Indian Summer Monsoon: critical transition, predictability and extremes

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The aim of this thesis is to uncover some of the mysteries surrounding the Indian Monsoon - a large-scale climatic phenomenon affecting more than 1 .7 billion people - by using modern methods of complex systems science. The variability, strength, onset and withdrawal of monsoonal rainfall have an enormous effect on Indian agriculture, economy, life and prosperity of the inhabitants of the Indian subcontinent. Consequently, understanding the mechanisms of the Indian monsoon and its successful forecasting is not only a question of great interest, but also a significant scientific challenge.

The first part of this thesis is devoted to extreme rainfall events over the Indian subcontinent before, during and after the Indian monsoon season. I have employed and generalized the tools of complex networks and a nonlinear correlation measure - event synchronization - to study spatial structures and synchronicity of rainfall extremes. The analysis reveals a coincidence between the occurrence of extreme rainfall events in a pair of geographical regions: the Eastern Ghats and North Pakistan. In this thesis, I have shown that a synchronicity between extreme rainfall events in the Eastern Ghats and North Pakistan regions is caused by the interplay between the Indian Monsoon and a non-monsoonal precipitation pattern driven by the Westerlies - Western Disturbances. This result highlights the importance of the North Pakistan region for inferring the interaction between the Indian Monsoon system and Western Disturbances, and, therefore, improves the understanding of the Indian Monsoon coupling with the extratropics.

The second part of this dissertation is concerned with the problem of the spatial and temporal organization of the abrupt transition to the Indian monsoon. The analysis of observational data uncovers that a threshold behavior at the transition to monsoon over the central part of India corresponds to the well-defined critical transition of the cusp catastrophe type. Based on these observations, I have proposed a novel mechanism of a spatio-temporal transition to monsoon. It has several advantages in comparison to existing explanations of the Indian Monsoon nature: it describes the abrupt transition to monsoon in a chosen region of the Indian subcontinent, as well as the spatial propagation and variability of the Indian Monsoon onset along the axis of advance of monsoon.

The third part of this thesis focuses on the problem of predictability of the Indian Monsoon. I have developed a novel method for prediction of monsoon timing based on a critical transition precursor. The main idea of the method is to identify geographic regions - tipping elements of the monsoon - and to use them as observation locations for predicting onset and withdrawal dates. Unlike most predictability methods, this approach does not rely on precipitation analysis, but on air temperature and relative humidity, which are well - represented both in models and observations. The proposed method predicts the onset and withdrawal dates more than two weeks and a month earlier than existing methods, respectively. In addition, the scheme allows the inclusion of the information about the El-Niño–Southern Oscillation in the forecasting of onset and withdrawal dates, thereby, significantly improving the prediction of monsoon timing during anomalous years associated with the El-Niño–Southern Oscillation. Finally, the proposed scheme can be directly implemented into the existing long-range forecasting system of the monsoon’s timing.