The extremely hot and dry 2018 summer in central and northern Europe from a multi-faceted weather and climate perspective

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44   **Abstract.** The summer of 2018 was an extraordinary season in climatological terms for northern and

45   central Europe, bringing simultaneous, widespread, and concurrent heat and drought extremes in large

46   parts of the continent with extensive impacts on agriculture, forests, water supply, and socio-economic

47   sector. Here, we present a comprehensive, multi-faceted analysis of the 2018 extreme summer in terms

48   of heat and drought in central and northern Europe, with a particular focus on Germany. The heatwave

49   first affected Scandinavia by mid-July, shifted towards central Europe in late July, while Iberia was

50   primarily affected in early August. The atmospheric circulation was characterized by strongly positive

51   blocking anomalies over Europe, in combination with a positive summer North Atlantic Oscillation and

52   a double jet stream configuration before the initiation of the heatwave. In terms of possible precursors

53   common to previous European heatwaves, the Eurasian double jet structure and a tripolar sea-surface

54   temperature anomaly over the North Atlantic were identified already in spring. While in the early stages

55   over Scandinavia the air masses at mid- and upper-levels were often of remote, maritime origin, at later

56   stages over Iberia the air masses had primarily a local-to-regional origin. The drought affected Germany

57   the most, starting with warmer than average conditions in spring, associated with enhanced latent heat

58   release that initiated a severe depletion of soil moisture. During summer, a continued precipitation

59   deficit exacerbated the problem, leading to hydrological and agricultural drought. A probabilistic

60   attribution assessment of the heatwave in Germany showed that such events of prolonged heat have

61   become more likely due to anthropogenic global warming. Regarding future projections, an extreme

62   summer such as this of 2018 is expected to occur every two out of three years in Europe under a 1.5 °C

63   warmer world and virtually every single year under 2 °C of global warming. With such large-scale and

64   impactful extreme events becoming more frequent and intense under anthropogenic climate change,

65   comprehensive and multi-faceted studies like the one presented here quantify the multitude of effects

66   and provide valuable information as basis for adaptation and mitigation strategies.

67   **1   Introduction**

68   Following an anomalously warm and dry spring, the summer of 2018 was characterized by record

69   breaking widespread heat and drought across Europe (Kennedy et al., 2019; Toreti et al., 2019) with

intense heatwaves affecting large parts of Scandinavia (Sinclair et al., 2019) and central Europe (e.g., Vogel et al. 2019). In Germany, both the months of April-May, as well as the April-July period, and the entire year, were identified as the warmest in the observational records starting in 1881. Moreover, Germany faced remarkably prolonged drought from February to November, with 2018 being the fourth driest year on record (after 1959, 1911, and 1921). A new record was also set for annual sunshine duration, amounting to 2015 hours (Friedrich and Kaspar, 2019). In Finland, the peak temperature in summer exceeded 33 °C, which is extremely unusual for a region located near the Arctic Circle, breaking historical records of the past 40 years (Liu et al., 2020). In the UK, summer 2018 joined 2006 as the hottest on record since 1884. In England itself, this was the warmest on record, while June 2018 was the driest June for England since 1925 (Kendon et al., 2019). Over the Iberian peninsula, a heatwave developed in early August 2018, with this month being the warmest in the region after 2003 (Barriopedro et al., 2020). The normal eastward propagation of weather systems was hindered in summer 2018 by the recurrent presence of blocking anticyclones, associated with a particularly meandering jet stream, which was reflected in the way the heatwave propagated, starting in Scandinavia (peaking mid of July), then developing in central Europe (end of July) and last in Iberia (beginning of August). For the European continent, 2018 was the second warmest summer on record (following 2010) as estimated from the CRUTEM4 dataset (Kennedy et al., 2019), prior to being marginally surpassed by the 2021 summer (Copernicus Climate Change Service, 2018; 2021).

In terms of amplitude, persistence and spatial extent, the 2018 heatwaves were comparable to the "mega-heatwaves" of 2003 and 2010 over Europe and Russia (Spensberger et al., 2020; Becker et al., 2022), during which more than one million square kilometers were simultaneously affected by heatwave conditions (Fink et al., 2004; Barriopedro et al., 2011). But, unlike 2003 and 2010, the exceptionally extreme heat in 2018 occurred under concurrent exceptionally dry conditions, thus making the events in 2018 a spatially and temporally compound extreme (Zscheischler et al. 2020; Bastos et al. 2021; Ionita et al., 2021). These co-occurring hot and dry extremes, not only in central Europe but also in multiple regions of the northern hemisphere midlatitudes (Vogel et al., 2019), caused vast aggregated impacts (Bakke et al., 2020), ranging from drought-inflicted forest mortality events of unprecedented scale (Schuldt et al., 2020; Senf and Seidl, 2021), up to 50 % reduction in agricultural yields (Toreti et al., 2019; Beillouin et al., 2020) and increased forest fire occurrence (San-Miguel-Ayanz et al., 2019), to excess heat-related human mortality (Pascal et al., 2021). Compared to previous droughts since 2000, summer 2018 occupied the largest extent of extreme and severe agriculture drought, centered around Germany, Poland, most of Scandinavia and the Baltic countries, affecting a larger extent of boreal forests and high latitude ecosystems (Peters et al., 2020). Further, from a temporal point of view, compared to other droughts of the past 40 years, 2018 was characterized by the sharpest transition from average-to-wet conditions in late winter to extremely strong soil-water deficits in summer (Bastos et al., 2020).

Surface heatwaves are typically co-located with the center of the associated blocking system (Kautz et al., 2022; their Figure 2b). If the blocking is intense and persistent, a heatwave will usually develop. On the other hand, unsteady weather conditions, like thunderstorms and heavy precipitation, are frequent on the flanks of the blocking system, which correspond to the air mass boundaries (Kautz et al., 2022). In fact, summer extremes can be exacerbated by different components of the Earth system, such as anomalous atmospheric circulation patterns, oceanic conditions, and the state of land surface (Wehrli et al., 2019; Di Capua et al., 2021). The atmospheric circulation during late spring and summer 2018 was characterized by the frequent presence of atmospheric blocking, and a persistent positive summer North Atlantic Oscillation (sNAO; Drouard et al., 2019; Li et al., 2020). Among the possible precursors of European heatwaves, here we analyzed spring sea-surface temperatures (SST) over the North Atlantic and soil moisture anomalies over Europe. In particular, the tripolar North Atlantic SST anomaly pattern is known to be influenced by the winter NAO, persisting over spring and affecting European climate in summer (Herceg-Bulić and Kucharski, 2014). The North Atlantic tripolar pattern has been associated with the East Atlantic Pattern (Gastineau and Frankignoul, 2015) and Atlantic Ridges (Ossó et al., 2020), leading to decreased summer precipitation (Saeed et al., 2013; Rousi et al., 2021) and increased summer temperatures over Europe (Chen et al., 2016). Additionally, Duchez et al. (2016) argues that a cold anomaly over the North Atlantic subpolar gyre (SPG) may be associated with a stationary position of the jet stream, enhancing European summer heat extremes. Moreover, soil moisture-temperature feedbacks can amplify heat extremes (Seneviratne et al., 2010). Through a positive feedback, soil moisture depletion by hot and dry atmospheric conditions leads to a reduction of evaporative cooling and suppressed convective available potential energy (CAPE) values, subsequently limiting the rainfall potential and increasing air temperatures further (Miralles et al., 2014; 2018; Prodhomme et al., 2021). Further, Schumacher et al. (2019) highlighted the important role of upwind land–atmosphere feedbacks in addition to local feedbacks, as they can favor heat advection and intensify midlatitude mega-heatwaves via soil desiccation.

Hot and dry summers in Europe are expected to occur more frequently under anthropogenic global warming (Masson-Delmotte et al. IPCC, 2021). McCarthy et al. (2019) conducted an attribution study for the 2018 summer heatwave in the UK based on CMIP5 models and found that the present-day likelihood of such extremes is around 11 %, which has been made 30-times higher due to anthropogenic climate change, while this likelihood increases to 53 % by the 2050s. Given the increase of hot and dry extremes in Europe (Manning et al., 2019; Perkins-Kirkpatrick and Lewis, 2020; Markonis et al., 2021) and their further expected increase under continued unmitigated anthropogenic climate change (Russo et al., 2014; 2015; Spinoni et al., 2018; 2020), comprehensive weather and climate studies analyzing regional heatwave and drought characteristics, drivers, and impacts are particularly important.

Within the German research initiative ClimXtreme, about 140 scientists from 35 institutions joined in 39 projects to further understand climate extremes, focusing on central Europe (https://climxtreme.net/index.php/en/). Inter-disciplinary task forces were formed, among which one on

143   heat and drought. This study brings together its members to study the 2018 European heat and drought

144   from a multi-faceted weather and climate perspective, making it the first comprehensive and spatially

145   exhaustive study looking at hot and dry summers over Europe using different analyses approaches to

146   study (a) the extremeness and attribution to anthropogenic climate change (climate perspective), as well

147   as (b) the synoptic dynamics in concert with the role of slowly varying boundary conditions at the ocean

148   and continental surfaces (seasonal and weather perspective). In the following, first, the data and methods

149   are presented (Sect. 2). Different metrics for the detection and description of the 2018 summer extremes

150   are shown in Sect. 3.1. Then, we present various features of the atmospheric circulation including

151   blocking, jet stream state, weather regimes, Rossby wave activity and air mass trajectories (see Sect.

152   3.2). Next, the role of low-frequency precursors, i.e. SSTs and soil moisture in spring, in setting the

153   scene and eventually shaping those extremes is investigated (see Sect. 3.3). Sect. 3.4. examines the

154   event from a large-ensemble climate model perspective, accompanied by a tailored attribution analysis

155   that incorporates the length of the heatwave in Germany based on CMIP6 models. The Discussion and

156   Conclusions section completes this paper.

157   **2 Data and Methods**

158   **2.1 Data**

159   In this paper we use a variety of datasets, including observational, reanalysis and model data. We are

160   using a common spatial domain for Europe (10° W–50 °E, 30°-70° N) and the reference period 1981–

161   2010 unless otherwise stated.

162

163   **2.1.1 Reanalysis and observational datasets**

164   ERA5 (Hersbach et al., 2020) and ERA5-HEAT (Di Napoli et al., 2021) reanalysis datasets were

165   utilized for the calculation of heatwave metrics (see Sect. 3.1), the dynamical drivers and their evolution,

166   such as Rossby wave activity, backward trajectories, double jet streams, atmospheric blocking, and

167   weather regimes (see Sect. 3.2), as well as the precursors, i.e. SSTs and soil moisture (see Sect. 3.3). E-

168   OBS gridded observational datasets (Haylock et al., 2008; Cornes et al., 2018) were used for the

169   calculation of the drought index (SPEI, see Sect. 3.1) and to estimate the return period of the heatwave

170   and select equivalent extreme events in CMIP6 model simulations for the attribution study (see Sect.

171   3.4). Observational datasets from DWD stations (Kaspar et al., 2013) were used for the

172   thermopluviogram for Germany (see Sect. 3.1).

173

174   **2.1.2 General Circulation Models**

175   The historical and RCP4.5 simulations of the Max Planck Grand Ensemble (MPI-GE; Maher et al.,

176   2019) were used to calculate the cumulative excess heat under recent climate (1979-2021), and future

177 1.5˚ C (2020-2049) and 2˚ C (2050-2079) warmer worlds (see Sect. 3.4). The advantage of this dataset

178 is that, apart from the forced response, it provides an estimate of the internal natural variability.

179 Historical simulations of several Coupled Model Intercomparison Project Phase 6 models (CMIP6;

180 Eyring et al., 2016) and pre-industrial type simulations (hist-nat) of the same models from the CMIP6-

181 endorsed Detection and Attribution Model Intercomparison Project (DAMIP; Gillett et al., 2016) were

182 used for the probabilistic attribution study (see Sect. 3.4). An overview of the analyzed CMIP6 models

183 is given in Table S1.

184 2.2 Methods

185 2.2.1 Heatwave metrics

186 Despite the fact that heatwaves have been a topic of active climate research for many decades, there is

187 no universal heatwave definition and there are multiple metrics and criteria depending on the region,

188 the season, and the purpose of the study (Becker et al., 2022). Here, we define a heatwave as an event

189 of at least three consecutive days during which the 90th percentile of the daily maximum temperature

190 based on each calendar day is exceeded (Fischer and Schär, 2010).We chose two different metrics to

191 characterize heatwave intensity, the cumulative heat, which uses temperature only, and the cumulative

192 Universal Thermal Climate Index (cUTCI) that represents human thermal comfort, taking into account

193 temperature, humidity, wind, and radiation. Cumulative heat and cUTCI refer to the integration of heat

194 exceedance over the threshold for all heatwave days of a season. In the present study, only summer

195 months (June to August; JJA) were considered, hence combining the intensity and persistence of

196 heatwaves (Perkins-Kirkpatrick and Lewis, 2020). The cUTCI was calculated for each day as in

197 Błazejczyk et al. (2013) and the 90th percentile of the daily time series was defined. The cumulative

198 intensity was then calculated as the integration of the exceedance above this threshold for the whole

199 season.

200 2.2.2 Drought indicator

201 For the characterization and detection of the 2018 drought we present the Standardized Precipitation

202 Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2014), a widely used drought indicator. We

203 show two aggregation periods, of three and six months, so that two types of droughts can be considered,

204 meteorological (SPEI3) and agricultural (SPEI6) (Heim, 2002; Zampieri et al., 2017). The SPEI was

205 calculated with the SPEI R Package (Beguería and Vicente-Serrano, 2013), based on monthly

206 precipitation sums and monthly mean maximum and minimum temperatures that are needed for the

207 calculation of the potential evapotranspiration (PET). PET was calculated based on the modified

208 Hargreaves equation (Droogers and Allen, 2002), a method that corrects the PET by using the monthly

209 rainfall amount as a proxy for insolation and based on the hypothesis that this amount can change the

210 humidity levels (Vicente-Serrano et al., 2014). The values obtained by this method are similar to those

211 obtained from the Penman-Monteith method (Allen et al., 2006).

212 **2.2.3 Atmospheric circulation metrics**

213 The large-scale atmospheric circulation patterns and the dynamical evolution of the atmosphere

214 associated with the 2018 extremes were analyzed using various metrics. First, we looked at the weather

215 regimes during summer in order to characterize large-scale circulation features. Five summer

216 circulation regimes were computed with k-means clustering (Crasemann et al., 2017) applied to ERA5

217 sea-level pressure (SLP) anomalies for the time period 1979-2018 over the North Atlantic/European

218 region (30-88° N, 90° W - 90° E). Further, blocking frequency anomalies were calculated at a grid point

219 level based on a hybrid, two-dimensional blocking index. Daily blocked grid points were identified

220 based on the inversion of meridional gradients in the 500 hPa geopotential height (gph) field according

221 to a modified version of the index from Scherrer et al. (2006), and on areas of strong positive gph

222 anomalies associated with the blocking detection. Finally, blocking events of a duration of at least 4

223 days and an area of $1.5 \times 10^6 \, \mathrm{km}^2$ were selected by a subsequent tracking algorithm described in Schuster

224 et al. (2019).

225 Next, we looked at the state of the jet stream. Jet stream states were identified with the use of Self-

226 Organizing Maps (SOMs), a neural network-based clustering algorithm (Kohonen, 2013; Rousi et al.,

227 2015). SOMs were applied on daily ERA5 data of Eurasian (25-80° N, 25° W - 180° E) zonal-mean

228 zonal wind data on different pressure levels (800 hPa -100 hPa) for the time period 1979-2020 (see

229 details in Rousi et al., 2022). Moreover, we applied the methodology of Fragkoulidis and Wirth (2020)

230 to identify Rossby wave packets and their amplitude (E) for the 2018 summer. The method employs the

231 meridional wind field (v) at 300 hPa at 2x2 degree resolution, which was taken from the ERA5 data.

232 The visualization of E and v (see Fig. 4) is adaptive to the latitude location of strong Rossby wave

233 packets and only the latitudinal belt of 40-90° N was taken into account. For each longitude, E and v

234 are averaged over 10 grid points that exceed the median of all values within that belt.

235 To analyze the origin of the air masses during the 2018 summer heatwave, we calculated backward

236 trajectories using Lagrangian analysis and the LAGRANTO tool (Sprenger and Wernli, 2015). In

237 particular, we calculated 10-day backward trajectories for the levels between 1000 and 500 hPa in steps

238 of 25 hPa using ERA5 data for three starting locations in Europe on the respective peak heatwave days.

239 As in Zschenderlein et al. (2020), starting points were also taken within the upper-tropospheric blocking

240 anticyclone, in this case over Scandinavia. These were defined as the grid points where the anomaly of

241 the vertically averaged potential vorticity (between 500 and 150 hPa, based on monthly climatology)

242 was below -0.7 PVU (1 PVU = 10^{-6} K kg^{-1} m² s^{-1}). For all grid points that fulfilled this criterion,

243 trajectories were initialized every 50 hPa between 500 and 150 hPa in the vertical dimension. To exclude

244 starting points in the stratosphere, only grid points with PV < 1 PVU were considered.

2.2.4 Low-frequency precursors

In order to analyze low-frequency precursors of the summer 2018 extremes, we considered SSTs, total precipitation and soil moisture in the preceding months. The SST anomalies, compared to the reference period of 1981-2010, over the North Atlantic and the seas surrounding Europe (Mediterranean, North Sea, Baltic Sea) were analyzed for the spring (March to May; MAM) and summer (June to August; JJA) months of 2018 in ERA5 data. Precipitation and soil moisture anomalies over Europe were also calculated for the same seasons in ERA5.

Additionally, we derived time series for the soil moisture-latent heat flux correlation in Germany based on ERA5 reanalysis data with a daily temporal resolution based on centered 92-day running windows. This approach was used because soil moisture limitation depends on various factors, such as the climatic conditions and vegetation characteristics (rooting depth, Leaf Area Index (LAI) and stomatal conductance), which vary spatially and can change during the course of a year (Duan et al., 2020). Therefore, the limitation cannot be easily represented by a unified, fixed value. The time series were spatially averaged over all land points for Northern Germany and surroundings (51-55° N and 4-16° E), as well as southern Germany and surroundings (48-51° N and 4-16° E). The German Alpine region was not included in the southern German region because the complex topography that cannot be accounted for in this study, influences the results.

2.2.5 Attribution of the 2018 extreme heat

Extreme event attribution typically addresses the question of whether and to what extent climate change has affected the severity and/or frequency of a specific extreme weather event (Shepherd, 2016). The most commonly used approach to extreme event attribution is probabilistic event attribution (Philip et al., 2020), which compares climate model simulations under different scenarios, i.e. a factual scenario which simulates the weather under current and past climate conditions, and a counterfactual scenario which simulates weather under climate conditions excluding anthropogenic influences.

Here we present two kinds of attribution approaches. In the first, we used the MPI-GE to estimate the probability of exceedance of the 2018 summer heat levels in the whole European domain for present and future climates, and in the second, we present a tailored extreme event attribution study for Germany based on CMIP6 simulations to calculate probability ratios for the persistent 2018 heat event in Germany.

The MPI-GE (Maher et al., 2019) was used to estimate and compare the probabilities of exceeding the 2018 summer levels of cumulative heat in the reanalysis data (ERA5, 1979–2021) and under recent (1979–2021), and future 1.5° C (2020–2049) and 2° C (2050–2079) warmer worlds. The same heatwave metric and parameters were used to calculate the cumulative heat as the ones described above (Sect. 2.2.1). The ERA5 data were regridded to a coarser resolution to match that of the MPI-GE and the probabilities were normalized to percentages (i.e. divided by the total number of years in each period).

Then, to estimate how the occurrence probability of the 2018 heatwave in Germany has been affected by anthropogenic climate change, a tailored probabilistic attribution study was conducted using CMIP6 simulations. The historical CMIP6 simulations provide the factual scenario while hist-nat simulations from DAMIP provide the counterfactual scenario. The analysis is based on an attribution system currently under development at DWD within the ClimXtreme project and involves (1) defining the extreme event, (2) analyzing observational data and estimating the probability/return period of such an event based on observations, (3) validating the climate model simulations, (4) preparing and analyzing the climate model simulations, and (5) calculating a probability ratio between the historical and hist-nat simulations.

Based on CMIP/DAMIP data available at the computing facility of the German Climate Computing Center (DKRZ) the most appropriate climate models were selected for the tailored attribution study by including the ones that had at least three initializations in the DAMIP archive and passed the validation tests outlined below for the maximum temperature (Tmax) that is analyzed in the attribution study. The climatology of Tmax and the spatial pattern of the yearly averaged maximum temperature were visually compared between the models and the gridded E-OBS dataset to evaluate whether the models are able to represent the climate conditions over Germany. Additionally, the parameters of a Generalized Extreme Value (GEV) distribution fitted to the simulation data were compared with a fit to the E-OBS data to check whether they agree within their uncertainty bounds. Furthermore, a general consistency check was performed for each model ensemble. The evaluation procedure is similar to the one used in World Weather Attribution studies (see e.g. Philip et al., 2020). Simulations of CMIP6 models that passed the validation were further analyzed (see Table S1 for a list of the models).

The following steps are required to calculate the risk ratio: CMIP and DAMIP Tmax data from all available initializations of the model were selected for the German region and for the 30-year timeframe from 1985-2014. The data were averaged over the region and a 17-day running mean was calculated, based on the event definition which is further elaborated in Sect. 3.4. The yearly block maxima were then selected from all initializations and a GEV fit was used to estimate the probability of heatwaves in the simulation data that are equivalent to the observed event of 2018. To account for offsets between observed and simulated temperatures, we analyzed a simulated heat event which has – in the historical simulations - the same probability as the observed heatwave, i.e. while the simulated event may not reach the same temperature as was observed in 2018, the temperature threshold used to analyze the simulations has the same return period as the observed event (see also Philip et al., 2020; Tradowsky et al., 2022). To increase the robustness of the results a 1000-member bootstrap was used and a GEV distribution was fitted to each of these 1000 alternative time series. The probability ratios (PR) were then calculated from the probabilities of such heatwaves in the historical and hist-nat simulations using the GEV fits to the original simulation time series and to the 1000 alternative time series, according to equation (1):

316 $$PR = \frac{P_{historical}}{P_{hist-nat}} \qquad (1)$$

317 $P_{historical}$ is the probability of the event to occur in the historical CMIP scenario and $P_{hist-nat}$ is the

318 probability in the naturalized DAMIP scenario in which anthropogenic greenhouse gas emissions are

319 fixed to pre-industrial times.

320 A probability ratio > 1 indicates an increase in the probability of such an event due to anthropogenic

321 climate change, a result which is typically found for recent heatwaves (see e.g. Stott et al., 2004; Philip

322 et al., 2022).

323 **3 Results**

324 **3.1 Detection and description of the 2018 summer extremes**

325 The 2018 summer was an extreme season from the climatological perspective for many regions in

326 Europe. An intense heatwave first affected Scandinavia in mid-July and then extended towards central

327 Europe and later Iberia, spanning a total period of four weeks. The maximum heatwave duration was

328 seen in Scandinavian regions, reaching 20 consecutive days (Fig. 1a). Cumulative heat reached peak

329 values in parts of Norway, Sweden, Germany, France, Ireland and the UK (Fig. 1b). The cUTCI index

330 showed periods of extreme heat stress in Portugal and southwestern Spain, very strong heat stress in

331 northern and central Germany, central-western Poland, large parts of France and Iberia, and strong heat

332 stress in most of eastern Europe, Finland, southern Scandinavia and parts of the British Isles (Fig. 1c).

333 The high intensities in Turkey and the Caucasian region were not caused by the same weather pattern

334 as the event described in this paper and are thus not discussed here.

335

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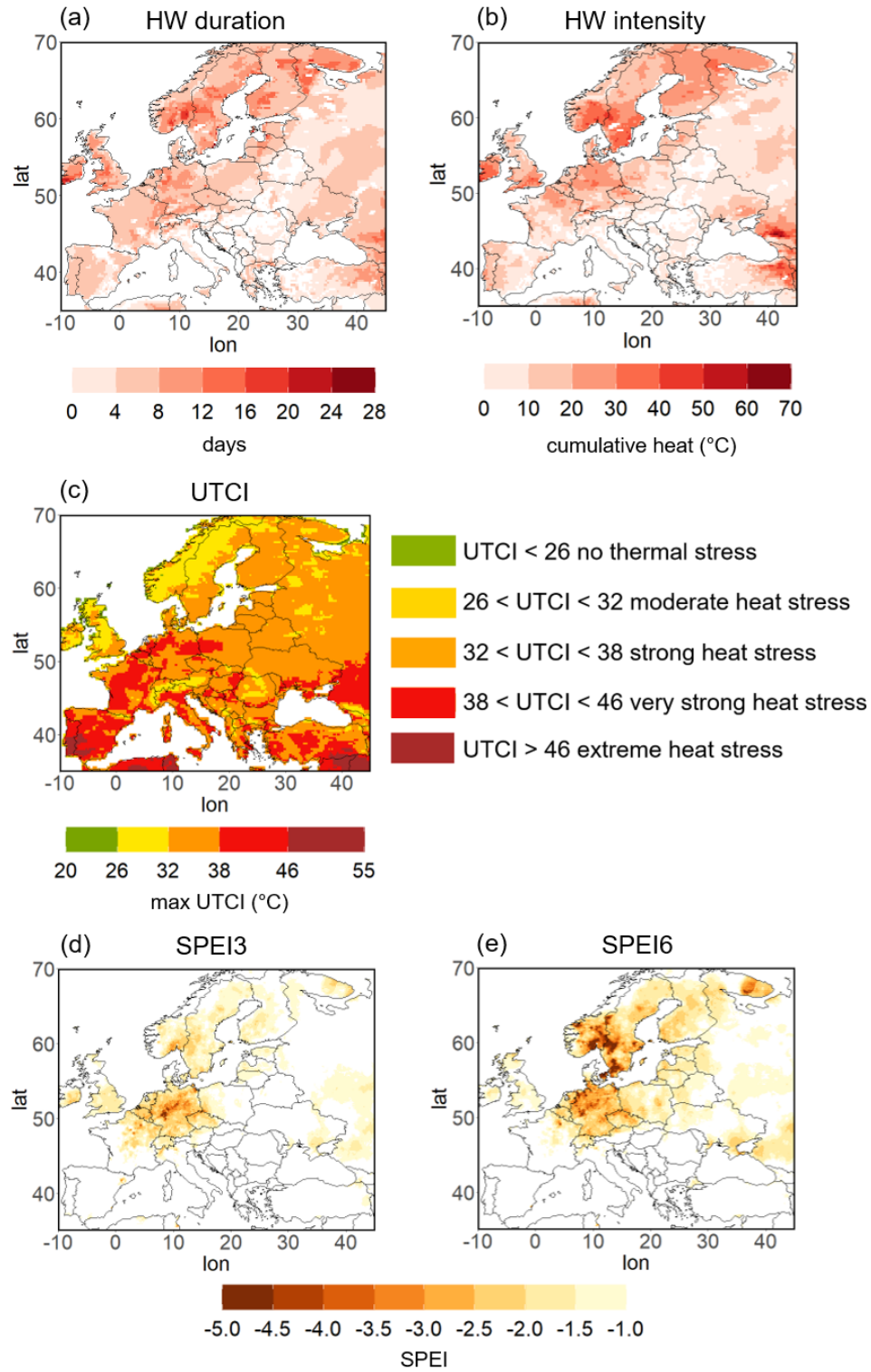


Figure 1: Spatial representation of European heatwave (ERA5) and drought (E-OBS) in the 2018 summer. (a) Maximum heatwave duration in days (grid point-based, exceedance of 90th percentile of daily maximum temperature). (b) Cumulative heat (in °C). (c) Maximum UTCI in the 2018 summer per grid point and respective heat stress category. (d) SPEI3 August. (e) SPEI6 August. Only SPEI values

below -1 are shown, in order to highlight drought conditions. Reference period used in all metrics: 1981-2010.

In northern and central Europe, the heatwave was preceded and accompanied by intense drought conditions. As an example, the meteorological drought is depicted in terms of the SPEI3 and SPEI6 values for August (Fig. 1d,e) that were particularly low in central and northern Europe. The cumulative effect of low precipitation and high evapotranspiration lead to lower values of the SPEI6 index in many European regions compared to SPEI3. The most extreme values (SPEI6 < -5) are identified for southern Norway and Sweden. The thermopluviogram for Germany depicts temperature and precipitation anomalies for Germany, and confirms that the extended warm period of April to October 2018 was the most exceptional in terms of precipitation deficit and heat anomaly compared to the reference period (1981-2010) since 1881 (Fig. 2b). When considering different seasonal periods, such as March to August, or June to August only, 2018 remains a very extreme season (see Fig. S1). In summary, while the heatwave was most intense in southern Scandinavia, 2018 stood out as the most intense compound heat and dry event in the observational history for Germany, in agreement with Zscheischler and Fischer (2020).

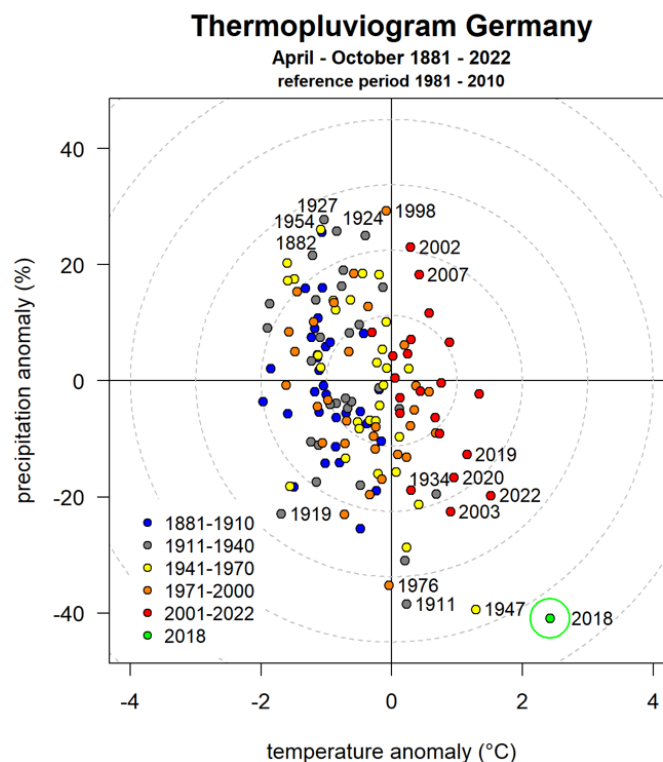



Figure 2: Thermopluviogram for the growing season, April to October, of the years 1881-2022 for Germany showing the temperature and precipitation anomalies from the climatological mean (DWD observational data, reference period 1981-2010). 2018 is highlighted with light green color. Thermopluviograms for different periods can be found in the Supplement (Fig. S1).

3.2 Dynamical drivers and evolution

In order to characterize large-scale circulation features for summer 2018, we used a number of different and complementary metrics to describe the multi-faceted characteristics of the event. First, we analyzed the blocking conditions for this season, as the occurrence of heatwaves is directly associated with summer blocking or – for the lower latitudes in Europe – to atmospheric ridges (Woollings et al., 2018; Sousa et al., 2018; Kautz et al., 2022). Using the blocking detection algorithm, we confirm that for the 2018 summer, blocking is detected over Great Britain from late June into the first ten days of July as well as over Scandinavian and Ural regions for most days of July (Fig. S2). Compared to the climatological occurrence of blocking frequency, the percentage of blocked days in June/July 2018 was 20-60 % higher in the mentioned areas (Fig. 3a,b), indicating blocking frequency values above the 90th percentile (Fig. S3). This large-scale set up for the summer time (see e.g., Kautz et al., 2022, their Figure 2b) leads to the development of a heatwave collocated with the center of the blocking, while unsteady weather conditions may happen on the block edges.

The establishment of a long-lived blocking anticyclone is consistent with the development of a double jet stream state over Eurasia, with two maxima of the zonal mean zonal wind at the 250 hPa level, which started as early as mid-May and persisted until 25th of July, with only a few days in between not characterized by double jets (Fig. 3c). The period 04–25 July was characterized by a continuous persistent double jet configuration, according to the SOM-based detection scheme of jet stream states. These 22 consecutive days of double jets make 2018 one of the longest such events in the study period (1979–2020), the longest being that of 2003 (Rousi et al., 2022; their Figure 4). The initiation of the heatwave in Europe happened a few days after the initiation of this persistent double jet event (see Fig. 4), highlighting a potential role of the double jet structure in preconditioning the flow and favoring the onset of a heatwave in the region of weak winds between the two jets, where the blocking anticyclone lies (Rousi et al., 2022). This large-scale set up typically corresponds to the occurrence of the summer NAO+ (sNAO+) regime, as confirmed by the circulation regime approach applied on the 2018 summer. Indeed, most of July 2018 was dominated by a sNAO+ index (Fig. 3d) and a spatial pattern, typically characterized by a more northerly location and smaller spatial scale than its winter counterpart (Folland et al., 2009). This is in agreement with previous studies (e.g. Drouard et al., 2019) showing a strong positive EOF-based NAO anomaly in this time period that is consistent with large parts of the seasonal anomalies observed during summer 2018.

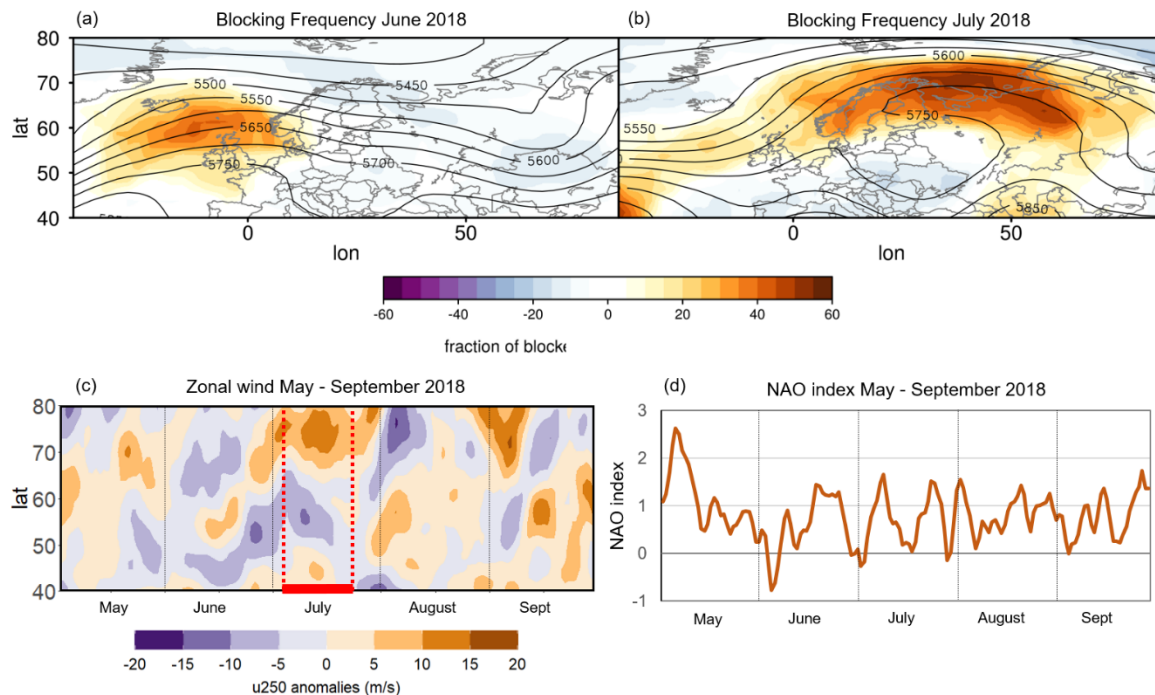



Figure 3: Blocking frequency anomalies for (a) June and (b) July 2018 (shading, contour lines show mean geopotential height at 500hPa plotted every 50hPa). (c) Eurasian zonal mean zonal wind at 250hPa for May-September 2018 (shading; 5day running means centered on each day from 01.05-30.09.2018). The red lines mark the duration of the longest double jet event (04-25.07.2018). (d) NAO index for May-September 2018.

The analysis of Rossby wave activity permits the evaluation of the development of the blocking, NAO+ phase and the corresponding double jet structure for the summer 2018. Results show an eastward propagation of Rossby wave packets from the Pacific towards the Atlantic Ocean, the British Isles, and finally towards the European continent during the last 10 to 15 days of June and before the initiation of the heatwave over Scandinavia (Fig. 4). On the other hand, this was not the case for August, when the peak over Iberia occurred, which highlights the different mechanisms involved in this heatwave, rather than Rossby wave activity coming from the Pacific. Indeed, heatwaves and precipitation deficits in this location are primarily associated with amplified subtropical atmospheric ridges rather than midlatitude blocking situations (see Woollings et al., 2011; Sousa et al., 2017; 2018).

Further, a backward trajectory analysis was conducted to determine the origins of the air masses that were present during the different heatwave phases and their evolution. Three grid points were chosen to represent the three affected areas and time segments of the heatwave: one over Scandinavia (Utsjoki, Finland) initialized on 18 July 2018, one over central Europe (Bernburg, Germany) on 31 July, and one over Iberia (Alvega, Portugal) on 4 August 2018 (Fig. 5). The backward trajectories showed the remote origin of the mid-troposphere air masses, especially in the case of Utsjoki (Fig. 5a), where it primarily originated over the central North Atlantic. This is also true for the mid-troposphere air

masses in the case of Bernburg (Fig. 5b). However, in the last 48 hours, descending air masses were observed, pointing to an adiabatic warming by compression. Trajectories starting in the lowest 200 hPa at Bernburg, indicate that air masses stemmed from a region to the south and east close to the starting location, indicating relatively stagnant air masses as already discussed in Spensberger et al. (2020). In the case of Alvega (Fig. 5c), air masses starting between 700 and 1000 hPa experienced several rising and sinking motions on their way from the south and southeast (e.g. Algerian desert, Atlas Mountains, Mediterranean Sea), towards the Iberian plateau and coastal regions, thus documenting their local-to-regional origin, in contrast to the remote origin of the air masses seen in central and northern Europe, and largely stagnant conditions (in line with Santos et al., 2015 and Sousa et al., 2019).

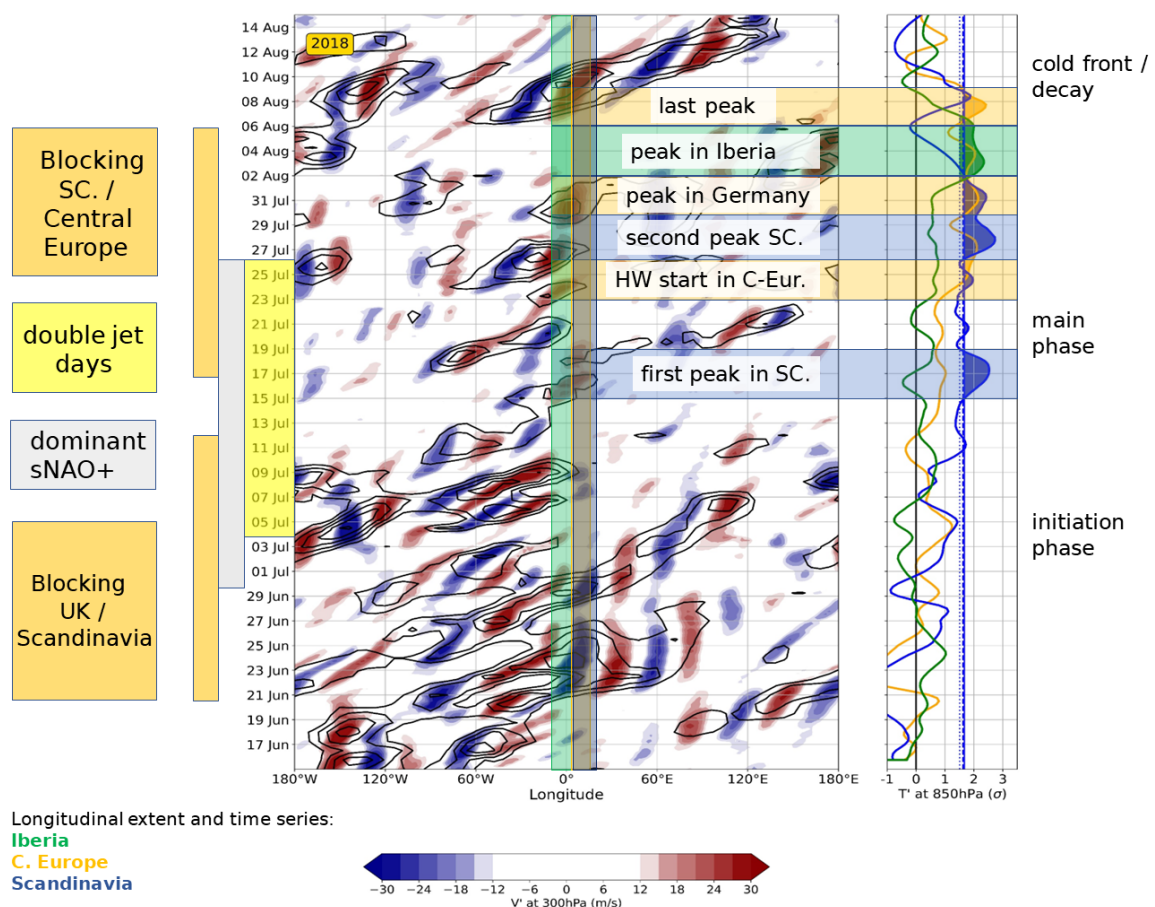



Figure 4: Hovmöller diagram for the period of 15.06.–15.08.2018. The longitudinal extent of three core heatwave regions (Iberia, Central Europe, Scandinavia), as well as their temperature time series at the 850 hPa level as standardized anomalies (T') on the right, are marked in green, orange and blue, respectively. Periods when T' was above the respective 95th percentiles are shaded. Both temperature (T') and meridional wind at the 300 hPa level (v') are anomalies with respect to their smoothed annual cycles. Rossby wave packet amplitude (E) is depicted in contours from 24 to 38 m/s in steps of 4 m/s, v' as color shading from -30 to 30 m/s. Both fields are weighted by the cosine of latitude and meridionally averaged over above-median grid points within the 40-80° N latitude band (self-adjusting,

 depending on the location of the largest amplitudes). Days with a dominant positive phase of the

summer North Atlantic Oscillation (sNAO+) pattern, double jet days, and blocking days are marked on

the left.

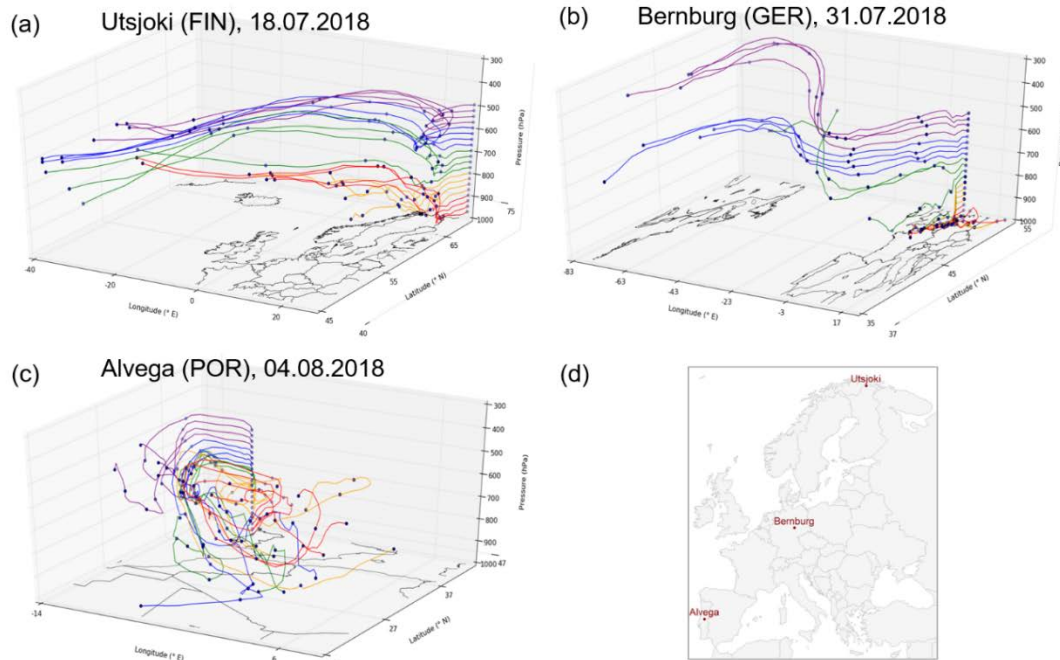



Figure 5: 10-day backward trajectories in 25 hPa steps between 1000 hPa and 500 hPa for the three

location coordinates. (a) Utsjoki, Finland, initialized 18.07.2018. (b) Bernburg, Germany, initialized

31.07.2018. (c)Alvega, Portugal, initialized 04.08.2018. For every 100 hPa, a different color is used for

the trajectories. Each black dot is representative of a 24-hour time step. (d) Geographical locations of

the three points.

In order to infer causal hypotheses for the existence of the Scandinavian block, the trajectory

approach was extended to obtain the origins of low potential vorticity (PV) air masses that formed the

upper-tropospheric part of the Scandinavian anticyclone (see Sect. 2.2.3). For the sake of brevity, only

maps of 7-day and 3-day trajectory density on 18 July 18 2018, around the maximum heatwave day in

Scandinavia, are shown in Figure 6, but other days corroborate the inferences below (not shown). Figure

6a shows the density of 7-day backward trajectories, indicating that air masses were steered from the

Western North Atlantic over the British Isles to Scandinavia. This is in line with the propagation of the

corresponding Rossby wave packet discussed above. Moreover, using the method described in

Zschenderlein et al. (2020(Zschenderlein et al., 2020)(Zschenderlein et al., 2020)(Zschenderlein et al.,

2020)(Zschenderlein et al., 2020)(Zschenderlein et al., 2020)(Zschenderlein et al., 2020) , their Fig. 4),

the role of a remote warm conveyor belt is suggested by ascending, diabatically heated trajectories over

the western Atlantic (not shown); PV is lowered in the warm conveyor belt and then transported in the

upper troposphere into the Scandinavian anticyclone (termed "remote branch" by Zschenderlein et al.,

2020). Interestingly, high trajectory densities over central to eastern Europe, which also strongly ascended and were diabatically heated (not shown), point towards an influence of moist convection observed under an upper-level trough in this area in feeding low PV air towards the Scandinavian anticyclone. Such a "nearby branch" was also mentioned by Zschenderlein et al. (2020) to be important for anticyclone persistence over central Europe. However, in the 2018 case the nearby branch is located to the southeast, not to the southwest as for central Europe. Three days before the peak of the heatwave, trajectories almost exclusively stem from this nearby branch, now located more to the south of the Scandinavian anticyclone (Fig. 6b). Clearly, determining causal pathways from this analysis is not possible, yet modelling studies with explicit convection could shed more light on the role of the remote branch (warm conveyor belt over the western Atlantic) versus the nearby branch over southeastern Europe for the establishment and maintenance of the Scandinavian anticyclone.

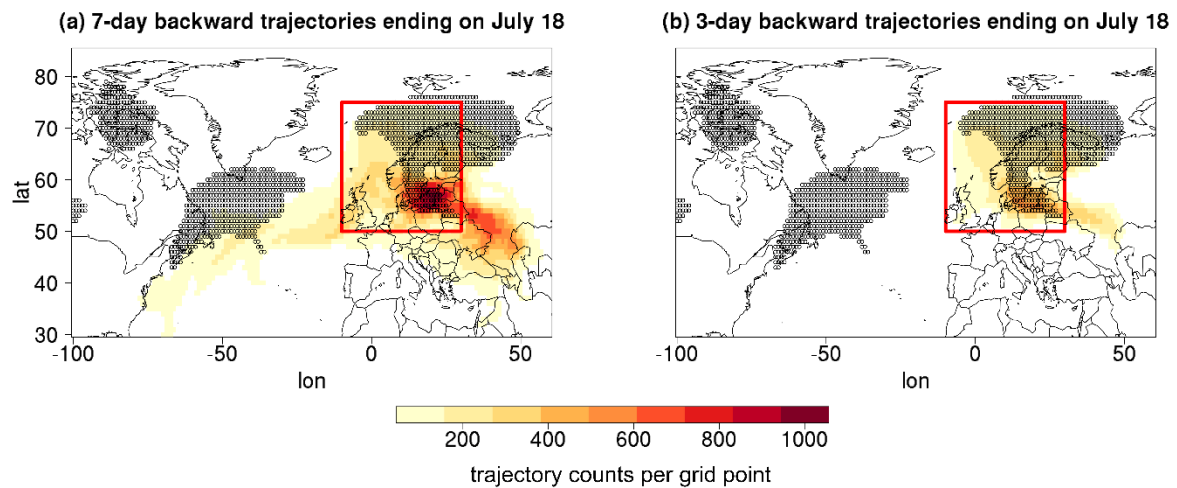



Figure 6: Backward trajectories for 7-days (a) and 3-days (b). Backward trajectory density maps ending on July 18, initiated in 50 hPa steps between 150 hPa and 500 hPa for grid points within the Scandinavian anticyclone (backward trajectories were initiated from the dotted points inside the red rectangle; the dotted points are those defined by vertically averaged PV anomaly based on monthly climatology < -0.7 PVU and PV < 1 PVU).

3.3 Low-frequency precursors

When addressing possible precursors for European heatwaves, SST anomalies over the North Atlantic (Dunstone et al., 2019; Ossó et al., 2020; Beobide-Arsuaga et al., 2023) and soil moisture anomalies over continental Europe (Quesada et al., 2012) are among the primary candidates, as outlined in the Introduction. A tripolar SST pattern with negative anomalies over the Subpolar Gyre (SPG) was evident in spring (MAM, northern box of Fig. 7a,b). At the same time, a pronounced precipitation deficit over Scandinavia in spring 2018 was present (Fig. 7c). The SST tripolar pattern persisted over time, with the cold SPG anomaly intensifying in summer (JJA, Fig. 7b), and the same is true for the precipitation deficit, which increased particularly in Germany and central Europe (Fig. 7d), as also discussed in Toreti

et al. (2019). The soil moisture anomaly for 2018 spring and summer (Fig. 7e,f) shows a pattern consistent with the precipitation anomaly.

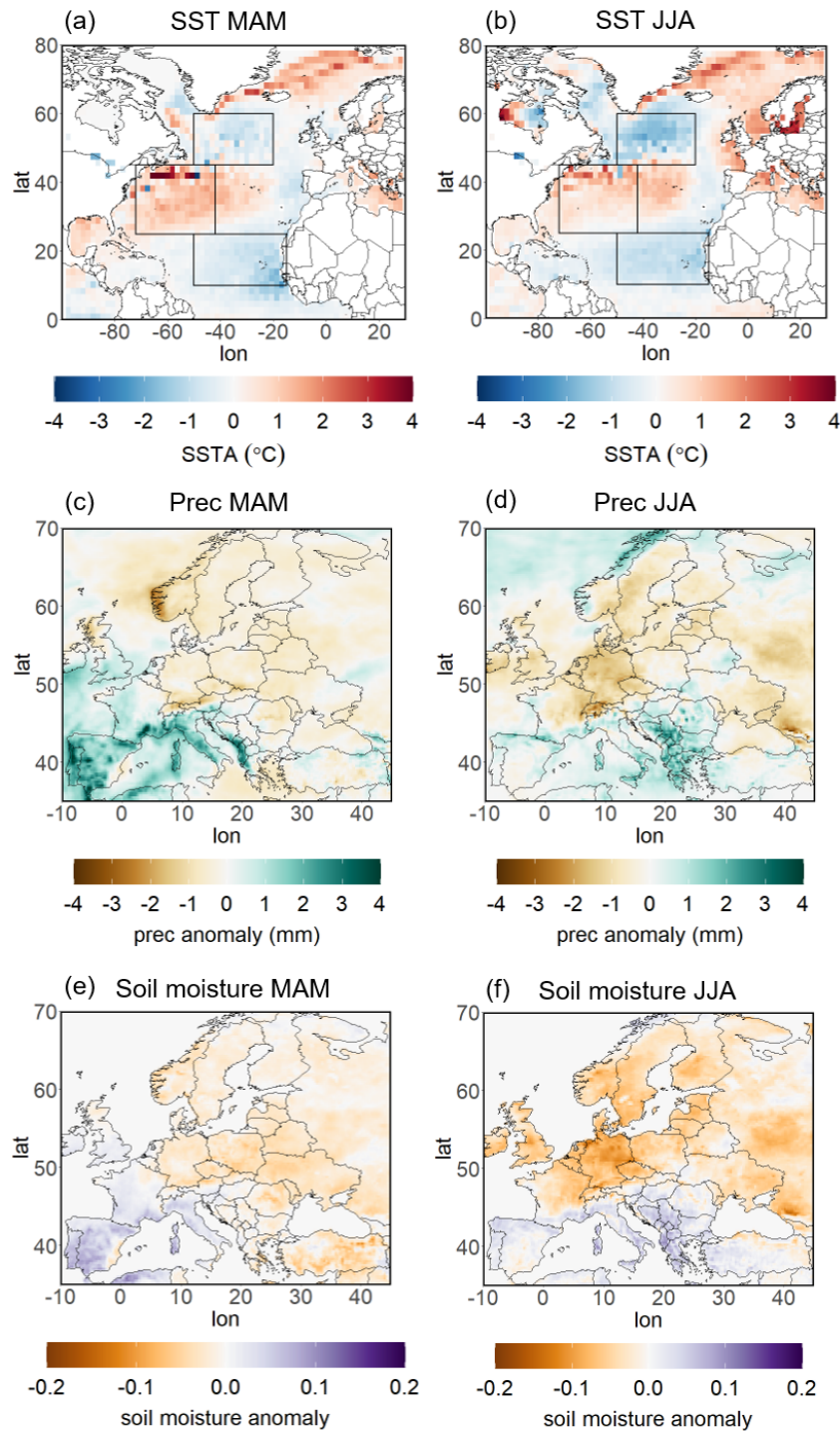
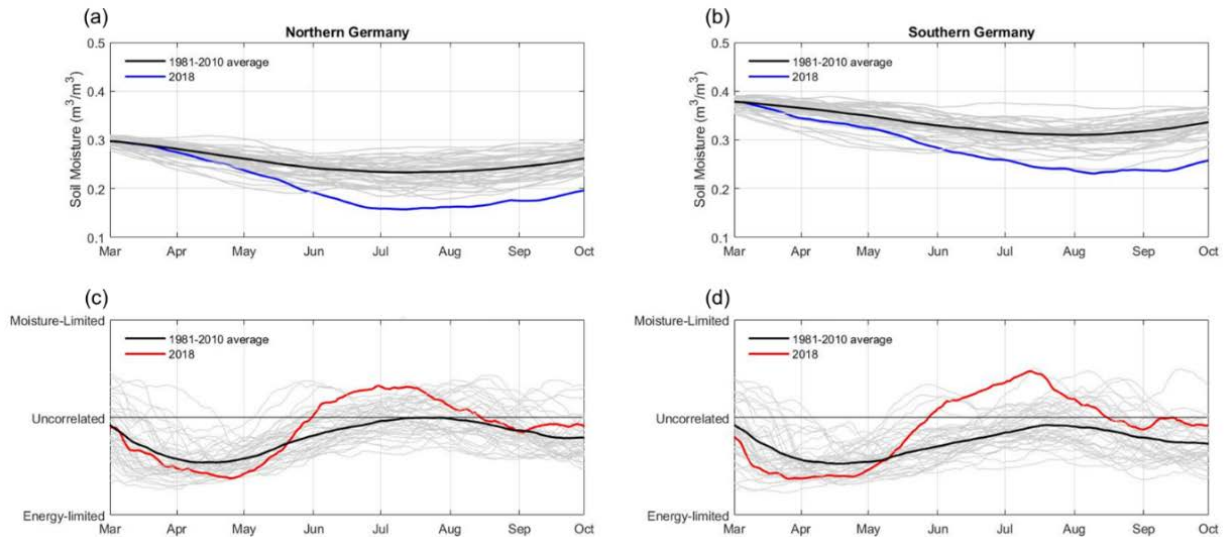



Figure 7: Anomalies of sea surface temperature (SST; a,b), precipitation (c,d) and soil moisture (e, f) in the ERA5 reanalysis (compared to the reference period 1981–2010) for spring (March to May; MAM; a, c, e) and summer (June to August; JJA; b, d, f) months. Boxes in (a) and (b) indicate the regions for the tripolar SST pattern.

492   Having established that the large-scale soil moisture anomaly is consistent with the SST and
493 precipitation anomalies, we investigated the temporal development of the soil moisture pattern over
494 Germany. Reduced soil moisture often facilitates the occurrence of summer drought and heatwaves
495 (Teuling, 2018), as the soil moisture determinant for evapotranspiration (or lack thereof) directly links
496 to the surface temperature and relative humidity at the land surface (Stéfanon et al., 2014; Miralles et
497 al., 2018). Thus, soil moisture and latent heat flux were used to identify periods of moisture limitation
498 (denoted by positive correlation coefficients between the two) and wet conditions (negative correlation
499 coefficients), under which the latent heat flux is primarily controlled by the atmosphere. The derived
500 time series for the soil moisture-latent heat flux correlations are based on daily data centered on 92-day
501 running periods for Germany (Fig. 8). Additionally, centered 92-day running mean soil moisture is
502 shown. The time series were spatially averaged over all land points for northern (Fig. 8a,c) and southern
503 Germany (Fig. 8b,d). Germany is usually not in the moisture-limited regime, but extraordinary
504 hydrologic conditions can lead to a shift from an energy-limited evaporative regime to moisture-limited
505 conditions (Lo et al., 2021), increasing the surface temperature and enhancing the sensible heat flux.
506 The soil moisture anomaly in March 2018 was low all over Germany (Fig. 8a,b) and thus did not yet
507 limit evapotranspiration and latent heat flux. Warm conditions in spring caused a high latent heat flux
508 all over Germany, indicating a strong energy-limitation (Fig. 8c,d). High latent heat fluxes, in turn, lead
509 to a severe depletion of the soil moisture up to a depth of 1 m, starting at the end of March and continuing
510 until July in northern Germany and mid-August in southern Germany. The precipitation deficit (Fig.
511 7c,d) further exacerbated the drying of the soils, and shifted the evaporative regime from energy-limited
512 to moisture-limited conditions. The latter prevailed between June and August 2018, indicating that the
513 anomalously dry soils during the 2018 summer further augmented the hot surface temperatures
514 (Dirmeyer et al., 2021; Orth, 2021).

515   In summary, the observed and modelled spring and early summer SST anomalies over the North
516 Atlantic and European soil moisture anomaly patterns for 2018 are in line with those identified for other
517 recent hot summers. Moreover, the dried-out soils and vegetation may have enhanced the maximum
518 temperatures by leading to anomalous latent heat fluxes locally, but also downwind via advected
519 sensible heat that can lead to abrupt increases in air temperatures further enhancing local land–
520 atmosphere feedbacks (Schumacher et al., 2022)

521
522 **Figure 8:** (a) Time series of centered 92-day running mean soil moisture averaged over all land points
523 of northern Germany (51° N – 55° N and 4° E – 16° E) for the period March-September of 1981-2020.
524 The grey lines denote individual years, the black line the average of 1981-2010, and the blue line 2018.
525 (b) As (a) but for southern Germany (48° N-51° N and 4° E – 16° E). (c) Time series of soil moisture-
526 latent heat flux coefficients based on 92-day running periods for the growing period covering March to
527 September for the years 1981-2020 for northern Germany. The grey lines denote individual years, the
528 black line the average of 1981-2010, and the red line 2018. Energy-limited is related to a correlation
529 coefficient of -1, and moisture-limited to a correlation coefficient of 1. (d) As (c) but for southern
530 Germany.

531 **3.4 Attribution of the 2018 extreme heat**

532 This section evaluates how anthropogenic climate change has affected the likelihood of similar
533 heatwaves under present climate conditions and how it will affect their likelihood at global warming
534 levels of +1.5° C and +2° C compared to pre-industrial times.

535 As defined by the cumulative heat metric, the 2018 summer was the 2nd warmest summer over
536 Europe following 2010, surpassed again in 2019 and 2021 (not shown), ranking it 4th warmest by now.
537 In the period of 1979-2021, ERA5 data exhibits a 7 % likelihood of 2018 cumulative heat levels (black
538 PDF in Fig. 9). MPI-GE, which is shown to adequately represent the variability and forced
539 anthropogenic changes in observed temperatures (Suarez-Gutierrez et al., 2018; 2021), is also well able
540 to capture cumulative heat (gray PDF in Fig. 9) as compared to ERA5. Under recent climate (1979-
541 2021) conditions, the 100 members of MPI-GE simulate a 9 % likelihood of exceeding 2018 levels,
542 making this roughly a 1-in-10-years event. This is in line with an earlier attribution study by the World
543 Weather Attribution (WWA) team who found return periods of about 1-in-10-years for Scandinavia
544 and slightly less in the Netherlands (WWA, 2018). Vogel et al. (2019) also showed that events of this
545 type, exhibiting concurrent hot temperature extremes over large parts of the northern hemisphere, were

546 unprecedented before 2010 and it is virtually certain that the 2018 events would not have occurred

547 without human-induced climate change. Under stronger global warming, this likelihood reaches 69 %

548 in a +1.5° C world, and 96 % in a +2° C world (orange and red PDFs in Fig. 9). Thus, conditions as

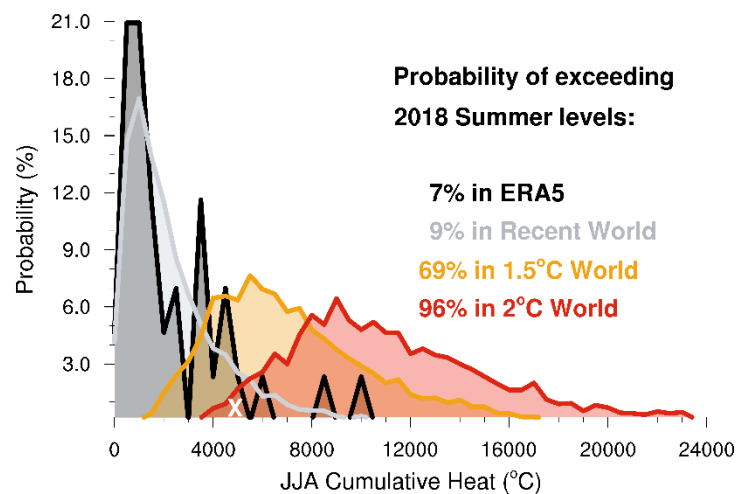
549 extreme as the summer 2018 are projected to occur two out of every three summers in a 1.5° C warmer

550 world, while given 2° C of global warming they occur virtually every single summer. The extreme

551 summer 2018 represents a fairly average summer in a +1.5° C world. In a 2° C warmer world, the

552 cumulative heat during the average summer is twice as large as the 2018 levels, while the most extreme

553 2° C world summers could exhibit more than four times more excess heat compared to the recent climate

554 conditions.

555
556 **Figure 9:** European ERA5 (1979-2021; black) cumulative heat versus MPI-GE under recent (1979-

557 2021; gray), future +1.5° C (2020-2049; orange), and +2° C (2050-2079; red) compared to pre-industrial

558 times warmer worlds. 2018 summer from ERA5 data is marked with white X. Daily maximum

559 temperatures (Tmax) for summer months (June to August; JJA) over land grid points only. Anomalies

560 with respect to 1981-2010. ERA5 data regridded to coarser resolution of MPI-GE. Probabilities are

561 normalized to percentages (divided by total number of years in period). Bin size is 500° C.

562
563   To estimate how much more likely the heat event of 2018 has become in Germany in recent decades

564 due to anthropogenic climate change, its probability ratio was calculated based on historical and hist-

565 nat (pre-industrial-type) simulations from the CMIP6 archive. In a first step, we defined the extreme

566 event for which the tailored attribution analysis for Germany was conducted. We analyzed the

567 maximum daily temperature (Tmax) averaged for a box over Germany (47.5-55° N, 6-15° E) and to

568 account for the prolonged heat of 2018, we used the Tmax as a spatial average over seventeen days

569 (Tmax17). This length was defined based on the longest period of consecutive days with Tmax above

570 30 °C in German weather stations on record. Using this length, resulted in the longest return period.

571 Thus, annual block maxima of this variable (Tmax17) were constructed within the GEV fit and the

572 return periods were calculated. The return period of the 2018 summer Tmax17 (approximately 31° C
573 in E-OBS) was estimated as 108 years, making it a heatwave that is expected less than once in a lifetime
574 and can therefore have considerable impacts. It should be acknowledged that such a return period
575 estimate contains uncertainties as the time series used to calculate it are shorter (about 70 years).
576 Following the analysis of observation-based data, the following models were analyzed: CanESM5,
577 CNRM-CM6-1, ACCESS-ESM1-5, IPSL-CM6A-LR, HadGEM3-GC31-LL, and MRI-ESM2-0 (see
578 Table S1 for further details on the models used).

579   The probability ratio of the 2018 summer heatwave occurrence in Germany is shown for all
580 analyzed models in Figure 10. For all models the probability ratio estimated on the original simulation
581 data is larger than 1, meaning that the probability of such a heatwave has increased due to anthropogenic
582 climate change. The red bars provide uncertainty ranges bases on the 1000 bootstraps. The best estimate
583 in all analysed CMIP6 models (black squares) is > 2, again in line with the WWA findings despite a
584 rather different event definition (WWA, 2018). For readability of the results, the x-axis in Figure 10 is
585 only extended to a value of 100 with larger values omitted due to the large uncertainties. In fact, the
586 upper range of probability ratios for some models is invalid as the event had a zero probability of
587 occurrence in the hist-nat scenario, indicating that such an extended heatwave would have been very
588 improbable under pre-industrial conditions.

589   In summary, the analysis of the impact of anthropogenic climate change on the heatwave in summer
590 2018 shows that such heat events have already become more frequent, i.e. their probability has increased
591 compared to pre-industrial conditions. Furthermore, it is expected that such heat events will become
592 even more likely in a warmer world.

593

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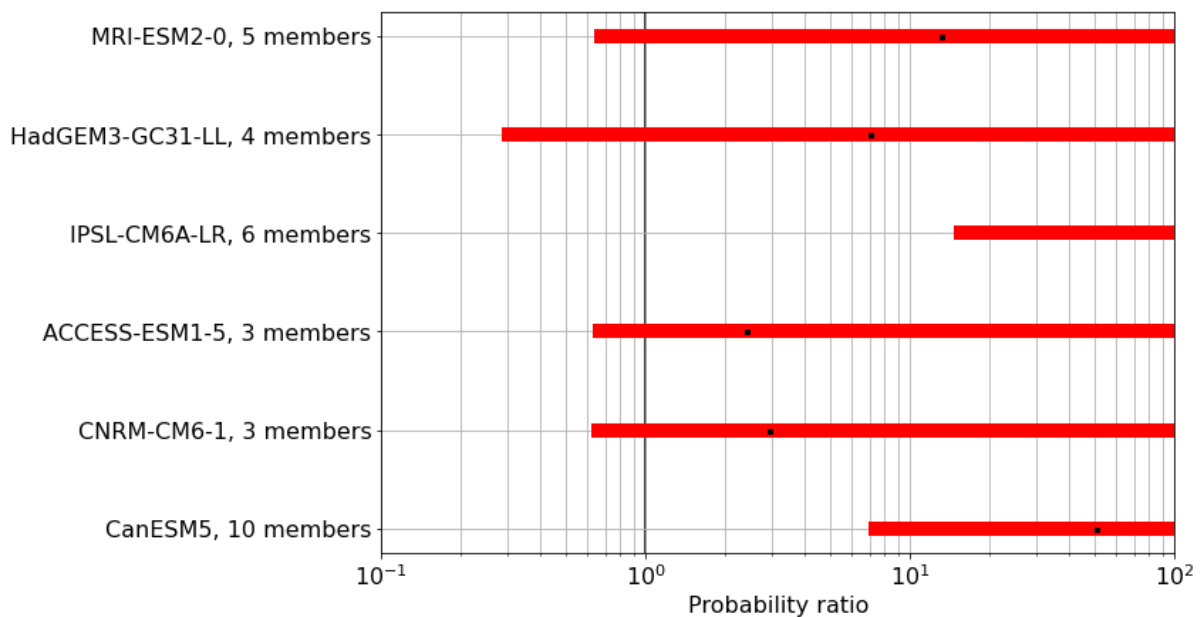
595 **Figure 10:** Probability ratio (PR) of the 2018 summer heatwave occurrence in Germany in the analyzed
596 CMIP6 models (see Table S1). The black squares show the PR estimated based on the original

597 simulation time series and the red bars show the 5th to 95th PR percentiles calculated from a 1000-
598 member bootstrap. The number of available DAMIP ensemble members is given together with the
599 model name and the originating institution on the y-axis. The vertical thick black line indicates a PR=1,
600 above which the likelihood of such an event has increased compared to pre-industrial times.

602 Drought attribution is notoriously difficult due to the fact that global models only crudely reproduce
603 convective precipitation, which is the main mode of rainfall in summer. While evapotranspiration is
604 increasing with warming, the question whether or not this can be compensated by stronger downpours
605 to avoid hydrological (or agricultural) drought cannot be answered with any degree of certainty at the
606 moment. Drought episodes are expected to increase (Masson-Delmotte et al. IPCC, 2021) across the
607 world, but the frequency of occurrence and the actual change in risk cannot be quantified yet.
608 Nevertheless, it is likely that the prolonged 2018 drought, followed by two more below-average rainfall
609 years in 2019 and 2020 in Germany, is partially attributable to human-induced climate change. Given
610 that attributable global warming is approximately 1.1° C (2011-2020), corresponding to 100% of the
611 observed warming, and warming over land is much more rapid, Europe has already warmed
612 disproportionately by ~2°C compared to pre-industrial times, with summer warming being particularly
613 amplified due to soil moisture feedbacks under increased sensible heat fluxes. Together with the
614 potential dynamic feedback discussed above, the average summer Tmax in Europe may well exceed 3°
615 C above pre-industrial conditions already. This is corroborated by a recent WWA study, which analyzed
616 the UK heat record during the exceptional 2022 heatwave (18-19 July 2022) and found that climate
617 change added 4° C to the observed record Tmax. What used to be a 36°C day is now a 40°C day (World
618 Weather Attribution (WWA), 2022).

619 **4   Discussion and conclusions**

620 The extreme heat and drought of the summer 2018 has been studied from a multi-faceted weather
621 and climate perspective. We looked at hot and dry summers over Europe using different analysis
622 approaches to study the extremeness and attribution to anthropogenic climate change (climate
623 perspective), as well as synoptic dynamics in concert with slowly varying boundary conditions at the
624 ocean and continental surfaces (seasonal and weather perspective). The 2018 summer is found to be a
625 unique historical example of persistent heatwave and drought conditions in large parts of Europe. This
626 is particularly true for northern and central Europe, regions which - unlike the seasonal drought in the
627 Mediterranean- are historically not so accustomed to this kind of concurrent hot and dry summer
628 extremes. The 2018 summer is one more case in a cluster of intense heatwaves facing Europe over the
629 last decades (Russo et al., 2015; Becker et al., 2022). The 2018 drought was an intense, large-scale
630 event, promoting strong land-atmosphere coupling that exacerbated the heatwave (Dirmeyer et al.,
631 2021).

Regarding the large-scale atmospheric conditions conducive of the summer 2018 extremes, we provided detailed evidence on the blocking anticyclones, persistent double jet stream configurations, sNAO+ phase, Rossby wave activity, and different air mass origins. For example, the persistent double jet stream event, combined with record high positive sNAO (Drouard et al., 2019), seems to have played a role in the long duration of the 2018 heatwave. Additionally, according to Li et al. (2020), the collaborative (not mutually exclusive) roles of sNAO+ and European blocking could favor the frequency, persistence, and magnitude of heatwaves over Europe, as the sNAO+ related blocking events are quasi-stationary and more persistent compared to the non-NAO+ related ones. New evidence is provided regarding the origin of the low PV air masses in the upper-tropospheric blocking anticyclone over Scandinavia; while in its initiation phase, backward trajectory analyses point to a role of a western North Atlantic warm conveyor belt, we provide hints that its maintenance could be supported by low PV air stemming from moist convection in the trough flanking the block to its southeast, i.e. over Eastern Europe. However, further analysis is needed to address the direction of causality behind this link. On the other hand, our analysis suggests that the later heatwave phase over Iberia has different drivers, as the air masses originated locally or were advected from nearby areas (e.g. North Africa) and are not necessarily directly associated with the propagation and breaking of large-scale Rossby waves as over Scandinavia (Santos et al., 2015; Sousa et al., 2019).

The dominant oceanic and large-scale conditions of the North Atlantic might have supported the development of the 2018 heatwave (Dunstone et al., 2019). The physical reasoning on the relationship between the North Atlantic SST tripole and exceptionally cold North Atlantic ocean, the jet stream set up and the occurrence of the heat wave was proposed by Duchez et al. (2016) based on the summer 2015 event. Here, we documented that similar anomalies were also observed during the spring of 2018. While the atmospheric forcing is associated with the anomalous jet stream positions and blocking, they in turn influence the precipitation patterns over Europe, leading to changes in the soil moisture content. Although such a process enhances the potential for a heat extreme, the meteorological factors are the ones that determine the timing and duration of the heatwave. Dedicated modeling experiments and causal inference algorithms will be key to test the hypothesis of a causal link between spring North Atlantic SSTs and subsequent summer extremes in Europe. Moreover, the patterns of North Atlantic SSTs are acting on top of the warming background climate, which may further modify the type or the magnitude of those relationships (McCarthy et al., 2019).

The severe soil moisture depletion in Germany between April and July of 2018 reflected the persistently warm and dry conditions and led to anomalously dry soils in summer. The drought conditions in the soil pushed its state into the transition zone conditions, in which soil wetness plays a direct role in influencing the climate by reducing the evaporative cooling effect at the land surface and thus enhancing hot and dry conditions. The moisture-limited conditions that prevailed between June and August 2018 indicated that the hot surface temperatures are directly linked to anomalously dry soils during the 2018 summer period (Dirmeyer et al., 2021; Orth, 2021).

669   We also showed that summer 2018 was extreme in the observational record for Europe and that
670   heat anomalies of this magnitude are expected to occur much more often in a warmer world, being
671   reached up to almost every year with global warming of +2° C. Wehrli et al. (2020) provided evidence
672   that the anthropogenic background warming was a strong contributor to the 2018 summer heatwave in
673   the Northern Hemisphere, highlighting that future extremes under similar atmospheric circulation
674   conditions at higher levels of global warming would reach dangerous levels. Our tailored attribution
675   study, which analyzed how the maximum temperature, averaged over 17 days over Germany, has been
676   impacted by anthropogenic climate change, showed that the probability of such a prolonged heat event
677   has increased in all CMIP6 models analyzed here. This adds to previous attribution studies that analyzed
678   the summer 2018 heatwave in other areas of Europe and also found an increase in its likelihood under
679   anthropogenic climate change (McCarthy et al., 2019; Vogel et al., 2019; Leach et al., 2020).

680   Here, we presented a comprehensive study of the extreme hot and dry 2018 summer in Europe,
681   investigating its emergence and evolution with a combination of conventional and more sophisticated
682   metrics and methods, with an emphasis on their synoptic-scale atmospheric drivers and a reference to
683   their potential precursors in spring. Moreover, by assessing the event from a climate perspective, we
684   provided evidence that anomalous summers of such extremity have already, and will further, become
685   much more frequent in a warming world. Overall, this study highlights the added value of multi-faceted
686   approaches for the analysis of such extreme events, and that collaboration among different fields is
687   crucial both for the process understanding and the subsequent quantification of impacts. The summer
688   of 2022 was yet another very extreme hot and dry summer that affected Europe, corroborating the
689   approach of this work and emphasizing the need to carry out multi-disciplinary impact studies.

690   **Code availability**

691   Code is available from the authors upon request.

692   **Data availability**

693   The ERA5 (Hersbach et al. 2020) and ERA5-HEAT (Di Napoli et al., 2021) reanalysis data are publicly
694   available via the Copernicus Climate Change Service (https://cds.climate.copernicus.eu/cdsapp). The
695   gridded observational datasets E-OBS (Haylock et al., 2008; Cornes et al., 2018) are publicly available
696   on   the   European   Climate   Assessment   &   Dataset   website
697   (https://www.ecad.eu/download/ensembles/download.php). The observational datasets from the
698   German Weather Service (DWD; Kaspar et al., 2013) are publicly available on the DWD website
699   (https://opendata.dwd.de/). The CMIP6 (Eyring et al., 2016) and the Max Planck Grand Ensemble
700   (MPI-GE; Maher et al., 2019) climate model data are publicly available via the Earth System Grid
701   Federation   portal   (https://esgf-data.dkrz.de/projects/esgf-dkrz/   and   https://esgf-

data.dkrz.de/projects/mpi-ge/ respectively). The North Atlantic Oscillation (NAO) index timeseries is publicly available on the National Weather Service Climate Predictions Center website (https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml).

Competing interests

At least one of the (co-)authors is a member of the editorial board of Natural Hazards and Earth System Sciences. The peer-review process was guided by an independent editor, and the authors have also no other competing interests to declare.

Author Contributions

ER and AF coordinated the inter-disciplinary task force on heat and drought within ClimXtreme and this collaborative paper; ER did the jet stream analysis, prepared Figures 1, 3c, 5d, 7 and curated most of the final figures with contributions from different co-authors (see below), and wrote the first draft of the paper with contributions from different co-authors; FB calculated UTCI, did the Rossby wave packet and the trajectories analysis and prepared Figures 4, 5, 6; GBA calculated the cumulate heat metric in ERA5 and the SST anomalies; DP calculated SPEI; DN and SS prepared Figure 2 and S1; AR did the blocking analysis and prepared Figures 3a,b, S2, and S3; JR did the weather regime analysis; LJ calculated precipitation and soil moisture anomalies in ERA5 and prepared Figure 8;; LSG did the MPI-GE attribution study and prepared Figure 9; JT did the CMIP6 attribution study and prepared Figure 10 and Table S1; GC contributed to the CMIP6 attribution study. All authors followed the analysis from the beginning, contributed text and edited/commented the final version of the manuscript.

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References

737 Allen, R. G., Pruitt, W. O., Wright, J. L., Howell, T. A., Ventura, F., Snyder, R., Itenfisu, D., Steduto,
738 P., Berengena, J., Yrisarry, J. B., Smith, M., Pereira, L. S., Raes, D., Perrier, A., Alves, I., Walter, I.
739 and Elliott, R.: A recommendation on standardized surface resistance for hourly calculation of
740 reference ETo by the FAO56 Penman-Monteith method, Agric. Water Manag., 81(1–2), 1–22,
741 doi:10.1016/J.AGWAT.2005.03.007, 2006.

742 Bakke, S. J., Ionita, M. and Tallaksen, L. M.: The 2018 northern European hydrological drought and
743 its drivers in a historical perspective, Hydrol. Earth Syst. Sci., 24(11), 5621–5653, doi:10.5194/hess-
744 24-5621-2020, 2020.

745 Barriopedro, D., Fischer, E. M., Luterbacher, J., Trigo, R. M. and García-Herrera, R.: The hot summer
746 of 2010: Redrawing the temperature record map of Europe, Science (80-.)., 332(6026), 220–224,
747 doi:10.1126/SCIENCE.1201224/SUPPL_FILE/PAP.PDF, 2011.

748 Barriopedro, D., Sousa, P. M., Trigo, R. M., García-Herrera, R. and Ramos, A. M.: The exceptional
749 Iberian heatwave of summer 2018, Bull. Am. Meteorol. Soc., 101(1), S29–S34, doi:10.1175/BAMS-
750 D-19-0159.1, 2020.

751 Bastos, A., Ciais, P., Friedlingstein, P., Sitch, S., Pongratz, J., Fan, L., Wigneron, J. P., Weber, U.,
752 Reichstein, M., Fu, Z., Anthoni, P., Arneth, A., Haverd, V., Jain, A. K., Joetzjer, E., Knauer, J.,
753 Lienert, S., Loughran, T., McGuire, P. C., Tian, H., Viovy, N. and Zaehle, S.: Direct and seasonal
754 legacy effects of the 2018 heat wave and drought on European ecosystem productivity, Sci. Adv.,
755 6(24), doi:10.1126/sciadv.aba2724, 2020.

756 Bastos, A., Orth, R., Reichstein, M., Ciais, P., Viovy, N., Zaehle, S., Anthoni, P., Arneth, A., Gentine,
757 P., Joetzjer, E., Lienert, S., Loughran, T., McGuire, P., O, S., Pongratz, J. and Sitch, S.: Increased
758 vulnerability of European ecosystems to two compound dry and hot summers in 2018 and 2019, Earth
759 Syst. Dyn. Discuss., 1–32, doi:10.5194/esd-2021-19, 2021.

760 Becker, F. N., Fink, A. H., Bissolli, P. and Pinto, J. G.: Towards a more comprehensive assessment of
761 the intensity of historical European heat waves (1979–2019), Atmos. Sci. Lett., e1120,
762 doi:10.1002/ASL.1120, 2022.

763 Beguería, S. and Vicente-Serrano, S. M.: SPEI: Calculation of Standardized Precipitation-
764 Evapotranspiration Index, R package version 1.6, [online] Available from:
765 https://www.rdocumentation.org/packages/SPEI/versions/1.6/topics/SPEI-package, 2013.

766 Beillouin, D., Schauberger, B., Bastos, A., Ciais, P. and Makowski, D.: Impact of extreme weather
767 conditions on European crop production in 2018, Philos. Trans. R. Soc. B, 375(1810),
768 doi:10.1098/RSTB.2019.0510, 2020.

769 Beobide-Arsuaga, G., Düsterhus, A., Müller, W. A., Barnes, E. A. and Baehr, J.: Spring Regional Sea
770 Surface Temperatures as a Precursor of European Summer Heatwaves, Geophys. Res. Lett., 50(2),
771 e2022GL100727, doi:10.1029/2022gl100727, 2023.

772 Błazejczyk, K., Jendritzky, G., Bröde, P., Fiala, D., Havenith, G., Epstein, Y., Psikuta, A. and
773 Kampmann, B.: An introduction to the Universal thermal climate index (UTCI), Geogr. Pol., 86(1),
774 5–10, doi:10.7163/GPol.2013.1, 2013.

775 Di Capua, G., Sparrow, S., Kornhuber, K., Rousi, E., Osprey, S., Wallom, D., van den Hurk, B. and
776 Coumou, D.: Drivers behind the summer 2010 wave train leading to Russian heatwave and Pakistan
777 flooding, npj Clim. Atmos. Sci., 4(1), 55, doi:10.1038/s41612-021-00211-9, 2021.

778 Chen, S., Wu, R. and Liu, Y.: Dominant Modes of Interannual Variability in Eurasian Surface Air
779 Temperature during Boreal Spring, J. Clim., 29(3), 1109–1125, doi:10.1175/JCLI-D-15-0524.1, 2016.

780 Climate Change Service: Dry and warm spring and summer, [online] Available from:
781 https://climate.copernicus.eu/dry-and-warm-spring-and-summer, 2018.

782 Climate Change Service: Warmest summer for Europe by small margin; August globally joint third

warmest on record, [online] Available from: https://climate.copernicus.eu/copernicus-warmest-summer-europe-small-margin-august-globally-joint-third-warmest-record, 2021.

Cornes, R. C., van der Schrier, G., van den Besselaar, E. J. M. and Jones, P. D.: An Ensemble Version of the E-OBS Temperature and Precipitation Data Sets, J. Geophys. Res. Atmos., 123(17), 9391–9409, doi:10.1029/2017JD028200, 2018.

Crasemann, B., Handorf, D., Jaiser, R., Dethloff, K., Nakamura, T., Ukita, J. and Yamazaki, K.: Can preferred atmospheric circulation patterns over the North-Atlantic-Eurasian region be associated with arctic sea ice loss?, Polar Sci., 14, 9–20, doi:10.1016/J.POLAR.2017.09.002, 2017.

Dirmeyer, P. A., Balsamo, G., Blyth, E. M., Morrison, R. and Cooper, H. M.: Land-Atmosphere Interactions Exacerbated the Drought and Heatwave Over Northern Europe During Summer 2018, AGU Adv., 2(2), e2020AV000283, doi:10.1029/2020AV000283, 2021.

Droogers, P. and Allen, R. G.: Estimating Reference Evapotranspiration Under Inaccurate Data Conditions, Irrig. Drain. Syst. 2002 161, 16(1), 33–45, doi:10.1023/A:1015508322413, 2002.

Drouard, M., Kornhuber, K. and Woollings, T.: Disentangling Dynamic Contributions to Summer 2018 Anomalous Weather Over Europe, Geophys. Res. Lett., 46(21), 12537–12546, doi:10.1029/2019GL084601, 2019.

Duan, S. Q., Findell, K. L. and Wright, J. S.: Three Regimes of Temperature Distribution Change Over Dry Land, Moist Land, and Oceanic Surfaces, Geophys. Res. Lett., 47(24), e2020GL090997, doi:10.1029/2020GL090997, 2020.

Duchez, A., Frajka-Williams, E., Josey, S. A., Evans, D. G., Grist, J. P., Marsh, R., McCarthy, G. D., Sinha, B., Berry, D. I. and Hirschi, J. J. M.: Drivers of exceptionally cold North Atlantic Ocean temperatures and their link to the 2015 European heat wave, Environ. Res. Lett., 11(7), 1–9, doi:10.1088/1748-9326/11/7/074004, 2016.

Dunstone, N., Smith, D., Hardiman, S., Eade, R., Gordon, M., Hermanson, L., Kay, G. and Scaife, A.: Skilful Real-Time Seasonal Forecasts of the Dry Northern European Summer 2018, Geophys. Res. Lett., 46(21), 12368–12376, doi:10.1029/2019GL084659, 2019.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J. and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geosci. Model Dev., 9(5), 1937–1958, doi:10.5194/GMD-9-1937-2016, 2016.

Fink, A. H., Brücher, T., Krüger, A., Leckebusch, G. C., Pinto, J. G. and Ulbrich, U.: The 2003 European summer heatwaves and drought –synoptic diagnosis and impacts, Weather, 59(8), 209–216, doi:10.1256/wea.73.04, 2004.

Fischer, E. M. and Schär, C.: Consistent geographical patterns of changes in high-impact European heatwaves, Nat. Geosci., 3(6), 398–403, doi:10.1038/ngeo866, 2010.

Folland, C. K., Knight, J., Linderholm, H. W., Fereday, D., Ineson, S. and Hurrel, J. W.: The summer North Atlantic oscillation: Past, present, and future, J. Clim., 22(5), 1082–1103, doi:10.1175/2008JCLI2459.1, 2009.

Fragkoulidis, G. and Wirth, V.: Local rossby wave packet amplitude, phase speed, and group velocity: Seasonal variability and their role in temperature extremes, J. Clim., 33(20), 8767–8787, doi:10.1175/JCLI-D-19-0377.1, 2020.

Friedrich, K. and Kaspar, F.: Rückblick auf das Jahr 2018 – das bisher wärmste Jahr in Deutschland, [online] Available from: https://www.dwd.de/DE/leistungen/besondereereignisse/temperatur/20190102_waermstes_jahr_in_deutschland_2018.pdf?__blob=publicationFile&v=2 am: 10.12.2021 (Accessed 4 April 2022), 2019.

Gastineau, G. and Frankignoul, C.: Influence of the North Atlantic SST variability on the atmospheric circulation during the twentieth century, J. Clim., 28(4), 1396–1416, doi:10.1175/JCLI-D-14-00424.1, 2015.

Gillett, N. P., Shiogama, H., Funke, B., Hegerl, G., Knutti, R., Matthes, K., Santer, B. D., Stone, D. and Tebaldi, C.: The Detection and Attribution Model Intercomparison Project (DAMIP v1.0) contribution to CMIP6, Geosci. Model Dev., 9(10), 3685–3697, doi:10.5194/GMD-9-3685-2016, 2016.

Haylock, M. R., Hofstra, N., Klein Tank, A. M. G., Klok, E. J., Jones, P. D. and New, M.: A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006, J. Geophys. Res. Atmos., 113(D20), 20119, doi:10.1029/2008JD010201, 2008.

Heim, R. R.: A Review of Twentieth-Century Drought Indices Used in the United States, Bull. Am.

838   Meteorol. Soc., 83(8), 1149–1166, doi:10.1175/1520-0477-83.8.1149, 2002.

839   Herceg-Bulić, I. and Kucharski, F.: North Atlantic SSTs as a Link between the Wintertime NAO and
840   the Following Spring Climate, J. Clim., 27(1), 186–201, doi:10.1175/JCLI-D-12-00273.1, 2014.

841   Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J.,
842   Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G.,
843   Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis,
844   M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan,
845   R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay,
846   P., Rozum, I., Vamborg, F., Villaume, S. and Thépaut, J. N.: The ERA5 global reanalysis, Q. J. R.
847   Meteorol. Soc., doi:10.1002/qj.3803, 2020.

848   Ionita, M., Caldarescu, D. E. and Nagavciuc, V.: Compound Hot and Dry Events in Europe:
849   Variability and Large-Scale Drivers, Front. Clim., 3, 58, doi:10.3389/fclim.2021.688991, 2021.

850   Jesús San-Miguel-Ayanz, Tracy Durrant, Roberto Boca, Giorgio Libertà, A. B., Daniele de Rigo,
851   Davide Ferrari, Pieralberto Maianti, Tomàs Artés Vivancos, Duarte Oom, Hans Pfeiffer, D. and
852   Nuijten, T. L.: Forest Fires in Europe, Middle East and North Africa 2018., 2019.

853   Kaspar, F., Müller-Westermeier, G., Penda, E., Mächel, H., Zimmermann, K., Kaiser-Weiss, A. and
854   Deutschländer, T.: Monitoring of climate change in Germany – data, products and services of
855   Germany's National Climate Data Centre, Adv. Sci. Res., 10(1), 99–106, doi:10.5194/ASR-10-99-
856   2013, 2013.

857   Kautz, L.-A., Martius, O., Pfahl, S., Pinto, J. G., Ramos, A. M., Sousa, P. M. and Woollings, T.:
858   Atmospheric blocking and weather extremes over the Euro-Atlantic sector – a review, Weather Clim.
859   Dyn., 3(1), 305–336, doi:10.5194/WCD-3-305-2022, 2022.

860   Kendon, M., McCarthy, M., Jevrejeva, S., Matthews, A. and Legg, T.: State of the UK climate 2018,
861   Int. J. Climatol., 39(S1), 1–55, doi:10.1002/joc.6213, 2019.

862   Kennedy, J. J., Killick, R. E., Dunn, R. J., McCarthy, M. P., Morice, C. P., Rayner, N. A. and
863   Titchner, H. A.: Global and regional climate in 2018, Weather, 74(10), 332–340,
864   doi:10.1002/wea.3600, 2019.

865   Kohonen, T.: Essentials of the self-organizing map, Neural Networks, 37, 52–65,
866   doi:10.1016/j.neunet.2012.09.018, 2013.

867   Leach, N. J., Li, S., Sparrow, S., Oldenborgh, G. J. van, Lott, F. C., Weisheimer, A. and Allen, M. R.:
868   Anthropogenic Influence on the 2018 Summer Warm Spell in Europe: The Impact of Different
869   Spatio-Temporal Scales, Bull. Am. Meteorol. Soc., 101(1), S41–S46, doi:10.1175/BAMS-D-19-
870   0201.1, 2020.

871   Li, M., Yao, Y., Simmonds, I., Luo, D., Zhong, L. and Chen, X.: Collaborative impact of the nao and
872   atmospheric blocking on european heatwaves, with a focus on the hot summer of 2018, Environ. Res.
873   Lett., 15(11), 114003, doi:10.1088/1748-9326/aba6ad, 2020.

874   Liu, X., He, B., Guo, L., Huang, L. and Chen, D.: Similarities and Differences in the Mechanisms
875   Causing the European Summer Heatwaves in 2003, 2010, and 2018, Earth's Futur., 8(4),
876   e2019EF001386, doi:10.1029/2019EF001386, 2020.

877   Lo, M. H., Wu, W. Y., Tang, L. I., Ryu, D., Rashid, M. and Wu, R. J.: Temporal Changes in Land
878   Surface Coupling Strength: An Example in a Semi-Arid Region of Australia, J. Clim., 34(4), 1503–
879   1513, doi:10.1175/JCLI-D-20-0250.1, 2021.

880   Maher, N., Milinski, S., Suarez-Gutierrez, L., Botzet, M., Dobrynin, M., Kornblueh, L., Kröger, J.,
881   Takano, Y., Ghosh, R., Hedemann, C., Li, C., Li, H., Manzini, E., Notz, D., Putrasahan, D., Boysen,
882   L., Claussen, M., Ilyina, T., Olonscheck, D., Raddatz, T., Stevens, B. and Marotzke, J.: The Max
883   Planck Institute Grand Ensemble: Enabling the Exploration of Climate System Variability, J. Adv.
884   Model. Earth Syst., 11(7), 2050–2069, doi:10.1029/2019MS001639, 2019.

885   Manning, C., Widmann, M., Bevacqua, E., Van Loon, A. F., Maraun, D. and Vrac, M.: Increased
886   probability of compound long-duration dry and hot events in Europe during summer (1950–2013),
887   Environ. Res. Lett., 14(9), 094006, doi:10.1088/1748-9326/AB23BF, 2019.

888   Markonis, Y., Kumar, R., Hanel, M., Rakovec, O., Máca, P. and Kouchak, A. A.: The rise of
889   compound warm-season droughts in Europe, Sci. Adv., 7(6),
890   doi:10.1126/SCIADV.ABB9668/SUPPL_FILE/ABB9668_SM.PDF, 2021.

891   Masson-Delmotte, V., P. Zhai, A. Pirani, S. L., Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L.
892   Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. and Matthews, T.K. Maycock, T.

Waterfield, O. Yelekçi, R. Yu, and B. Z. (eds. .: IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, New York., 2021.

McCarthy, M., Christidis, N., Dunstone, N., Fereday, D., Kay, G., Klein-Tank, A., Lowe, J., Petch, J., Scaife, A. and Stott, P.: Drivers of the UK summer heatwave of 2018, Weather, 74(11), 390–396, doi:10.1002/WEA.3628, 2019.

Miralles, D. G., Teuling, A. J., van Heerwaarden, C. C. and Vilà-Guerau de Arellano, J.: Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation, Nat. Geosci., 7(5), 345–349, doi:10.1038/ngeo2141, 2014.

Miralles, D. G., Gentine, P., Seneviratne, S. I. and Teuling, A. J.: Land–atmospheric feedbacks during droughts and heatwaves: state of the science and current challenges, Ann. N. Y. Acad. Sci., 1436(1), 19–35, doi:10.1111/nyas.13912, 2018.

Di Napoli, C., Barnard, C., Prudhomme, C., Cloke, H. L. and Pappenberger, F.: ERA5-HEAT: A global gridded historical dataset of human thermal comfort indices from climate reanalysis, Geosci. Data J., 8(1), 2–10, doi:10.1002/gdj3.102, 2021.

Orth, R.: When the Land Surface Shifts Gears, AGU Adv., 2(2), e2021AV000414, doi:10.1029/2021av000414, 2021.

Ossó, A., Sutton, R., Shaffrey, L. and Dong, B.: Development, Amplification, and Decay of Atlantic/European Summer Weather Patterns Linked to Spring North Atlantic Sea Surface Temperatures, J. Clim., 33(14), 5939–5951, doi:10.1175/JCLI-D-19-0613.1, 2020.

Pascal, M., Lagarrigue, R., Tabai, A., Bonmarin, I., Camail, S., Laaidi, K., Le Tertre, A. and Denys, S.: Evolving heat waves characteristics challenge heat warning systems and prevention plans, Int. J. Biometeorol., 65(10), 1683–1694, doi:10.1007/S00484-021-02123-Y/FIGURES/5, 2021.

Perkins-Kirkpatrick, S. E. and Lewis, S. C.: Increasing trends in regional heatwaves, Nat. Commun., 11(1), 3357, doi:10.1038/s41467-020-16970-7, 2020.

Peters, W., Bastos, A., Ciais, P. and Vermeulen, A.: A historical, geographical and ecological perspective on the 2018 European summer drought, Philos. Trans. R. Soc. B, 375(1810), doi:10.1098/RSTB.2019.0505, 2020.

Philip, S., Kew, S., van Oldenborgh, G. J., Otto, F., Vautard, R., van der Wiel, K., King, A., Lott, F., Arrighi, J., Singh, R. and van Aalst, M.: A protocol for probabilistic extreme event attribution analyses, Adv. Stat. Climatol. Meteorol. Oceanogr., 6(2), 177–203, doi:10.5194/ascmo-6-177-2020, 2020.

Philip, S. Y., Kew, S. F., van Oldenborgh, G. J., Anslow, F. S., Seneviratne, S. I., Vautard, R., Coumou, D., Ebi, K. L., Arrighi, J., Singh, R., van Aalst, M., Pereira Marghidan, C., Wehner, M., Yang, W., Li, S., Schumacher, D. L., Hauser, M., Bonnet, R., Luu, L. N., Lehner, F., Gillett, N., Tradowsky, J. S., Vecchi, G. A., Rodell, C., Stull, R. B., Howard, R. and Otto, F. E. L.: Rapid attribution analysis of the extraordinary heat wave on the Pacific coast of the US and Canada in June 2021, Earth Syst. Dyn., 13(4), 1689–1713, doi:10.5194/ESD-13-1689-2022, 2022.

Prodhomme, C., Materia, S., Ardilouze, C., White, R. H., Batté, L., Guemas, V., Fragkoulidis, G. and García-Serrano, J.: Seasonal prediction of European summer heatwaves, Clim. Dyn., 1, 3, doi:10.1007/s00382-021-05828-3, 2021.

Quesada, B., Vautard, R., Yiou, P., Hirschi, M. and Seneviratne, S. I.: Asymmetric European summer heat predictability from wet and dry southern winters and springs, Nat. Clim. Chang. 2012 210, 2(10), 736–741, doi:10.1038/nclimate1536, 2012.

Rousi, E., Anagnostopoulou, C., Tolika, K. and Maheras, P.: Representing teleconnection patterns over Europe: A comparison of SOM and PCA methods, Atmos. Res., 152, 123–137, doi:10.1016/j.atmosres.2013.11.010, 2015.

Rousi, E., Selten, F., Rahmstorf, S. and Coumou, D.: Changes in North Atlantic Atmospheric Circulation in a Warmer Climate Favor Winter Flooding and Summer Drought over Europe, J. Clim., 34(6), 2277–2295, doi:10.1175/JCLI-D-20-0311.1, 2021.

Rousi, E., Kornhuber, K., Beobide-Arsuaga, G., Luo, F. and Coumou, D.: Accelerated western European heatwave trends linked to more-persistent double jets over Eurasia, Nat. Commun., 13(1), 1–11, doi:10.1038/s41467-022-31432-y, 2022.

Russo, S., Dosio, A., Graversen, R. G., Sillmann, J., Carrao, H., Dunbar, M. B., Singleton, A., Montagna, P., Barbola, P. and Vogt, J. V.: Magnitude of extreme heat waves in present climate and

their projection in a warming world, J. Geophys. Res. Atmos., 119(22), 12,500-12,512, doi:10.1002/2014JD022098, 2014.

Russo, S., Sillmann, J. and Fischer, E. M.: Top ten European heatwaves since 1950 and their occurrence in the coming decades, Environ. Res. Lett., 10(12), 124003, doi:10.1088/1748-9326/10/12/124003, 2015.

Saeed, S., Van Lipzig, N., Müller, W. A., Saeed, F. and Zanchettin, D.: Influence of the circumglobal wave-train on European summer precipitation, Clim. Dyn. 2013 431, 43(1), 503–515, doi:10.1007/S00382-013-1871-0, 2013.

Santos, J. A., Pfahl, S., Pinto, J. G. and Wernli, H.: Mechanisms underlying temperature extremes in Iberia: a Lagrangian perspective, New pub Stock. uni Press, 67(1), 1–15, doi:10.3402/TELLUSA.V67.26032, 2015.

Scherrer, S. C., Croci-Maspoli, M., Schwierz, C. and Appenzeller, C.: Two-dimensional indices of atmospheric blocking and their statistical relationship with winter climate patterns in the Euro-Atlantic region, Int. J. Climatol., 26(2), 233–249, doi:10.1002/JOC.1250, 2006.

Schuldt, B., Buras, A., Arend, M., Vitasse, Y., Beierkuhnlein, C., Damm, A., Gharun, M., Grams, T. E. E., Hauck, M., Hajek, P., Hartmann, H., Hiltbrunner, E., Hoch, G., Holloway-Phillips, M., Körner, C., Larysch, E., Lübbe, T., Nelson, D. B., Rammig, A., Rigling, A., Rose, L., Ruehr, N. K., Schumann, K., Weiser, F., Werner, C., Wohlgemuth, T., Zang, C. S. and Kahmen, A.: A first assessment of the impact of the extreme 2018 summer drought on Central European forests, Basic Appl. Ecol., 45, 86–103, doi:10.1016/J.BAAE.2020.04.003, 2020.

Schumacher, D. L., Keune, J., van Heerwaarden, C. C., Vilà-Guerau de Arellano, J., Teuling, A. J. and Miralles, D. G.: Amplification of mega-heatwaves through heat torrents fuelled by upwind drought, Nat. Geosci. 2019 129, 12(9), 712–717, doi:10.1038/s41561-019-0431-6, 2019.

Schumacher, D. L., Keune, J., Dirmeyer, P. and Miralles, D. G.: Drought self-propagation in drylands due to land–atmosphere feedbacks, Nat. Geosci. 2022 154, 15(4), 262–268, doi:10.1038/s41561-022-00912-7, 2022.

Schuster, M., Grieger, J., Richling, A., Schartner, T., Illing, S., Kadow, C., Müller, W. A., Pohlmann, H., Pfahl, S. and Ulbrich, U.: Improvement in the decadal prediction skill of the North Atlantic extratropical winter circulation through increased model resolution, Earth Syst. Dyn., 10(4), 901–917, doi:10.5194/esd-10-901-2019, 2019.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B. and Teuling, A. J.: Investigating soil moisture–climate interactions in a changing climate: A review, Earth-Science Rev., 99(3), 125–161, doi:https://doi.org/10.1016/j.earscirev.2010.02.004, 2010.

Senf, C. and Seidl, R.: Persistent impacts of the 2018 drought on forest disturbance regimes in Europe, Biogeosciences, 18(18), 5223–5230, doi:10.5194/BG-18-5223-2021, 2021.

Shepherd, T. G.: A Common Framework for Approaches to Extreme Event Attribution, Curr. Clim. Chang. Reports, 2(1), 28–38, doi:10.1007/S40641-016-0033-Y/FIGURES/7, 2016.

Sinclair, V. A., Mikkola, J., Rantanen, M. and Räisänen, J.: The summer 2018 heatwave in Finland, Weather, 74(11), 403–409, doi:10.1002/WEA.3525, 2019.

Sousa, P. M., Trigo, R. M., Barriopedro, D., Soares, P. M. M., Ramos, A. M. and Liberato, M. L. R.: Responses of European precipitation distributions and regimes to different blocking locations, Clim. Dyn., 48(3–4), 1141–1160, doi:10.1007/S00382-016-3132-5/FIGURES/12, 2017.

Sousa, P. M., Trigo, R. M., Barriopedro, D., Soares, P. M. M. and Santos, J. A.: European temperature responses to blocking and ridge regional patterns, Clim. Dyn., 50(1–2), 457–477, doi:10.1007/s00382-017-3620-2, 2018.

Sousa, P. M., Barriopedro, D., Ramos, A. M., García-Herrera, R., Espírito-Santo, F. and Trigo, R. M.: Saharan air intrusions as a relevant mechanism for Iberian heatwaves: The record breaking events of August 2018 and June 2019, Weather Clim. Extrem., 26, 100224, doi:10.1016/j.wace.2019.100224, 2019.

Spensberger, C., Madonna, E., Boettcher, M., Grams, C. M., Papritz, L., Quinting, J. F., Röthlisberger, M., Sprenger, M. and Zschenderlein, P.: Dynamics of concurrent and sequential Central European and Scandinavian heatwaves, Q. J. R. Meteorol. Soc., 146(732), 2998–3013, doi:10.1002/qj.3822, 2020.

Spinoni, J., Vogt, J. V., Naumann, G., Barbosa, P. and Dosio, A.: Will drought events become more frequent and severe in Europe?, Int. J. Climatol., 38(4), 1718–1736, doi:10.1002/JOC.5291, 2018.

1003   Spinoni, J., Barbosa, P., Bucchignani, E., Cassano, J., Cavazos, T., Christensen, J. H., Christensen, O.
1004   B., Coppola, E., Evans, J., Geyer, B., Giorgi, F., Hadjinicolaou, P., Jacob, D., Katzfey, J., Koenigk,
1005   T., Laprise, R., Lennard, C. J., Kurnaz, M. L., Delei, L. I., Llopart, M., McCormick, N., Naumann, G.,
1006   Nikulin, G., Ozturk, T., Panitz, H. J., da Rocha, R. P., Rockel, B., Solman, S. A., Syktus, J., Tangang,
1007   F., Teichmann, C., Vautard, R., Vogt, J. V., Winger, K., Zittis, G. and Dosio, A.: Future global
1008   meteorological drought hot spots: A study based on CORDEX data, J. Clim., 33(9), 3635–3661,
1009   doi:10.1175/JCLI-D-19-0084.1, 2020.
1010   Sprenger, M. and Wernli, H.: The LAGRANTO Lagrangian analysis tool - Version 2.0, Geosci.
1011   Model Dev., 8(8), 2569–2586, doi:10.5194/GMD-8-2569-2015, 2015.
1012   Stéfanon, M., Drobinski, P., D'Andrea, F., Lebeaupin-Brossier, C. and Bastin, S.: Soil moisture-
1013   temperature feedbacks at meso-scale during summer heat waves over Western Europe, Clim. Dyn.,
1014   42(5–6), 1309–1324, doi:10.1007/S00382-013-1794-9/FIGURES/12, 2014.
1015   Stott, P. A., Stone, D. A. and Allen, M. R.: Human contribution to the European heatwave of 2003,
1016   Nature, 432(7017), 610–614, doi:10.1038/nature03089, 2004.
1017   Suarez-Gutierrez, L., Li, C., Müller, W. A. and Marotzke, J.: Internal variability in European summer
1018   temperatures at 1.5 °C and 2 °C of global warming, Environ. Res. Lett., 13(6), 064026,
1019   doi:10.1088/1748-9326/AABA58, 2018.
1020   Suarez-Gutierrez, L., Milinski, S. and Maher, N.: Exploiting large ensembles for a better yet simpler
1021   climate model evaluation, Clim. Dyn., 57(9–10), 2557–2580, doi:10.1007/S00382-021-05821-
1022   W/FIGURES/8, 2021.
1023   Teuling, A. J.: A hot future for European droughts, Nat. Clim. Chang., 8(5), 364–365,
1024   doi:10.1038/s41558-018-0154-5, 2018.
1025   Toreti, A., Belward, A., Perez-Dominguez, I., Naumann, G., Luterbacher, J., Cronie, O., Seguini, L.,
1026   Manfron, G., Lopez-Lozano, R., Baruth, B., van den Berg, M., Dentener, F., Ceglar, A.,
1027   Chatzopoulos, T. and Zampieri, M.: The Exceptional 2018 European Water Seesaw Calls for Action
1028   on Adaptation, Earth's Futur., 7(6), 652–663, doi:10.1029/2019EF001170, 2019.
1029   Tradowsky, J. S., Bird, L., Kreft, P. V., Rosier, S. M., Soltanzadeh, I., Stone, D. A. and Bodeker, G.
1030   E.: Toward Near-Real-Time Attribution of Extreme Weather Events in Aotearoa New Zealand, Bull.
1031   Am. Meteorol. Soc., 103(3), S105–S110, doi:10.1175/BAMS-D-21-0236.1, 2022.
1032   Vicente-Serrano, S. M., Azorin-Molina, C., Sanchez-Lorenzo, A., Revuelto, J., Morán-Tejeda, E.,
1033   Lõpez-Moreno, J. I. and Espejo, F.: Sensitivity of reference evapotranspiration to changes in
1034   meteorological parameters in Spain (1961–2011), Water Resour. Res., 50(11), 8458–8480,
1035   doi:10.1002/2014WR015427, 2014.
1036   Vogel, M. M., Zscheischler, J., Wartenburger, R., Dee, D. and Seneviratne, S. I.: Concurrent 2018
1037   Hot Extremes Across Northern Hemisphere Due to Human-Induced Climate Change, Earth's Futur.,
1038   7(7), 692–703, doi:10.1029/2019EF001189, 2019.
1039   Wehrli, K., Guillod, B. P., Hauser, M., Leclair, M. and Seneviratne, S. I.: Identifying Key Driving
1040   Processes of Major Recent Heat Waves, J. Geophys. Res. Atmos., 124(22), 11746–11765,
1041   doi:10.1029/2019JD030635, 2019.
1042   Wehrli, K., Hauser, M. and Seneviratne, S. I.: Storylines of the 2018 Northern Hemisphere heatwave
1043   at pre-industrial and higher global warming levels, Earth Syst. Dyn., 11(4), 855–873,
1044   doi:10.5194/ESD-11-855-2020, 2020.
1045   Woollings, T., Pinto, J. G. and Santos, J. A.: Dynamical Evolution of North Atlantic Ridges and
1046   Poleward Jet Stream Displacements, J. Atmos. Sci., 68(5), 954–963, doi:10.1175/2011JAS3661.1,
1047   2011.
1048   Woollings, T., Barriopedro, D., Methven, J., Son, S. W., Martius, O., Harvey, B., Sillmann, J., Lupo,
1049   A. R. and Seneviratne, S.: Blocking and its Response to Climate Change, Curr. Clim. Chang. Reports,
1050   4(3), 287–300, doi:10.1007/s40641-018-0108-z, 2018.
1051   World Weather Attribution (WWA): Heatwave in northern Europe, summer 2018, [online] Available
1052   from: https://www.worldweatherattribution.org/attribution-of-the-2018-heat-in-northern-europe/
1053   (Accessed 18 August 2022), 2018.
1054   World Weather Attribution (WWA): Without human-caused climate change temperatures of 40°C in
1055   the UK would have been extremely unlikely, [online] Available from:
1056   https://www.worldweatherattribution.org/without-human-caused-climate-change-temperatures-of-
1057   40c-in-the-uk-would-have-been-extremely-unlikely/ (Accessed 18 August 2022), 2022.

1058 Zampieri, M., Ceglar, A., Dentener, F. and Toreti, A.: Wheat yield loss attributable to heat waves,
1059 drought and water excess at the global, national and subnational scales, Environ. Res. Lett., 12(6),
1060 064008, doi:10.1088/1748-9326/AA723B, 2017.
1061 Zscheischler, J. and Fischer, E. M.: The record-breaking compound hot and dry 2018 growing season
1062 in Germany, Weather Clim. Extrem., 29, 100270, doi:10.1016/j.wace.2020.100270, 2020.
1063 Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R. M., van den Hurk,
1064 B., AghaKouchak, A., Jézéquel, A., Mahecha, M. D., Maraun, D., Ramos, A. M., Ridder, N. N.,
1065 Thiery, W. and Vignotto, E.: A typology of compound weather and climate events, Nat. Rev. Earth
1066 Environ., 1(7), 333–347, doi:10.1038/s43017-020-0060-z, 2020.
1067 Zschenderlein, P., Pfahl, S., Wernli, H. and Fink, A. H.: A Lagrangian analysis of upper-tropospheric
1068 anticyclones associated with heat waves in Europe, Weather Clim. Dyn., 1(1), 191–206,
1069 doi:10.5194/wcd-1-191-2020, 2020.