



### Supplement of

# **European heatwaves in present and future climate simulations: a Lagrangian analysis**

Lisa Schielicke and Stephan Pfahl

Correspondence to: Lisa Schielicke (lisa.schielicke@met.fu-berlin.de)

The copyright of individual parts of the supplement might differ from the article licence.

### Supplement

### Distribution of heatwave day of occurrence in present and future simulations

Supplementary Table S1: Parameters of fitted distributions to the number of heatwave days with respect to the day of year, they occurred. The abbreviation Std stands for standard deviation. Significant differences between means and variances per region are printed in bold. These have been calculated by a Mann-Whitney U-test and a Levene's test, respectively, and significance is assumed for p-values smaller than 0.0001.

Region	Simulation	Skew normal distribution			Normal distribution		Total
							number
		Shape	Location	Scale	Mean	$\operatorname{Std}$	of days
BI	20C	-1.97564	223.26	34.58	198.57	24.21	1733
	RCP8.5	-2.37201	231.27	34.70	205.64	23.39	2345
CE	20C	-1.67227	222.65	26.41	204.52	19.21	1770
	RCP8.5	-0.98093	222.53	19.44	211.66	16.12	1899
GI	20C	-1.09779	224.02	19.63	212.46	15.84	2676
	RCP8.5	-1.19259	223.67	16.11	213.81	12.74	2524
IP	20C	0.00005	210.75	16.85	210.75	16.85	1478
	RCP8.5	0.24860	209.87	16.32	213.01	16.02	1410
$\mathbf{Sc}$	20C	-0.61132	205.44	20.28	197.00	18.44	2284
	RCP8.5	0.00005	197.71	17.77	197.71	17.77	2383
WR	20C	0.48901	194.53	20.70	201.78	19.39	2784
	RCP8.5	-1.51499	215.43	19.38	202.50	14.43	2388
ALL	20C	-1.55772	222.19	26.83	204.15	19.86	12725
	RCP8.5	-1.65094	223.82	24.83	206.88	18.15	12949



**Supplementary Figure** S1: Probability density function (PDF) of heatwave day occurrence with respect to the day of the year: blue bars (1991-2000); orange bars (2091-2100); brownish colours show the overlap of the blue and orange histograms. Dashed lines show fitted skew normal distributions; parameters are given in Supplementary Table T1.



**Supplementary Figure** S2: Probability density function (PDF) of heatwave day occurrence in different regions with respect to the day of the year: blue bars (1991-2000); orange (2091-2100); brownish colours: overlap of both. Dashed lines show fitted skew normal distributions; for parameters of the respective distributions see Supplementary Table T1.

### 0.20 0.20 (a) Bl (b) CE 0.15 0.15 لم 0.10 لم 0.10 0.05 0.05 0.00 <del>|\*</del> 15 0.00 <del>|</del> 15 45 55 20 20 25 30 35 40 50 25 30 35 40 45 50 55 0.20 0.20 (c) Gl (d) IP 0.15 0.15 لم 0.10 습 0.10 0.05 0.05 0.00 15 0.00 15 20 25 30 35 40 50 55 20 30 35 40 45 50 55 45 25 0.20 0.20 (f) WR (e) Sc Fut. dist. wrt hist. mean 0.15 0.15 1991-2000 2091-2100 법 0.10 습 0.10 0.05 0.05 0.00∔ 15 0.00 <del>|-</del> 15 45 55 20 20 25 30 35 40 50 25 30 35 40 45 50 55 Maximum Temperature (°C) per heatwave day Maximum Temperature (°C) per heatwave day

## Probability density function of the daily maximum temperature on heatwave days

**Supplementary Figure** S3: Probability density function (PDF, kernel density estimate) of the daily maximum temperature on heatwave days. Note that only the grid point with the maximum temperature is considered per day and region: blue (1991-2000); orange (2091-2100); brownish colours: overlap of both. Black dashed line show shifted future distributions such that the mean corresponds to the mean of the historic distribution.

### Distribution of HWMId values of present and future heatwaves



**Supplementary Figure** S4: Probability density function (PDF) of the sum of the HWMId values in each region per heatwave day: blue bars (1991-2000); orange (2091-2100); brownish colours: overlap of both; bin width is 5. Insets show the tail of the histograms.

Spatial distribution of trajectories 3 days prior to the arrival in the British Isles (BI) region



**Supplementary Figure** S5: Spatial distribution of trajectories 3 days prior to the arrival in BI: (a) heatwaves in the historic time slice (b) heatwaves in the future time slice (c) JJA climatology, historic (d) JJA climatology, future. Colored lines represent the 2.2‰ for heatwave parcels and 1‰ (for JJA climatology),respectively: orange: parcels in category A; red: Bsd; cyan: Bwd. Violet contour represents the 0.1‰ density of backward trajectories seven days before initiation (a) in BI.

Spatial distribution of difference in parcel densities between heatwaves and JJA climatology 3 days prior to the arrival in the British Isles (BI), Central Europe (CE), Greece and Italy (GI) regions



Supplementary Figure S6: Spatial distribution of the trajectories initialized during heatwaves in (a-c) BI, (d-f) CE, and (g-i) GI. Difference in densities (in %) given by red-blue color shading: (a,d,g) Difference between historic heatwave  $HW_{his}$  and climatological historic JJA trajectories  $JJA_{his}$ ; (b,e,h) Difference between future heatwave  $HW_{fut}$  and climatological future JJA trajectories  $JJA_{fut}$ ; (c,f,i) Difference between future  $JJA_{fut}$  and historic, climatological JJA trajectories  $JJA_{his}$ . Yellow/black polygon shows the study region that was used to initiate the backward trajectories. Solid (dashed) black contour marks +0.2% (-0.2%) difference in parcel density. Significance of parcel densities was determined by creating a distribution at each grid point by randomly drawing 100 times from the original data with replacement. A 99% confidence interval from the Student's t-distribution was calculated at each grid point. Grid points marked by a green dot show no significant difference in parcel densities between the respective two distributions.

Spatial distribution of difference in parcel densities between heatwaves and JJA climatology 3 days prior to the arrival in the Iberian Peninsula (IP), Scandinavian (Sc), Western Russian (WR) regions



Supplementary Figure S7: As in S6, but for IP, Sc and WR

### Thermodynamic properties of the trajectories



Supplementary Figure S8: Thermodynamic properties of trajectories in regions (a)-(d) BI, (e)-(h) CE and (i)-(l) GI: (a,e,i) Scatterplot of properties, each dot represents the properties of one trajectory, descent/ascent in the three days prior to the heatwave  $\Delta P_{3d}$  are given by colors; (b,c,f,g,j,k) Probability density function (Gaussian kernel-density estimate determined with Python function scipy.stats.gaussian.kde()) of trajectory counts in CE for heatwaves (b,f,j) in the historic simulations and (c,g,k) in the future simulations. Violet to yellow colors give the probability in grids of  $2K \times 2K$ . Probabilities < 0.00001 are omitted; (d,h,l) Difference between PDFs shown in third minus second column; absolute values of probability differences smaller than < 0.000001 are omitted. Solid (dashed) black contour in (d), (h), (l) marks a value of +0.00005 (-0.00005) of the difference in PDFs.



Supplementary Figure S9: As in Fig. S8, but for (a)-(d) IP, (e)-(h) Sc and (i)-(l) WR.



Supplementary Figure S10: Maximum temperature difference  $\Delta T_{max}$  along trajectories plotted against the maximum potential temperature difference  $\Delta \theta_{max}$  for (a)-(d) CE; (e)-(h) IP and (i)-(l) WR. Displayed is the difference between PDFs (as in Supplementary Figs. S8,S9, right column). Different regions are shown in rows (four figures per region) and several different plots are shown in columns: (1st column) Difference between future and historic heatwave distributions; (2nd column) historic heatwaves PDF minus historic climatological JJA PDF; (3rd column) future heatwaves PDF minus future, climatological JJA PDF; (4th column) difference between future and historic climatological JJA PDFs. The probability has been calculated in grid boxes of  $2K \times 2K$  and absolute values of probability differences smaller than < 0.000001 are omitted. Solid (dashed) black contour in (d) marks a value of +0.00005 (-0.00005) of the difference in PDFs.



Supplementary Figure S11: Trajectory properties of clusters (defined in section 2.4) calculated at heatwave days in comparison to climatological (JJA) values in different European regions: (a)-(d) CE, (e)-(h) GI, (i)-(l) IP. Top row shows the difference in pressure  $\Delta P_{3d}$  three days prior to the heat event/prior to arrival in the target region; second row from top shows the maximum change in potential temperature  $\Delta \theta_{max}$  along the trajectory; third row from top is the maximum change in temperature  $\Delta T_{max}$  along the trajectory, and bottom row is the potential temperature seven days prior to the arrival in the respective region. *Historic* (violet, third boxes) and *future* (red, fourth) boxes refer to air parcels started at heatwave days, *historic\_clim* (green, first boxes) and *future\_clim* (yellow, second) boxes show the JJA climatology. Black stars above the boxes indicate that the difference between the means of either future and historic heatwaves or climatologies is insignificant (p-value of 0.05 based on a t-test). All other means are significantly different.