatwaves; as Fig. 9 shows, this is almost entirely limited to the 15 with the most extreme

SSR-anomalies. At the same time, the ranked-SSR exhibit unchanged and slightly less extreme anomalies, respectively. For LHF, the median anomalies in the unprecedented heatwaves are very similar to those approximately 1σ lower than during the moderate heatwaves from the CESM2-LE, causing a switch from positive to negative median anomalies. This magnitude effect on LHF is noticeably greater than the combined model and climate effects, suggesting that the more negative SM anomalies are primarily responsible for the difference in LHF between historical and unprecedented heatwaves.

Another way of studying the temporal structure is to evaluate the persistence of different variables (see Sect. ?? for details). To this end, we compare the occurrence of periods in which the anomalies of TM and Z500 exceed $+1\sigma$, and in which the anomalies of U500 and SM remain below -1σ , respectively, between the unprecedented simulated heatwaves, ERA5, and the CESM2-LE (Fig. 10). With only one exception, the persistence in TM during However, the shift from energy-limited to moisture-limited conditions also appears to have an effect among the unprecedented heatwaves themselves. The absolute values of SM are on average more than 15% lower in the unprecedented heatwaves (red circles) is shorter than the historical record of 21 (yellow line in occurring in model year 2031 (parent ensemble P2) than in the other unprecedented heatwaves occurring in model year 2015 (parent ensemble P1, see Fig. 10a), and similar behaviour is found for both Z500 (Fig. 10b, two record-breaking events) and U500 (B1c). This is presumably why their LHF anomalies are much more negative despite only slightly more negative SM anomalies (see, for example, U4 and U8 in Fig. 10e, no record-breaking events). For both TM and Z500, CESM2 appears to capture the frequencies of short persistence periods (<10) quite well, but substantially underestimates the frequency of longer persistence periods, suggesting that these persistent events may be rarer in CESM2 than in the real world. This is consistent with the finding of previous studies that global circulation models (GCMs) struggle to reproduce persistent blocking regimes (Tibaldi and Molteni, 1990; Davini and D'Andrea, 2016; Liu et al., 2022). However, for persistence in U500, there does not appear to be a systematic bias in CESM2 relative to ERA5. B2b). This highlights an important limitation of our anomaly-based framework when comparing SM anomalies in different background climates, as this approach cannot capture non-linear behaviour such as changes in the regime of land-atmosphere interactions. At the same time, it also highlights the value of explicitly analysing anomalies in SHF, LHF, and EF, because these variables contain valuable information about the land-atmosphere interaction regime.

Persistence of TM, Z500, U500, and SM. Number of consecutive days in the summer season (JJA) where the daily anomaly is higher than $+1\sigma$ (for TM and Z500) or lower than -1σ (for U500 and SM), respectively. Shown are the relative frequencies in ERA5 (yellow) and the CESM2-LE (blue), compared to the values during the simulated unprecedented heatwaves U1–U10 (red circles) and the ten most extreme historical heatwaves H1–H10 (yellow circles). Note the different x-axis for SM in panel (d).

In contrast, CESM2 overestimates the frequency of long persistence periods in SM: The CESM2-LE simulates a much higher frequency of long persistence periods in SM (>15) and six What conclusions does this analysis allow us to draw regarding the plausibility of unprecedented heatwaves? During historical, moderate, and unprecedented heatwaves, the largest anomalies consistently occur in the same physical drivers, most notably Z500, SSR, U500, and SM, and the unprecedented heatwaves feature persistence periods longer than the historical record more extreme anomalies in these drivers than the less extreme historical heatwaves (Fig. 10d4c). This is because, relative to ERA5 Land, implies that these unprecedented heatwaves are

caused by “extreme anomalies of common drivers” (Fischer et al., 2021). This indicates that these heatwaves are internally consistent within CESM2 overestimates the occurrence of negative SM anomalies (Fig. B6). This is consistent with previous findings that (1) climate models tend to overestimate soil drying due to land-atmosphere feedbacks (Vogel et al., 2018) and (2) for heatwaves over land, CESM2 overestimates the diabatic contribution and underestimates the adiabatic contribution relative to ERA5 (?). In contrast, despite substantial regional and intermodel differences, monthly soil moisture memory is generally well represented in GCMs (Seneviratne et al., 2006). However, it should be noted that soil moisture is difficult to compare between CESM2 and ERA5 because reanalysis data sets also involve large uncertainties and should thus be interpreted with care. ~~also have external empirical support from historical precedent in ERA5. We also find that physically plausible, non-linear regime shifts in land-atmosphere interactions can limit the comparability of SM anomalies for future climate states.~~

In conclusion, the ranked anomalies during the simulated unprecedented heatwaves are largely in accordance with historical precedent, and the existing differences appear to be generally consistent between the different variables. In contrast, CESM2 struggles to accurately capture persistence periods relative to ERA5, in line with the existing literature. This means that the unprecedented heatwaves simulated by CESM2 occur for “partly the wrong reasons” (?). These biases between the roles of diabatic and adiabatic contributions appear to partially compensate, but overall CESM2 still substantially underestimates the persistence in TM. The fact that the TM persistence periods during some unprecedented heatwaves nevertheless exceed the historical record suggests that heatwaves of comparable or even longer persistence are plausible to occur in the real world.

3.3 Bivariate relationships

Another way of assessing plausibility is to analyse bivariate relationships between different relevant physical

3.3 Relationships between variables

The previous analysis has demonstrated that the relevant drivers of unprecedented heatwaves are similar to those during less extreme heatwaves in both CESM2 and ERA5. To further assess the internal consistency and physical conformity of these heatwaves, we now study the bivariate and multivariate relationships between relevant heatwaves variables. This serves to test in more detail whether the physical drivers during these unprecedented heatwaves conform to physical principles allows us to test whether these variables follow well-known physical principles that govern their intervariate relationships and whether anomalies in different drivers are internally consistent.

3.3.1 Bivariate relationships

We first investigate the bivariate relationships between different relevant physical variables. For this, we select the maxima of the summer season (JJA) annual JJA maxima in 30-day z_{TM} in ERA5 (1965–2009/1965–2010, 45 heatwaves) and the CESM2-LE (2005–2035, 3100 heatwaves). We then compare the bivariate distributions of the 30-day anomalies in the drivers and characteristics of the heatwave variables during unprecedented heatwaves with those of the during heatwaves in ERA5 and the CESM2-LE (Figs. 5 and 6). All ten unprecedented heatwaves are more extreme in terms of the TM anomaly than

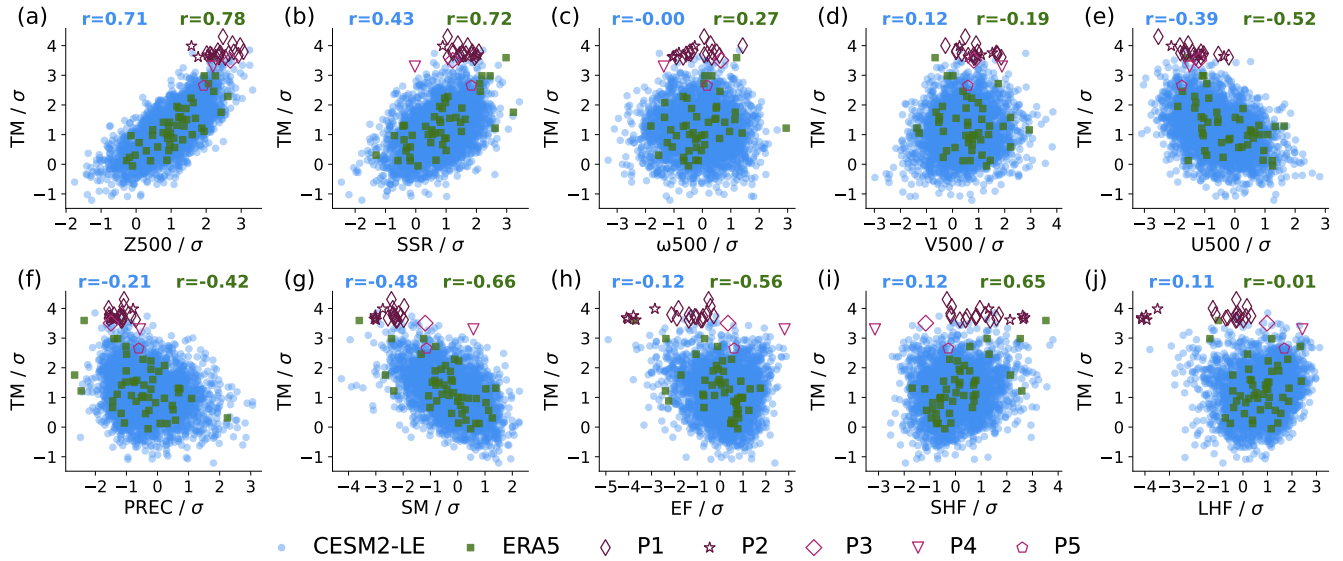


Figure 5. Bivariate distributions between TM and analysed heatwave drivers. Shown are the annual JJA maxima of 30-day temperature anomalies in CESM2-LE (2005–2035, blue circles) and ERA5 (1965–2010, green squares), as well as the 30-day anomalies during unprecedented heatwaves (purple) and preceded heatwaves (pink). The respective correlation coefficient r is noted at the top of the panel for CESM2-LE heatwaves (blue) and the ERA5 heatwaves (green).

the most extreme heatwave in Unprecedented heatwaves for which knowledge of the bivariate distributions in ERA5 and more extreme than and CESM2-LE and the anomaly in a given variable provides a good estimate of the anomaly in a second variable are considered plausible from a bivariate perspective. Conversely, obvious visual outliers from the mentioned bivariate distributions can count against plausibility of a given unprecedented heatwave if they cannot be explained by the behaviour of a third variable.

By definition, all unprecedented heatwaves have more extreme TM anomalies than heatwaves in ERA5 and almost all heatwaves in the CESM2-LE, placing them at the upper edge of all bivariate distributions involving TM (Fig. 5). The different physical drivers can be broadly grouped into three different categories.

Bivariate distributions between TM and analysed heatwave drivers. Shown are the 30-day anomalies during the ten unprecedented heatwaves (red numbers) and during the maximum 30-day temperature anomaly in each summer season in both the CESM2-LE (2005–2035, blue circles) and ERA5 (1965–2009, yellow squares). For the CESM2-LE and ERA5 heatwaves, the correlation coefficient between the respective variables is noted at the top of the panel.

Same as Fig. 5, but for selected cross-relationships between different heatwave drivers and characteristics, including the diurnal temperature range (TX–TN), for which we subtract the anomalies in TN from those in TX.

First, several drivers exhibit comparatively strong (1) Several drivers exhibit rather high correlations with TM, and their anomalies during the preceded and unprecedented heatwaves are also mostly generally at the extreme end relative to ends of

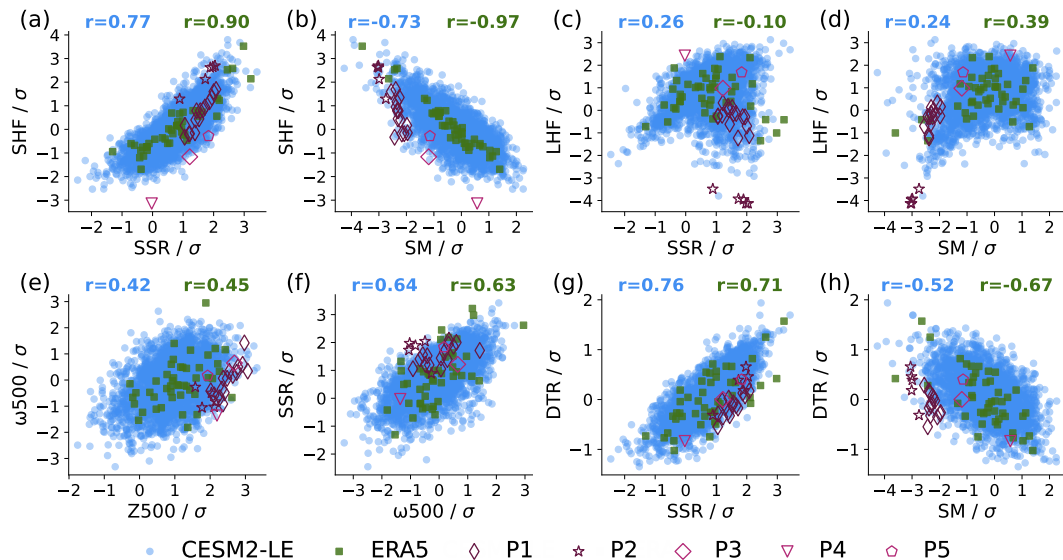


Figure 6. Same as Fig. 5, but for selected cross-relationships between different heatwave drivers and characteristics.

the CSM2-LE and ERA5 distributions. This is the case for Z500 (Fig. 5a), U500 (Fig. 5e), SM (Fig. 5h) and, to a lesser extent, PREC (Fig. 5f). These correlations align with expectations from physical process understanding, highlighting the importance of blocking anticyclones and drought conditions that favour during heatwaves. Furthermore, the anomalies of these drivers are consistent with other heatwaves in the CSM2-LE, but also with historical heatwaves in ERA5.

Second, (2) Anomalies in ω_{500} (Fig. 5c) and V500 (Fig. 5d) have weak correlations with TM. For V500 this is not surprising given that temperature advection, by definition, mostly occurs non-locally. For ω_{500} , this is in contradiction contrary to the expectation that on average more extreme heatwaves would be associated with stronger sinking motion. This is presumably again because the 30-day mean can average out short periods of vertical sinking subsidence or southerly wind (see Sect. 3.1.2). Furthermore, as mentioned above, the Eulerian anomalies in WE the regional anomalies on a single vertical level we use here do not capture the full effect of these processes; for example, the signal might can be more pronounced on other vertical levels (Hotz et al., 2024). Indeed, our temperature budget analysis at the 850 hPa level reveals substantial adiabatic sinking during unprecedented heatwaves (Sect. 3.1.1). Nevertheless, the near-zero ω_{500} anomalies of many preceded and unprecedented heatwaves are quite similar to the behaviour of heatwaves in the CSM2-LE and ERA5, and the anomalies in ω_{500} appear to be consistent with the and consistent with anomalies in Z500 (Fig. 6f) and in and SSR (Fig. 6g,f).

Third, the relationships of (3) The relationships of the surface heat flux variables with TM differ between CSM2 and ERA5. For EF and SHF in particular, CSM2 shows a much weaker correlation with T2M than ERA5 (Fig. 5h,i). This discrepancy should not be overinterpreted, given that During almost all preceded and unprecedented heatwaves, SHF follows the strongly linear relationships with SSR and SM seen in ERA5 is notoriously not closing the (surface) energy budget (Hersbach et al., 2020). For LHF and CSM2-LE (Figs. 6a,b). The only exception is P4, presumably due to the combined

occurrence of low SSR anomalies and high SM anomalies, both of which directly affect SHF, but whose individual contributions alone are not enough to explain the large negative SHF anomaly. In contrast, both CESM2 and ERA5 show very weak correlations ~~with~~ between LHF and T2M, but tend to show heteroscedastic behaviour: Average TM anomalies feature a smaller spread in LHF than the most extreme TM anomalies, consistent with the fact that LHF anomalies vary strongly ~~between the ten~~ among the unprecedented heatwaves (Fig. 5j). This behaviour is not surprising given that surface fluxes strongly differ between moisture-limited and energy-limited conditions; during extreme conditions, this can be amplified through land-atmosphere feedbacks. ~~When disentangling the behaviour of SHF and LHF with respect to~~ LHF also features strong non-linearities in its relationships with SSR and SM ~~, we find that SHF during the unprecedented heatwaves mostly follows the strongly linear relationships seen in ERA5 and the CESM2-LE (Figs. 6a,b). In contrast, LHF features strong non-linearities in both in~~ CESM2 and ERA5 (Figs. 6c,d). Most ~~precedented and~~ unprecedented heatwaves fall within the phase space covered by CESM2-LE and ERA5, ~~whereas two heatwaves (U4 & U8)~~ but heatwaves from the parent ensemble P2 (model year 2031) fall outside the range covered by ERA5 and are only similar to a single ~~event in the heatwave in~~ CESM2-LE. ~~This is again,~~ presumably due to their lower absolute values in SM ~~, as described in~~ (Sect. 3.2).

The only variable that does not ~~nicely~~ fall into any of ~~these the three mentioned~~ categories is SSR, which shows a ~~generally solid positive linear~~ substantial positive correlation with TM, ~~particularly in ERA5~~ (Fig. 5b). The SSR anomalies during the ~~ten unprecedented~~ unprecedented and most ~~precedented~~ heatwaves align with the most extreme heatwaves in ~~the~~ CESM2-LE; however, they are noticeably less extreme than expected from the bivariate distribution in ERA5. ~~This could be caused by differences in cloud fraction or aerosol concentration (see Sects. 3.1.1 and 3.1.2).~~ Nevertheless, the behaviours of other ~~drivers variables~~ appear to be mostly consistent with relatively weak SSR anomalies, most notably the anomalies in SHF (Fig. 6a) ~~and ω_{500} (Fig. 6g).~~ Furthermore, ~~the diurnal temperature range (TX-TN) is also quite weak and is in line with the anomalies in SSR-f) and DTR (Fig. 6h).~~ Finally, the ~~weak SSR anomaly is~~ small SSR anomalies during unprecedented heatwaves are also presumably the reason why ~~the diurnal temperature range is weaker than would be~~ their DTR anomalies are smaller than expected from the SM anomaly alone (Fig. 6i).

In conclusion, most of the bivariate relationships analysed are consistent with the bivariate distributions seen in heatwaves in both CESM2-LE and ERA5, ~~indicating that they are plausible from a bivariate perspective.~~ In cases where this is not the case, ~~this discrepancy appears to the discrepancies~~ propagate to other variables in a physically consistent way. ~~However, this still raises the question of~~ This primarily concerns variables related to land-atmosphere interactions, which should be interpreted with caution given their substantial uncertainties in both CESM2 and ERA5/ERA5-Land. Furthermore, these discrepancies in part simply reflect changes in the land-atmosphere regime under climate change rather than physical inconsistencies. However, given the fact that many variables depend on more than one other variable, the bivariate approach is inherently limited in its ability to reliably detect multivariate outliers. This is therefore studied more thoroughly below.

3.3.2 Multivariate relationships

We now investigate how consistent the TM anomalies during the unprecedented (~~and precedented~~) heatwaves are given the combinations of anomalies in multiple different drivers.

3.4 Multivariate perspective

~~To address this question, we now analyse whether these heatwaves are consistent from a multivariate perspective. To this~~
680 ~~this~~ end, we employ a simple multilinear statistical model that infers the 30-day temperature anomaly based on the 30-day anomalies in ~~a subset of~~ five physical drivers: Z500, U500, V500, SM, and SSR. This selection is to some extent inherently arbitrary; it represents a compromise between model simplicity, predictor independence, and explained variance (see Sect. ??
~~for details~~).

2.6). We use six different versions of the multilinear model, separately trained to infer TM, TX, and TN based on heatwaves
685 in ~~the~~ CESM2-LE and ERA5, respectively. These different ~~versions of the model are then~~ model versions are used to infer ~~the~~ 30-day anomalies in TM, TX, and TN ~~; respectively, during the ten during preceded and~~ unprecedented heatwaves based on ~~the~~ anomalies in the five predictors (Fig. 7). The ~~model trained on the~~ CESM2-LE trained model is primarily used to assess ~~the internal consistency of unprecedented heatwaves. The model trained on internal consistency, while the~~ ERA5 ~~also evaluates these unprecedented heatwaves in terms of precedent, that is, trained model evaluates~~ whether the processes during
690 these heatwaves are in line with those during ~~observed historical heatwaves~~ historical heatwaves in reanalysis.

If both the CESM2-LE and ERA5 trained models are able to infer the temperature anomalies of unprecedented heatwaves based only on anomalies of the five drivers, this suggests that the magnitudes of these heatwaves are explained by well-established physical processes that behave linearly even outside the training data and across different models, supporting plausibility. Conversely, non-linearities of land-atmosphere interactions discussed above could cause some discrepancies between actual
695 and inferred temperature anomalies. However, the model should still be able to infer a large fraction of the temperature anomaly from the other drivers (and the linear component of SM), particularly given the high explained variance within the training data. Therefore, substantial overestimations or underestimations of temperature anomalies by a model would question the plausibility of the heatwave from a multivariate perspective. In this way, the multilinear model serves as a more quantitative and holistic assessment of plausibility from a multivariate perspective compared to the more qualitative, bivariate assessment in the previous
700 section.

~~These models capture around 60–65~~ Our multilinear models capture 80–85 % of the variance in ~~TN, around TX,~~ 75 % in TM, ~~and around 80–85~~ but only 60–65 % ~~in TX~~ of the variance in TN. The lowest explained variance in TN is not surprising, because it is more strongly affected by processes not directly captured in our model, such as the downwelling longwave radiation from water vapour and clouds. Although our models explain the majority of the variance in the training data and
705 thus perform well on average, they tend to underestimate the magnitude of the most extreme heatwaves, both for the training data and ~~for the unprecedented the (un)precedented~~ heatwaves to which ~~it is~~ they are applied. This is not surprising given that (1) the models are trained to perform well in the most extreme heatwave in an average summer and are thus affected by regression to the mean, and (2) our simple least-squares approach neglects uncertainty in the independent variable and is thus sensitive to regression dilution (Pitkänen et al., 2016). This behaviour is further favoured by the strongly non-linear
710 nature ~~in particular~~ of land-atmosphere interactions and our omission of several relevant variables to achieve model simplicity. However, the main goal here is not to perfectly capture all processes affecting TM anomalies, but rather to assess whether

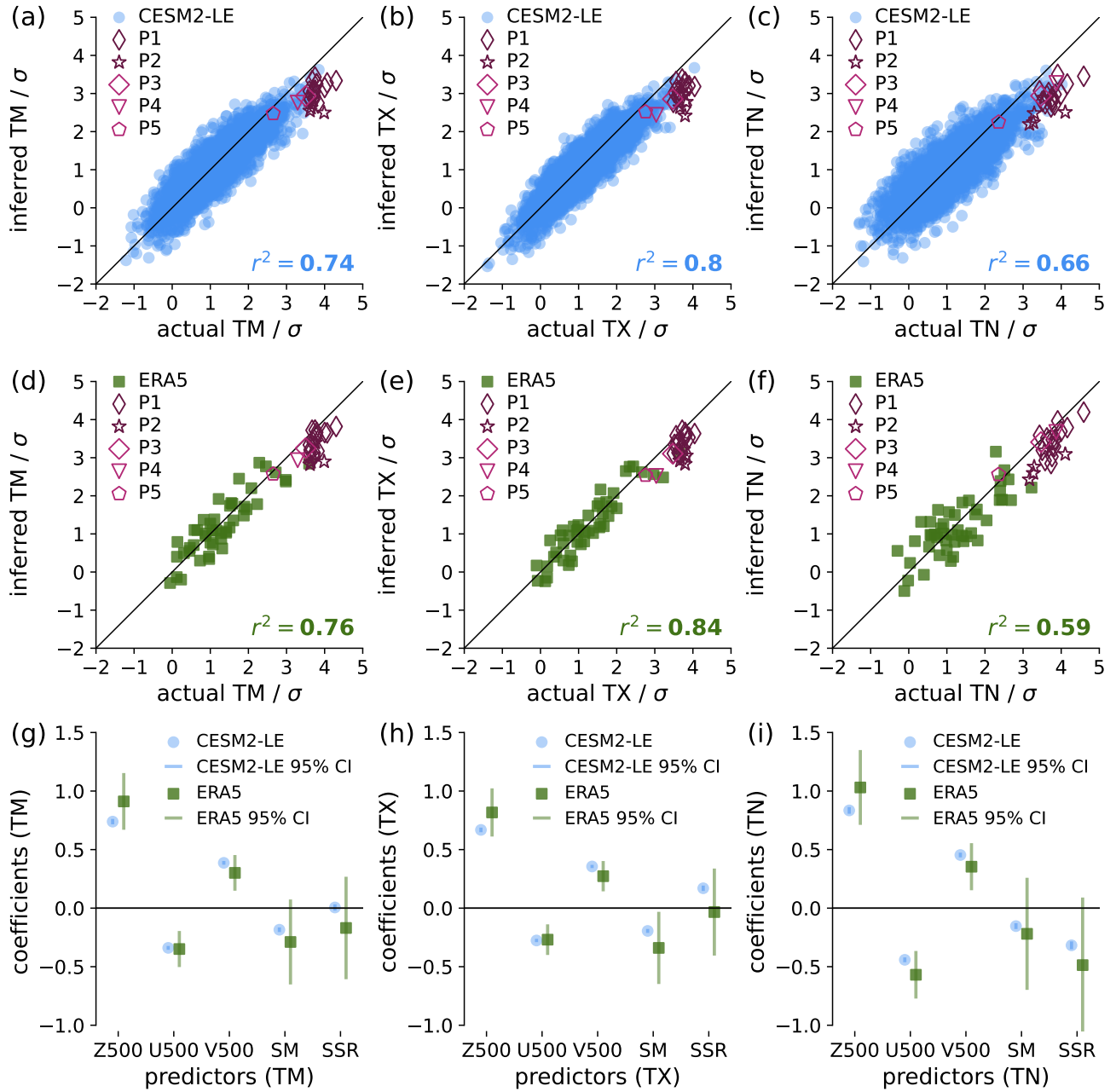


Figure 7. Actual anomalies of TM (a,d), TX (b,e), and TN (c,f) and anomalies inferred using our multilinear statistical model. Shown are the training data, namely the annual maxima of 30-day TM anomalies in WE during the summer season (JJA) in ~~the~~ CESM2-LE (a–c, blue circles) and in ERA5 (d–f, ~~yellow-green~~ squares), respectively. The model is applied to 30-day anomalies of TM, TX, and TN in WE during ~~the~~ unprecedented heatwaves U1–U10 (~~red numbers~~ purple) and precedented heatwaves (pink). For reference, the 1:1 line and the explained variance r^2 of each model are also shown. The regression coefficients of each predictor and their 95 % confidence intervals (CI) are compared for TM (g), TX (h), and TN (i).

the ~~ten~~ unprecedented heatwaves behave similarly in a multivariate phase space compared to other ~~simulated or observed~~ ~~heatwaves~~ heatwaves in climate models and reanalysis. In Fig. 7, this corresponds to the question whether the data points of the unprecedented heatwaves behave consistently with the most extreme heatwaves in the training data.

715 In general, ~~most unprecedented heatwaves appear to behave~~ precedented and unprecedented heatwaves behave remarkably similarly to heatwaves in both CESM2-LE and ERA5. ~~In other words, although their magnitude is~~ Although their magnitudes ~~are underestimated by our model, this underestimation models, this underestimate~~ are underestimated by our ~~model, this underestimation models, this underestimate~~ is similar to the ~~underestimation underestimate~~ of the most extreme heatwaves in the training data. ~~The magnitude of U5 and especially U4 is~~ For some heatwaves from parent ~~P2, the magnitudes are~~ P2, the magnitudes are underestimated more strongly than comparable heatwaves in the training data; however, the magni-
720 tude of the deviation from the 1-1 line is still comparable to the differences found for less extreme heatwaves in the training data. ~~The underestimation of U4 is presumably enhanced by its lower absolute value of SM~~ This underestimate is presumably ~~related to non-linear shifts in the land-atmosphere interaction regime~~, as discussed in Sect. 3.2. Five of the six models include training data heatwaves of comparable magnitude to the unprecedented heatwaves, that is, the anomalies during ~~U1–U10~~ the ~~unprecedented heatwaves~~ unprecedented heatwaves only slightly exceed the most extreme heatwave in the training data. However, the TN anomalies
725 of ~~U1–U10~~ many unprecedented heatwaves are far more extreme than any heatwave in ERA5 (Fig. 7f). ~~Remarkably, despite~~ Despite this fact, the ~~model trained on~~ ERA5 trained model only slightly underestimates the TN anomalies of the unprecedented heatwaves. This shows that these unprecedented heatwaves ~~, despite their record-shattering magnitude,~~ are governed by processes very similar to those of historical heatwaves.

Another way to assess plausibility from a multivariate perspective is through the model coefficients (Fig. 7g–i). In general,
730 the differences in coefficients between the different prognostic variables exhibit physically reasonable behaviour. For example, the SSR coefficient is most positive for TX and most negative for TN, presumably due to the associated lower ~~cloud cover~~ during the night ~~nighttime cloud cover~~. These two effects appear to largely cancel, which is why the effect of SSR on TM is much smaller than that of the other variables analysed. Furthermore, SM seems to play a larger role for TX than for TN, presumably as a result of surface heat fluxes induced by solar heating during the day. In contrast, the coefficients of the
735 adiabatic and advective variables (Z500, U500, V500) are much stronger for TN than for TX. The coefficients for the models trained on CESM2-LE and ERA5 are generally similar ~~; they and~~ lie within their respective 95 % confidence intervals ~~for all~~ configurations. Compared to ERA5, CESM2 has less positive Z500 coefficients, more positive V500 coefficients, less negative SM coefficients, and systematically higher SSR coefficients (more positive for TX, less negative for TM and TN). However, these differences should ~~be interpreted with care~~ not be overinterpreted, given the large confidence intervals ~~of the model~~ coefficients trained on ERA5 for the ERA5-trained model, caused by the small sample size and the high collinearity between SSR and SM in ERA5 (not shown).

To further investigate the role of non-linearities in land-atmosphere fluxes, we use the same model setup to predict SHF, LHF, and EF based on TM, SM, and SSR (see Sect. 2.6, Fig. B4). For SHF, the multilinear models capture 80–90 % of the variance in the training data, a surprisingly high value given that the models do not contain information on the near-surface wind
745 (Fig. B4a,d). The CESM2-LE trained model performs decently in inferring SHF during (un)precedented heatwaves, while the ERA5 trained model systematically overestimates SHF during these heatwaves. For LHF, the multilinear model only explains

40–60 % of the variance (Fig. B4b,e). This is presumably due to missing information about near-surface wind and humidity and due to non-linearities between SM and LHF, visible from the strong deviations from the 1:1 line at large negative LHF anomalies for the CESM2-LE model in particular. These effects also affect EF, but to a somewhat lesser extent (Fig. B4c,f).

750 These multivariate models confirm that the surface fluxes during the preceded heatwave P4, which lie outside the respective bivariate distributions, are predicted reasonably well by the CESM2-LE trained model, but not by the ERA5 trained model — not surprising given different parametrisations of surface fluxes in CESM2 and ERA5. This is also apparent from the very different model coefficients of our multilinear model (Fig. B4g–i), demonstrating that, even in anomaly space, one should be careful in directly comparing them. Given the comparatively poor performance of our multilinear models in inferring surface fluxes during preceded and unpreceded heatwaves, it is remarkable that our models perform as well as they do in inferring temperature anomalies during the same heatwaves. This is particularly notable for the ERA5 trained model, given the demonstrated discrepancies in the treatment of surface fluxes compared to CESM2. This demonstrates that, despite the presence of non-linearities in land-atmosphere interactions, temperatures during unpreceded heatwaves can be well explained by a linear combination of five predictors. This solidifies that it is in fact “extreme anomalies of common drivers” acting in an approximately linear way to cause these heatwaves.

760 In summary, all of our model versions can infer temperature anomalies during the unpreceded heatwaves with ~~an accuracy comparable to that of~~ accuracies similar to those in the training data itself. Remarkably, this includes the ~~the~~. This suggests that the linear combination of five drivers can explain most of the magnitude of the unpreceded heatwaves, and that, even very far in the tail, non-linearities appear to play a secondary role. Within CESM2, this is not entirely surprising, but, given substantial tuning to represent the mean climate state, it is still an important finding that internal consistency of physical processes still holds for extremes far in the tail. Remarkably, this consistency even applies to model versions trained only on historical heatwaves in ERA5, showing that the multilinear model is robust across training data from different physical models. We can thus conclude that, although these unpreceded heatwaves are far more extreme than the most extreme historical heatwaves, they ~~are externally consistent~~ appear to be internally consistent and have external empirical support from a multivariate perspective.

4 Discussion & Limitations

~~We demonstrate the feasibility of our process-based plausibility assessment approach for heatwaves, since these represent the extreme events with~~

3.1 Temporal substructure

775 The analyses above have exclusively focused on temporal averages over the entire 30-day durations of the unpreceded heatwaves. While this contains valuable information about the mean state during these heatwaves, it can average out variations on shorter time scales, and is thus inherently limited in fully assessing the relevant underlying processes. In the following, we therefore focus on the temporal substructure of unpreceded heatwaves on the daily timescale.

3.1.1 Temperature budget analysis

780 First, we perform a Eulerian temperature budget analysis at the 850 hPa level, disentangling the advective, diabatic, and
adiabatic contributions to historical and recent heatwaves in ERA5 and to precededented and unprecedented heatwaves in CESM2
(Fig. 8, see Sect 2.4). In this analysis, the plausibility of unprecedented heatwaves would be confirmed by local temperature
tendencies that occur due to similar physical processes, whereas it would be questioned for substantially different underlying
processes. We average the tendencies separately for days with increasing local temperature (“warming days”, Fig. 8a) and
785 decreasing local temperature (“cooling days”, Fig. 8b). Because the analysis is based on absolute values rather than anomalies,
it is subject to systematic model biases. However, the local tendencies during the heatwaves analysed are generally quite
similar, allowing for a comparison of the relative importance of the underlying processes.

During warming days, unprecedented heatwaves feature weaker adiabatic warming than ERA5 heatwaves. This difference
is small for heatwaves from the P1 ensemble, but exceeds 50 % for the five heatwaves from the P2 ensemble. During the three
790 precededented heatwaves P3–P5, the adiabatic contribution is very similar to ~~the most solid understanding of the underlying
physical processes. In principle, our approach can also be applied to other extreme events, but it should be noted that the
physical drivers of these events are less well understood and in some cases less straight-forward to implement in our framework.~~
ERA5 heatwaves. Conversely, there is net diabatic cooling during ERA5 heatwaves, presumably dominated by longwave
radiation and evaporation, but net diabatic warming during unprecedented heatwaves. This is particularly pronounced for P2
795 heatwaves, consistent with their extreme anomalies in SM and SHF, while the precededented heatwaves P3–P5 feature net diabatic
cooling, consistent with their much less extreme anomalies in SM and SHF (Fig. 5i). The zonal and meridional advective
tendencies are smaller in magnitude, with ERA5 heatwaves featuring net meridional warming rather than cooling, but also
non-negligible positive residuals.

During cooling days, temperature tendencies are dominated by advective cooling, but while ERA5 heatwaves feature strong
800 zonal cooling and weak meridional warming, unprecedented heatwaves feature weak zonal and meridional cooling. Again,
precedented heatwaves are more similar to ERA5 heatwaves in this respect. Furthermore, CESM2 heatwaves feature close to
zero adiabatic contributions, in contrast to substantial adiabatic cooling during ERA5 heatwaves. The diabatic tendencies are of
smaller magnitude than during warming days, but feature the same discrepancies regarding their signs. However, the residual
terms are substantial and of opposite sign, and thus these results should be interpreted with caution.

805 Overall, we find that the unprecedented heatwaves in CESM2 are caused by stronger diabatic and weaker adiabatic tendencies
than historical heatwaves in ERA5. This is in line with the findings of Röthlisberger et al. (2026) who found biases of CESM2
relative to ERA5 based on Lagrangian backward trajectories that are consistent with the differences found here. However,
the less extreme precededented heatwaves feature much more similar contributions compared with ERA5, indicating that these
results depend on the exact heatwaves analysed. Nevertheless, these discrepancies in the processes that cause unprecedented
810 heatwaves in CESM2 casts some doubt on their physical conformity. Because the discrepancies mainly concern the relative
contributions of diabatic vs. adiabatic terms, some of this can compensate to still yield similar behaviour in temperature, as
discussed below.

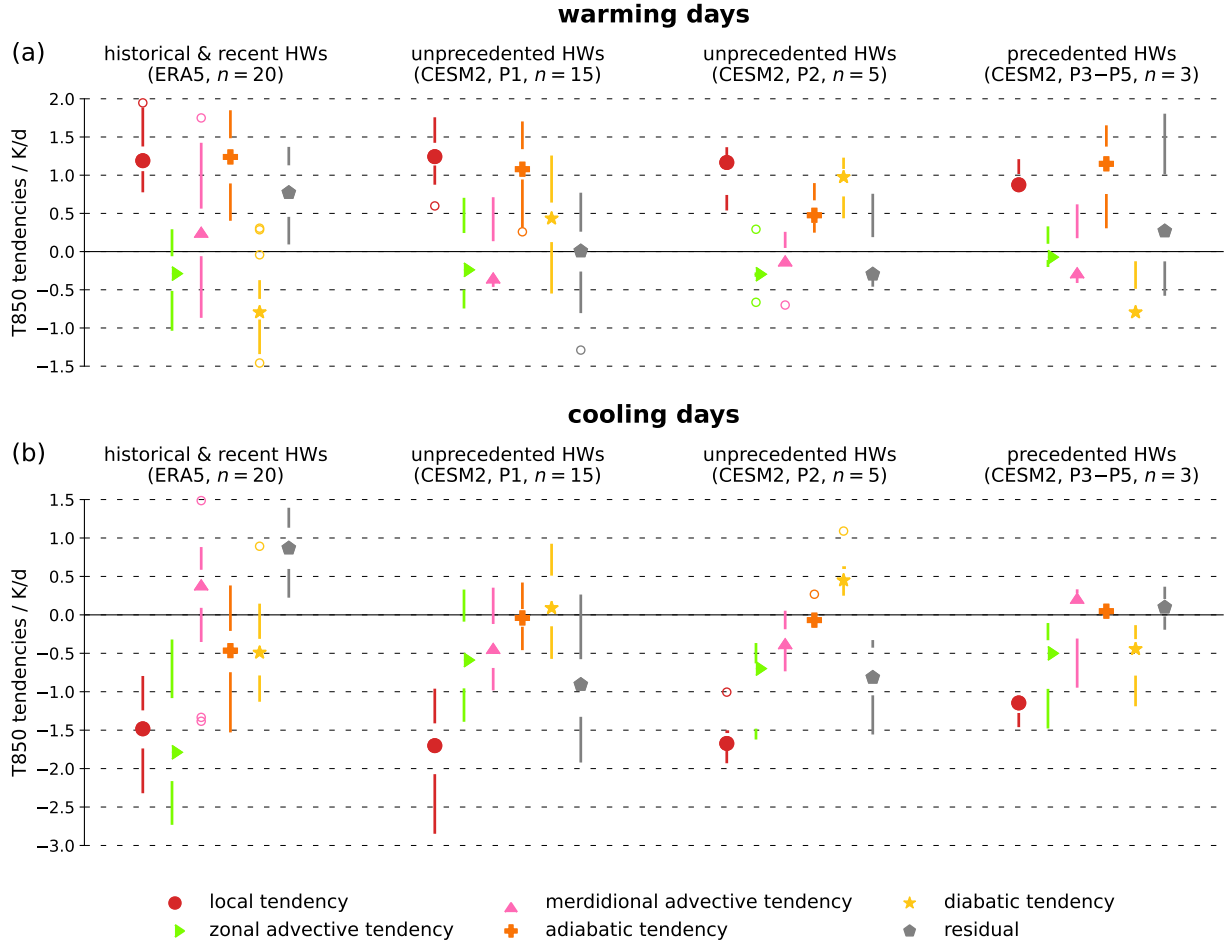


Figure 8. Tendencies of 850 hPa temperature (T850) during historical and recent heatwaves in ERA5, as well as precededented and unprecedented heatwaves in CESM2, shown separately for different parent ensembles. Shown are the terms of Eq. (2), averaged over each event during days with positive (a) and negative local T850 tendency (b): Median (filled symbols), inter-quartile range (IQR, empty space), whiskers (1.5 IQR, solid lines) and outliers (empty circles).

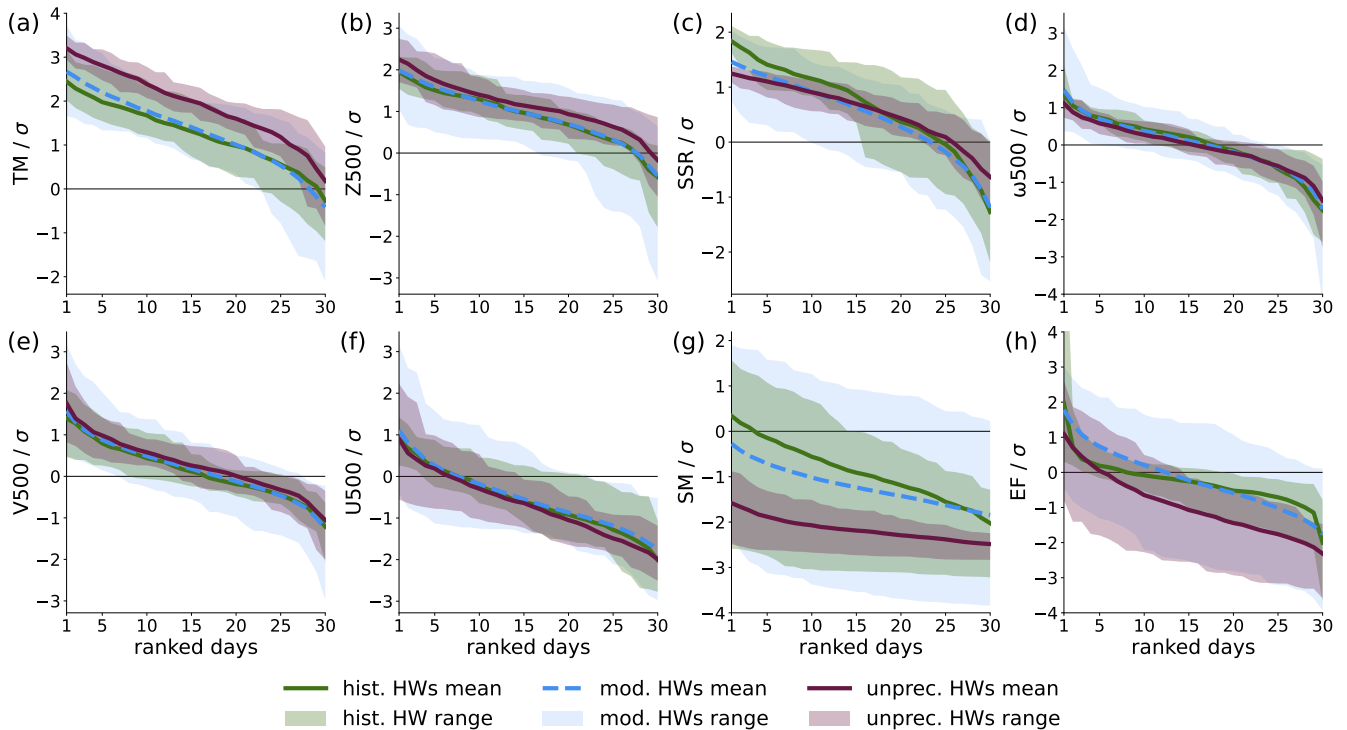


Figure 9. Ranked daily anomalies of heatwave variables. Shown are the mean (lines) and range (shading) during historical heatwaves (green), moderate heatwaves (blue), and unprecedented heatwaves (purple). Variables are sorted from highest to lowest anomalies, meaning that the most favourable conditions for heatwaves are found at low-ranked days in panels (a)–(e), but at high-ranked days in panels (f)–(h).

3.1.2 Rank anomalies

Next, we rank the daily anomalies of heatwave variables from highest to lowest within the 30-day historical, moderate, and unprecedented heatwaves (Fig. 9), similar to the approach of Röthlisberger et al. (2020). Because we rank the anomalies separately for each variable, the ranked days of the different variables do not correspond to each other. To be plausible, unprecedented heatwaves should feature similar relationships between the most extreme and least extreme daily anomalies as historical and moderate heatwaves. In contrast, unprecedented heatwaves dominated by only a few days of outliers would be considered less plausible. For this analysis, we only consider the model effect (ERA5 vs. CESM2) and the magnitude effect (moderate vs. unprecedented heatwaves) but not the much smaller climate effect (historical vs. present climate; see Sect. 3.2). Thus, we only include moderate heatwaves from the present climate (2005–2035). The two effects are discussed below.

(1) The model effect: The temporal substructures of most variables are very similar during historical and moderate heatwaves of the same magnitude (TM, Z500, ω_{500} , V500, and U500; Figs. 9,a,b,d,e,f), with three notable exceptions. (a) SSR anomalies on the sunniest days are less positive in moderate heatwaves (ranked days 1–15 in Fig. 9c). As discussed above, this is presumably related to differences in cloud fraction, indicating that even on the sunniest days, CESM2 might still simulate

some cloud cover. It might also be affected by different aerosol concentrations, as aerosol-radiation interactions are most important on days with low cloud cover. (b) SM anomalies on less dry days are more negative in the moderate heatwaves, suggesting discrepancies in the persistence of agricultural droughts in CESM2 (ranked days 1–20 in Fig. 9g; see Sect. 3.1.3). (c) EF anomalies exhibit more strongly positive and more strongly negative daily anomalies in moderate heatwaves, while most daily anomalies during historical heatwaves are much closer to zero (Fig. 9h). This discrepancy presumably reflects differences in the parametrisation of surface heat fluxes between ERA5 and CESM2.

(2) The magnitude effect: Features (a)–(c) appear to be model specific, as they can also be detected for the unprecedented heatwaves. In addition, unprecedented heatwaves unsurprisingly feature substantially greater daily TM anomalies throughout the 30-day period than moderate heatwaves, with a weaker shift on the coolest days (ranked days 25–30 in Fig. 9a). Most other variables also exhibit very similar daily anomaly distributions between moderate and unprecedented heatwaves (Z500, SSR, ω 500, V500, and U500; Figs. 9b,c,d,e,f). For Z500, unprecedented heatwaves exhibit a shift of the ranked anomalies towards more positive values for days of weaker Z500, indicating more persistent anticyclones (ranked days 20–30 in Fig. 9b). For V500 and ω 500, the temporal substructures reveal that their small 30-day mean anomalies are partially due to the long averaging period; short-term periods of southerly wind or vertical subsidence are largely cancelled out by periods of negative anomalies as the anticyclone itself moves (Fig. 9d,e). SM anomalies are more negative during unprecedented heatwaves throughout the 30-day periods, but particularly for less dry days (ranked days 1–20 in Fig. 9g). This suggests that it is the persistence of low SM, rather than the driest SM days, that makes the unprecedented heatwaves so exceptional. Interestingly, this behaviour is not mirrored by EF, whose shift towards more negative anomalies is strongest for days with intermediate and low EF anomalies (ranked days 10–25 in Fig. 9h), which might be partially explained by the smaller SSR anomalies on sunny days.

To assess how representative these results are, we repeat this analysis for the three preceded heatwaves from three different parent ensembles (Fig. B5). Although the small sample size means that the results should not be overinterpreted, we find that most variables again feature similar daily anomaly distributions (TM, Z500, ω 500, V500, U500) and that the daily anomalies in SM and EF show the opposite behaviour of the unprecedented heatwaves, with uniform shifts to substantially less negative (or even positive) anomalies throughout their duration. This suggests that the much less dry soil is primarily responsible for the less extreme TM anomalies compared to the unprecedented heatwaves.

Overall, the temporal substructures of most variables are internally consistent within CESM2 and have external empirical support from historical precedent in ERA5. The most notable exception is the apparent overestimation of persistence in SM anomalies by CESM2, which will be analysed in more detail next.

3.1.3 Persistence

Finally, we evaluate the temporal persistence of relevant heatwaves variables, comparing the occurrence of periods in which the anomalies of TM and Z500 exceed $+1\sigma$, and in which the anomalies of SM remain below -1σ , respectively. For this, we compare preceded and unprecedented heatwaves with historical heatwaves, as well as with the JJA distributions of ERA5 and CESM2-LE (see Sect. 2.5). With this analysis, we assess the systematic differences between ERA5 and CESM2 and the position of the unprecedented heatwaves relative to the CESM2 distribution and the historical heatwaves. Findings that would

860 support their plausibility include: (1) ERA5 and CESM2-LE exhibiting similar distributions, (2) the unprecedented heatwaves consistently remaining within CESM2-LE distribution, and (3) the persistence of the unprecedented heatwaves being higher than that of historical heatwaves, but still of roughly comparable magnitude. If one or more of these conditions are not met, this would argue against the plausibility of these heatwaves. For the persistence of TM, a systematic overestimation by CESM2 would count against plausibility, as it would indicate that a simulated heatwave occurs only due to model biases. In contrast, a
865 systematic underestimation of TM persistence by CESM2 would not necessarily suggest the same, but might instead indicate that the persistence of real-world heatwaves could even exceed that of unprecedented heatwaves.

For example, it should be quite straight-forward to apply our approach to large-scale events that can be realistically simulated in general circulation models, such as cold spells or droughts. For smaller-scale events, such as heavy convective precipitation or wind storms, high-resolution modelling may be required to test the plausibility of local processes in simulations. Z500, CESM2
870 captures the frequencies of short persistence durations (<10 days) quite well, but it substantially underestimates the frequency of longer persistence durations (Fig. 10a). The discrepancy is even more pronounced when we compare the persistence of atmospheric blocking (Fig. 10b, Sect. 2.5). CESM2 strongly underestimates the occurrence of consecutive blocked days for short persistence durations and even more strongly for long persistence durations. This systematic underestimate of persistent atmospheric blocking regimes in CESM2 also seems to affect the unprecedented and preceded heatwaves. Although they
875 tend to exhibit longer persistence durations with respect to 1σ -threshold exceedances of Z500 anomalies than historical heatwaves, the picture is almost exactly reversed for consecutive blocked days, except for only the preceded P3 heatwave. This is consistent with previous findings that global circulation models (GCMs) struggle to reproduce persistent blocking regimes (Tibaldi and Molteni, 1990; Davini and D'Andrea, 2016; Liu et al., 2022).

Furthermore, there are a number of caveats and limitations of our approach that should be considered. First, while
880 The opposite phenomenon can be seen for SM, where CESM2 simulates a higher frequency of long persistence durations (>15 days). Furthermore, while preceded heatwaves feature persistence durations comparable to historical heatwaves, unprecedented heatwaves feature persistence durations up to three times longer (Fig. 10c). Presumably, this is at least partially because CESM2 simulates many more negative SM anomalies relative to ERA5-Land (Fig. B6). It is also consistent with the findings of Vogel et al. (2018) that climate models tend to overestimate soil drying due to land-atmosphere feedbacks.
885 Furthermore, although monthly soil moisture memory is generally well represented in GCMs, there are substantial regional and intermodel differences (Seneviratne et al., 2006).

The net effect of these two processes can be seen in the persistence of TM, where CESM2 and ERA5 simulate very similar occurrences of short persistence durations (Fig. 10d). CESM2 underestimates the occurrence of longer persistence durations in TM, but the differences relative to ERA5 are smaller than for Z500 and SM. Despite this systematic underestimate, preceded
890 and unprecedented heatwaves on average feature longer persistence durations in TM than historical heatwaves.

Overall, CESM2 struggles to accurately capture persistence durations relative to ERA5, with substantial discrepancies between the roles of diabatic contributions (related to persistence of SM) and adiabatic contributions (related to persistence of Z500), as already shown above. Thus, unprecedented heatwaves simulated by CESM2 occur for “partly the wrong reasons”, in line with previous findings (Röthlisberger et al., 2026). These limitations of CESM2 in simulating the physical processes

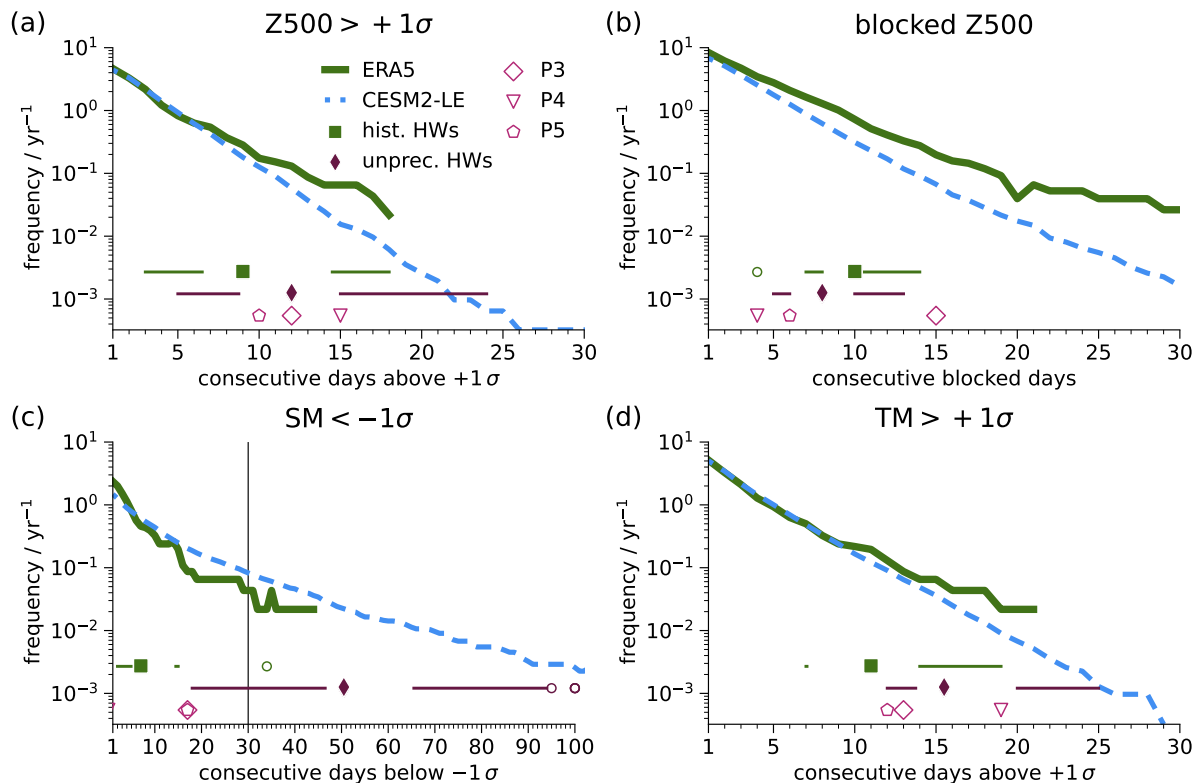


Figure 10. Persistence of selected heatwave variables. (a,c,d) Number of consecutive days in JJA with daily anomalies $> +1\sigma$ (TM and Z500) or $\leq -1\sigma$ (SM). Shown are the relative frequencies in ERA5 (green) and CESM2-LE (blue), and box plots of values during historical heatwaves (green) and unprecedented heatwaves (purple): Median (filled symbols), inter-quartile range (IQR, empty space), whiskers (1.5 IQR, solid lines) and outliers (empty circles). The values during the preceded heatwaves from other parent heatwaves are also shown (pink symbols). Note the different x-axis for SM in panel (c). (b) As panel (a), but showing the number of consecutive blocked days (Sect. 2.5.)

895 causing long persistence durations consistently with historical precedent raise concerns regarding the physical conformity —
and thus the overall plausibility — of the unprecedented heatwaves. Nevertheless, despite these discrepancies in the underlying
processes, the discrepancies in the persistence of TM itself are comparatively smaller. Given that CESM2 underestimates the
persistence of TM and only a few unprecedented heatwaves feature longer TM persistence durations than seen in the short
reanalysis record, this suggests that heatwaves with comparable or even longer persistence of TM are plausible to occur in the
900 real world, although with different roles for diabatic and adiabatic processes. In fact, we argue that these heatwaves might even
represent a conservative estimate for worst-case long-lasting heatwaves in terms of their persistence in TM.

4 Discussion

Our assessment of plausibility is mostly based on standardised anomalies, which is essential to meaningfully compare extremes occurring in different background climates. By construction, this approach removes systematic differences in mean state and variability between CESM2 and ERA5. Thus, our assessment that extreme heatwaves simulated in CESM2 are plausible to occur in the real world refers primarily to standardised anomalies rather than to the absolute physical state. This means that even for plausible heatwaves, absolute values should be treated with caution, an important caveat given that impact studies are generally based on absolute thresholds rather than anomalies. Thus, it remains essential to perform a bias correction of the raw model output when model-based storylines are used for stress testing and disaster preparedness (Lüthi et al., 2024).

Although standardised anomalies correct for many model biases in mean state and variability, some systematic differences remain. Compared to observations, GCMs tend to overestimate soil drying during heatwaves due to differences in the representation of land-atmosphere feedbacks (Vogel et al., 2018). Furthermore, the atmospheric circulation in GCMs is too zonal, that is, GCMs systematically underestimate the occurrence and persistence of atmospheric blocking, a major driver of heatwaves (Tibaldi and Molteni, 1990; Davini and D'Andrea, 2016; Liu et al., 2022). These biases can partially compensate, leading to simulated heatwaves that occur for “partly the wrong reasons” (Sects. 3.1.1 and 3.1.3; Röthlisberger et al., 2026).

Furthermore, although we often refer to the non-temperature variables analysed as heatwave “drivers”, it is not always possible to cleanly separate cause and effect. For example, soil moisture can cause temperature anomalies, but can also be amplified by them through land-atmosphere feedbacks (Seneviratne et al., 2010). Therefore, one must be careful in asserting causality ~~when interpreting anomalies in associated variables during heatwaves~~, especially at a monthly time scale. For this reason, we further analyse the partitioning of latent and sensible heat flux in the evaporative fraction and focus on internal consistency rather than causal relationships.

Another caveat ~~already alluded to above~~ concerns the use of monthly regional anomalies in V500, ω 500, and SHF ~~in WE~~ as proxies for temperature advection, adiabatic ~~sinking~~ subsidence, and diabatic warming ~~which in some of our assessments~~. ~~This neglects upstream and non-local processes. Furthermore, it is an oversimplification because it neglects the vertical variations of these variables throughout, and vertical variations in~~ the atmosphere (Hotz et al., 2024). ~~This can only be properly accounted for by taking a Lagrangian approach of calculating back-trajectories of air parcels within the heatwave region, as for example done by~~ For further studies, our approach could therefore be complemented by a more comprehensive analysis of the underlying atmospheric dynamics, for example, using Lagrangian backward trajectories or circulation-regime diagnostics (Röthlisberger and Papritz, 2023; Hochman et al., 2021). Our Eulerian approach ~~has the advantage that it is~~ is motivated by two main arguments: (1) It is much easier and less computationally expensive to implement and could therefore realistically be included in an operational assessment of plausibility (Kelder et al., 2022a). ~~However, it should be noted that this Eulerian approach might be less appropriate when analysing other types of extreme events, such as heavy precipitation or wind storms, particularly at short~~ (2) The stationarity of the weather systems required to produce heatwaves on a monthly time scale makes the Eulerian approach much more suitable than for heatwaves or other extreme events occurring on shorter time scales. ~~In contrast, extremes on a monthly time scale might lend themselves more naturally to a Eulerian perspective due to the required persistence and stationarity of the associated weather systems~~

In order to still gain more insights into the underlying processes, we perform a Eulerian temperature budget analysis, but this also comes with a few caveats: Our focus on the 850 hPa level reduces the effects of topography, but does not remove them. This leads to large residuals over mountain ranges, which is why we exclusively evaluate the temperature budget for the regional WE mean. Furthermore, focusing on the 850 hPa level presumably underestimates the diabatic contributions of land-atmosphere exchanges, which are strongest close to the surface. Furthermore, the systematically opposite signs of both the diabatic contribution and the residuals between CESM2 and ERA5 might reflect differences in the parametrisations underlying the diabatic tendencies. Finally, part of the non-negligible residual terms are presumably explained by our use of daily time steps, whereas the spatial resolution of the model output seems to play only a secondary role for the regional WE mean budget.

As indicated earlier, finding historical analogues Evaluating historical precedent for heatwaves in a rapidly warming climate is inherently challenging, but is made possible by our approach of considering standardised anomalies relative to a time-evolving climatology (although the issue of small sample sizes in reanalysis remains). While useful, this view can in principle obscure the fact that the same anomaly might be plausible in past climates, but not necessarily in future climates. This is particularly true for non-negative variables that can exhibit substantial non-Gaussianity, such as PREC or SM, particularly when combined with a decreasing trend over time. But it can also complicate the interpretation of negative anomalies in U500, as it is not obvious whether ~~negative U500 anomalies refer to~~ they imply weaker-than-average westerlies or ~~rather~~ easterly winds.

~~Furthermore, the~~ The time-evolving climatology itself is also subject to uncertainties. ~~For example, the~~ for example, a 30-year climatology is difficult to precisely constrain in regions ~~where the last 20–30 are with~~ unusually warm or cold ~~due to periods caused by~~ internal variability. Nevertheless, it offers clear improvements in assessing the extremeness of an event relative to the climate in which it occurred compared to a climatology based on a fixed time period.

~~In addition to this, although standardised anomalies account for many model biases in both mean state and variability, some systematic differences between~~ Another limitation concerns the inherently limited sample size of historical heatwaves in the reanalysis record. Some of this might be overcome by choosing a longer data set for reanalysis, such as the Twentieth Century Reanalysis (Compo et al., 2011). However, by their very nature, unprecedented heatwaves do not have precedents of comparable magnitude in reanalysis data sets, regardless of the covered time period. Furthermore, due to much sparser observations in the first half of the twentieth century, such reanalyses are much less constrained by observations and instead rely much more heavily on the underlying physical model, leading to additional uncertainties and potential biases.

For related reasons, it is important to be careful when comparing surface energy variables between CESM2 and ERA5 ~~are harder to remove. For example, compared to observations, GCMs tend to overestimate soil drying during heatwaves due to differences in the representation of~~. Although temperature and circulation variables in reanalysis are strongly constrained by observations, this constraint is much weaker for variables related to the surface energy budget, such as SHF, LHF, and SM. Instead, their values are strongly affected by the atmospheric and land surface models and parametrisations of land-atmosphere ~~feedbacks (Vogel et al., 2018). The atmospheric circulation in GCMs is also known to be “too zonal”, that is, they systematically underestimate the occurrence and persistence of atmospheric blocking — a major driver of heatwaves (Tibaldi and Molteni, 1990; Davini and D’Andrea, 2016; Liu et al., 2022). As shown in Sect. 3.1, these biases can partially~~

compensate, leading to simulated heatwaves that occur for “partly the wrong reasons” (?). Despite these limitations, our analysis of the different underlying processes shows that simulated unprecedented heatwaves cannot be ruled out as implausible. Nevertheless, this does not mean that the simulated temperatures during these heatwaves should be taken at face value; rather, it is still important to perform a bias correction when, for example, studying the impact of a heatwave (Lüthi et al., 2024) interactions used; furthermore, ERA5 fails to close the surface energy budget (Hersbach et al., 2020; Muñoz-Sabater et al., 2021). Therefore, reanalysis values of these variables should not be considered as “ground truth” but instead be interpreted cautiously. Our anomaly-based approach is designed to correct for many of these discrepancies, including biases in the mean and variance of surface variables, but not for differences in higher-order moments of the distributions.

We demonstrate the feasibility of our process-based plausibility assessment approach for heatwaves, because these are the extreme events with the most solid understanding of the underlying physical processes. In principle, our approach can also be applied to other extreme events, but it should be noted that the physical drivers of these events are less well understood and in some cases less straight-forward to implement in our framework. For example, it should be quite straight-forward to apply our approach to large-scale events that can be realistically simulated in general circulation models, such as cold spells or droughts. For smaller-scale events, such as heavy convective precipitation or wind storms, high-resolution modelling is required.

~~For simplicity~~ Finally, all unprecedented heatwaves analysed in this study are based on a single model (CESM2). ~~However, given the~~ Given well-documented intermodel differences among GCMs, ~~it would be very valuable to repeat this~~ inherently limits the generalisability of our results. Our approach presented here can serve as a blueprint for performing similar analyses with other models, which would be very valuable to allow conclusions to be made less dependent on the specific climate model. In particular, models that have already been used to create climate storylines should be evaluated in this way, which could provide a better picture of how plausible extreme ~~events~~ heatwaves they simulate are.

5 Conclusions

We present a process-based approach to assess the plausibility of unprecedented climate storylines. ~~We and~~ apply it to month-long heatwaves in Western Europe that would exceed the most extreme historical heatwaves by ~~around more than~~ 5 K (Lüthi et al., 2024). ~~Our approach uses standardised anomalies relative to a time-evolving climatology of various heatwave drivers and compares them between simulated unprecedented heatwaves and historical heatwaves. We compare the ten most extreme. We compare 20 unprecedented~~ month-long heatwaves in Western Europe from CESM2 ensemble boosting simulations with the ~~ten~~ most extreme historical ~~month-long~~ heatwaves in ERA5 ~~relative to the respective background climate using standardised anomalies relative to a time-evolving climatology.~~

The ~~anomalies of most heatwave drivers are slightly more intense on average during the unprecedented heatwaves, but they are comparable in magnitude and~~ unprecedented heatwaves are associated with physical drivers well-known from less extreme heatwaves in climate models and reanalysis, including strong anticyclones, low levels of soil moisture, and high values of surface solar radiation, demonstrating the physical conformity of these heatwaves. Compared to historical heatwaves, the anomalies in these drivers are unusually extreme, leading to the conclusion that these unprecedented heatwaves are caused

1005 by “extreme anomalies of common drivers” (Fischer et al., 2021). Furthermore, the studied physical drivers are very similar in temporal substructure to observed historical heatwaves, their spatial patterns, and in their relationships with each other, demonstrating that they are internally consistent.

However, CESM2 underestimates the persistence in Z500, while it overestimates the persistence in SM, indicating that the long persistences of these systematically underestimates adiabatic contributions, including persistent blocking anticyclones, and overestimates diabatic contributions, primarily land-atmosphere interactions, and it is similarly biased in their respective temporal persistence. This indicates that unprecedented heatwaves occur for “partly the wrong reasons”(?). On the whole, a known weakness of climate models (Röthlisberger et al., 2026; Vogel et al., 2018). These discrepancies raise some doubts about the physical conformity of CESM2 to simulate unprecedented long-lasting heatwaves. However, the fact that CESM2 systematically underestimates the frequency of long temperature persistence, indicating that even longer-lasting heatwaves could be plausible to occur in the real world. Finally, the unprecedented heatwaves are also consistent internally within CESM2 and externally compared to ERA5 when analysed from a multivariate perspective, indicating that they are caused by “extreme anomalies of common drivers” (Fischer et al., 2021). Overall, despite some discrepancies between the unprecedented heatwaves and the historical heatwaves, our analysis shows that the drivers and characteristics of these heatwaves conform with physical principles, are internally consistent and align well with historical precedents. From this we conclude that these unprecedented heatwaves cannot suggests that, if anything, the simulated temperature persistence during these unprecedented heatwaves might represent a conservative estimate of what worst-case heatwaves in the real world might look like, which is an important consideration for disaster preparedness. We therefore conclude that such unprecedented heatwaves should not be ruled out as implausible, and thus such events but rather should be included in risk assessments when preparing adaptation measures, ideally using bias-corrected model output.

1025 The possible There are many ways to assess the plausibility of extreme weather and climate events are as diverse as the exact definition of plausibility itself (van der Helm, 2006). With our approach presented here, we show a way to perform this assessment that builds on existing approaches (Vautard et al., 2019; Kelder et al., 2022b) and on our understanding of the relevant physical processes during heatwaves developed by. Our process-based approach complements existing methods and builds on understanding the community over the years (Barriopedro et al., 2023). Although the exact methodology needs to be modified depending on the type of extreme event that is analysed underlying physical processes. Future studies could expand on our approach by using Lagrangian methods to study the atmospheric dynamics during unprecedented heatwaves. Furthermore, our methodology would also have to be adjusted before it can be applied to other types of extreme events. Nevertheless, our approach contains many several important ingredients that can provide powerful insights into the plausibility of different extreme events. This includes the use of a time-evolving climatology to meaningfully compare anomalies across different background climates, as well as a multivariate perspective that provides a holistic picture of the underlying dynamics of unprecedented events.

Focusing on plausibility rather than probability of unprecedented events is useful in a wide range of fields, ranging from epidemiology to economics (Derbyshire, 2022; Goodwin and Wright, 2010). This is because studying extreme events that are considered plausible — irrespective of their probability of occurrence — allows for the exploration of future scenarios

1040 while embracing inherent uncertainties (Selin and Guimarães Pereira, 2013). Therefore, studying plausible future extremes is essential for providing tangible what-if scenarios that are needed to educate disaster preparation.

Code and data availability. The code used to perform the analysis is available at <https://doi.org/10.5281/zenodo.19492889> (Roemer et al., 2026a). Pre-processed data to reproduce the figures is available at <https://doi.org/10.5281/zenodo.19494785> (Roemer et al., 2026b). CESM2-LE data are publicly available from the NSF NCAR Geoscience Data Exchange at <https://gdex.ucar.edu/datasets/d651056/> (Danabasoglu et al., 2020; Rodgers et al., 2021). Reanalysis data is publicly available from the Copernicus Climate Change Service Climate Data Store: ERA5 data on pressure levels at <https://doi.org/10.24381/cds.bd0915c6> (Hersbach et al., 2023a), ERA5 data on single levels at <https://doi.org/10.24381/cds.adbb2d47> (Hersbach et al., 2023b), and ERA5-Land data at <https://doi.org/10.24381/cds.e9c9c792> (Muñoz-Sabater, 2019).

Appendix A: ~~Selected heatwaves~~

Appendix A: Ensemble boosting simulations

1050 Ensemble boosting is a computationally efficient method to simulate record-breaking extremes in the CESM2 climate model (Gessner et al., 2021). It consists of re-initialising a model run a few weeks before an extreme event and creating new ensembles based on round-off sized perturbations in the humidity field. The simulations used here are based on a 35-member CESM2 ensemble running from 2005 to 2035 under the historical (2005–2014) and SSP3-7.0 (2015–2035) scenarios (Fischer et al., 2023; Lüthi et al., 2024). From this ensemble, the five most extreme 14-day heat extremes in Switzerland (“parents”) were selected, occurring in the model years 2015, 2028, 2028, 2030, and 2031 in different ensemble members. For each parent, 100 ensemble members per day start 14–25 days before the peak of the parent event and subsequently run for 50 days, yielding 1100 alternative realisations of each parent heatwave. These simulations were already used and described by Lüthi et al. (2024).

1060 To estimate the return periods of the unprecedented heatwaves from the ensemble boosting simulations, we use a method that was specifically developed for this purpose and is described in detail by Bloin-Wibe et al. (2025). In short, this method uses the shared antecedent conditions between a boosted simulation and its parents to derive conditional probabilities of exceeding a threshold TM_{ref} and uses bootstrapping to derive the 95 % confidence interval of the estimated return period. It provides an unbiased estimate of return periods and offers clear improvements over approaches based on fitting extreme value distributions.

1065 When applying this method to our simulations, it should be noted that the parent heatwaves were selected based on the 14-day absolute TM in Switzerland, while our study considers the 30-day TM anomaly in WE. As a consequence, the five selected parent heatwaves are not among the most extreme heatwaves in the ensemble; rather, they are ranked 16th, 23rd, 133rd, 265th, and 294th in terms of their 30-day TM anomaly in WE (out of the 35 ensemble members · 31 ensemble years = 1085 simulated years; see Fig. 1b). Thus, setting TM_{ref} equal to the least extreme parent run, the antecedent conditions are sampled less efficiently than is theoretically possible, but, importantly, this does not affect the quality of the return period estimator. Return

1070 periods of heatwaves in the 35-member ensemble (including parent heatwaves) are estimated using an empirical frequency estimator based on the occurrence within the ensemble (Bloin-Wibe et al., 2025).

The ten selected unprecedented heatwaves are from ensemble members that are re-initialised 11–20 days before the peak of the 30-day TM anomaly in WE in the parent run and thus we use all ensemble members with lead times of 11–20 days to estimate conditional probabilities. Note that these lead times do not correspond directly to the lead times defined with respect to the 14-day TM in Switzerland in Sect. 2.1. All days of the unprecedented 30-day heatwaves occur after the re-initialisation and thus do not include any simulated days from the respective parent simulation.

Appendix B: Selected heatwaves

This appendix provides more detailed information ~~(exact period and 30-day TM anomalies) on the ten on~~ unprecedented and unprecedented heatwaves (U1–U10, Tab. B1) ~~and the ten~~ historical heatwaves (H1–H10, Tab. B2) ~~analysed in this manuscript. For~~ the and recent heatwaves analysed (Tab. B3). For unprecedented heatwaves, further details are given on ~~the selected ensemble members (Tab. B1), the historical analogues detected (Tab. ??), and the daily TM anomalies during the~~ daily time series of TM Z500 and SM (Fig. B1). Furthermore, 30-day anomalies of heatwave drivers during individual unprecedented, preceded, and historical heatwaves are shown (Fig. B2). We also include the temporal substructure of preceded heatwaves (Fig. B5), climatological distributions of SM in ERA5-Land and CESM2-LE (Fig. B6), and the results of our multilinear model for SHF, LHF, and EF (Fig. B4).

Furthermore, we compare unprecedented heatwaves with recent heatwaves in terms of 30-day mean absolute values and daily time series of relevant heatwave variables (Fig. B3). On average, unprecedented heatwaves are around 5 K warmer than recent heatwaves, but the 2026 heatwave exhibits an almost as high 30-day TX as some unprecedented heatwaves (Fig. B1). ~~Furthermore, we provide additional details on the PREC anomalies preceding the unprecedented~~ B3a-d). On average, the 500 hPa geopotential height is also substantially higher during unprecedented heatwaves, while the surface solar radiation (SSR) is very similar but shows substantial variability (Fig. B3e-h). Furthermore, unprecedented heatwaves occur under drier conditions with less evaporative cooling of the surface (Fig. B3i-l). Overall, although the unprecedented heatwaves are much more extreme than recent heatwaves, several variables are similar to the 2026 heatwave.

Comparing the time series of the 2026 heatwave with selected unprecedented heatwaves, we find that during the U1 heatwave ~~and its historical analogue~~, TX is strikingly similar to that of 2026 in the first and last 10 days of the respective 30-day periods, only differing noticeably between (Fig. ??), ~~as well as on the climatological differences in SM between ERA5-Land and the CESM2-LE~~ B3a). The 2026 heatwave features systematically lower values in TN and Z500 and slightly higher values in SSR compared to the unprecedented heatwaves (Fig. B3c,e,g). The 2026 heatwave starts out with a much higher SM in the beginning, but dries out strongly and exhibits SM values similar to the unprecedented heatwaves at the end of the 30-day period (Fig. B6B3i).

Table B1. ~~Ten-unprecedented~~Unprecedented (U1–U20) and precedented 30-day heatwaves in WEsimulated-using-ensemble-boosting-in CESM2. Listed are the parent heatwaves, the date of re-initialisation, the selected ensemble member, the beginning and end of the ~~selected~~ 30-day period, and the 30-day TM anomalyduring-that-period.

heatwave	parent	re-initialisation	member	day 1	day 30	TM / σ
U1	P1	2015-07-09	3	2015-07-25	2015-08-23	4.3
U2	P1	2015-07-11	37	2015-07-27	2015-08-25	4.1
U3	P1	2015-07-16	7	2015-07-30	2015-08-28	4.0
U4	P2	2031-07-12	29	2031-07-23	2031-08-21	4.0
U5	P1	2015-07-17	50	2015-07-26	2015-08-24	3.8
U6	P1	2015-07-12	62	2015-07-30	2015-08-28	3.8
U7	P1	2015-07-17	63	2015-07-23	2015-08-21	3.8
U8	P2	2031-07-13	76	2031-07-31	2031-08-29	3.8
U9	P1	2015-07-16	47	2015-07-22	2015-08-20	3.7
U10	P1	2015-07-13	6	2015-07-24	2015-08-22	3.7
<u>U11</u>	<u>P1</u>	<u>2015-07-10</u>	<u>56</u>	<u>2015-07-21</u>	<u>2015-08-19</u>	<u>3.7</u>
<u>U12</u>	<u>P1</u>	<u>2015-07-11</u>	<u>92</u>	<u>2015-07-27</u>	<u>2015-08-25</u>	<u>3.7</u>
<u>U13</u>	<u>P1</u>	<u>2015-07-10</u>	<u>74</u>	<u>2015-07-25</u>	<u>2015-08-23</u>	<u>3.7</u>
<u>U14</u>	<u>P2</u>	<u>2031-07-18</u>	<u>83</u>	<u>2031-07-31</u>	<u>2031-08-29</u>	<u>3.7</u>
<u>U15</u>	<u>P1</u>	<u>2015-07-11</u>	<u>51</u>	<u>2015-07-22</u>	<u>2015-08-20</u>	<u>3.7</u>
<u>U16</u>	<u>P2</u>	<u>2031-07-18</u>	<u>33</u>	<u>2031-07-30</u>	<u>2031-08-28</u>	<u>3.6</u>
<u>U17</u>	<u>P1</u>	<u>2015-07-15</u>	<u>47</u>	<u>2015-07-29</u>	<u>2015-08-27</u>	<u>3.6</u>
<u>U18</u>	<u>P1</u>	<u>2031-07-18</u>	<u>40</u>	<u>2031-07-30</u>	<u>2031-08-28</u>	<u>3.6</u>
<u>U19</u>	<u>P1</u>	<u>2015-07-13</u>	<u>53</u>	<u>2015-07-27</u>	<u>2015-08-25</u>	<u>3.6</u>
<u>U20</u>	<u>P1</u>	<u>2015-07-12</u>	<u>19</u>	<u>2015-07-25</u>	<u>2015-08-23</u>	<u>3.6</u>
	<u>P3</u>	<u>2030-08-06</u>	<u>75</u>	<u>2030-08-20</u>	<u>2030-09-18</u>	<u>3.5</u>
	<u>P4</u>	<u>2028-07-17</u>	<u>78</u>	<u>2028-07-05</u>	<u>2028-08-03</u>	<u>3.3</u>
	<u>P5</u>	<u>2028-07-18</u>	<u>100</u>	<u>2028-07-31</u>	<u>2028-08-29</u>	<u>2.7</u>

Author contributions. FR, EF, and RK conceived the idea for this study. FR carried out the analysis and drafted the manuscript. EF and RN helped with developing and refining the methodology. All authors contributed to discussing the results and revising the manuscript.

Competing interests. At least one of the (co-)authors is a member of the editorial board of Weather and Climate Dynamics.

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Table B2. ~~Ten historical~~ Historical 30-day heatwaves (HW) in WE selected from ERA5 ~~Listed are the~~ (beginning and end of the selected 30-day period ~~and the~~), sorted in descending order by their 30-day mean TM anomaly during that period.

	day 1	day 30	TM / σ
heatwave-	H1 1976-06-07	1976-07-06	3.6
	H2 2003-08-01	2003-08-30	3.0
	H3 1973-08-11	1973-08-09 <u>1973-09-09</u>	3.0
	H4 2003-05-29	2003-06-27	3.0
	H5 1983-07-03	1983-08-01	2.7
	H6 2006-07-01	2006-07-30	2.5
	H7 1969-07-16	1969-08-15 <u>1969-08-14</u>	2.3
	H8 1997-08-08	1997-09-06	2.2
	H9 1994-07-11	1994-08-09	2.1
	H10 1975-07-30	1975-08-28	2.0
	<u>1995-07-07</u>	<u>1995-08-05</u>	<u>1.9</u>

Table B3. ~~Selected analogues from the ERA5 reanalysis for the ten unprecedented~~ Recent 30-day heatwaves ~~simulated in CESM2 ensemble boosting simulations. Listed are the~~ WE selected from ERA5 (beginning and end of the selected 30-day period ~~and the~~) in chronological order, with their absolute 30-day mean TM anomaly during that period.

	day 1	day 30	TM / σ <u>°C</u>
U1	2013-07-07	1976-06-21 <u>2013-08-05</u>	1976-07-20 3.3 <u>20.9</u>
U2	2015-06-25	2003-05-21 <u>2015-07-24</u>	2003-06-23 2.6 <u>21.2</u>
U3	2018-07-12	1973-08-11 <u>2018-08-10</u>	1973-09-09 3.0 <u>21.9</u>
U4	2019-06-26	2006-06-29 <u>2019-07-25</u>	2006-07-28 2.4 <u>20.9</u>
U5	2020-07-23	2006-07-01 <u>2020-08-21</u>	2006-07-30 2.5 <u>21.4</u>
U6	2022-07-16	1976-06-21 <u>2022-08-14</u>	1976-07-20 3.3 <u>21.6</u>
U7	2023-08-13	2003-07-19 <u>2023-09-11</u>	2003-08-17 2.8 <u>20.3</u>
U8	2024-07-18	2003-05-24 <u>2024-08-16</u>	2003-06-22 2.5 <u>20.8</u>
U9	2025-06-12	2003-05-24 <u>2025-07-11</u>	2003-06-22 2.5 <u>20.6</u>
U10	2026-06-17	2006-07-01 <u>2026-07-16</u>	2006-07-30 2.5 <u>24.0</u>

acquiring additional CESM2 data, and P. Stott for encouraging feedback on an early version of this work. RN has received funding from the Swiss National Science Foundation (SNSF) through grant No. 216710. RK is part of SPEED2ZERO, a Joint Initiative co-financed by the ETH Board. This research was supported by the NCCR CLIM+, funded by the Swiss National Science Foundation (grant 51AU-0_229306).

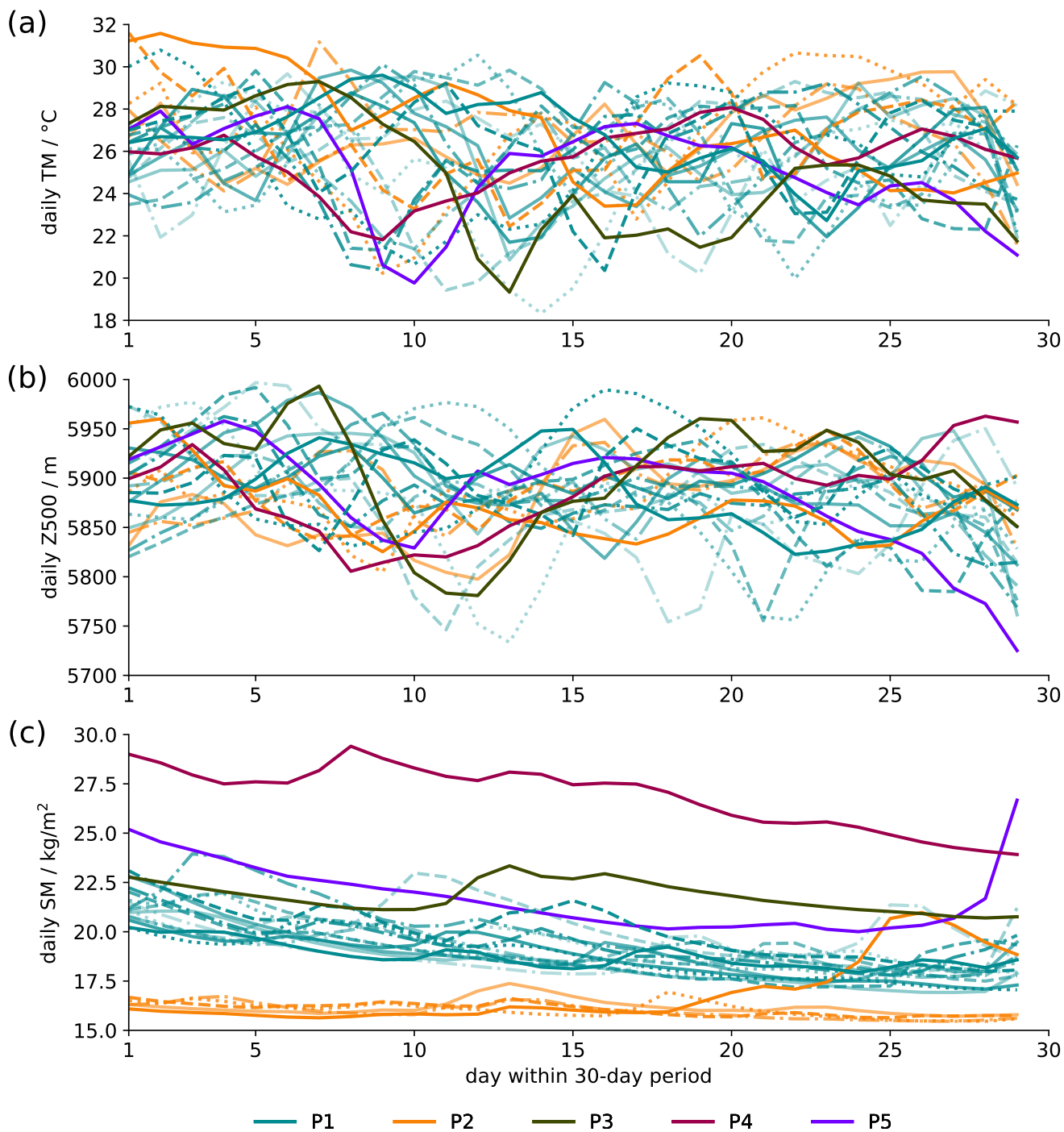


Figure B1. Daily values of (a) TManomalies, (b) Z500, (c) SM during the ten-selected-unprecedented 30-day-heatwaves (U1–U10) and preceded heatwaves (P3–P5).

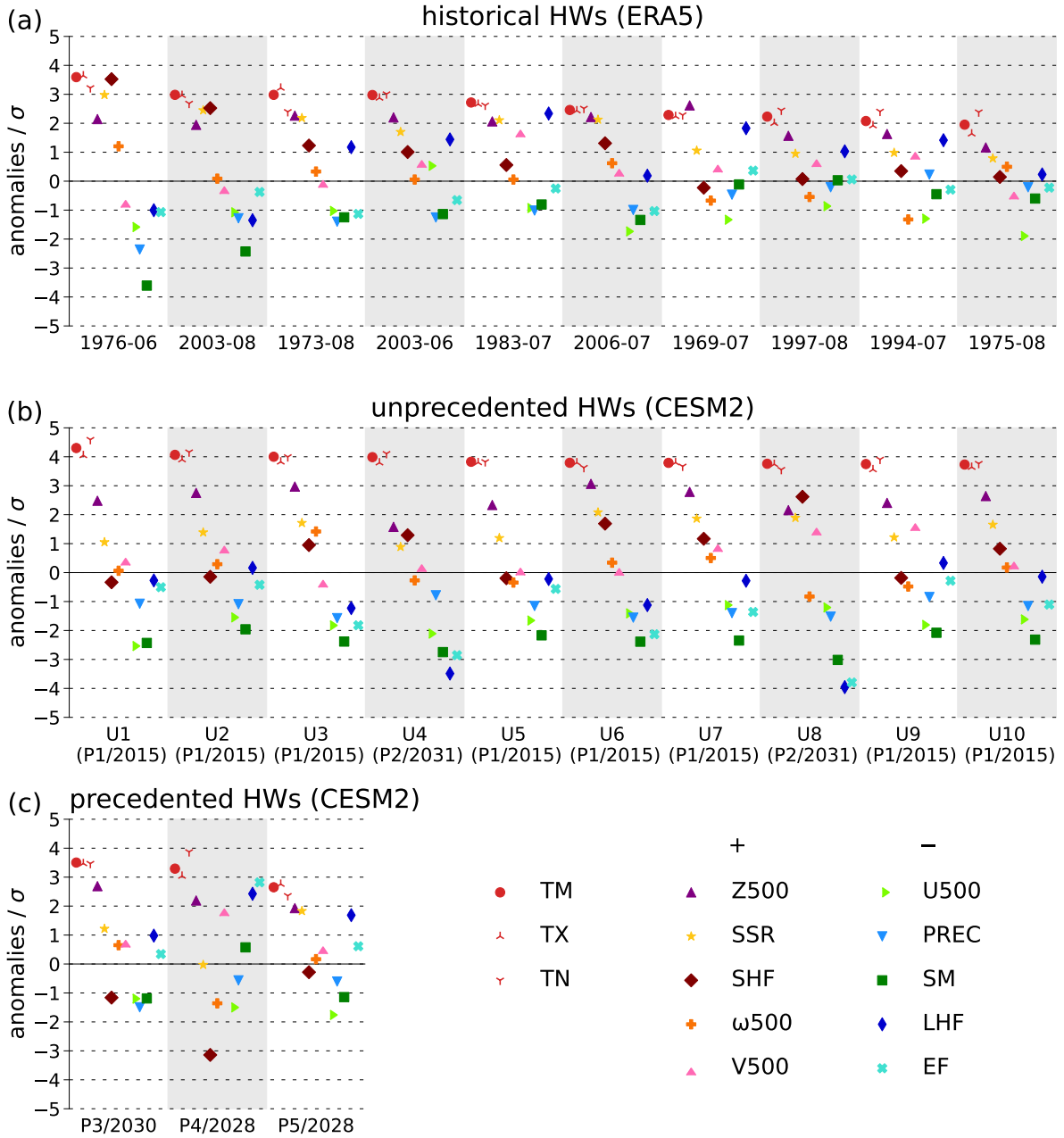


Figure B2. Anomalies of heatwave characteristics and drivers in WE of selected heatwaves (Tab. 1). (a) Ten most extreme historical month-long heatwaves in ERA5 (Tab. B2) (b) Ten most extreme unprecedented month-long heatwaves in CESM2 ensemble boosting simulations (Tab. B1). (c) The most extreme heatwaves from the parent ensembles P3–P5 (Tab. B1). Shown are the temperature variables (red), and variables with expected positive (“+”) and negative (“–”) anomalies during heatwaves. This separation is a simplification primarily adopted for ease of visualization; several variables feature substantial anomalies of both signs during heatwaves.

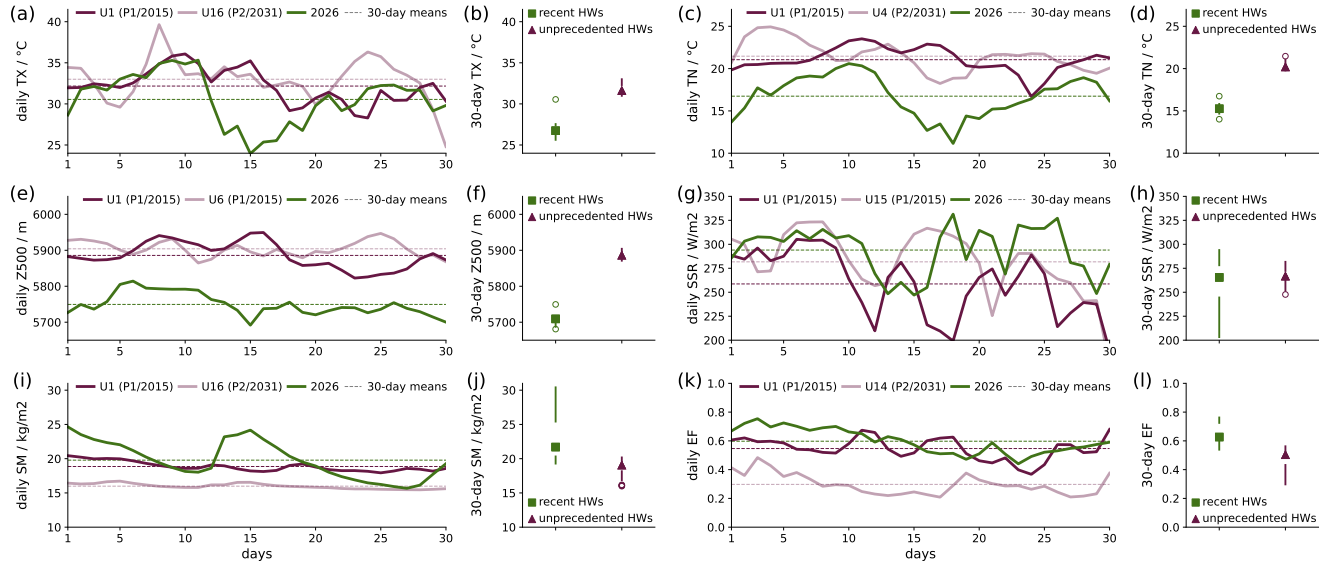


Figure B3. 30-day-running-mean-PREC anomalies-Absolute values in selected variables of unprecedented heatwaves and recent heatwaves. Time series for the months preceding 2026 heatwave (green) and for two unprecedented heatwaves: the most extreme in terms of TM anomaly (U1 heatwave), and its 1976 historical analogue the most extreme in terms of absolute value of the respective variable (first and third column). 30-day means of unprecedented and recent heatwaves: Median (filled symbols), inter-quartile range (IQR, empty space), whiskers (1.5 IQR, solid lines) and outliers (empty circles) (second and fourth column).

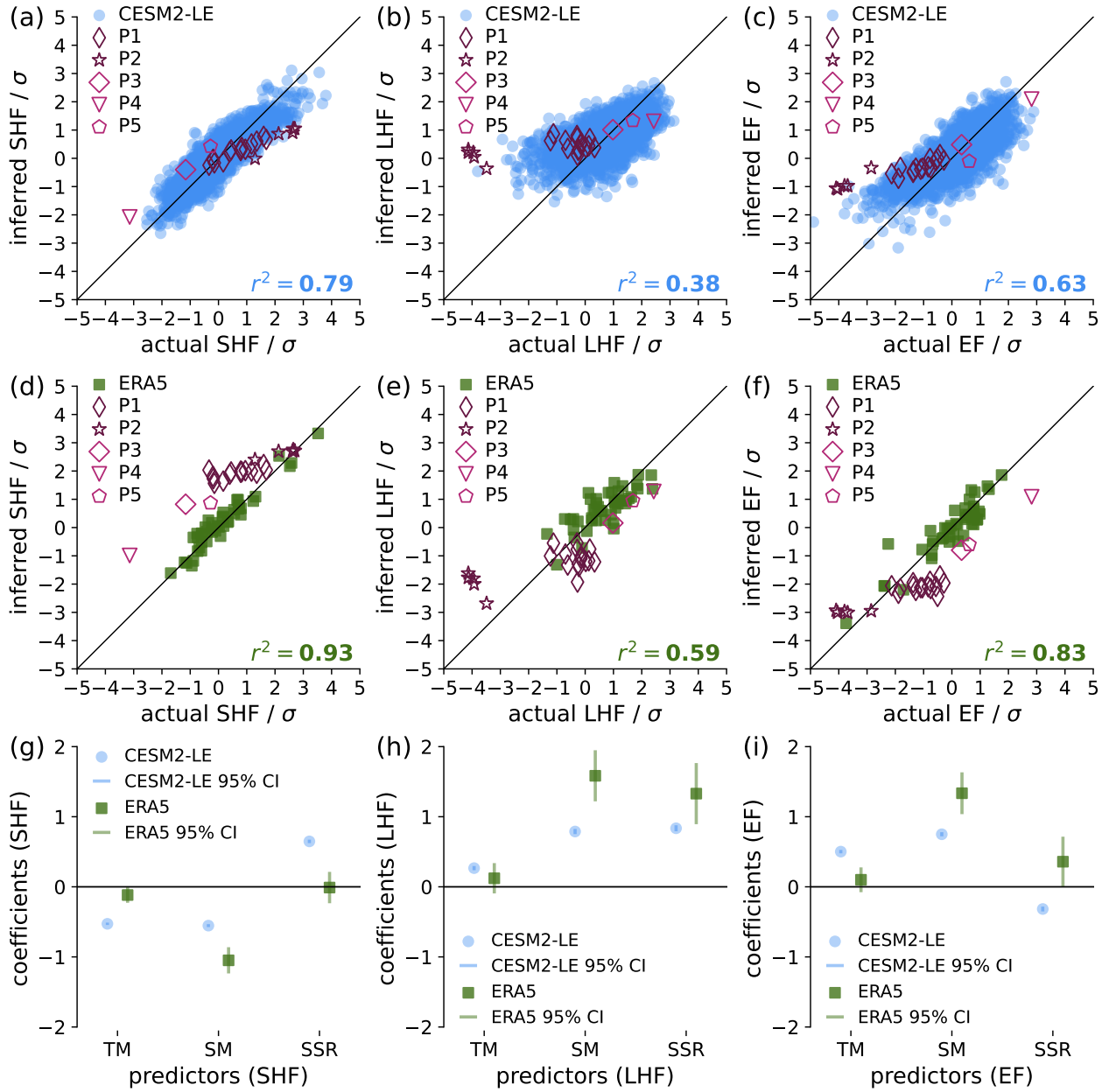


Figure B4. Actual anomalies of SHF (a,d), LHF (b,e), and EF (c,f) and anomalies inferred using our multilinear statistical model. Shown are the training data, namely the annual maxima of 30-day TM anomalies in WE during the summer season (JJA) in CESM2-LE (a–c, blue circles) and in ERA5 (d–f, green squares), respectively. The model is applied to 30-day anomalies of SHF, LHF, and EF in WE during the unprecedented heatwaves (purple) and three less extreme heatwaves from CESM2 boosting simulations (pink). For reference, the 1:1 line and the explained variance r^2 of each model are also shown. The regression coefficients of each predictor and their 95 % confidence intervals (CI) are compared for LHF (g), SHF (h), and EF (i).

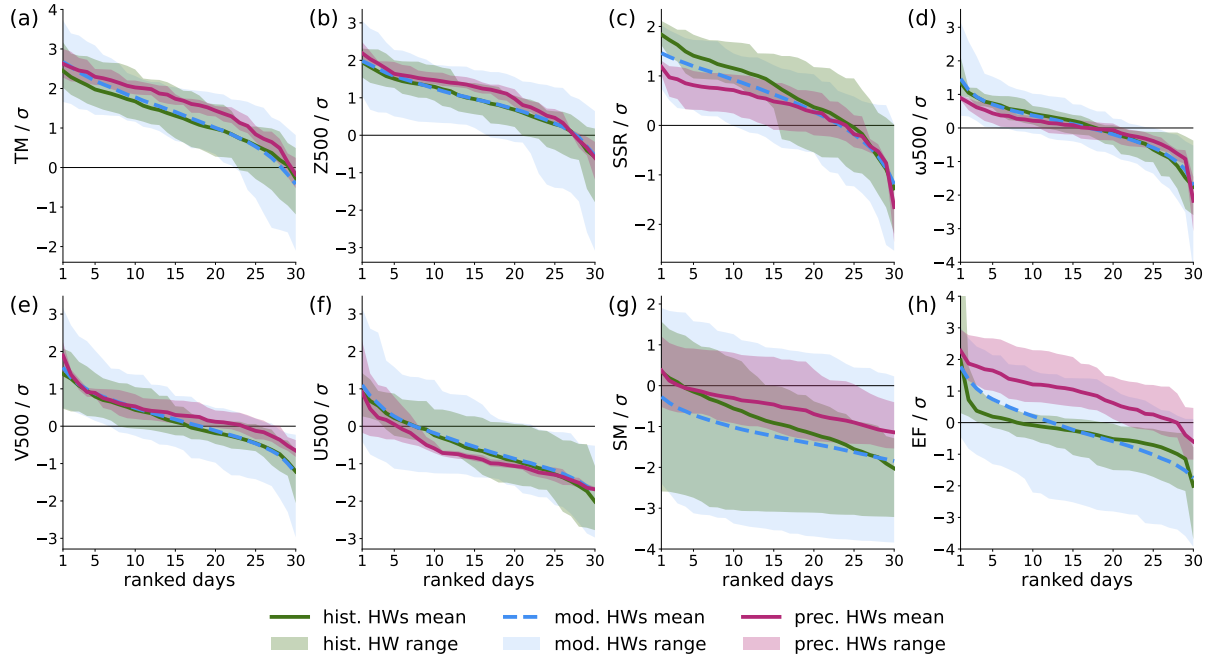


Figure B5. Ranked daily anomalies of heatwave characteristics and drivers during historical heatwaves (green), moderate heatwaves (blue), and preceded heatwaves from CESM2 boosting simulations (pin). Variables are sorted from highest to lowest anomalies, meaning that the most favourable conditions for heatwaves can be found at low ranked days panels (a)–(e), but at high ranked days for panels (f)–(h).

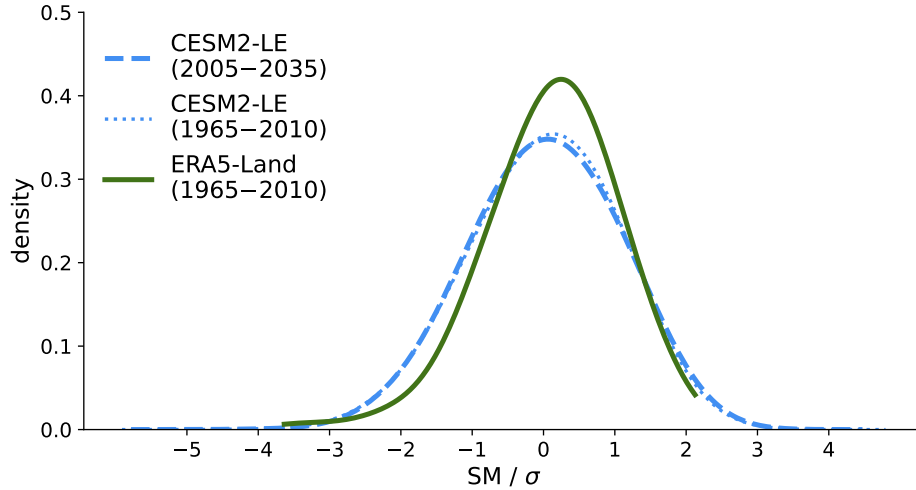


Figure B6. Kernel density estimates of 30-day SM anomalies during the summer season (JJA) in ERA5-Land (1965–2009, yellowgreen) and in the CESM2-LE (1965–2009, blue and 2005–2035, blue), using a Gaussian kernel with a bandwidth of 0.5σ , truncated at the data limits.

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