CLOUDS

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Outline

Introduction

- Role of clouds in the climate system
- Cloud types
- Cloud life cycle

Cloud formation and precipitation

- Cooling
- Warm Clouds
- Cold clouds
- Precipitation

Special aspects from recent studies

- IWC of cirrus clouds
- Super-Supersaturation
- Contrails

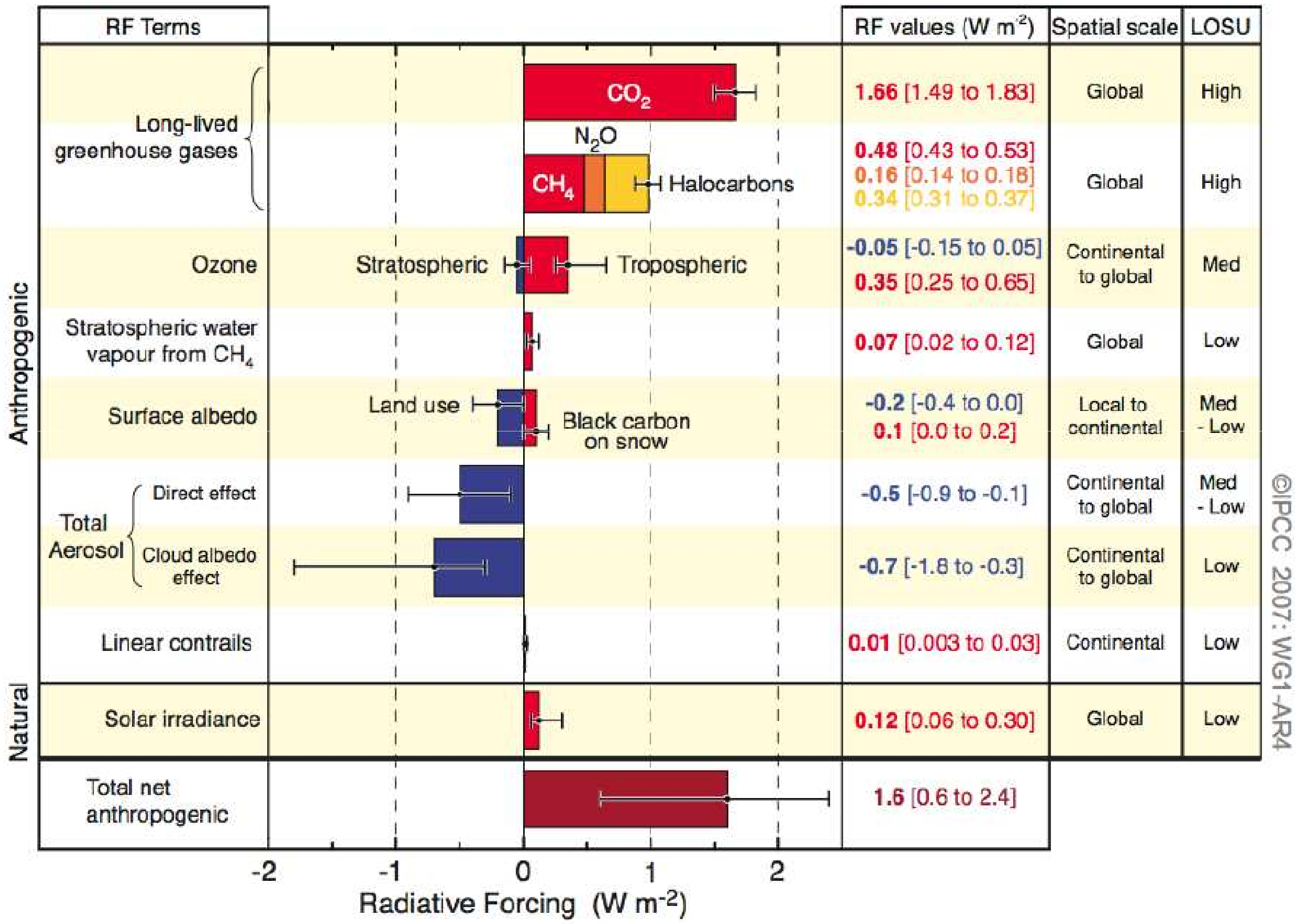
Literature

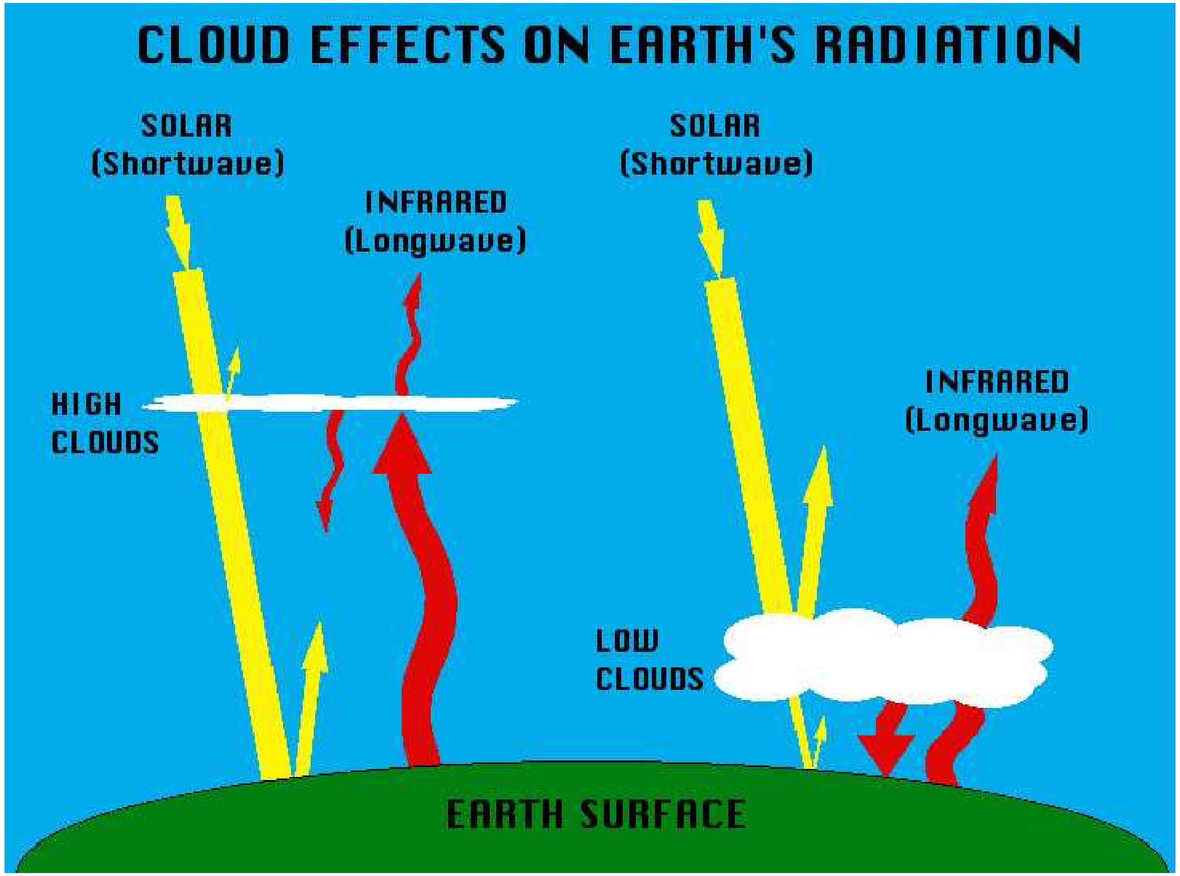
- Seinfeld, J. H. and S. H. Pandis, Atmospheric Chemistry and Physics, Wiley Interscience, 1997
- Pruppacher, H. R., and J. D. Klett, Microphysics of Clouds and Precipitation, D. Reidel Publishing Company, 1978
- Lynch, D. K., K. Sassen, D. O'C. Starr, G. Stephens (eds.), Cirrus, Oxford Univ. Press., 2002
- IPCC, Climate Change 2007 – The Physical Science Basis, Cambridge Univ. Press., 2007
- Peter, T. et al., When dry air is too humid, Science, 2005
- + many individual publications
- + Meteorology standard textbooks

Role of clouds in the climate system

- **Clouds are a major factor in the Earth‘s radiation budget**
- **Clouds are a key step in the hydrological cycle**
- **Clouds provide a medium for (heterogeneous) chemical reactions**
- **Clouds affect significantly vertical transport and redistribution of species in the atmosphere**

Radiative Forcing Components





More CCN

→ more but smaller drops (cloud albedo/Twomey effect)

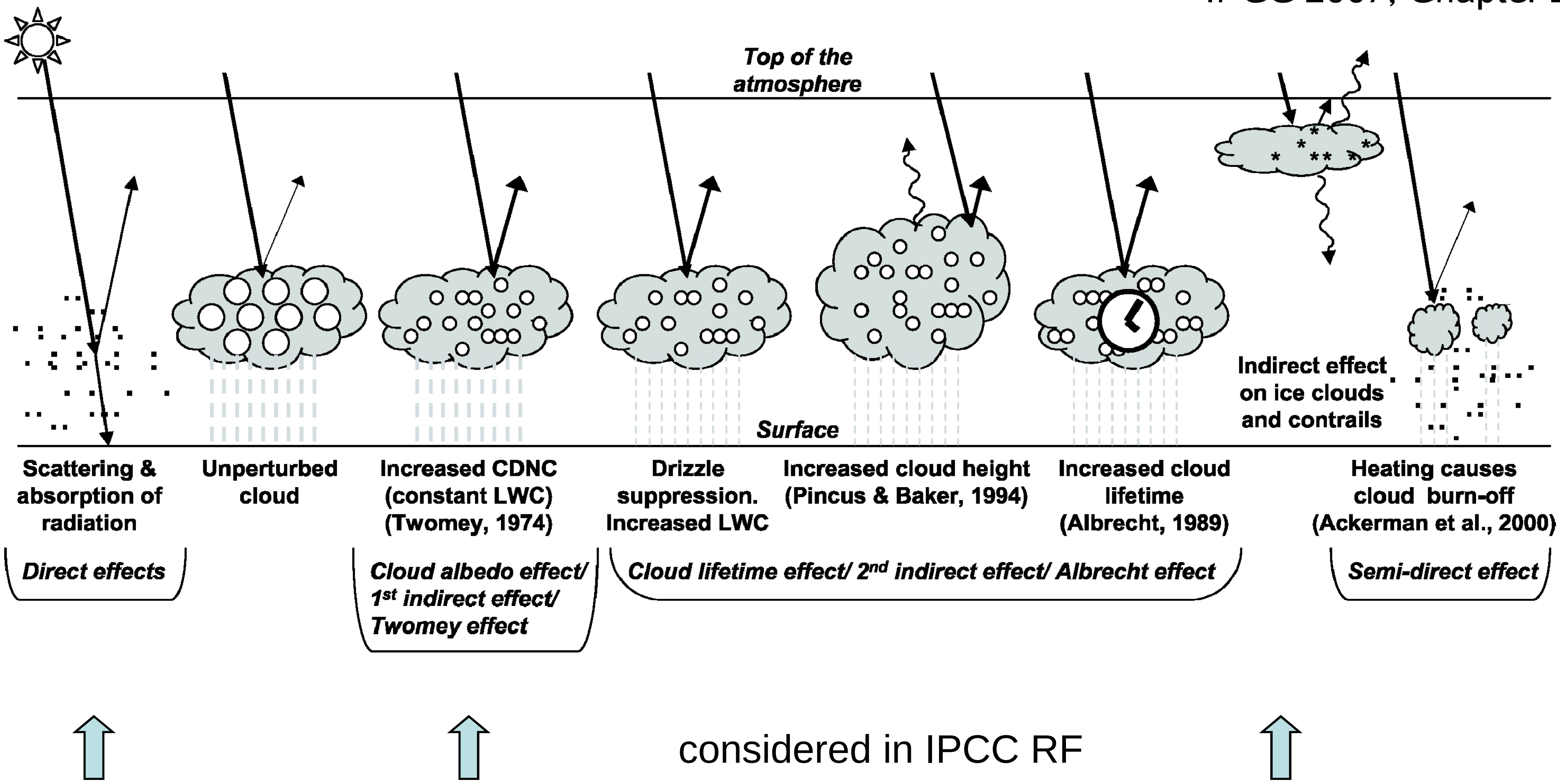
→ higher reflectivity & longer lifetime

→ less sun on Earth’s surface

→ cooling

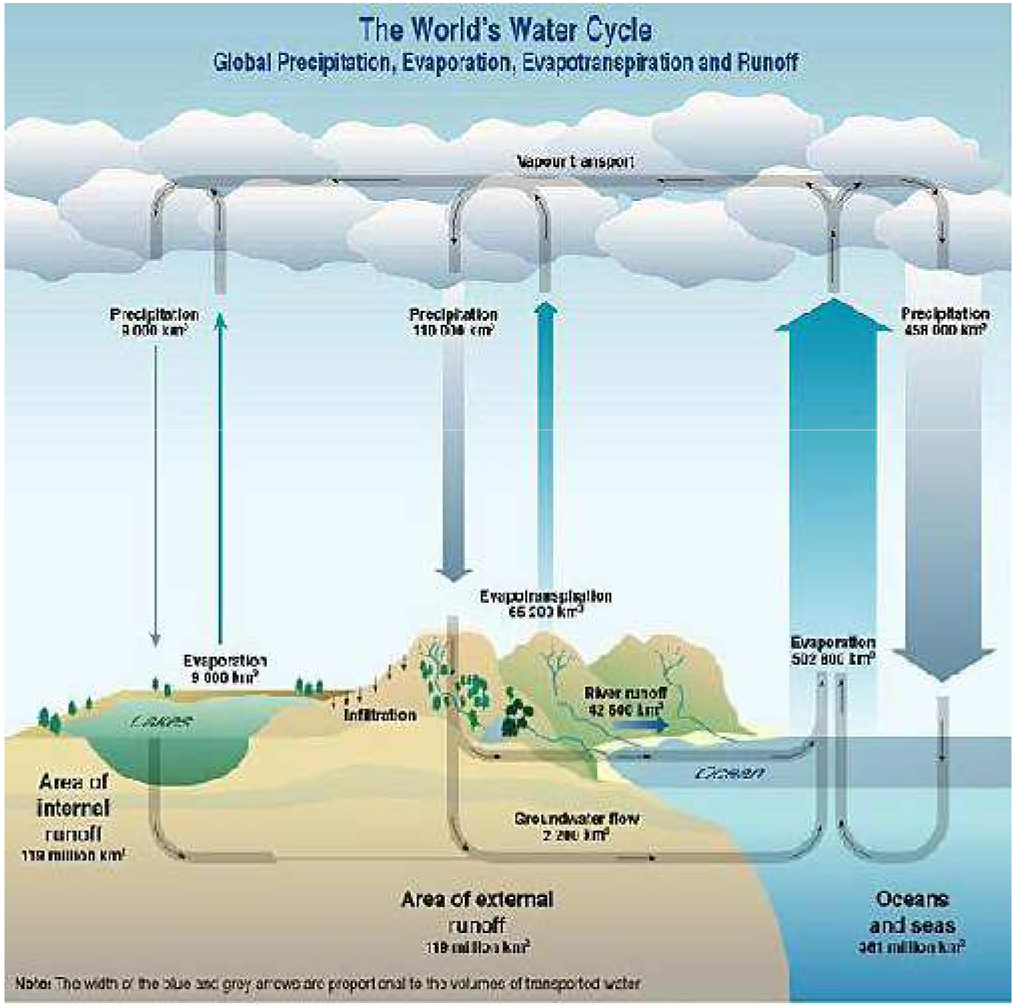
Aerosols – Clouds – Climate

IPCC 2007, Chapter 2



considered in IPCC RF

Hydrological cycle



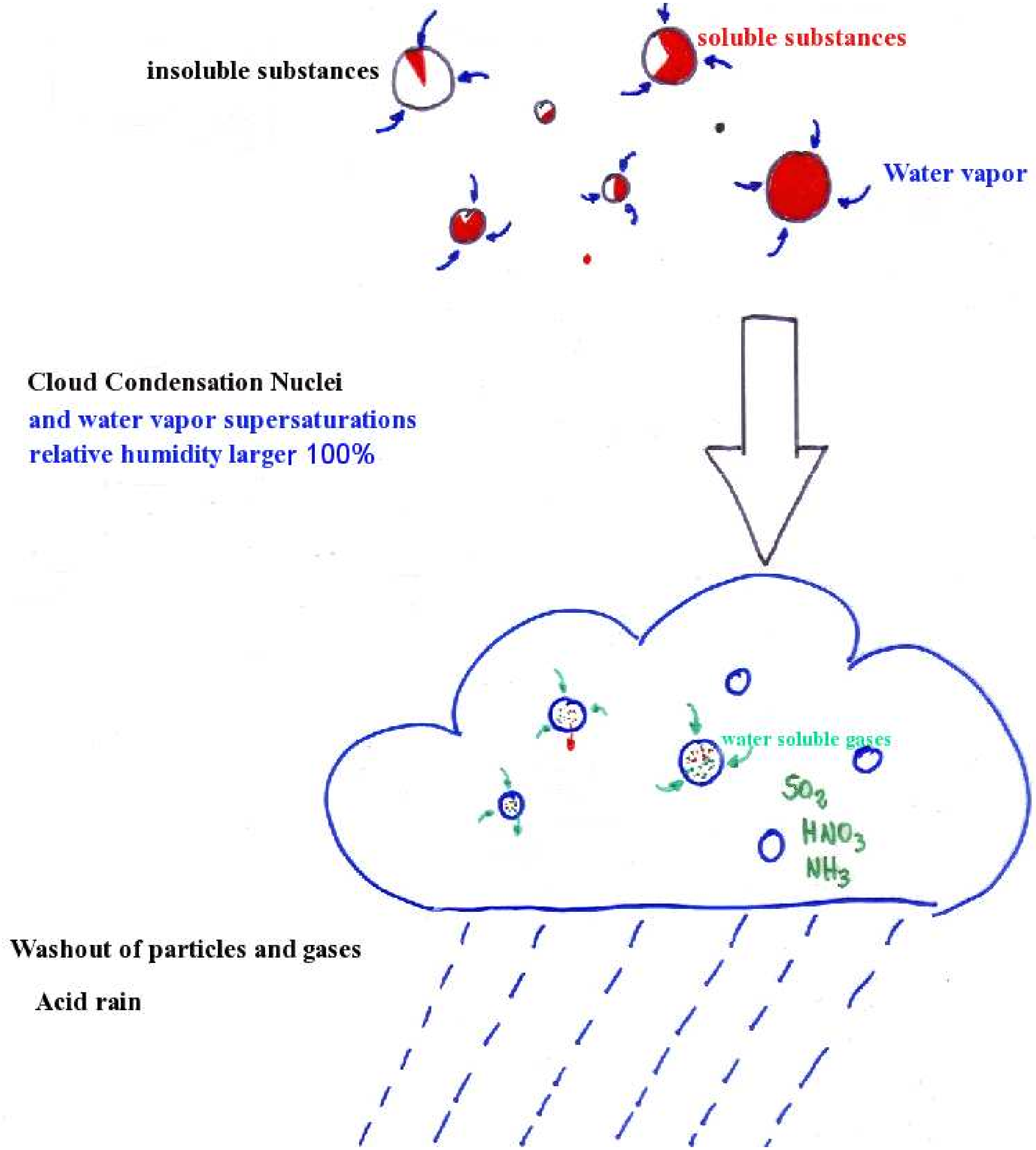
total water on Earth: $1.4 \cdot 10^9$ km^3

oceans	97.4 %
polar ice	1.9 %
ground water	0.5 %
soil	0.01 %
biosphere	0.003 %
atmosphere	0.001 %

atmospheric H_2O 4% - 1 ppmv

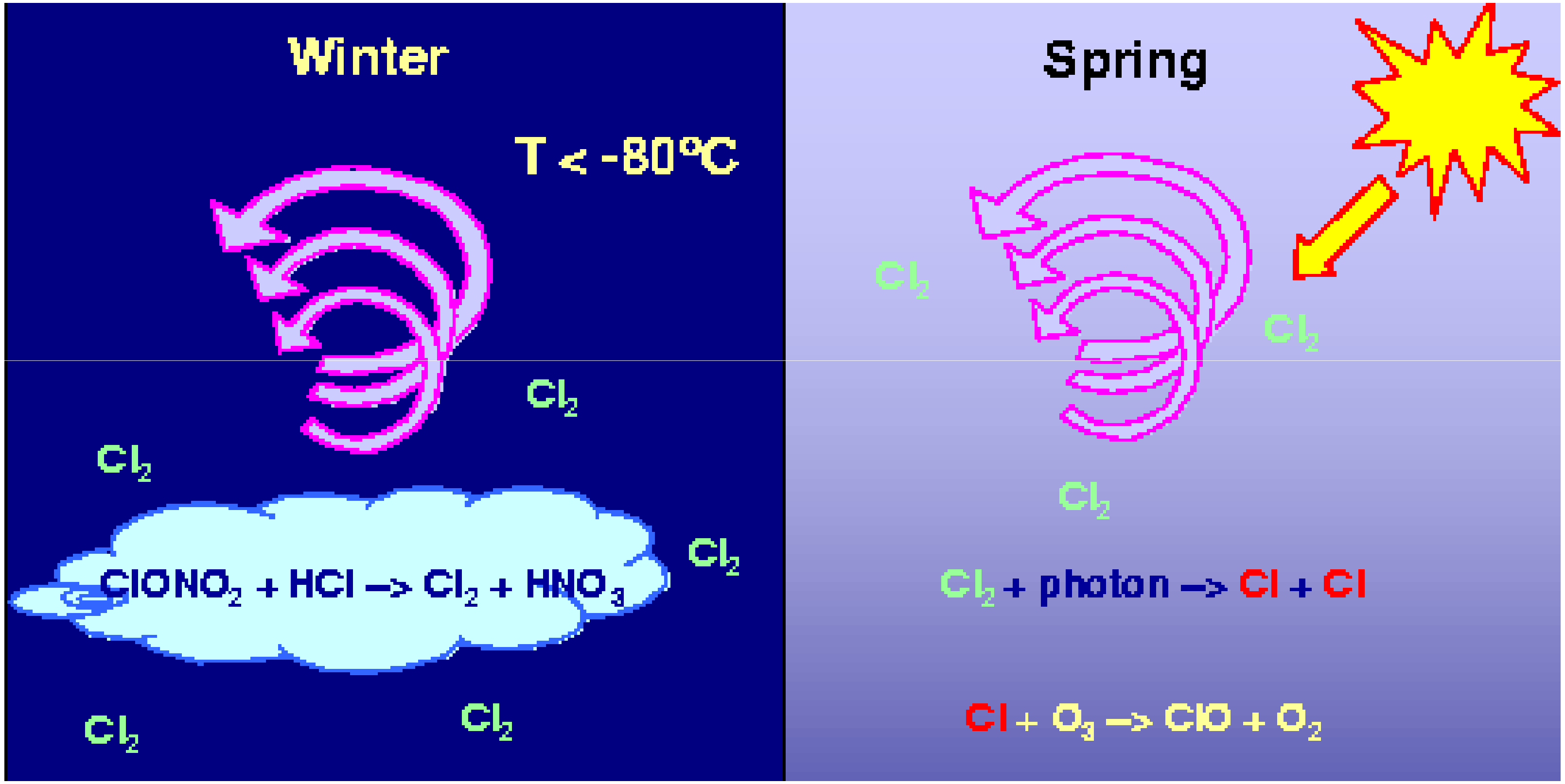
total atmospheric H_2O	25 mm
annual precipitation	800 mm
H_2O exchange rate	10-11 days

Chemical reactions in clouds: washout



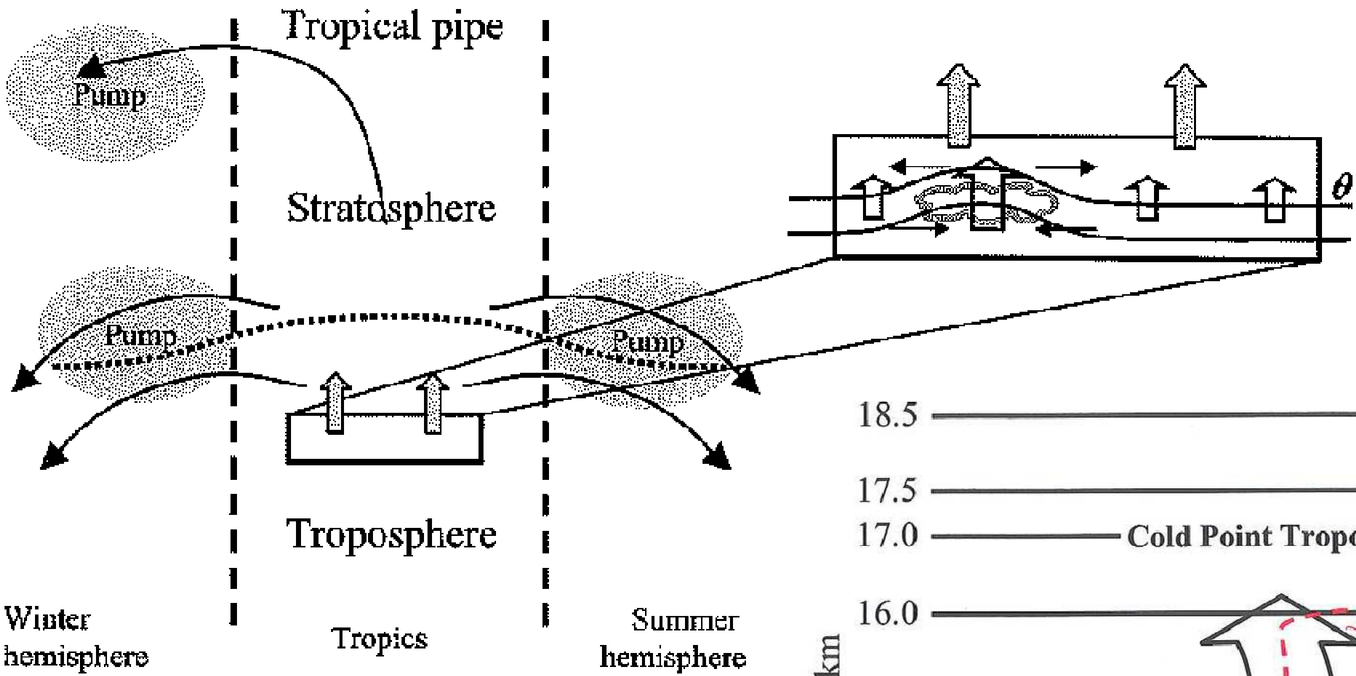
Chemical reactions in clouds: surface reactions

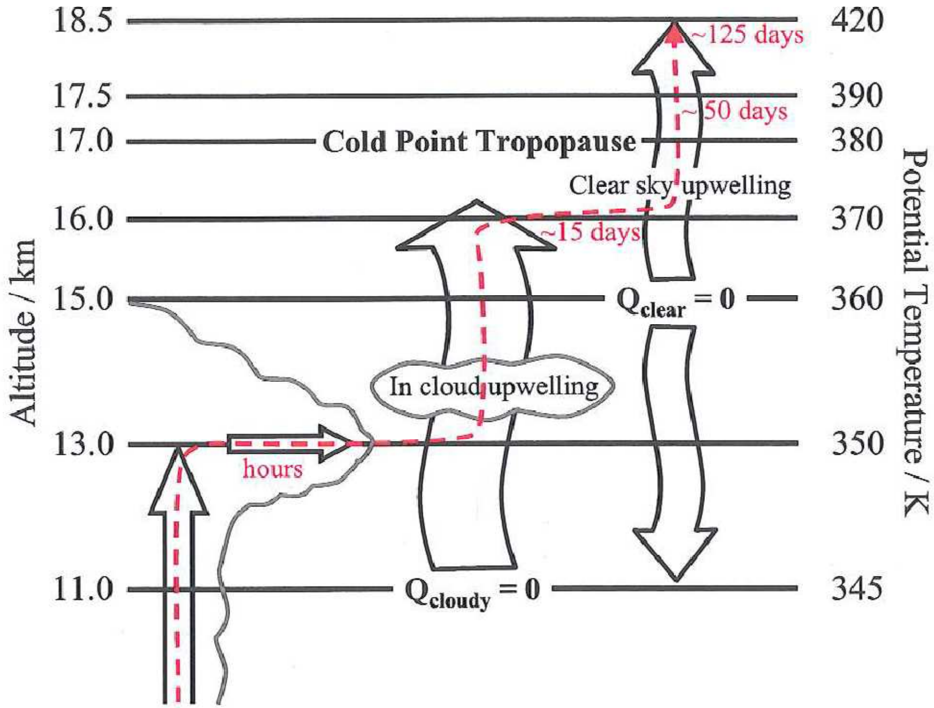
stratospheric ozone



source gas	reservoirs	reactive
CFC	HCl, $ClONO_2$	Cl_2, Cl, ClO, $(ClO)_2$

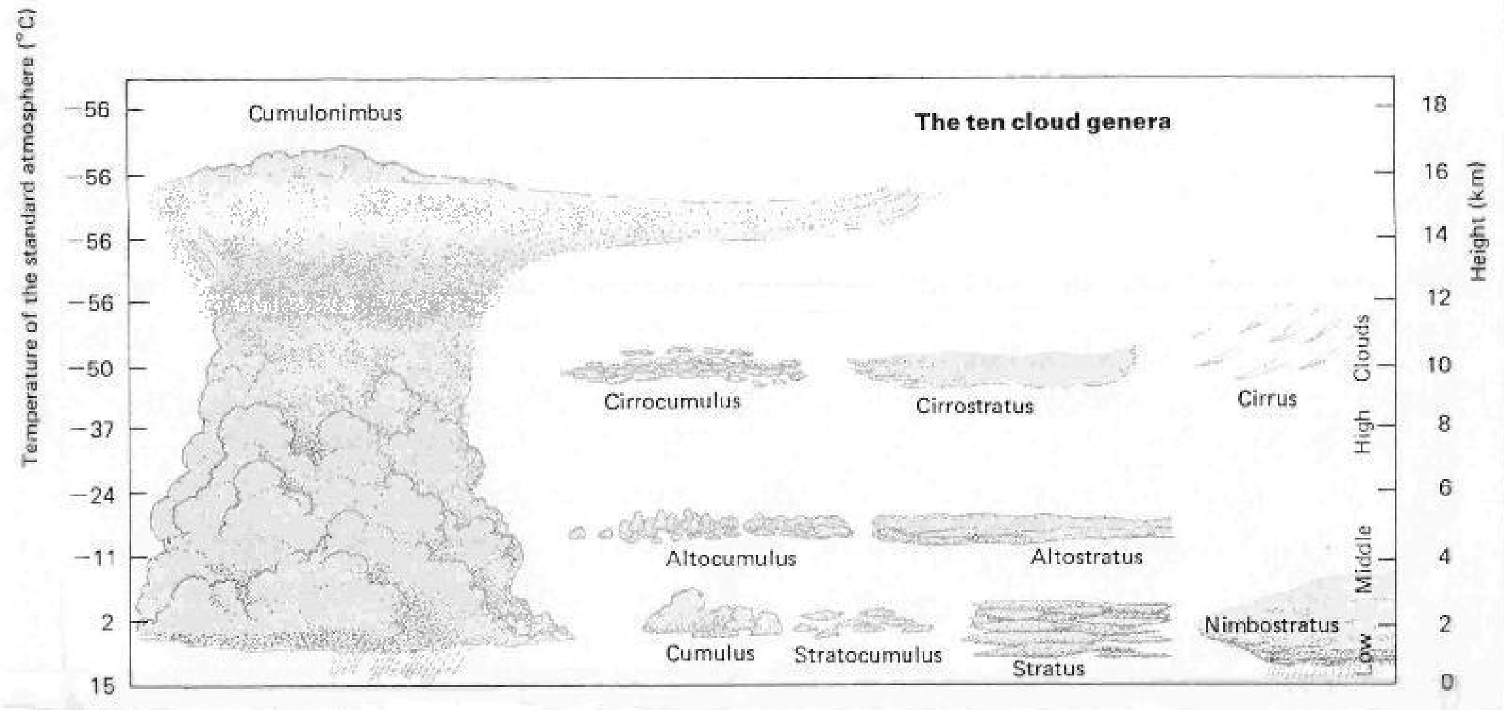
Cloud impact on vertical transport





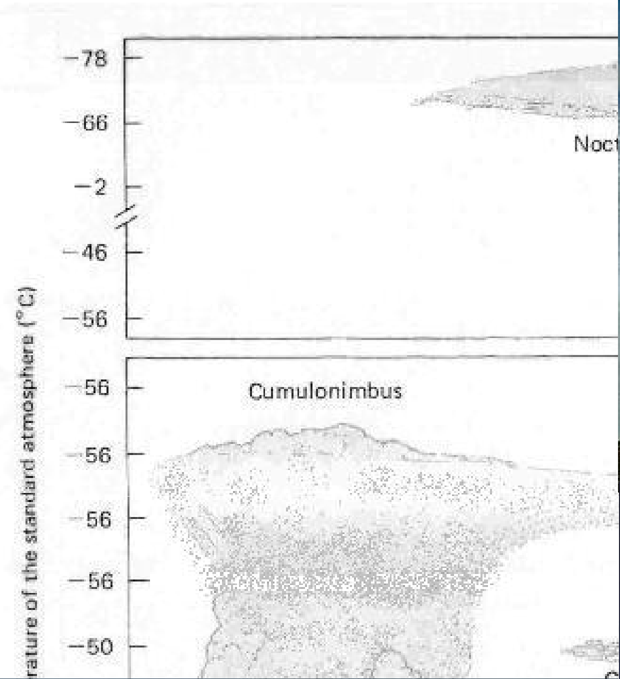
Corti et al.

Cloud types



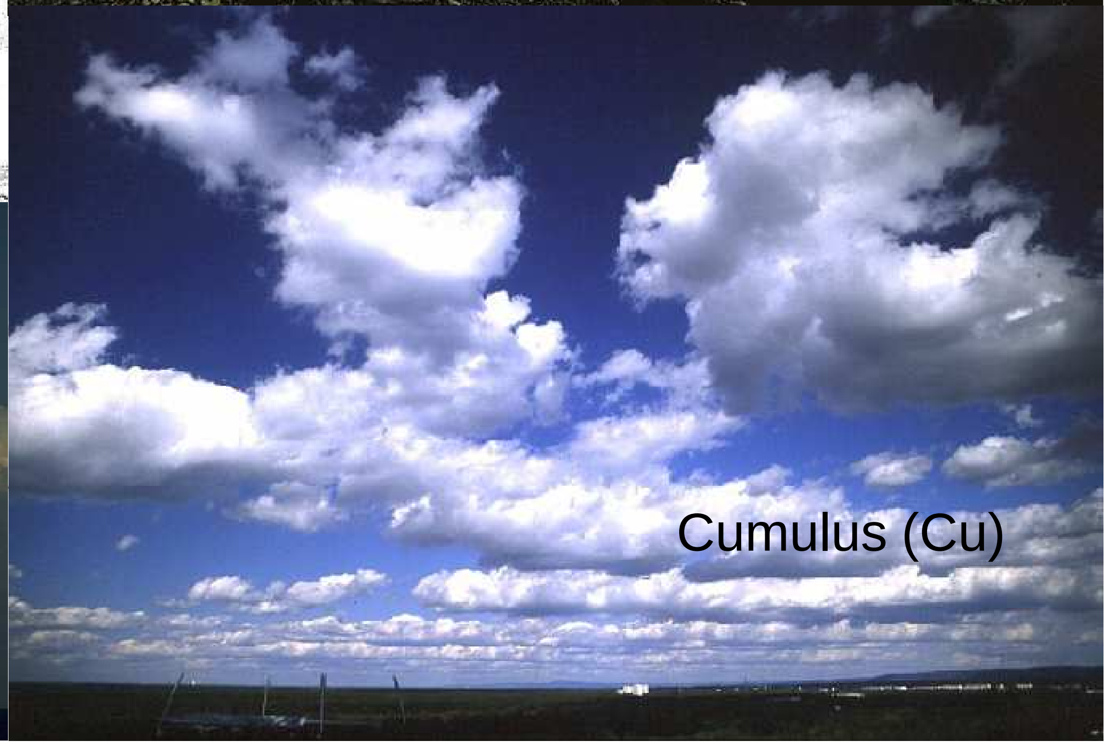
Temperature of the standard atmosphere (°C)
−56
−56
−56
−56
−50
−37
−24
−11
2
15
Cumulonimbus
The ten cloud genera
Cirrocumulus
Cirrostratus
Cirrus
Altocumulus
Altostratus
Cumulus
Stratocumulus
Stratus
Nimbostratus
High Clouds
Middle
Low
18
16
14
12
10
8
6
4
2
0
Height (km)

Low Clouds

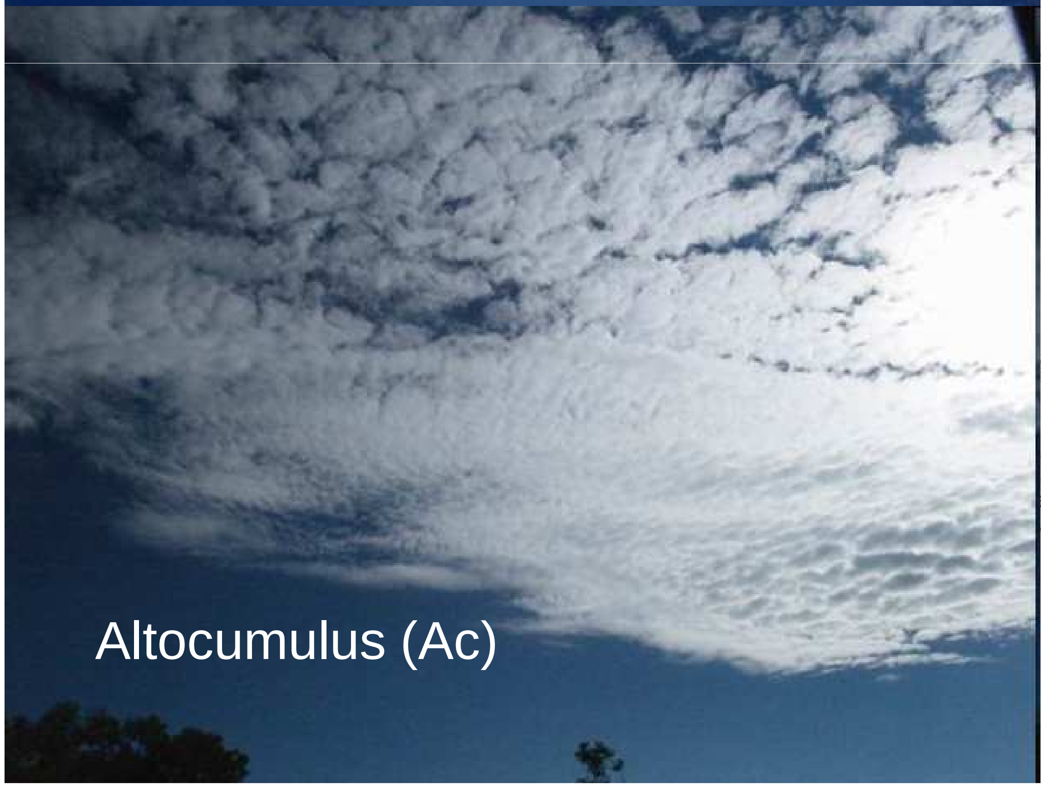

−78
−66
−2
−46
−56
Cumulonimbus
−56
−56
−56
−56
−50

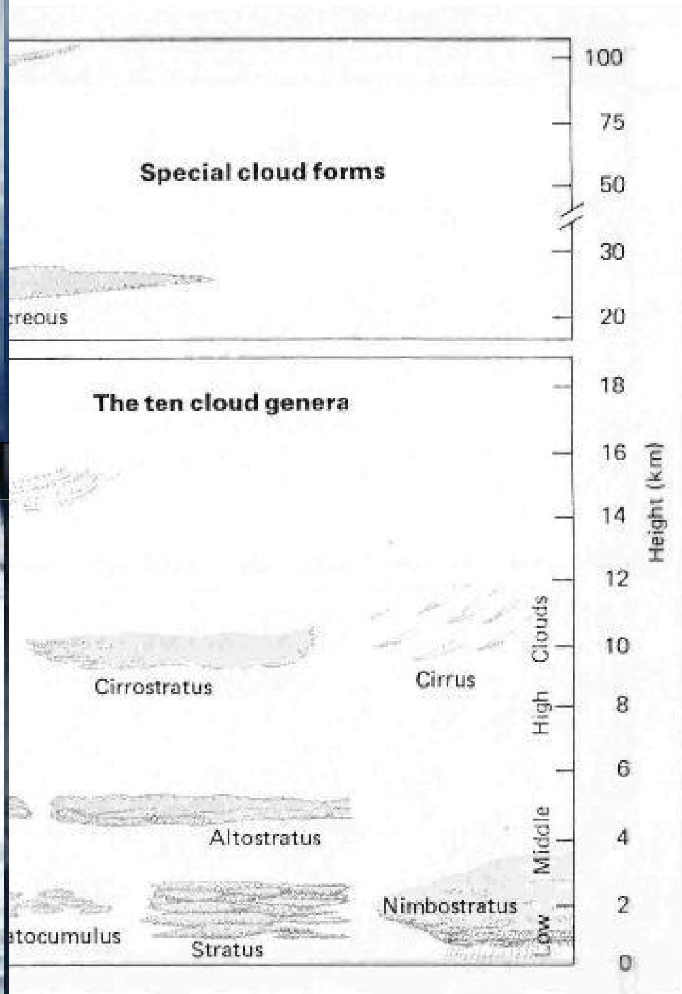

Stratus (St)


Cumulus Congestus


Cumulus (Cu)

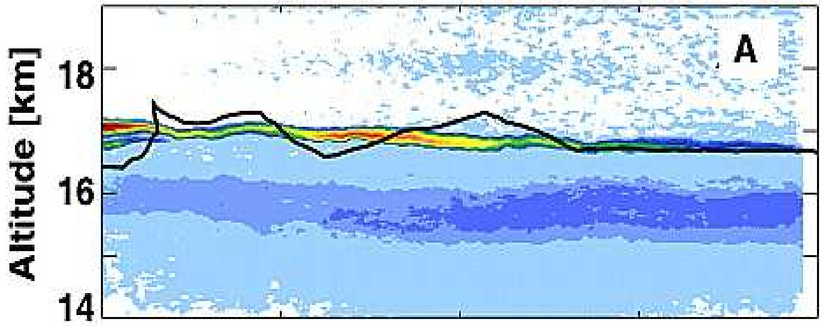
Medium-high Clouds

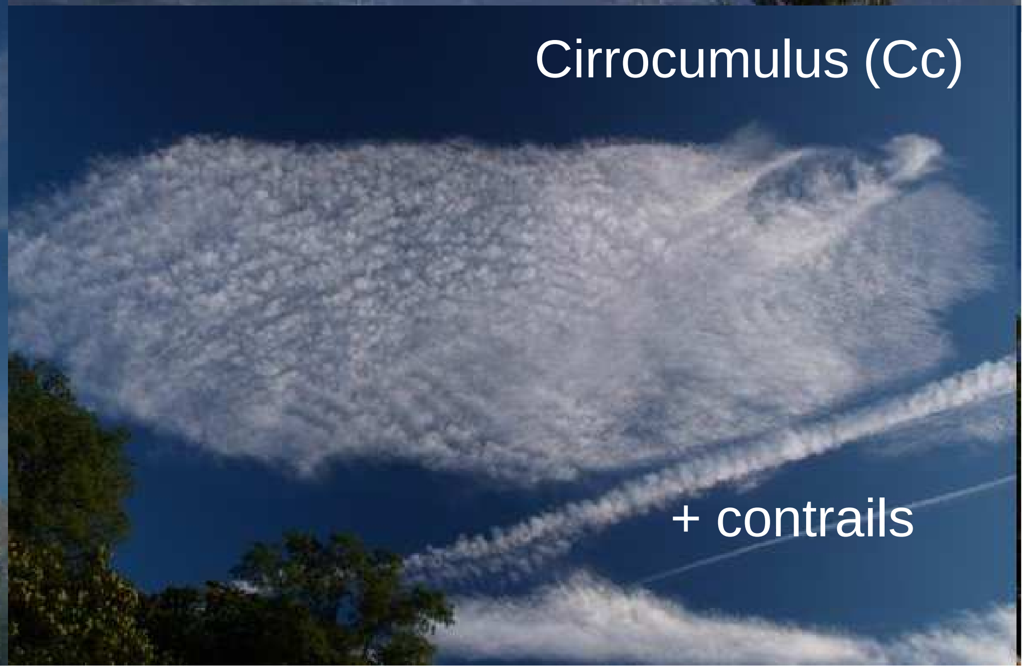




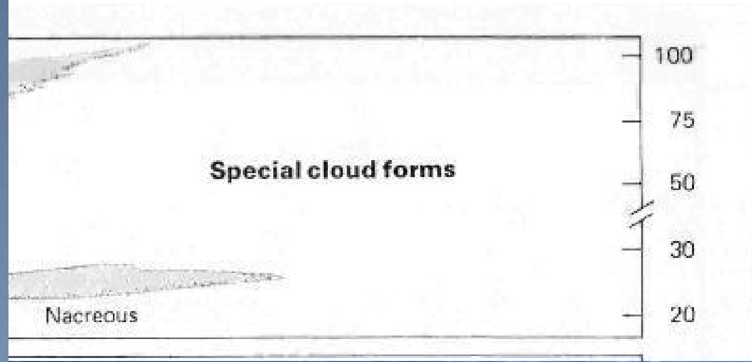
High Clouds

Subvisible cirrus (SVC/UTTC)

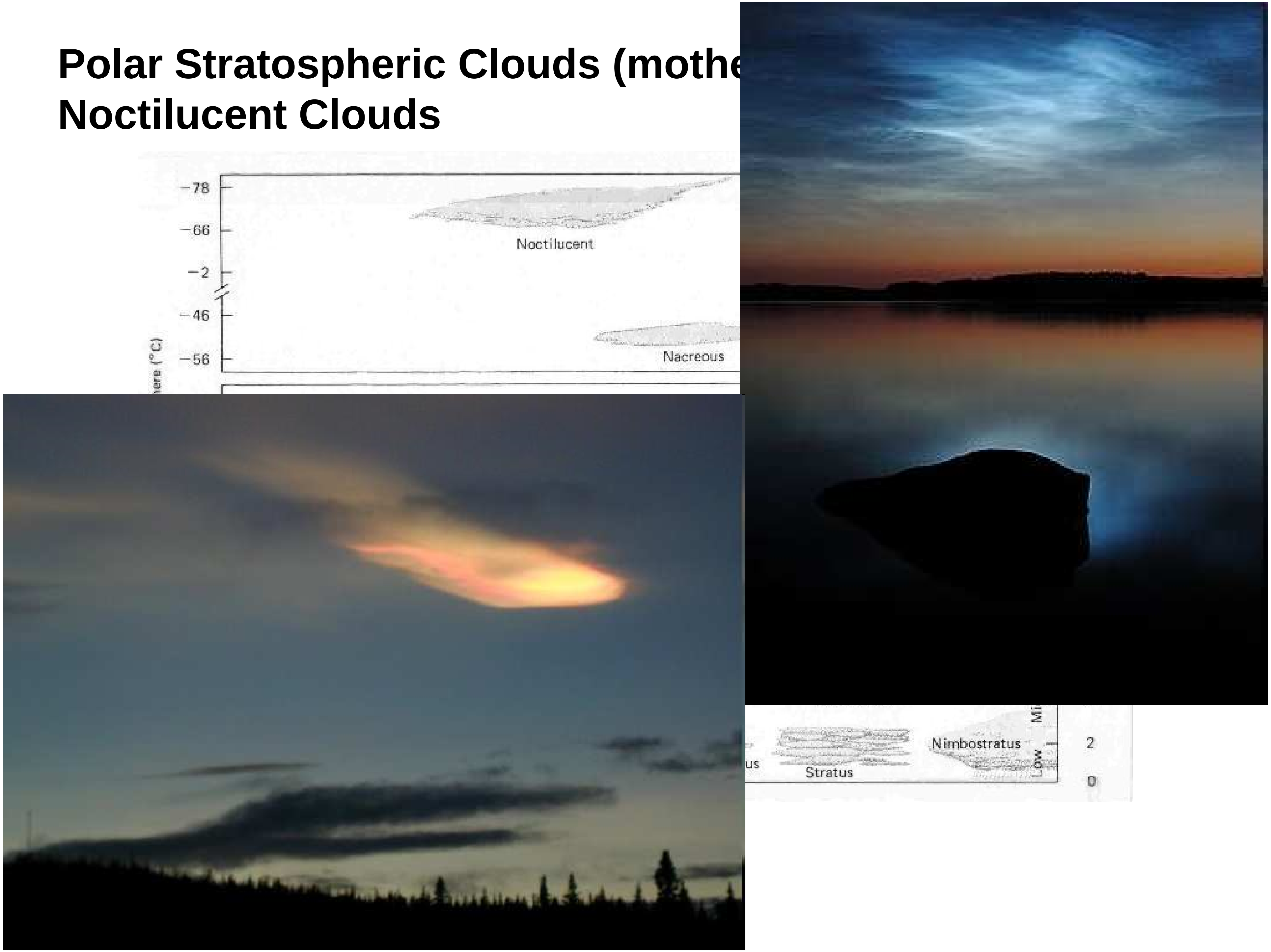


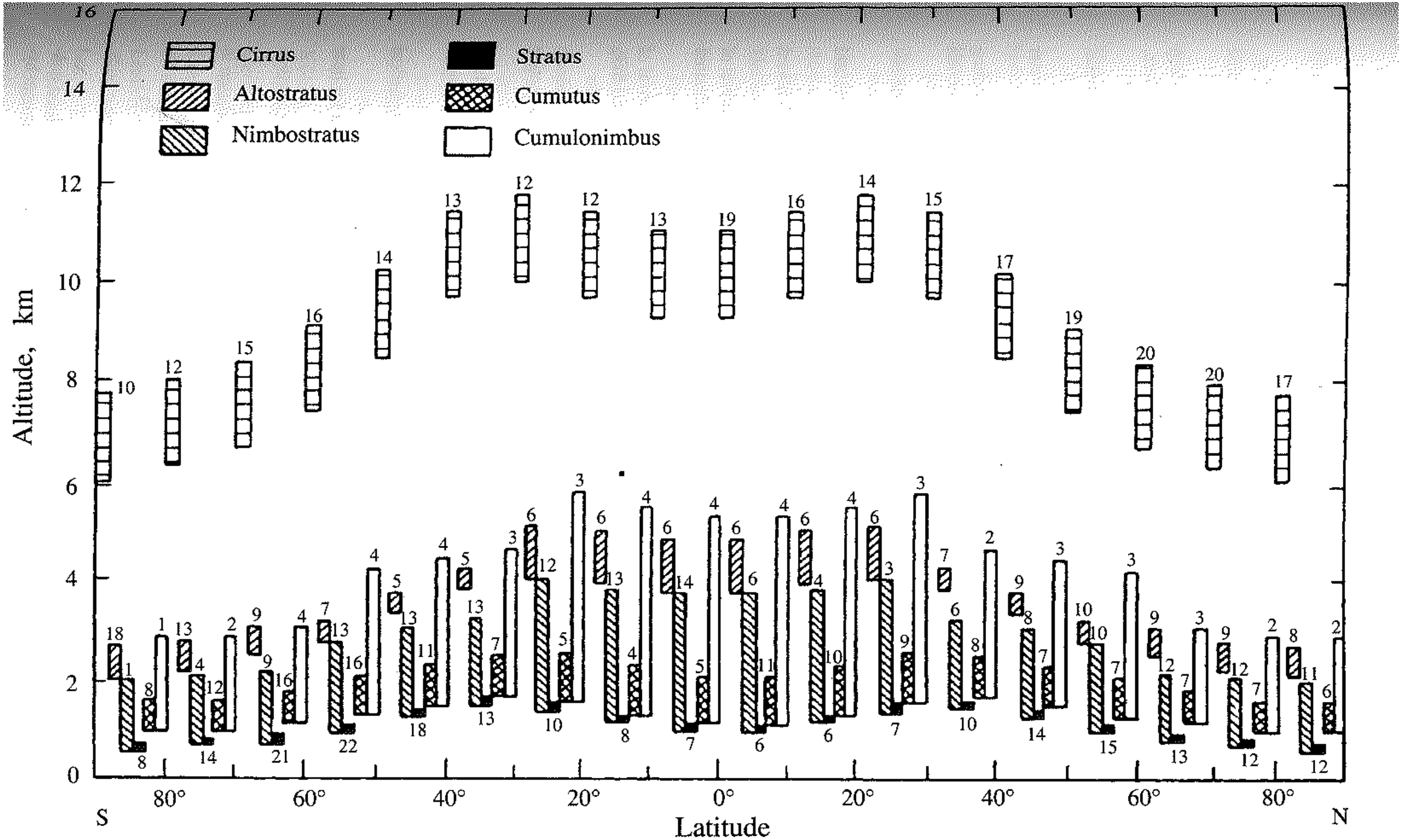


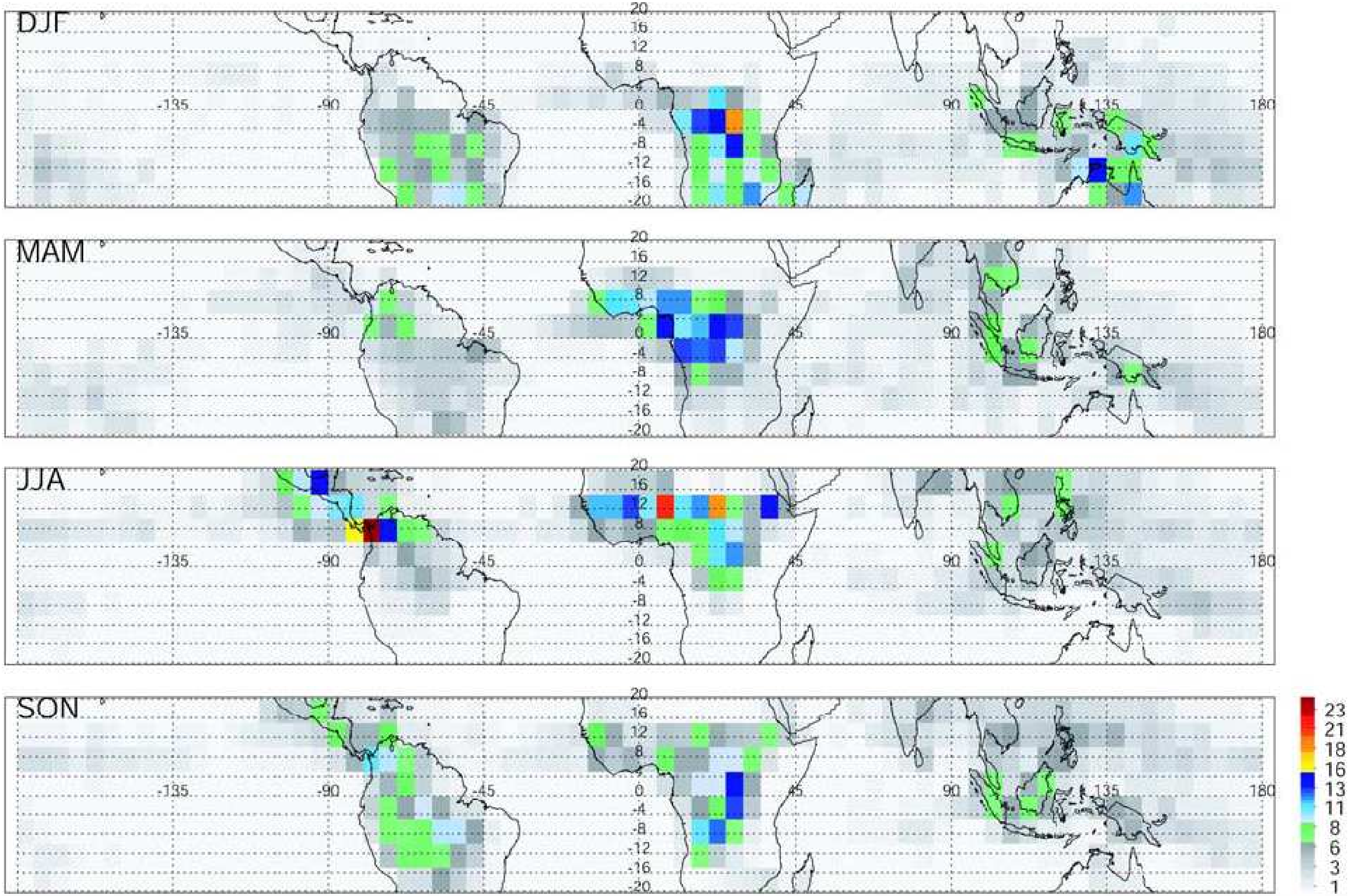
Cumulonimbus (Cb)



Polar Stratospheric Clouds (mothe
Noctilucent Clouds




Cirrus
Altostratus
Nimbostratus
Stratus
Cumutus
Cumulonimbus
Altitude, km
0
2
4
6
8
10
12
14
16
Latitude
S
80°
60°
40°
20°
0°
20°
40°
60°
80°
N

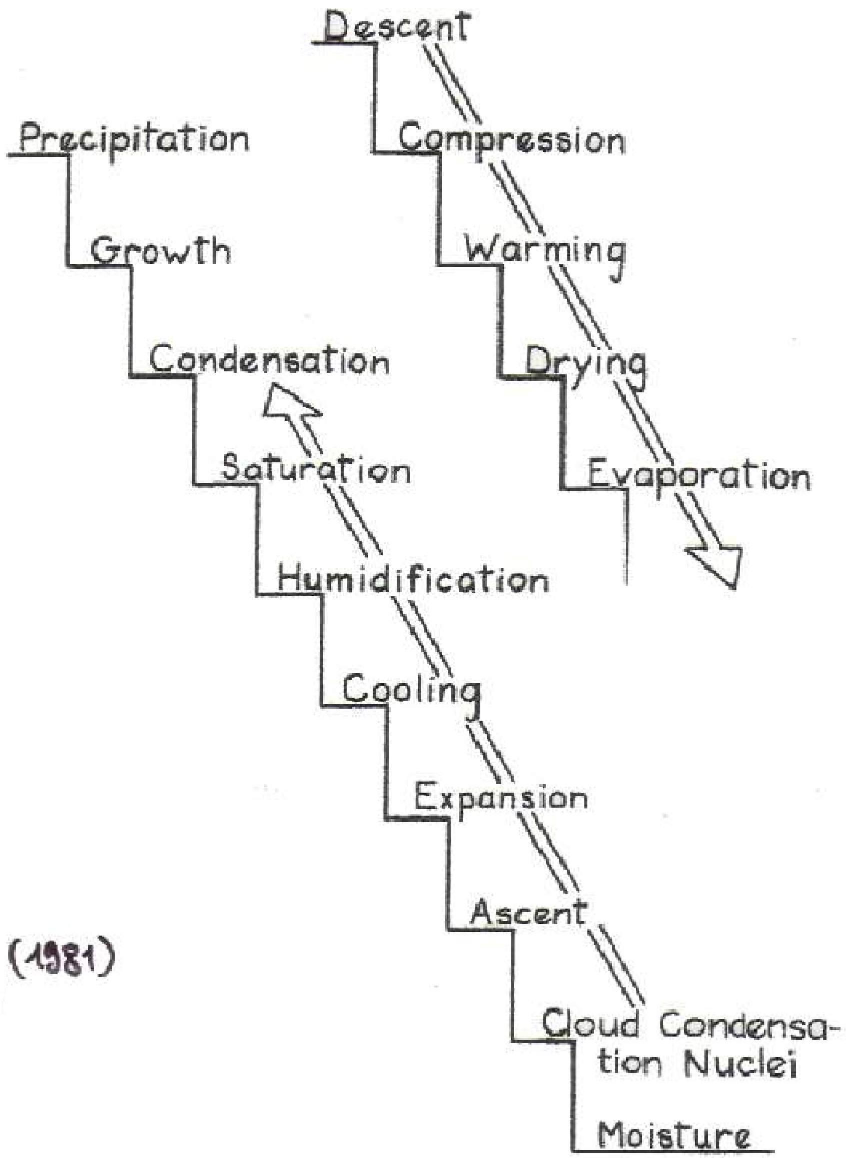


Liu & Zipser, TRMM cloud occurence > 14 km

Precipitation staircase

Prerequisites for cloud formation:

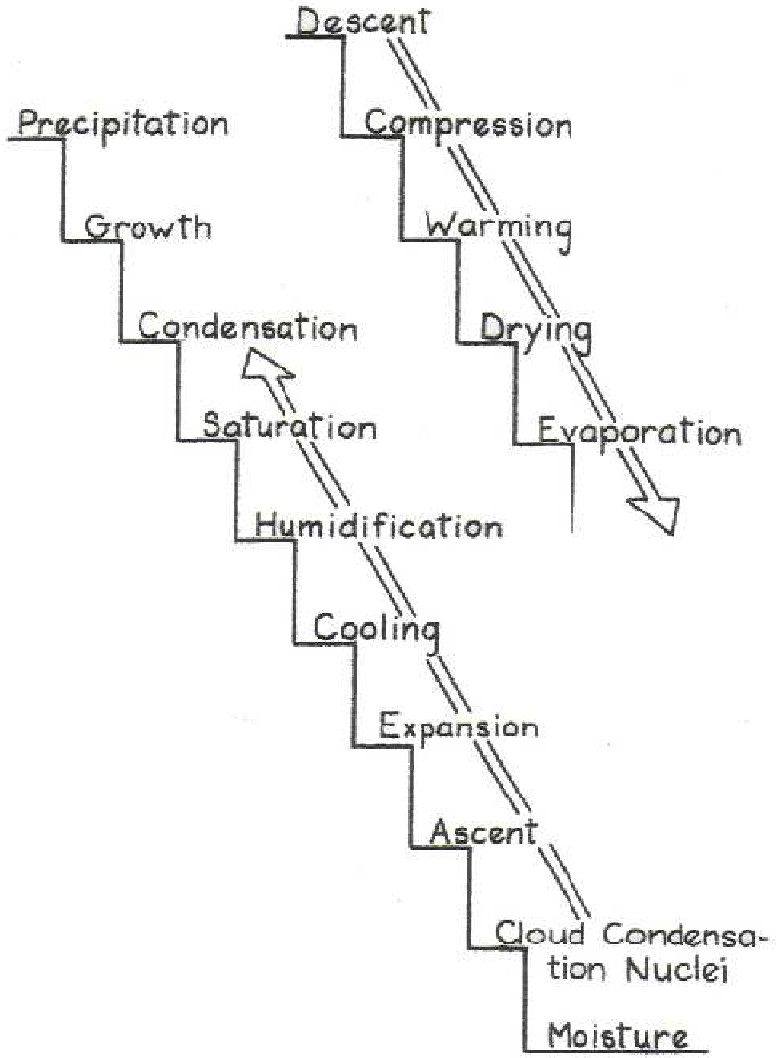
- water
- low T
- supersaturation
- Cloud Condensation Nuclei (CCN) or Ice Nuclei (IN)



Schaefer & Day (1981)

Cloud formation and precipitation

- Cooling
- Warm Clouds
- Cold clouds
- Precipitation



Cooling

- Isobaric cooling
- Adiabatic cooling

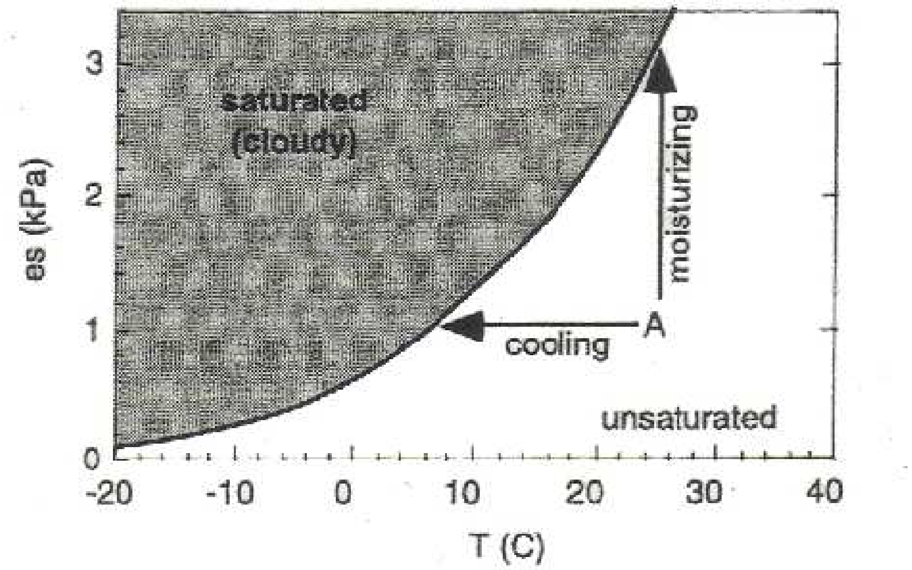


Figure 6.5
Unsaturated air parcel A can become saturated by the addition of moisture, or by cooling. (Meteorol. Today, Ahrens 1982)
Stull 1995

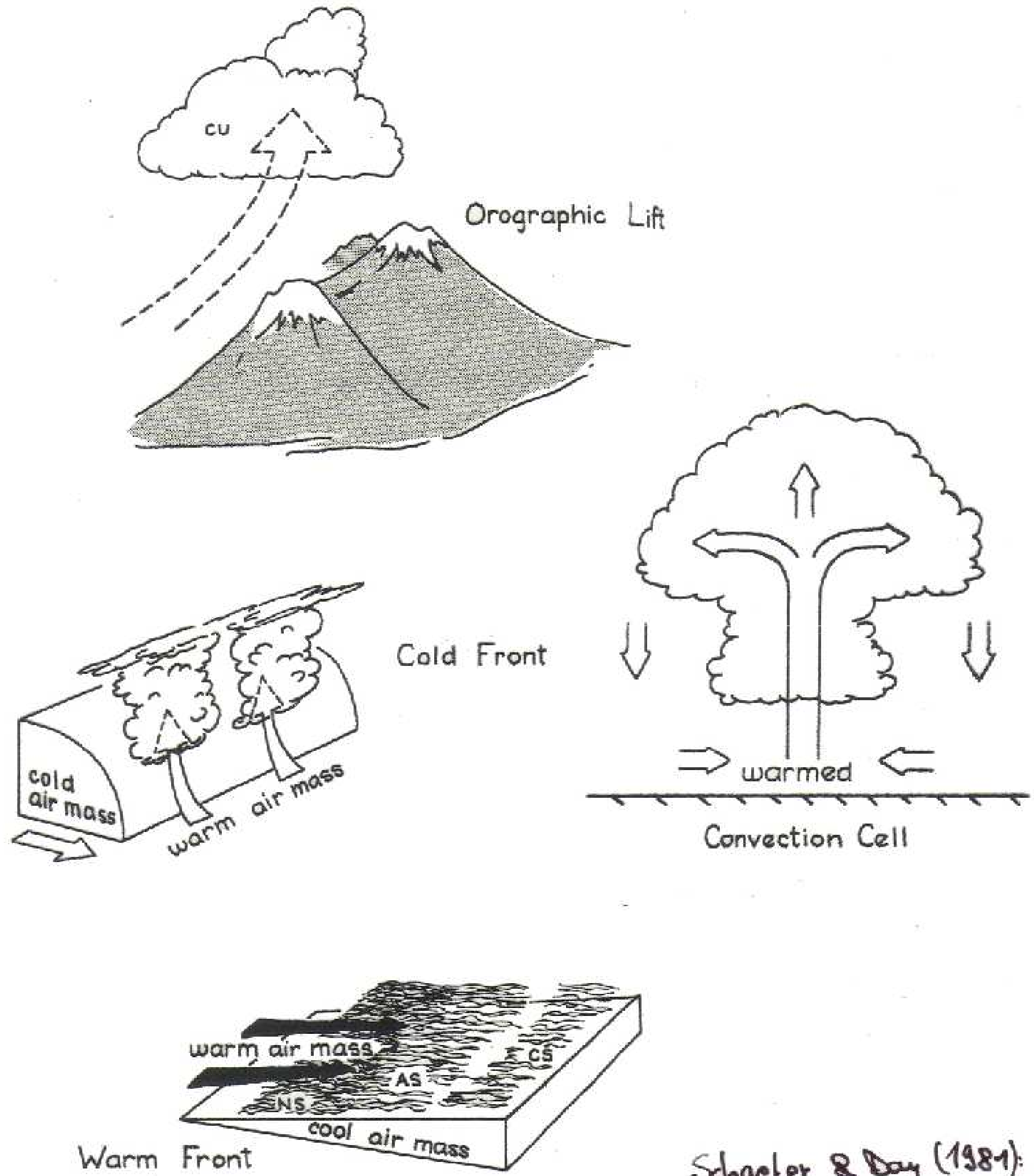
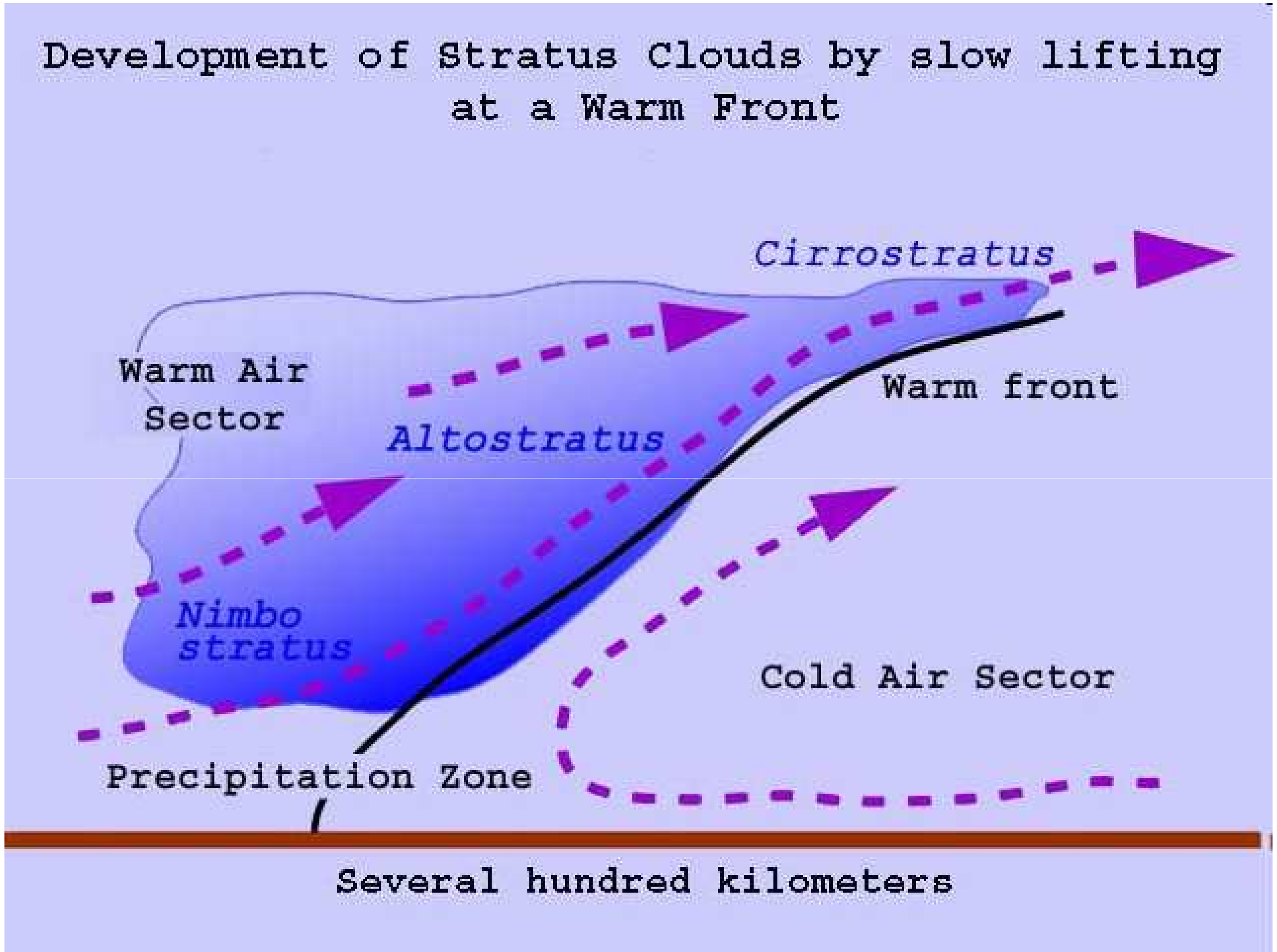


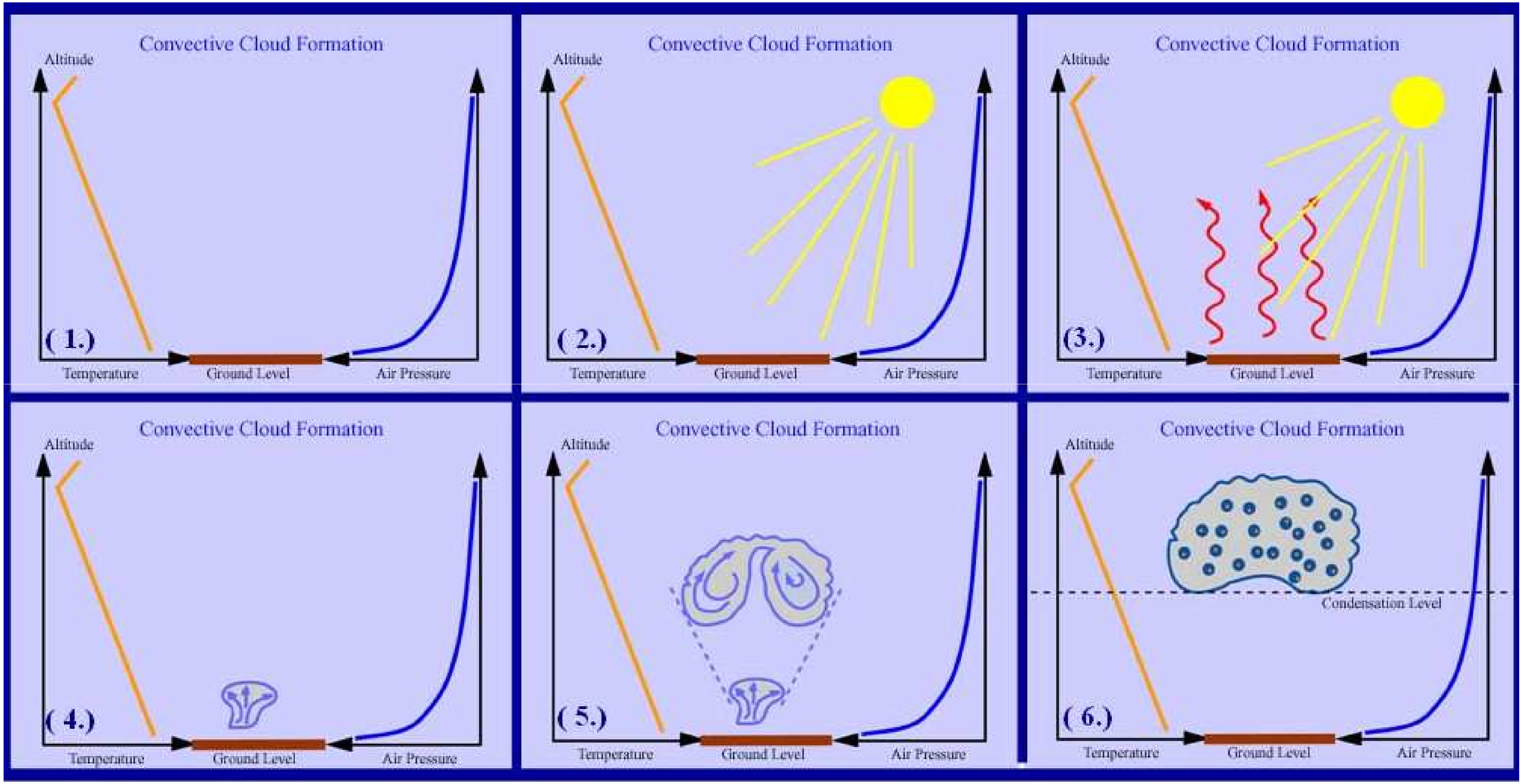
Fig. 14 Cloud and front formation—causes of rising air.

Schaefer & Day (1981):
A field guide to the
atmosphere

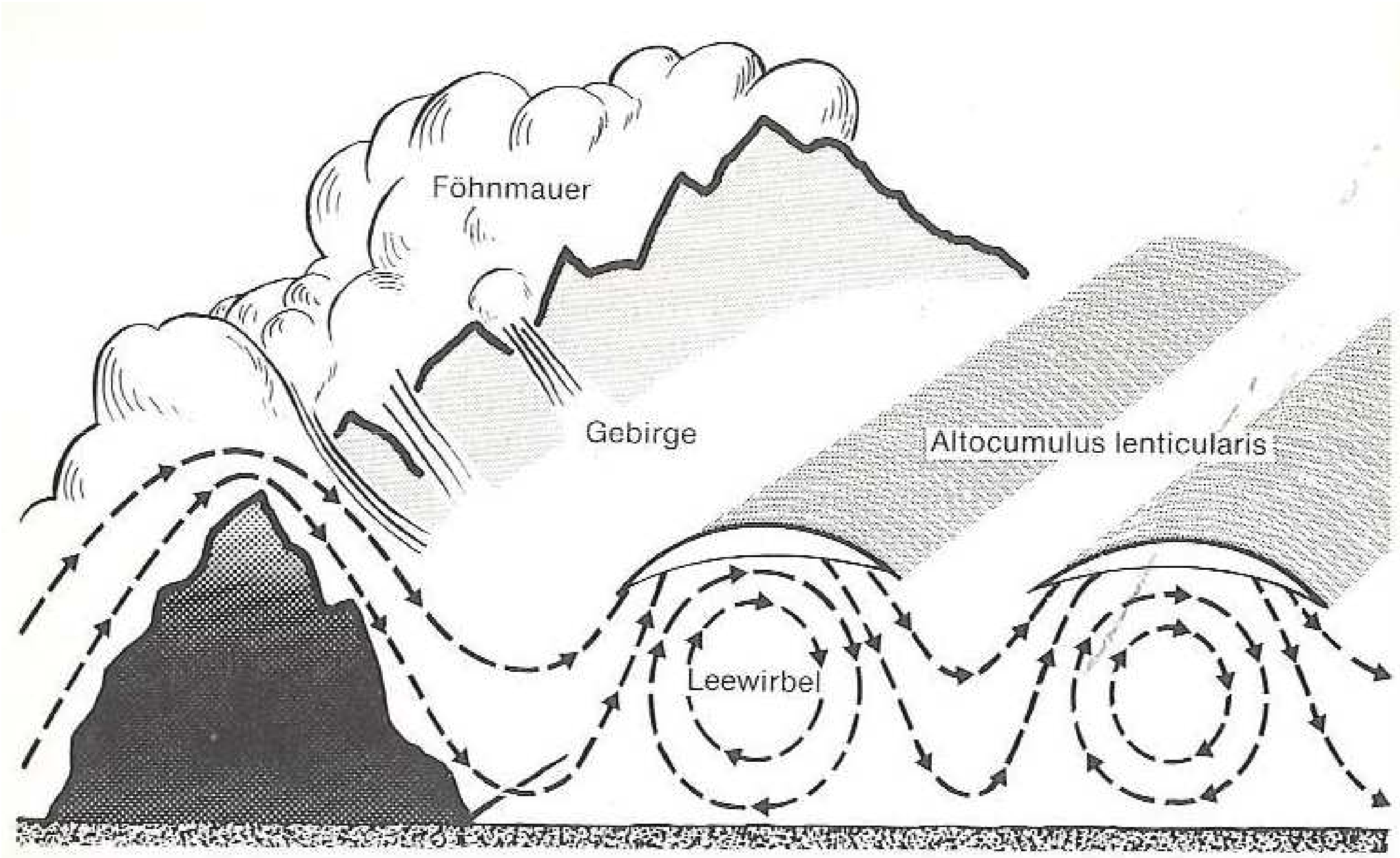
Frontal cloud formation



Convective cloud formation

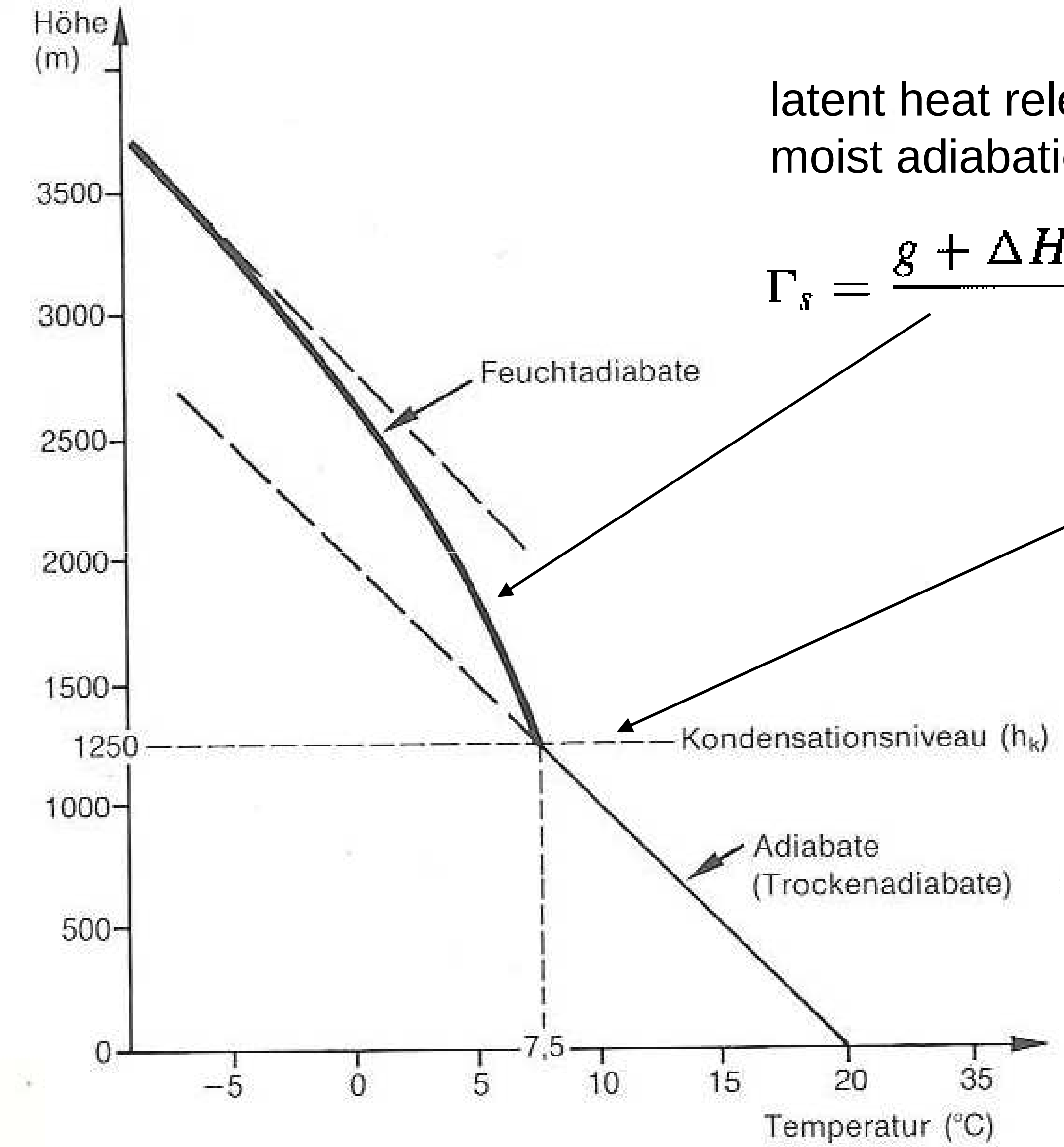


Orographic cloud formation



also up to cirrus / PSC altitudes

Adiabatic cooling



latent heat release ΔH_v by condensation
moist adiabatic lapse rate:

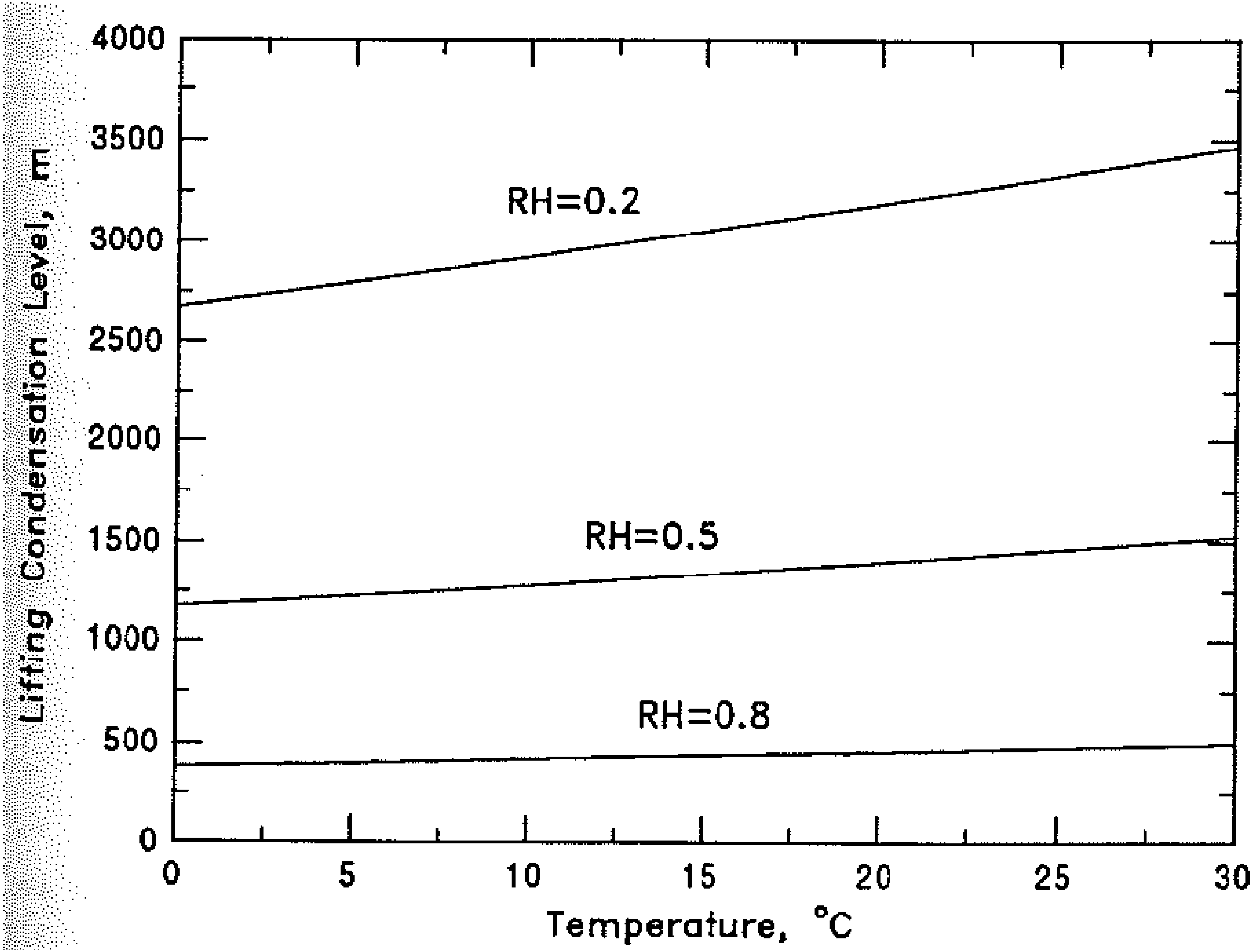
$$\Gamma_s = \frac{g + \Delta H_v (dw_{vs}/dz)}{\hat{c}_p} < \Gamma$$

lifting condensation level

$$h_{LCL} = \frac{T_0 - T_L}{\Gamma}$$

$$\frac{dT}{dz} = -\Gamma \quad \text{or} \quad dT/dt = -\Gamma \cdot w$$

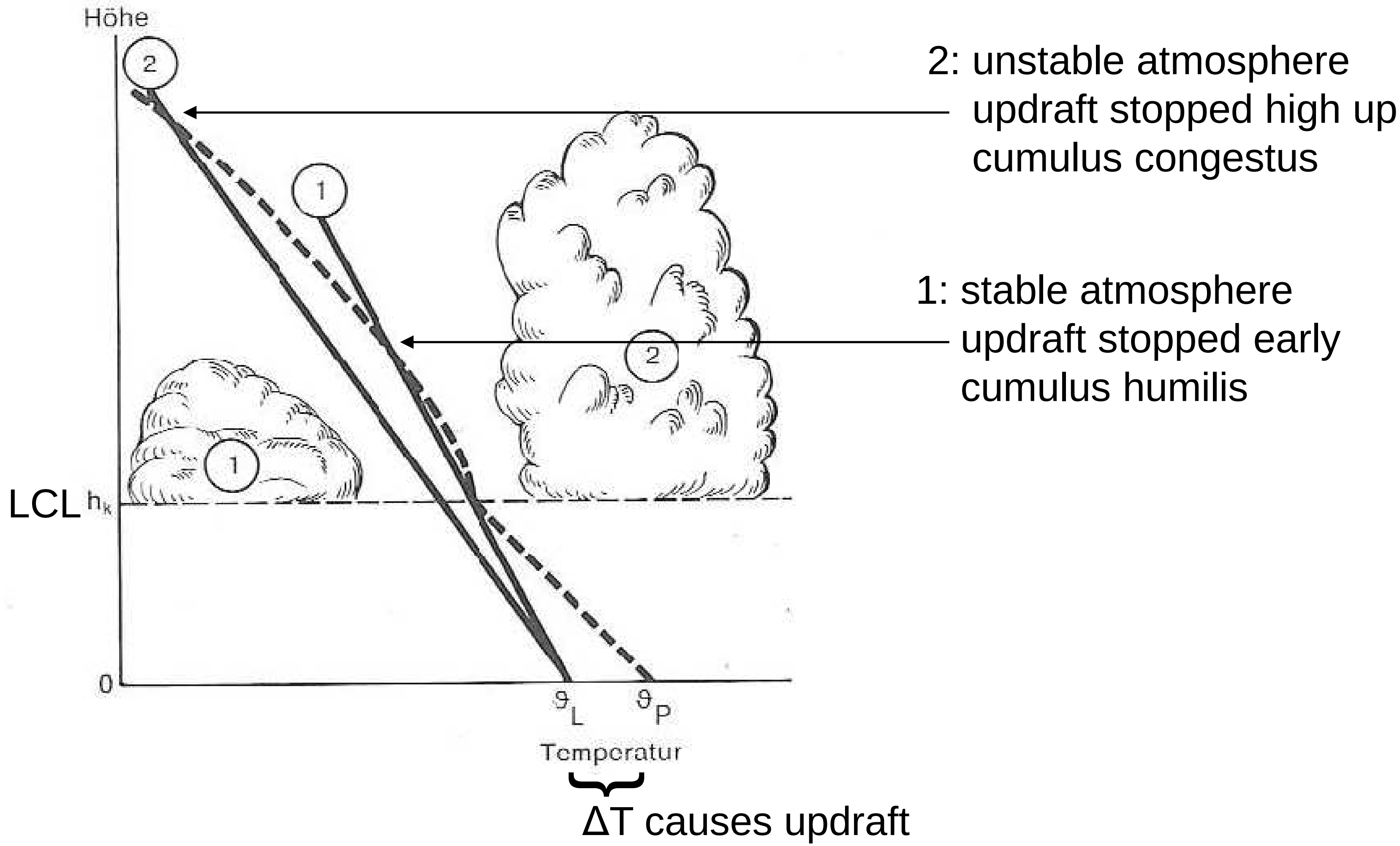
$\Gamma = g/\hat{c}_p$ dry adiabatic lapse rate



Lifting Condensation Level, m
4000
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
Temperature, °C
RH=0.2
RH=0.5
RH=0.8

Cumulus formation

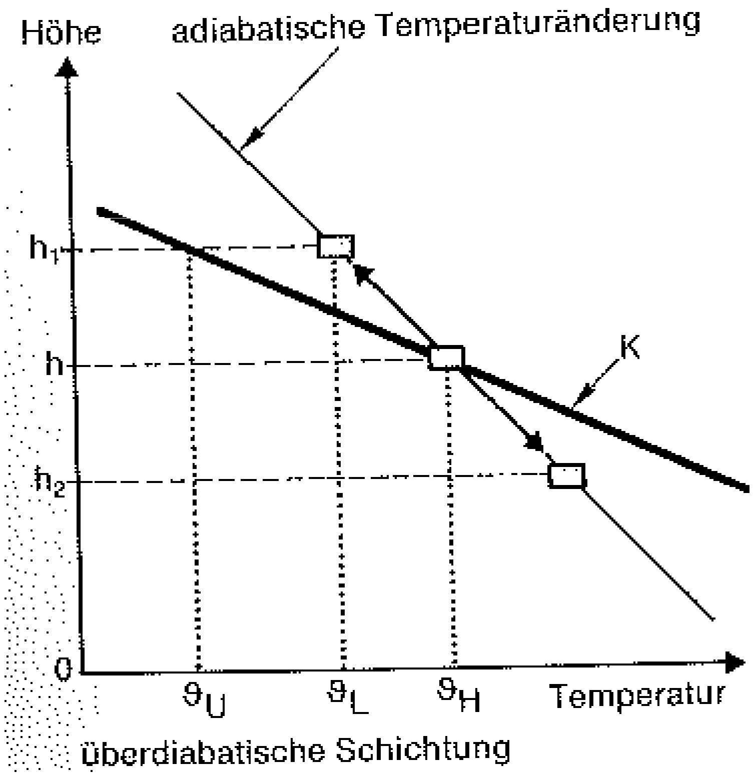
depends on H_2O content and stability of atmosphere

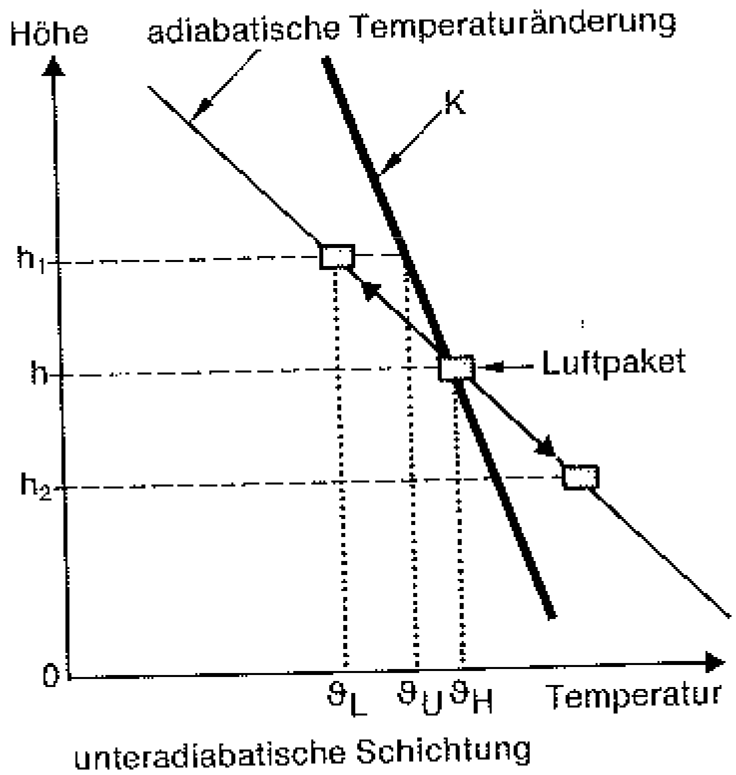


Stability in the atmosphere

unstable
strong T-gradient

stable
weak T-gradient or inversion





Warm Clouds

Equilibrium between phases: Clausius Clapeyron equation

vapour/water

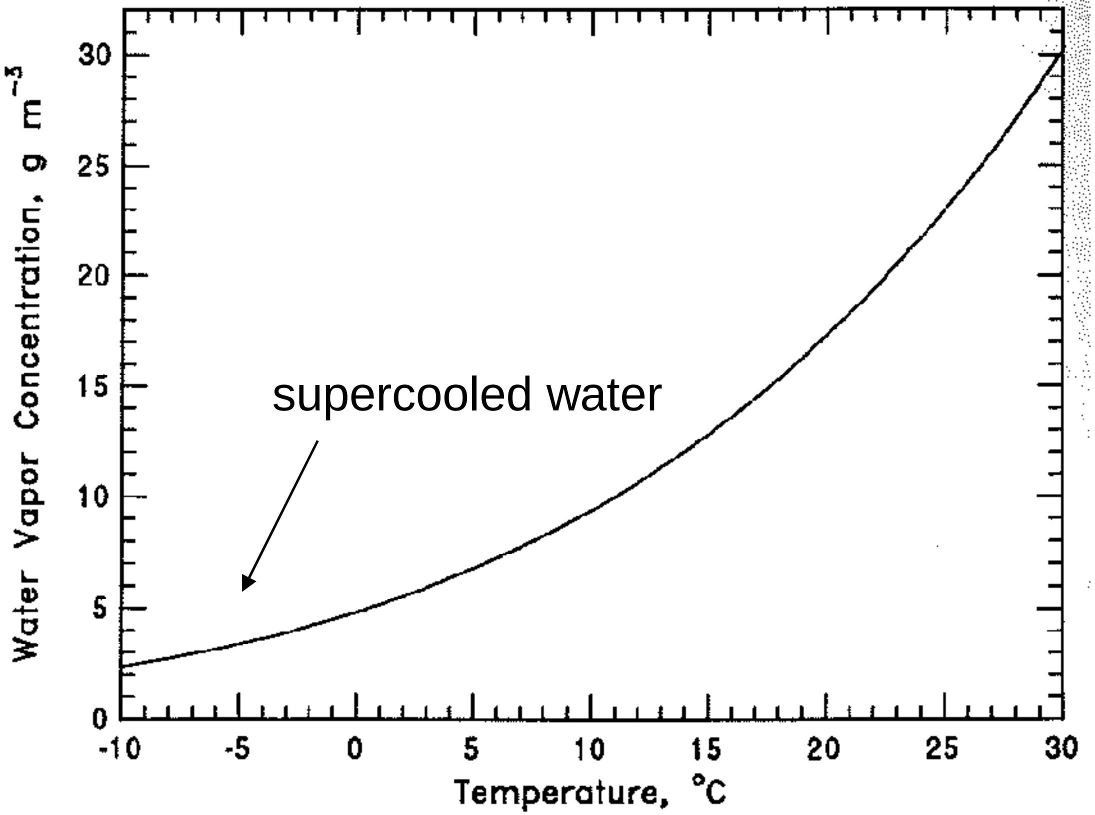
$$\frac{dp^\circ}{dT} = \frac{\Delta H_v(T) M_w}{T(v_v - v_w)}$$

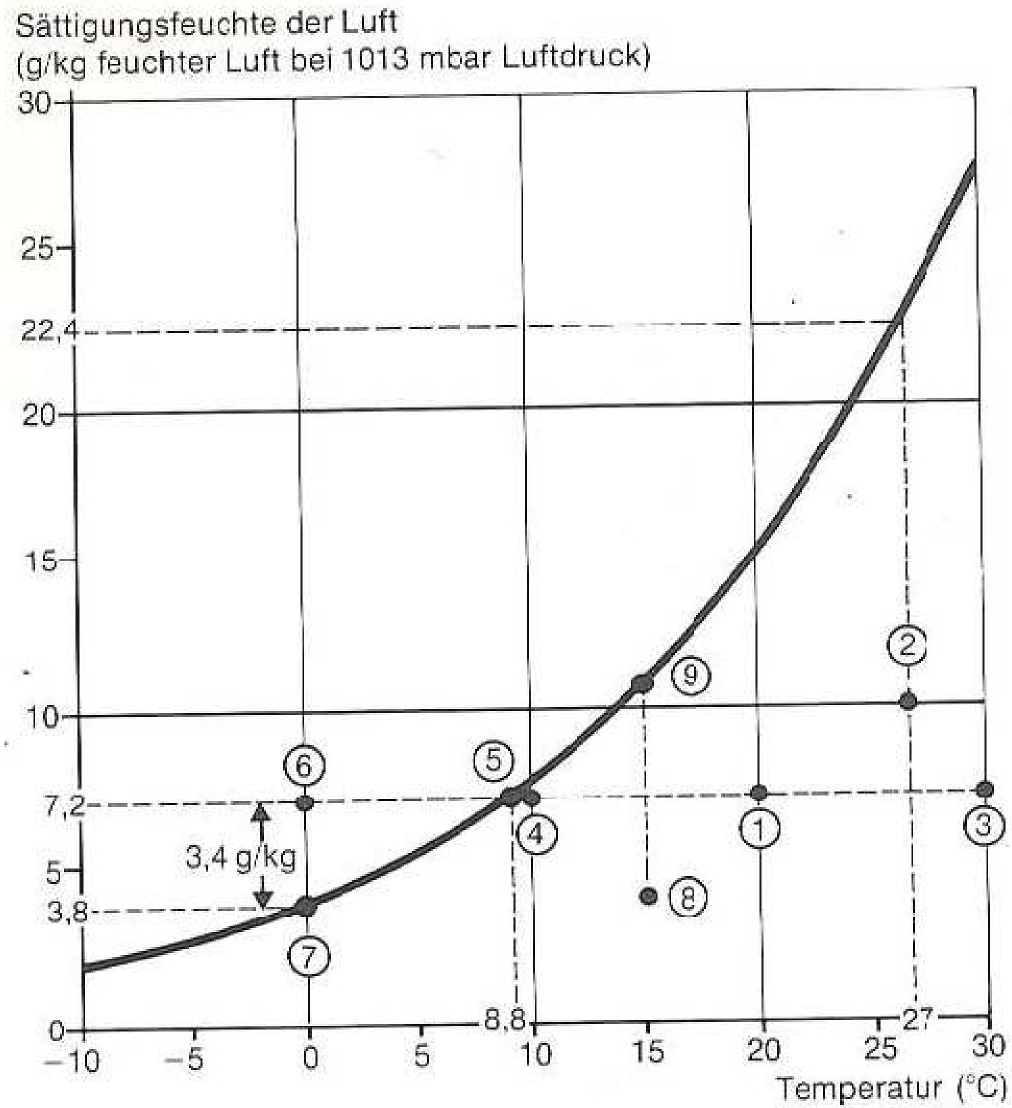
$\Delta H_v(T)$ specific heat (water evap.)
M_w molecular weight

$$v_v \gg v_w$$

$$p^\circ v_v = RT$$

$$\frac{dp^\circ}{dT} \simeq \frac{\Delta H_v(T) p^\circ M_w}{RT^2}$$

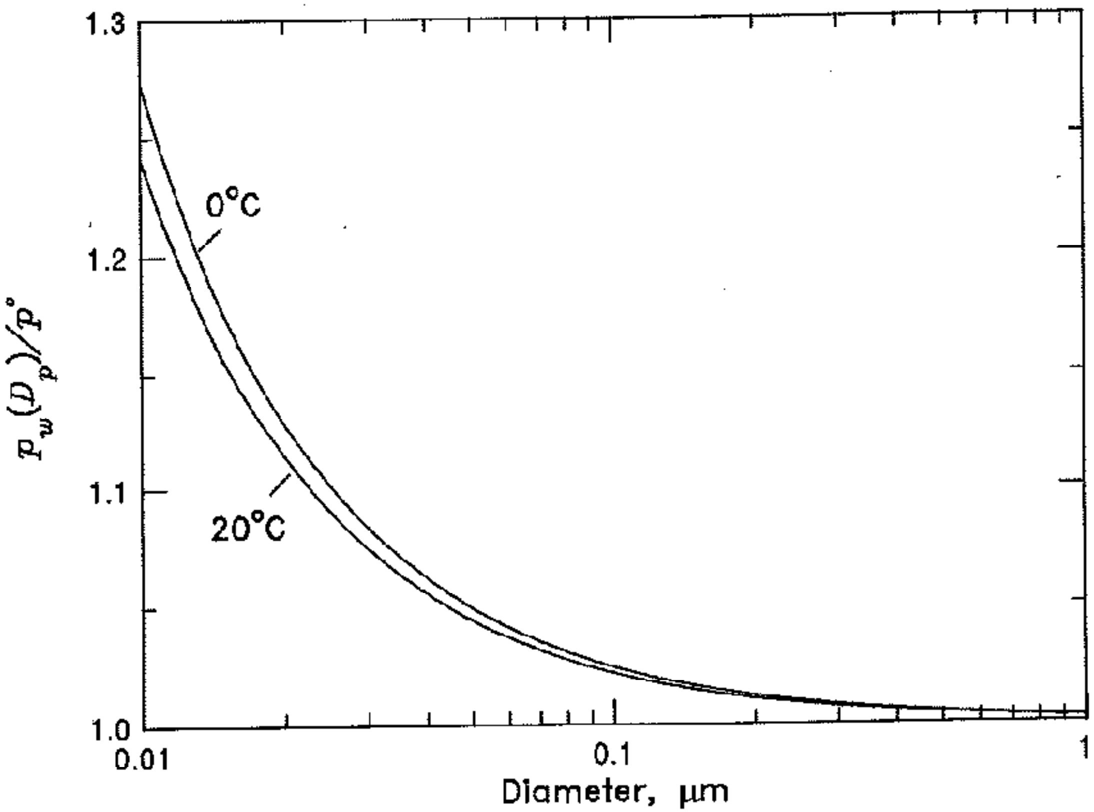



Sättigungsfeuchte der Luft
(g/kg feuchter Luft bei 1013 mbar Luftdruck)
30
25
22,4
20
15
10
7,2
5
3,8
0
3,4 g/kg
1
2
3
4
5
6
7
8
9
8,8
27
−10
−5
0
5
10
15
20
25
30
Temperatur (°C)

Equilibrium of water droplet vs flat surface

Kelvin equation

$$\frac{p_w(D_p)}{p^\circ} = \exp\left(\frac{4M_w\sigma_{wo}}{RT\rho_w D_p}\right)$$



$p_w > p^\circ$ → for equilibrium of droplet, air needs to be supersaturated

Vapour pressure over an aqueous solution: Köhler equation

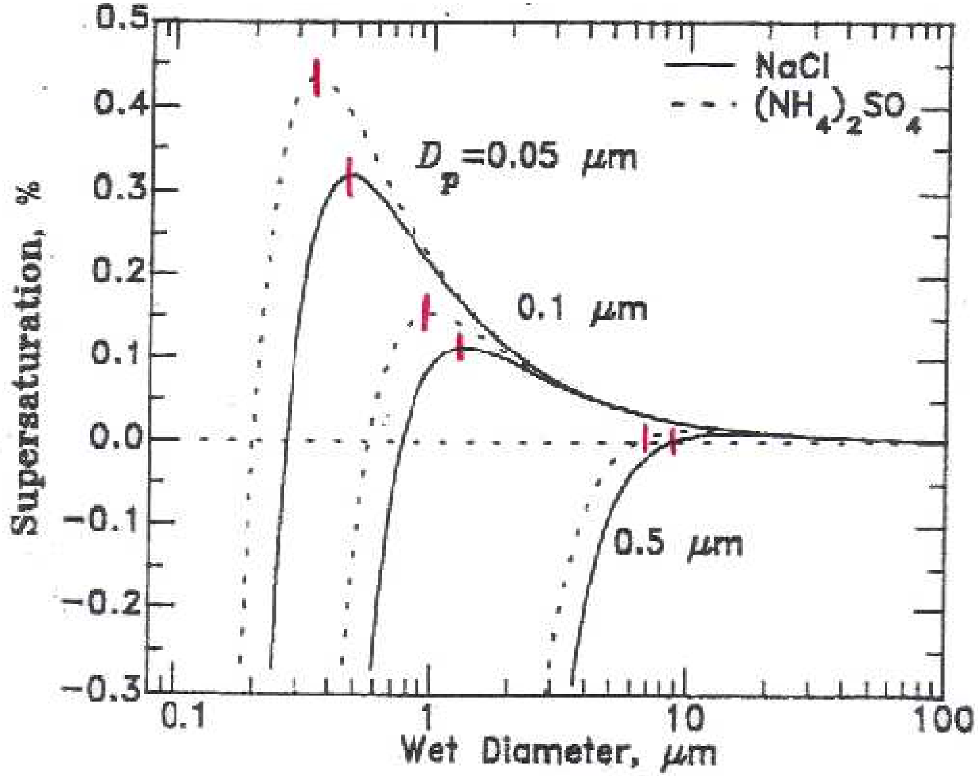
activation of particles to drops

Supersaturation of several 100% required in particle-free air → cloud condensation nuclei (CCN) required

Higher critical supersaturation is needed for

- less particle solubility (bad water uptake)
- smaller particles

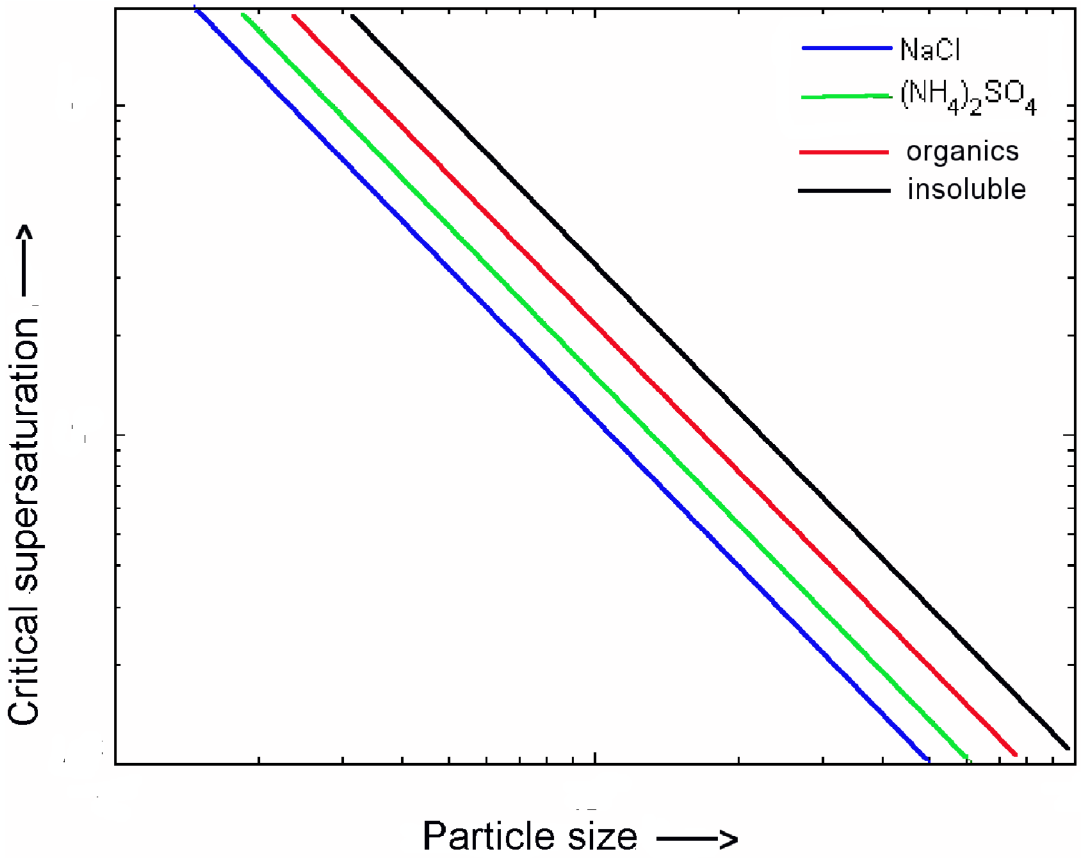
particles < critical size < drops



$$\ln\left(\frac{p_w(D_p)}{p^\circ}\right) = \frac{A}{D_p} - \frac{B}{D_p^3}$$

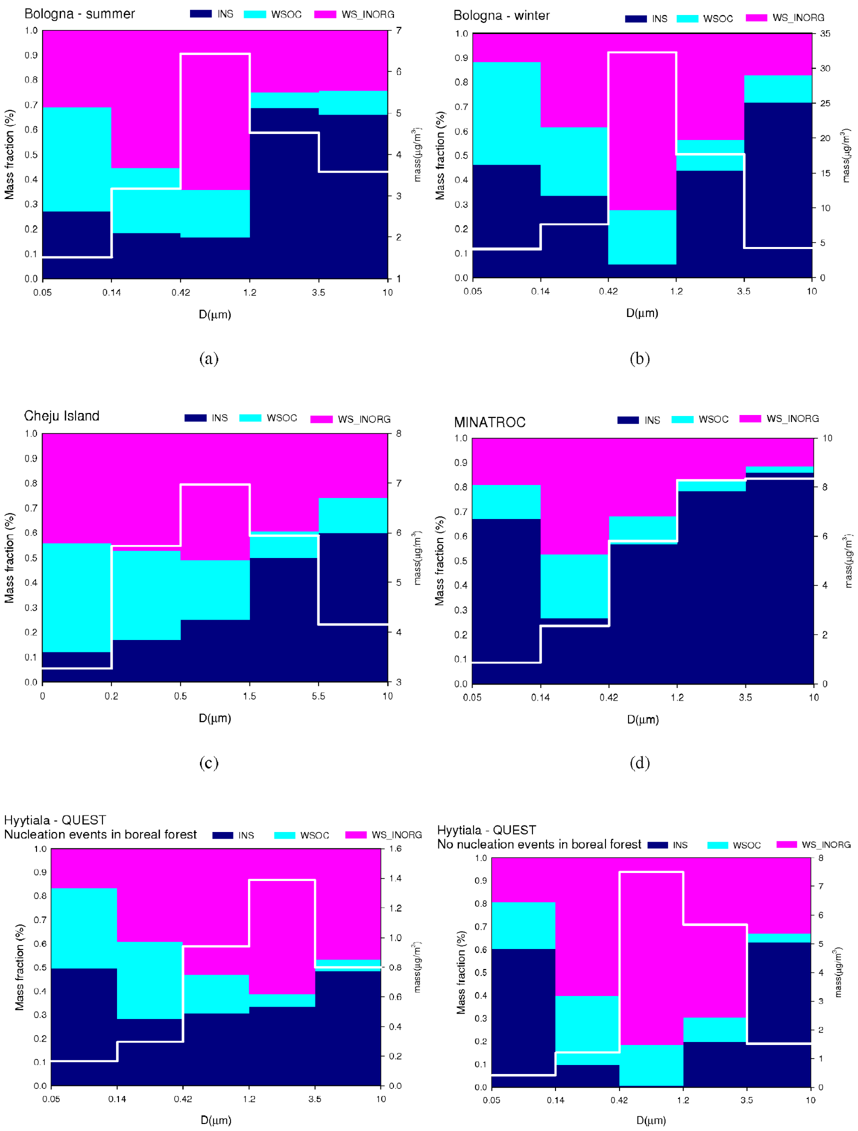
curvature term   solute effect

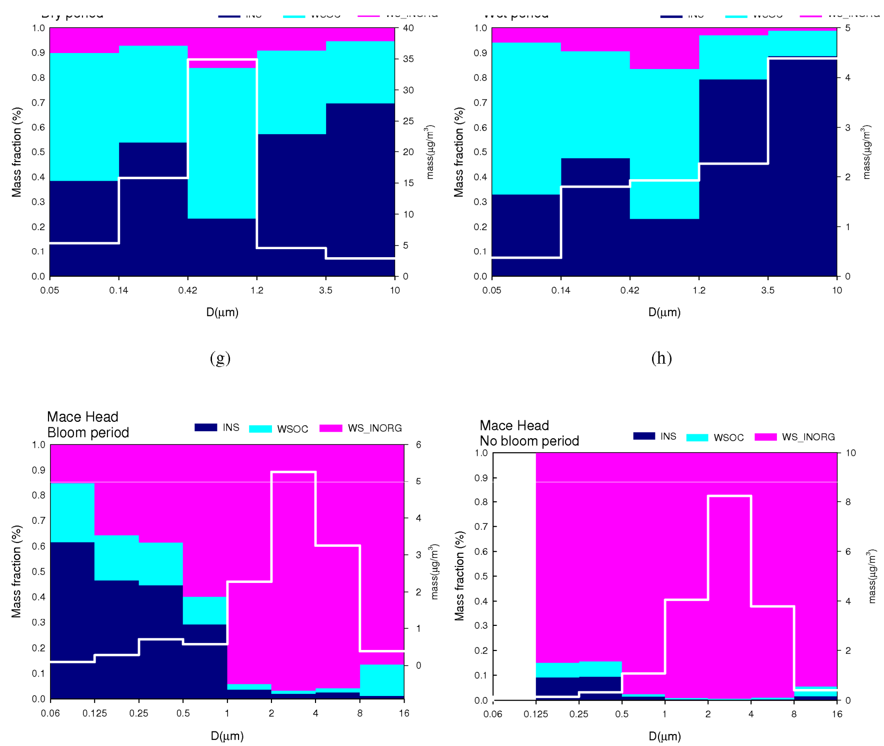
Activation of aerosol particles to drops



Good CCN: large, high water soluble fraction, i.e. salts
Bad CCN: small, high insoluble fraction, i.e. soot, dust or high organic fraction

Aerosol Composition





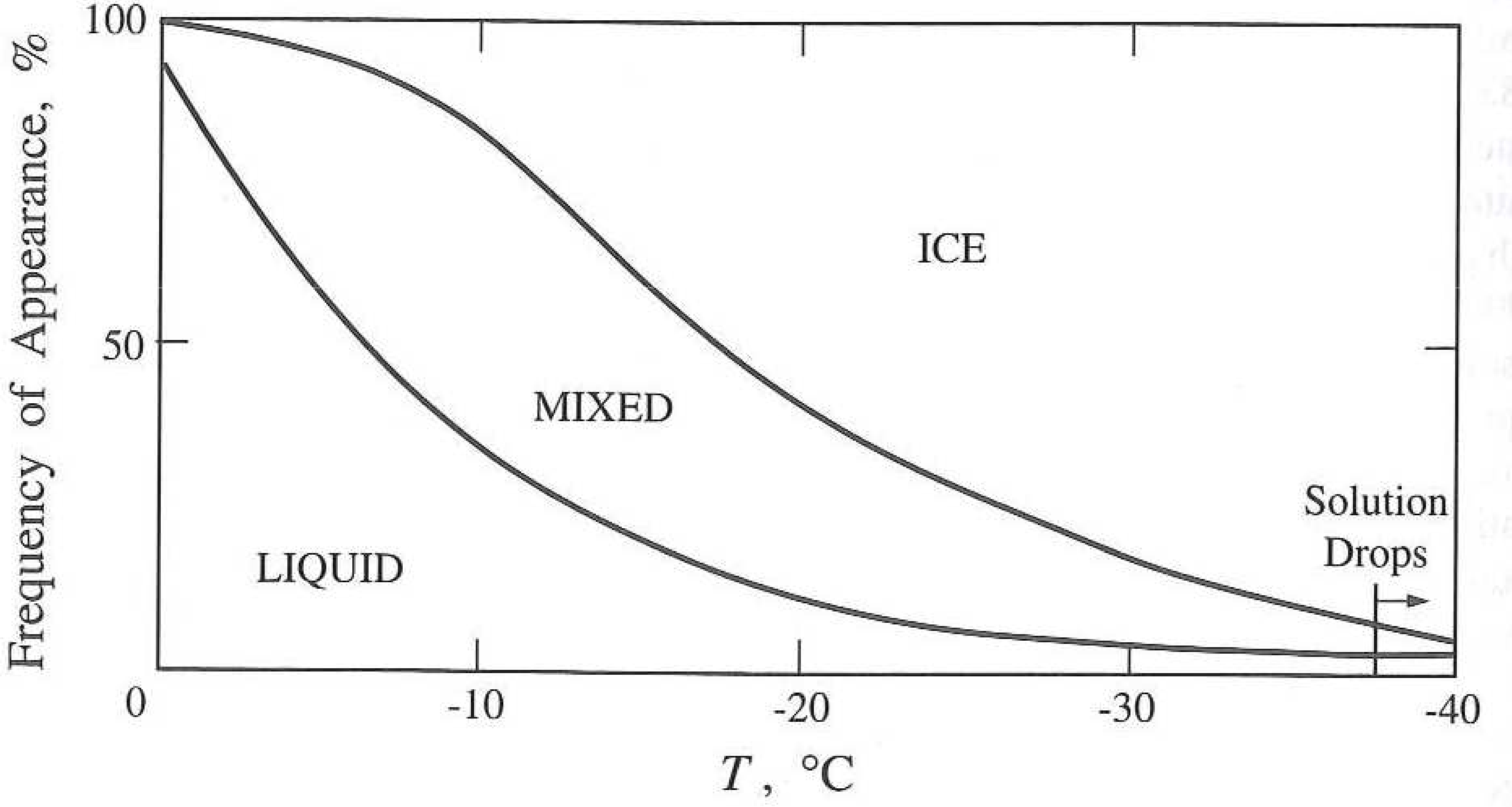
Water soluble inorganic
Water soluble organic
Insoluble

McFiggins et al. (2006), ACP

Cold (ice) clouds




Supercooled water, mixed phase, ice clouds



Clausius Clapeyron equation

vapour/ice

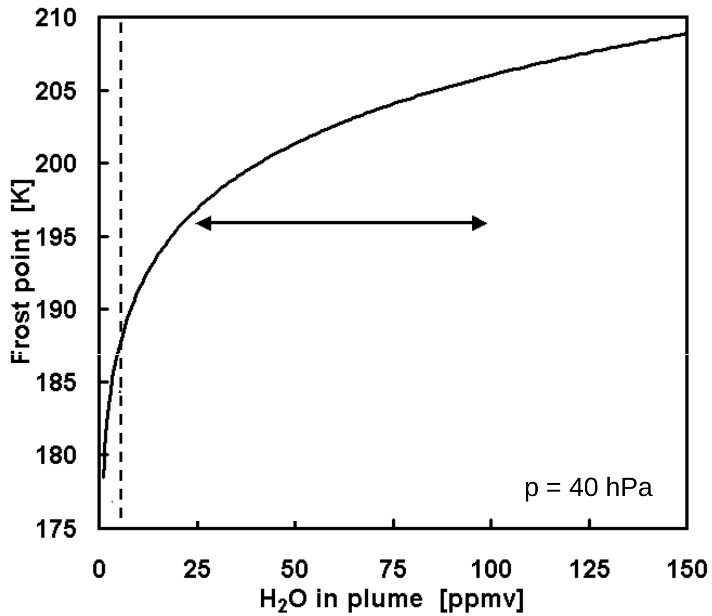
$$\frac{dp_{\text{sat},i}}{dT} = \frac{\Delta H_s}{T(v_v - v_i)}$$

$$\frac{d \ln p_{\text{sat},i}}{dT} \simeq \frac{\Delta H_s}{RT^2}$$

ΔH_s molar enthalpy for ice sublimation

Integration $\ln p_{H2O} = -A/T + C$
[Marti & Mauersberger, GRL 1993]

$\Delta[H_2O] = 1$ ppmv $\Rightarrow$ $\Delta T_{frost} \approx 1$ K

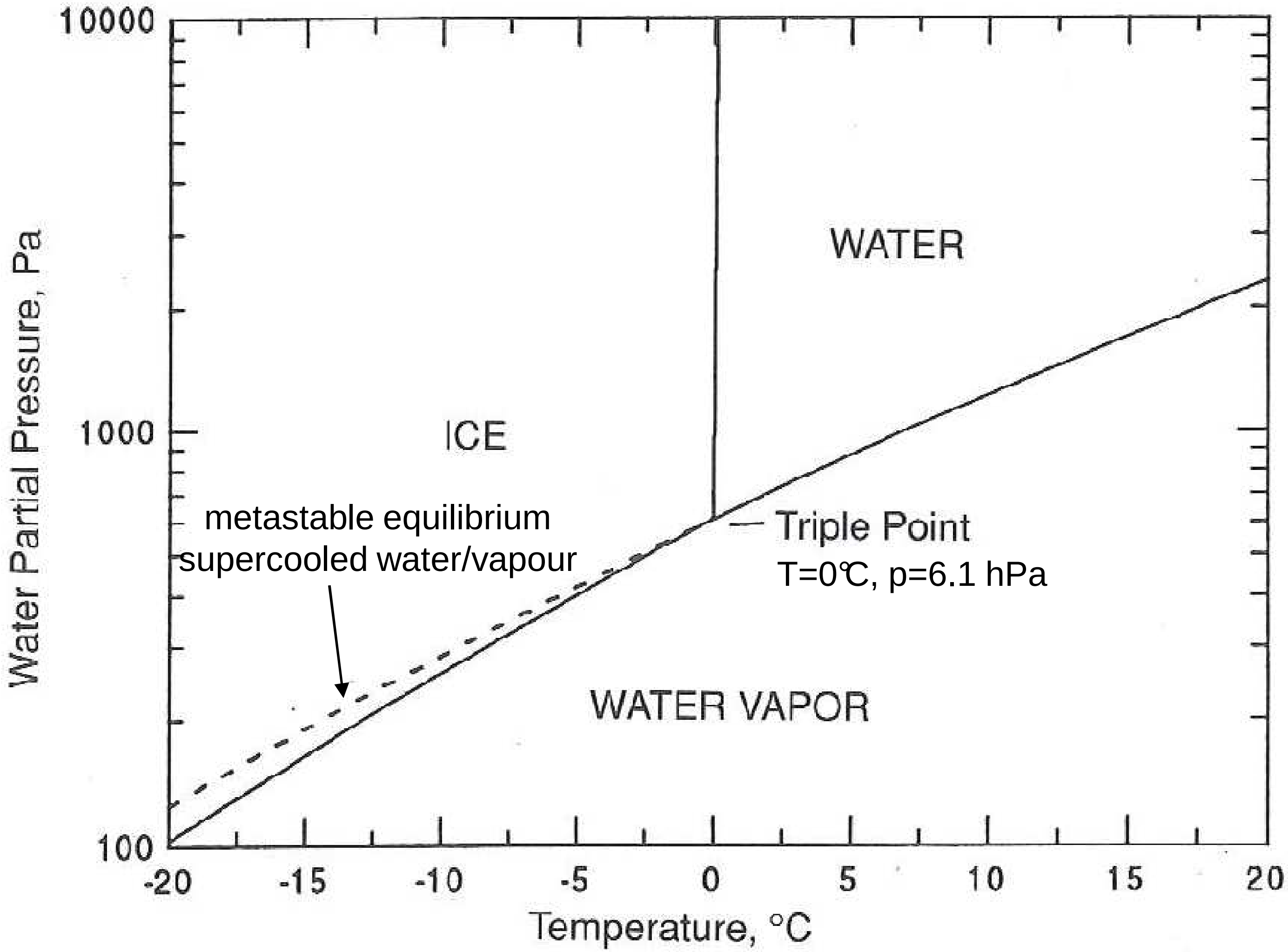


water/ice

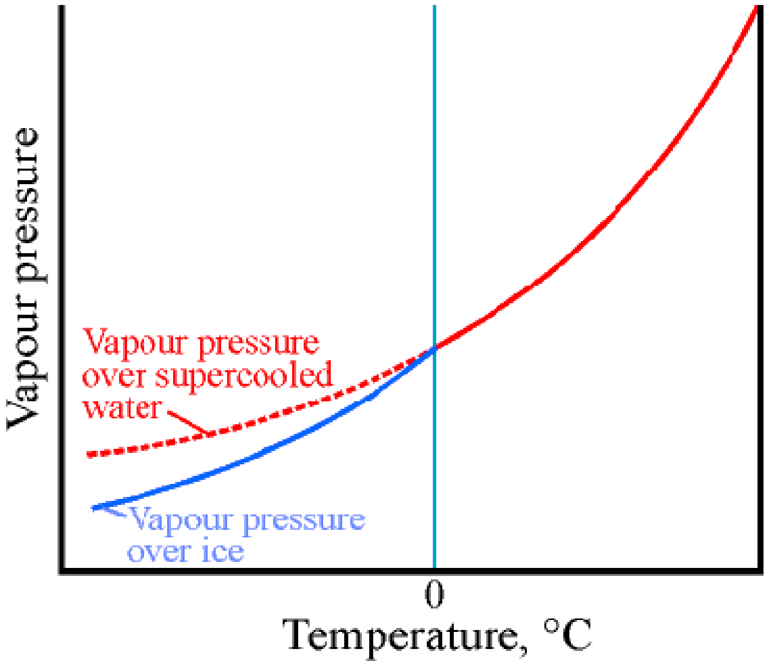
$$\frac{dp_m}{dT} = \frac{\Delta H_m}{T(v_w - v_i)}$$

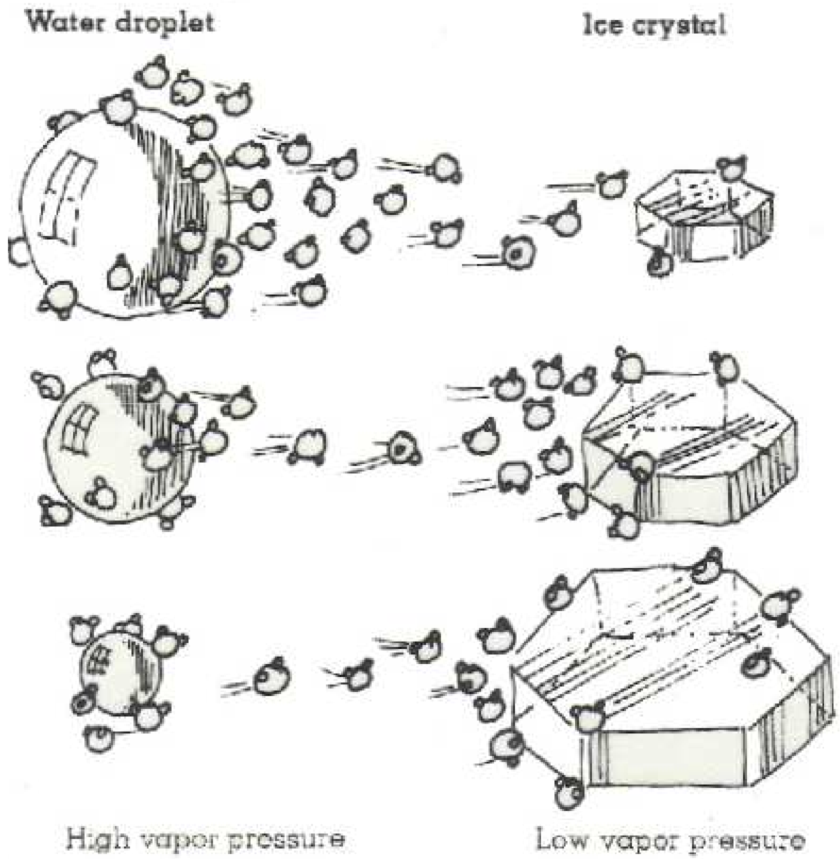
ΔH_m enthalpy for melting

p-T phase diagram for water



Bergeron-Findeisen process

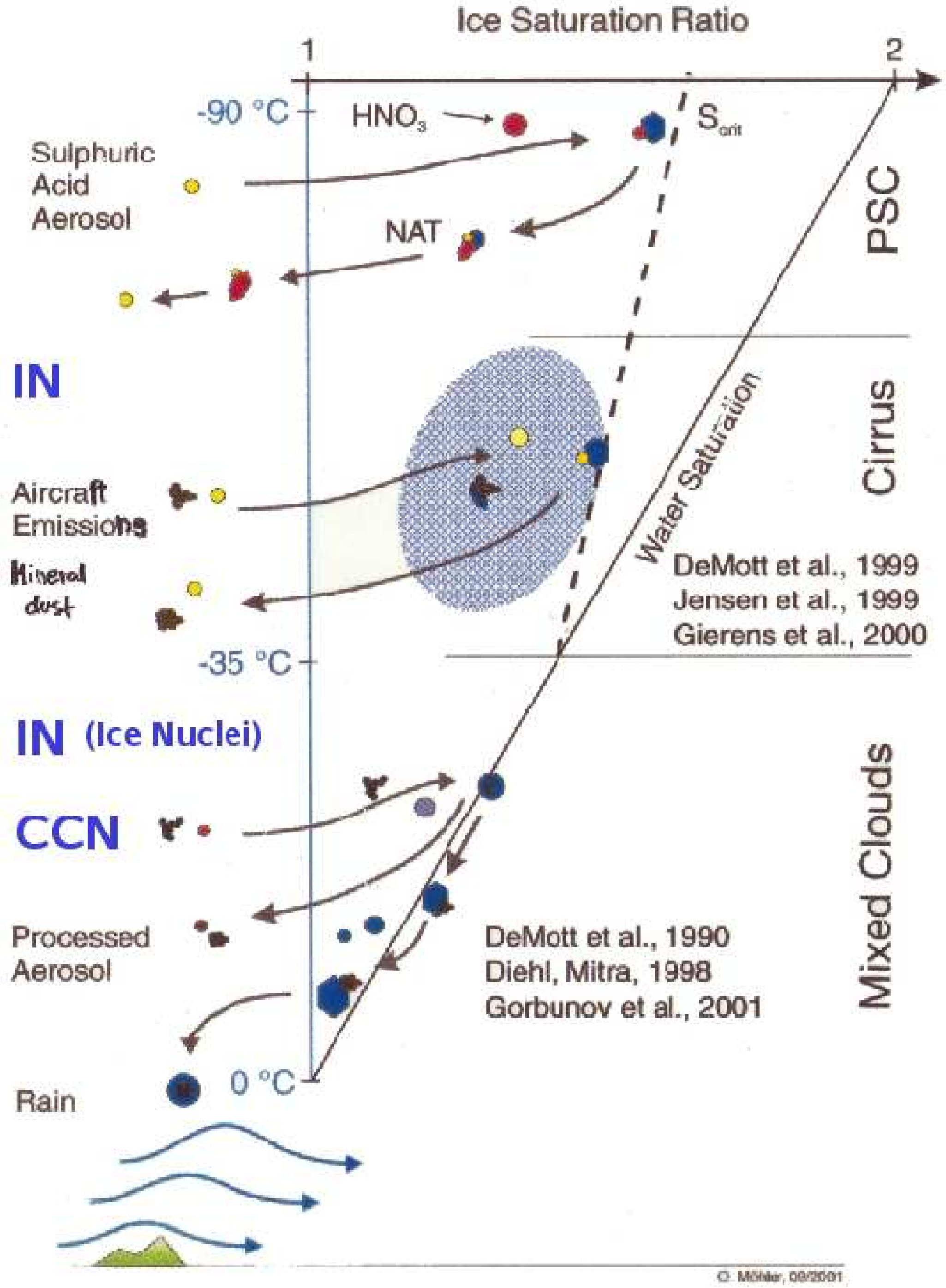




T < 0℃, $p_{sat,w} > p_{sat,i}$

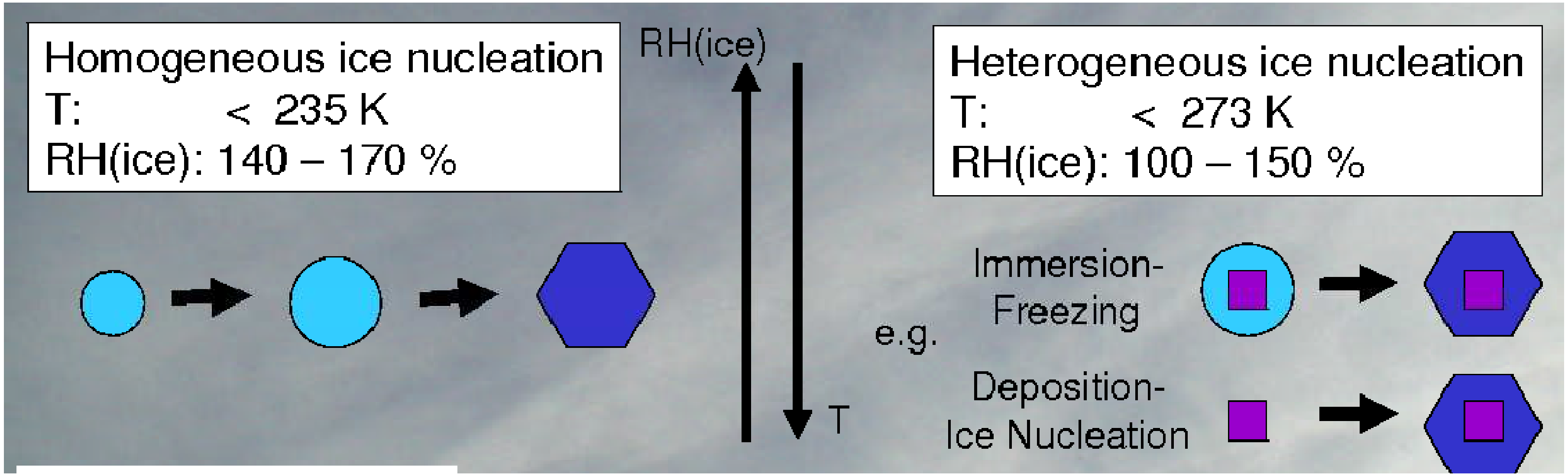
supercooled droplets cannot coexist in equilibrium with ice crystals

Ice Nuclei (IN)



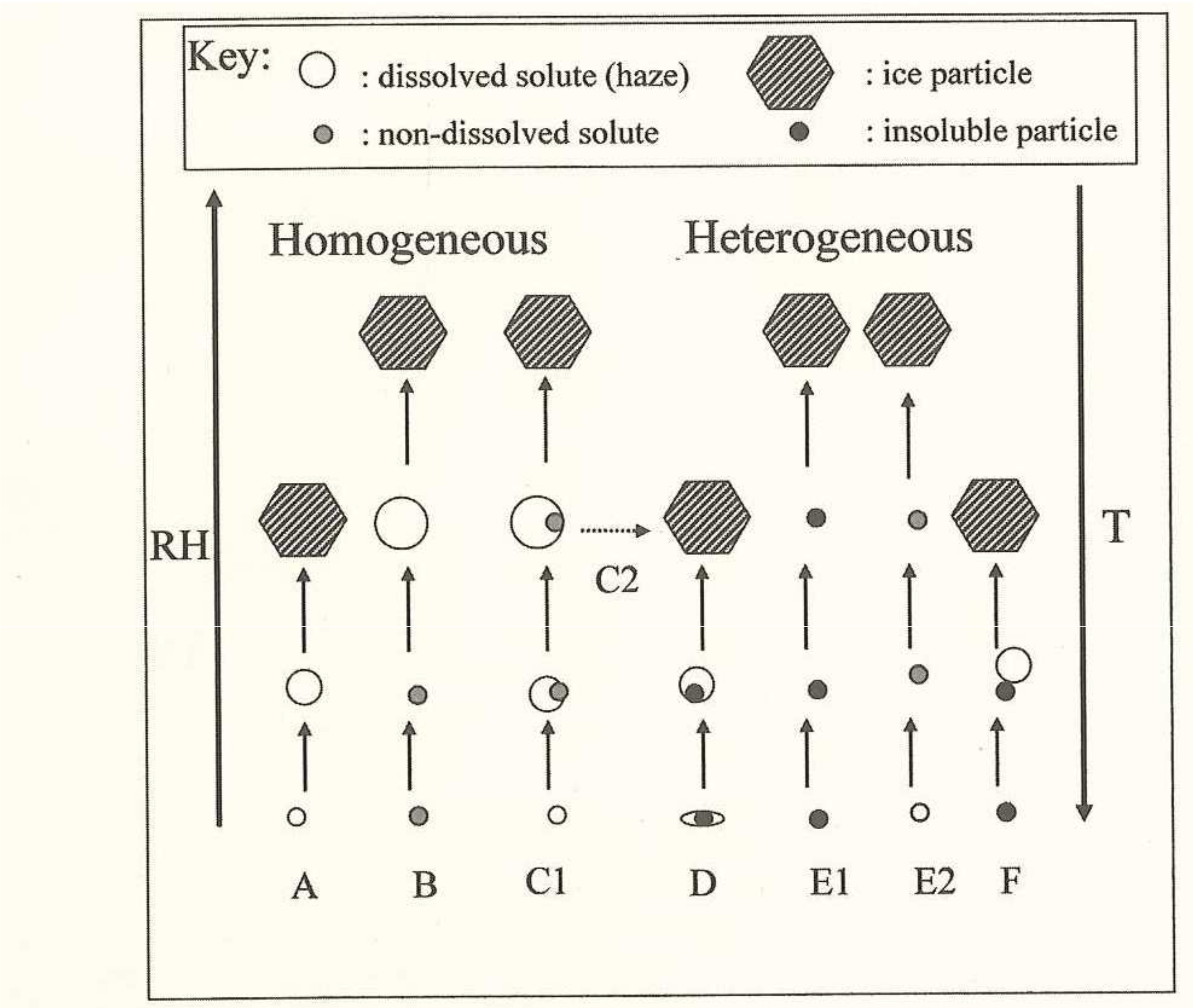
Homogeneous / heterogeneous ice nucleation

determind by IN composition and supersaturation



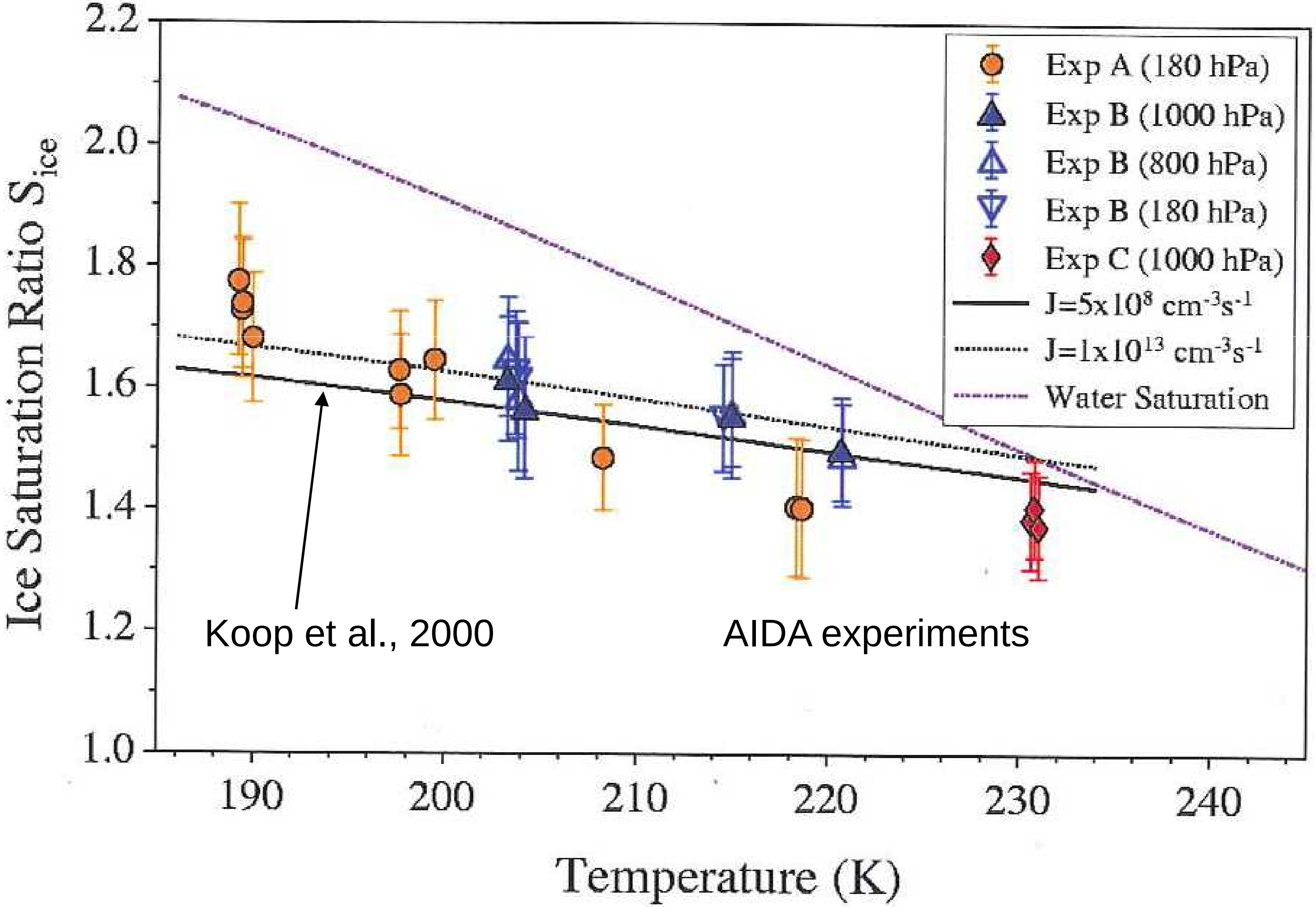
bad IN: soluble solutions
organics

good IN: soot
mineral dust

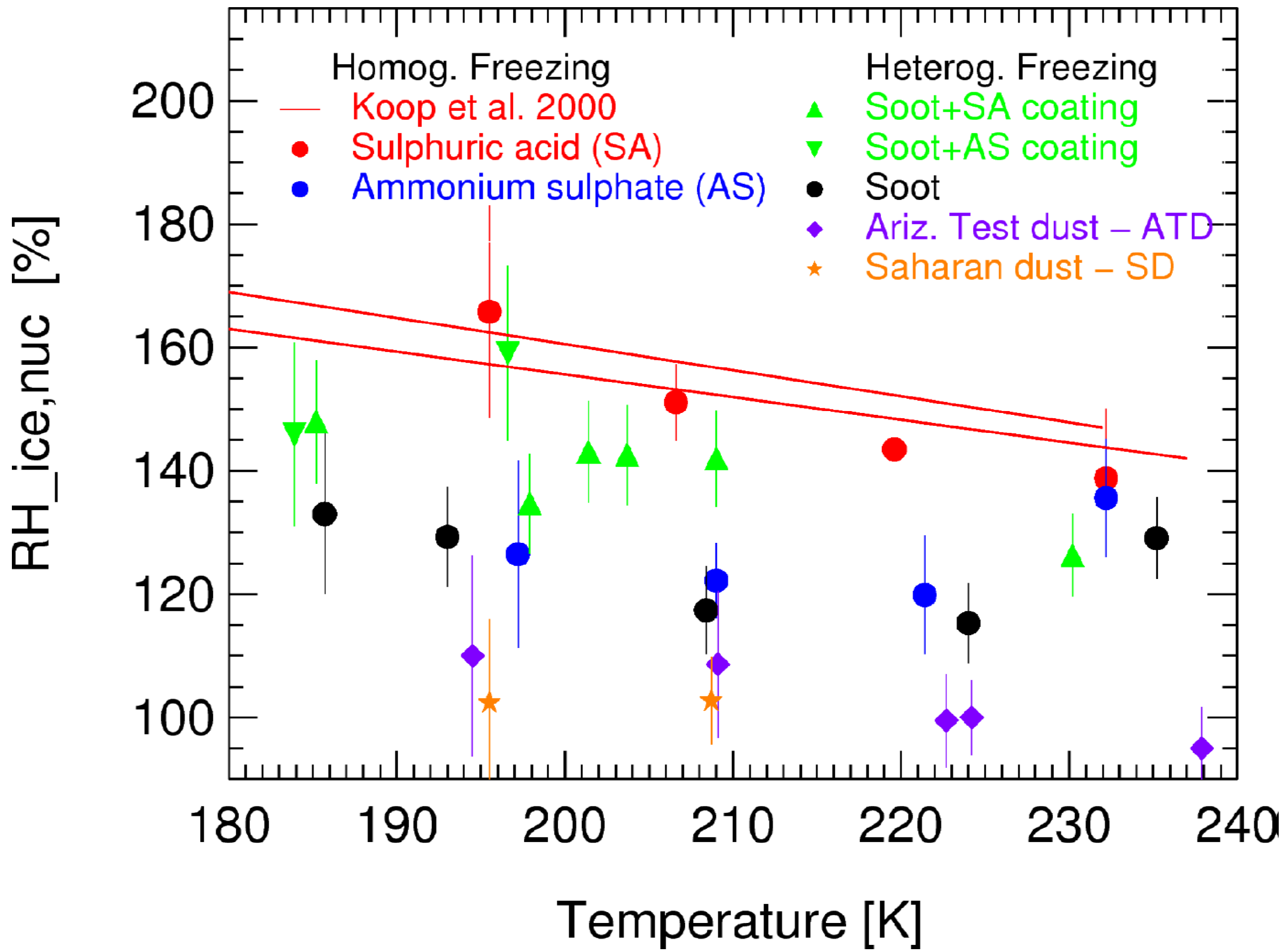


A hom. freez. of solution droplets
B deliquescence + hom. freez.
C hom/het freez. + secondary phase cryst. (immersion freezing)
D het. freez. of solution droplets
E deposition nucl. on insoluble/anhydrous particle
F contact freezing nucleation

Ice saturation at low T: Homogeneous nucleation

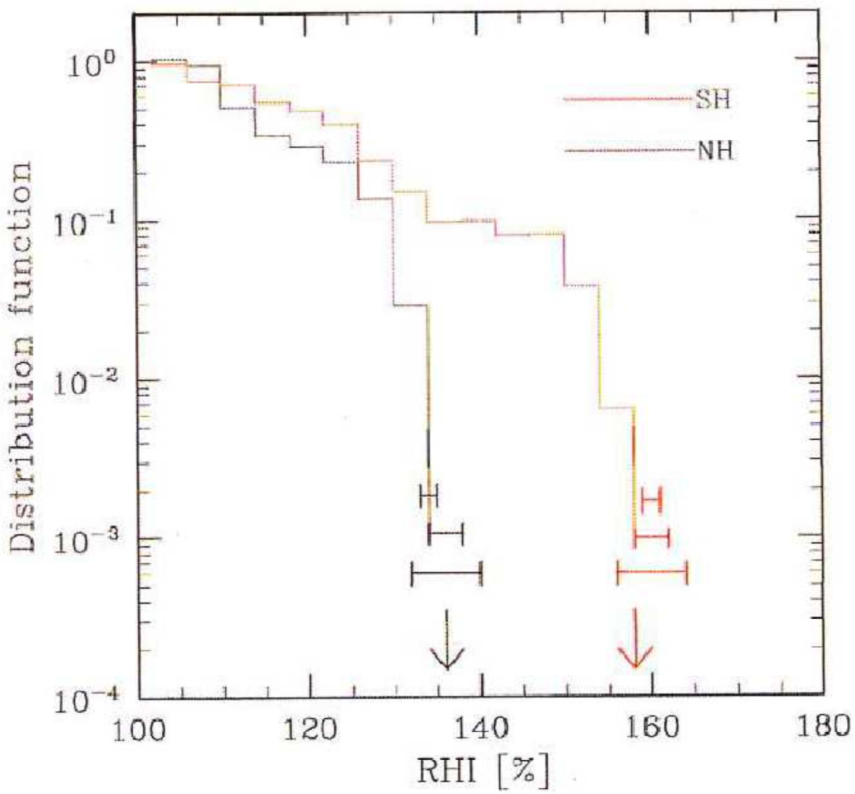


Ice saturation at low T: Heterogeneous nucleation

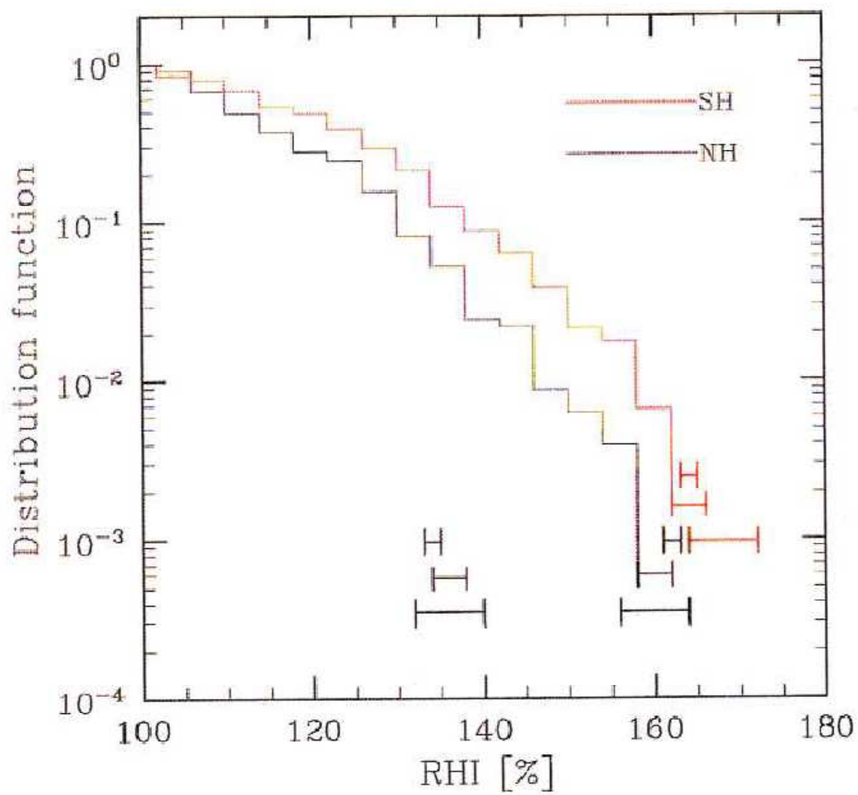


Supersaturation in the atmosphere

inside clouds



outside clouds



Ovarlez et al.

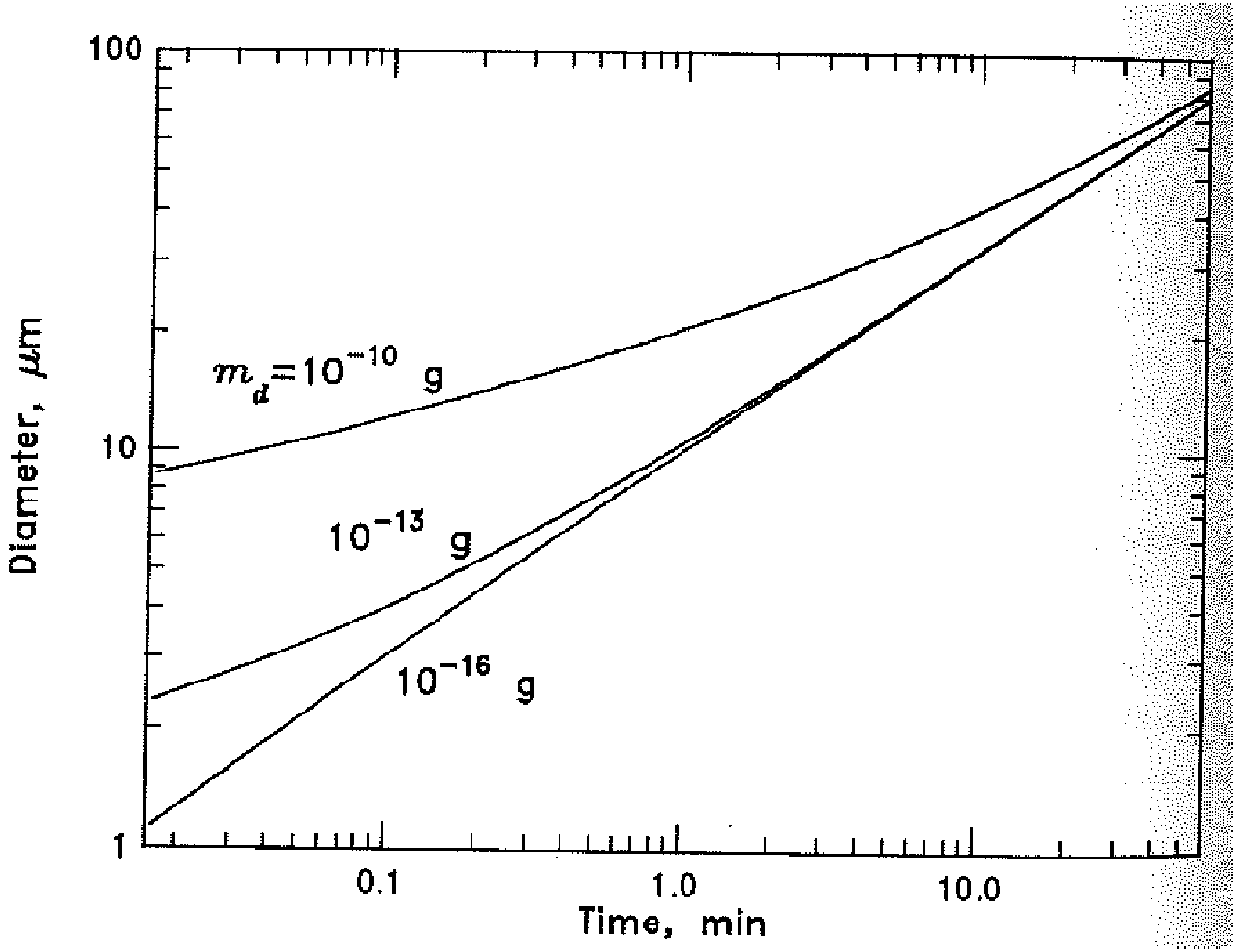
Precipitation

(some) drops need to grow to precipitable size

mechanisms:

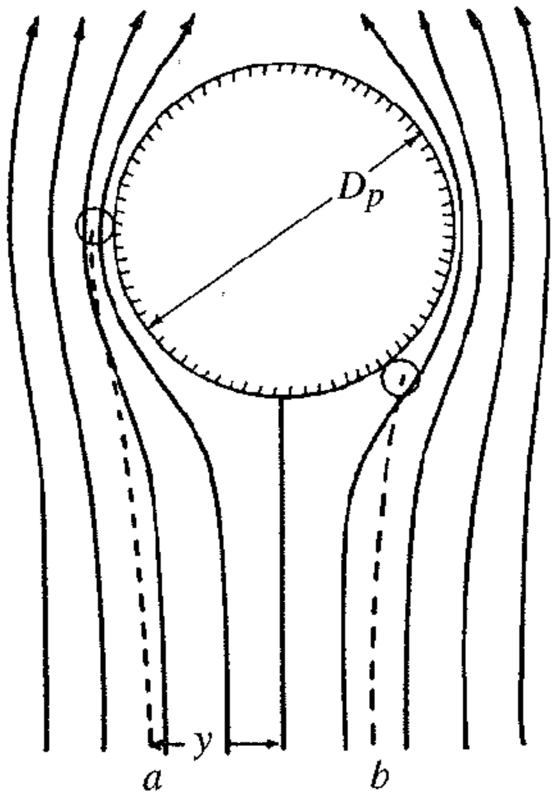
- water vapour condensation
- droplet coalescence
- ice processes

Diffusional growth of drops



Droplet coalescence

falling (large) drops collect smaller drops in fall path (*Mt* 25,29)

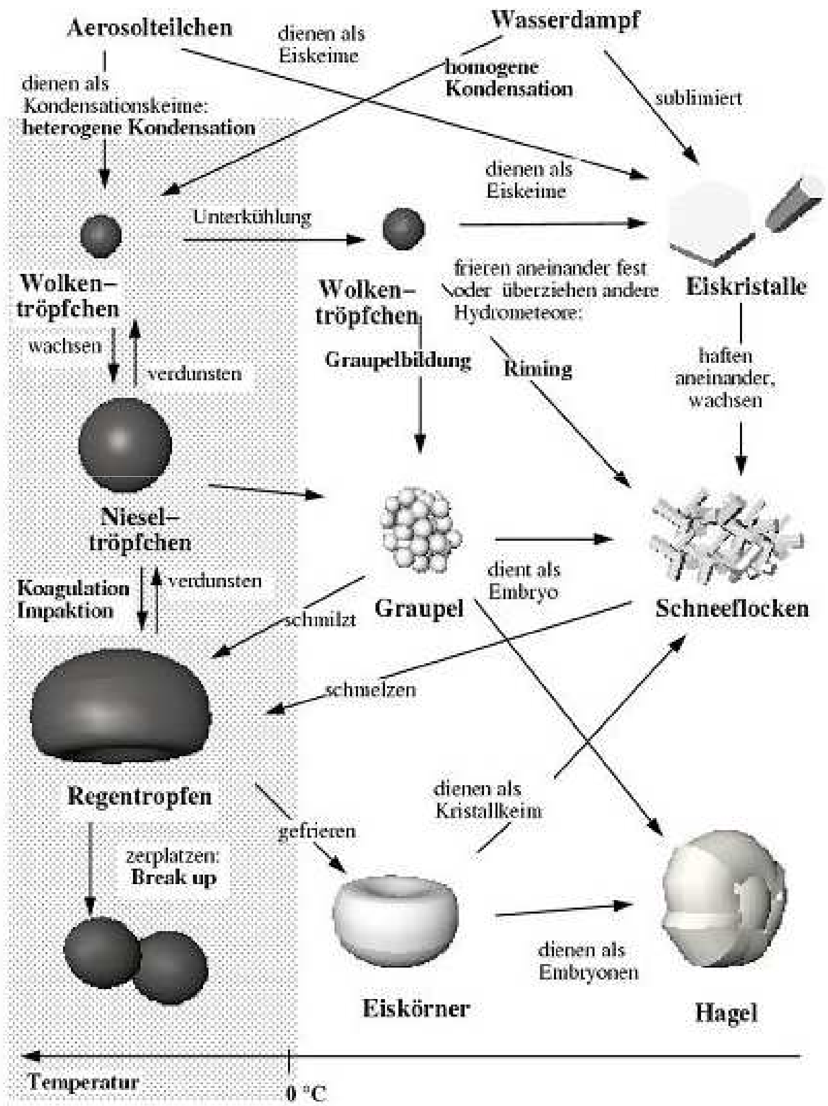


For everyone who has will be given more, and he will have an abundance. Whoever does not have, even what he has will be taken from him.

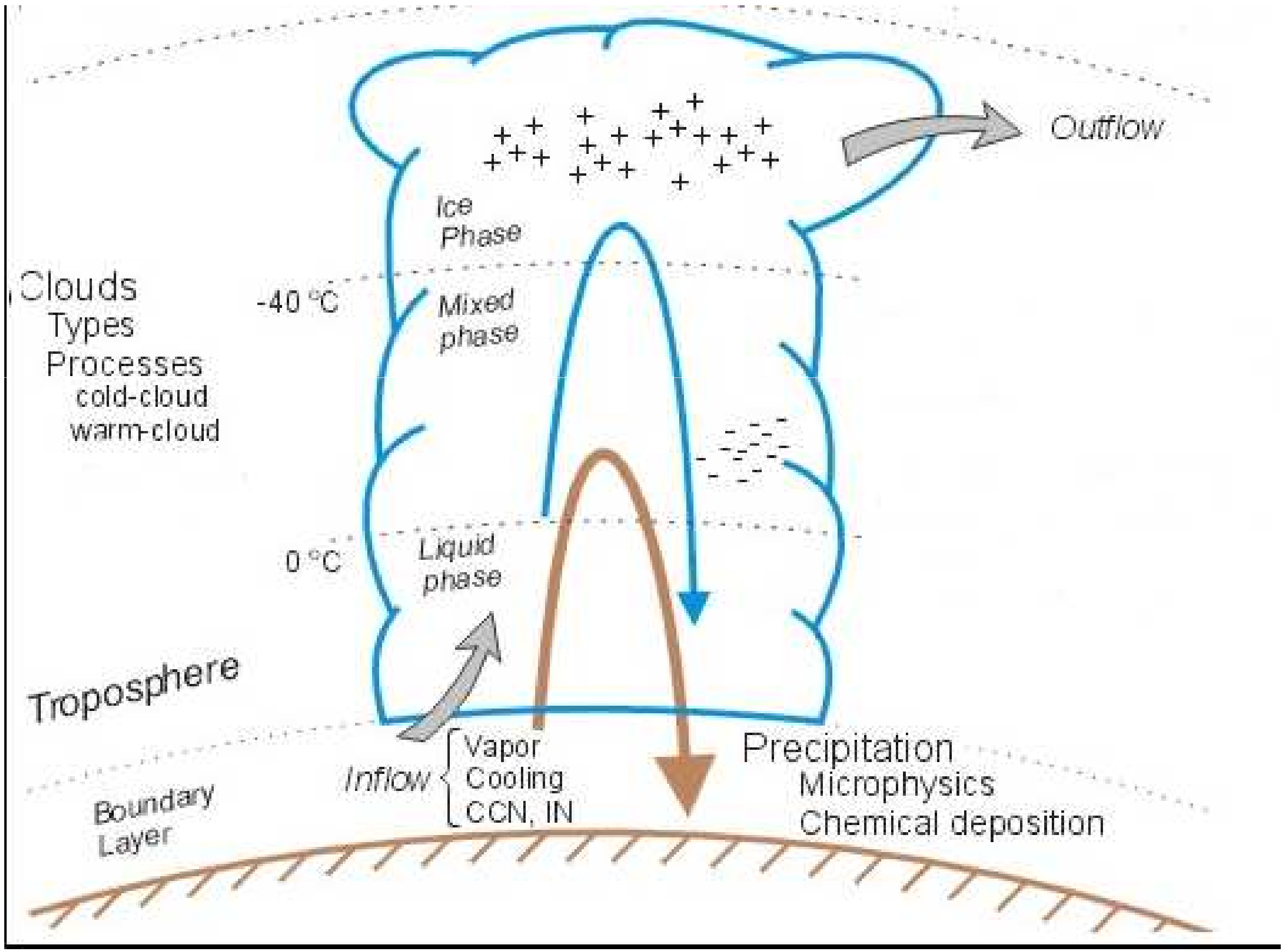
Denn wer hat, dem wird gegeben, und er wird im Überfluss haben; wer aber nicht hat, dem wird auch noch weggenommen, was er hat.

Car à celui qui a, on donnera, et il aura encore davantage; mais à celui qui n'a pas, on ôtera même ce qu'il a.

Ice processes



Example: Microphysics in a Cb cloud

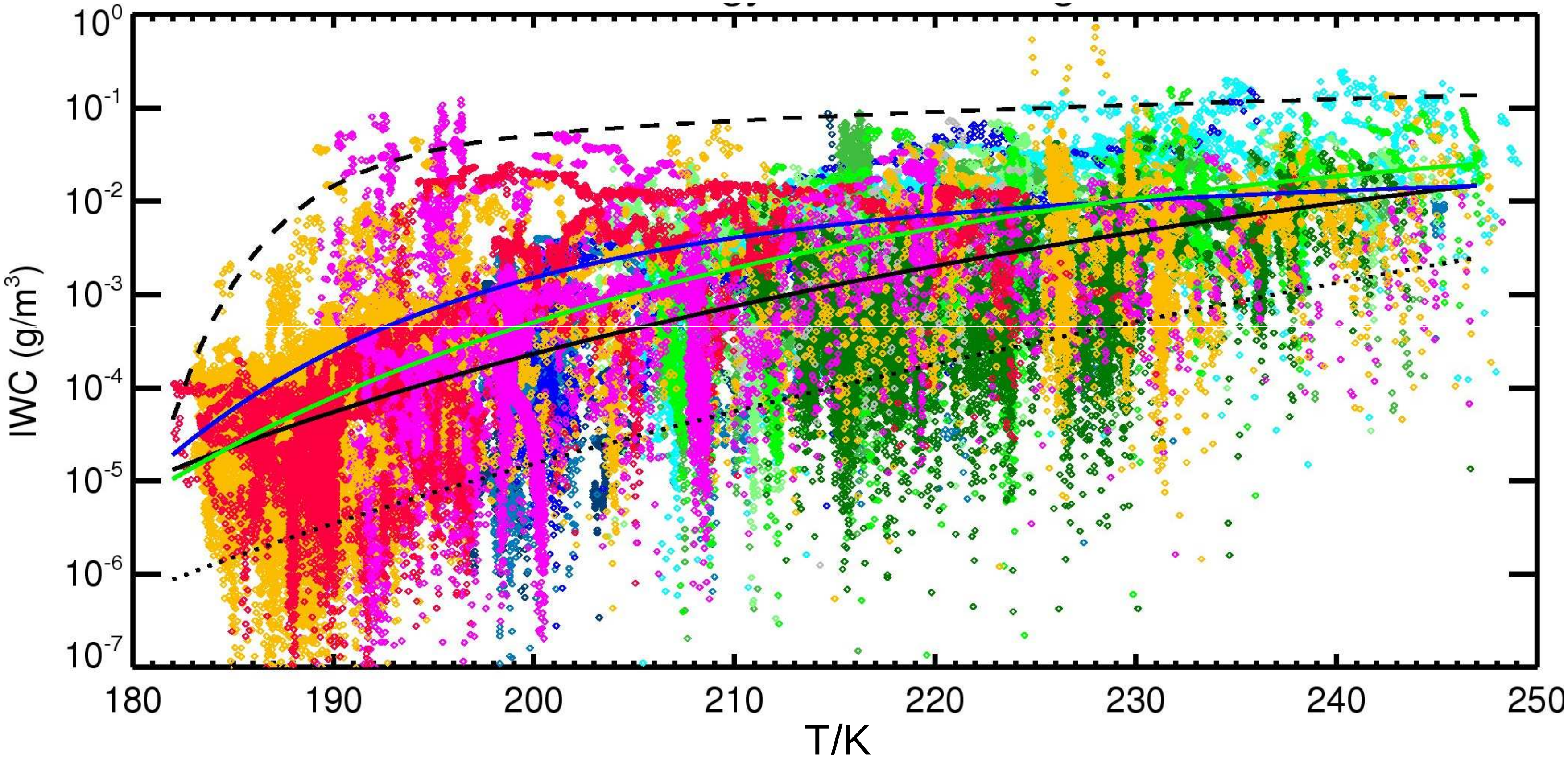


Clouds 3
Special aspects from recent studies

- IWC of cirrus clouds
- Super-supersaturation (part 1, part 2 by TP)
- Contrails and contrail cirrus

Ice Water Content (IWC) of cirrus

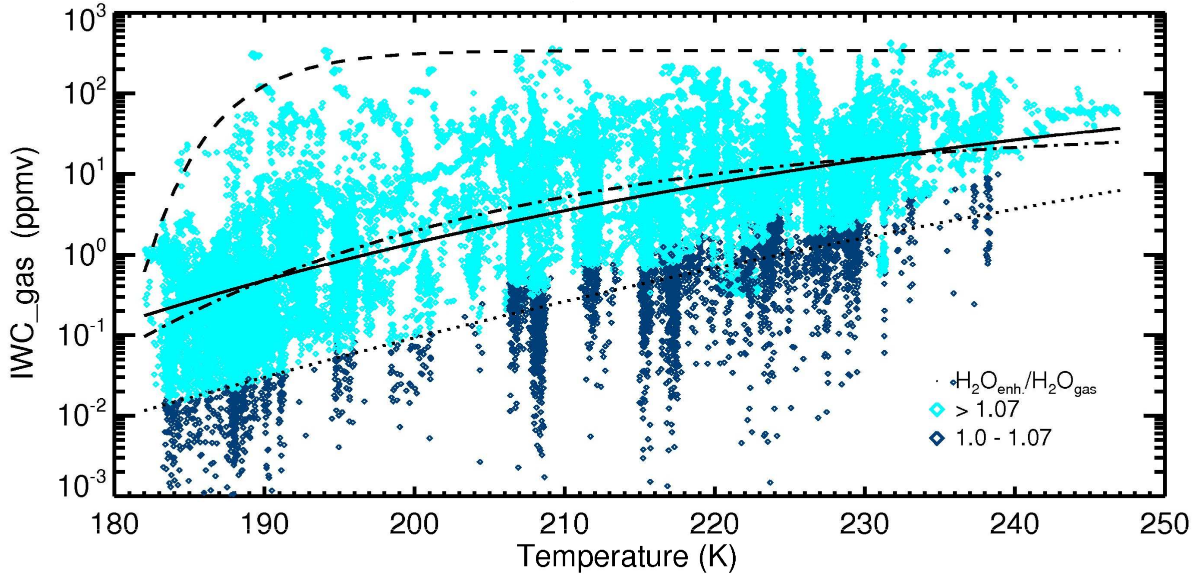
Measurement: total water – gas phase water



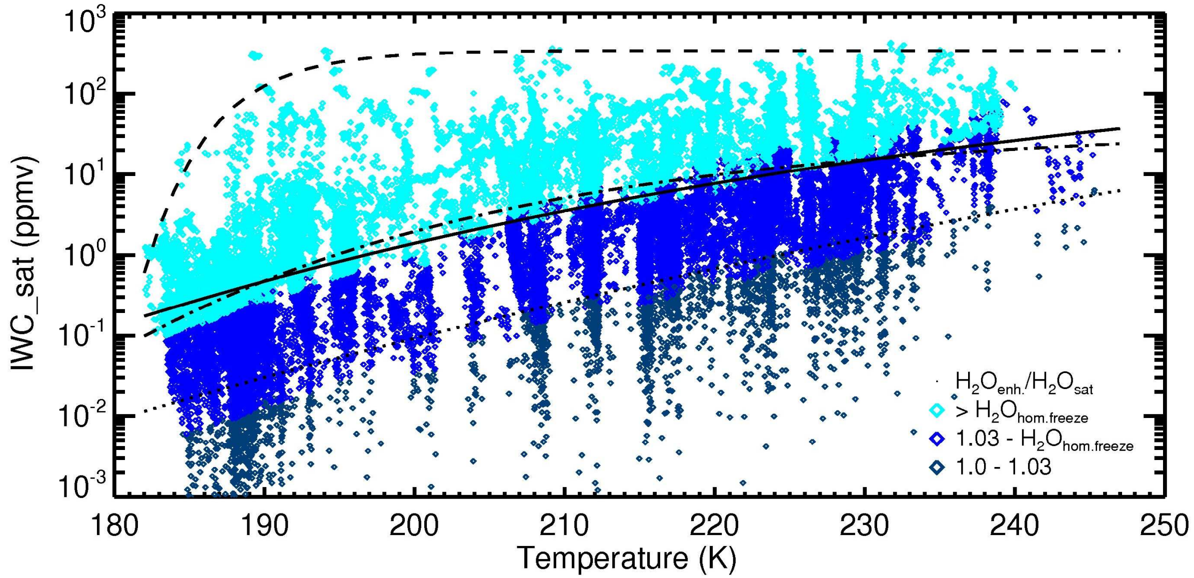
> 5 aircraft campaigns

Schiller et al., 2008 tropical cirrus midlatitude cirrus polar cirrus

Detection limits

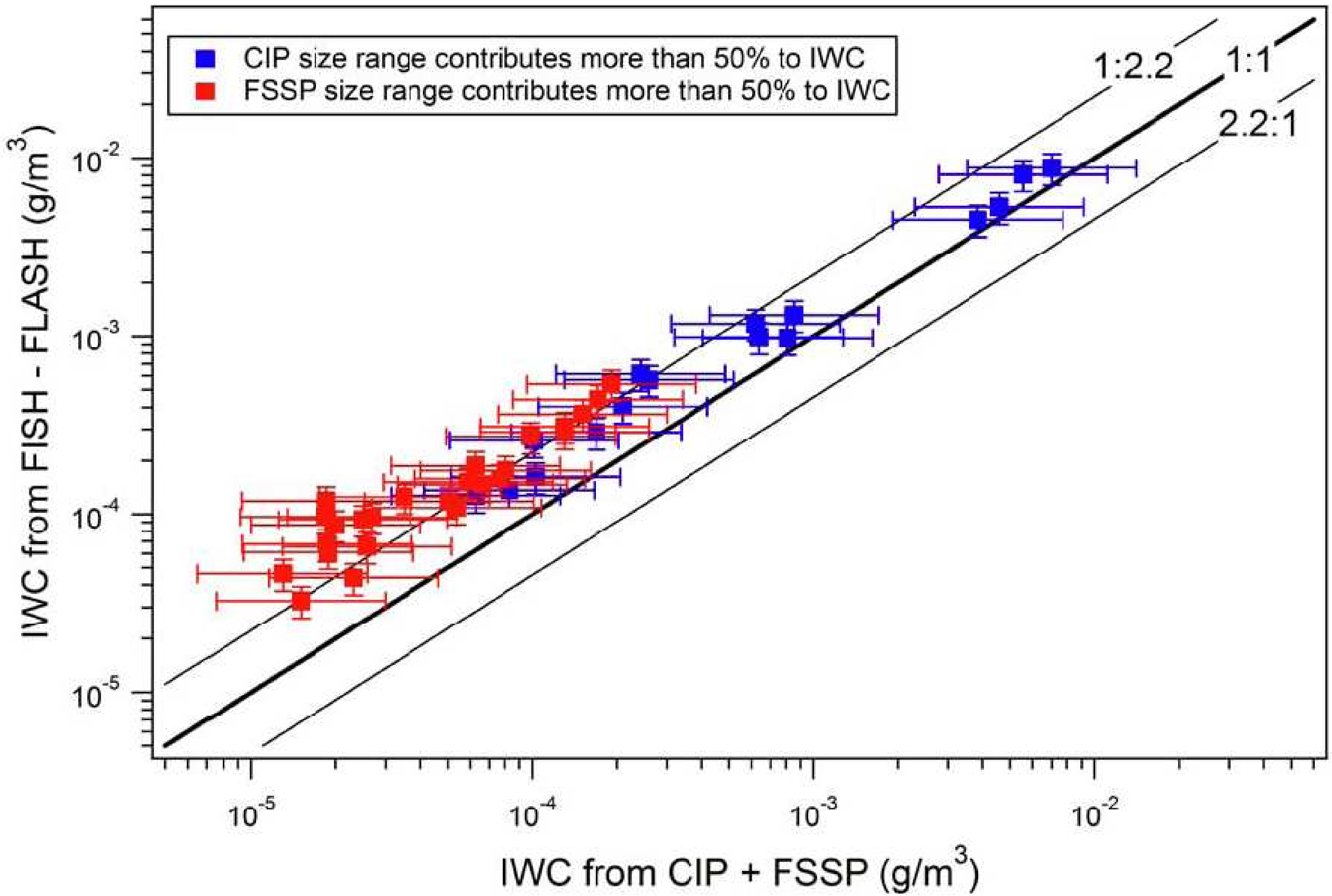


1st method
total water –
measured gas phase

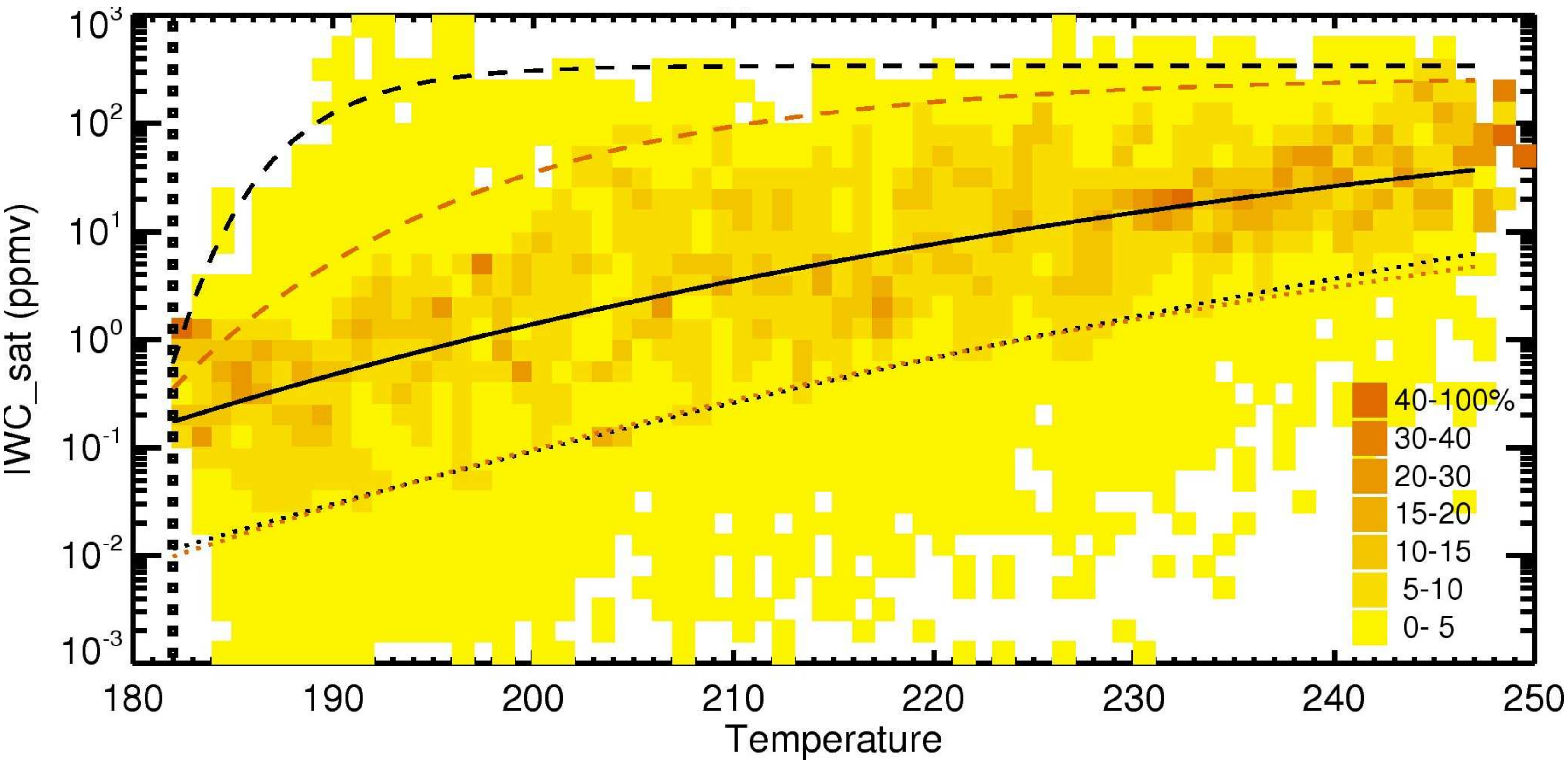


2nd method
total water – saturation
(from pT measurement)

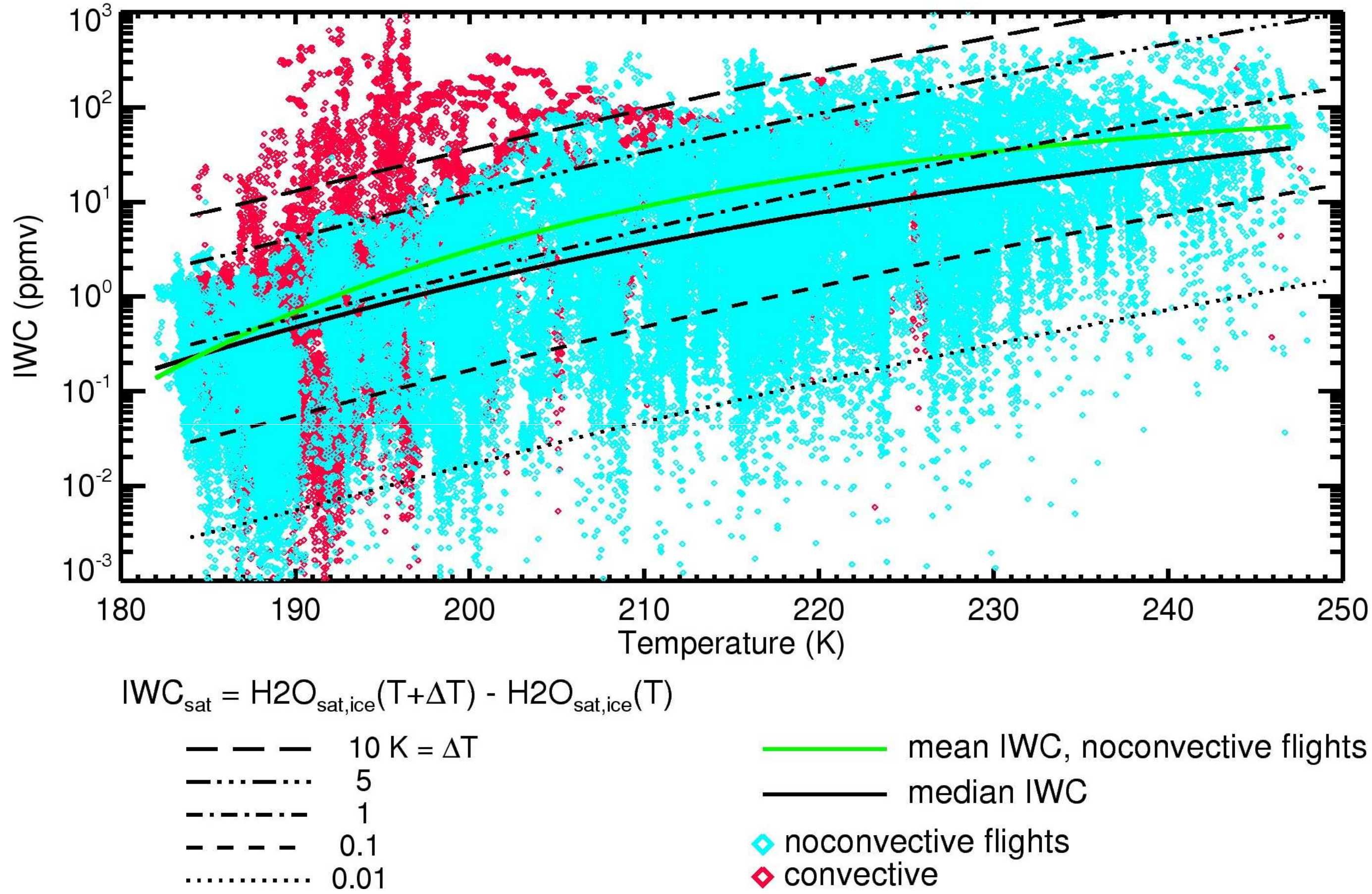
FISH/FLASH vs FSSP IWC



Mean IWC and frequency distribution

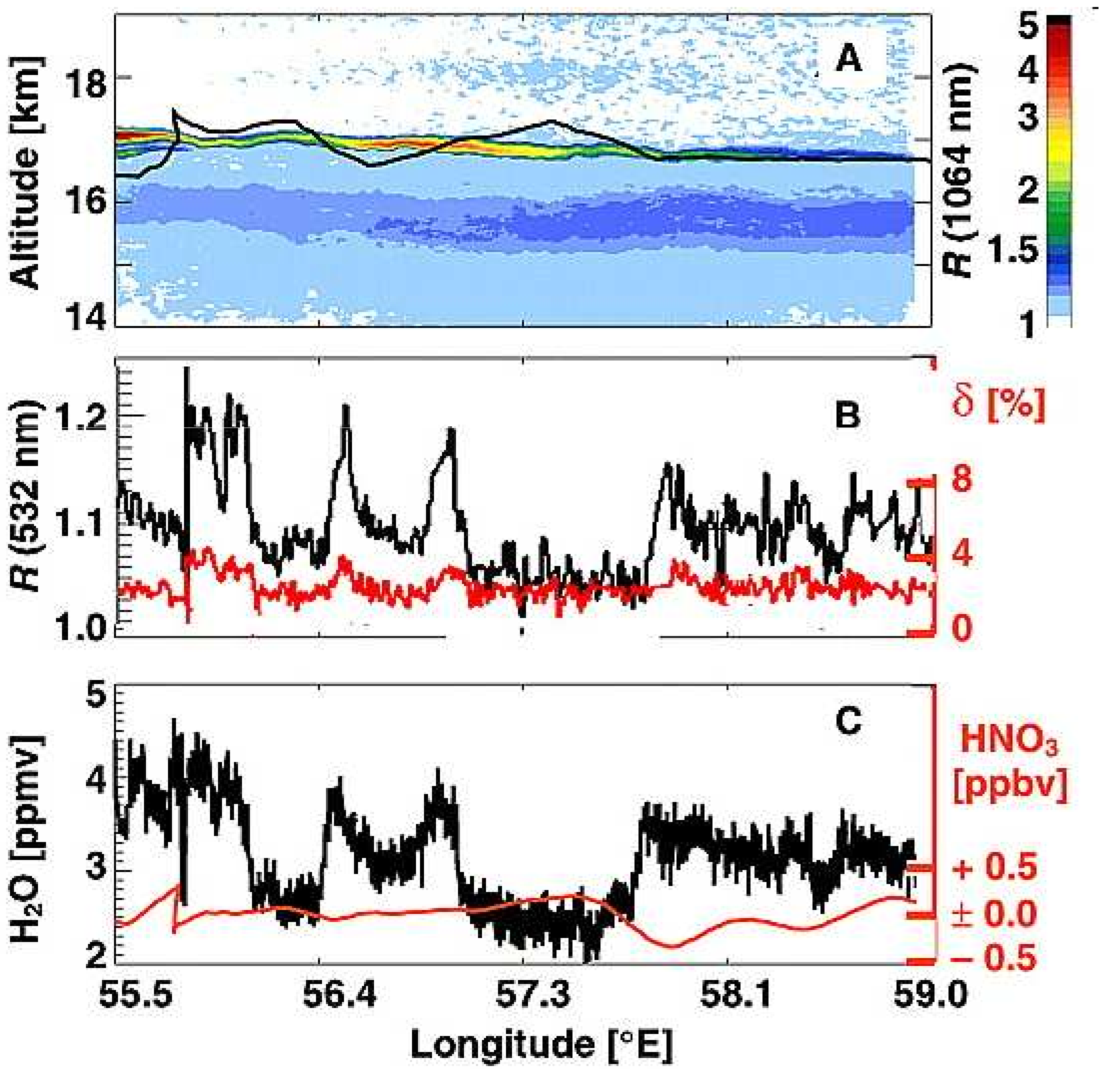


IWC and cooling / convection



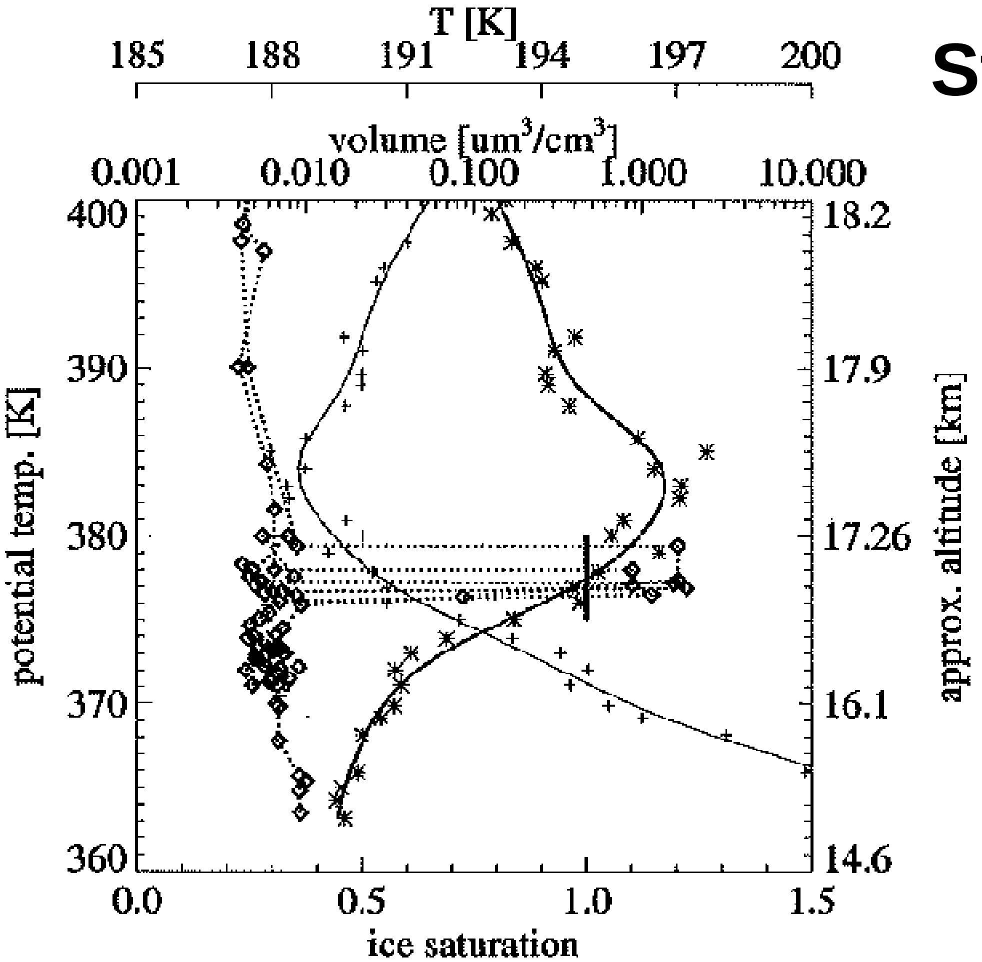
Utrathin tropical cirrus (UTTC)

final step of dehydration of stratospheric air



Peter et al., 2002

Stabilisation of UTTC

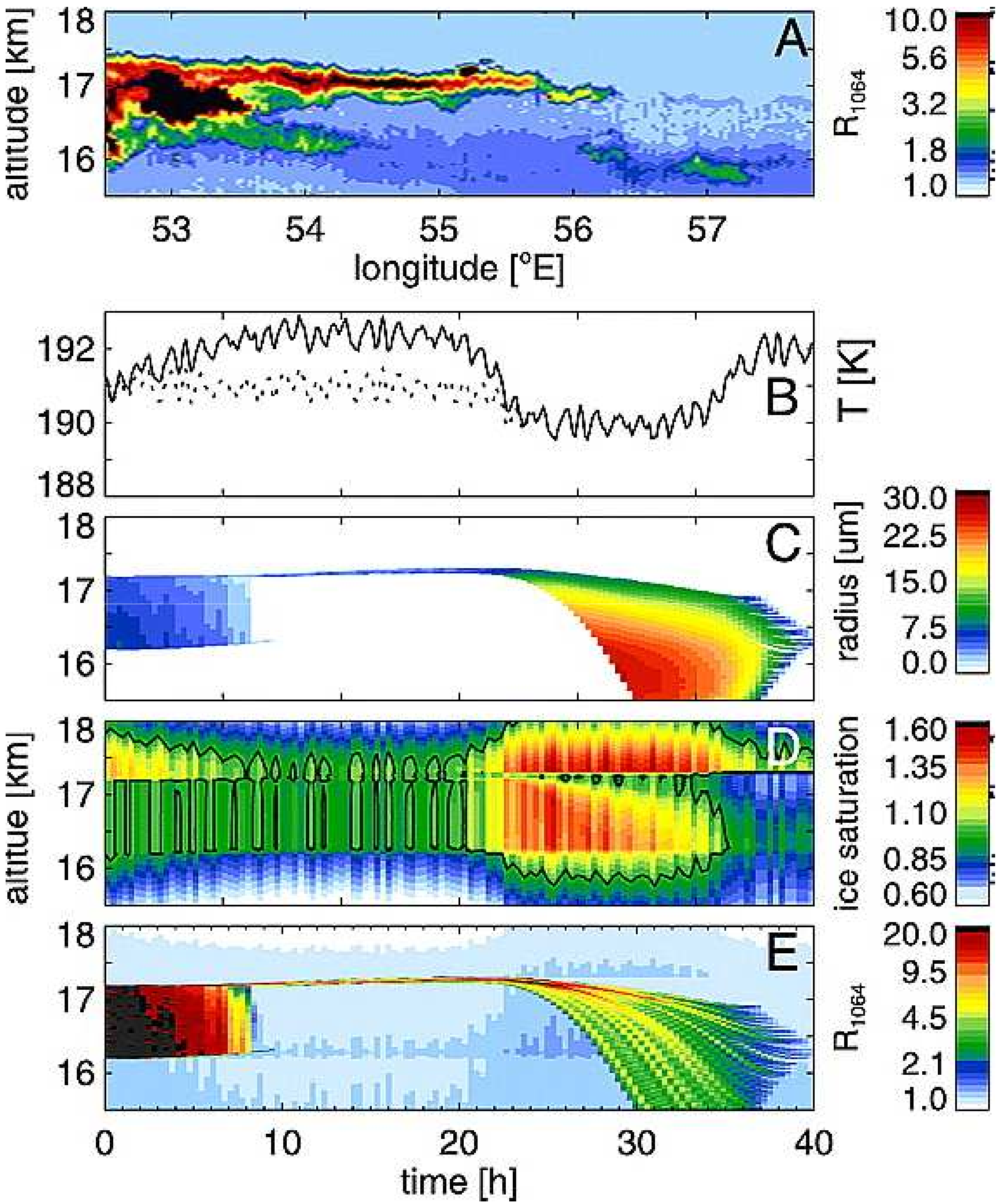


Vertical motion of a particle

$$\frac{dz}{dt} = v^{air}(z) - \frac{2g\rho r^2}{9\eta},$$

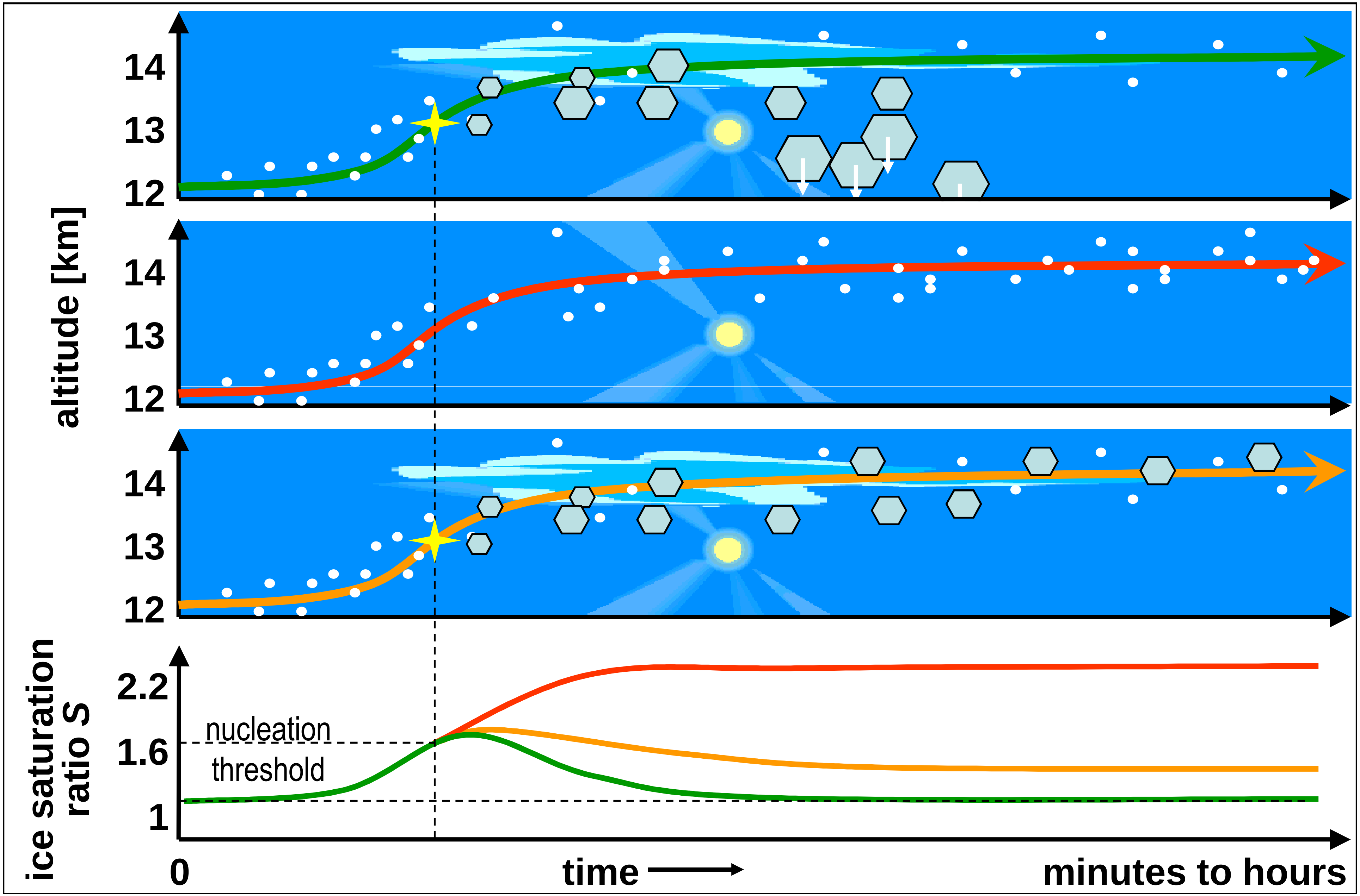
Growth/evaporation of particles

$$\frac{dr^2}{dt} = 2\frac{m}{\rho} D_{\mathrm{H_2O}} n^{\mathrm{vap}}_{\mathrm{H_2O}} [S_{\mathrm{ice}}(z) - 1].$$

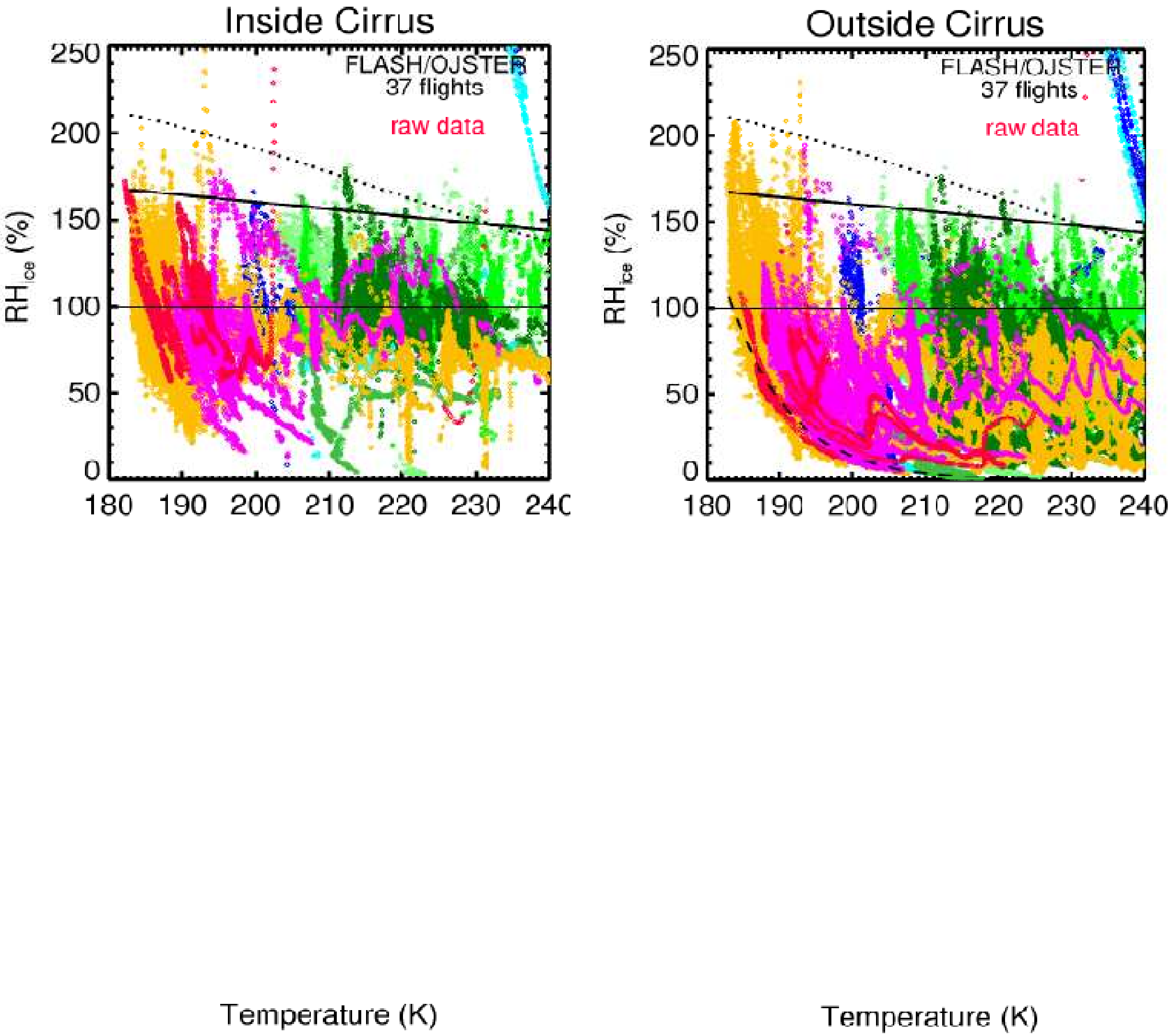

A
B
C
D
E
altitude [km]
longitude [°E]
T [K]
time [h]
R1064
radius [um]
ice saturation
altitue [km]
18
17
16
53
54
55
56
57
192
190
188
0
10
20
30
40
10.0
5.6
3.2
1.8
1.0
30.0
22.5
15.0
7.5
0.0
1.60
1.35
1.10
0.85
0.60
20.0
9.5
4.5
2.1
1.0

Peter et al., 2007

The High Supersaturation Puzzle



FLASH/OJSTER: supersaturation climatology

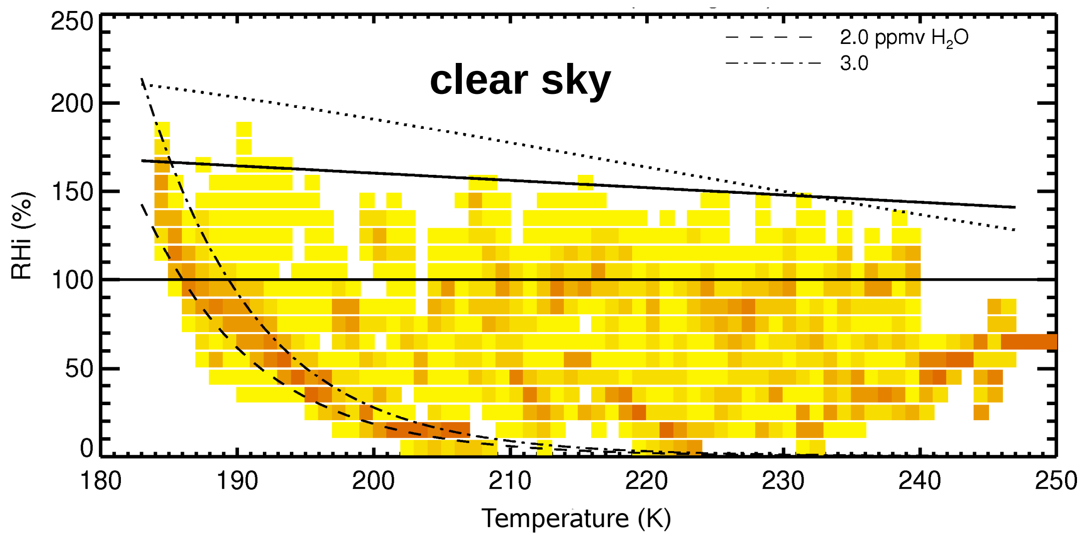


green: mid latitudes
blue: high latitudes
red/yellow: tropics

Aircraft
Geophysica
Falcon
Lear Jet

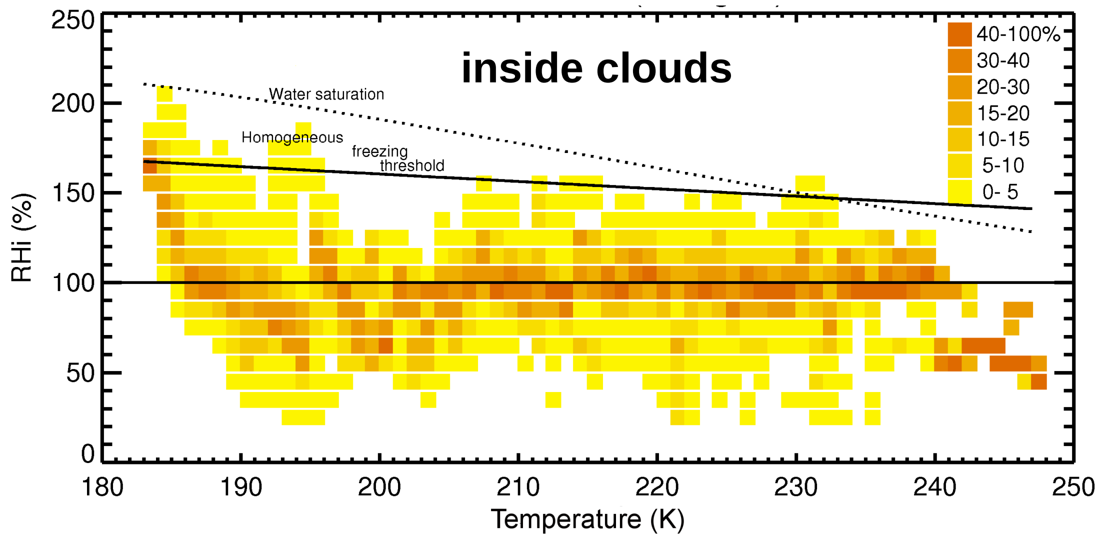
Krämer et al., 2009

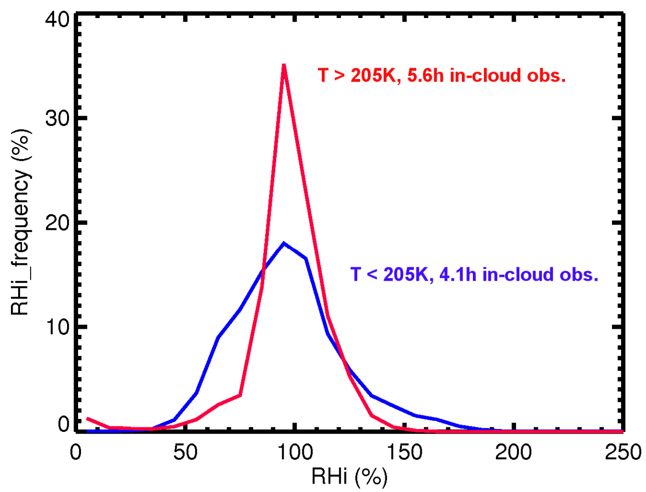
Supersaturation: frequency distribution and T-dependence



reprocessed data (28 flights)

- only few data > homogeneous f.t.
- no data > water saturation
- inside cloud RHi peaks at 100%
- broader distribution at T < 205 K





Krämer et al., 2009

Saturation ratio with respect to ice:

$$S = \frac{p_{H_2O}}{p_{vap}(T)} = \frac{n_{H_2O}}{n_{vap}(T)}$$

p_{H_2O} = partial pressure of water

$p_{vap}(T)$ = vapor pressure of ice

$S > 1$ → ice particles grow

$S = 1$ → ice particles are in equilibrium with the gas phase

$S < 1$ → ice particles evaporate

How does water vapor condense on ice particles?

$$\frac{dn_{H_2O}}{dt} = \underbrace{-4\pi D^* r\, n_{ice}}\,(n_{H_2O} - n_{vap})$$

$$\tau_{cond} = \frac{1}{4\pi D^* r\, n_{ice}}$$

How is supersaturation maintained?

$$\frac{dn_{vap}}{dt} = \frac{dT}{dt}\frac{dn_{vap}}{dT} = \underbrace{-\Gamma w \frac{B}{T^2}(1 - T/B)}\,n_{vap}$$

$$\tau_{cool} = \frac{1}{\Gamma w(B/T^2)\,(1 - T/B)}$$

$$p_{vap}(T) = A\, e^{-B/T}$$

$$\frac{dn_{\mathrm{H_2O}}}{dt} = \quad \ldots$$

$$\frac{dn_{\mathrm{vap}}}{dt} = \quad \ldots$$

$$\frac{dS}{dt} = \frac{d}{dt}\frac{n_{\mathrm{H_2O}}}{n_{\mathrm{vap}}}$$

$$= -\frac{S-1}{\tau_{cond}} + \frac{S}{\tau_{cool}}$$

$$\tau_{cond} = \frac{1}{4\pi D^{*} r\, n_{\mathrm{ice}}} \;, \quad \tau_{cool} = \frac{1}{\Gamma w(B/T^{2})\,(1-T/B)}$$

Steady-state *S* in an upwelling air parcel (w)

$$\frac{dS}{dt} = -\frac{S-1}{\tau_{cond}} + \frac{S}{\tau_{cool}} = 0$$

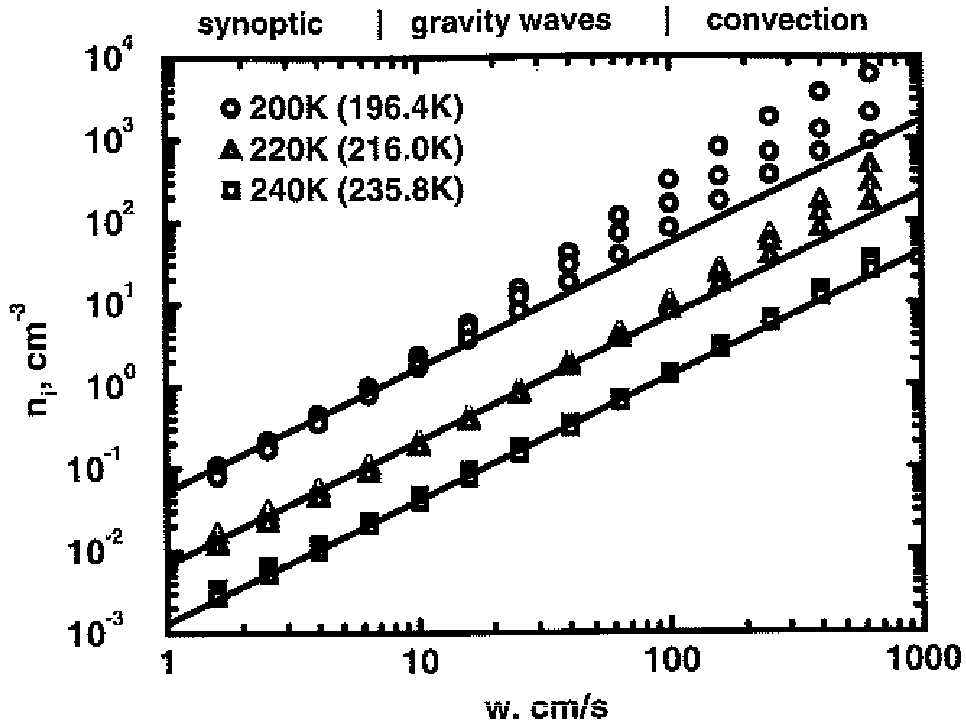
$$\boxed{S - 1 \approx \frac{S\,\hat{w}}{\hat{r}\,\hat{n}_{\text{ice}}}}$$

$$\hat{w} = w \,/\, (1\ \text{m/s})$$

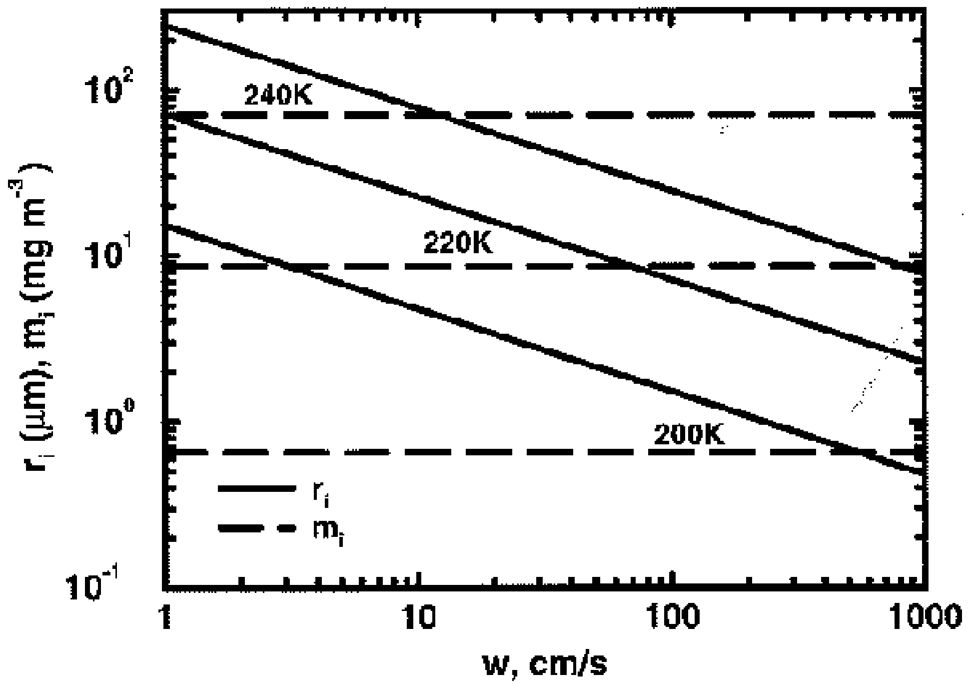
$$\hat{r} = r \,/\, (1\ \mu\text{m})$$

$$\hat{n}_{\text{ice}} = n_{\text{ice}} \,/\, (1\ \text{cm}^{-3})$$

Ice crystal number densities
- vertical velocity w
- frost point at which air starts
- aerosol properties varied



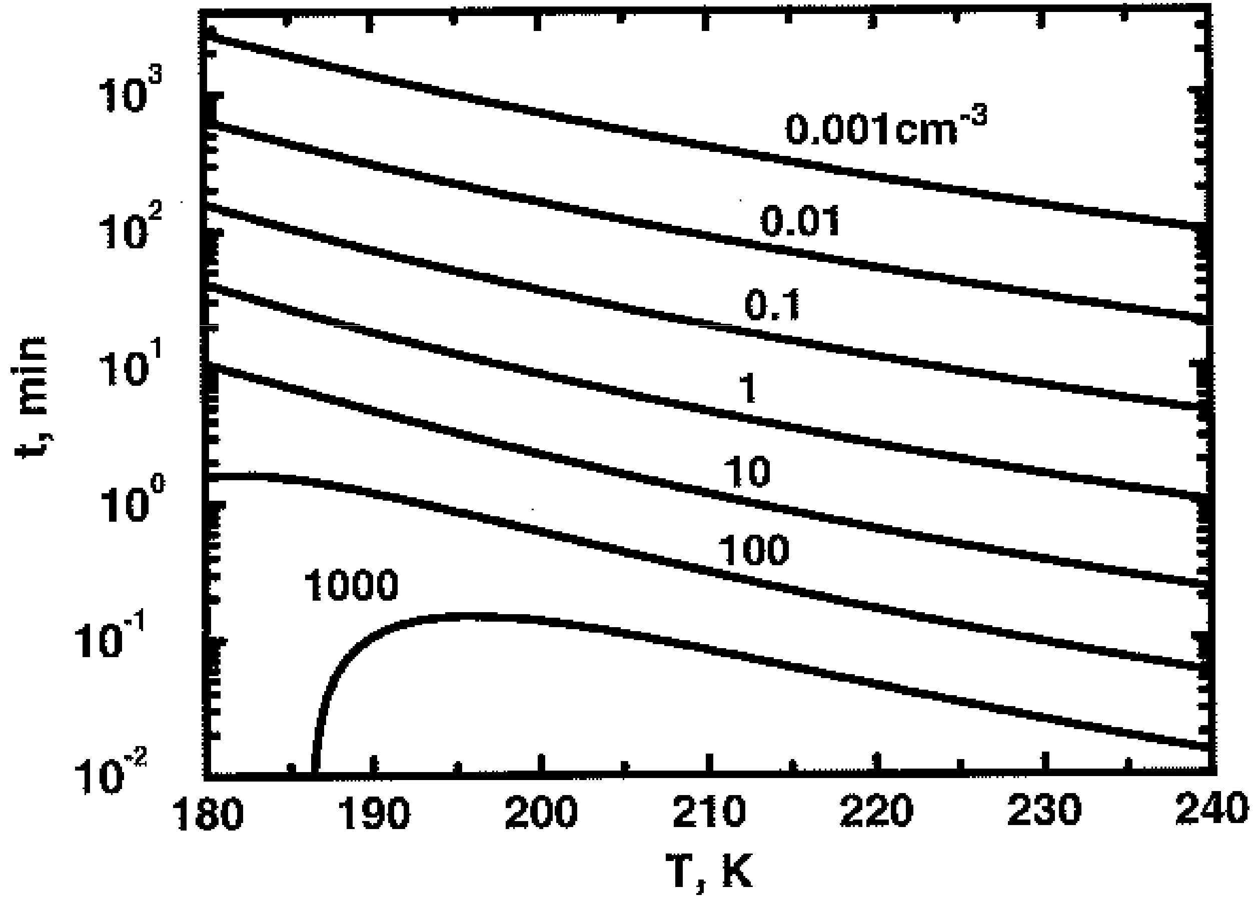
Mean ice crystal radii
Ice water content



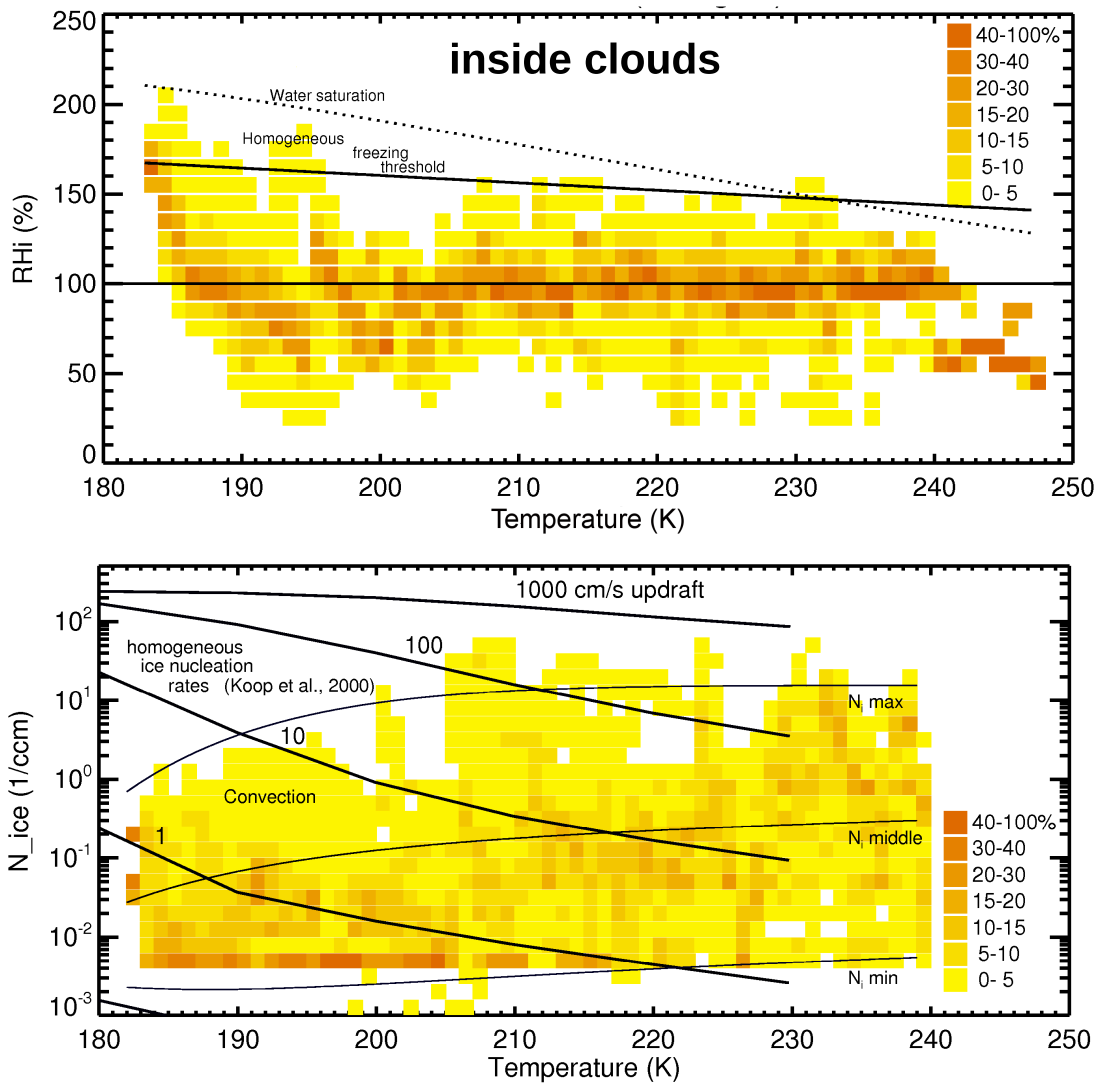
Kärcher & Lohmann, 2002

Growth time of ice particles

(up to 80% of equilibrium radius)



Supersaturation and N_{ice}



FSSP measurements from 20 flights by S. Borrmann and M. deReus

(persisitent) supersaturation consistent with low N_{ice}

supersaturation puzzle → freezing suppression puzzle

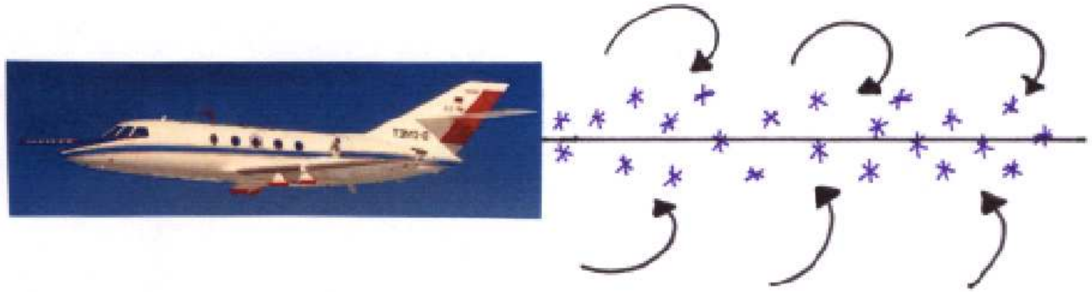
homogen. freezing and low u_z?

heterogen. freezing?

freezing supression by organics?

Contrails / contrail cirrus

Contrails and RHi

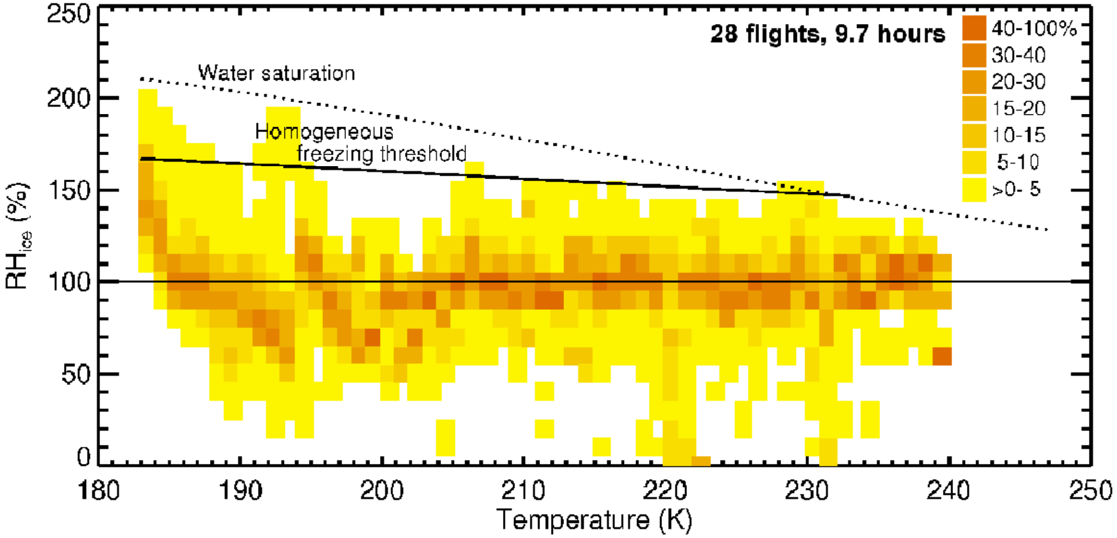


RHi > 100%
persistent contrails

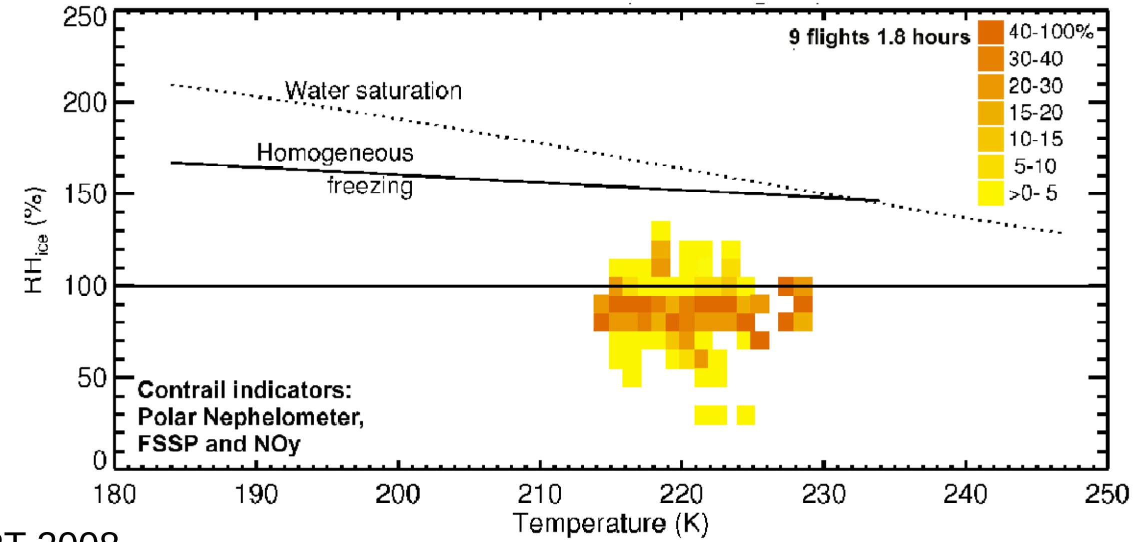
RHi < 100%
lifetime of minutes

embedded in (sub-)visible cirrus?
generating new cirrus?

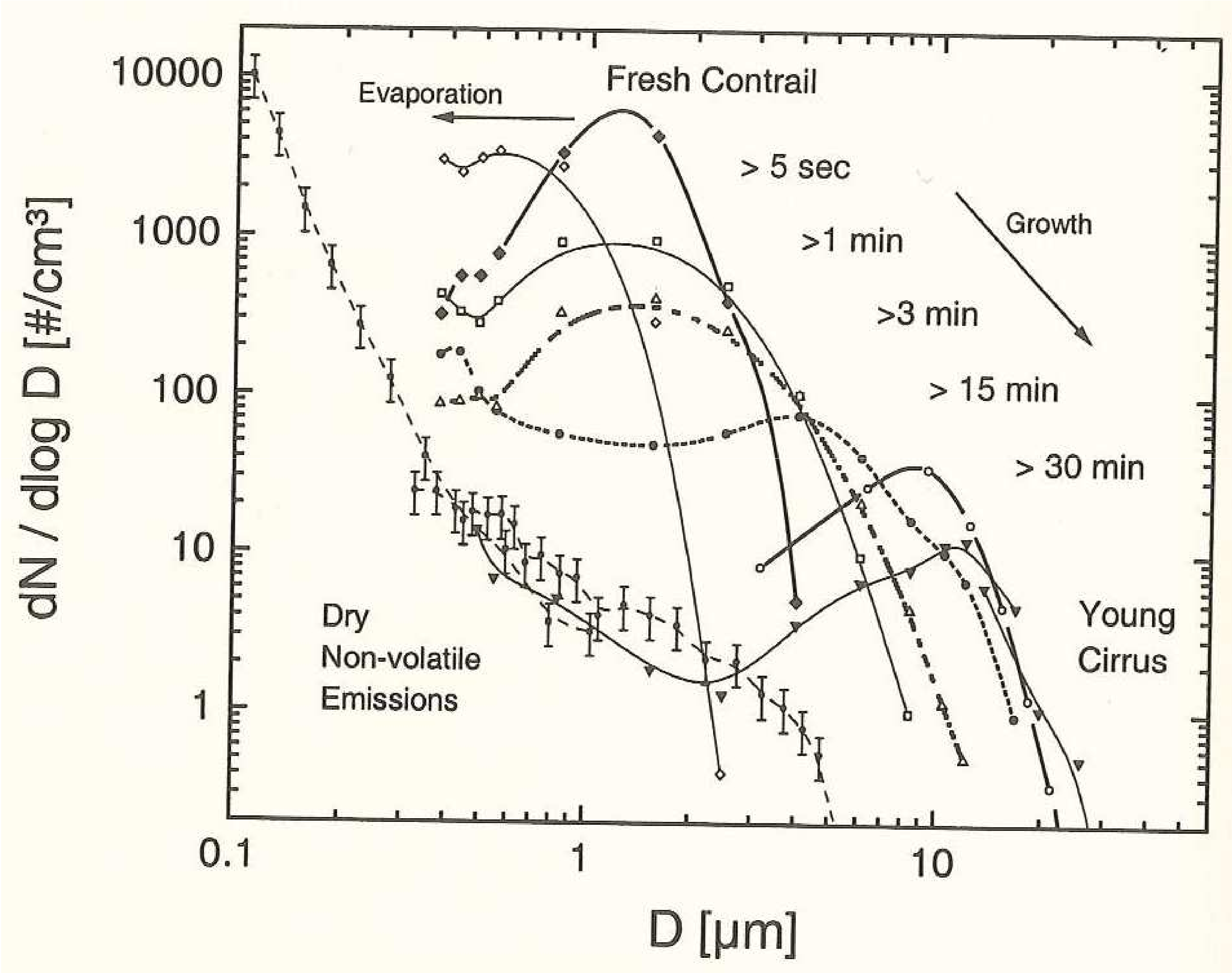
Cirrus



Contrails

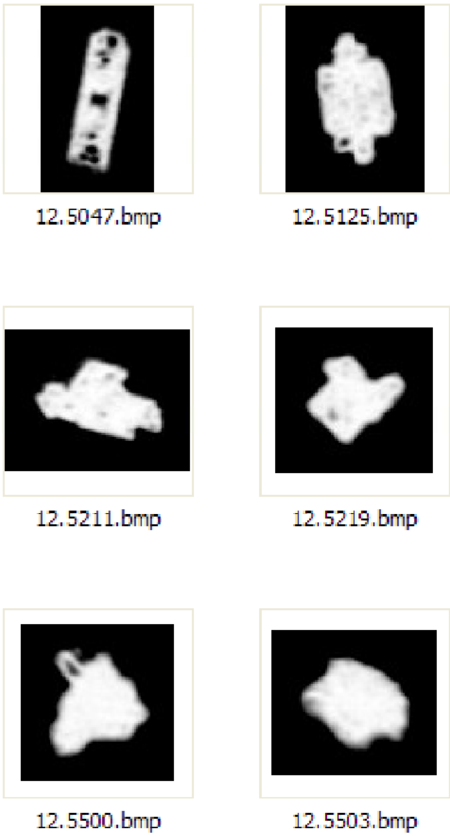


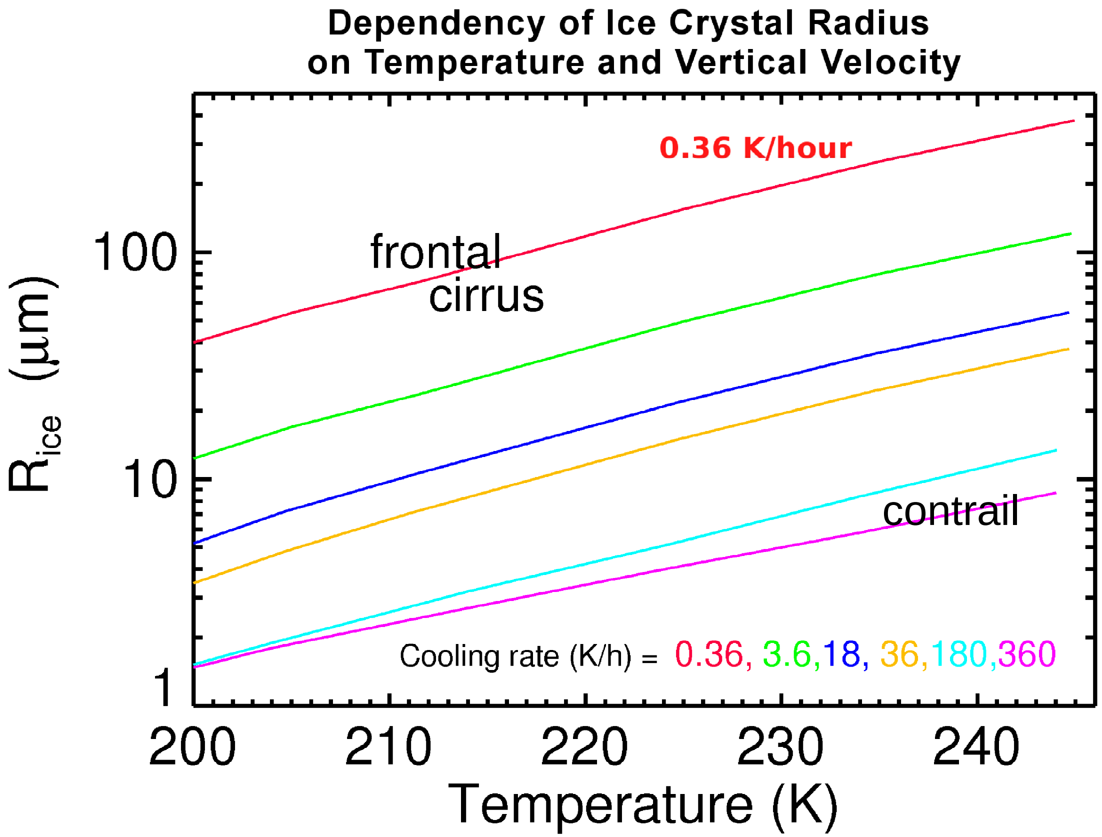
Krämer, CONCERT 2008



Schumann, 2002

Particles in a fresh contrail





During CONCERT large ice crystals (100µm) observed in short-lived contrail
→ entrainment from surrounding cirrus