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Bifurcations in a model of the Indian Summer Monsoon

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Monsoon rainfall plays an important role in the lives of large numbers of people, and previous authors have examined large-scale transitions in monsoon regimes using reduced form box-models. Because of nonlinear dependence with temperature of the net dry static energy flux into the box representing the atmospheric column over land, these models contain bifurcations and can exhibit discontinuous transitions to a state with little or no monsoon rainfall if external parameters controlling net radiation into the atmospheric column are reduced.

Contrary to previous models, we show that nonlinear dependence of dry static energy fluxes with temperatures cannot drive a bifurcation, when these are correctly formulated to account for multiple circulation regimes (normal monsoon and reversed). Under the correct formulation, net dry static energy flux into the atmospheric column over land decreases monotonically with land temperature, with negative fluxes when land is warmer than the ocean and positive fluxes if the reverse is true. Despite nonlinearity, advection by itself does nothing more than to drive land temperature to equal that of the ocean.

We show that for a bifurcation to occur, as a consequence of the implicit function theorem, there must be a process that can oppose this temperature dependence of net dry static energy flux into the atmospheric column, i.e. by warming the column at a rate that increases with its temperature. Increase of the longwave greenhouse effect with warming and latent heating of the atmospheric column over land are possible processes that can contribute to a bifurcation.

When land is warmer than ocean, temperature dependence of latent heating can cause a bifurcation and its qualitative dependence on temperature governs the qualitative dynamics of the monsoon. Consequently there can be multiple equilibria with land warmer than the ocean, but only a single equilibrium in which ocean is warmer than land. The latter is contrary to previous reduced-form models exhibiting multiple equilibria.

We discuss the nature of these equilibria, and identify minimal conditions for bifurcation in the monsoon model. We illustrate the range of bifurcation phenomena that are possible as the exponent in the scaling relationship between latent heating and temperature is varied in the model. We also discuss implications for transitions in monsoon regimes over paleoclimate timescales and for monsoon stability in the anthropocene.