Numerically efficient description of homogeneous mixed cloud microphysics

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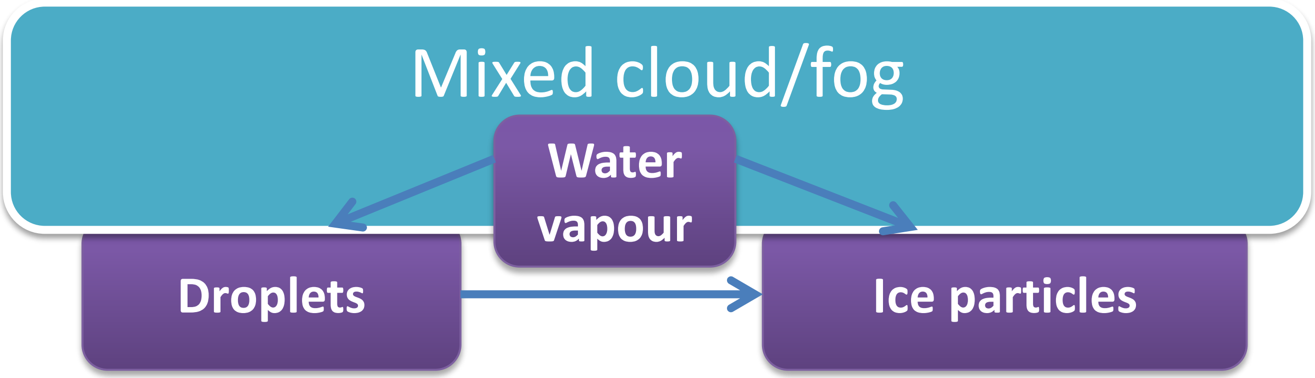
Problems and motivation

- Due to expanding urban areas as sources of anthropogenic aerosols, cases with dense and dangerous low clouds or fogs have been increased and expect to increase further.
- Fog could became a real hazard at negative temperatures since leads to formation of hoar including icing of transportation facilities particularly aviation, electrical power lines, roads and other exposed surfaces.
- Many recent studies have shown that formation of low stratus clouds (fog) cannot be properly presented and predicted by current NWP and climate models.
- Obviously, the problem of such forecasting is in cloud/ precipitation parameterizations used in numerical models.



BIN

- Prescribed and/or calculated cloud / precipitation particle size distrubutions (spectra)
- Predicted supersaturation
- Activation of CCN and IN
- Condensational growth
- Freezing/glaciation
- Stochastic coagulation
- Other microphysical processes and interactions

BIG GAP

BULK

- In many cases only warm processes (e.g. Kessler)
- One-moment parameterization (water/ice content or mixing ratios for a few classes of cloud/precipitation particles)
- Artificially introduced thresholds
- Artificially introduced autoconversion to form raindrop
- Two-moment parameterization with number concentrations of species improves representations of particle size distributions

Main tasks and questions

- To study microphysical processes in homogeneous cloud/fog from IN activation up to its complete glaciation
- What are the scenarios for the evolution of supercooled mixed cloud/fog?
- What parameters determine the type of cloud evolution?
- How to simplify the description of the system in typical and interesting situations to practice?
- Create a basis for more general representation of mixed cloud/fog formation and recommendations for improvement of their parameterization in NWP and climate models

System of main equations of the model

$$\frac{dq}{dt} = -\sum_{k=1}^{K} 4\pi D r_k n_k (q - q_s) - 4\pi D R N (q - Q_s)\,,$$

$$\frac{dr_k}{dt} = \frac{D}{\rho_w}\frac{(q - q_s)}{r_k}, \qquad l = \sum_{k=1}^{K} \frac{4}{3}\pi r_k^3 n_k \rho_w$$

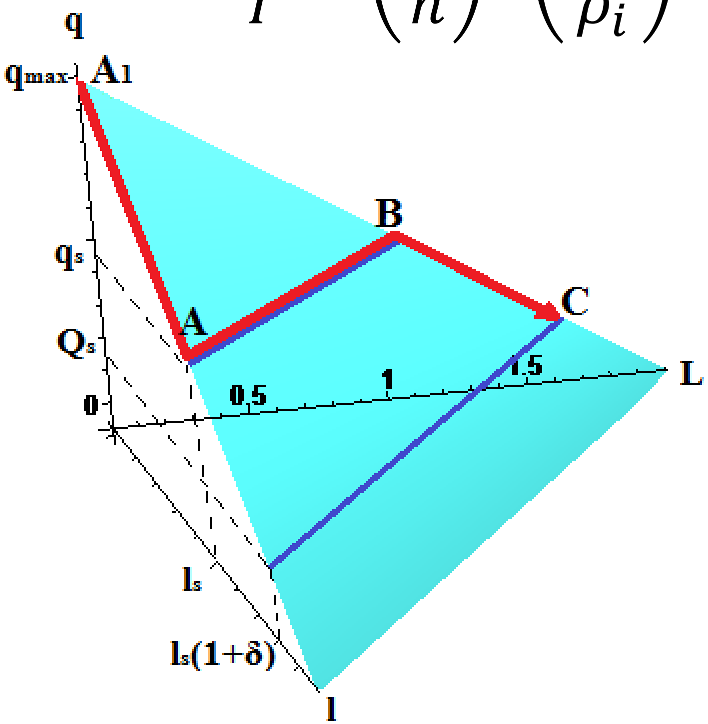
$$\frac{dR}{dt} = \frac{D}{\rho_i}\frac{(q - Q_s)}{R} + \frac{1}{4}\frac{\alpha}{\rho_i} R^2 l, \qquad \mathrm{L} = \frac{4}{3}\pi R^3 N \rho_i,\ N = const,$$

$$\frac{dn}{dt} = -N\pi R^2 |U| n, \qquad U = \alpha R^2, \qquad \alpha = \frac{2}{9}\frac{(\rho_i - \rho_{air})}{\mu} g$$

$\boldsymbol{q, q_s, r, n, l}$ and $\boldsymbol{Q, Q_s, R, N, L}$are absolute and saturated vapor densities, radius, number concentration and mass density of droplets and ice crystals respectively; $\boldsymbol{\rho_w, \rho_i}$ and $\boldsymbol{\rho_{air}}$ are water, ice and air mass densities respectively; ***D***is the diffusion coefficient; ***U*** is the fall rate of ice particles determined by Stoke's law; ***μ***is the air dynamic viscosity; ***g***is the gravitational acceleration

System of water vapor-droplets-ice particles

$$\varepsilon = \frac{\tau}{T} = \left(\frac{N}{n}\right)^{\frac{2}{3}} \left(\frac{\rho_w}{\rho_i}\right)^{\frac{1}{3}}$$



- A1-A relaxation of droplets with time

$$\tau = (4\pi D n_0 r_s)^{-1} \quad T = (4\pi D N R_s)^{-1}$$

- A-B Depositional and/or collectional growth of ice particles from r_s to R_s

$$r_s = \left(\frac{3l_s}{4\pi\rho_w n}\right)^{\frac{1}{3}}, \; R_s = \left(\frac{3l_s}{4\pi\rho_i N}\right)^{\frac{1}{3}}$$

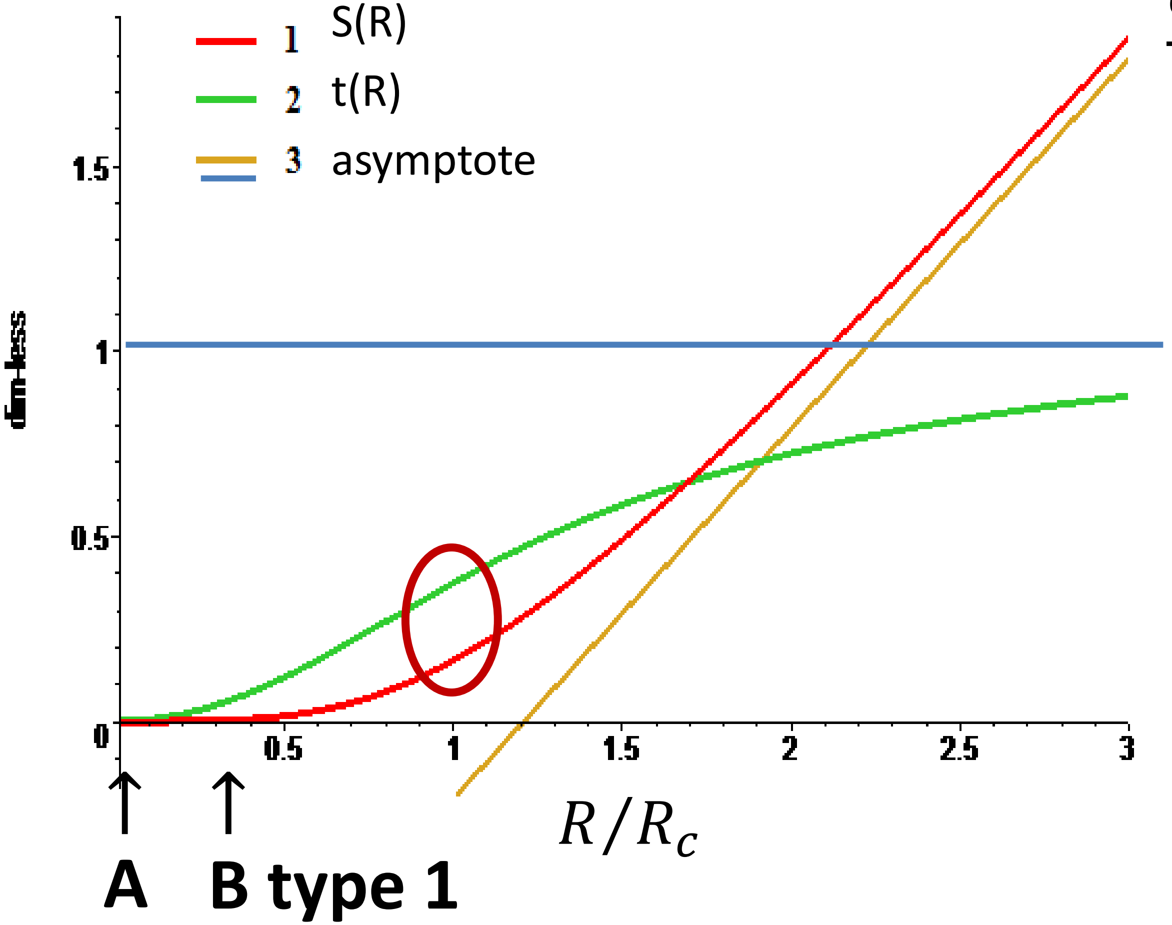
- B-C relaxation of ice particles
- C final state with time T and max R_m

Mass conservation of water

$$\boldsymbol{q(t) + l(t) + L(t) = q_{max}}$$

$$R_m = R_s(1+\delta)^{\frac{1}{3}}, \; \delta = \frac{q_s - Q_s}{l_s} = \frac{\Delta}{l_s}$$

Individual ice particle growth (A-B): from deposition to collection



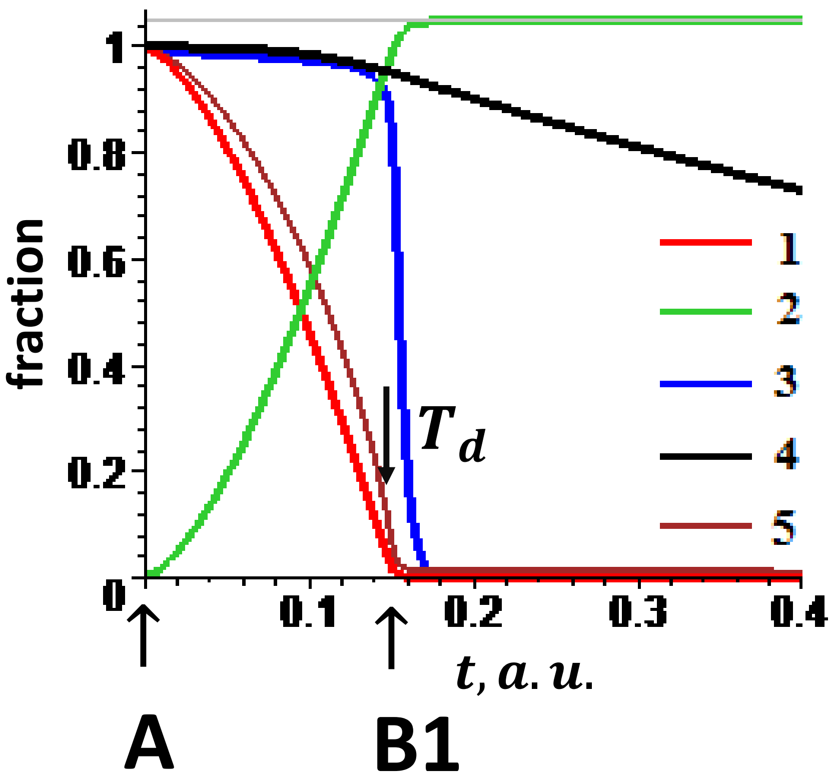
$$\frac{dR}{dt} = \frac{D\Delta}{\rho_i R} + \frac{l_s}{4\rho_i}\alpha R^2$$

$$\frac{dR}{dS} = \frac{D}{\rho_i}\frac{\Delta}{\alpha R^3} + \frac{l_s}{4\rho_i}$$

$$\boldsymbol{R_c = \left(\frac{4D\delta}{\alpha}\right)^{\frac{1}{3}}}$$

$$\boldsymbol{R_c \in [40; 200]\mu m}$$

Evolution type 1
Predominant depositional growth



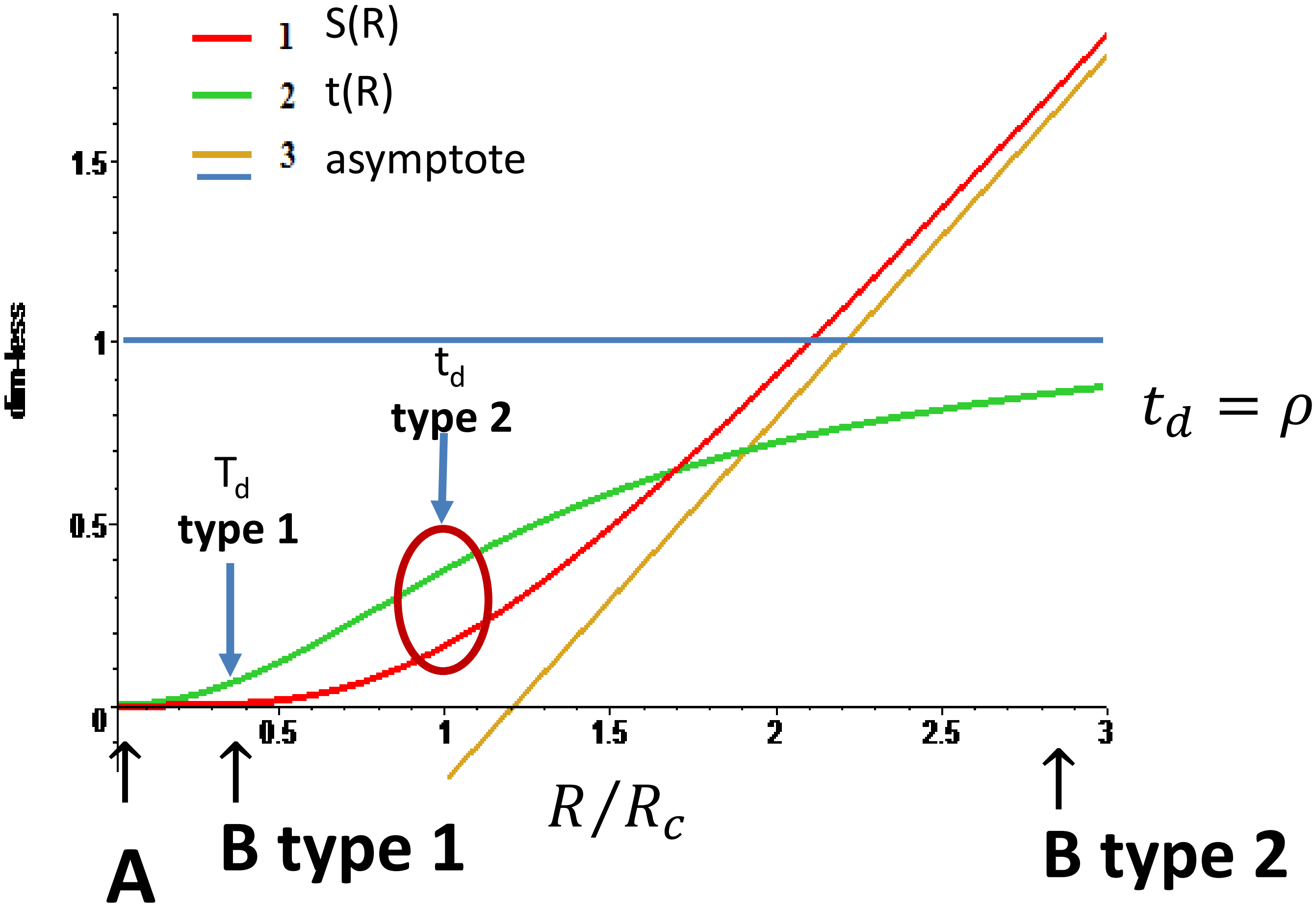
$$T_d = \frac{1}{4\pi D\Delta}\left(\frac{4\pi\rho_i}{3}\right)^{\frac{1}{3}}\left(\frac{l_s}{N}\right)^{\frac{2}{3}}$$

(1) *Droplets' volume* $x(t')$
(2) *Ice particles' volume* $y(t')$
(3) *Relative humidity* $q'(t')\,\frac{q - Q_s}{q_s - Q_s}$
(4) *Droplet number concentration* $n(t')$
(5) *Visibility in fog* $h(t')$ *relative to it's initial value* h_0

$$\frac{h}{h_0} = n\left(\frac{r}{r_s}\right)^2$$

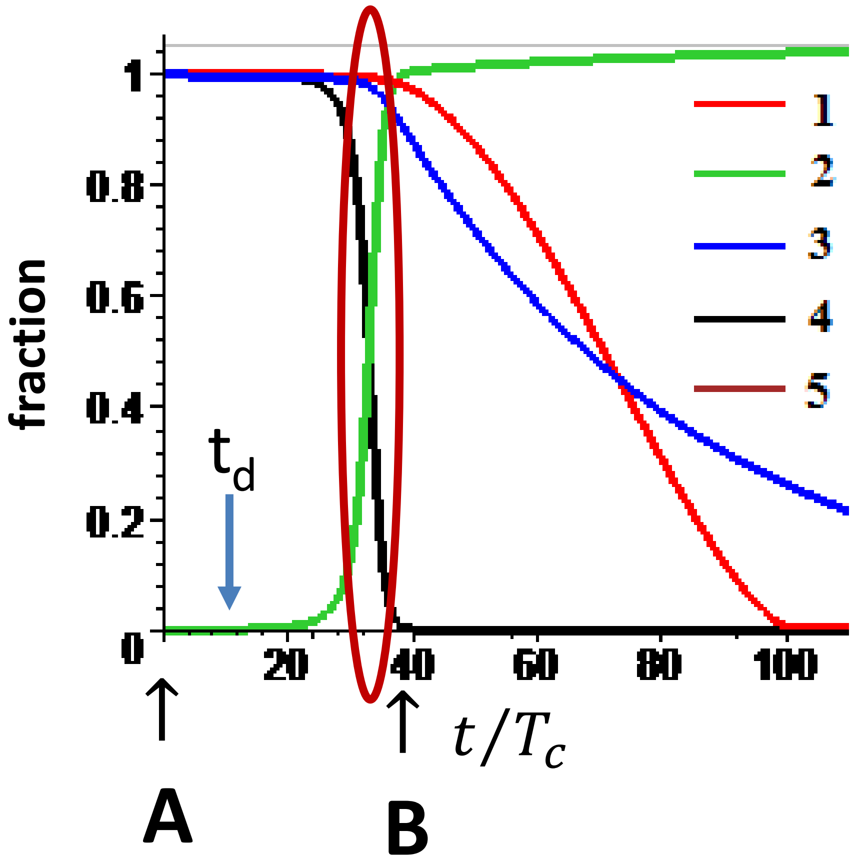
Evolution type 2

$$(n = const, q = q_s = const, n \gg N)$$



$$t_d = \rho_i \left(\frac{4}{3\alpha}\right)^{\frac{2}{3}} \left(\frac{1}{3\Delta D {l_s}^2}\right)^{\frac{1}{3}}$$

Evolution type 2
Predominant and fast collectional growth

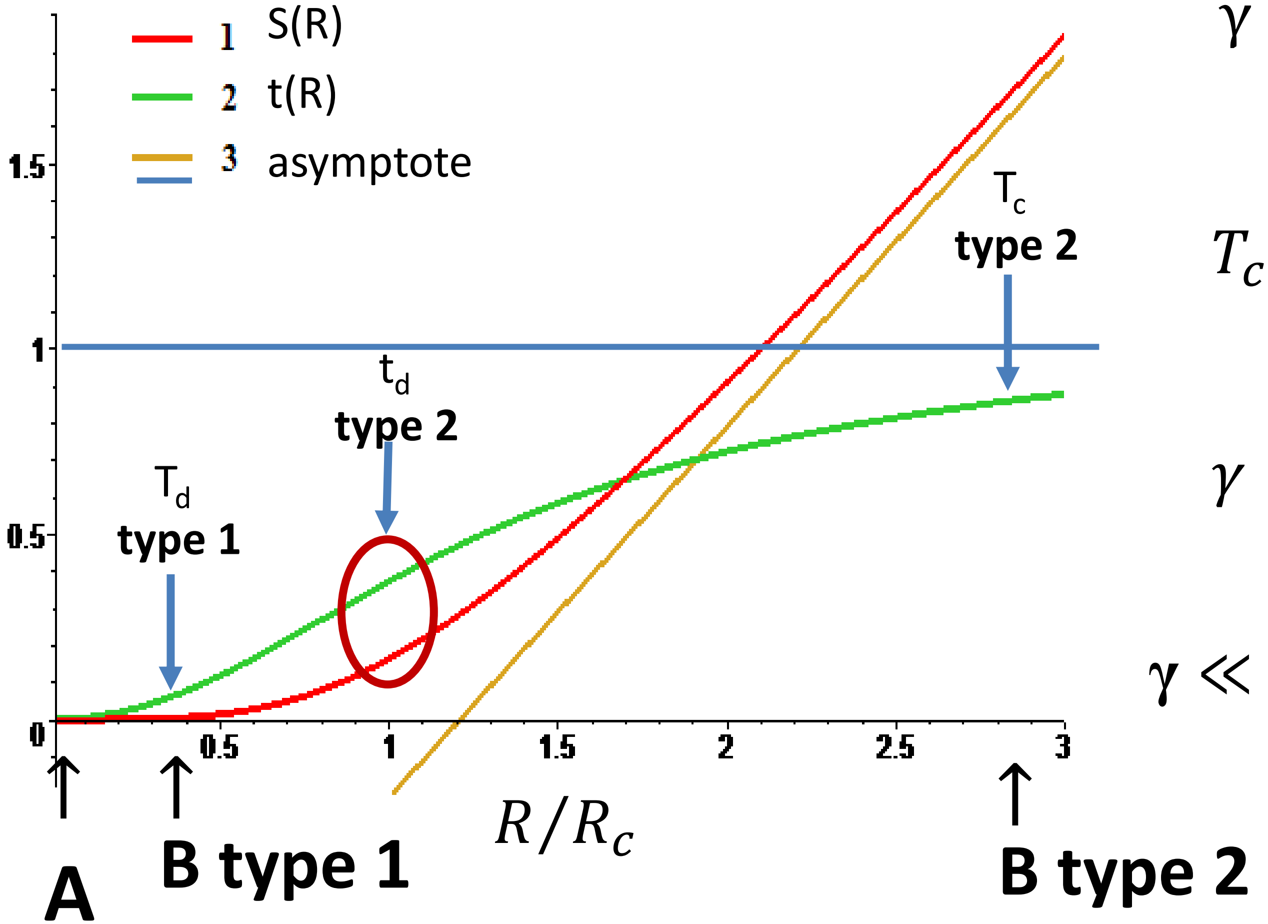


(1) *Droplets' volume* $x(t')$
(2) *Ice particles' volume* $y(t')$
(3) *Relative humidity* $q'(t') \dfrac{q - Q_s}{q_s - Q_s}$
(4) *Droplet number concentration* $n(t')$
(5) *Visibility in fog* $h(t')$ *relative to it's initial value* h_0

$$T_c = \frac{4\rho_i}{3\alpha l_s}\left(\frac{4\pi\rho_i N}{3 l_s}\right)^{\frac{1}{3}}$$

$$\boldsymbol{T_c \ll t_d}$$

Parameter of the transition from Type 1 (γ>>1) to Type 2 (γ<<1)



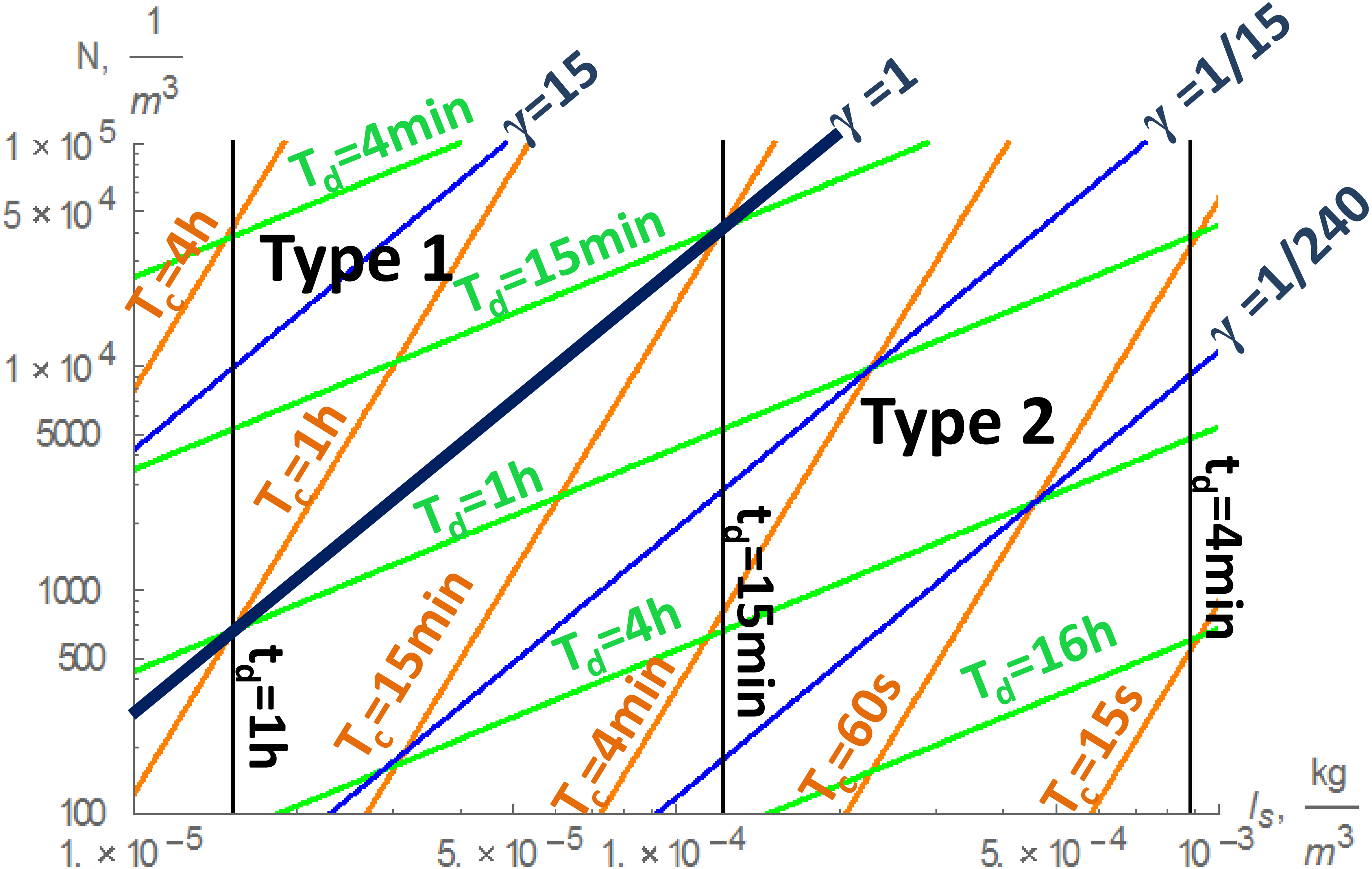
$$\gamma = \frac{T_c}{T_d} = \left(\frac{R_c}{R_s}\right)^3$$

$$T_c = T_d \gamma = t_d \gamma^{\frac{1}{3}}$$

$$\gamma = \frac{16\pi D}{3\alpha} \frac{N \Delta\rho_i}{l_s^2}$$

$$\gamma \ll 1, \boldsymbol{T_c < t_d < T_d}$$

Variation of times and γ with mass density of droplets l_s and number concentration of ice particles N



Scientifically-based simplifications with controlled accuracy

Set of eqs. for *R*, *r*, *n* and *q rewritten*

in dimensionless variables

$$T_c \frac{dy}{dt} = \left((1 - \varepsilon a(t)) \frac{y}{\gamma} + (1 - \varepsilon \delta a(t) - y) \right) y^{\frac{4}{3}},$$

$$y = \left(\frac{R}{R_s}\right)^3$$

Small parameters

$$\varepsilon a(t) = -\frac{q(t) - q_s}{q_s - Q_s}$$

$$\varepsilon \approx \left(\frac{N}{n_0}\right)^{\frac{2}{3}} \sim 10^{-4}, \delta \sim (0.1 \div 10), \varepsilon\delta \sim 10^{-2}(max), a(t) \sim 1$$

Simplified ice growth eq.

$$\varepsilon \ll 1: \quad T_c \frac{dy}{dt} = \gamma y^{\frac{1}{3}} + (1 - y) y^{\frac{4}{3}}$$

Summary

- In the considered situations, the process of ice particles' growth until the disappearance of cloud droplets occurs at a practically constant humidity $q = q_s$, which corresponds to the saturation humidity with respect to water, regardless of the values of all other parameters. This process growth can be described by the one differential equation of the first order
- The process (in dimensionless variables) depends on a single dimensionless parameter γ,whichessentially gives quantitative criterion of transition from dominant depositional to intense collectional growth of ice particles

$$\gamma \sim \frac{N(q_s - Q_s)}{l_s^2}$$

- It can be recommended for use in numerical models with bulk parameterization of cloud and precipitation formation processes

Perspective work

Include in the consideration

- more sophisticated ice nucleation
- spectra of droplets and ice particles
- self-collection of ice particles
- ice precipitation formation
- fall rate of snow
- income and removal of ice particles due to gravitational settling

To estimate vertical displacement of ice particles and its timescales to refer with gridbox size of outer hydrodynamic model

Two-way interaction with NWP and climate models

Thank you for your attention!