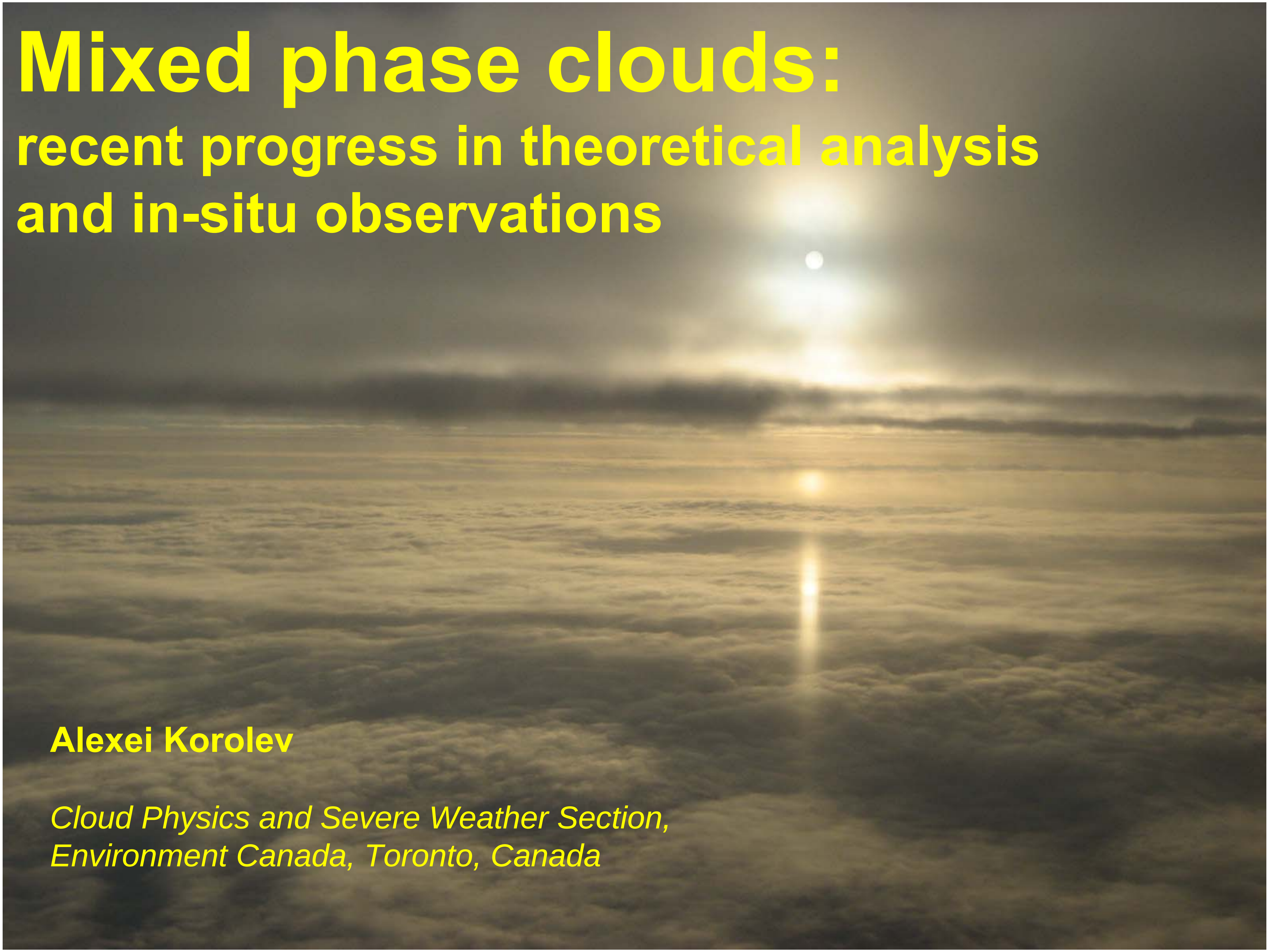

Mixed phase clouds:

recent progress in theoretical analysis and in-situ observations

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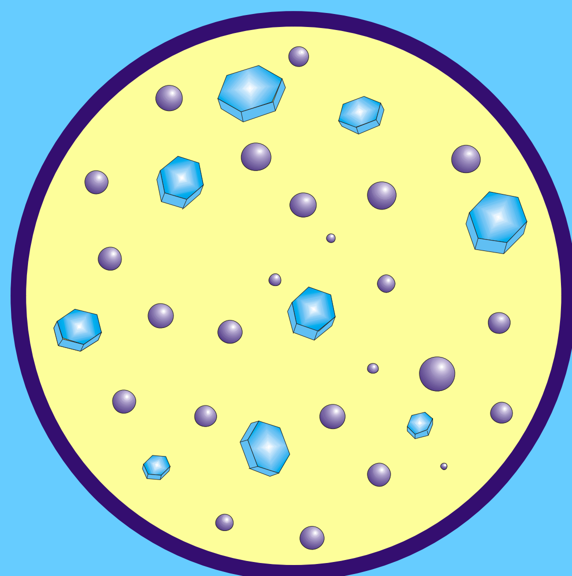
Outline:

1. In-situ observations of mixed phase clouds

2. Theoretical consideration of mixed phase

Cloud droplets may stay in a metastable liquid condition down to approximately –40^{o}C.

A population of cloud particles below 0^{o}C may consist of a mixture of ice particles and liquid droplets.

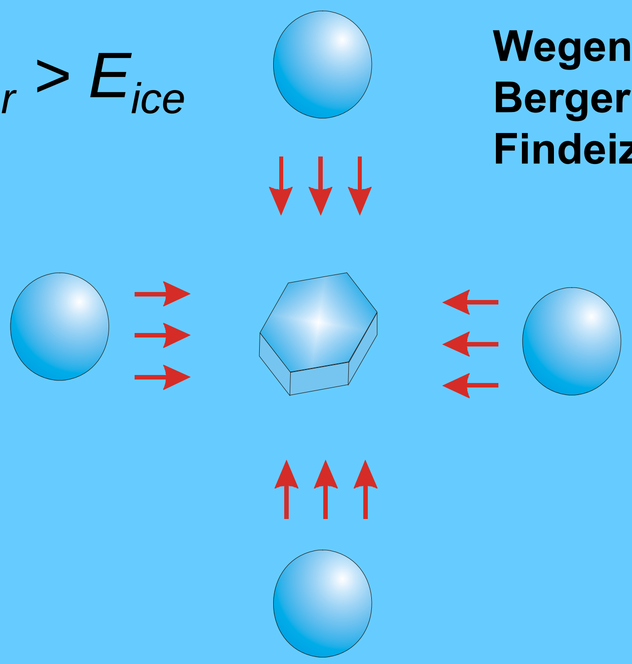


Mixed-phase clouds

$-40<T<0$C

1. **Mixed phase clouds is a three-phase system consisting of water vapour, liquid droplets and ice particles**
2. **Mixed phase clouds are fundamentally unstable**
3. **Important for precipitation formation, radiation budget**
4. **Aviation safety**
5. **Notoriously difficult for simulations in cloud and weather prediction and climate models**

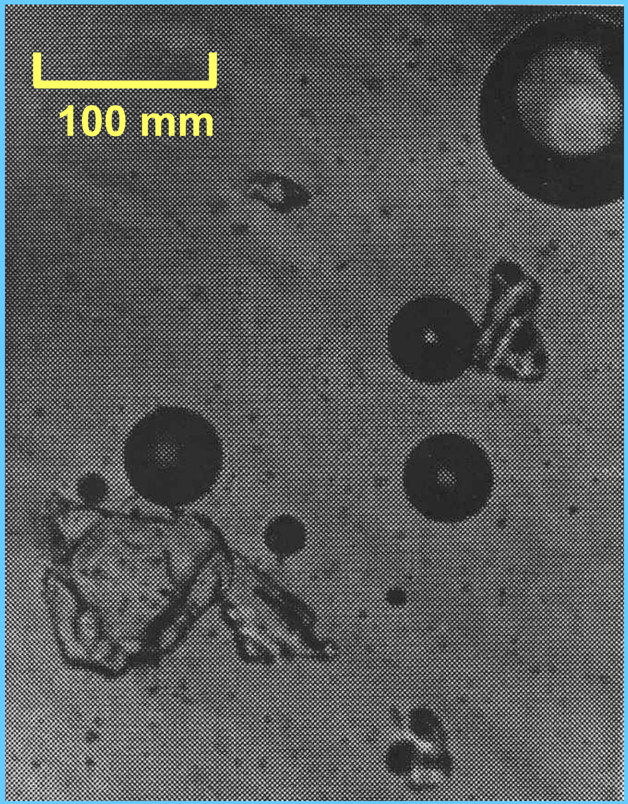
$E_{water} > E_{ice}$



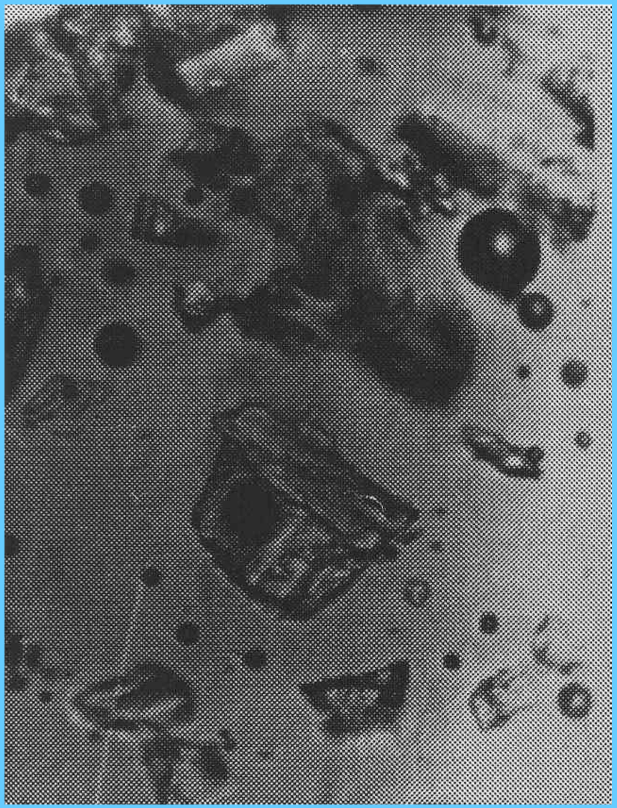
Wegener, 1911
Bergeron, 1935
Findeizen, 1938

Early aircraft observations of mixed phase clouds:

Zak (1937), Peppler (1940), Weickmann (1945)



Ns, H=900m; T=-5C

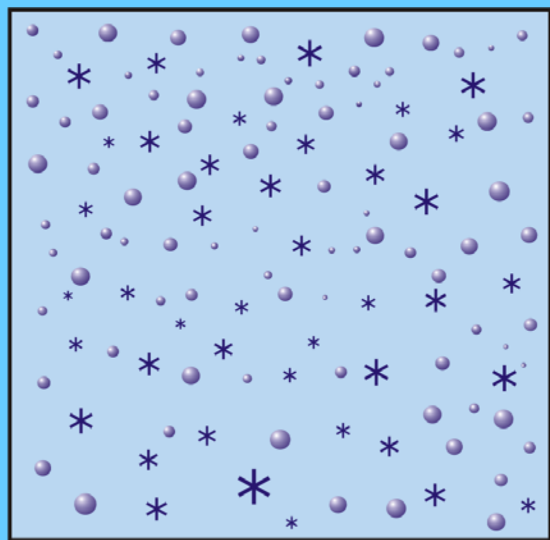


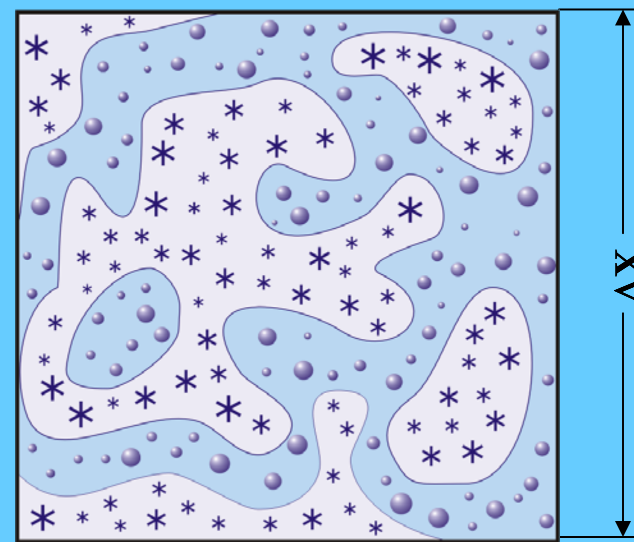
As, H=3060m; T=-19C

As, H=4300m; T=-27C

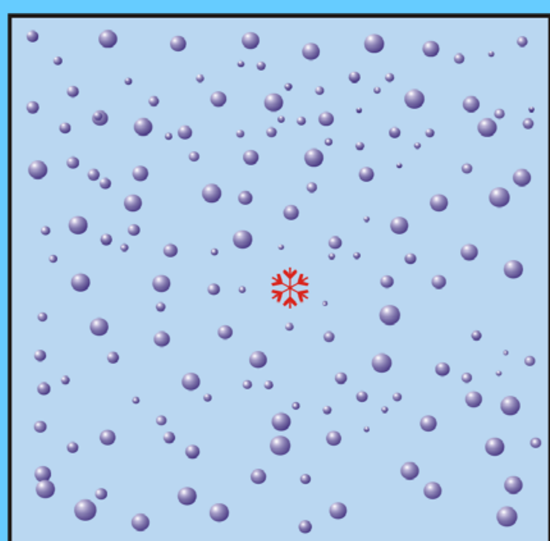
Borovokov, 1951

What is a mixed phase cloud?

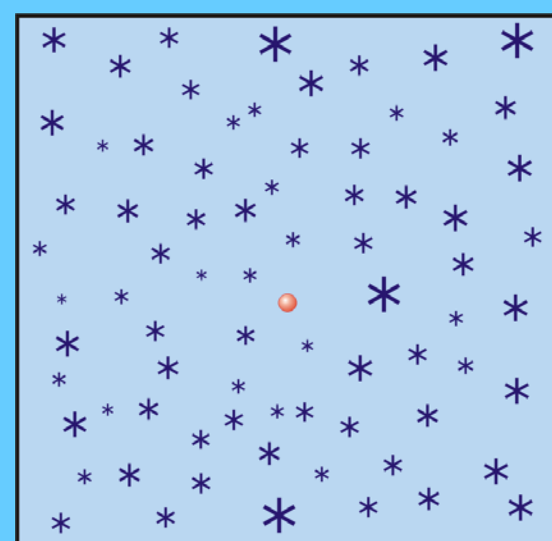




ΔX = 1cm?….10km?



1 ice particle per 10^{100} droplets?



1 droplet per 10^{100} ice particles?

Definition of mixed phase clouds

$$\mu_n = \frac{\sum_j \alpha_{ice\ j} N_{ice\ j} D^n_{ice\ j}}{\sum_j \alpha_{ice\ j} N_{ice\ j} D^n_{ice\ j} + \sum_i \alpha_{liq\ j} N_{liquid\ i} D^n_{liquid\ i}} = \frac{\alpha_{ice} N_{ice} \overline{D^n_{ice}}}{\alpha_{ice} N_{ice} \overline{D^n_{ice}} + \alpha_{liq} N_{liquid} \overline{D^n_{liquid}}}$$

Concentration (0th moment)

$$\mu_0 = \frac{N_{ice}}{N_{ice} + N_{liquid}}$$

Water content (3rd moment)

$$\mu_3 = \frac{W_{ice}}{W_{ice} + W_{liquid}}$$

Extinction coefficient (2nd moment)

$$\mu_2 = \frac{\beta_{ice}}{\beta_{ice} + \beta_{liquid}}$$

Radar reflectivity (6th moment)

$$\mu_6 = \frac{Z_{ice}}{Z_{ice} + Z_{liquid}}$$

range of changes

all liquid $0<\mu<1$ all ice

Korolev, 1998

Definition of ice, liquid and mixed phase clouds in this study

TWC	>0.01g/m^3
Liquid cloud	IWC/TWC=<0.1
Mixed phase	0.1<IWC/TWC<0.9
Ice cloud	IWC/TWC>=0.9
Spatial resolution	100m

Type of clouds ***St, Sc, Ns, As, Ac, Ci*** **associated with frontal systems**

Total cloud length **61,770 km**

Temperature **-40 < T < 0C**

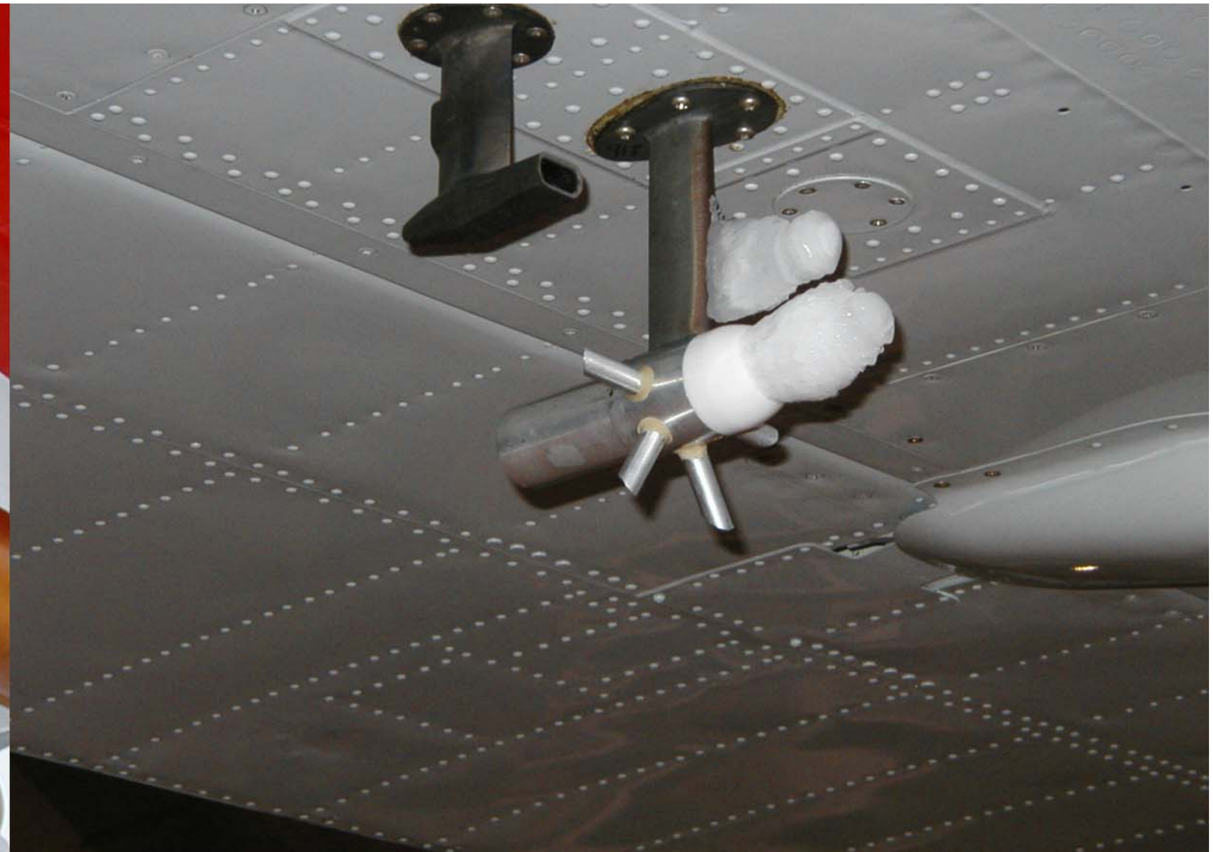
Height **0 < H < 7km**

Projects: **BASE, CFDE1, CFDE3, FIRE.ACE, AIRS1, AIRS1.5, AIRS2**

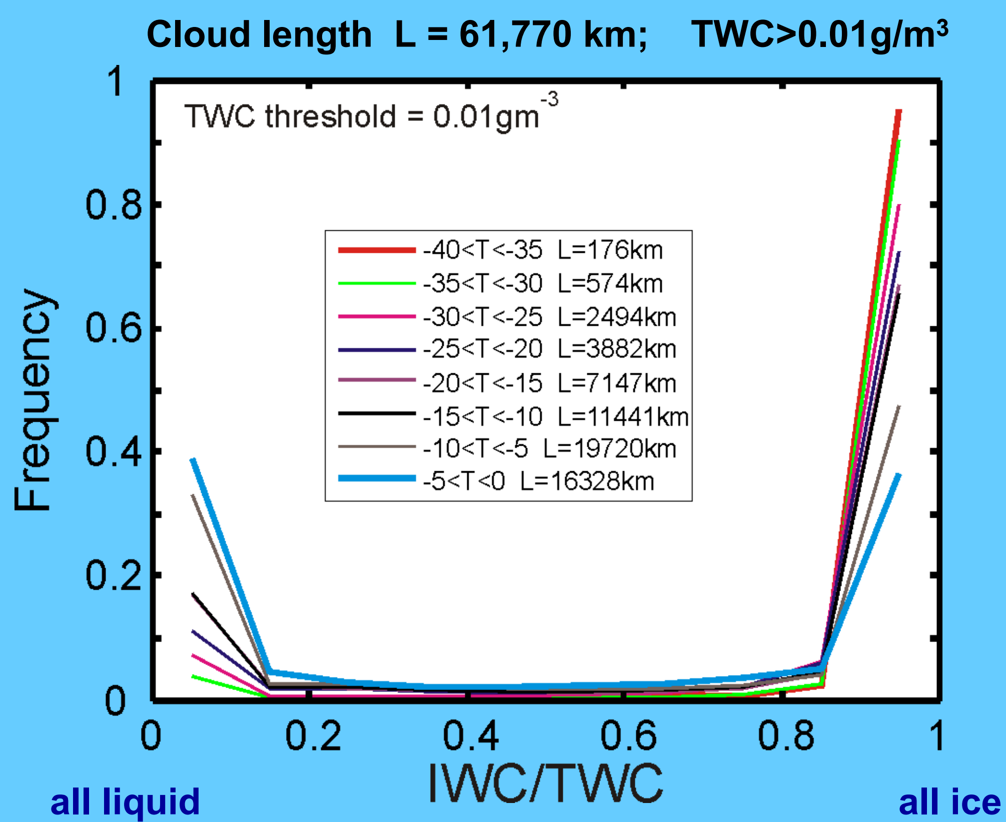
Convair 580
National Research Council of Canada


Nevzorov probe
King probe
FSSP (5-95μm)
CIP (25-1600μm)
FSSP (2-47μm)
Rosemount Icing Detector
OAP-2DP (200-6400μm)
OAP-2DC (25-800μm)
HVPS (200-51200μm)
2DS (10-1280μm)


CNRC



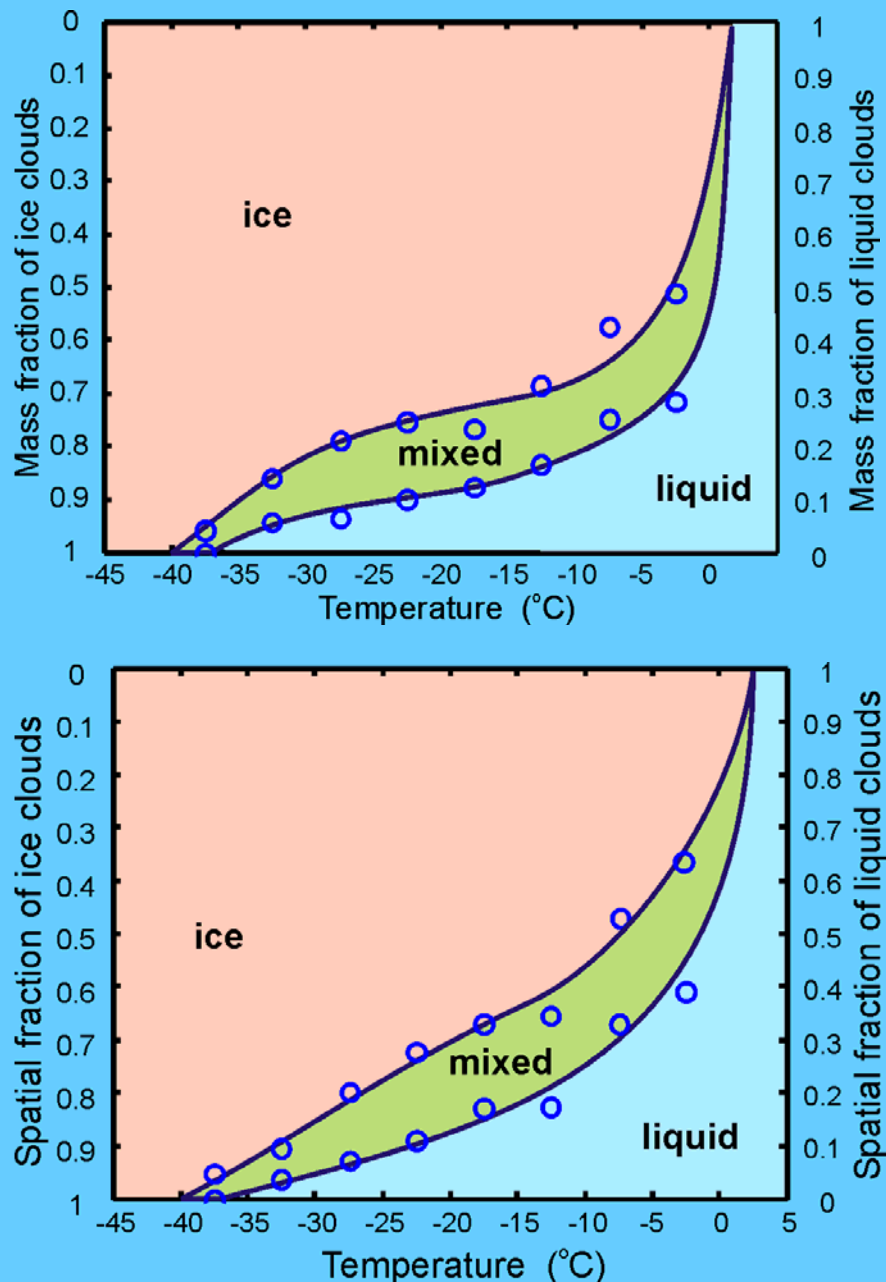
Frequency of occurrence of ice fraction in midlatitude stratiform clouds at ΔL=100m



The probability density function of ice mass fraction in stratiform clouds has U-shape at –35C<T<0C

Korolev et al., 2003, QJRMS

Frequency of occurrence of mixed phase clouds



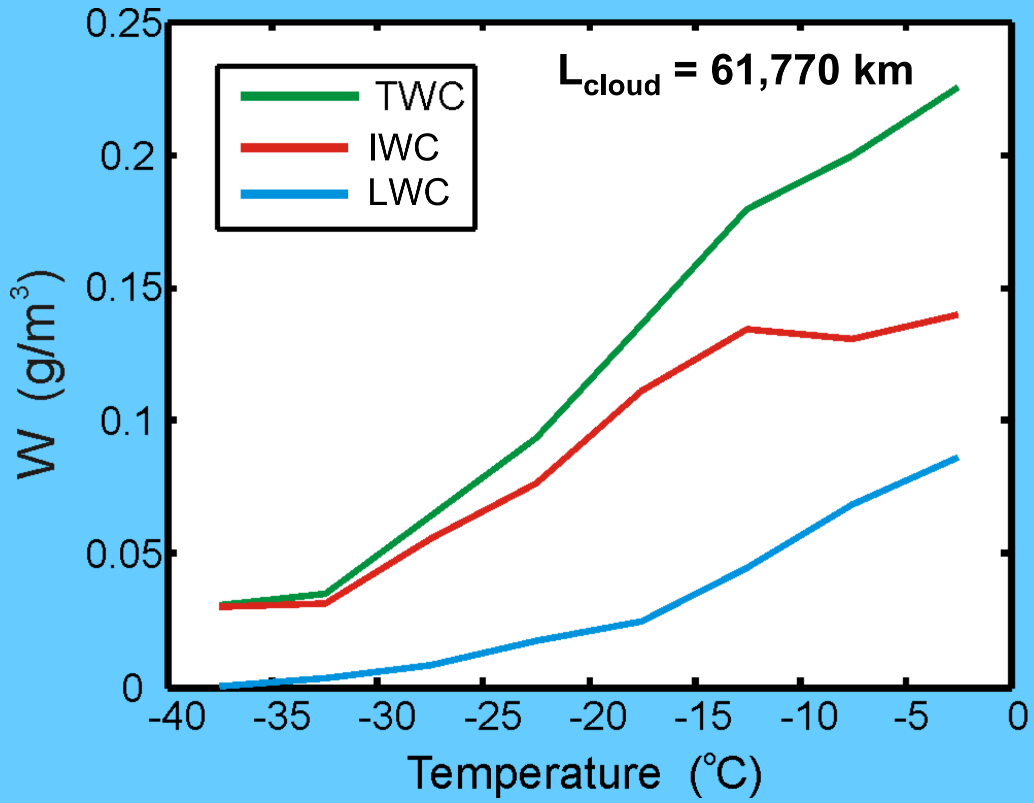
Cloud length L = 61,770 km

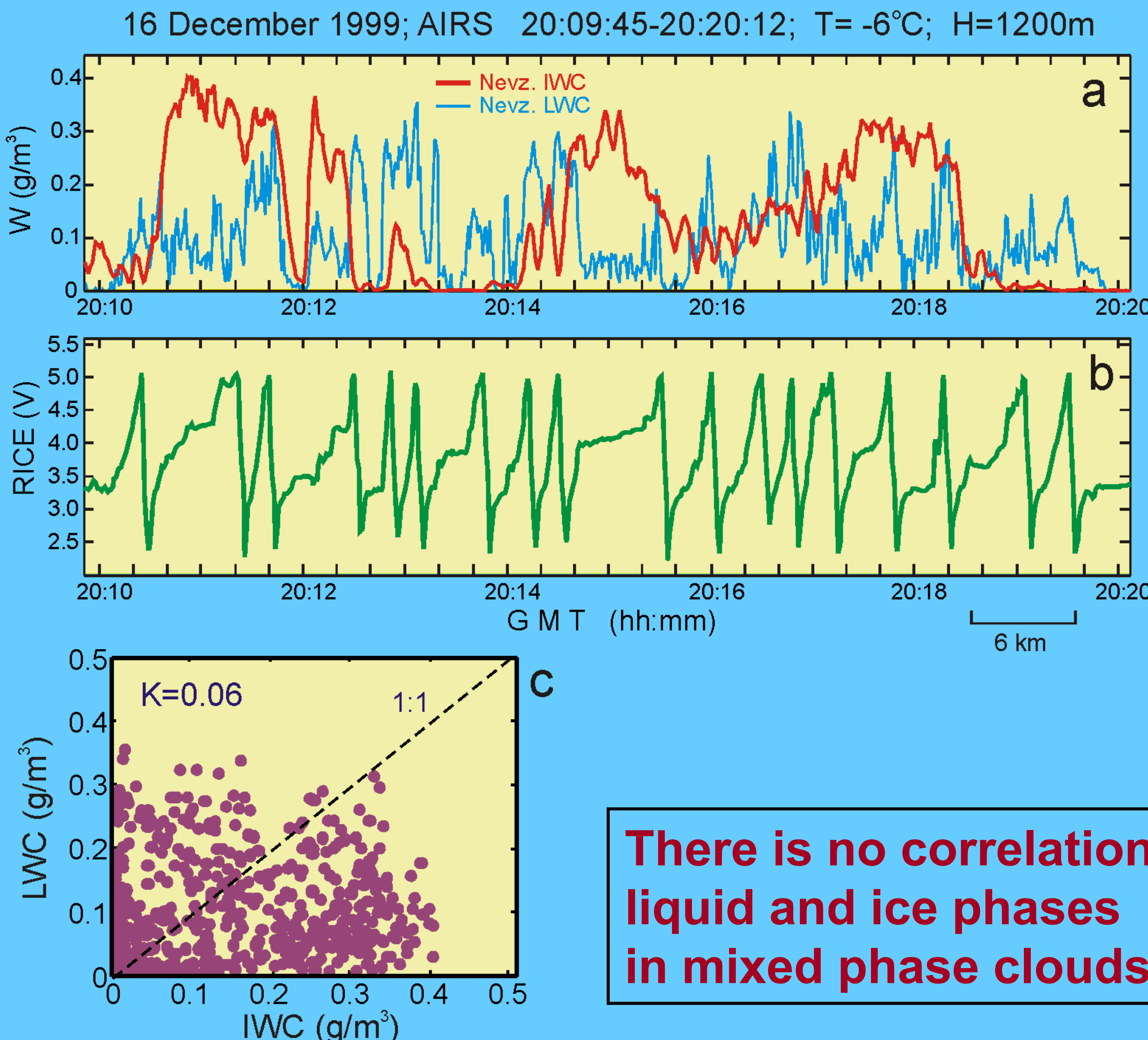
TWC threshold=0.01kg/m^3

Spatial resolution ΔL=100m

Average LWC, IWC, TWC in stratiform midlatitude clouds

(TWC>0.01g/m³)

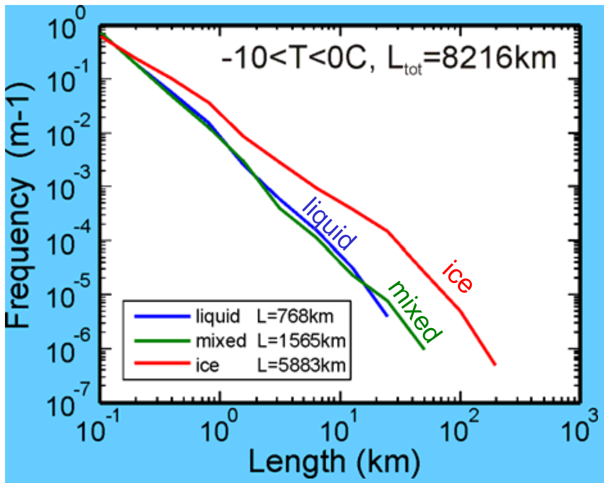


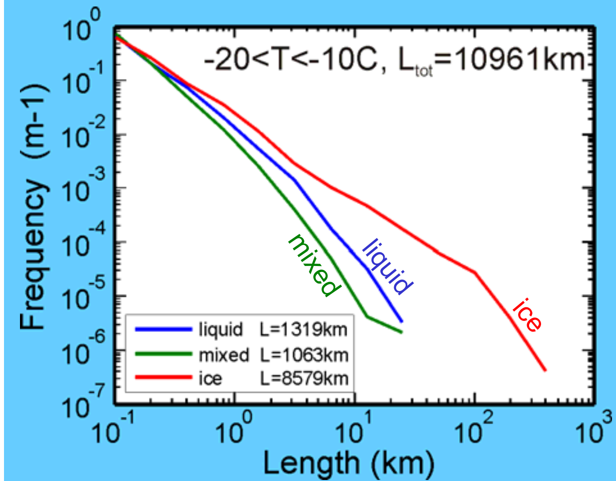


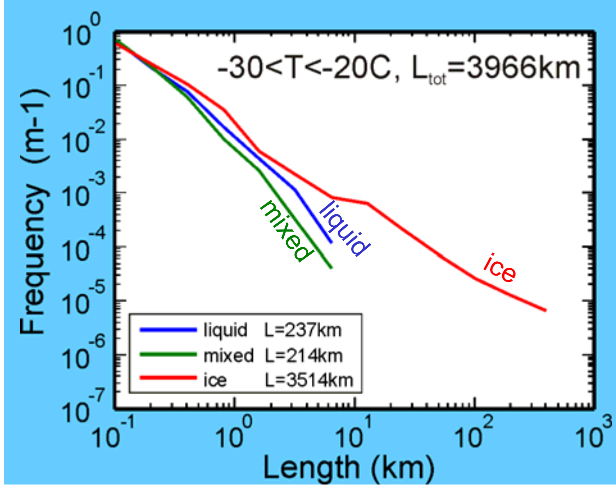
There is no correlation between liquid and ice phases in mixed phase clouds

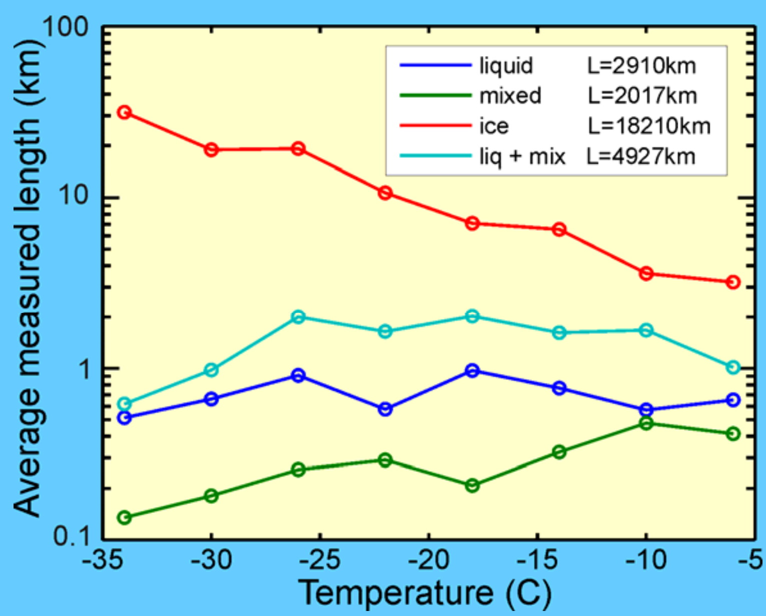
Occurrence of lengths of liquid, mixed phase and ice cloud zones

TWC threshold=0.01kg/m³   Spatial resolution ΔL=100m







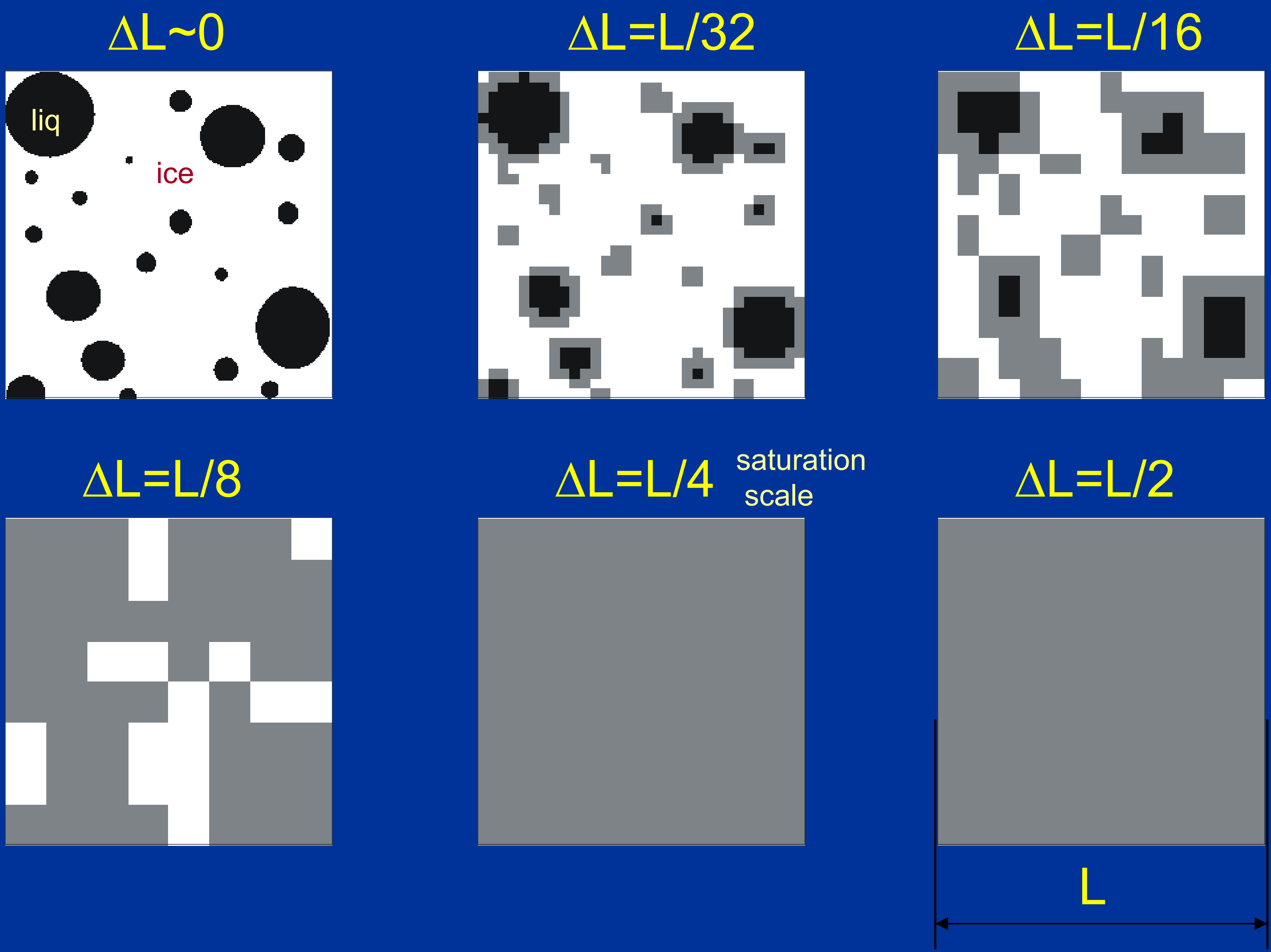


The average length of continuous liquid zones stays constant with temperature : L_w~500m

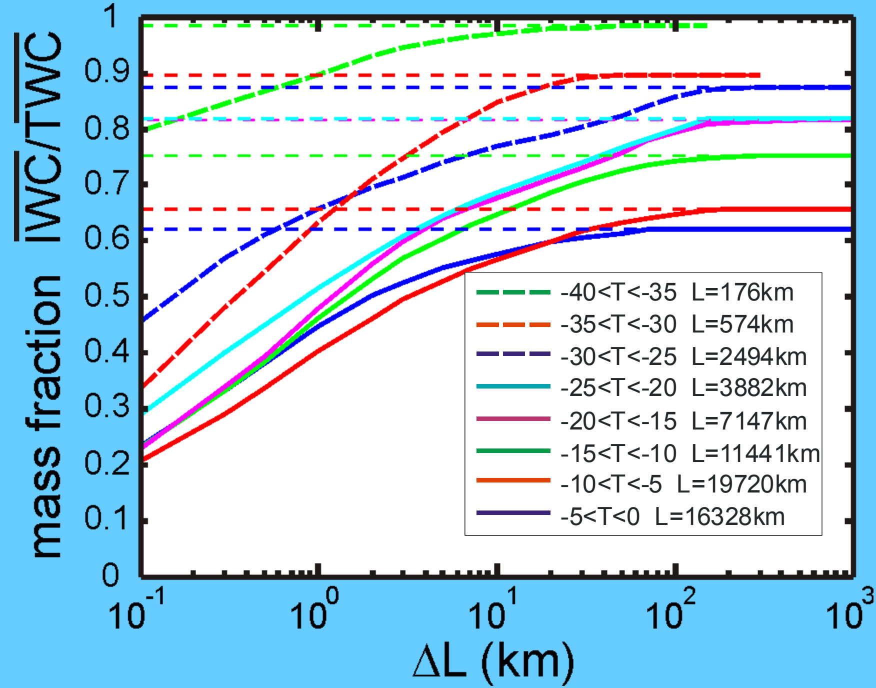
The continuous length of mixed phase zones decreases with decrease of T: 100m< L_m<500m

The continuous length of ice zones increases with the decrease of T : 4km<L_i<40km

Effect of averaging on the mixed phase measurements

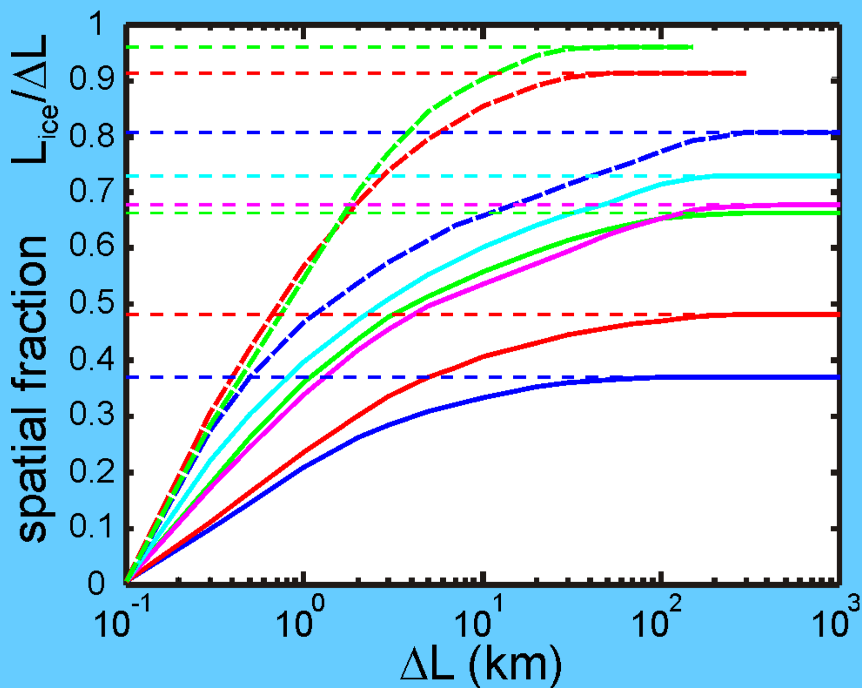


Spatial and mass fractions of ice in liquid containing clouds at different averaging scales *ΔL*



Cloud length L = 61,770 km
TWC threshold=0.01kg/m^3

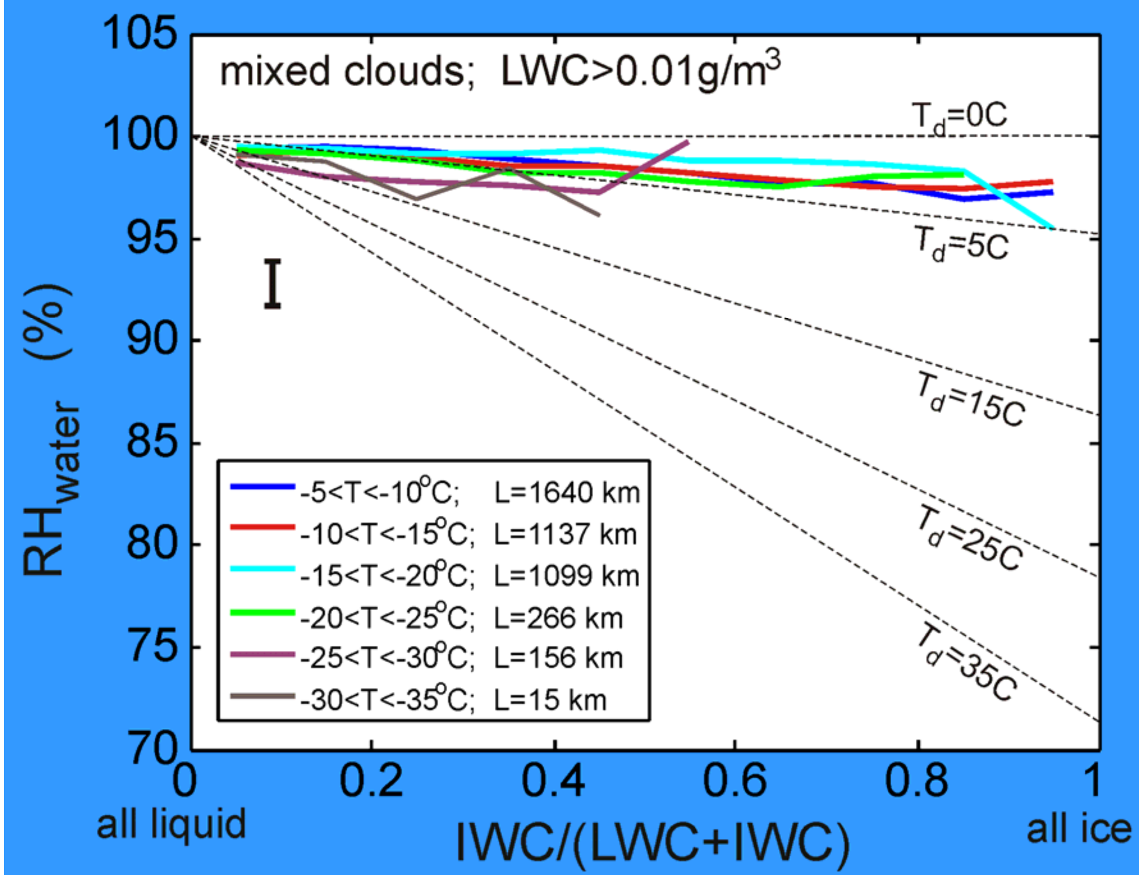
Saturation spatial scale
ΔL_S~70÷200km



Cold clouds (-40<T<0C)
at the averaging scale L >ΔL_S
are always mixed phase

Relative Humidity in Mixed Clouds

(averaging scale 100m)



$$RH = \frac{RH_w m_w + RH_i m_i}{m_w + m_i}$$

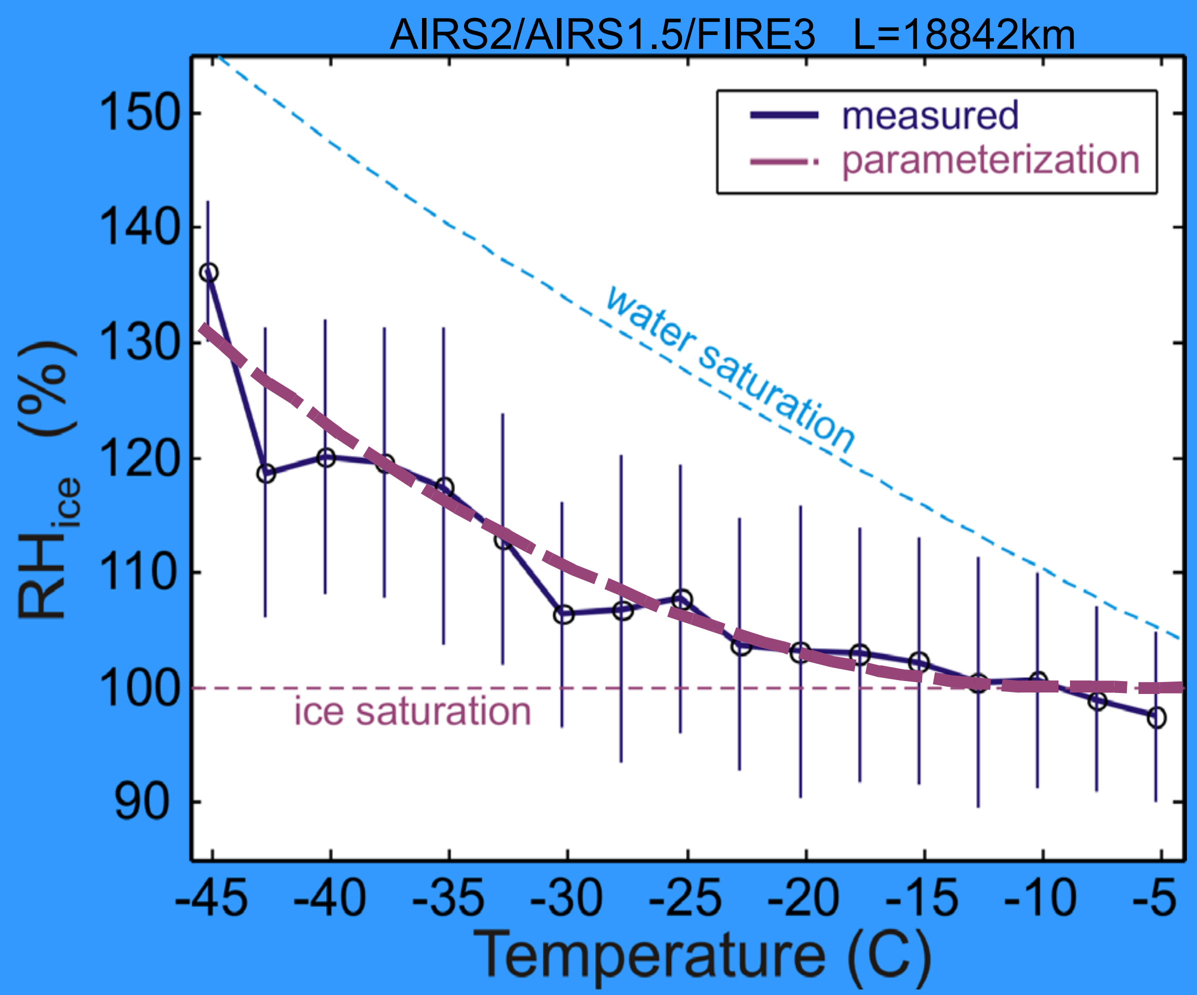
parameterization of RH in mixed clouds used in cloud and mesoscale simulations

Here m_w and m_i are the masses of liquid and ice

Relative humidity in mixed phase clouds is close to saturation over water at all *T* and μ.

Korolev and Isaac, 2006, JAS

Relative Humidity in Ice Clouds (Δx=100m)



$$RH_{ice} = 0.0191T^2 + 0.2093T + 99$$

Korolev and Isaac, 2006, JAS

Theoretical considerations

1. Theoretical framework
2. Characteristic time scales of the phase transformation
3. Humidity in mixed phase clouds
4. Glaciation of mixed phase clouds
5. Conditions for maintenance of mixed phase

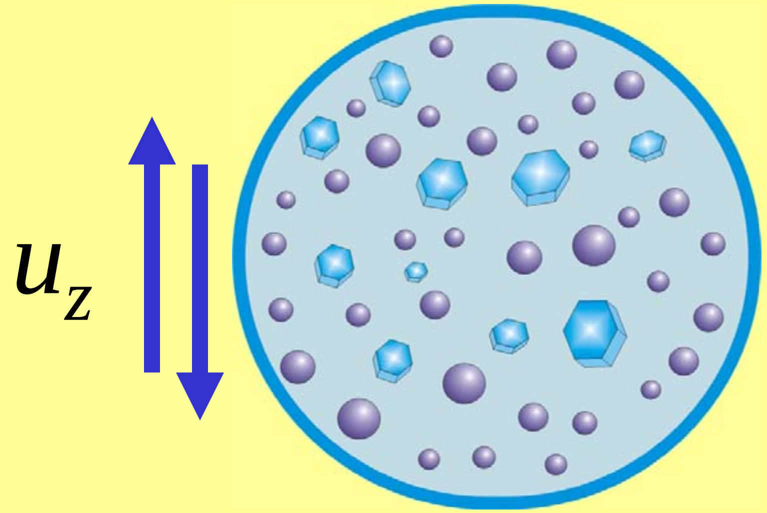
Basic assumptions:

1. adiabatic parcel
2. ice particles and droplets are uniformly mixed
3. ice concentration $N_{ice}(t) = const$
4. droplet concentration $N_{droplets}(t) = const$
5. temperature $T(x,y,z)=const$
6. water vapor $E(x,y,z)=const$

$\tau_{turb} << \tau_{diff}$; $K_{turb} >> K_{diff}$ =>

=> regular condensation

Mixed-phase cloud parcel



Equation for supersaturation in mixed phase cloud

$$S_w = \frac{e - E_w}{E_w}$$ supersaturation over liquid water (definition)

$$\frac{dS_w}{dt} = \frac{1}{E_w}\frac{de}{dt} - \frac{e}{E_w^2}\frac{dE_w}{dt} \quad \Rightarrow$$

$$\frac{1}{S_w+1}\frac{dS_w}{dt} = a_0 u_z - a_2 N_i \sqrt{r_{i0}^2 + 2cA_i \int_0^t \left(\xi S_w(t') + \xi - 1\right) dt'} -$$
$$- \left(a_1 B_w N_w \sqrt{r_{w0}^2 + 2A_w \int_0^t S_w(t') dt'} + a_2 B_i N_i \sqrt{r_{i0}^2 + 2cA_i \int_0^t \left(\xi S_w(t') + \xi - 1\right) dt'} \right) S_w$$

E_w saturation vapor pressure over water
r_w, r_i radii of droplets and ice particles
N_w, N_i concentration of droplets and ice particles
u_z vertical velocity
a, b, B coefficients dependent on P, T

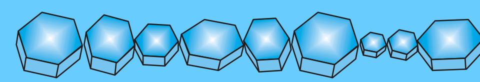
Features:
1. Single variable equation
2. No analytical solution
3. Easy to integrate into numerical models
4. Gives accurate solution for -1km<ΔZ<1km

Korolev and Mazin, 2003, JAS

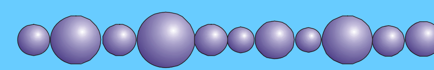
Equation for supersaturation in mixed phase cloud

$$\frac{1}{S_w+1}\frac{dS_w}{dt} = a_0 u_z - a_2 B_i^* N_i \bar{r}_i - \left(a_1 B_w N_w \bar{r}_w + a_2 B_i N_i \bar{r}_i\right) S_w$$

Equation for supersaturation in mixed-phase clouds (Korolev and Mazin, 2003, JAS)



$N_i \bar{r}_i$



$N_w \bar{r}_w$

$$\bar{r}_i = const$$
$$\bar{r}_w = const$$

quasi-steady approximation

$N_i \bar{r}_i$ integral radius of ice particles

$N_w \bar{r}_w$ integral radius of droplets

u_z vertical velocity

a, b, B coefficients dependent of P, T

$$S_w = \frac{S_{qs\ w} - C_0 \exp(-t/\tau_p)}{1 + C_0 \exp(-t/\tau_p)}$$

$$S_{qs\ w} = \frac{a_0 u_z - b_i^* N_i \bar{r}_i}{b_w N_w \bar{r}_w + b_i N_i \bar{r}_i}$$

quasi-steady supersaturation

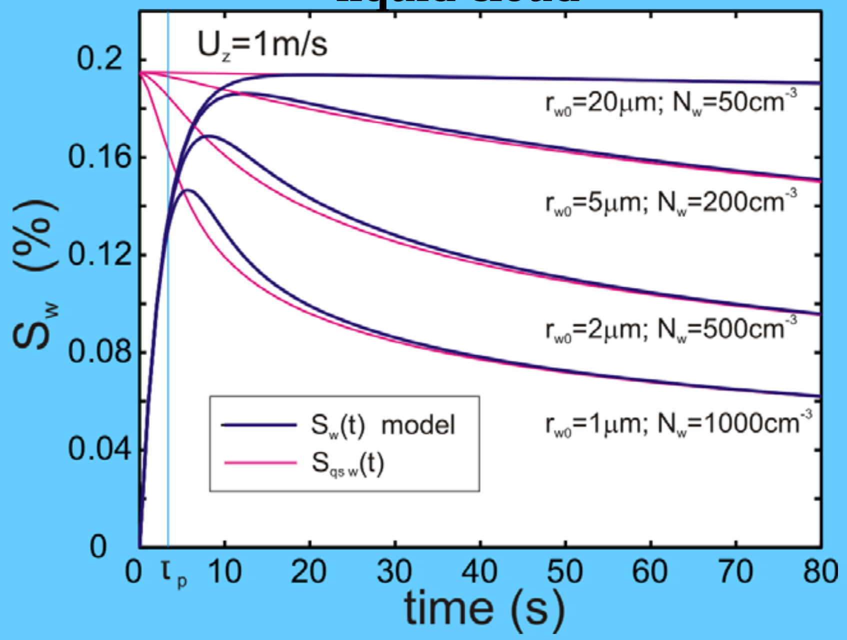
$$\tau_p = \frac{1}{a_0 u_z + b_w N_w \bar{r}_w + (b_i + b_i^*) N_i \bar{r}_i}$$

time of phase relaxation

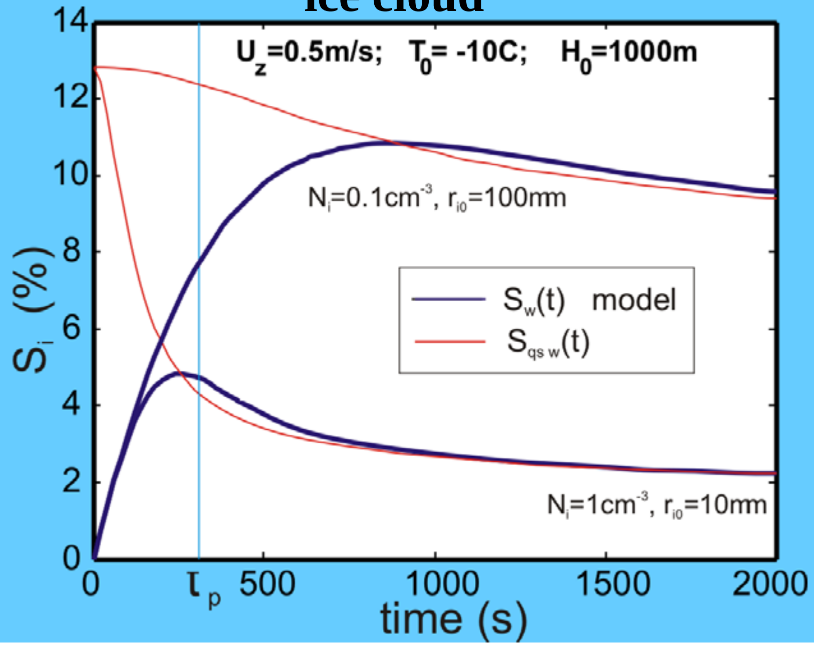
Korolev and Mazin, 2003, JAS

Asymptotic behavior of S_{qs}

liquid cloud



ice cloud



$$\lim_{t\to\infty} S_{qs}(t) = S(t)$$

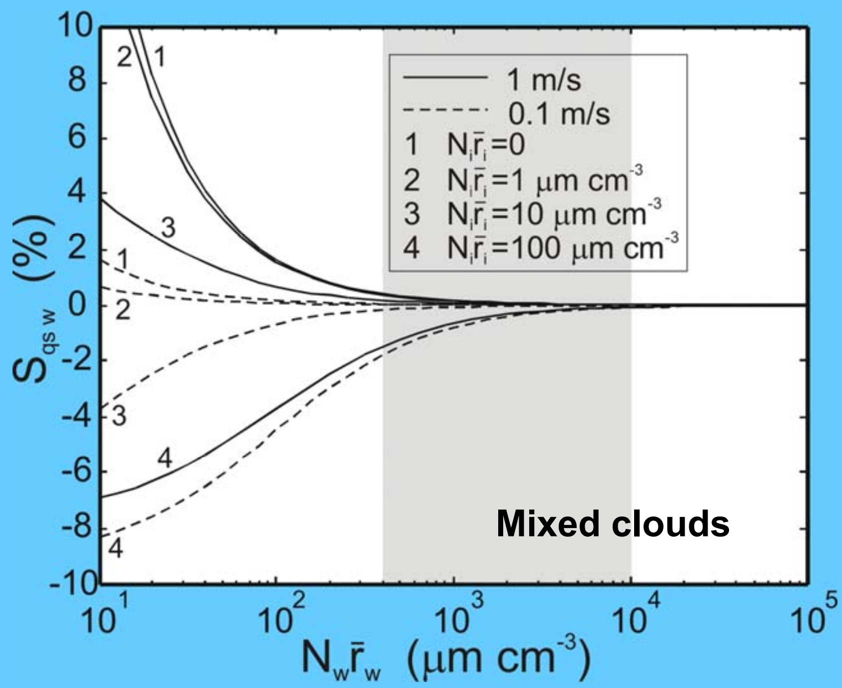
$$S_{qs\ w} = \frac{a_0 u_z - b_i^* N_i \bar{r}_i}{b_w N_w \bar{r}_w + b_i N_i \bar{r}_i}$$

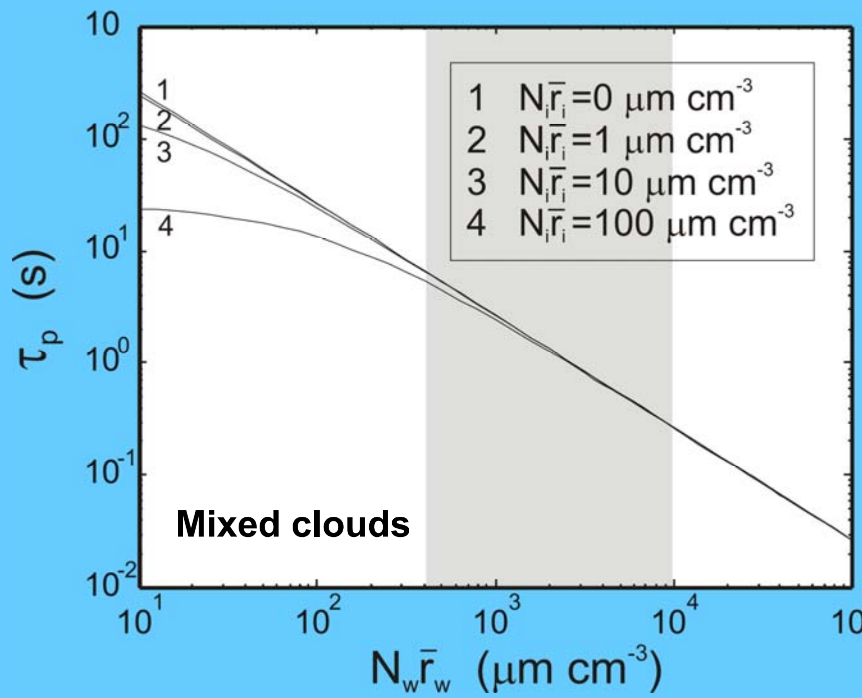
$$\tau_p = \frac{1}{a_0 u_z + b_w N_w \bar{r}_w + (b_i + b_i^*) N_i \bar{r}_i}$$

Supersaturation and time of phase relaxation in mixed phase clouds

$$S_{qs\ w} = \frac{a_0 u_z - b_i^* N_i \bar{r}_i}{b_w N_w \bar{r}_w + b_i N_i \bar{r}_i}$$

$$\tau_p = \frac{1}{a_0 u_z + b_w N_w \bar{r}_w + (b_i + b_i^*) N_i \bar{r}_i}$$





RH_w~100%

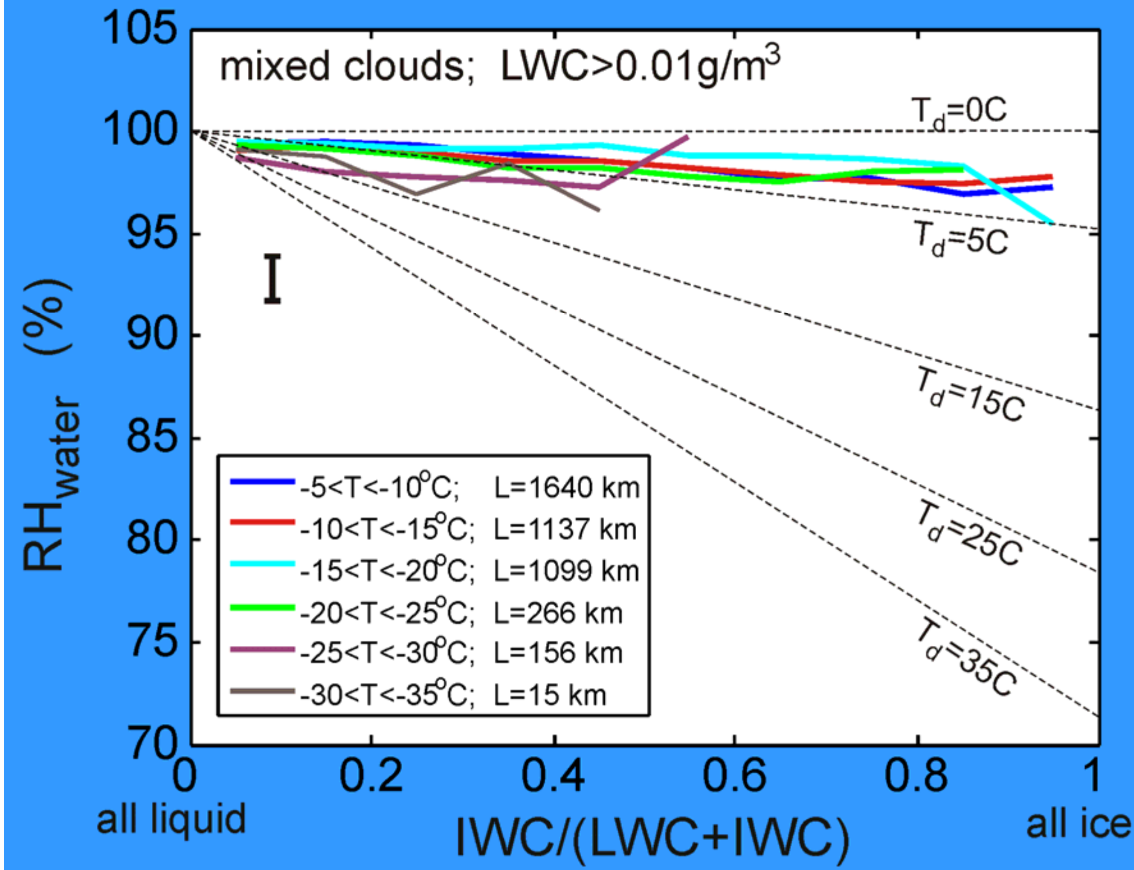
τ_p~10^0s

- RH in mixed phase clouds is close to saturation over water.
- Time of phase relaxation is of the order of seconds.

Korolev and Mazin, 2003, JAS

Relative Humidity in Mixed Clouds

(averaging scale 100m)



$$RH = \frac{RH_w m_w + RH_i m_i}{m_w + m_i}$$

parameterization of RH in mixed clouds used in cloud and mesoscale simulations

Here m_w and m_i are the masses of liquid and ice

Relative humidity in mixed phase clouds is close to saturation over water at all *T* and μ.

Korolev and Isaac, 2006, JAS

Rates of phase transformation in mixed-phase clouds

liquid droplets

$$\frac{dq_w}{dt} = B_w S_w N_w \bar{r}_w \quad \Rightarrow \quad \dot{q}_w = \frac{\left(a_0 u_z - b_i^* N_i \bar{r}_i\right) B_w N_w \bar{r}_w}{b_w N_w \bar{r}_w + b_i N_i \bar{r}_i}$$

ice particles

$$\frac{dq_i}{dt} = B_{i0} S_i N_i \overline{r_i c} \quad \Rightarrow \quad \dot{q}_i = \frac{\left(a_0 u_z - \dfrac{1-\xi}{\xi} b_w N_w \bar{r}_w\right) B_i N_i \bar{r}_i}{b_w N_w \bar{r}_w + b_i N_i \bar{r}_i}$$

water vapor

$$\frac{dq_v}{dt} = -\frac{dq_w}{dt} - \frac{dq_i}{dt} \quad \Rightarrow \quad \dot{q}_v = \frac{B_w B_i^* \left(a_1 - a_2\right) N_w \bar{r}_w N_i \bar{r}_i - a_0 u_z \left(B_w N_w \bar{r}_w + B_i N_i \bar{r}_i\right)}{b_w N_w \bar{r}_w + b_i N_i \bar{r}_i}$$

$$S_i = \xi S_w + \xi - 1$$

$$S_{qsw} = \frac{a_0 u_z - b_i^* N_i \bar{r}_i}{b_w N_w \bar{r}_w + b_i N_i \bar{r}_i}$$

q_w mixing ratio of liquid

q_i mixing ratio of ice

q_v mixing ratio of water vapor

Three equilibrium points of phase transformation in mixed-phase clouds

Liquid water equilibrium: $\dot{q}_w = 0$

$$\dot{q}_w = \frac{\left(a_0 u_z - b_i^* N_i \bar{r}_i\right) B_w N_w \bar{r}_w}{b_w N_w \bar{r}_w + b_i N_i \bar{r}_i} \Rightarrow$$

threshold velocity for liquid water equilibrium

$$u_z^* = \frac{E_w - E_i}{E_i} \eta N_i \bar{r}_i$$

$$10^{-2} < u_z^* < 10^0 \, m/s$$

Ice equilibrium: $\dot{q}_i = 0$

$$\dot{q}_i = \frac{\left(a_0 u_z - \frac{1-\xi}{\xi} b_w N_w \bar{r}_w\right) B_i N_i \bar{r}_i}{b_w N_w \bar{r}_w + b_i N_i \bar{r}_i} \Rightarrow$$

threshold velocity for ice equilibrium

$$u_z^o = \frac{E_i - E_w}{E_w} \chi N_w \bar{r}_w$$

$$-10^3 < u_z^o < -10^0 \, m/s$$

Water vapor equilibrium: $\dot{q}_v = 0$

$$\dot{q}_v = \frac{B_w B_i^* (a_1 - a_2) N_w \bar{r}_w N_i \bar{r}_i - a_0 u_z \left(B_w N_w \bar{r}_w + B_i N_i \bar{r}_i\right)}{b_w N_w \bar{r}_w + b_i N_i \bar{r}_i} \Rightarrow$$

threshold velocity for water vapor equilibrium

$$u_z^+ = \frac{(\xi - 1)\left(B_w b_i - b_w B_i\right) N_w \bar{r}_w N_i \bar{r}_i}{a_0 \xi \left(B_w N_w \bar{r}_w + B_i N_i \bar{r}_i\right)}$$

$$10^{-4} < u_z^+ < 10^{-2} \, m/s \sim 0 \, m/s$$

Wegener, 1911: *Thermodynamik der Atmosphäre*

"***<u>The vapour tension will adjust itself to a value in between the saturation values over ice and over water</u>.*** *The effect of this must then be, that condensation continuously will take place on the ice, whereas at the same time liquid water evaporates, and this process must go on until the liquid phase is entirely consumed*"

$$E_i < e < E_w$$
$$\dot{q}_w < 0$$
$$\dot{q}_i > 0$$

The Glossary of Meteorology (2000)

"Bergeron-Findeisen process":

"…*The basis of this theory is in fact that the equilibrium water vapour pressure with respect to ice is less than that with respect to liquid at the same subfreezing temperature. Thus within an admixture of these (ice and liquid) particles, and provided that the total water content were sufficiently high,* ***<u>the ice crystals would gain mass by vapour deposition at the expense of the liquid drops that would lose their mass by evaporation</u>***".

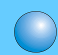
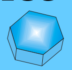
Four scenarios of mixed phase evolution

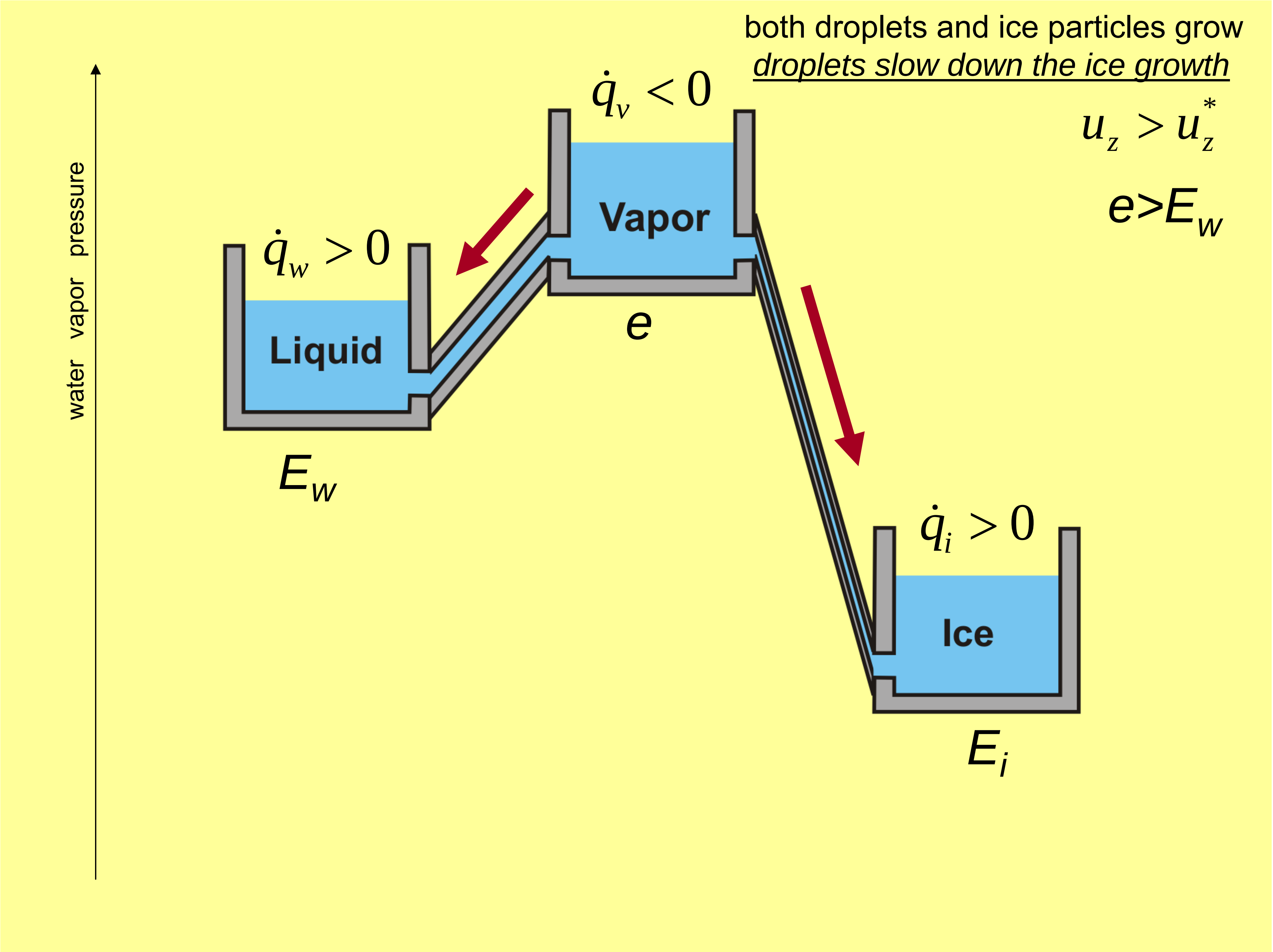
$$u_z^o < u_z^+ < u_z^*$$

ice vapor liquid

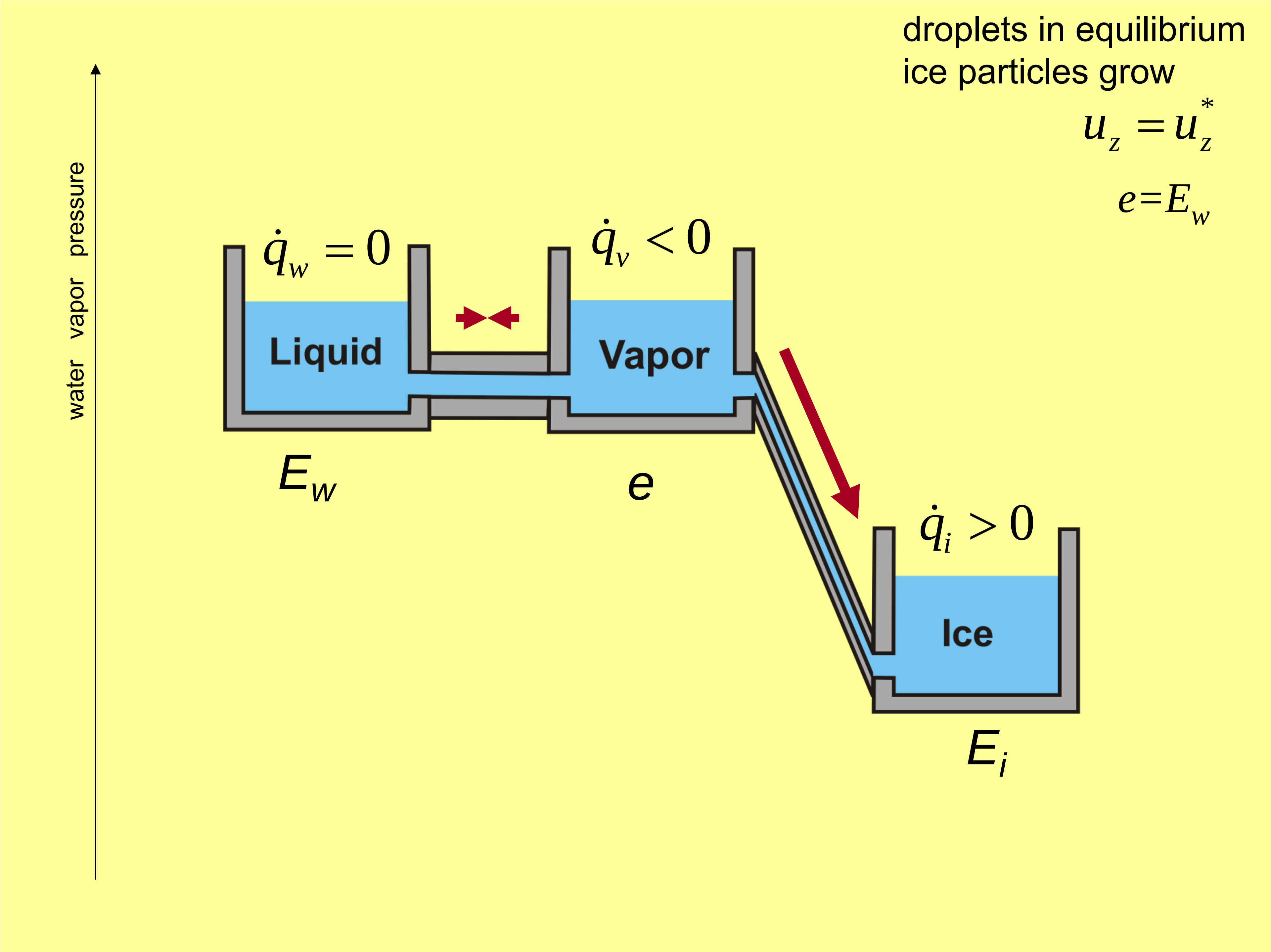
always true
for any $N_i r_i$, $N_w r_w$

$\Rightarrow$ **four possible inequalities for u_z**

u_z	e	**liquid** 	**vapour**	**ice** 	
$u_z < u_z^o$	$e<E_i$	evaporate	increase	evaporate	**not WBF**
$u_z^o < u_z < u_z^+$	$E_i<e<E_v$	evaporate	increase	grow	**WBF**
$u_z^+ < u_z < u_z^*$	$E_v<e<E_w$	evaporate	decrease	grow	**WBF**
$u_z > u_z^*$	$e>E_w$	grow	decrease	grow	**not WBF**



both droplets and ice particles grow
droplets slow down the ice growth
$\dot{q}_v < 0$
$u_z > u_z^*$
$e > E_w$
Vapor
e
$\dot{q}_w > 0$
Liquid
E_w
$\dot{q}_i > 0$
Ice
E_i
water vapor pressure


droplets in equilibrium
ice particles grow
$u_z = u_z^*$
$e = E_w$
water vapor pressure
$\dot{q}_w = 0$
Liquid
E_w
$\dot{q}_v < 0$
Vapor
e
$\dot{q}_i > 0$
Ice
E_i

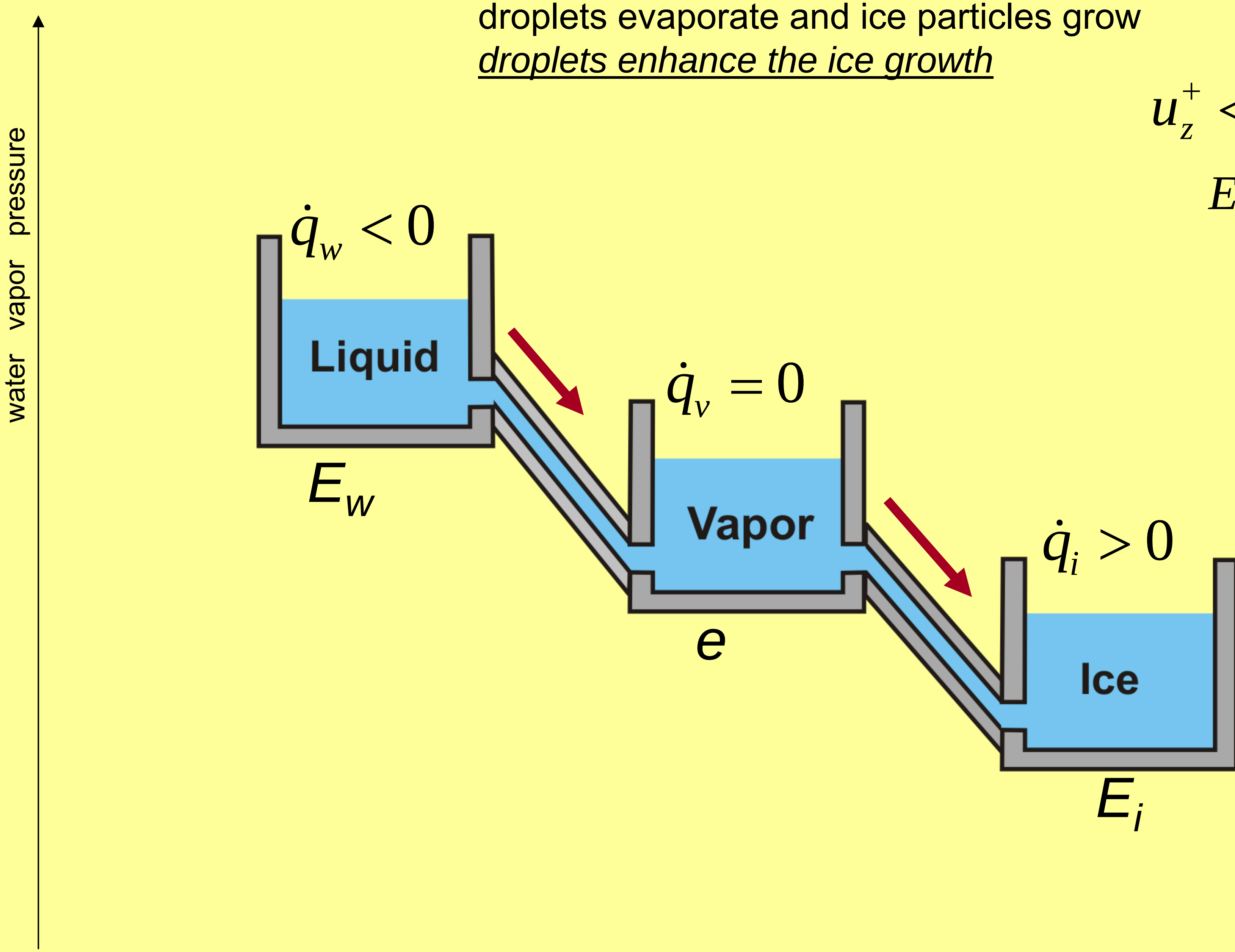
condition for Wegener-Bergeron-Findeisen mechanism

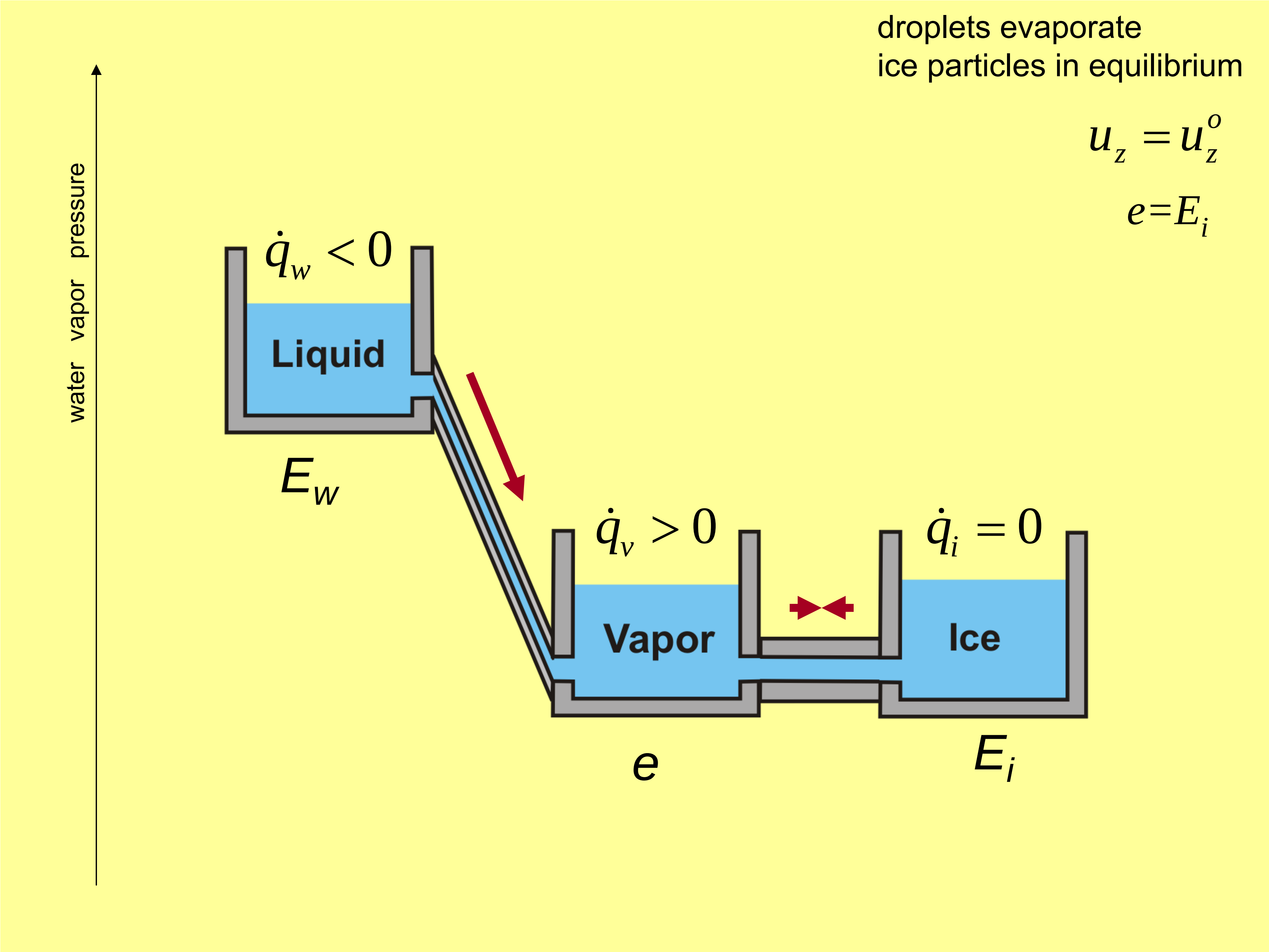
droplets evaporate and ice particles grow

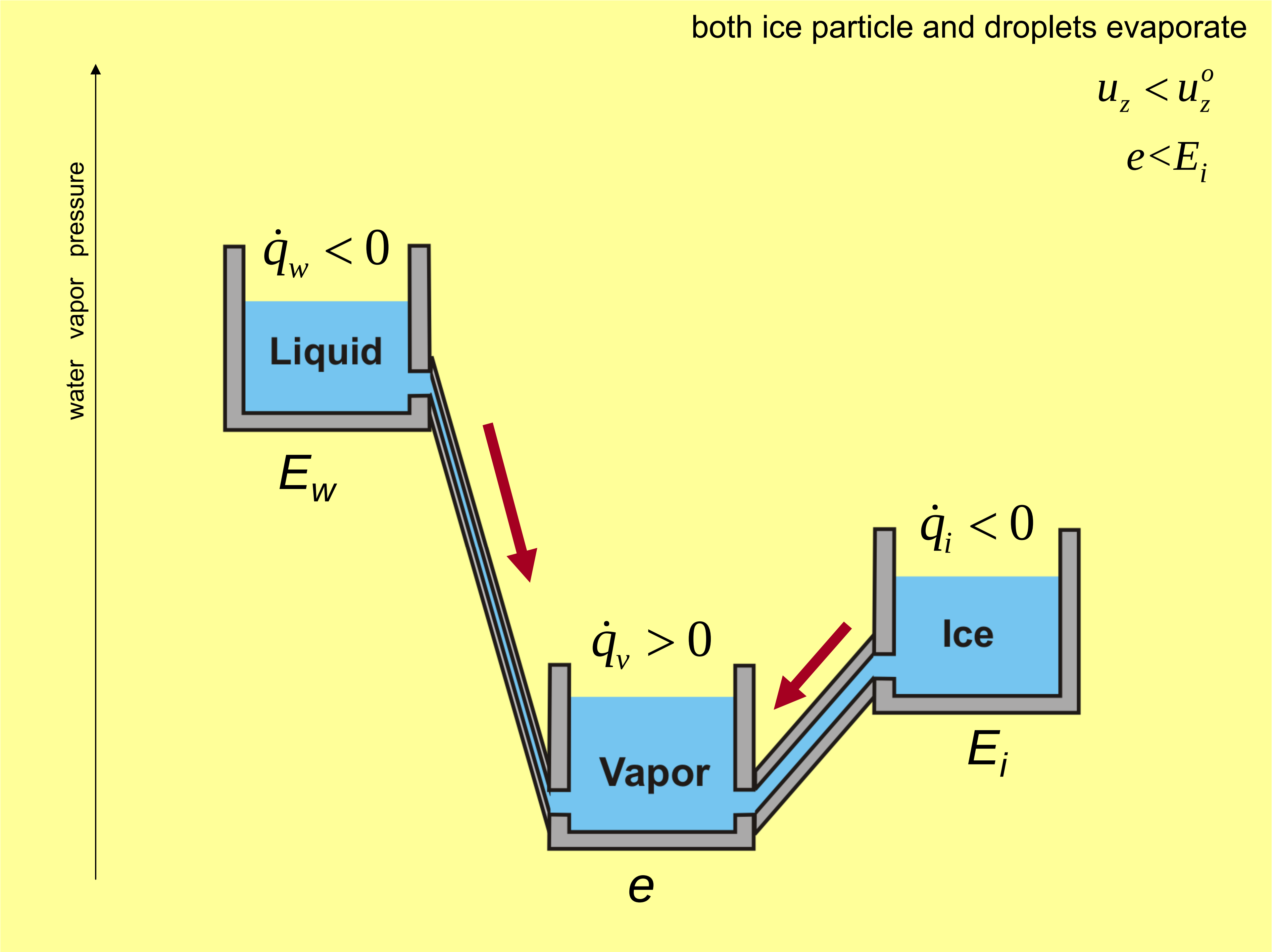
droplets enhance the ice growth

$$u_z^+ < u_z < u_z^*$$

$$E_i < e < E_v$$



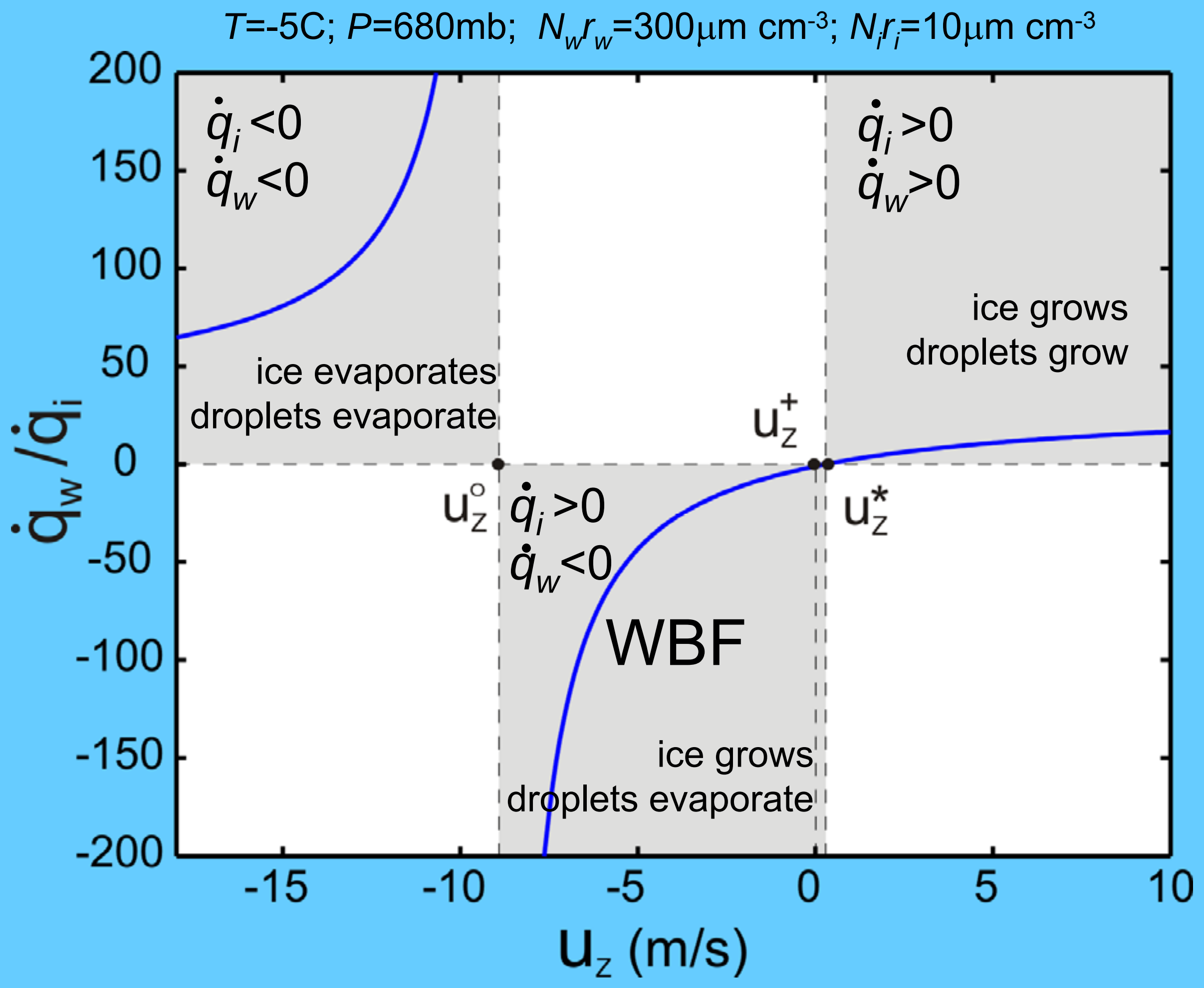

droplets evaporate
ice particles in equilibrium
$u_z = u_z^o$
$e = E_i$
water vapor pressure
$\dot{q}_w < 0$
Liquid
E_w
$\dot{q}_v > 0$
Vapor
e
$\dot{q}_i = 0$
Ice
E_i



both ice particle and droplets evaporate
$u_z < u_z^o$
$e < E_i$
water vapor pressure
$\dot{q}_w < 0$
Liquid
E_w
$\dot{q}_v > 0$
Vapor
e
$\dot{q}_i < 0$
Ice
E_i

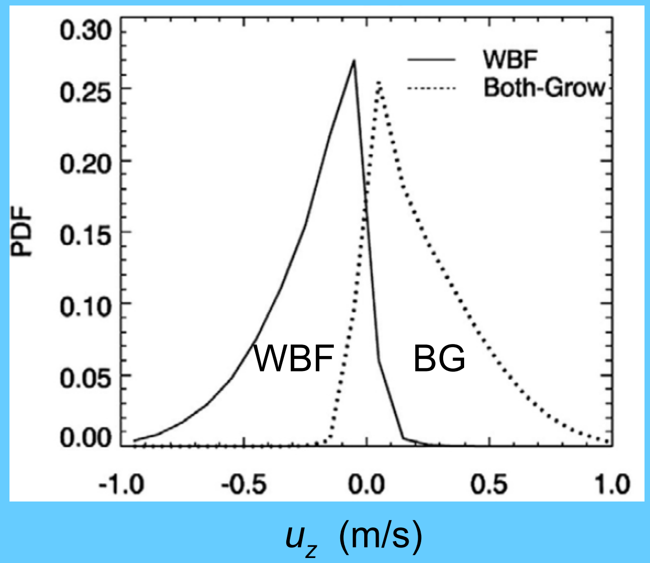
Limited range of conditions for the WBF process

$$\frac{\dot{q}_w}{\dot{q}_i} = \frac{\left(a_0 u_z - b_i^* N_i \bar{r}_i\right) B_w N_w \bar{r}_w}{\left(a_0 u_z - \frac{1-\xi}{\xi} b_w N_w \bar{r}_w\right) B_i N_i \bar{r}}$$



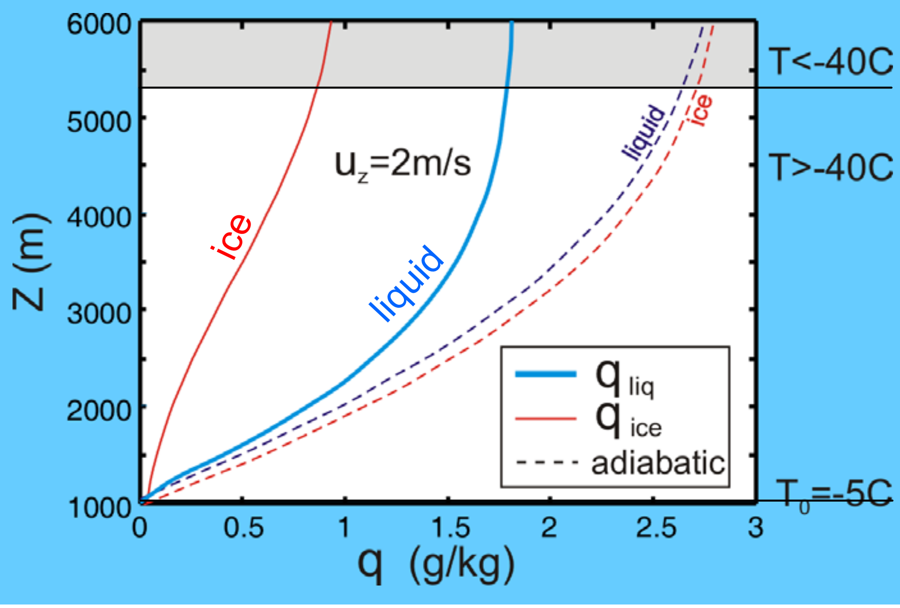
Korolev, 2008, QJRMS

WBF process versus "Both-Grow" process in mixed phase



In shallow stratiform mixed phase clouds the WBF process is enabled in approximately 50% of time

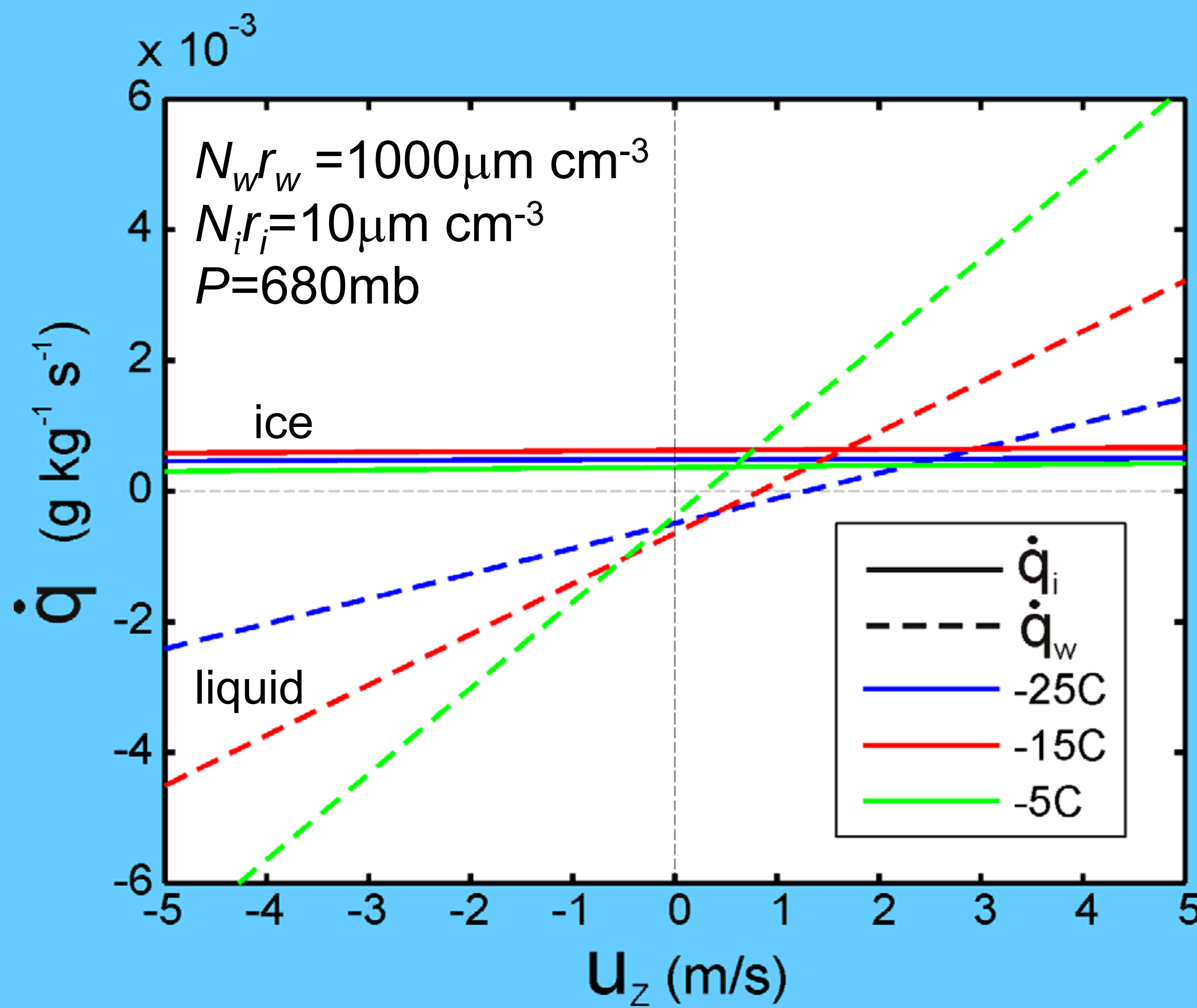
Fan et al., 2011, JGR



In convective cores in cumulus clouds the WBF process is disabled even during a moderate ascent

Korolev, 2007, JAS

Growth rate of ice and liquid water content in mixed phase cloud



$$\dot{q}_w = \frac{\left(a_0 u_z - b_i^* N_i \bar{r}_i\right) B_w N_w \bar{r}_w}{b_w N_w \bar{r}_w + b_i N_i \bar{r}_i}$$

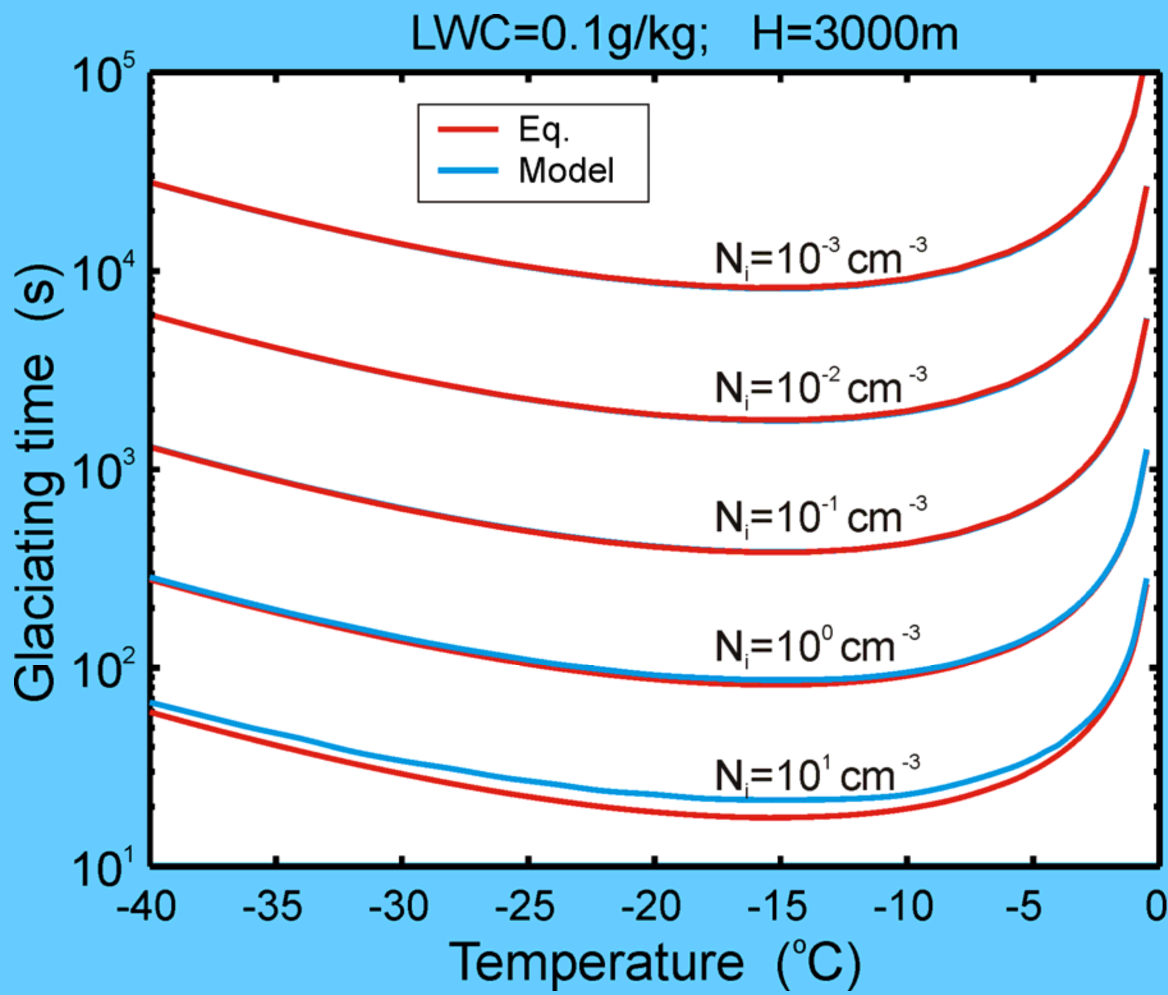
$$\dot{q}_i = \frac{\left(a_0 u_z - \frac{1-\xi}{\xi} b_w N_w \bar{r}_w\right) B_i N_i \bar{r}_i}{b_w N_w \bar{r}_w + b_i N_i \bar{r}_i}$$

In mixed phase clouds the growth rate of liquid droplets is more sensitive to the vertical velocity in comparisons to that of ice particles

Korolev, 2008, QJRMS

Glaciation time for U_z=0

$$\tau_{gl} = \frac{1}{4\pi c A_i S_i}\left(\frac{9\pi\rho_i}{2}\right)^{1/3}\left(\left(\frac{W_w(t_0)+W_i(t_0)}{N_i}\right)^{2/3} - \left(\frac{W_i(t_0)}{N_i}\right)^{2/3}\right)$$



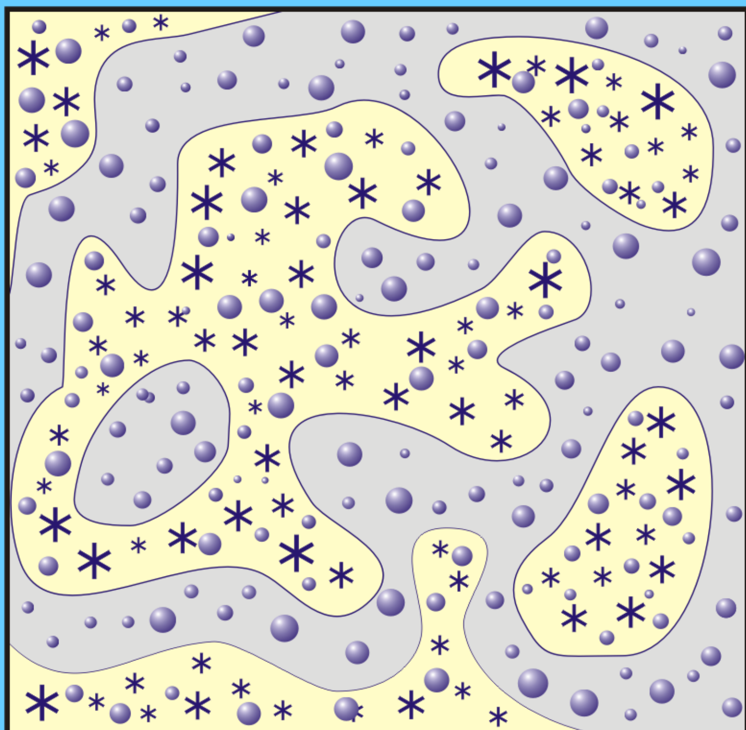
$$\tau_{gl} = k\left(\frac{W_{LWC}}{N_{ice}}\right)^{2/3}$$

Korolev and Isaac (2003)

Two competing processes: glaciating and mixing

$$\tau_{gl} > \tau_t$$

The condition for the existence of isolated single-phase liquid and ice zones with the characteristic scale *L* in clouds with isotropic turbulence



$$\tau_t = \left(\frac{L^2}{\varepsilon}\right)^{1/3} \qquad \tau_{gl} = k\left(\frac{W_{LWC}}{N_{ice}}\right)^{2/3}$$

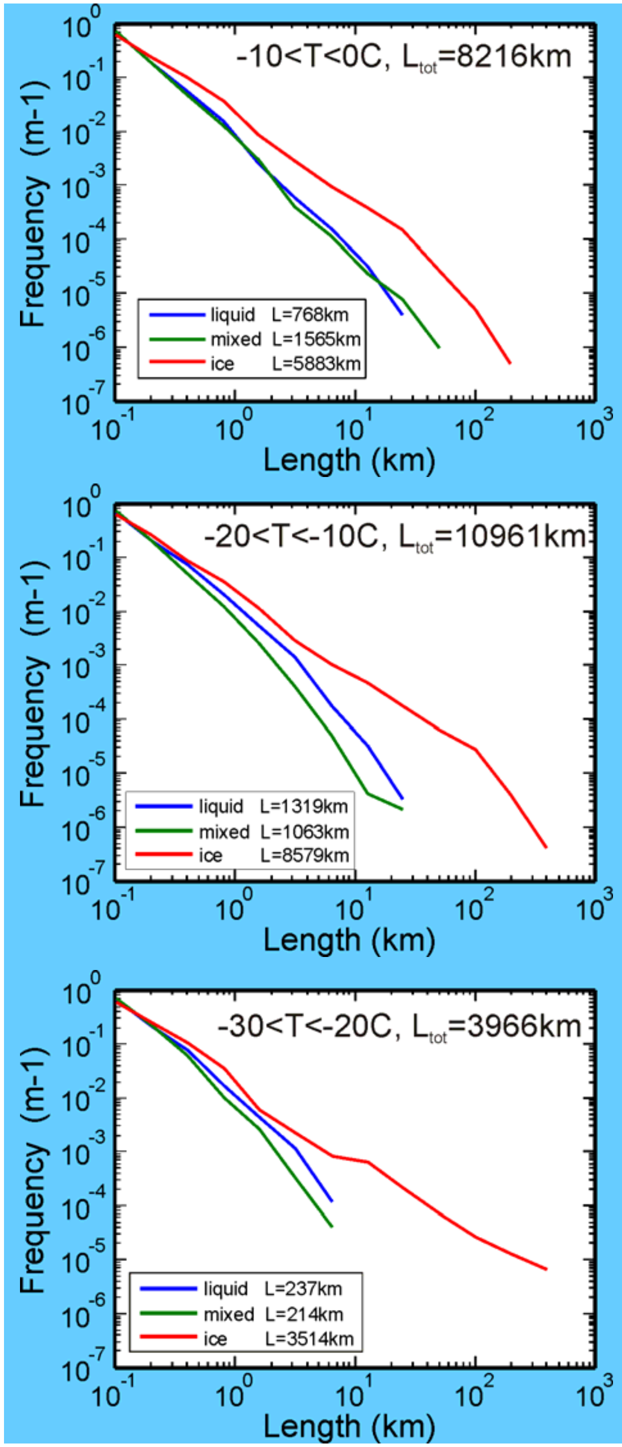
$\tau_{gl} \sim 10^2 - 10^3$ s;

$\varepsilon \sim 10^{-3} - 10^{-4}$ m^2/s^3

The characteristic spatial scale of the single phase zones in mixed phase clouds

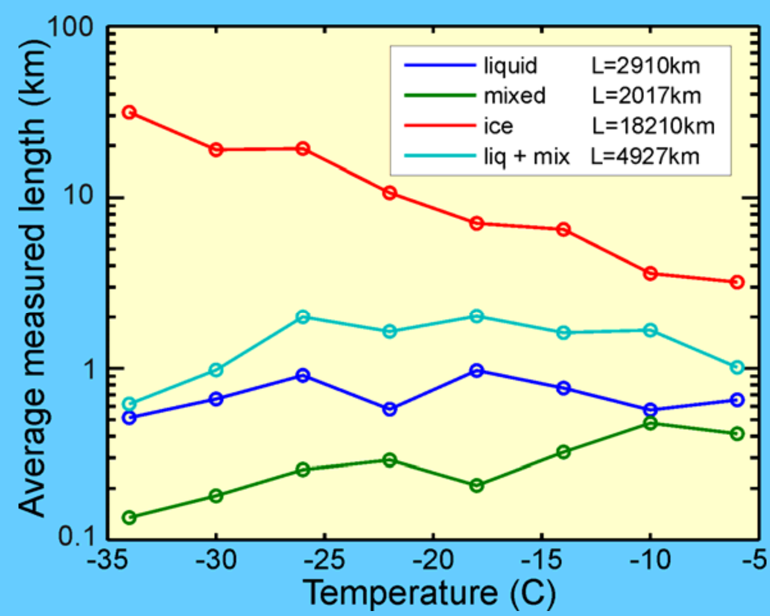
$$L_{ph} \sim k\varepsilon^{1/2}\frac{W_{LWC}}{N_{ice}} \sim 10^1 - 10^3\, m$$

Sustained single phase zones may exist at the spatial scales $L<L_{ph}$



Occurrence of lengths of liquid, mixed phase and ice cloud zones

TWC threshold=0.01kg/m³



The average length of continuous liquid zones stays constant with temperature L_w~500m

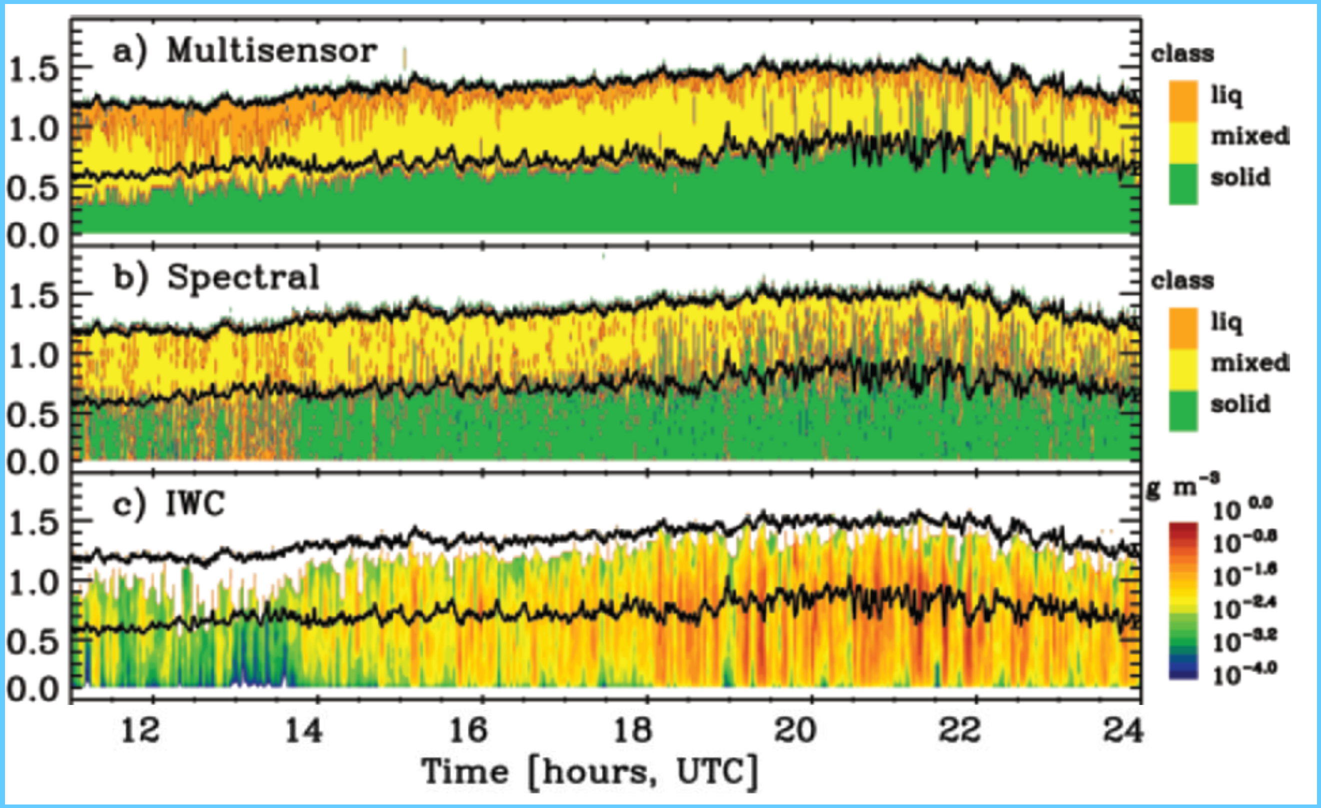
The continuous length of mixed phase zones decreases with decrease of T 100m< L_m<500m

The continuous length of ice zones increases with the decrease of T 4km<L_i<40km

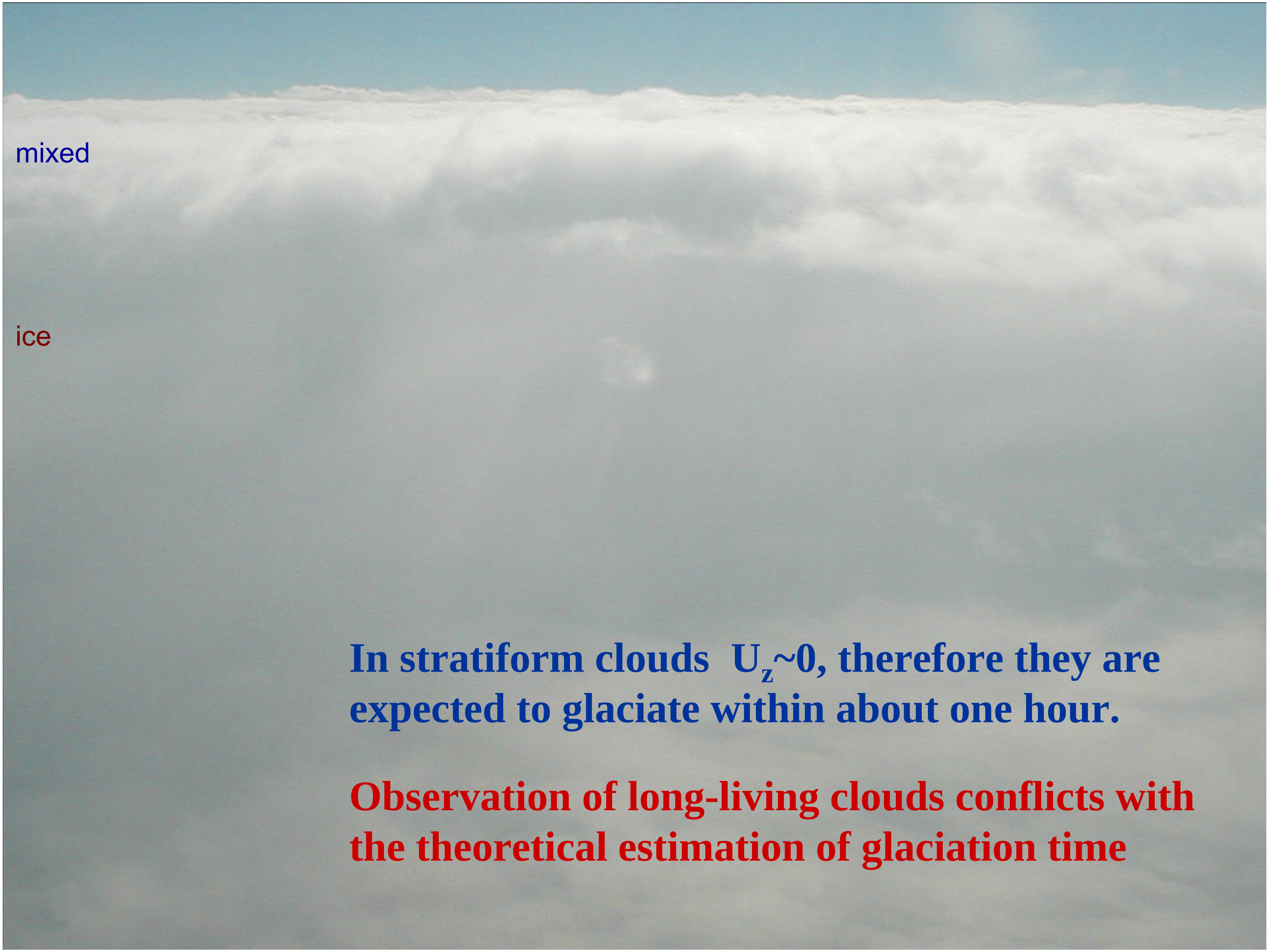
The documentation of long-living mixed phase stratiform layers at temperatures as low as -30C

Rauber, R.M. and A. Tokay, 1991: *J. Atmos. Sci.*,
Pinto, J.O., 1998: *J. Atmos. Sci.*

09 Oct 2004, Barrow, Alaska, NSA ARM site,

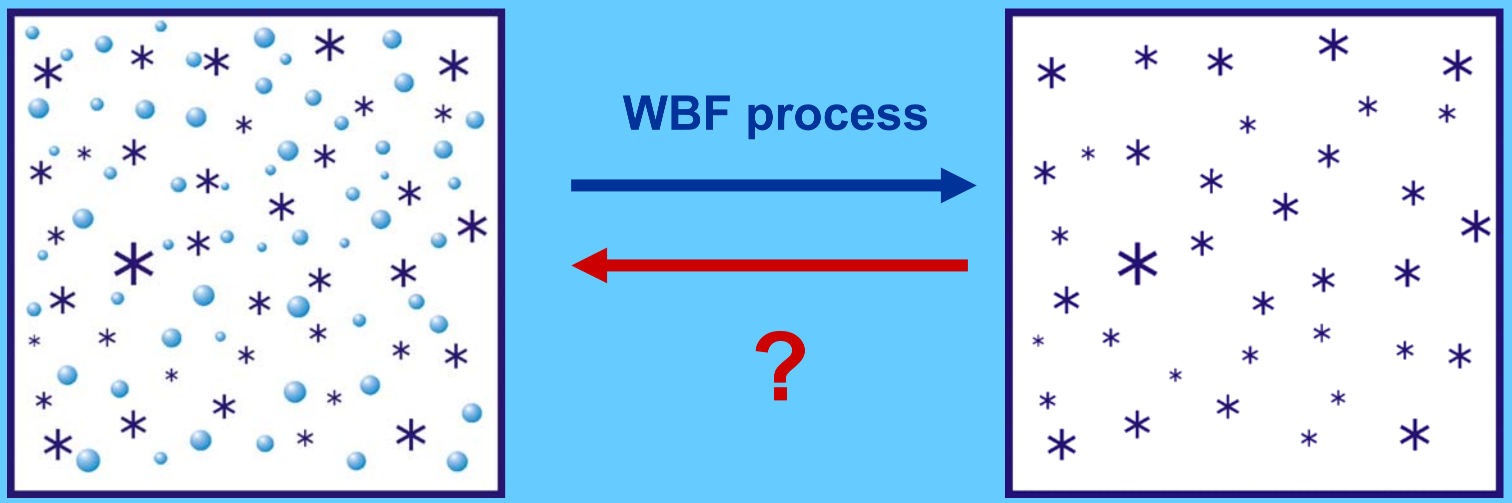


Shupe et al. 2008, BAMS.



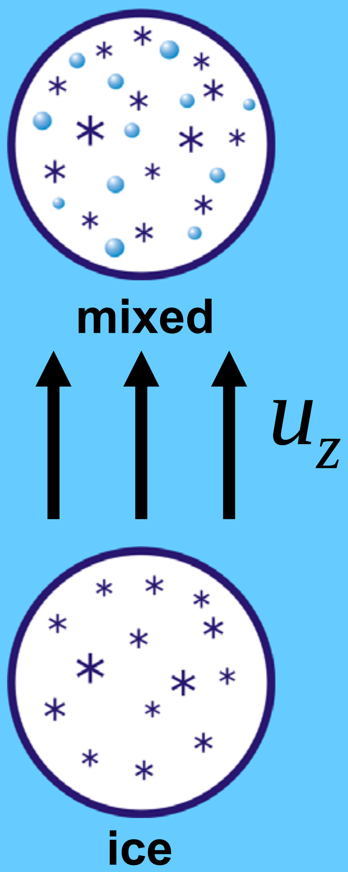
In stratiform clouds U_z~0, therefore they are expected to glaciate within about one hour.

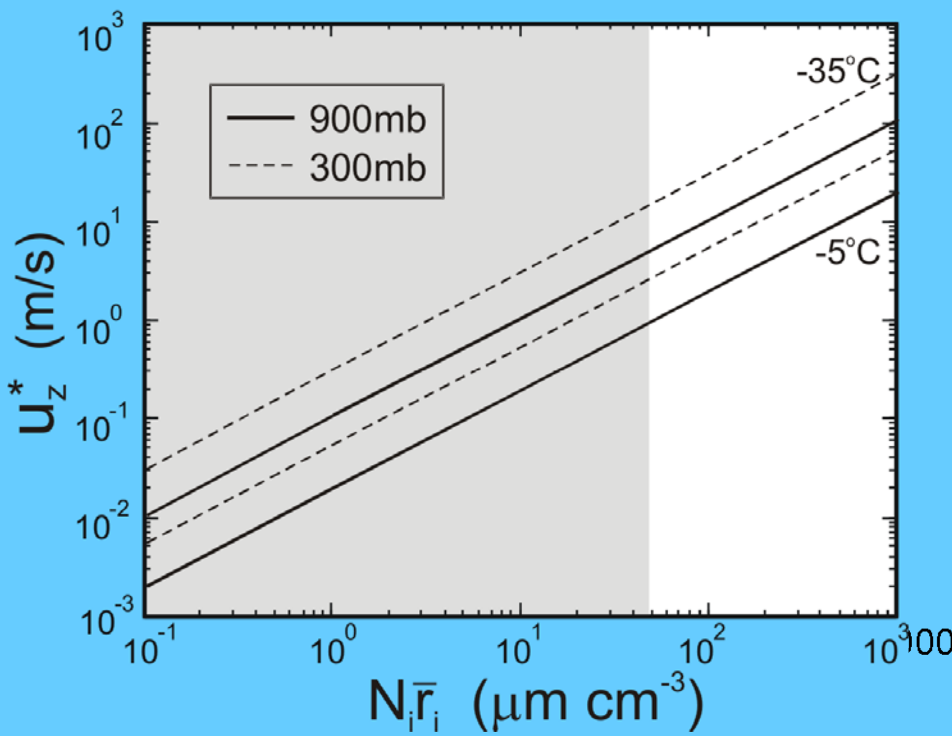
Observation of long-living clouds conflicts with the theoretical estimation of glaciation time


WBF process
?

$$u_z^* = \frac{b_i^* N_i \bar{r}_i}{a_{0w}}$$ threshold vertical velocity, when $e = E_w$

$$u_z > u_z^*$$ condition for activation of liquid water in ice cloud



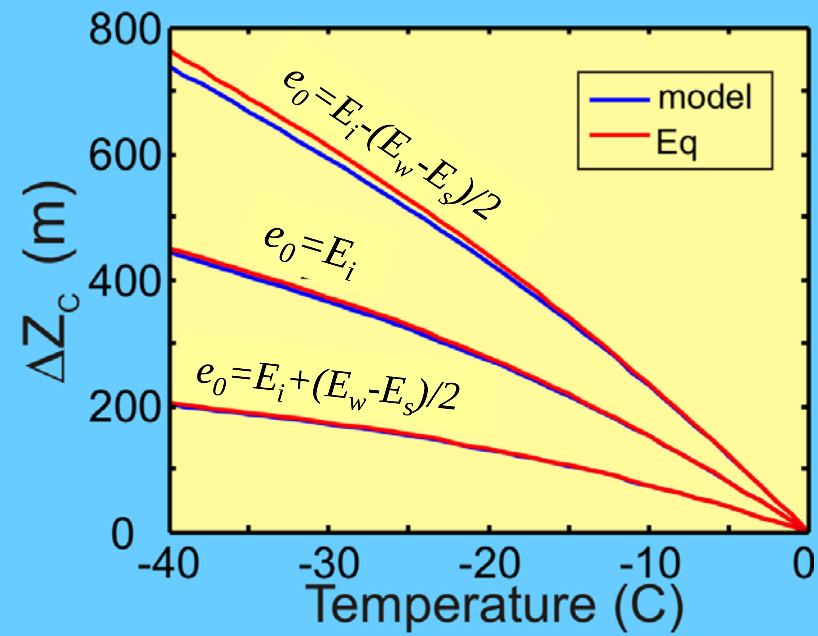


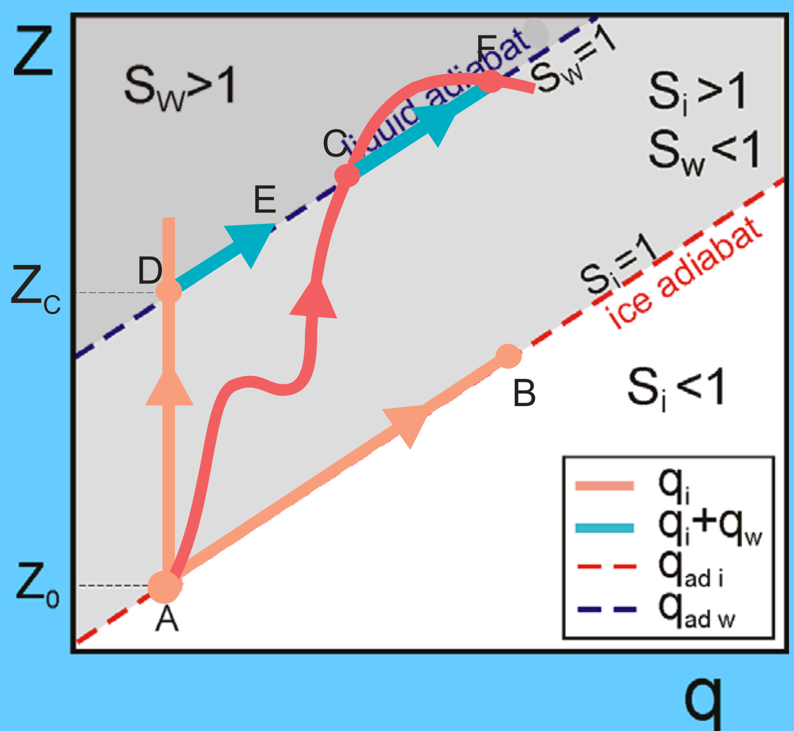
$$\tau_{ph} \approx \frac{b(T)}{N_i \bar{r}_{i0}}$$ time of phase relaxation

$$\tau_z \approx \frac{\Delta Z}{u_Z}$$ characteristic time of vertical motion

$$\tau_z >> \tau_{ph} \quad \rightarrow$$ line AB

$$\tau_z << \tau_{ph} \quad \rightarrow$$ line AD





$$\frac{1}{S_w+1}\frac{dS_w}{dz} = a_w \quad \rightarrow \quad \boxed{\Delta Z_c = a_w^{-1} \ln\left(\frac{E_w}{e_0}\right)}$$

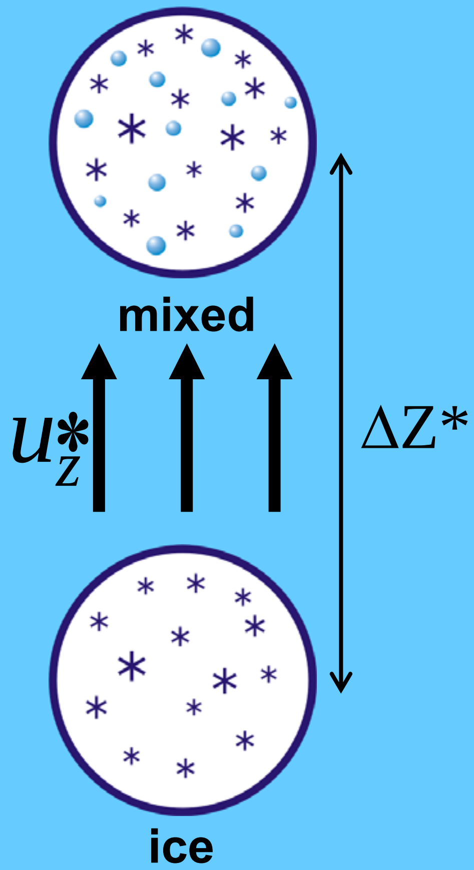
$$\boxed{\Delta Z > \Delta Z^*}$$ condition for activation of liquid water in ice cloud

$$\Delta Z^*_{\min} = \Delta Z_C \quad \text{for} \quad u_z \rightarrow \infty$$

$$\Delta Z < \Delta Z_C$$ no activation of liquid is possible

Dynamic forcing of mixed phase in preexisting ice cloud:

formulation of the necessary and sufficient conditions for the activation of liquid in ice clouds



1st Necessary Condition: The vertical velocity of an ice cloud parcel must exceed a threshold velocity to activate liquid water.

$$u_z > u_z^*$$

$$u_z^* = \frac{b_i^* N_i \bar{r}_i}{a_{0w}}$$

2nd Necessary Condition: The activation of liquid water within an ice cloud parcel, below water saturation, requires a vertical ascent (ΔZ) above some threshold altitude (ΔZ*) to bring the vapor pressure of the parcel to water saturation:

$$\Delta Z > \Delta Z^*$$

$$\Delta Z_c^* = a_w^{-1} \ln\left(\frac{E_w}{e_0}\right)$$

1st and 2nd conditions give a set of **necessary and sufficient** conditions of activation of liquid in ice cloud

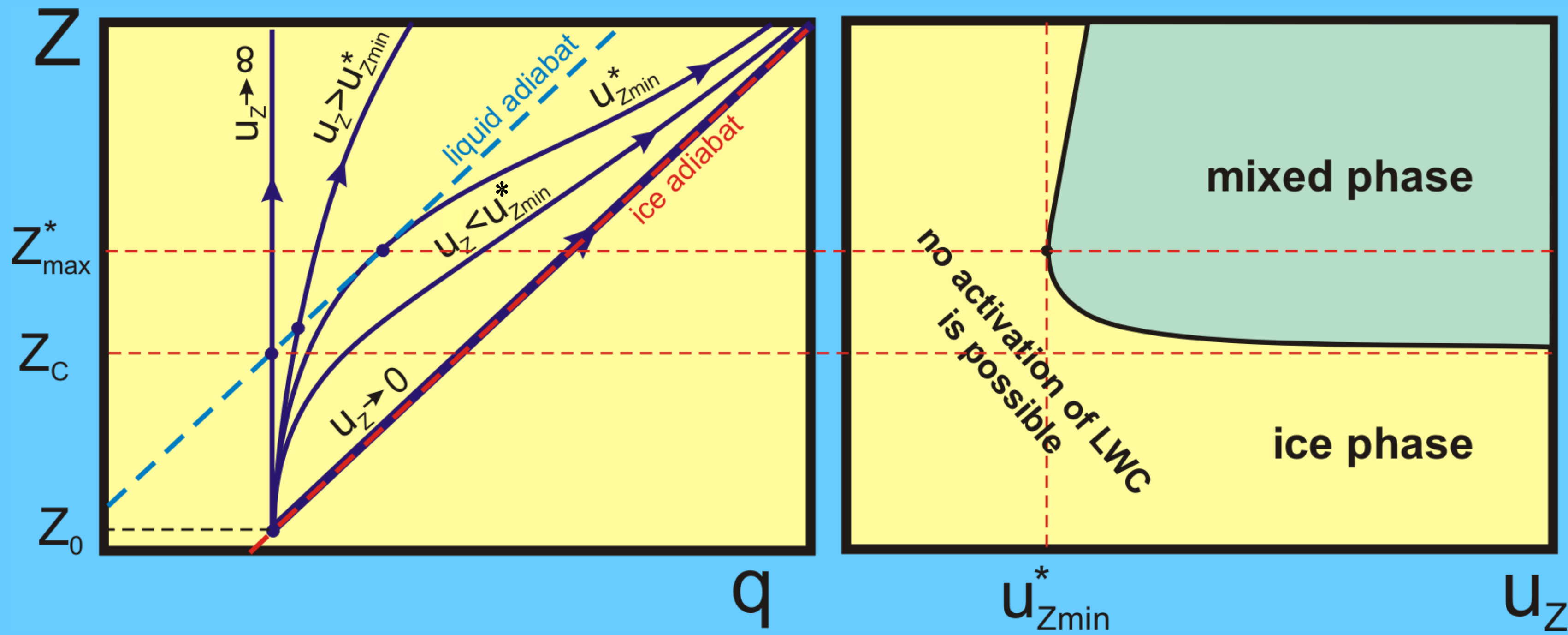
Korolev and Field, 2007, JAS

Lower sun pillar, subsun

Lower sun pillar, subsun

UNIFORM ASCENT

(necessary and sufficient conditions)



Necessary and sufficient condition for the activation of liquid water in ice clouds for *uniform ascent*.

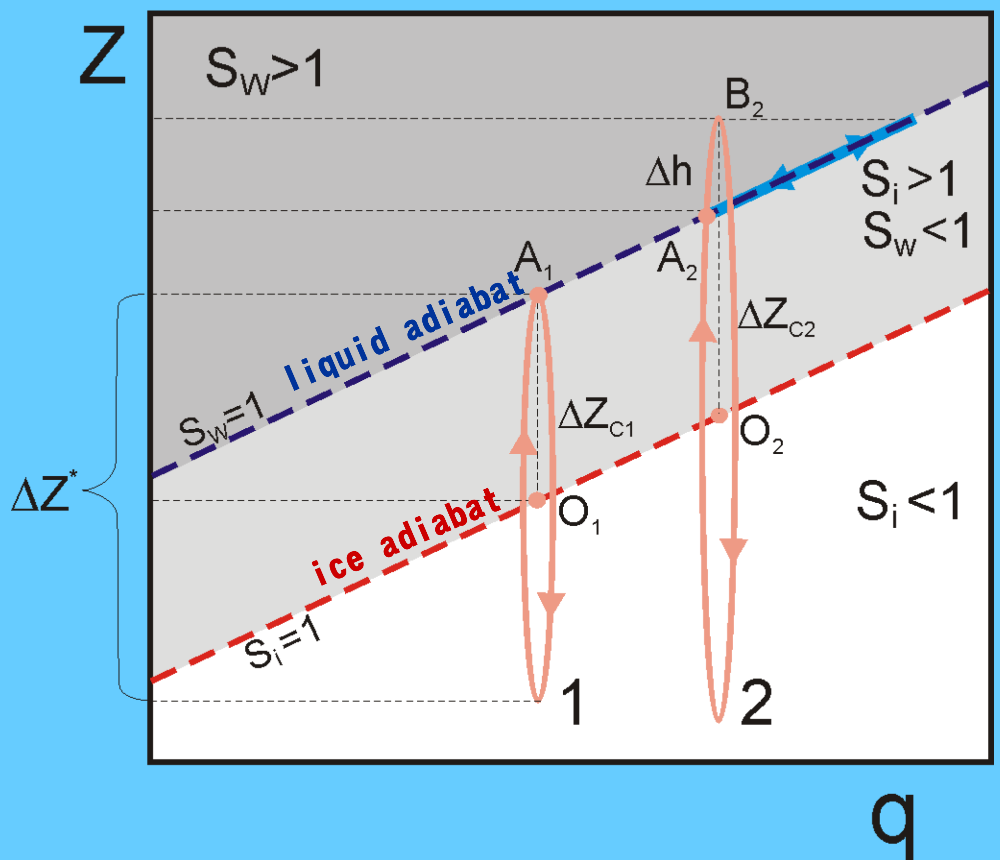
$$u_z > u_z^*$$
$$\Delta Z > \Delta Z^*$$

$$u^*_{Z\,\min}(N_i, r_{i0}, T_0)$$

$$\Delta Z^*_{\max}(N_i, r_{i0}, T_0)$$

$$\Delta Z_C(T_0)$$

Maintenance of mixed phase clouds during vertical fluctuations of U_z



$$u_0^* = \frac{k_0 b_m (E_w - E_i) N_i \bar{r}_m \Delta Z}{E_i \sqrt{\Delta Z^2 - 4a_w^2 \ln^2\left(\frac{E_w}{E_i}\right)}}$$

$$u_0 > u_0^*$$

$$\Delta Z > 2\Delta Z_c$$

Necessary and sufficient conditions for the indefinitely long maintenance of mixed phase during *harmonic oscillations*.

HARMONIC OSCILLATIONS

modeling of the activation of liquid water in ice cloud during vertical harmonic oscillations.

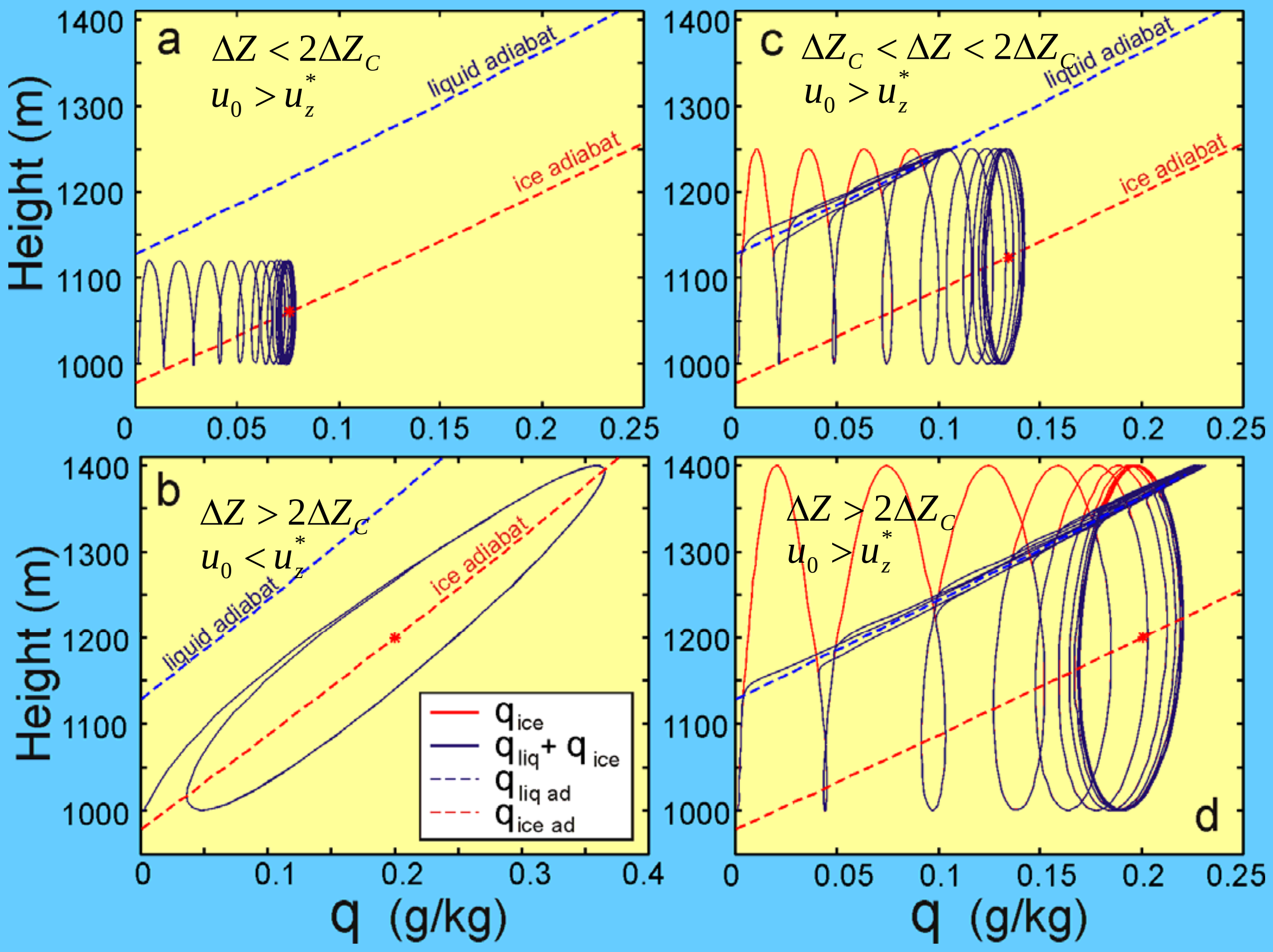
N_{ice}=50l^{-1}, r_{i0}=20μm, S_{i0}=1.01, T_0=-10C, ΔZ_C=153m.

(a) ΔZ=125m, u_0=0.5m/s, u_0^*=0.08m/s; ΔZ_C=153m

(c) ΔZ=250m, u_0=1m/s, u_0^*= 0.10m/s; ΔZ_C=153m

(b) ΔZ=400m, u_0=0.05m/s, u_0^*= 0.12m/s; ΔZ_C=153m

(d) ΔZ=400m, u_0=1m/s; u_0^*= 0.12m/s ΔZ_C=153m

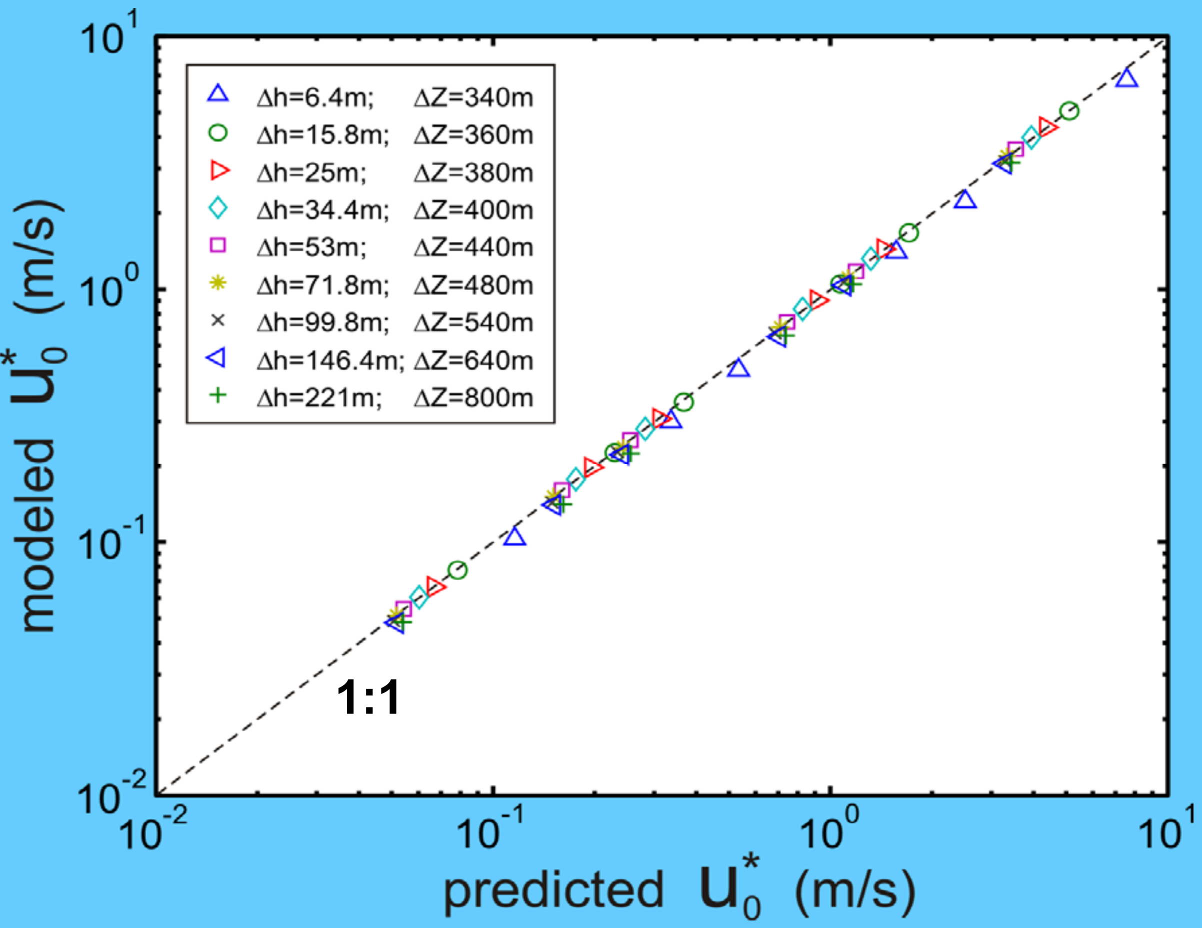


HARMONIC OSCILLATIONS

Comparison of the theoretical and modeled threshold velocity U^*_0

T_0=-10C, 340m<ΔZ<800m; 0.05m/s<u_0<6m/s;

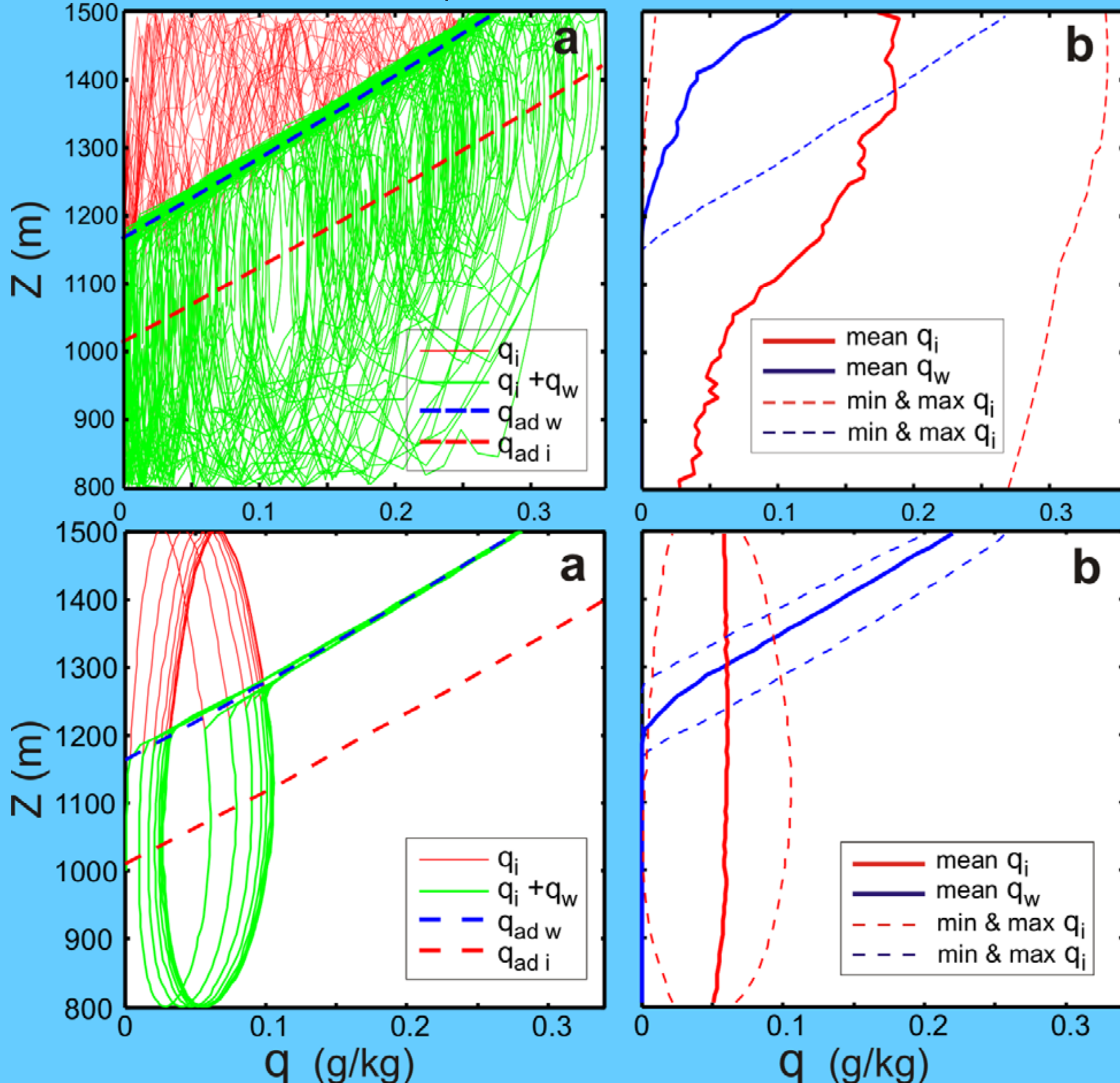
20μm<r_{i0}<200μm; 50l^{-1} <N_i< 5000l^{-1}



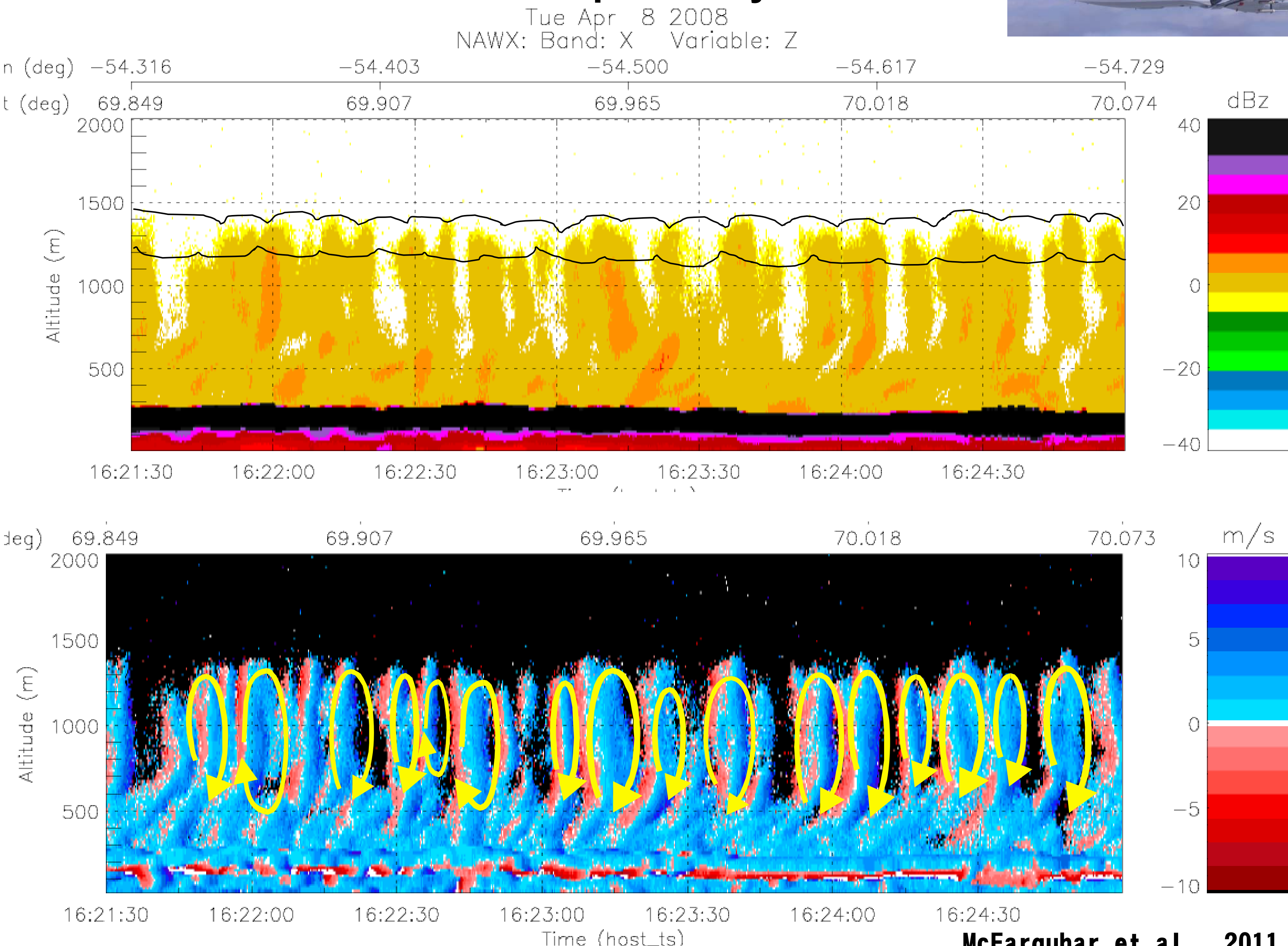
$$u_0^* = \frac{k_0 b_m (E_w - E_i) N_i \bar{r}_m \Delta Z}{E_i \sqrt{\Delta Z^2 - 4a_w^2 \ln^2\left(\frac{E_w}{E_i}\right)}}$$

Random vertical fluctuations

N_{ice}=50l^{-1}; T_{top}=-14°C; T_{base}=-8°C; σ_u=0.75m/s

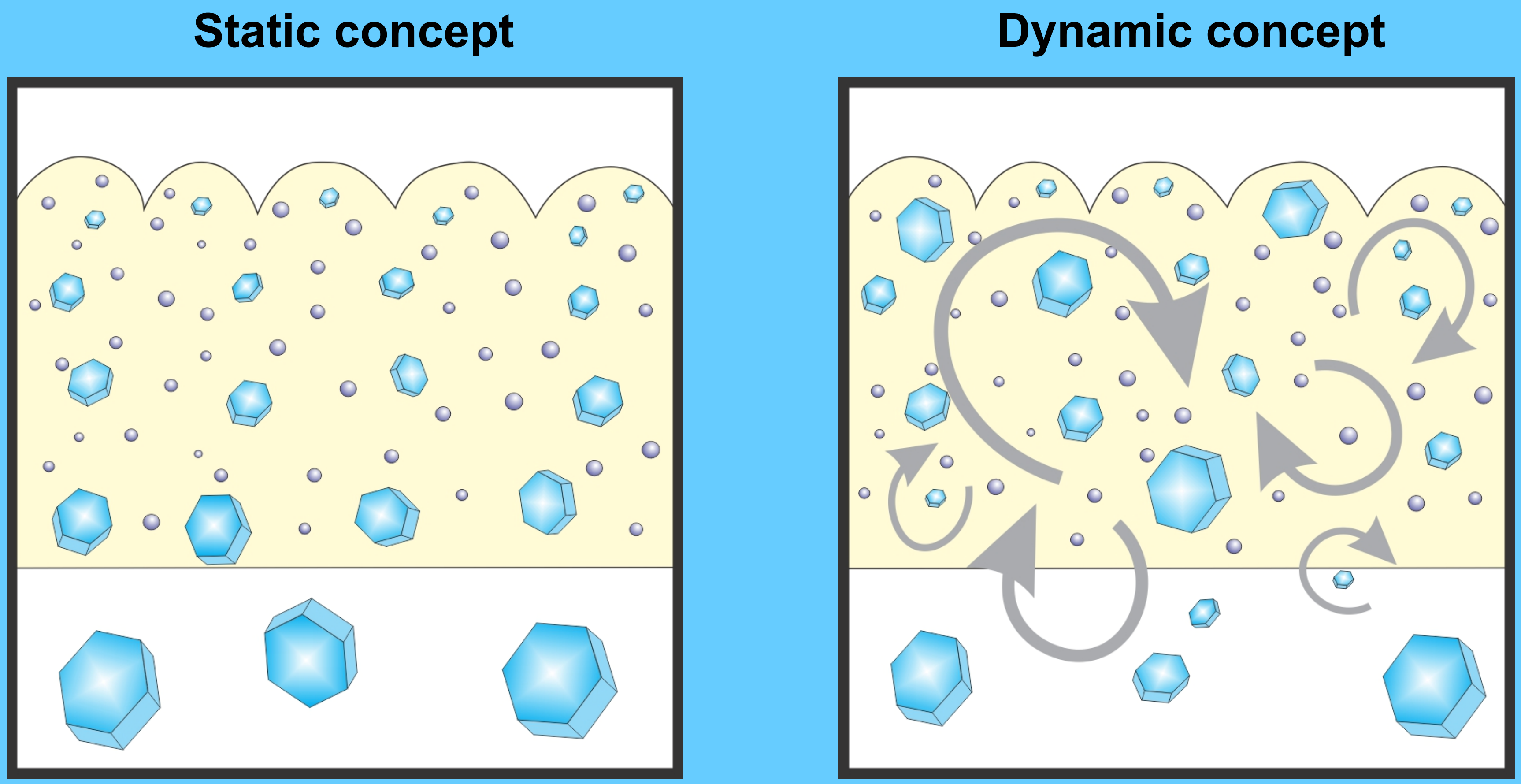


ISDAC, Alaska, NRC NAX radar stratiform mixed phase layer



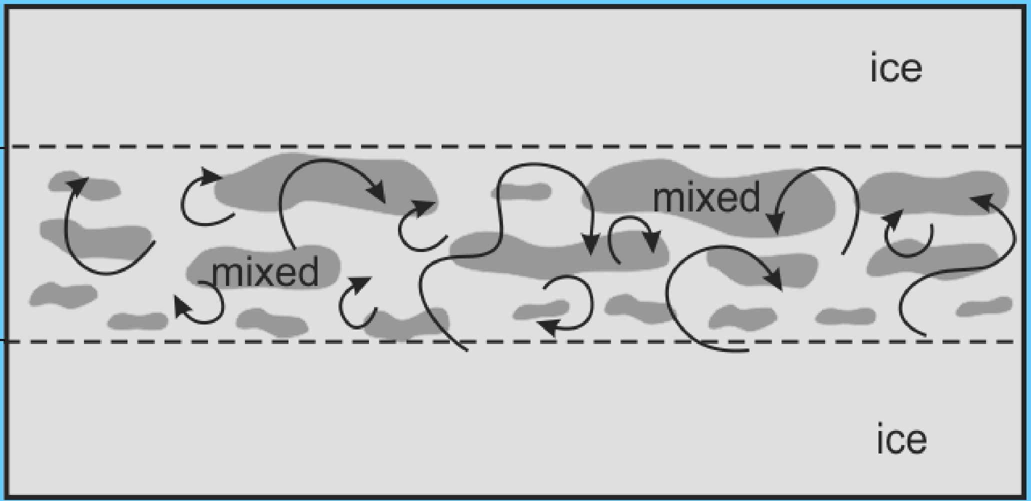
McFarquhar et al., 2011, BAMS

Effect of dynamics on the formation of stratiform mixed phase clouds



Stochastic approach to dynamic forcing of mixed phase

P, T, N_i, r_i, S_E, s_u, e, L



$$\frac{1}{S_i+1}\frac{dS_i}{dt} = a_i u_z - b_i B_0 M_1 S_i$$

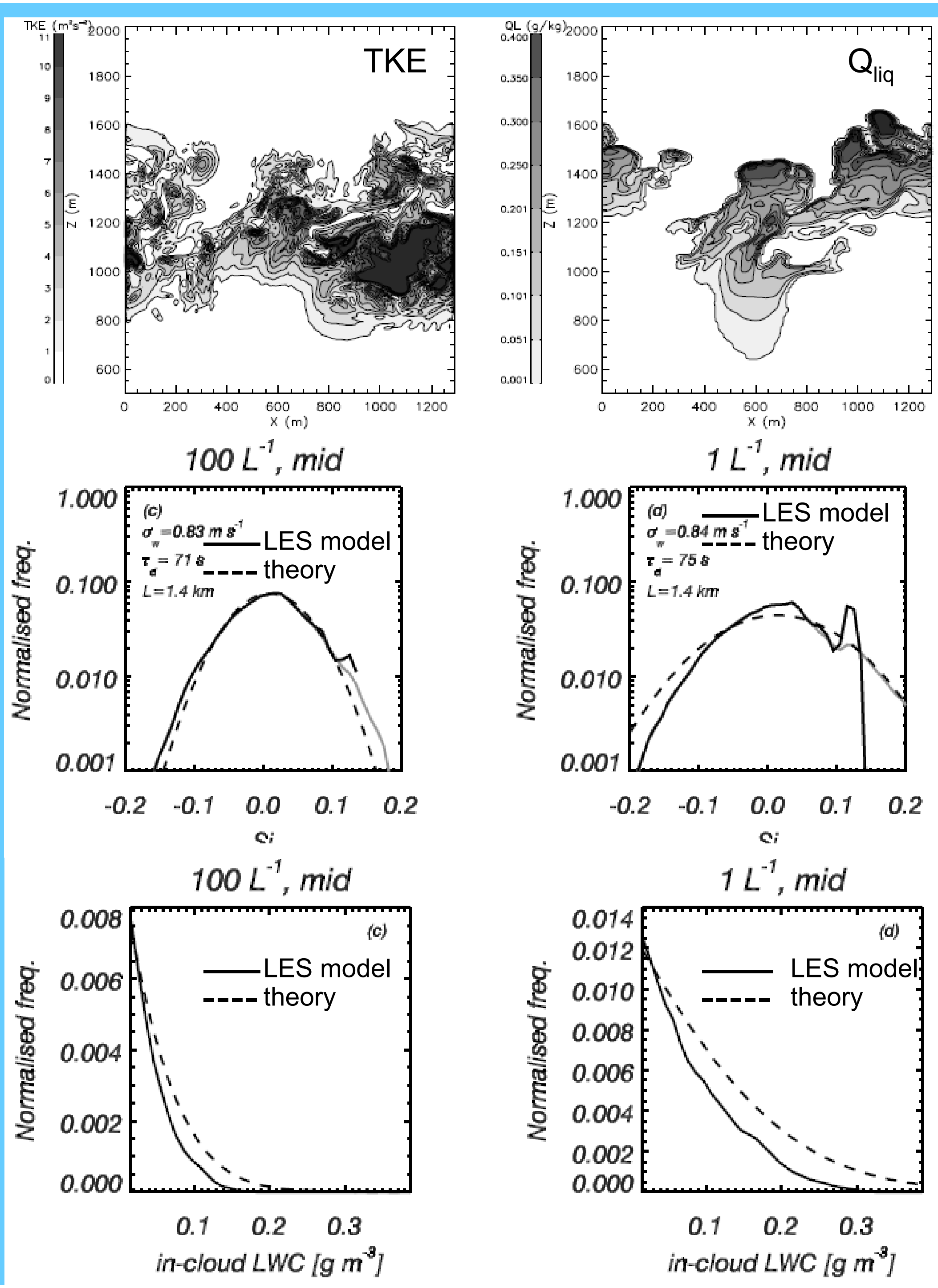
Differential equation for supersaturation in a Largangian parcel

$$\frac{dS_i}{dt} = a_i \sigma_u(t) - b_i B_0 M_1 S_i + \left(\frac{\varepsilon}{L^2}\right)^{1/3}\left(S_E - S_i\right)$$

Stochastic differential equation for supersaturation averaged over an ensemble of parcels

$$S_i(t) = \exp\left(-(B+C)t\right)\left[S_0 + S_E\frac{C}{B+C}\left(1-\exp\left(-(B+C)t\right)\right) + \int_0^t \exp\left(-(B+C)(t-r)\right)\xi dr\right]$$

Field et al. 2013 QJRMS (in press)



Hill et al. 2013 QJRMS (in press)

$$f(S_i) = \frac{1}{\sigma_S\sqrt{2\pi}} \exp\left(\frac{-\left(S_i - \langle S_i \rangle\right)^2}{2\sigma_S^2}\right)$$

$$\sigma_S^2 = \frac{S_E a_i^2 \sigma_u^2 \tau_d}{2\left(b_i B_0 M_1 + \left(\frac{\varepsilon}{L^2}\right)^{1/3}\right)}$$

$$\langle S_i \rangle = S_E \frac{\left(\frac{\varepsilon}{L^2}\right)^{1/3}}{b_i B_0 M_1 + \left(\frac{\varepsilon}{L^2}\right)^{1/3}}$$

$$\langle q \rangle = \int_{S_{iu}}^{\infty} (S_i - S_{iu}) f(S_i) \rho_a q_{si} dS_i$$

Field et al. 2013 QJRMS (in press)

Theoretical and experimental problems in mixed phase physics:

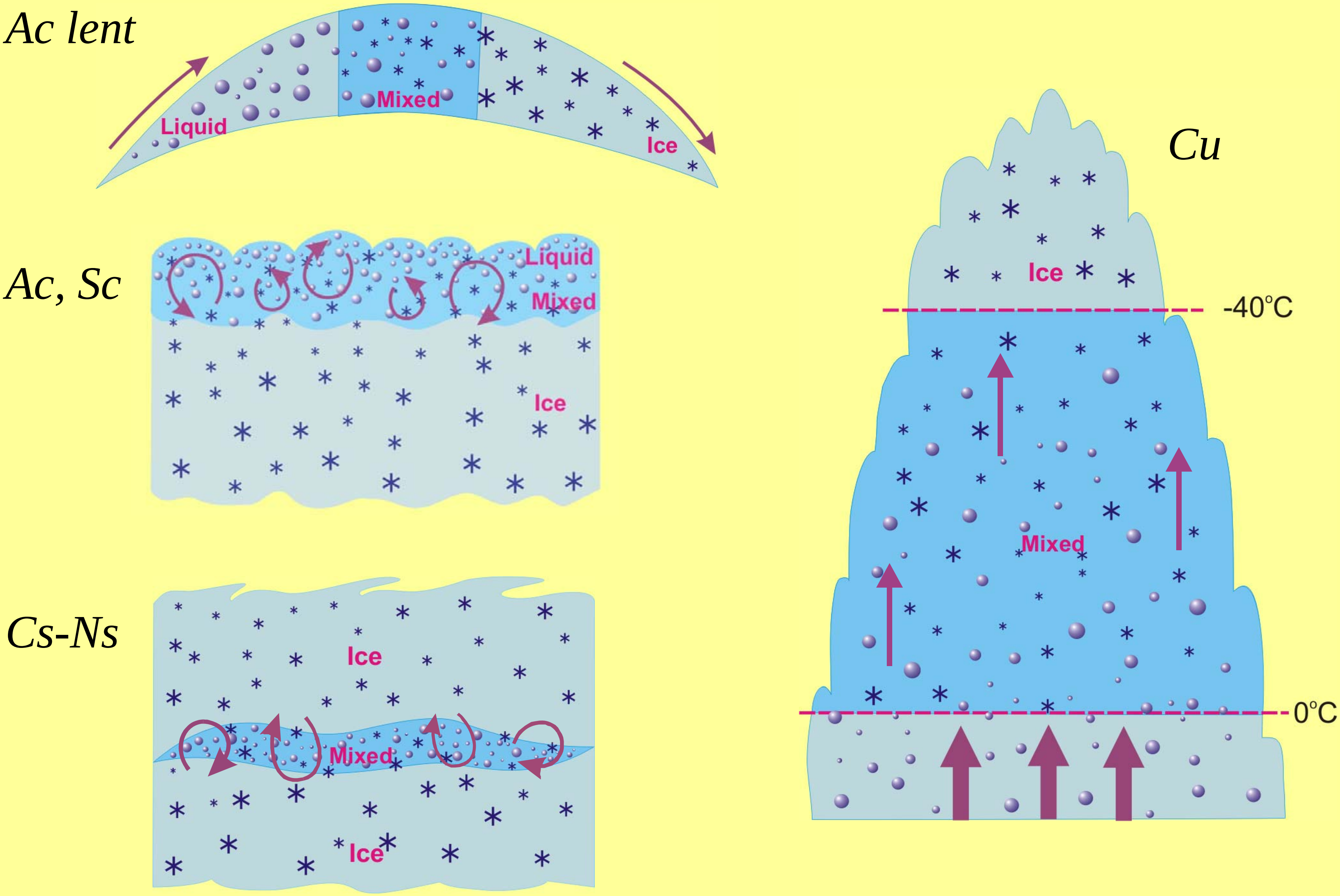
1. **Absence of physically based definition of mixed phase**

2. **Assumption of regular condensation in the description of mixed phase does not have theoretical or experimental justification ($K_t \rightarrow \infty$; $\tau_{mix} \rightarrow 0$)**

3. **Poor understanding of diffusional ice growth under varying environmental conditions (*RH, T, P*)**

4. **Characteristic spatial scales of mixed and single phase clouds at L<100m**

Instead of conclusion



Thank you

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