Theory of In-Cloud Activation and Microphysical Quasi-Equilibrium in Deep Ascent

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Overview

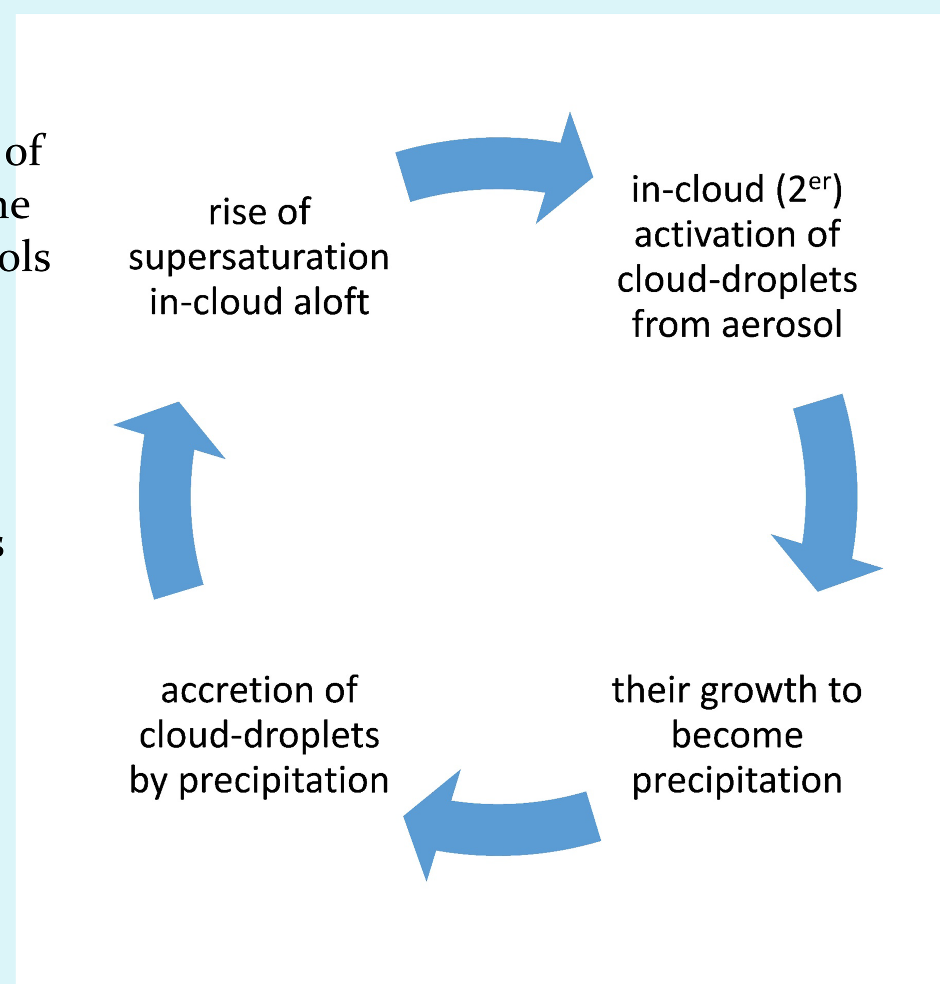
Ascent organizes the microphysical processes in clouds, as it is the source of supersaturation. The increase of supersaturation with height drives 'in-cloud activation', which is the source of most cloud-droplets aloft in deep convective updrafts.

Any cloud can be viewed as a system of feedback processes linking the various microphysical species of hydrometeors.

Here the microphysical quasi-equilibrium (QE) in an ascending adiabatic parcel of a single phase, either liquid or ice, is elucidated by an analytical theory in zero-D with drastic simplifications (Phillips 2022).

Description of in-cloud activation

- In-cloud activation of cloud-particles is the conversion of aerosols to cloud-particles during ascent
- Promoted by precipitation (Ochs 1978)



Description of Model

dimensionless (tilde symbols) mixing ratios for mass ($\tilde{q}, \tilde{q}_p$)

CLOUD (condensation, accretion)

$$\frac{D\tilde{q}}{D\tilde{t}} \approx \tilde{c} - \tilde{q}\tilde{q}_p$$

PRECIPITATION (accretion, sedimentation)

$$\frac{D\tilde{q}_p}{D\tilde{t}} \approx \tilde{q}_p\tilde{q} - \tilde{\varphi}\tilde{q}_p^{\,\beta}$$

dimensionless particle-number mixing ratio ($\tilde{n}$)

CLOUD (in-cloud activation, sedimentation)

$$\frac{D\tilde{n}}{D\tilde{t}} \approx \tilde{n}^{-k}\frac{\tilde{f} - \tilde{q}_p\tilde{n}^{k+1}}{1 + \tilde{A}/\tilde{n}^{k+1}}$$

in-cloud activation efficiency; aerosol-activity parameter; vertical acceleration parameter

$$\tilde{f} = \tilde{W}\tilde{A}$$

condensation-precipitation efficiency

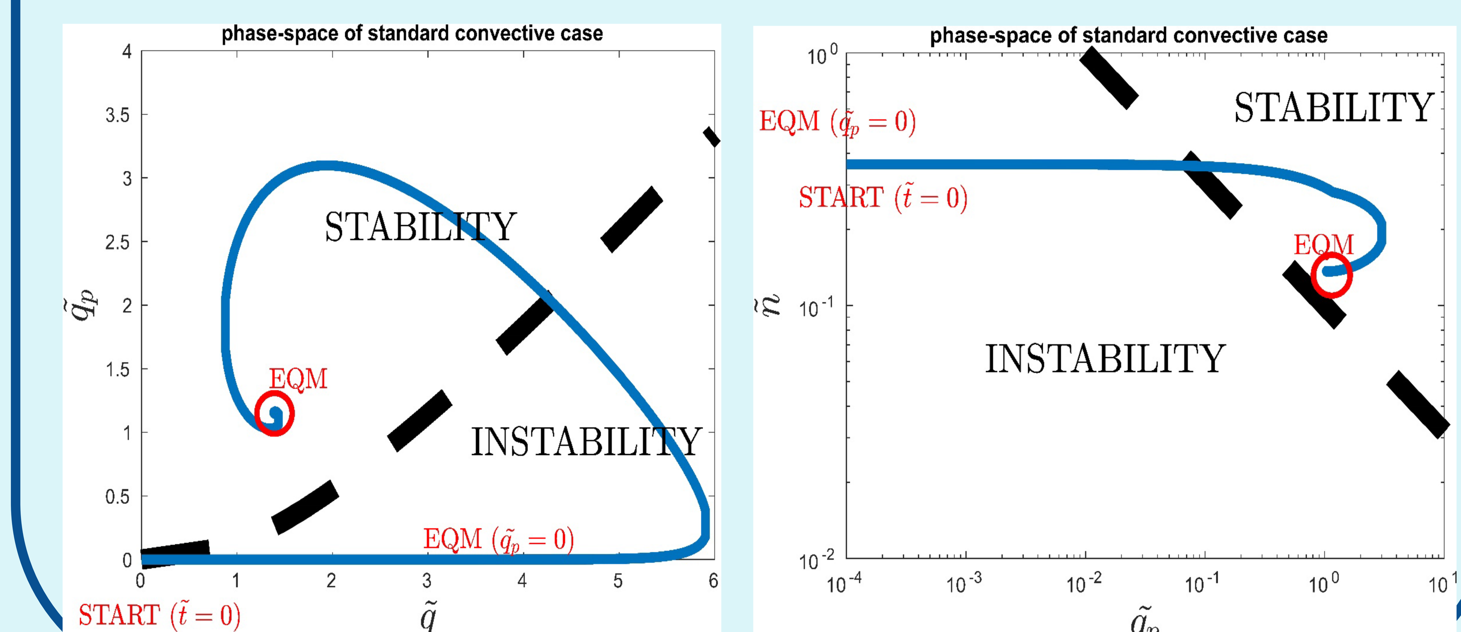
$$\tilde{c} = c_0 c_3 \tau_{fall}^2$$

condensate rate (kg/kg/sec); ascent (m/s)

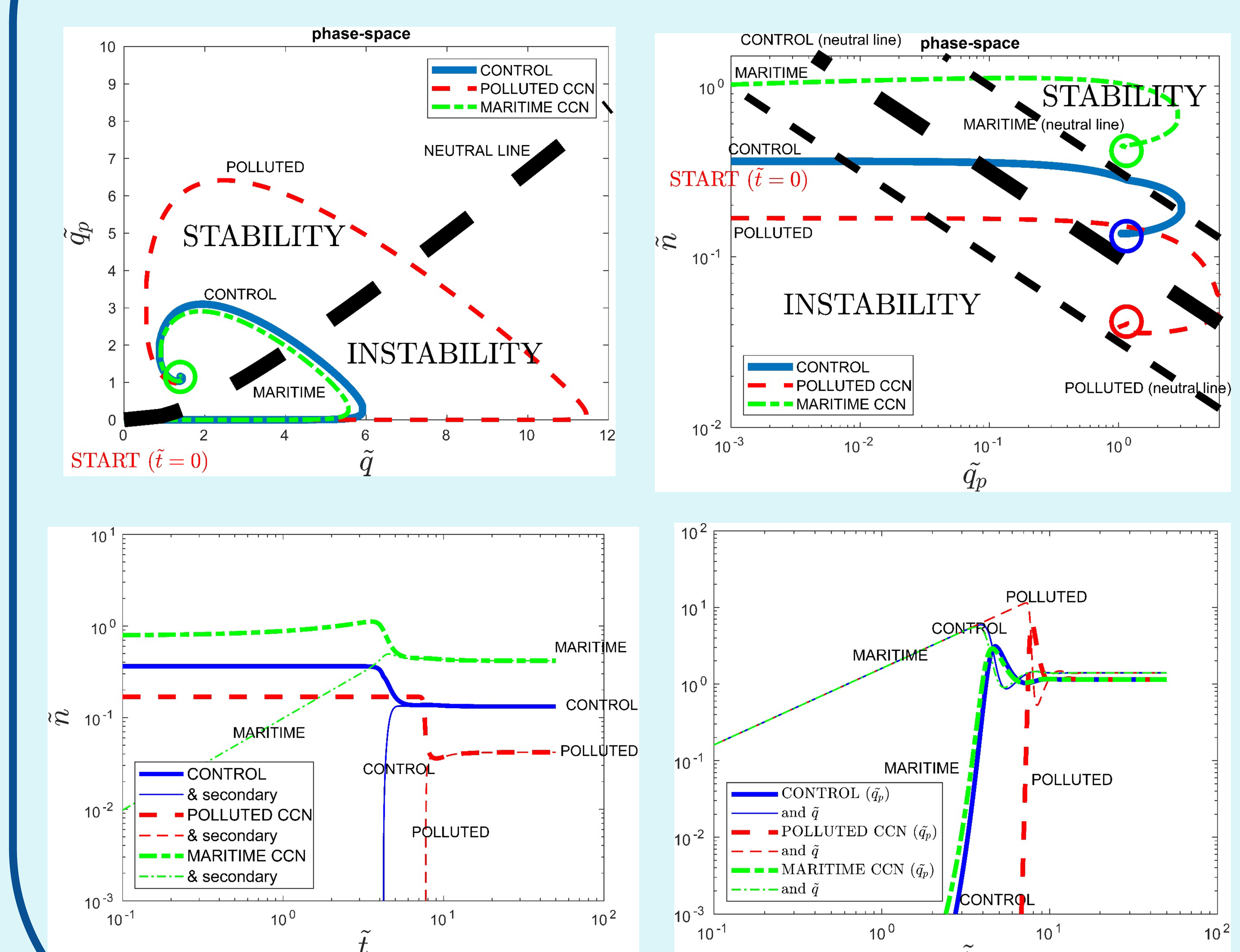
$$c_0 = c_6(T)w$$

Results: Trajectory in Phase-Space and Stability

- Linear perturbation analysis yields the feedback parameter, revealing a neutral line in the phase-space.
- Standard case: $w = 1$ m/s at cloud-base (1 km MSL), 5 m/s (6 km MSL), normalized CCN of $c_1 = 1000$ cm^{-3} (s = 1%, $k = 1$).



Results: Sensitivity to Aerosol Conditions



Results: QE and Contrast between Convective and Stratiform Clouds

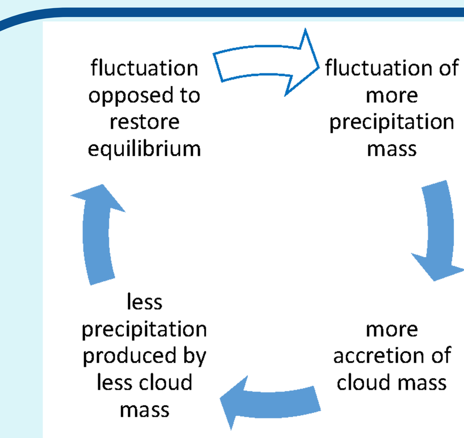
- Theory predicts the orders of magnitude of convective-stratiform contrast observed
- w and cloud-liquid mass seen to differ by factors of 10^2 and 10, while $\beta \equiv 1/\omega \approx 2$

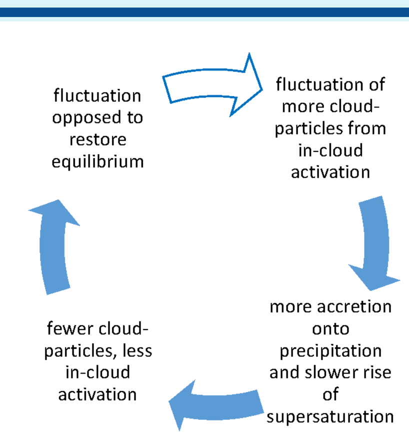
$$\tilde{q}_{eq} \approx \tilde{c}/\tilde{q}_{p,eq} = \tilde{c}^{1-\omega}\tilde{\varphi}^{\omega} \quad \propto w^{1-1/\beta}$$

$$\tilde{q}_{p,eq} \approx \left(\frac{\tilde{c}}{\tilde{\varphi}}\right)^{\omega} \quad \propto w^{1/\beta}$$

$$\tilde{n}_{eq} \approx \left(\frac{\tilde{f}}{\tilde{q}_{p,eq}}\right)^{\frac{1}{k+1}} \approx \left(\frac{\tilde{f}\tilde{\varphi}^{\omega}}{\tilde{c}^{\omega}}\right)^{\frac{1}{k+1}} \Rightarrow n_{eq} \propto c_1^{1/(k+1)} w^{k-\omega}(dw/dz)$$

Conclusions





- Prolonged in-cloud droplet activation during deep ascent is predicted here, and involves precipitation depleting cloud-liquid, which causes an inexorably increasing supersaturation.
- In-cloud activation is triggered by the onset of precipitation during sufficient ascent, with ascent only needing to exceed twice that at cloud-base.
- Feedbacks are initially positive, with explosive growth of the system state until it attains a realm of negative feedbacks and stability. Quasi-equilibria are reached (flow-charts above).
- Stratiform-vs-convective contrast adequately predicted.

References and Acknowledgements

Ochs, H., 1978: Moment-conserving techniques for warm cloud microphysical computation. Part II. Model testing and results. *J. Atmos. Sci.*, **35**, 1959-1973

V. T. J. Phillips, 2022: Theory of in-cloud activation of aerosols and microphysical quasi-equilibrium in a deep updraft. *J. Atmos. Sci.*, **79**, in press

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