Model hierarchies and bifurcations in convective quasi-equilibrium monsoon models

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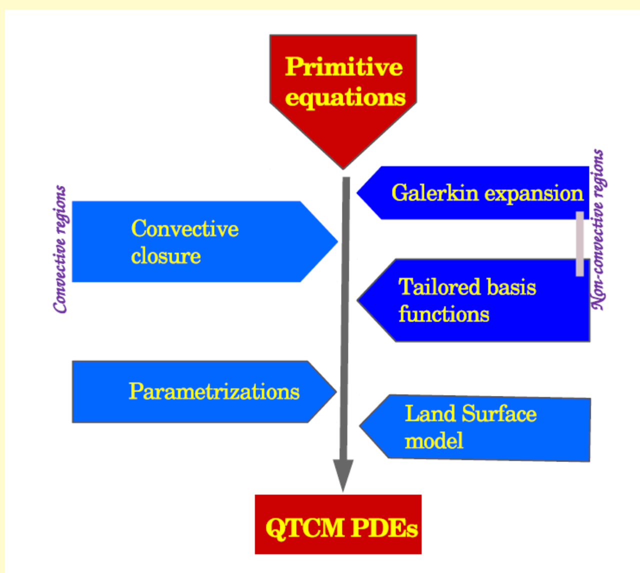
S. Krishna Kumar[1] and Ashwin K Seshadri[1,2],

[1]Divecha Centre for Climate Change, Indian Institute of Science, Bengaluru, India

[2] Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bengaluru, India

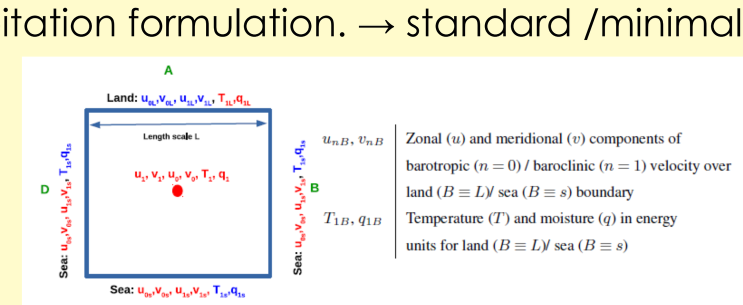
Convective quasi-equilibrium and tipping points

- The onset of South Asian monsoon a major research interest, and a range of models have been studied to address major questions, including presence or absence of tipping points.
- Interaction between convection in convective zones and large scale dynamics is a defining aspect of monsoon system.
- Quasi-equiilibrium Tropical Convective model (QTCM), a versatile model of intermediate complexity- permits various simplifications via assumptions, leading to a hierarchy of models.
- QTCM PDEs use convective approximations to simulate dynamics in the non-convective regions, using tailored basis functions for the momentum, thermodynamics and moisture variables.
- Broadly, QTCM PDES relate radiative energy input to nonlinear advection of momentum, temperature and moisture, thermal and moisture stratification effects, precipitation parameterization coupling the thermodynamic and moisture equations.

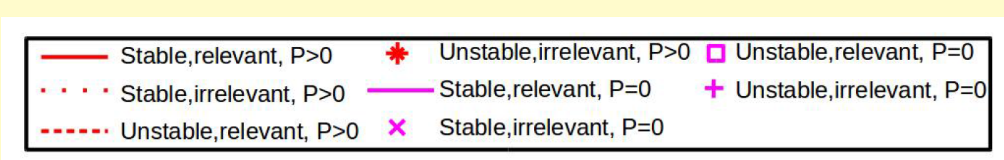


Model hierarchy

- Assumptions to yield a hierarchy of models- neglect of zonal velocity components, isolation of baroclinic components and neglecting barotropic ones, neglect of rotation, no nonlinear advection of momentum etc.
- Common elements to all models- linear baroclinic meridional velocity equation, thermodynamic and moisture equation with nonlinear advection of respective fields and stratification terms, and a Heaviside based precipitation formulation. → standard /minimal model used in the study.



- Use of Finite difference based single column framework yields various sets of ODEs *(See Kumar S.K, and Seshadri A.K, 2022)*.A Land-Ocean-Ocean-Ocean (LOOO) column is considered. Equilibria for the steady state form of equations found for two cases of the heaviside function- zero precipitation (pink curves) and non-zero precipitation (red curves)- with different equilibria being indicated as :



- Kumar S.K. and Seshadri A.K. (2022) suggested both near linear and tipping point like bifurcations can be exhibited by same model, depending on physical relevance of the equilibria.
- Here, we present brief introduction to the interplay between increasing complexity in the model hierarchy, nonlinearities included in the model and boundary conditions.

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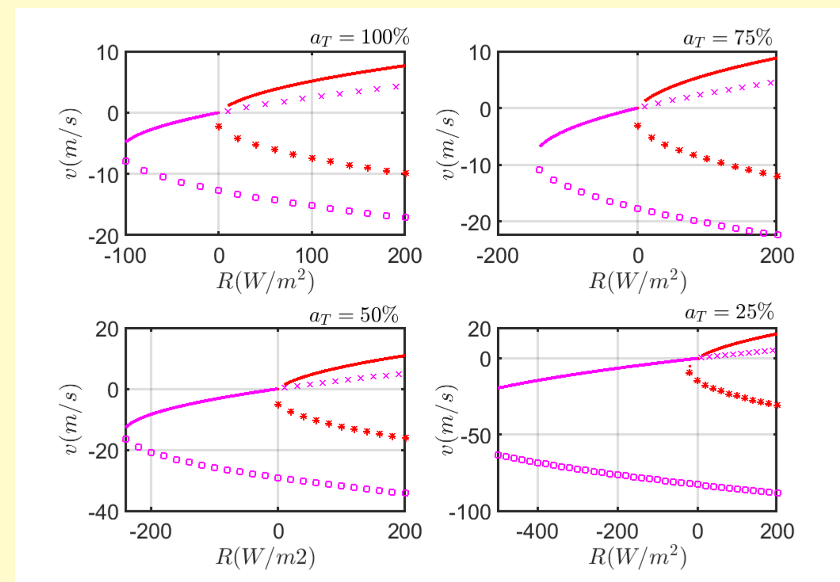

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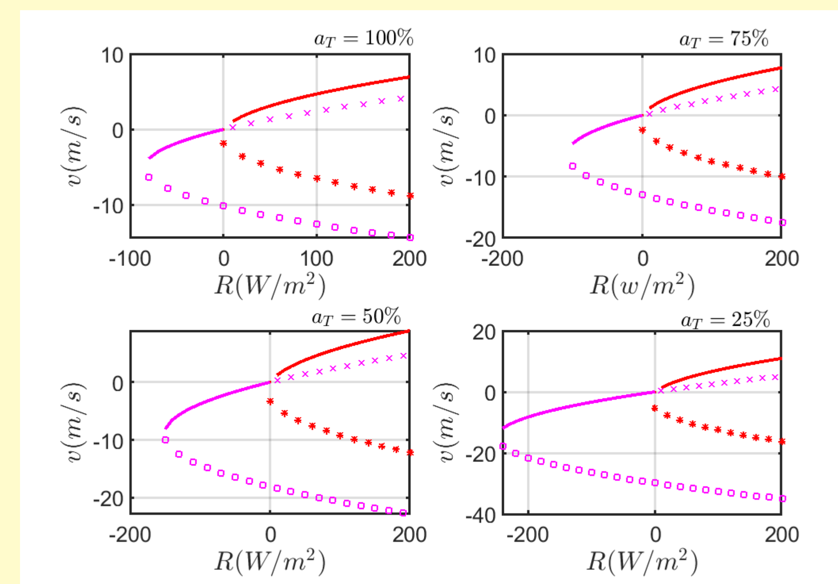

Nonlinear advection of temperature

- The panels show the bifurcation diagrams for change in nonlinear advection coefficient (a_T) in thermodynamic equation, reduced from 100 % of its default value to lower values. Note that the choice of boundaries (LOOO) leads to zero zonal gradients.
- Partial suppression of nonlinear advection still preserves the saddle-node structures, with lower a_T only changing the equilibrium values quantitatively, and change in bifurcation points
- Inclusion of rotation in model also leads to only quantitative changes. Inclusion of rotation leads to a fourth ODE- zonal baroclinic velocity equations. The meridional velocity is only quantitatively affected due to the linear nature of the two momentum equations.

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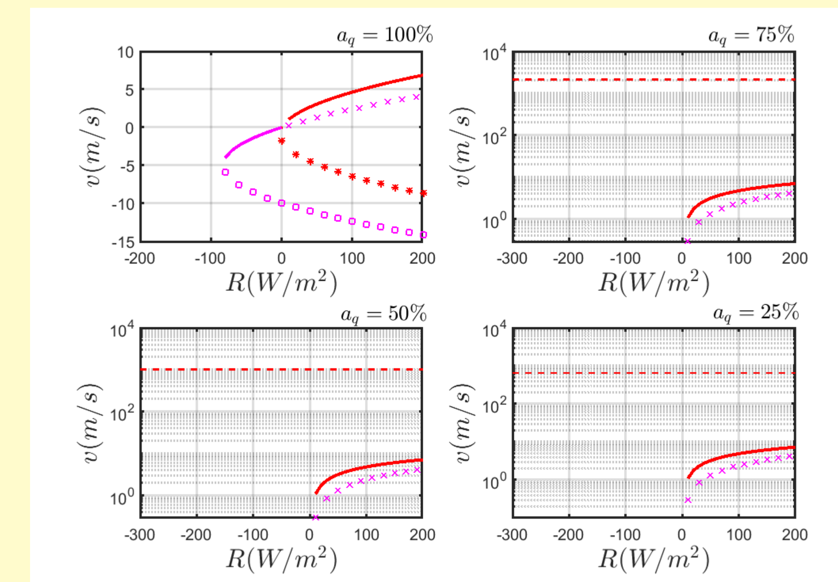

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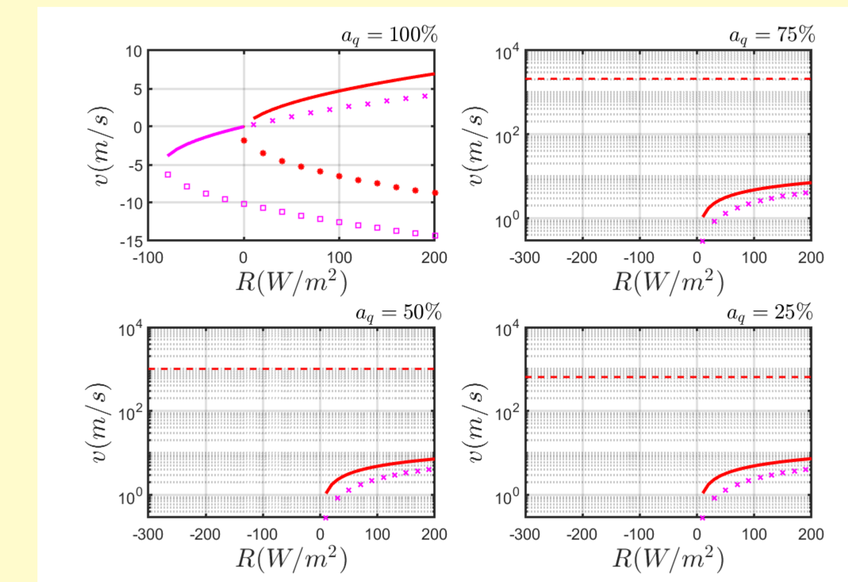

Nonlinear advection of Moisture

- The panels show the bifurcation diagrams for change in nonlinear advection coefficient (a_q) in the moisture equation, reduced from 100 % of its default value to lower values. Inclusion of rotation in model also leads to only slight quantitative changes, again due to the linear nature of the simplified momentum equations.
- Partial suppression of nonlinear advection still preserves the saddle-node structures, but an additional unstable equilibrium emerges for the non zero precipitation case (red). This is due to the fact that nonlinear advection of moisture and moisture stratification govern the cubic term in the resultant equilibrium equation for the system (*See Kumar S.K, and Seshadri A.K, 2022)*. Note that only positive equilibria are plotted for the plots in log (v) scale.

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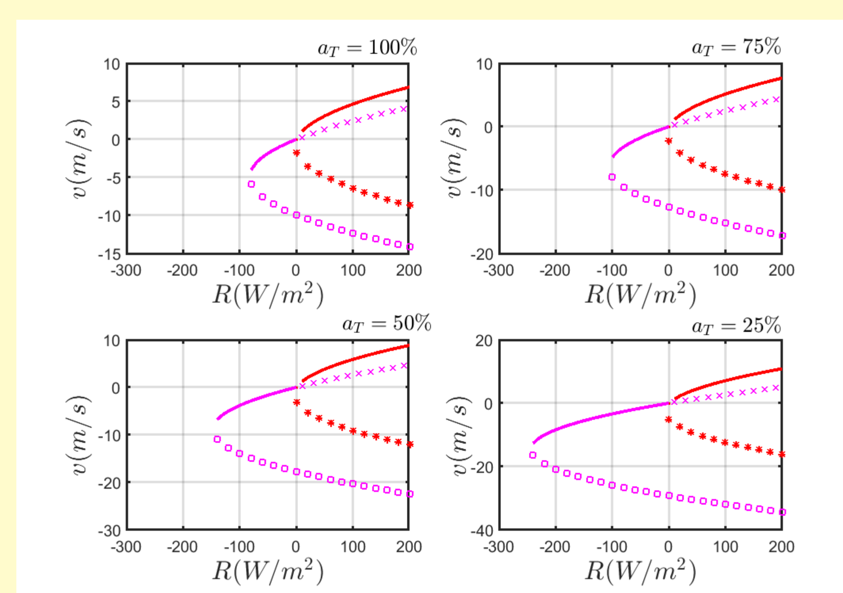

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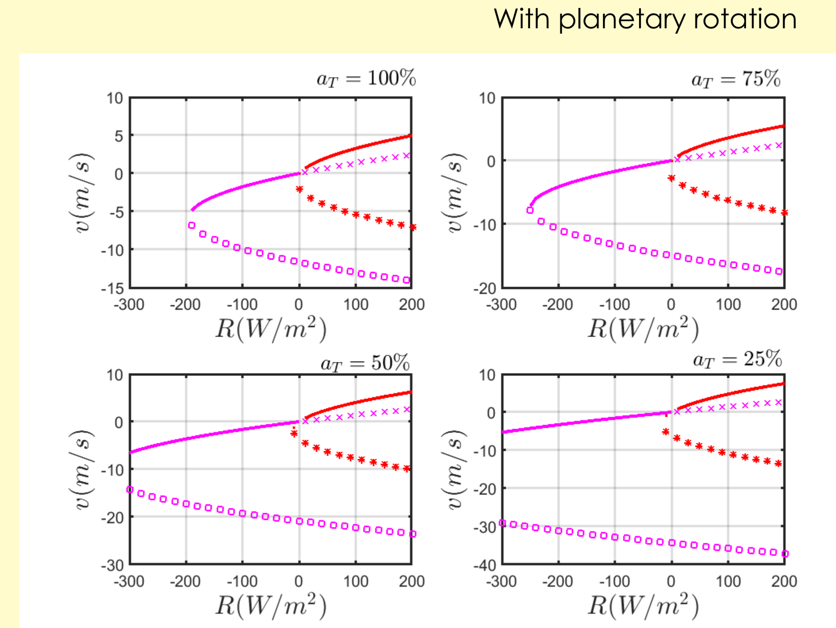

Nonlinear advection of temperature, changed boundaries

- The results are for a varied boundary condition, LLOO with non-zero zonal gradients. Consequently the zonal velocity could be stronger than for the LOOO case.
- The panels show the bifurcation diagrams for change in nonlinear advection term a_T, reduced from 100 % of its defualt value to lower values.
- The broad trends are qualitatively same as the other boundary conditions case suggesting that presence of zonal gradients still doesn't generate qualitative changes to bifurcations..

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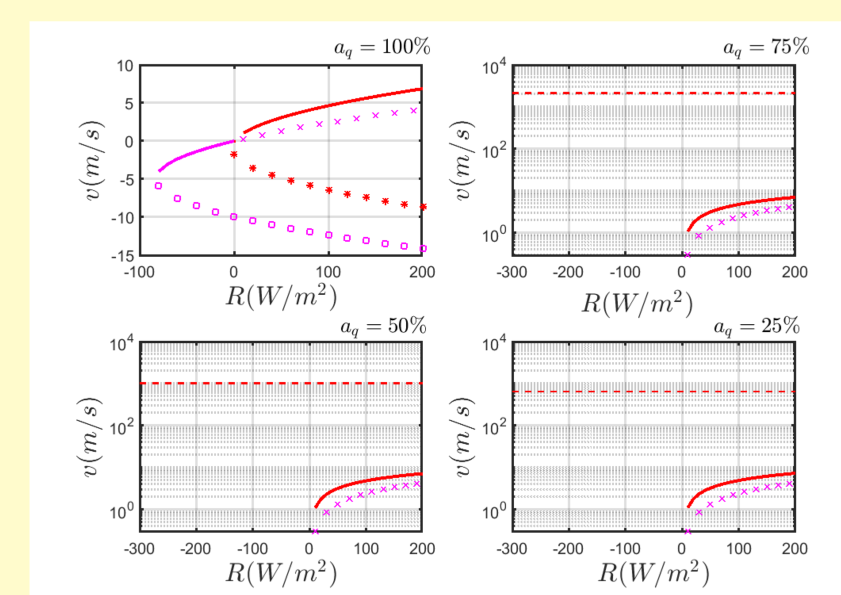

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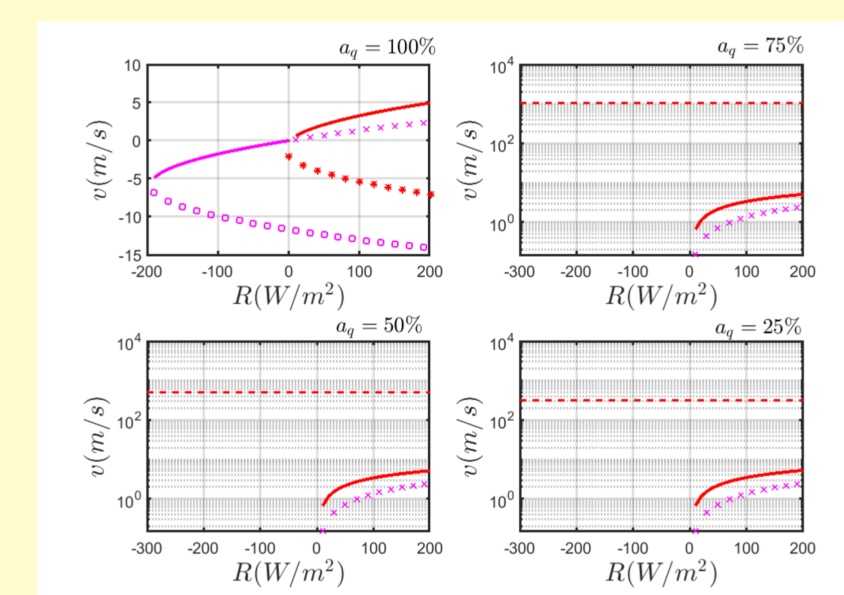

Nonlinear advection of moisture, changed boundaries

- The results are for a varied boundary condition, LLOO with non-zero zonal gradients.
- The appearance of third equilibrium (an unfolding of pitchfork bifurcation, see Kumar S.K. and Seshadri A.K., 2022) is also not affected by the changes, similar to case of change in a_T .
- Broadly, change in boundary conditions seems to have brought only a quantitative change
- Advection term in moisture equation seems to affect cubic term in the equilibrium equation and hence change in the qualitative form with change in a_q.

Summary

- QTCM based models can form a hierarchy of models which can be used to study monsoon dynamics at different levels of complexity
- The nonlinear advection of moisture seems to drive appearance of a third equilibrium, in addition to the saddle node equilibria. This is in contrast to nonlinear advection of temperature.
- It is seen that a change in level of model complexity does not seem to change dynamics qualitatively, chiefly due to linear nature of momentum equation used.
- Thus, a change in model complexity is closely dependent on included nonlinearities to exhibit a change in dynamics.

Reference- Kumar, S. K. and Seshadri, A. K.: Origins and suppression of bifurcation phenomena in lower-order monsoon models, Earth Syst. Dynam. Discuss. [preprint], https://doi.org/10.5194/esd-2022-30, in review, 2022

Further details: mailbox.skk@gmail.com