Towards improving parameterizations of mixed stratus cloud/fog formation in climate models and NWP

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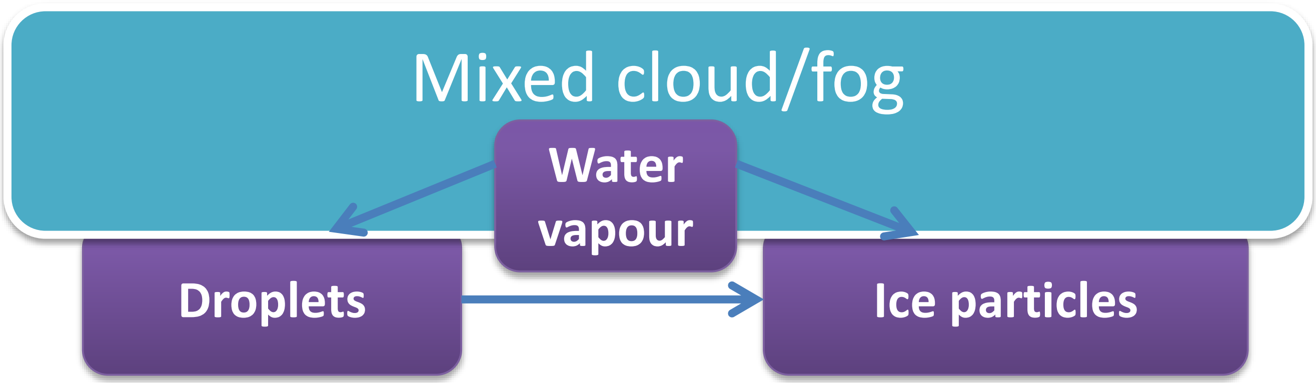
Problems and motivation

- 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 in used 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

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

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

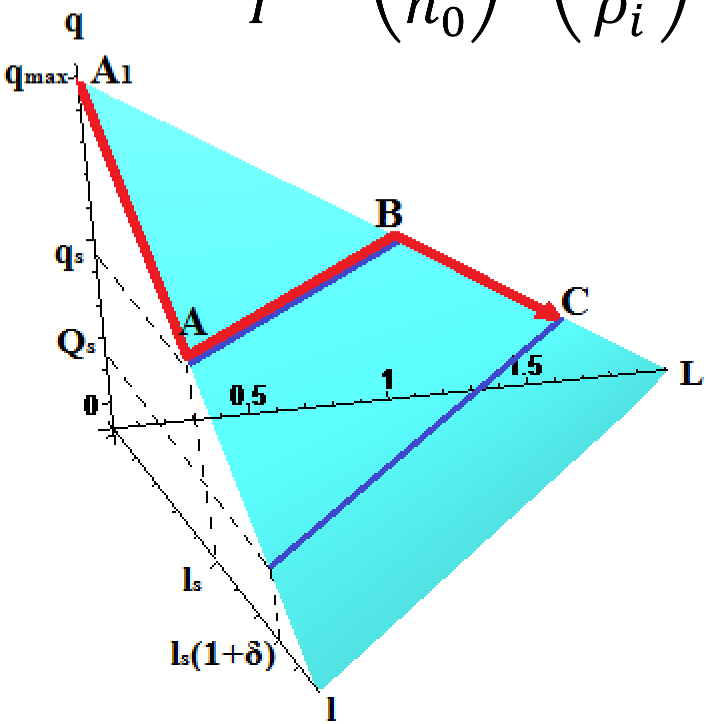
$$\frac{dR}{dt} = \frac{D}{\rho_i}\frac{(q - Q_s)}{R} + \frac{1}{4}\frac{\alpha}{\rho_i} R^2 l, \qquad \mathrm{L} = \frac{4}{3}\pi R^3 N \rho_i,\ N = const,$$

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

$\boldsymbol{q}, \boldsymbol{q_s}, \boldsymbol{r}, \boldsymbol{n}, \boldsymbol{l}$ and $\boldsymbol{Q}, \boldsymbol{Q_s}, \boldsymbol{R}, \boldsymbol{N}, \boldsymbol{L}$ are absolute and saturated vapor densities, radius, number concentration and mass density of droplets and ice crystals respectively; $\boldsymbol{\rho_w}, \boldsymbol{\rho_i}\ and \boldsymbol{\rho_{air}}$ 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; $\boldsymbol{\mu}$ is the air dynamic viscosity; ***g*** is the gravitational acceleration

System of water vapor-droplets-ice particles

$$\varepsilon = \frac{\tau}{T} = \left(\frac{N}{n_0}\right)^{\frac{2}{3}} \left(\frac{\rho_w}{\rho_i}\right)^{\frac{1}{3}}$$



Mass conservation of water

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

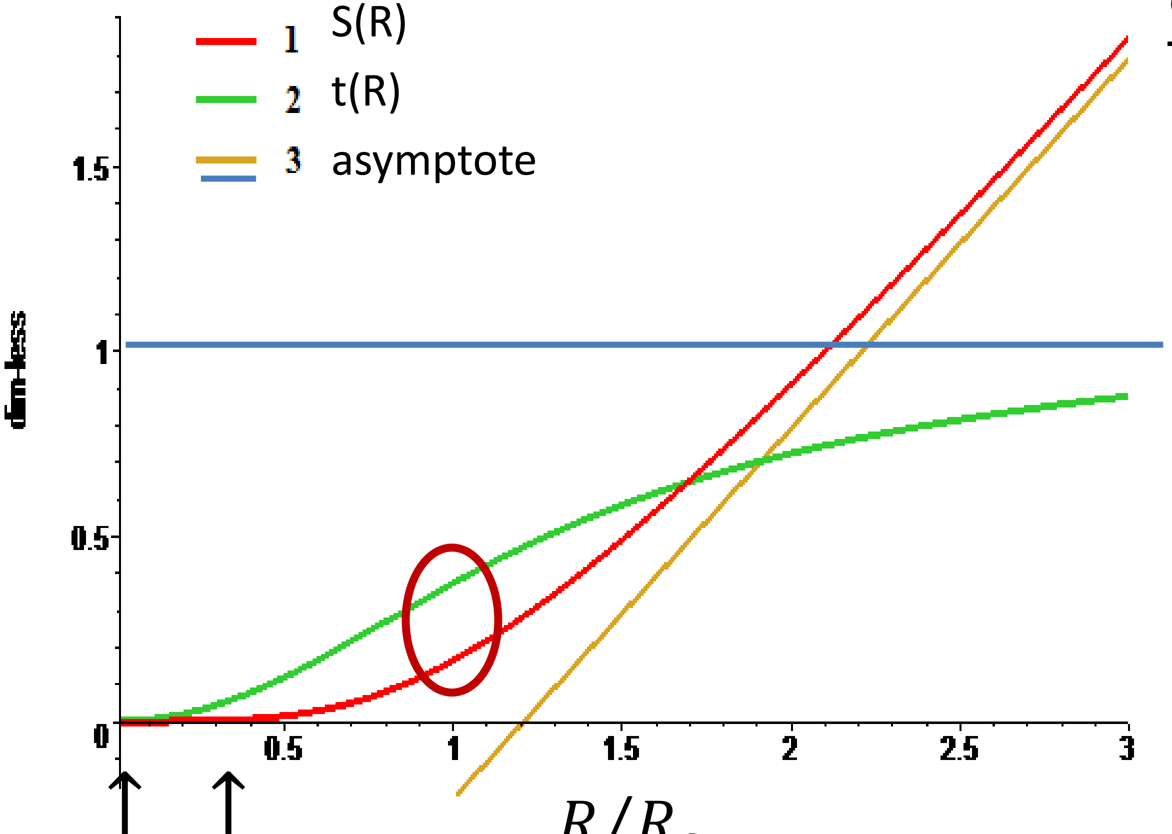
- A1-A relaxation of droplets with time $\tau = (4\pi D n_0 r_s)^{-1}$ $T = (4\pi D N R_s)^{-1}$
- A-B Depositional and/or collectional growth of ice particles from r_s to R_s

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

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

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

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



R/R_c

A B type 1

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

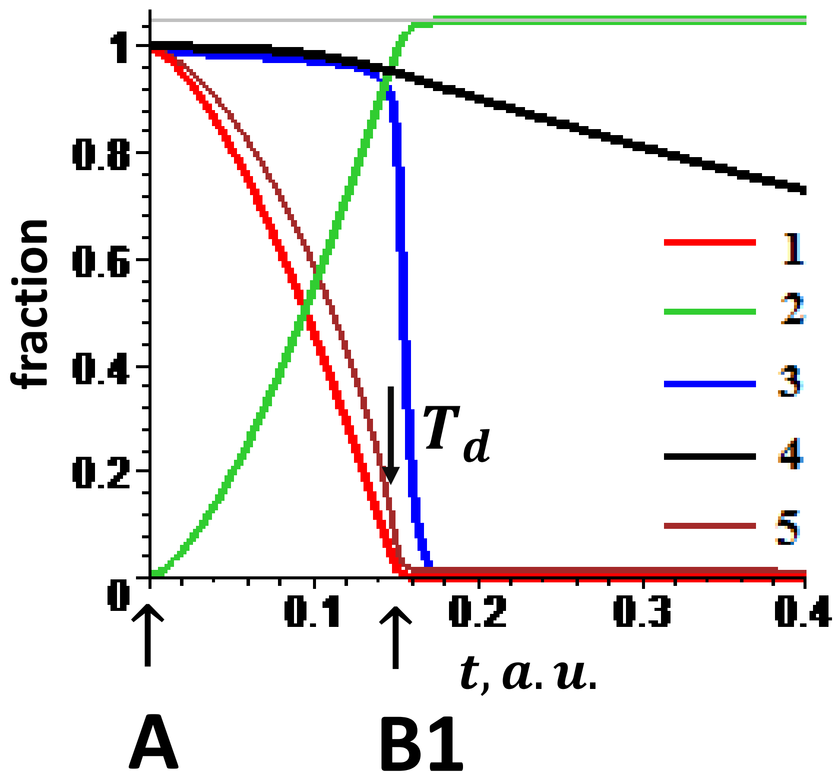
$$\frac{dR}{dS} = \frac{D}{q_i}\frac{\Delta}{\alpha R^3} + \frac{l_s}{4q_i}$$

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

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

Evolution type 1
Predominant depositional growth

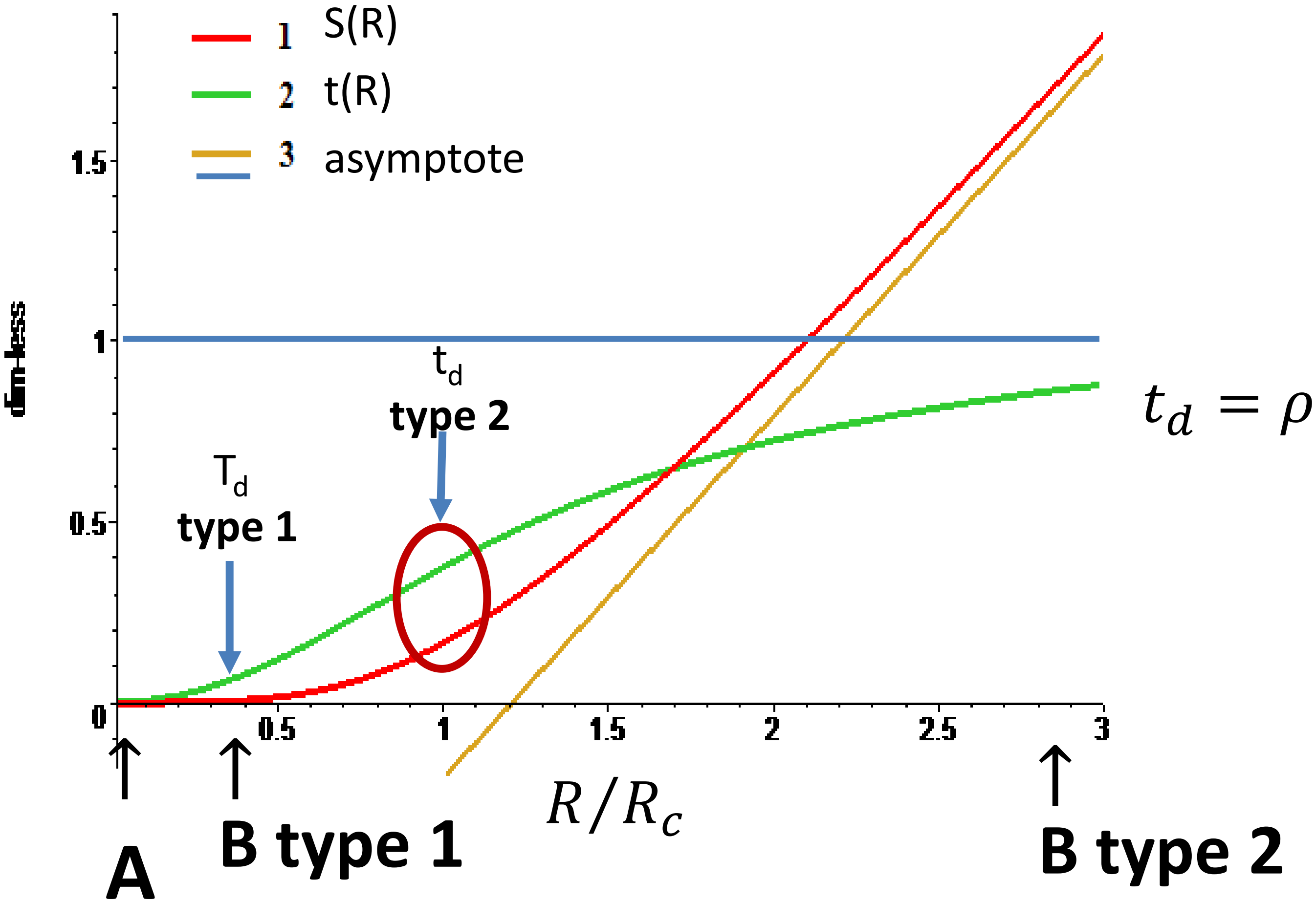
$$T_d = \frac{1}{4\pi D\Delta}\left(\frac{4\pi\rho_i}{3}\right)^{\frac{1}{3}}\left(\frac{l_s}{N}\right)^{\frac{2}{3}}$$



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

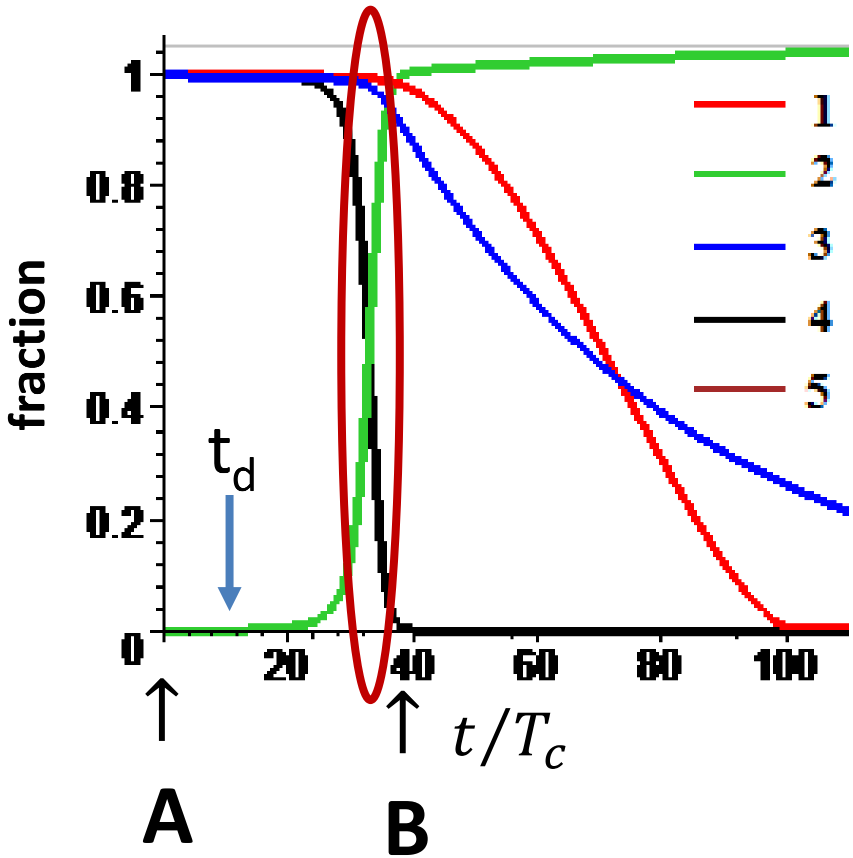
Evolution type 2

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



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

Evolution type 2
Predominant and fast collectional growth



1 *Droplets' volume* $x(t')$

2 *Ice particles' volume* $y(t')$

3 *Relative humidity* $q'(t') = \frac{q - Q_s}{q_s - Q_s}$

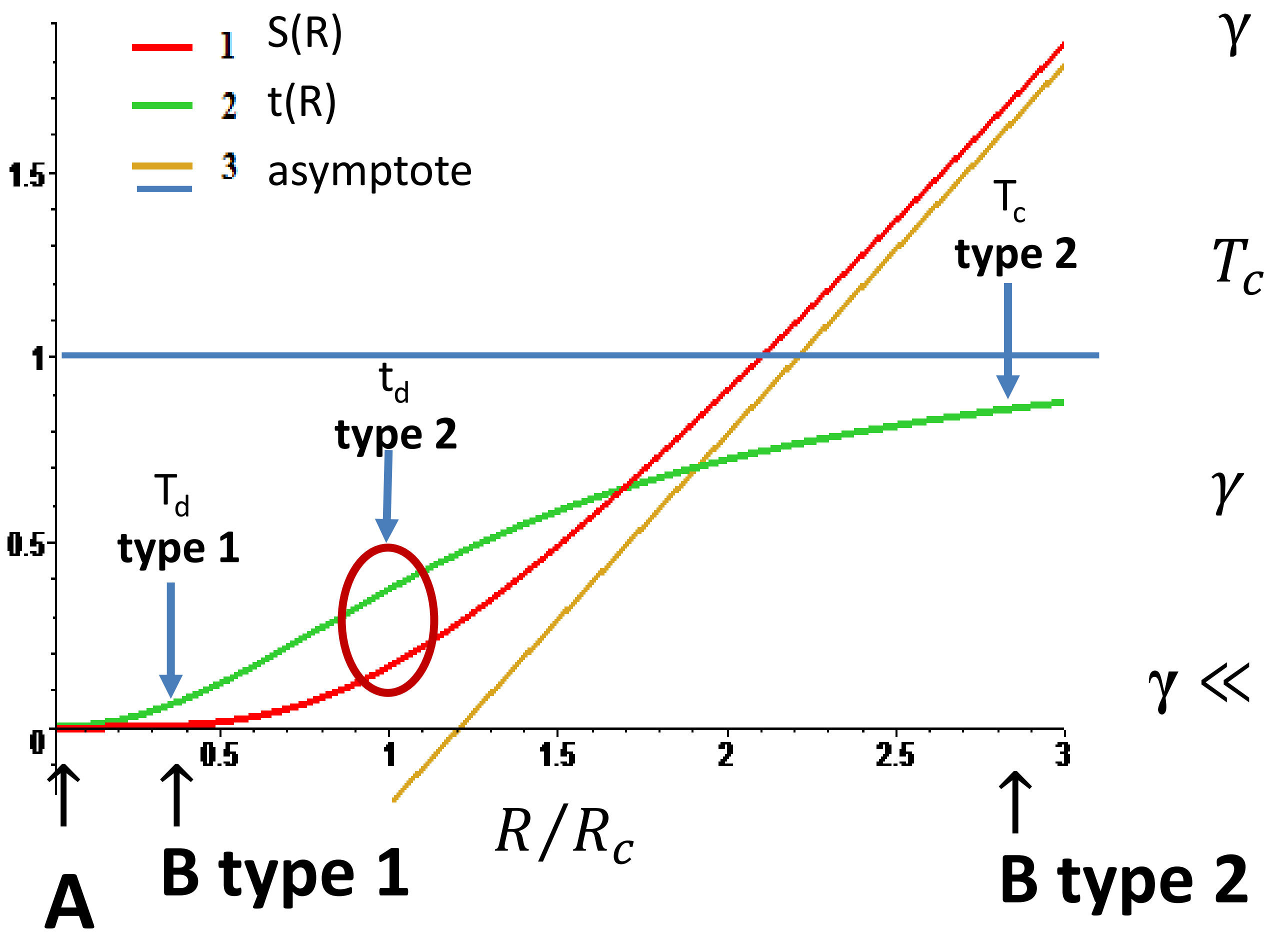
4 *Droplet number concentration* $n(t')$

5 *Visibility in fog* $h(t')$ *relative to it's initial value* h_0

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

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

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



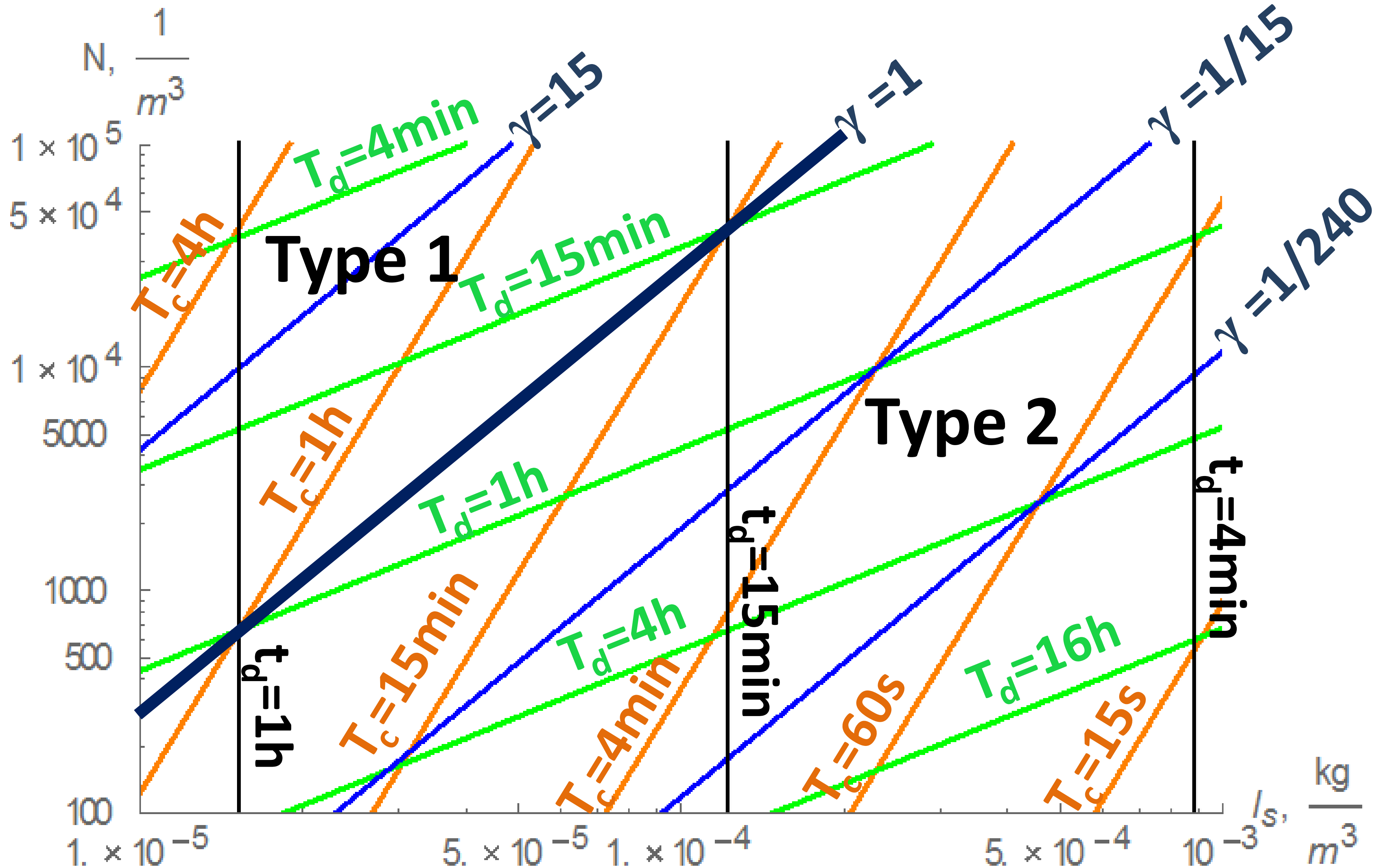
$$\gamma = \frac{T_c}{T_d} = \left(\frac{R_c}{R_s}\right)^3$$

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

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

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

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

- Regardless of the values of all other parameters, the process of growth of ice particles 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 in the considered situations
- The process (in dimensionless variables) depends on a single dimensionless parameter

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

- Ice particles growth can be described by the one differential equation of the first order
- Proposed parameter γ essentially gives quantitative criterion of transition from dominant depositional to intense collectional growth of ice particles
- 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