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Supplement of

A combined storyline-statistical approach for conditional extreme event attribution

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S1 Analogue detection performance and mean behavior

S1.1 5-day reference flow pattern for analogue detection

In Figure S1 we show the reference flow pattern used to identify the analogue events to the heatwave of interest. We use the 5-day sequence (July 31st to August 4th) preceding the heatwave peak. In Figure S2 we show the temperature anomalies during these days.

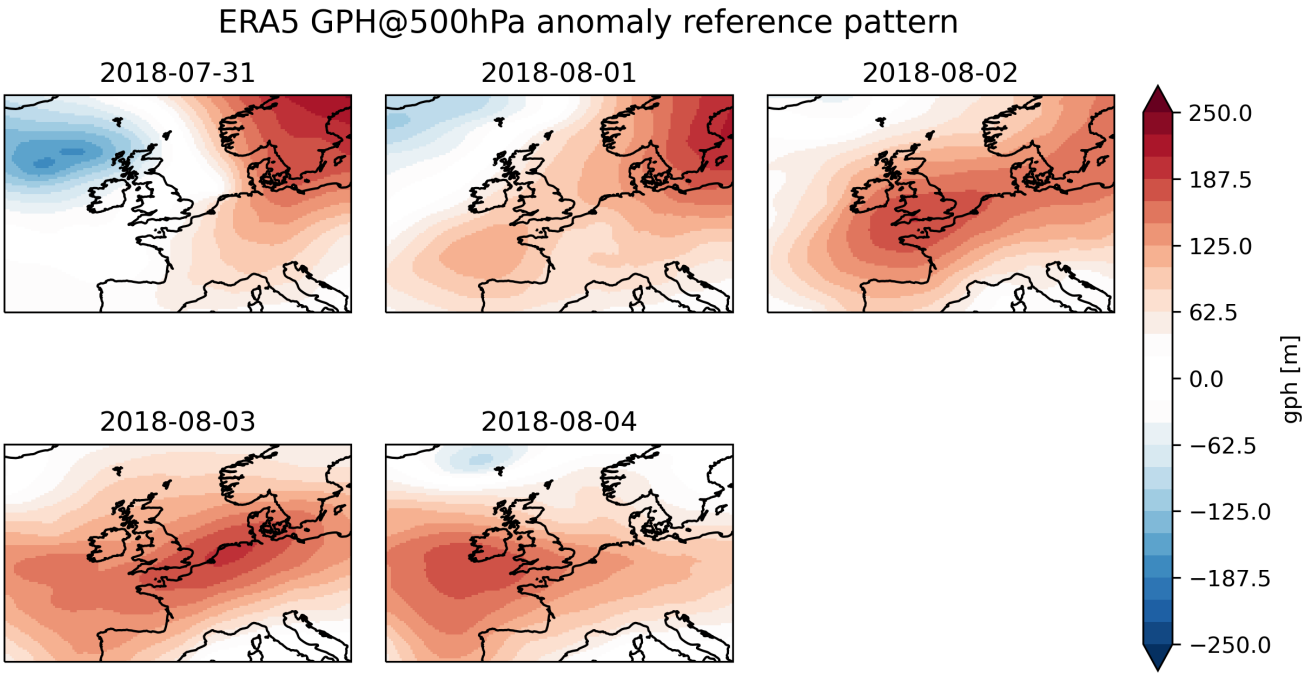

Figure S1. ERA5 Reference flow pattern. 5-day sequence of GPH@500hPa anomaly preceding the heatwave peak.

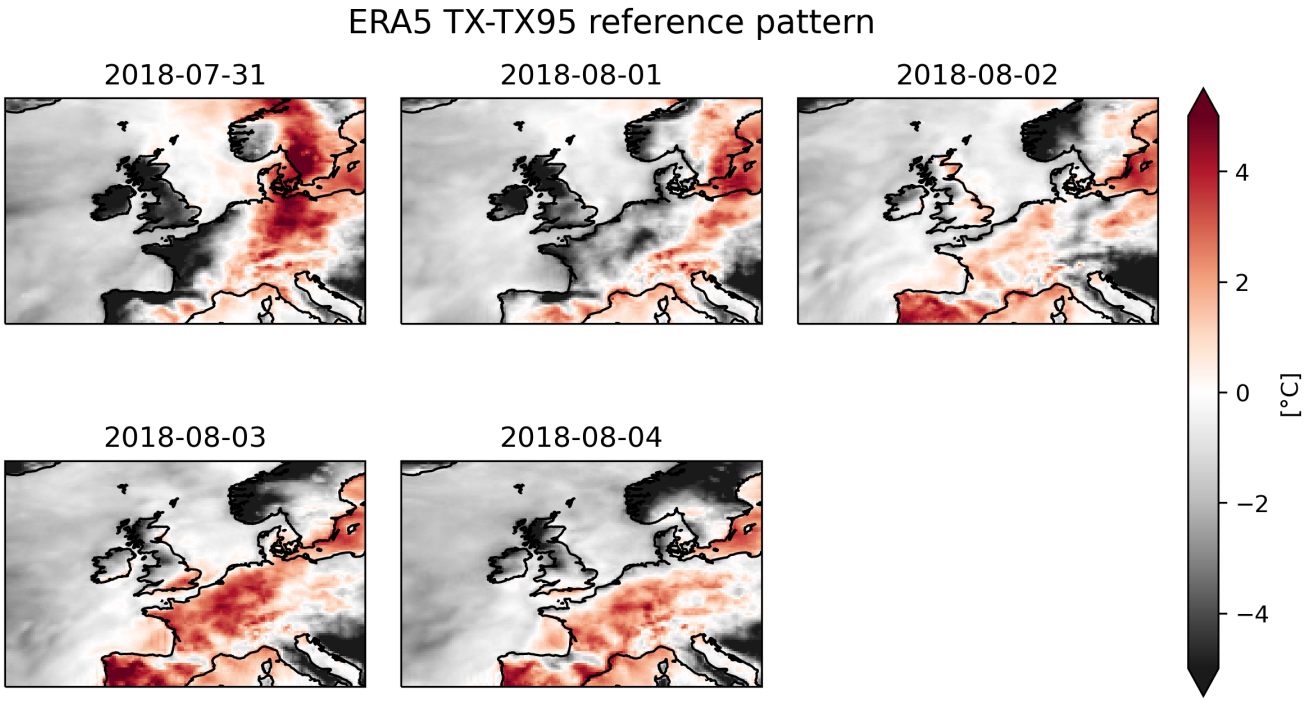

Figure S2. ERA5 Reference temperature anomaly. 5-day sequence of daily maximum temperature anomaly relative to the 95th percentile of the 1985-2014 climatology.

S1.2 Region for analogue detection

In Fig. S3 we illustrate the outcome of using the 2-step analogue detection in: a large region capturing the synoptic domain (box 1), the west shifted domain used to include the dipole pattern (box 2), a smaller region surrounding Central Europe (box 3). In general, using box 1 and box 2 allows us to account for large-scale gradients in the geopotential field. In combination with the inclusion of multiple days, we are thereby able to narrow down the selection of analogues to those with a very similar evolution of the large-scale flow, also with regard to the advection of air masses.

In Fig. S3b, the temperature anomalies in Central Europe indicate that the distribution remains quite comparable between box 1 and box 2, with the disadvantage of box 1 having a highly reduced number of analogues. The small region (box 3) results in selecting many more cases that also feature high geopotential over Central Europe, but with possibly quite different developments of the synoptic-scale flow and advection of air masses. The drawback of box 3 is that it captures any high pressure system over Central Europe, neglecting information about the characteristics of the blocking system. Therefore, we find that box 2 is the most suitable for our study.

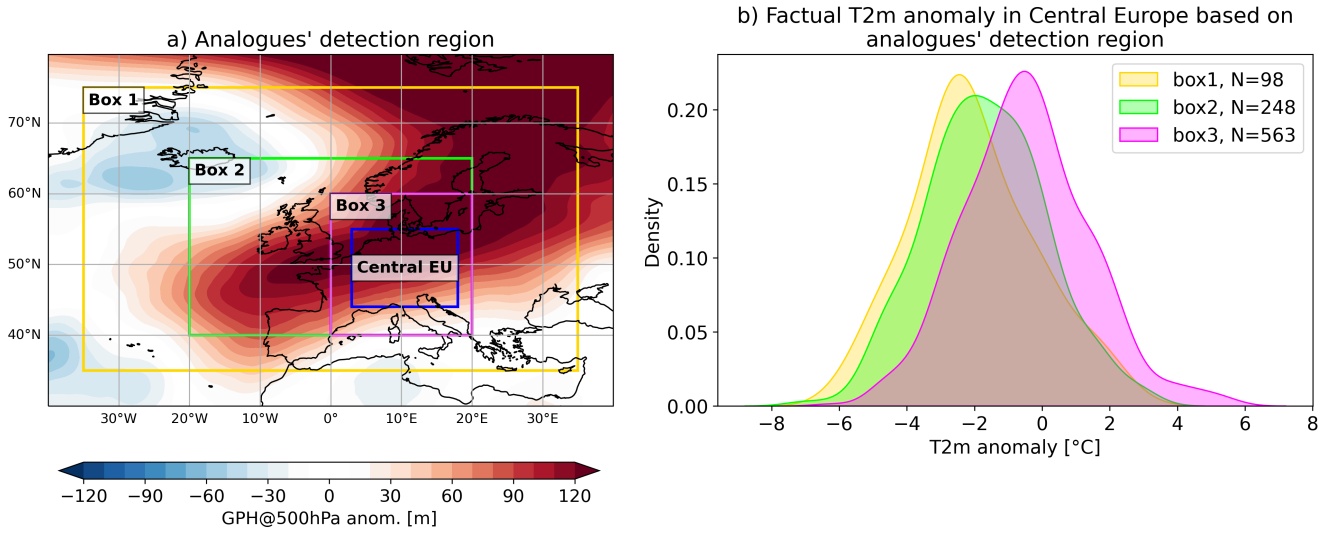

Figure S3. Region for analogue detection. a) Geographical domains used for the analogue detection: the Central European target region (blue), the larger synoptic domain (yellow), smaller synoptic domain box (green), and the surrounding Central-European subregion (magenta). b) Distribution function of t2m anomalies (TX-TX95) associated with analogue occurrences for each region, N show the number of analogues detected (see label), illustrating how the choice of analogue domain influences the temperature distribution in Central Europe.

S1.3 Analogues' spatial correlation to reference pattern

The correlation matrixes in Fig. S4 show the quality of the analogues detected from the 1000 years of daily data coming from the 50 members of the MPI-ESM-LR Grand Ensemble, where each member has 20 years of data surrounding the global warming level of interest (Factual, +2K, +3K, +4K). The spatial correlations represent the comparison of the time-averaged 5-day sequences detected as analogues with the time-averaged 5-day reference flow pattern in ERA5 (Fig. S1). Given that a minimum threshold of 0.8 is required for an analogue to be good, not all members have the same number of analogues.

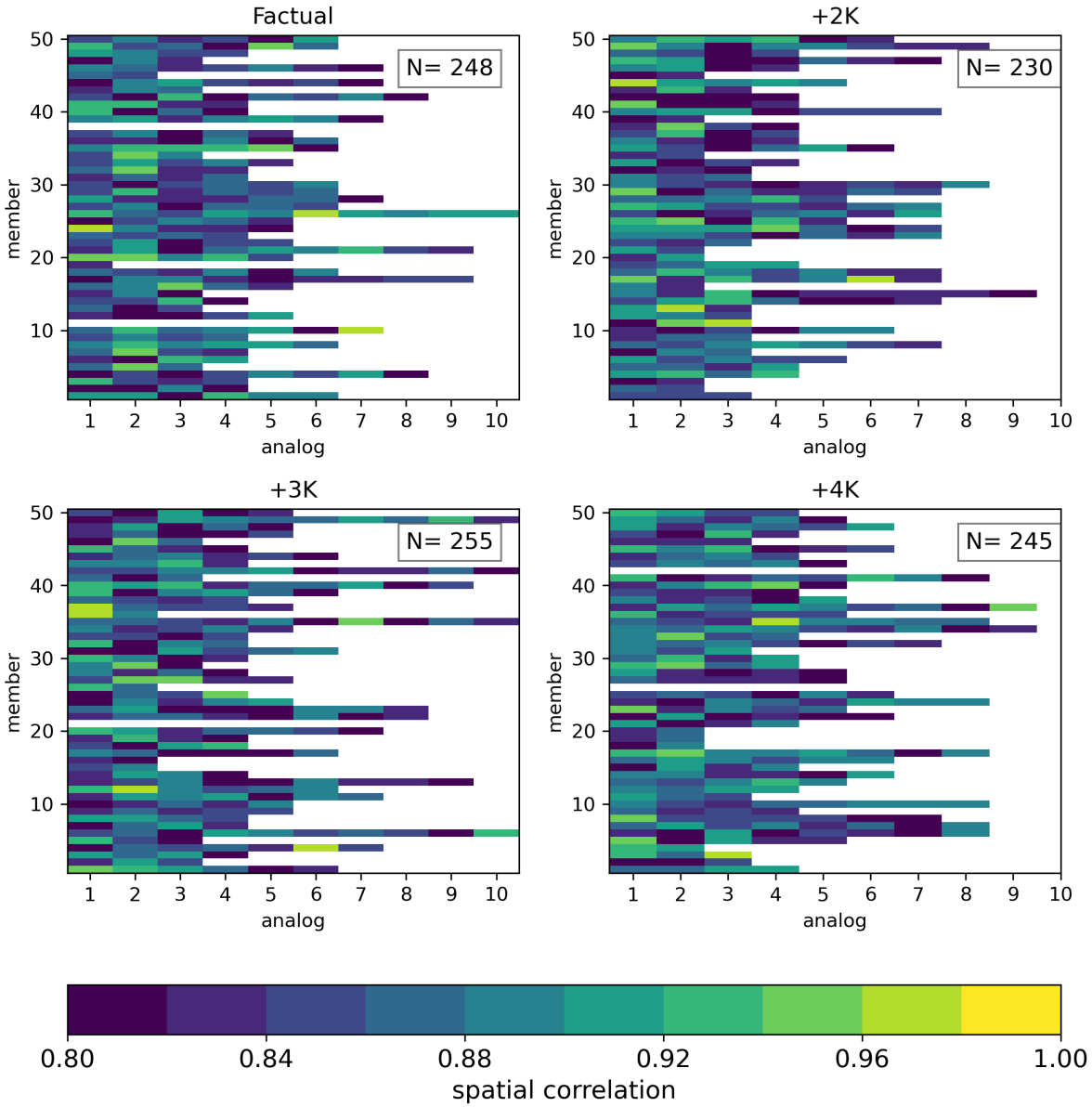

Figure S4. Flow-analogue's spatial correlation matrix relative to ERA5 reference flow pattern per degree of global warming level. Each correlation matrix shows the spatial correlation of analogues detected for each ensemble member of the MPI-ESM-LR Grand Ensemble. The label N corresponds to the total number of analogues identified in such a dataset.

S1.4 Mean flow-analogue behavior

The overall mean behavior in GPH anomalies is very well captured by the detected analogues. In Fig. S5, it is evident that regardless of the global warming level, the mean behavior remains similar to the mean reference flow pattern in ERA5 and NCEP.

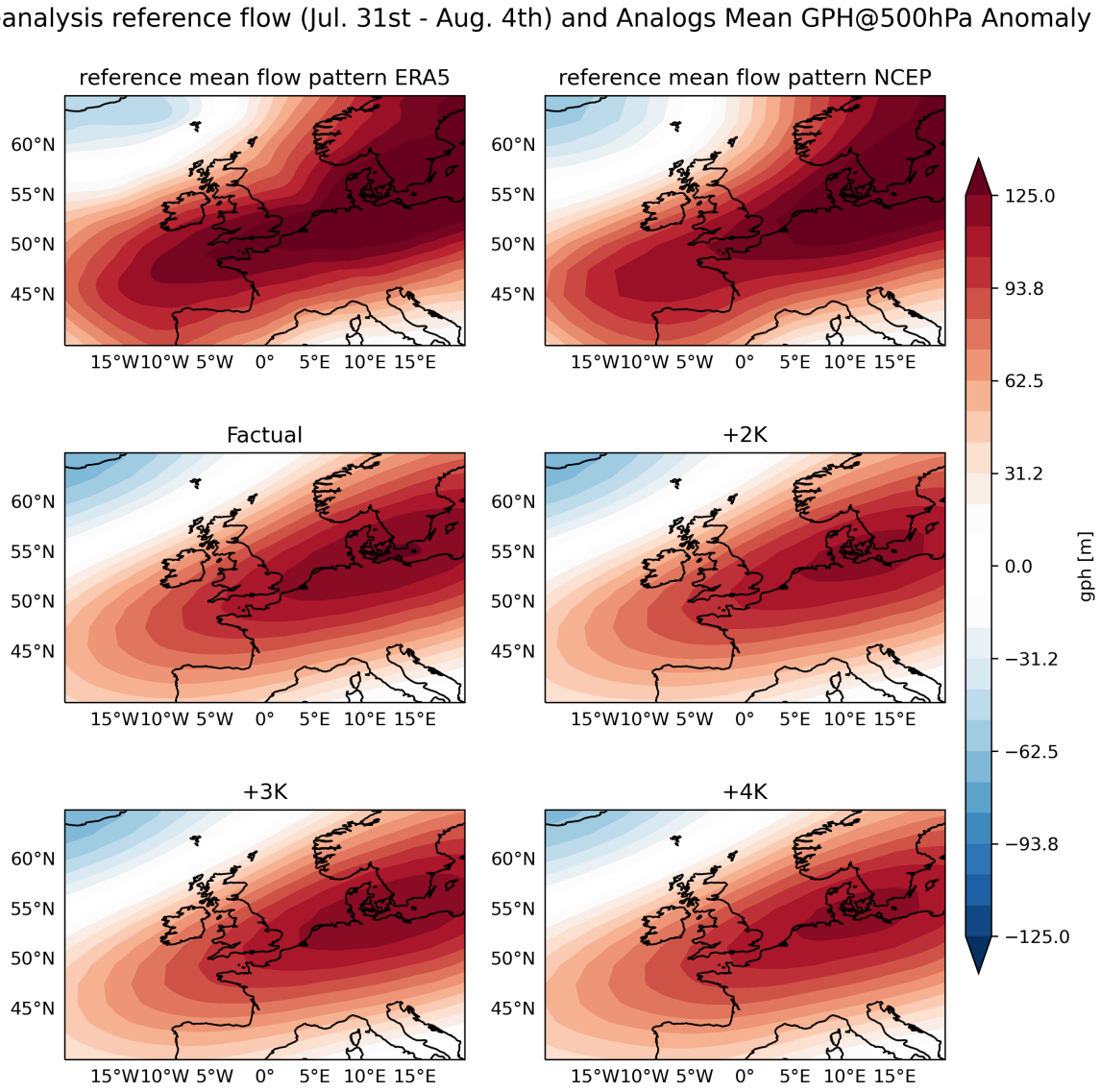

Figure S5. Analogues' ensemble mean time-averaged GPH@500hPa anomaly compared to reanalysis (ERA5 & NCEP) mean flow pattern. The fields portrayed for Factual, +2K, +3K, and +4K correspond to the 5-day time-average from the N analogues detected out of the 50 members in the MPI-ESM-LR Grand Ensemble.

S1.5 Comparison between future levels of global warming and present time

When examining the differences between the mean flow patterns for future levels of global warming compared to the present time, a slight shift towards the east is observed in the upper left corner of the pattern.

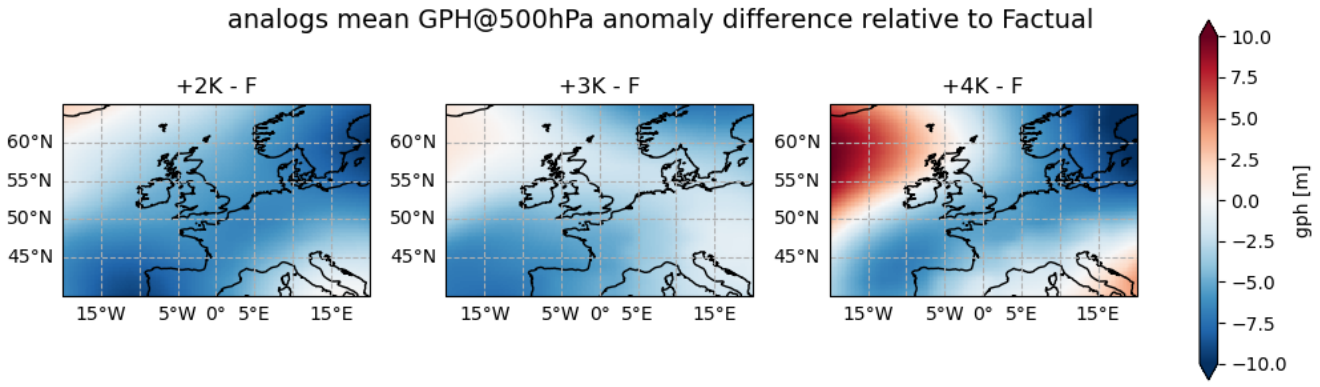

Figure S6. Analogues mean GPH@500hPa anomaly difference for future levels of global warming relative to factual (present times). Differences include the ensemble mean of the 5-day sequence for each analogue detected at each level of global warming.

S1.6 Flow pattern

The July 2018 heatwave over Scandinavia and Central Europe occurred due to a blocking system affecting mainly Scandinavia. In Figure S7 we show the sequence for every second day during the entire heatwave event (July 24th to August 10th).

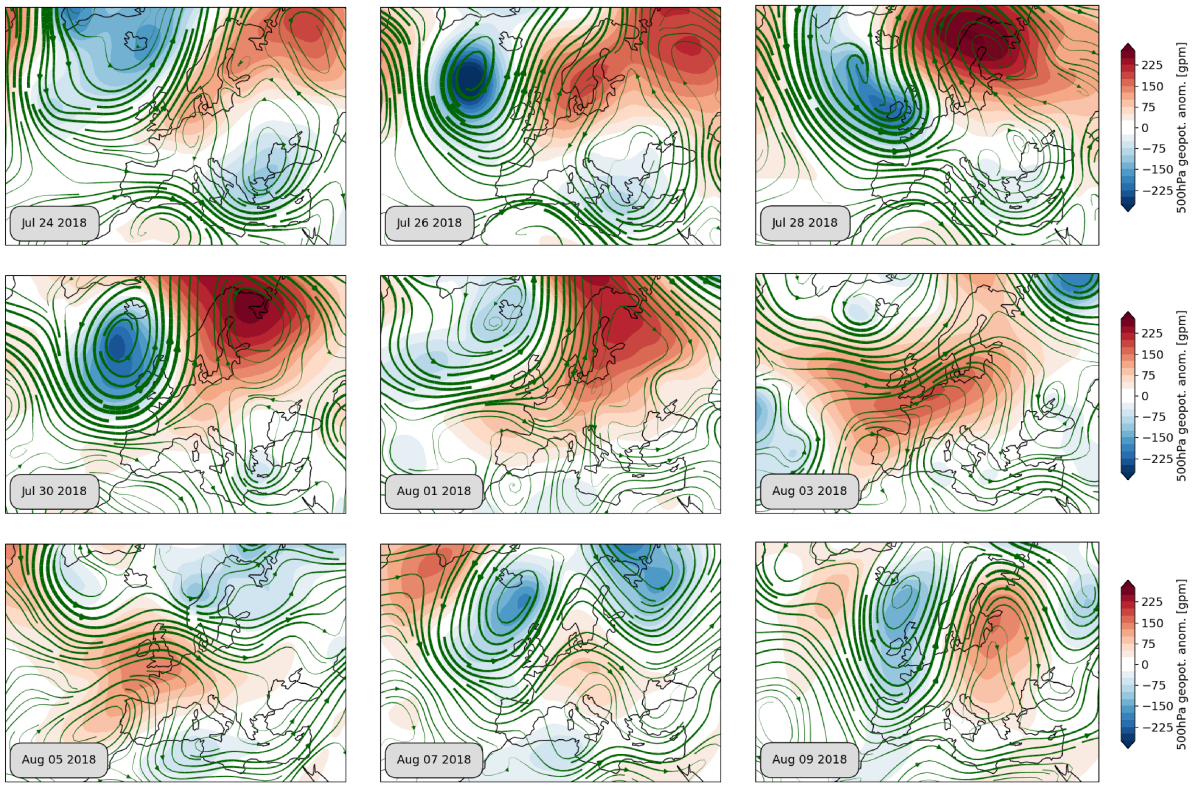

Figure S7. Geopotential height anomaly and wind velocity at 500hPa during the entire heatwave event (July 24th - August 10th). The sequence shows every 2-day flow patterns, with wind streamlines showing wind velocity. The anomalies are relative to the 1985-2014 climatology mean.