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Studying heat waves and warm summers in numerical climate models with a rare event algorithm

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Extreme events are a major topic of interest in climate science. Studying rare extreme events with complex numerical climate models is computationally challenging, since in principle very long simulations are needed to sample a sufficient number of events to provide a reliable statistics. This problem can be tackled using rare event algorithms, numerical tools developed in the past decades in mathematics and statistical physics, dedicated to the reduction of the computational effort required to sample rare events in dynamical systems. Typically they are designed as genetic algorithms, in which a set of suppression and cloning rules are applied to an ensemble simulation in order to focus the computational effort on the trajectories leading to the events of interest. Recently we showed the great potential of rare event algorithms for climate modelling, applying a rare event algorithm to study extremes of European surface temperature in Plasim, an intermediate complexity model, in absence of external time dependent forcings (no seasonal and daily cycles). Here we go beyond these limitations, studying extreme heat waves and warm summers in the Northern extratropics in fully realistic conditions including daily and seasonal cycles, both in Plasim and in the state of the art Earth system model CESM. We show how the algorithm allows to sample extreme events characterised by persistency on different time scales, discussing links with large deviation theory. We show how one can characterise the statistics of heat waves and warm summers with extremely large return times, with computational costs orders of magnitude smaller than with direct sampling, and reach ultra rare events that would have been impossible to observe otherwise. We analyse the emergence of teleconnection patterns during the extreme events and their relation to the dynamics of planetary waves. Finally we discuss how these results open the way to the systematic application of these techniques to a vast range of applicative and theoretical studies.