

Spatio-temporal evolution of compound hot and dry extremes synchronizations in Europe

Supplementary Information

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S1 NAO and SNAO indices computation

The NAO index is based on the difference of normalized daily mean sea level pressure (SLP) between Ponta Delgada, Portugal (37.74°N, -25.68°E) and Reykjavik,

21 Iceland (64.13°N, -21.83°E) (Hurrell, 1995; Jones et al., 1997). We compute it at daily
 22 resolution for the study period 1941–2020 and for the DJF season.

First, the SLP at station A (Ponta Delgada) and day d , $SLP_{A,d}$, is normalized based on the mean and standard deviation computed from the reference period 1941–1970:

$$SLP'_{A,d} = \frac{SLP_{A,d} - \overline{SLP_{A,d}}}{\sigma_{A,d}} = \frac{SLP_{A,d} - \frac{\sum_{1941}^{1970} SLP_{A,d}}{n}}{\sqrt{\frac{\sum_{1941}^{1970} (SLP_{A,d} - \overline{SLP_{A,d}})^2}{n-1}}}, \quad (1)$$

where $SLP'_{A,d}$ is the normalized SLP at station A and day d , $\overline{SLP_{A,d}}$ and $\sigma_{A,d}$ are the SLP mean and standard deviation at station A and day d during the reference period 1941–1970, and n is the number of days d in the reference period, i.e., 30. Similarly, the normalized SLP at station B (Reykjavik) and day d is also derived. The daily NAO index is then computed by differencing the two normalized series:

$$NAO_d = SLP'_{A,d} - SLP'_{B,d}. \quad (2)$$

23 The monthly NAO index and the DJF one are simply computed by averaging the
 24 daily index over the month and the DJF season, respectively.

25 The NAO index can be also computed using other methodologies, such as empirical
 26 orthogonal analysis (EOF) (Folland et al., 2009), which is suited to account for the
 27 annual migration of NAO centers of action. However, since we compute the NAO
 28 index only for the DJF season, computing the index using fixed locations is enough
 29 (Cropper et al., 2015).

30 The SNAO index is based on the difference of normalized daily mean sea level
 31 pressure between two domains: one at coordinates 25°W–5°E, 45–55°N and one at
 32 52–22°W, 60–70°N. These are selected to cover the SNAO centers of action (Dunstone
 33 et al., 2023; Wang and Ting, 2022) during summer. It is computed following the same
 34 approach described for the NAO but for the JJA season, where $SLP_{A,d}$ is the daily

mean sea level pressure averaged over the domain 25°W–5°E, 45–55°N and $SLP_{B,d}$ is the daily mean sea level pressure averaged over the domain 52–22°W, 60–70°N.

S2 Number of events and synchronicity scenarios

In the context of the present study, it is crucial to distinguish between number of events at location i and location j and number of possible significant synchronizations between events at location i and events at location j . This distinction is indeed the core motivation of this work, as assessing compounds evolution is not the same as assessing compound synchronizations evolution. Even if we expect these two quantities to generally correlate, this is not always true, as we are going to explain in the following.

Let us consider nodes i and j and let us assume that they are both characterized by a relatively high number of events occurrences, say S_i and S_j , w.r.t. the length of the analysed period L . If the events are randomly placed, we expect the number of synchronized events to be relatively high (Figure S3a-b).

Although this is what we statistically anticipate, the climate system does not operate fully at random, thus it may happen that such event series could be even more synchronous (Figures S3c-d, e.g., think of two adjacent locations, if a very refined spatial resolution is used) or almost fully anti-correlated in events occurrences (Figures S3e-f). Thus, a high number of events does not imply high number of synchronizations. The reverse is also true, i.e., a low number of events does not imply low synchronizations, as shown in Figure S4.

In our specific case, these circumstances do sometimes take place. In JJA, a high number of events in northern Europe results in high average DC (please compare Figures 3a and 5a of the main text), similarly as the case depicted in Figures S3a-b. Conversely, in DJF we find that Great Britain, northern France, and Germany, have high DC even if few events are detected (please compare Figures 3b and 5b of the main text), similarly as the case depicted in Figures S4c-d.

61 Similar reasoning is applied when analyzing the events trend and the synchro-
62 nizations trend, i.e., in the comparison between Figures 3c-d and Figures 6a-b of the
63 main text. During JJA, we find that some locations in Finland, northern Poland, and
64 the Baltic display a significant increasing DC (Figure 6a of the main text), while the
65 number of compound events is not significantly growing (Figure 3c of the main text).
66 Conversely, southern Portugal, southern Spain, and Northwest Africa do not display
67 an increasing DC (Figure 6a of the main text) but are characterized by an increasing
68 number of events (Figure 3c of the main text).

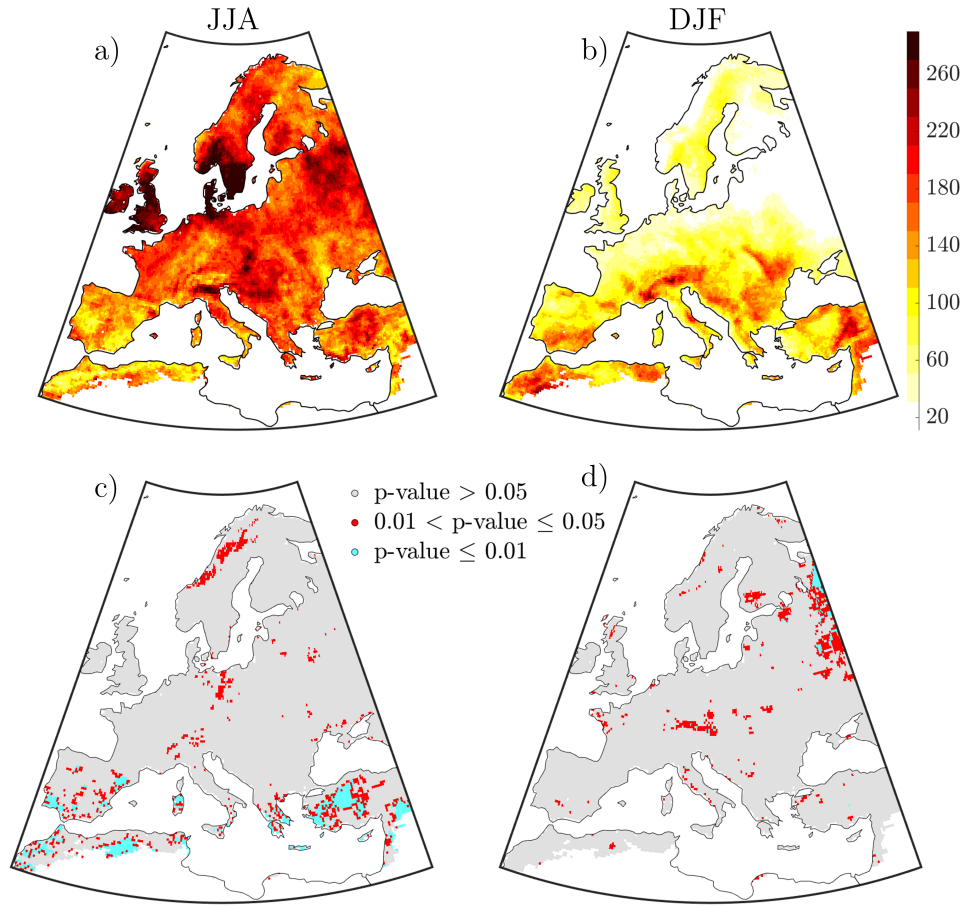


Fig. S1 Spatial distribution and trend significance of compound events. Number of compound events during 1941 – 2020 for **a)** the JJA season and **b)** the DJF season. P-values of the detected seasonal trends of compound events for **c)** the JJA season and **d)** the DJF season.

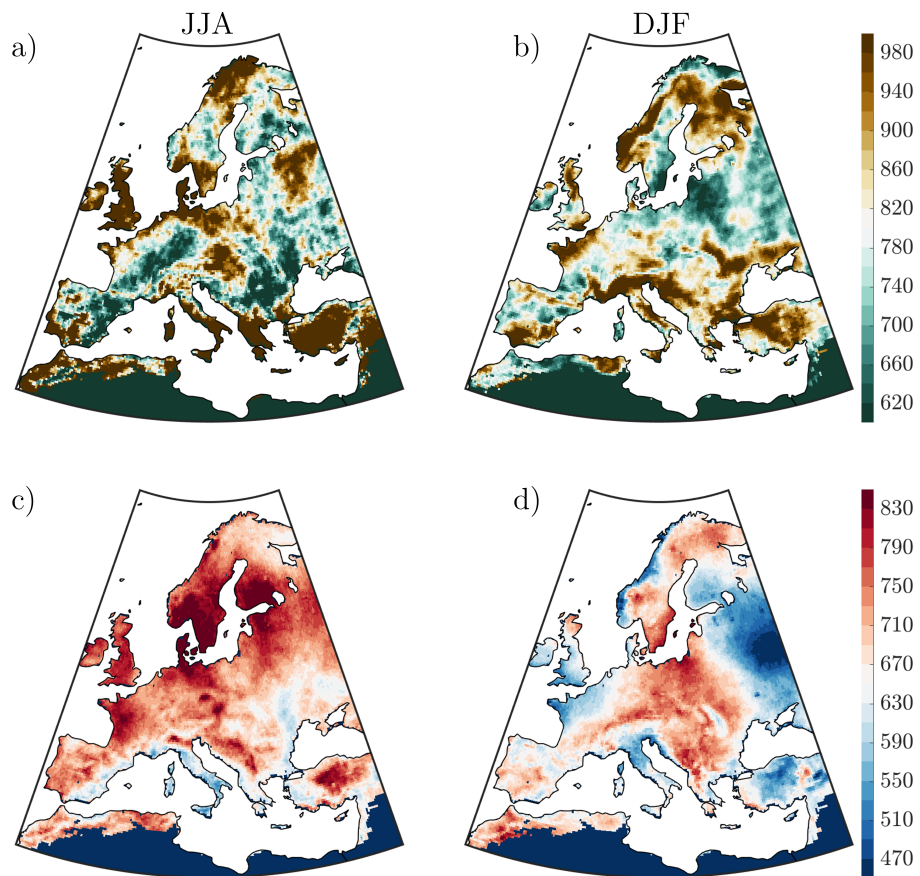


Fig. S2 Spatial distribution of hot and dry extremes. Number of dry extremes during 1941 – 2020 for **a)** the JJA season and **b)** the DJF season. Number of hot extremes during 1941 – 2020 for **c)** the JJA season and **d)** the DJF season.

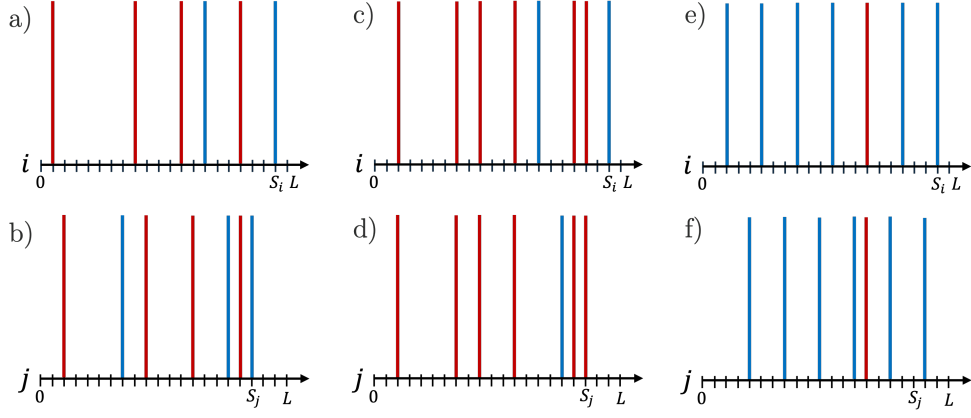


Fig. S3 Series with high number of events and their synchronizations. **a)** Random event series of total length L of location i , with S_i being the total number of events. An event marked in red is synchronized with an event at j , while events marked in blue are not synchronized. **b)** Same as **(a)** but for event series j . **c-d)** Same as panels **(a-b)** but for almost fully synchronized event series. **e-f)** Same as panels **(a-b)** but for almost fully de-synchronized event series.

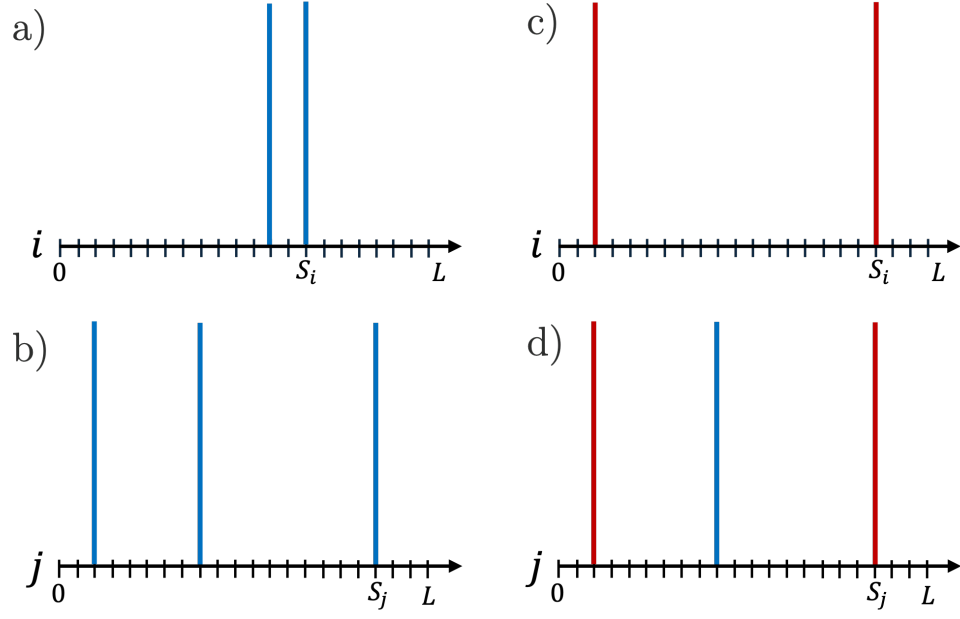


Fig. S4 Series with low number of events and their synchronizations. **a)** Random event series of total length L of location i , with S_i being the total number of events. An event marked in red is synchronized with an event at j , while events marked in blue are not synchronized. **b)** Same as **(a)** but for event series j . **c-d)** Same as panels **(a-b)** but for almost fully synchronized event series.

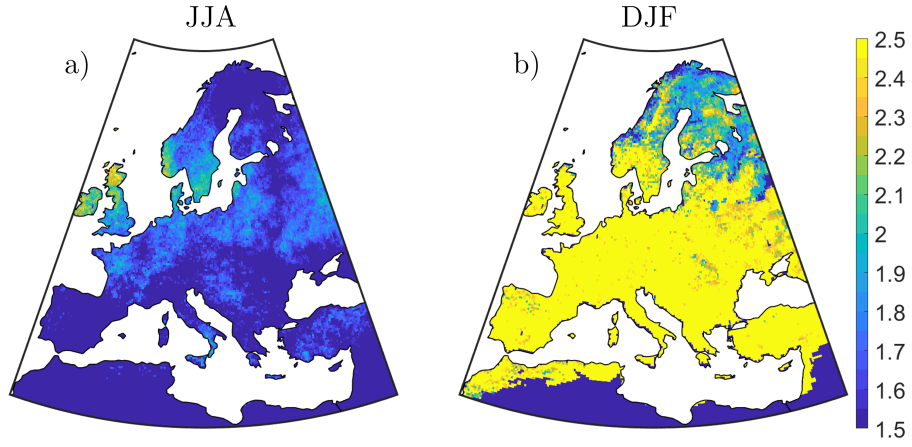


Fig. S5 Average clustering coefficient. Average value of CC across the 51 network blocks for **a)** the JJA season and **b)** the DJF season. The CC is dimensionless because of the correction of bias due to spatial embedding.

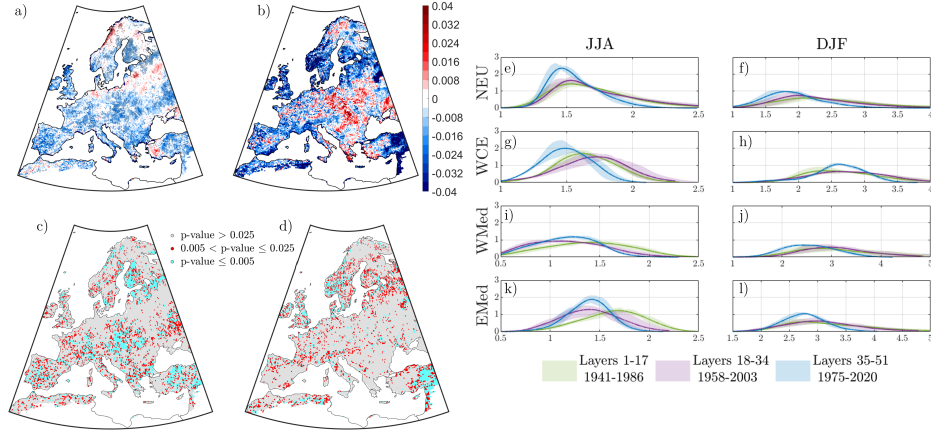


Fig. S6 Evolution of clustering coefficient. CC trend for **c)** the JJA season and **d)** the DJF season. Dots are drawn if the trend is significant at $\alpha = 0.05$ (two-sided sieve bootstrap t-test). P-values of the detected CC trends for **c)** the JJA season and **d)** the DJF season. **e-l)** Pdfs (empirically estimated via Gaussian-Kernel distributions) of the clustering coefficient for JJA and DJF and for every European region. The 51 distributions are divided in 3 groups for which we show the average value (solid lines) and 1 s.t.d. confidence bound (shades). The CC is dimensionless because of the correction of bias due to spatial embedding.

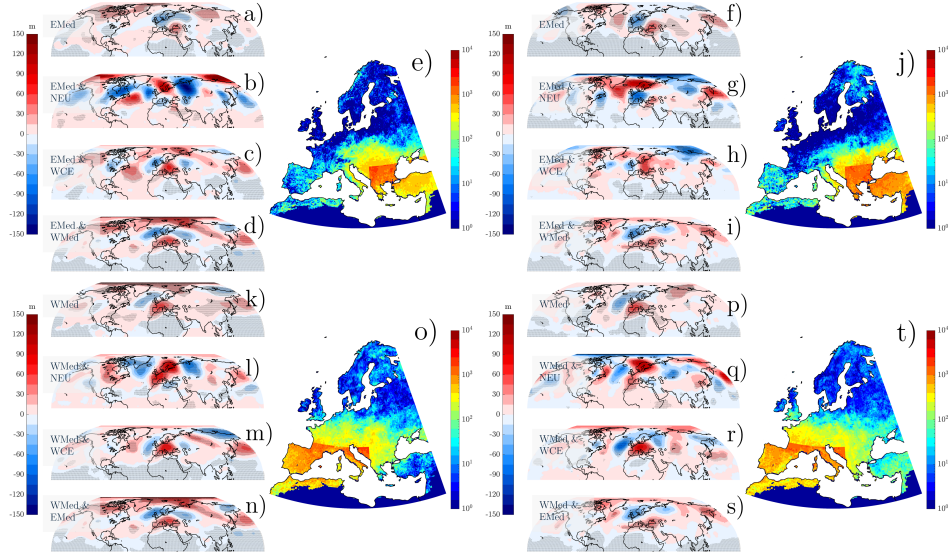


Fig. S7 Geopotential height composites and links variations during JJA. a-d) Z500 composites during the top 10% of days for number of compound events occurrences for the indicated regions and for the period 1941-1970. e) Number of links directed to EMed found in the 1941-1970 network block for each node. f-j) Same as panels (a-e), but considering the last 30 years of the analysed period, i.e. 1991-2020. k-t) Same as panels (a-j) but with respect to WMed. For all the composites, black dots are drawn if the Z500 anomaly is significant at $\alpha = 0.05$.

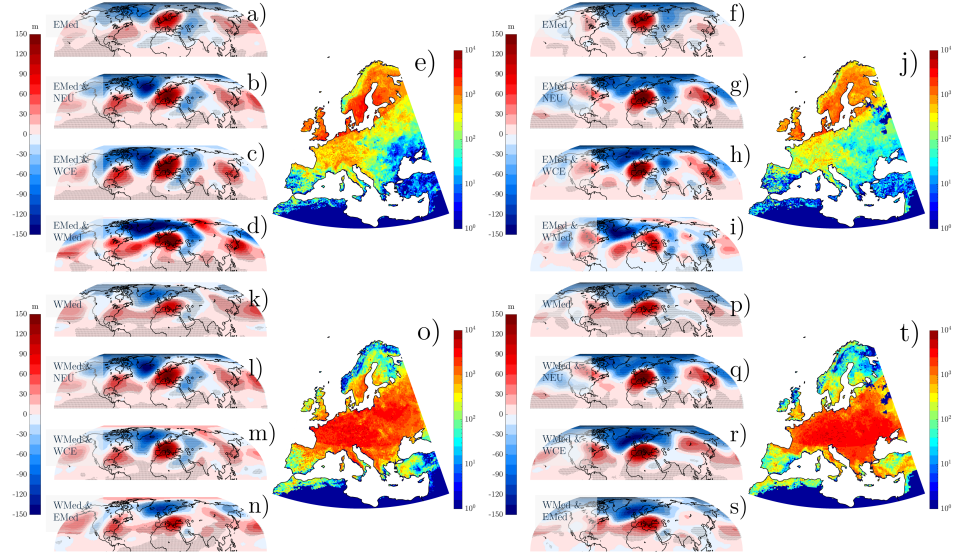


Fig. S8 Geopotential height composites and links variations during DJF. **a-d)** Z500 composites during the top 10% of days for number of compound events occurrences for the indicated regions and for the period 1941-1970. **e)** Number of links directed to NEU found in the 1941-1970 network block for each node. **f-j)** Same as panels (a-e), but considering the last 30 years of the analysed period, i.e. 1991-2020. **k-t)** Same as panels (a-j) but with respect to WCE. For all the composites, black dots are drawn if the Z500 anomaly is significant at $\alpha = 0.05$.

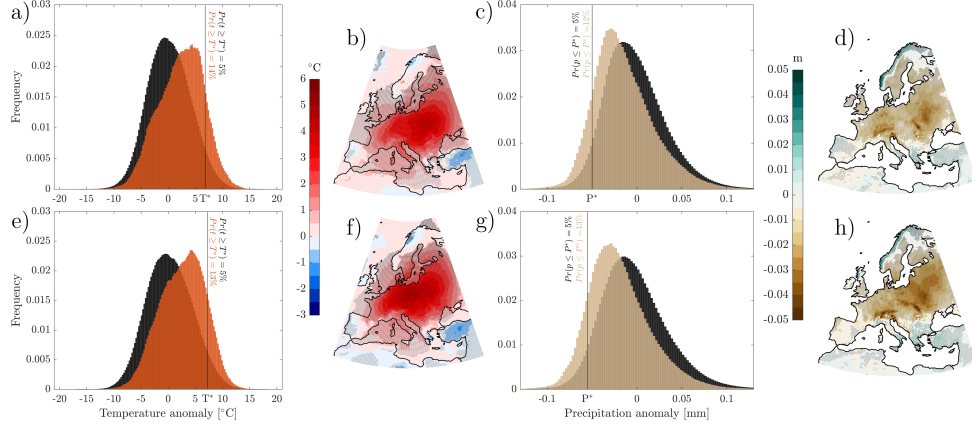


Fig. S9 Temperature and precipitation anomalies for WCE in JJA. **a,c)** Histogram plots of temperature (a) and precipitation (b) for the JJA season in 1941-1970 (black histograms) and for high compound days (temperature in red and precipitation in brown). The black line indicates the 95th (5th) percentile T^* (P^*) of the complete JJA temperature (precipitation) distribution. The probability of exceeding this temperature (precipitation) level during high compound days is shown in red (brown). The number of elements in each bin is normalized with the to the total number of elements. **b,d)** Temperature (b) and precipitation (d) composites during high compound days. Black dots are drawn if the anomaly is significant at $\alpha = 0.05$. **e,h)** Same as (a-d) but for 1991-2020.

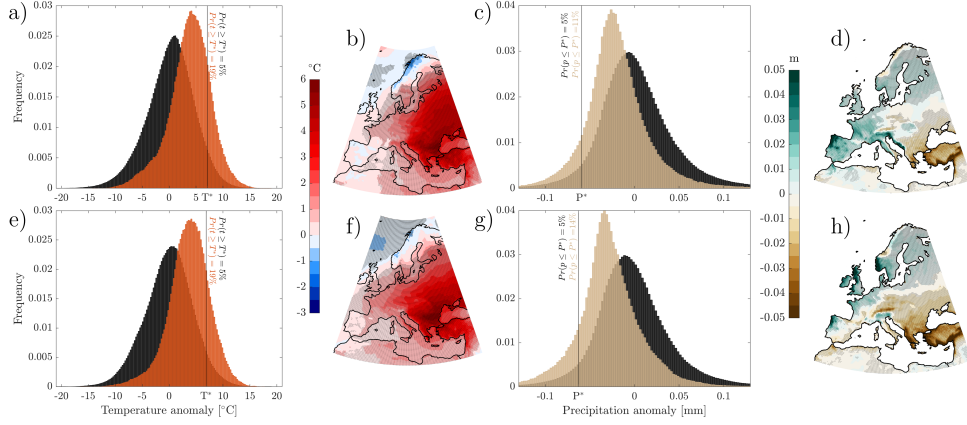


Fig. S10 Temperature and precipitation anomalies for EMed in DJF. **a,c)** Histogram plots of temperature (a) and precipitation (b) for the DJF season in 1941-1970 (black histograms) and for high compound days (temperature in red and precipitation in brown). The black line indicates the 95th (5th) percentile T^* (P^*) of the complete DJF temperature (precipitation) distribution. The probability of exceeding this temperature (precipitation) level during high compound days is shown in red (brown). The number of elements in each bin is normalized with the to the total number of elements. **b,d)** Temperature (b) and precipitation (d) composites during high compound days. Black dots are drawn if the anomaly is significant at $\alpha = 0.05$. **e,h)** Same as (a-d) but for 1991-2020.

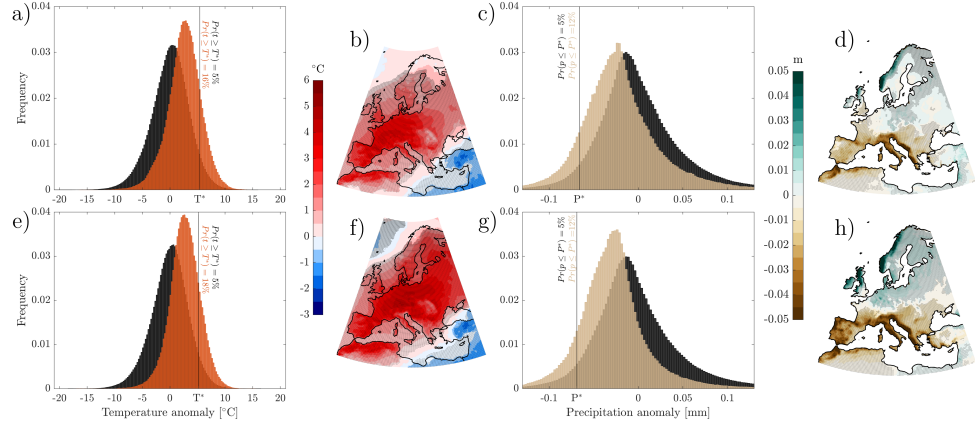


Fig. S11 Temperature and precipitation anomalies for WMed in DJF. **a,c)** Histogram plots of temperature (a) and precipitation (b) for the JJA season in 1941-1970 (black histograms) and for high compound days (temperature in red and precipitation in brown). The black line indicates the 95th (5th) percentile T^* (P^*) of the complete JJA temperature (precipitation) distribution. The probability of exceeding this temperature (precipitation) level during high compound days is shown in red (brown). The number of elements in each bin is normalized with the total number of elements. **b,d)** Temperature (b) and precipitation (d) composites during high compound days. Black dots are drawn if the anomaly is significant at $\alpha = 0.05$. **e,h)** Same as (a-d) but for 1991-2020.

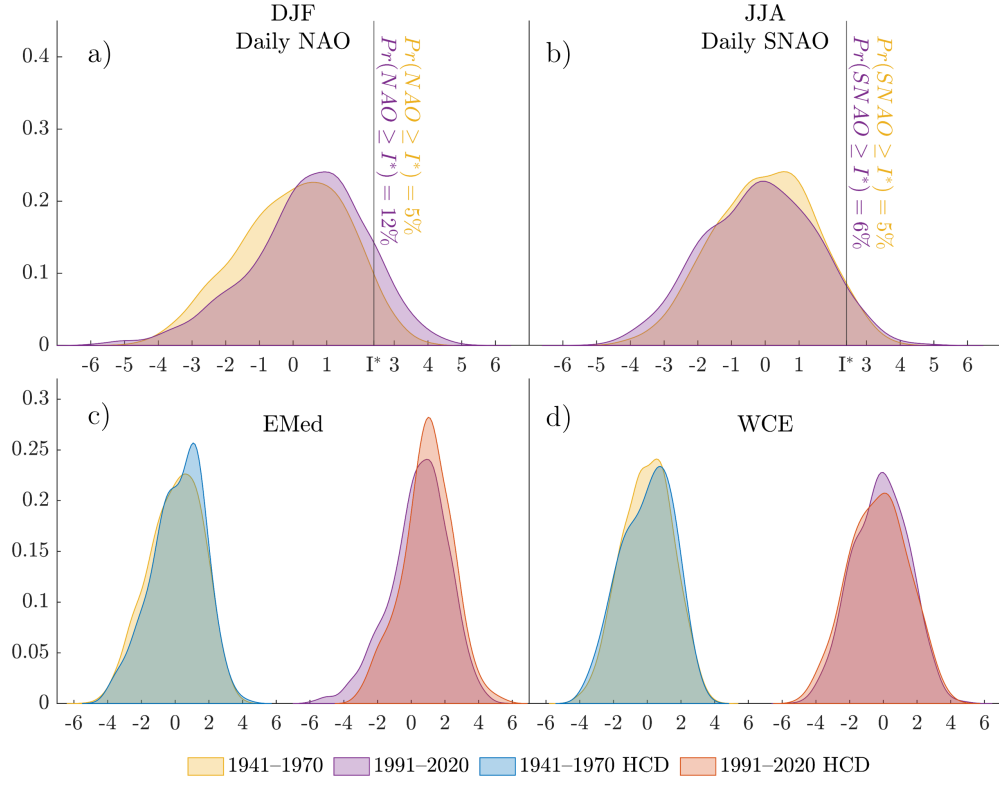


Fig. S12 The evolution of daily NAO and SNAO indices and their relation with high compound days. **a)** Daily NAO intensity evolution in DJF between 1941–1970 (yellow distribution) and 1991–2020 (violet). **b)** Same as (a) but for the SNAO daily index in JJA. **c)** Comparison between daily DJF NAO intensity during 1941–1970 (yellow) and daily DJF NAO intensity during EMed HCD in 1941–1970 (blue) and analogously for 1991–2020 (violet) and EMed HCD in 1991–2020 (red). **d)** Same as (c) but for JJA SNAO and WCE.

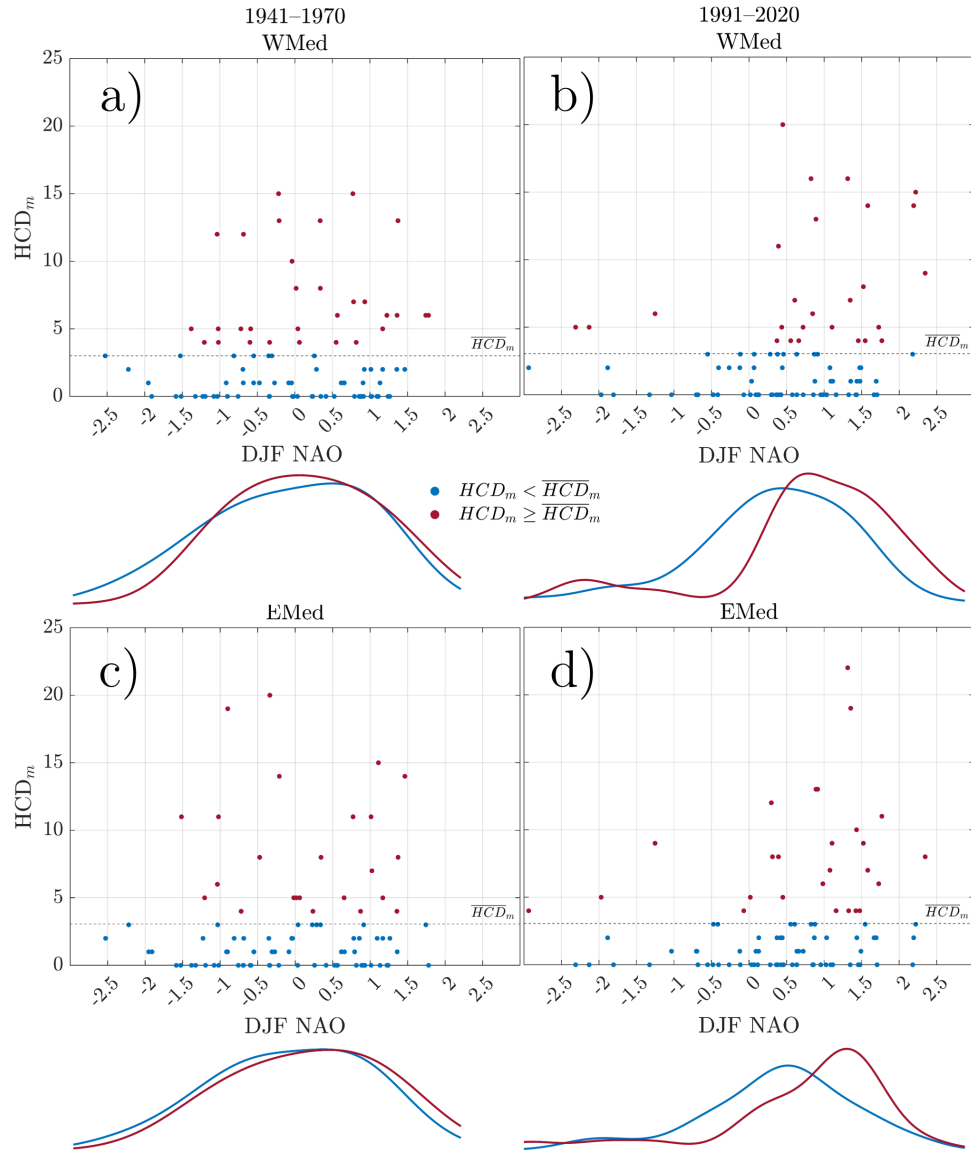


Fig. S13 Monthly HCD Vs. monthly NAO index. **a)** Scatter plot of the number of HCD in WMed during one month (HCD_m) and the corresponding value of the DJF monthly NAO index for the 1941–1970 period. Red dots are months whose HCD_m is higher than the expected number of HCD if HCD were uniformly distributed in time ($\overline{HCD_m}$). Marginal distributions of the NAO index of red and blue dots are depicted below the graph. **b)** Same as (a) but for WMed during 1991–2020. **c)** Same as (a) but for EMed during 1941–1971. **d)** Same as (a) but for EMed during 1991–2020.

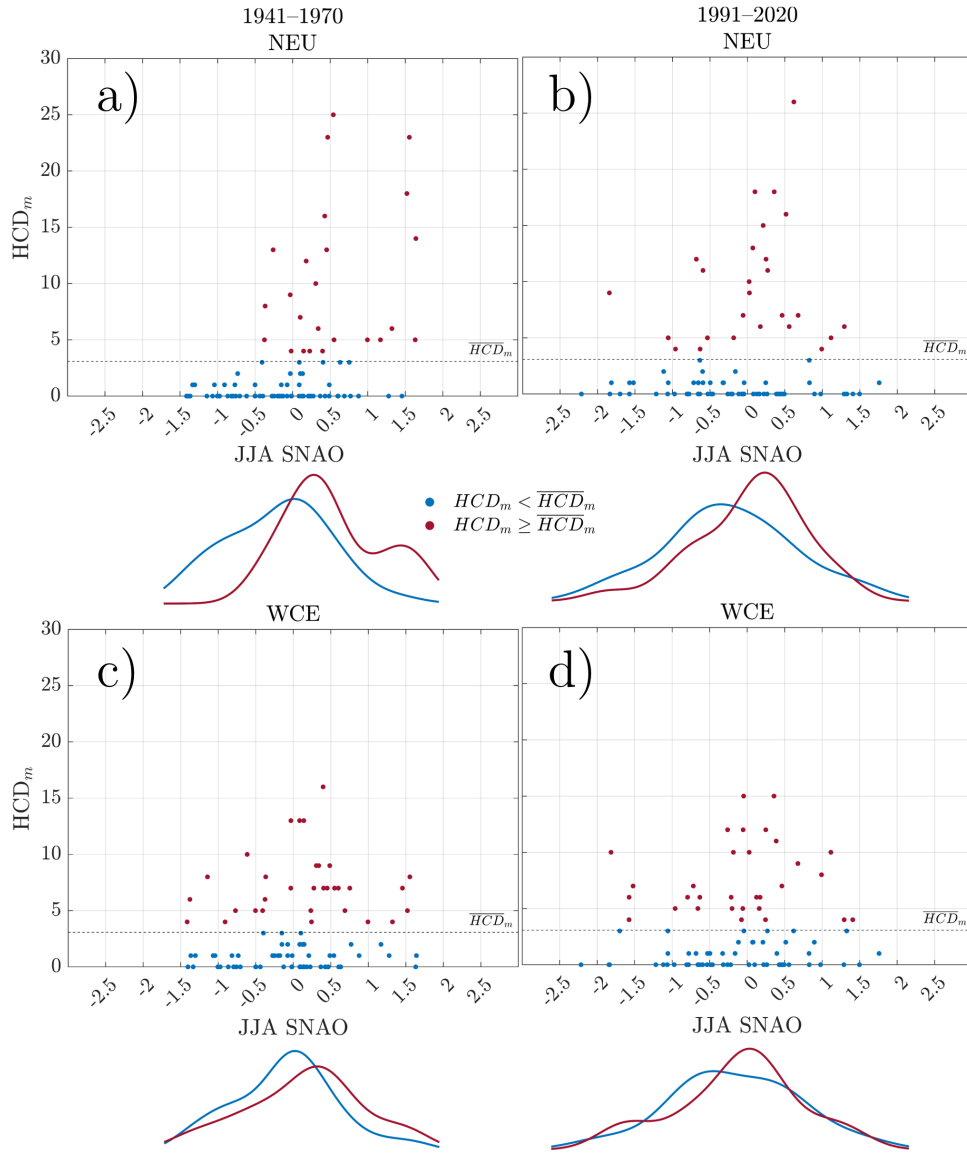


Fig. S14 Monthly HCD Vs. monthly SNAO index. **a)** Scatter plot of the number of HCD in NEU during one month (HCD_m) and the corresponding value of the JJA monthly SNAO index for the 1941–1970 period. Red dots are months whose HCD_m is higher than the expected number of HCD if HCD were uniformly distributed in time ($\overline{HCD_m}$). Marginal distributions of the SNAO index of red and blue dots are depicted below the graph. **b)** Same as (a) but for NEU during 1991–2020. **c)** Same as (a) but for WCE during 1941–1971. **d)** Same as (a) but for WCE during 1991–2020.

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