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# Large Deviations in the Climate System: Extreme Events and Metastability

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The climate system is a complex, chaotic system with many degrees of freedom and variability on a vast range of temporal and spatial scales. Attaining a deeper level of understanding of its dynamical processes is a scientific challenge of great urgency, especially given the ongoing climate change and the evolving climate crisis. In statistical physics, complex, many-particle systems are studied successfully using the Large Deviation Theory (LDT). In the spirit of Hasselmann's programme, a great potential exists for applying LDT to problems relevant for climate science. In particular, LDT allows for understanding the fundamental properties of persistent deviations of climatic fields from the long-term averages and for associating them to low-frequency, large scale patterns of variability. This allows one to introduce a notion of typicality with regard to extreme events. These applications are of key importance to improve our understanding of high-impact weather and climate events. We will present several applications to the case of recent heatwaves (2010 Russian Heatwave, 2021 Western North America Heatwave) and cold spells (2010 Mongolian Dzud, 2019 Canadian Cold Spell). Furthermore, taking advantage of the formalism of Graham's quasipotential, LDT provides powerful tools for evaluating the probability of noise-induced transitions between competing metastable states of the climate system and for understanding the multiscale, hierarchical properties of the so-called dynamical landscape. We will show how this framework can be used to better understand the - arguably - most important critical transition of the Earth system, associated with the dichotomy between Snowball and Warm climate. The final transition to the Warm state that occurred about 600 Mya has been key for the eventual emergence of multicellular life in our planet. References: V.M. Galfi, V. Lucarini, Fingerprinting Heatwaves and Cold Spells and Assessing Their Response to Climate Change using Large Deviation Theory, Phys. Rev. Lett. 127, 058701 (2021) V.M. Galfi, V. Lucarini, F. Ragone, J. Wouters, Applications of Large Deviation Theory in Climate Science and Geophysical Fluid Dynamics, Riv. Nuovo Cimento 44, 291–363 (2021) G. Margazoglou, T. Grafke, A. Laio, V. Lucarini, Dynamical Landscape and Multistability of the Earth's Climate, Proc. R. Soc. A 477, 2021001920210019 V. Lucarini, T. Bodai, Global Stability Properties of the Climate: Melancholia States, Invariant Measures, and Phase Transitions, Nonlinearity 33, R59 (2020) V. Lucarini, T. Bodai, Transitions across Melancholia States in a Climate Model: Reconciling the Deterministic and Stochastic Points of View, Phys. Rev. Lett. 122,158701 (2019)

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