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## The substructure of extremely hot summers in the Northern Hemisphere

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In the last decades, extremely hot summers (hereafter extreme summers) have challenged societies worldwide through their adverse ecological, economic and public health effects. In this study, extreme summers are identified at all grid points in the Northern Hemisphere in the upper tail of the July–August (JJA) seasonal mean 2-meter temperature (T2m) distribution, separately in ERA-Interim reanalyses and in 700 simulated years with the Community Earth System Model (CESM) large ensemble for present-day climate conditions. A novel approach is introduced to characterize the substructure of extreme summers, i.e., to elucidate whether an extreme summer is mainly the result of the warmest days being anomalously hot, or of the coldest days being anomalously mild, or of a general shift towards warmer temperatures on all days of the season. Such a statistical characterization can be obtained from considering so-called rank day anomalies for each extreme summer, that is, by sorting the 92 daily mean T2m values of an extreme summer and by calculating, for every rank, the deviation from the climatological mean rank value of T2m.

Applying this method in the entire Northern Hemisphere reveals spatially strongly varying extreme summer substructures, which agree remarkably well in the reanalysis and climate model data sets. For example, in eastern India the hottest 30 days of an extreme summer contribute more than 70% to the total extreme summer T2m anomaly, while the colder days are close to climatology. In the high Arctic, however, extreme summers occur when the coldest 30 days are substantially warmer than climatology. Furthermore, in roughly half of the Northern Hemisphere land area, the coldest third of summer days contribute more to extreme summers than the hottest third, which highlights that milder than normal coldest summer days are a key ingredient of many extreme summers. In certain regions, e.g., over western Europe and western Russia, the substructure of different extreme summers shows large variability and no common characteristic substructure emerges. Furthermore, we show that the typical extreme summer substructure in a certain region is directly related to the region's overall T2m rank day variability pattern. This indicates that in regions where the warmest summer days vary particularly strongly from one year to the other, these warmest days are also particularly anomalous in extreme summers (and analogously for regions where variability is largest for the coldest days). Finally, for three selected regions, thermodynamic and dynamical causes of extreme summer substructures are briefly discussed, indicating that, for instance, the onset of monsoons, physical boundaries like the sea ice edge, or the frequency of occurrence of Rossby wave breaking, strongly determine the substructure of

extreme summers in certain regions.