ÉCOLE DE PHYSIQUE des HOUCHES

Cloud microphysics

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Met Office

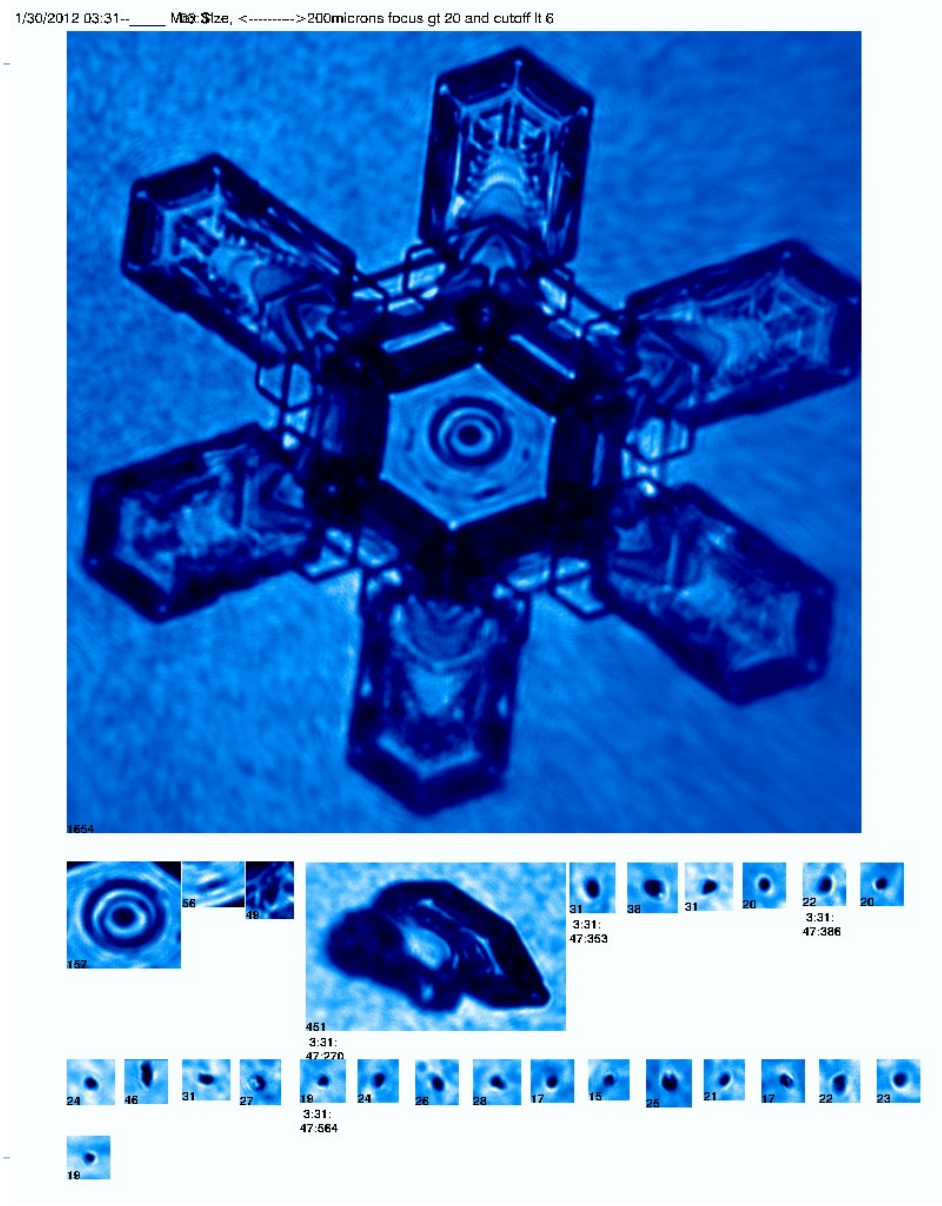
Microphysics processes
Cold clouds

Cold clouds

- Ice morphology

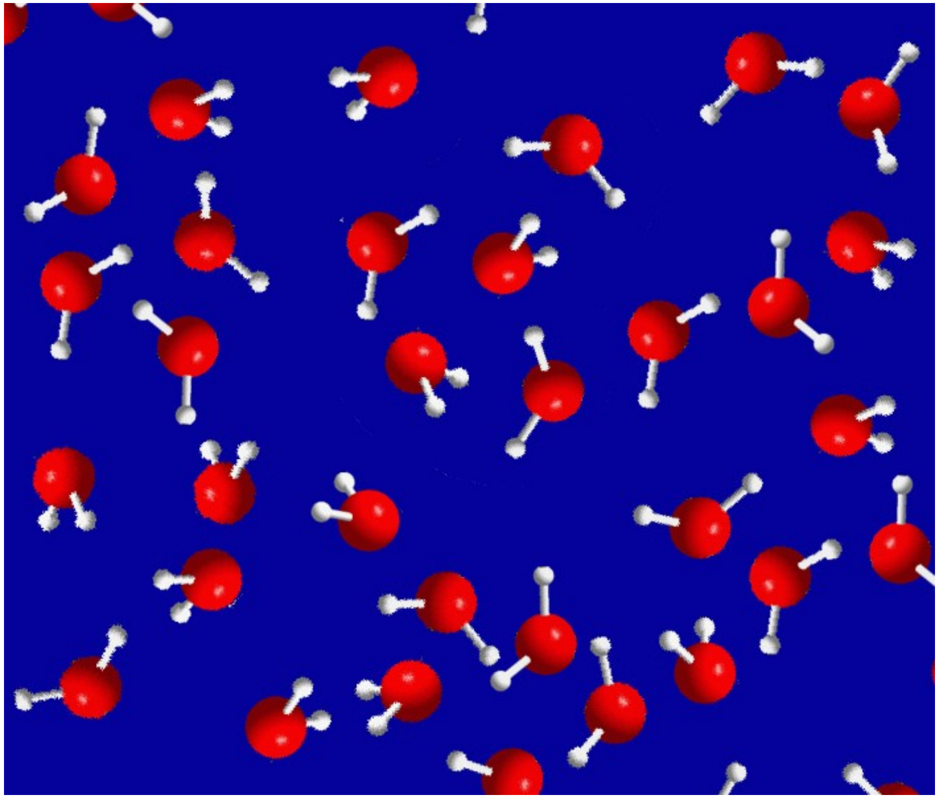
Ice crystals

- An example of an ice crystal observed in-situ during a flight through cirrus (PIKNMIX campaign)
- A regular hexagonal structure forms around the initial freezing site.



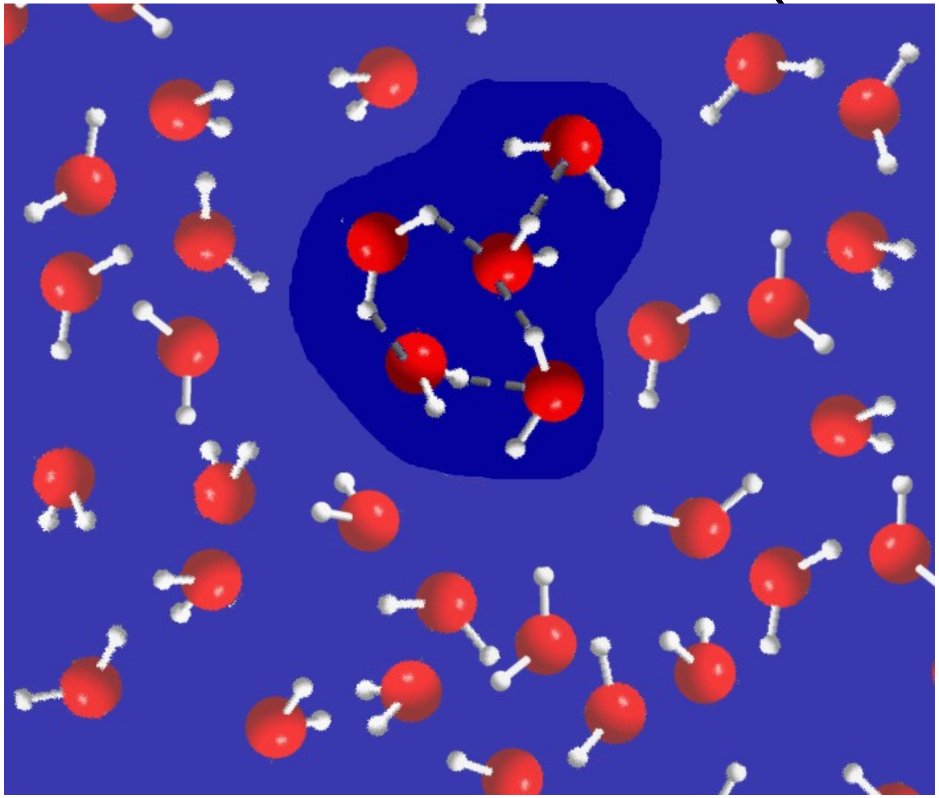
Ice formation

- Water molecules in the vapour and liquid phases are generally randomly orientated and free to move throughout the fluid.



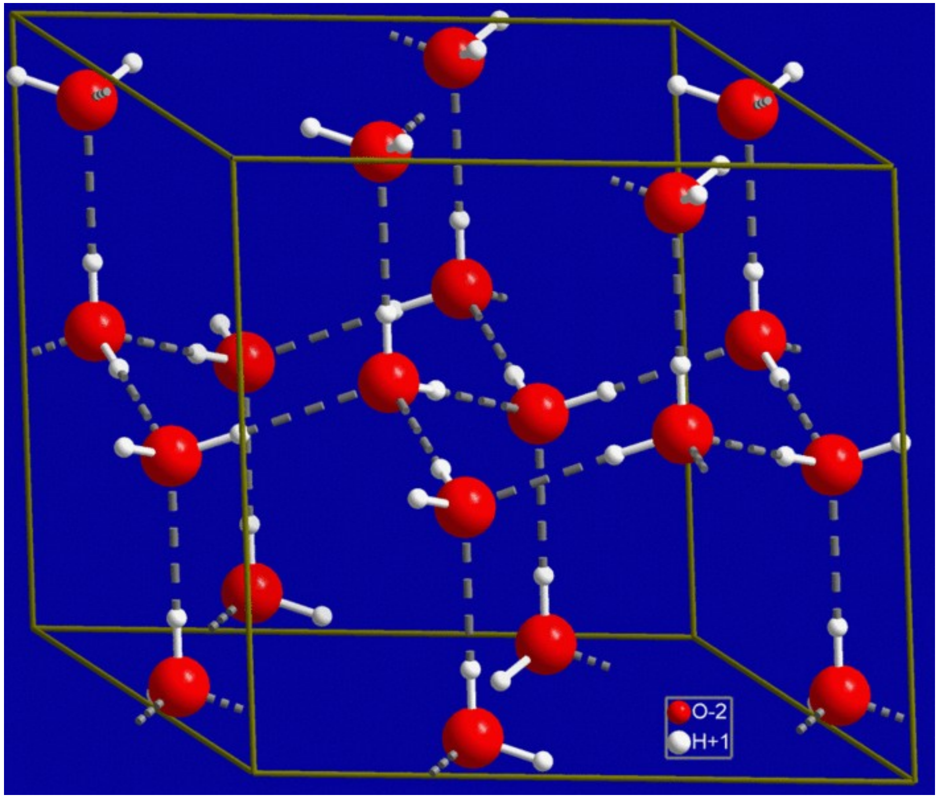
Ice formation

- Occasionally, small clusters can form spontaneously, but these are usually too small to remain stable (see Kohler discussion for liquid phase)



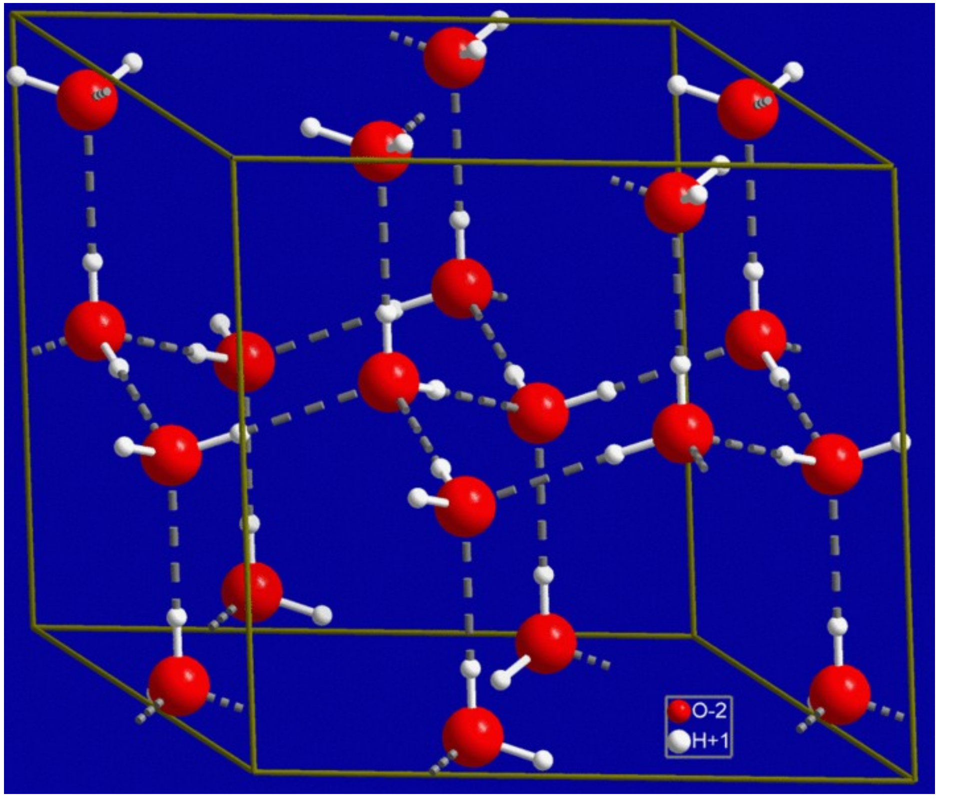
Crystallization

- Ice forms in a rigid structure
- As with droplet formation an embryo of sufficient size must form so that it remains stable and can grow.



Crystallization

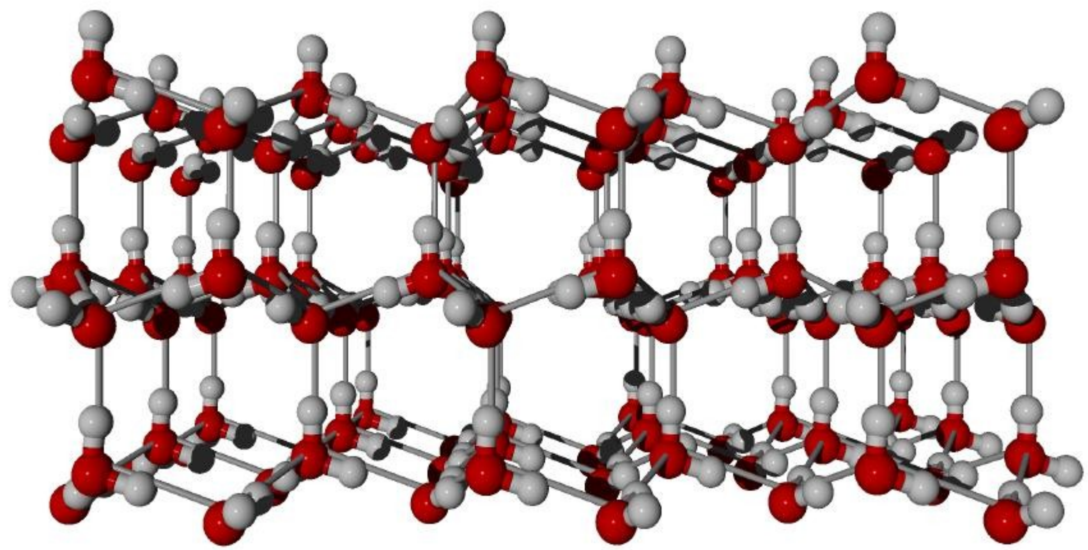
- There are 15 known stable crystal lattices found in solid water form.
- At typical atmospheric pressures and temperatures only the a hexagonal ice-Ih structure is formed
- At very low temperature and pressure, such as that found in the upper troposphere, cubic can form(ice-Ic).



Hexagonal arrangement of Ice-Ih

Crystallization

- Bernal-Fowler rules determine the positioning of hydrogen atoms in ideal ice-Ih: (Bernal & Fowler, 1933)
- As a result, ice crystals grow in hexagonal structures
- Natural ice contains defects which sometim lead to deviations in the hexagonal structure an subsequent growth of particles

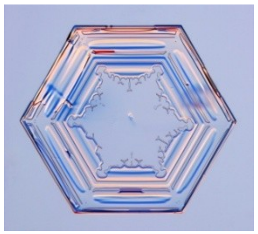
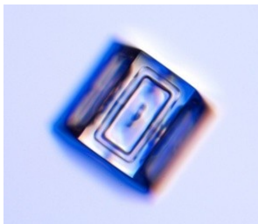


Alternative view shows hexagonal arrangement

Ice habits

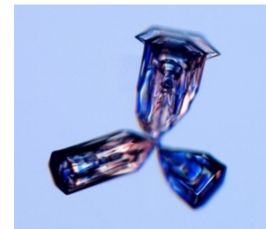
Images from Snowcrystals.com

Prisms and Plates

Needles


Bullet rosettes

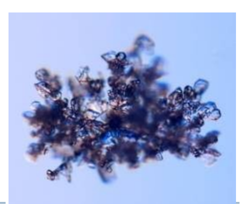



Stellar plates


Hollow columns


Dendrites

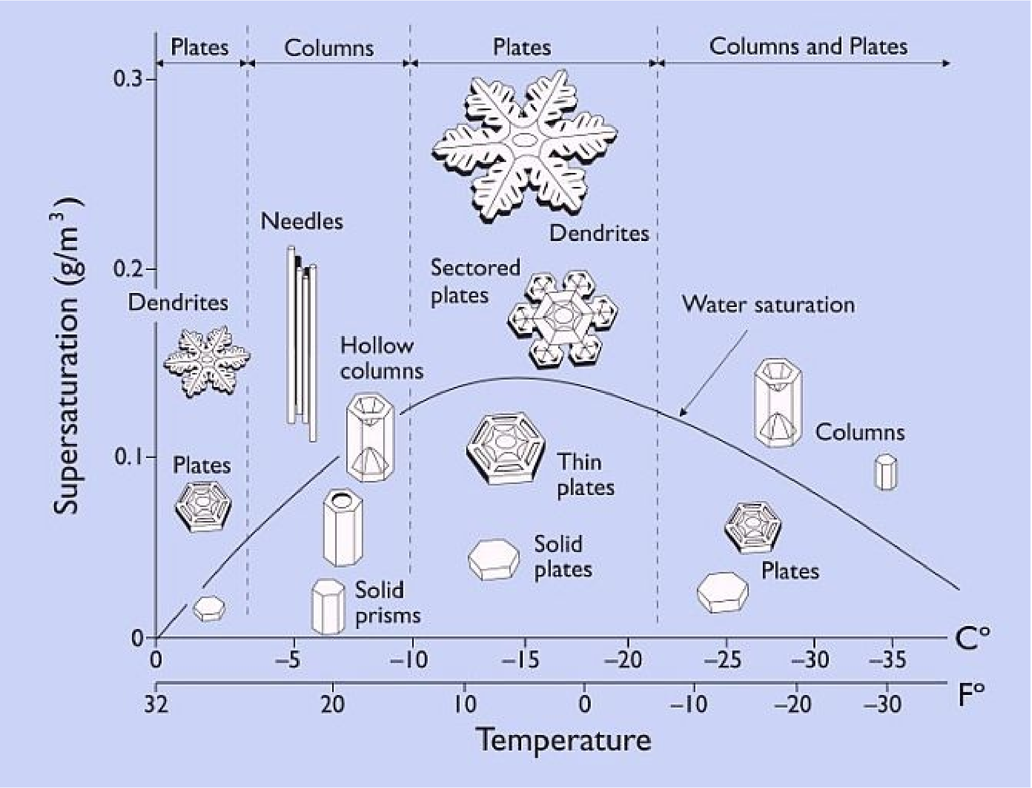

Irregular crystals



Ice habits

Images from Snowcrystals.com

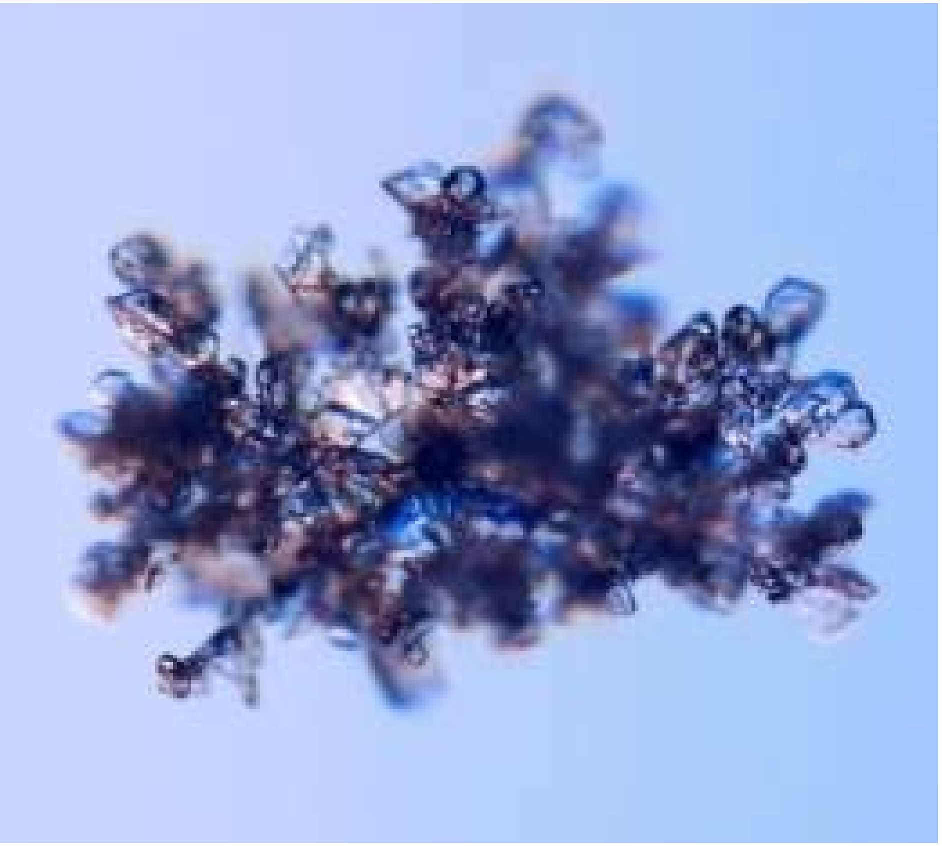
- Different growth regimes can be identified
- E.g. dendrites tend to form in more humid conditions and plates in drier conditions.



Ice habits

Images from Snowcrystals.com

- However, most commonly observed crystals have irregular or complex shapes.



Cold clouds

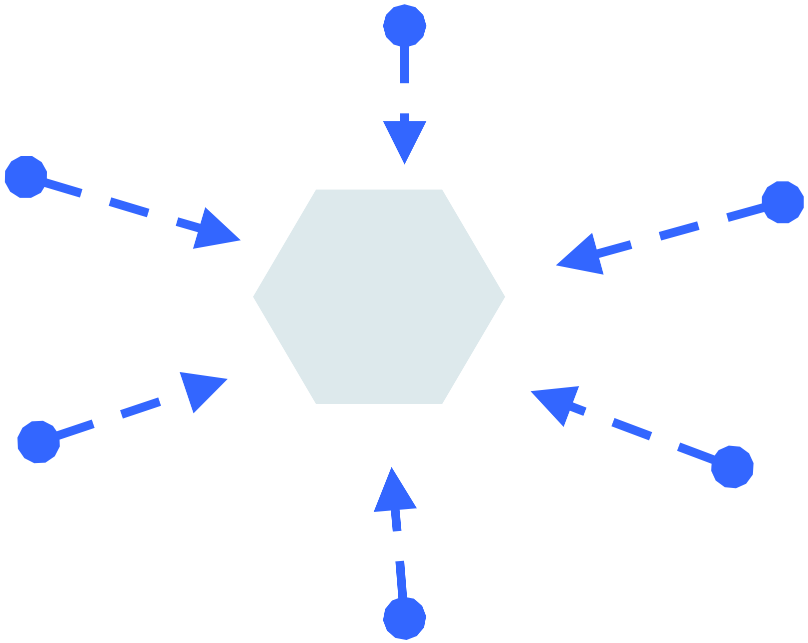
- Ice nucleation

Homogeneous and heterogeneous freezing

- Spontaneous cluster formation is unlikely to produce embryos large enough to survive to form stable crystal structures
- Not until temperatures reach around -40°C do we see pure liquid droplets freezing to form ice (Homogeneous freezing)
- As with liquid water droplet formation, the process can be catalyzed by foreign particles known as ice nuclei (IN). (Heterogeneous freezing)
- The foreign particle must allow water molecules to bond to it and initiate the crystallization process.

Heterogeneous freezing mechanisms

- There are several ways in which a foreign particle might initiate ice nucleation:
  - Deposition freezing:

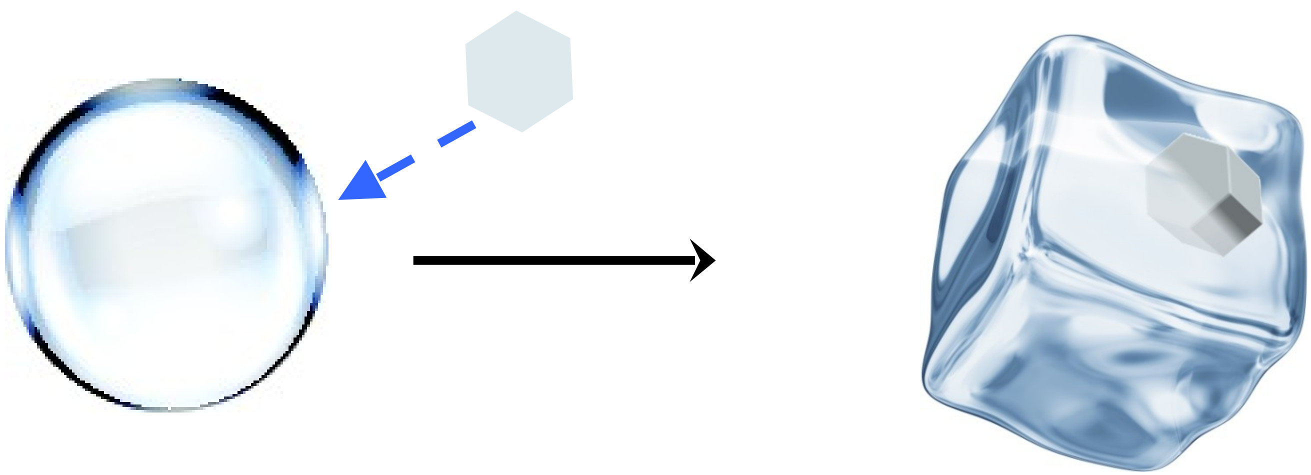


Vapour deposits directly onto the ice nucleus

Heterogeneous freezing mechanisms

- There are several ways in which a foreign particle might initiate ice nucleation:
  - Contact freezing:

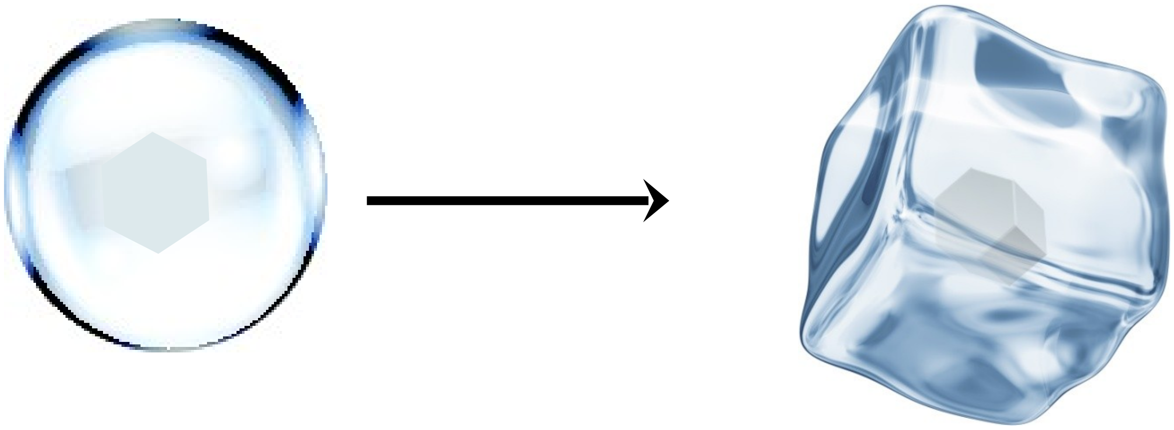
Ice nucleus impacts upon supercooled liquid droplets



Heterogeneous freezing mechanisms

- There are several ways in which a foreign particle might initiate ice nucleation:
  - Immersion freezing:

Ice nucleus resides inside a supercooled liquid droplet



Heterogeneous freezing mechanisms

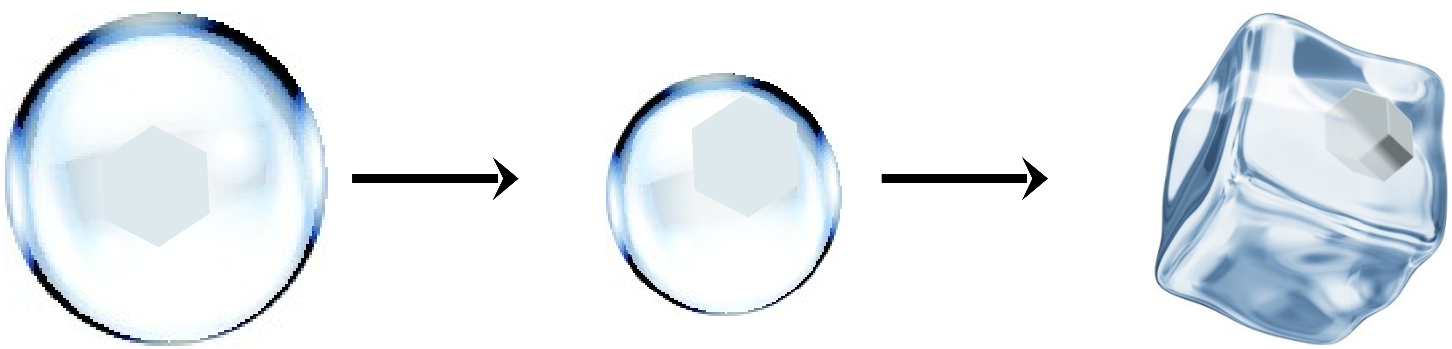
- There are several ways in which a foreign particle might initiate ice nucleation:
  - Condensation freezing:

Ice nucleus contains soluble material which deliqueses before immediately freezing.

Heterogeneous freezing mechanisms

- There are several ways in which a foreign particle might initiate ice nucleation:
  - Evaporation freezing:

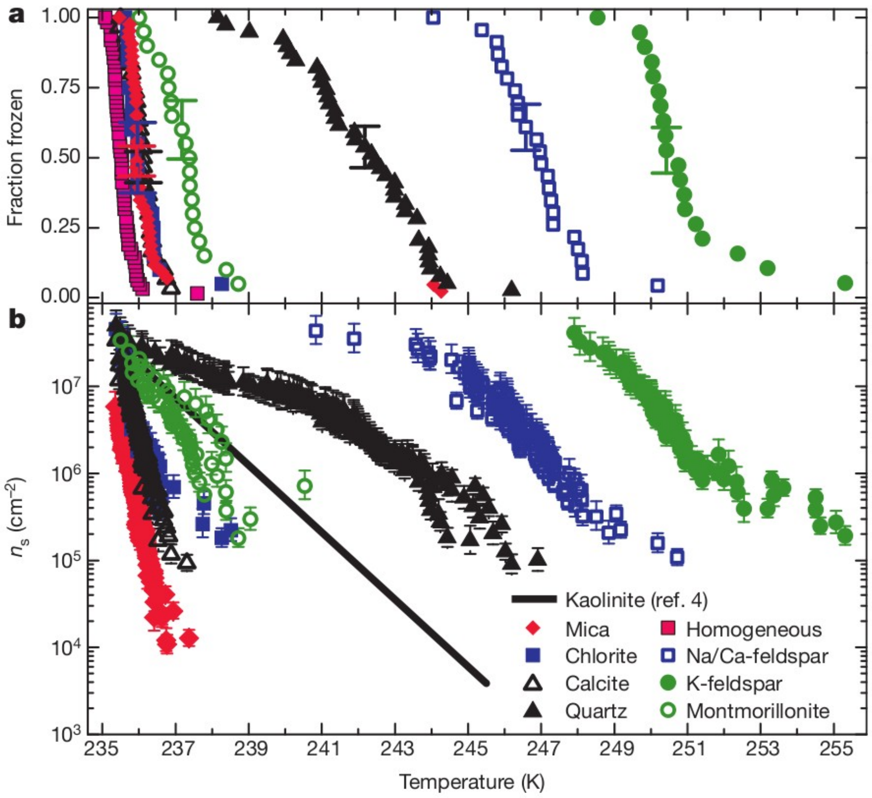
Ice nucleus moves closer to droplet surface as the droplet evaporates. ‘Inside-out’ contact freezing



What makes a good ice nucleus?

- Complete understanding of ice nucleation remains elusive and a subject of ongoing research, however (with certain exceptions) the following properties are generally desirable in a good IN:
  - Insoluble: If soluble, the particle will break up and become too small to form an embryo large enough
  - Size: Larger particles are more likely to form large embryos
  - Chemistry: Hydrogen bond must be available at the particle surface in order to bond with water molecules
  - Crystallography: The geometrical arrangement of bonds on the particle surface must reflect the arrangement of molecules in an ice crystal lattice.

What makes a good ice nucleus?



Recent evidence suggests that one particular type of mineral (Feldspar) may be responsible for much of the immersion mode IN

Atkinson et al, Nature, 2013

Cold clouds

- Diffusional growth

Diffusional growth

- Using the same ideas as for the condensational growth of liquid droplets, the growth of ice particles by vapour diffusion can be written as:

$$\frac{dm}{dt} = 4\pi C D_v \left(\rho_{v,\infty} - \rho_{s,r} \right)$$

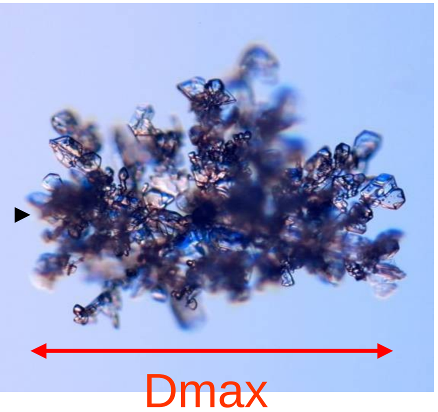
- Unlike liquid droplets, which were assumed spherical, the shape of the ice particle determines the value of C. (NB for a sphere, C=r, the radius).
- The form of this equation is chosen to be analogous with that used in electrostatics to determine the leakage of charge from an arbitrarily shaped conductor. Hence the coefficient,C, is termed the **capacitance**.

Diffusional growth: Capacitance

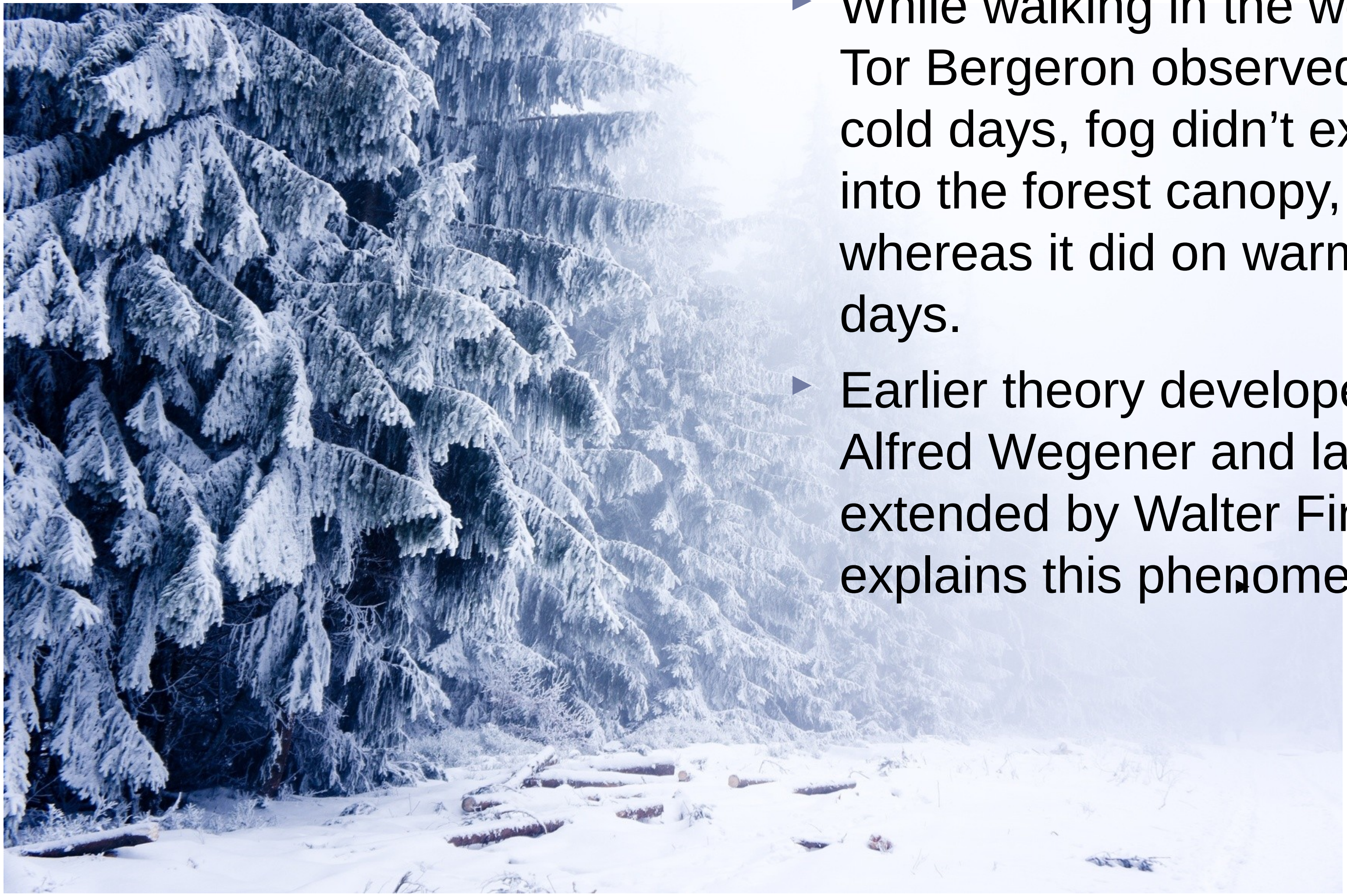
Images from Snowcrystals.com

- Theoretical, numerical, experimental and observational studies tell us how we might expect C to change with ice particle shape.
- Importantly, aggregates show little sensitivity to the shape of their constituent parts, but depend on the maximum diameter,

Shape	Capacitance	reference
Sphere, diameter D	$C = \frac{1}{2}D$	McDonald(1963) (theoretical)
Thin disk, diameter D	$C = \frac{D}{\pi}$	"
Prolate spheroid: major axis a, minor axis b	$C = A/\ln[(a+A)/b]$; $A = \sqrt{a^2 - b^2}$	"
Circular cylinder: radius a, aspect ratio ϕ	$C = 0.637a(1 + 0.868\phi^{0.76})$	Smythe (1962) (numerical)
Hexagonal columns: half-width a, aspect ratio ϕ	$C = 0.58a(1 + 0.95\phi^{0.75})$	Westbrook et al (2008) (numerical)
6-point bullet rosette: max diameter D_{Max}, aspect ratio of each arm ϕ	$C = 0.4\phi^{0.25}D_{max}$	"
Aggregates, max. diameter D_{max}	$C = \lambda D_{max}$ $\lambda = 0.25 - 0.28$	"
	$C = 0.26 D_{max}$	Field et al (2008) (in-situ observations)



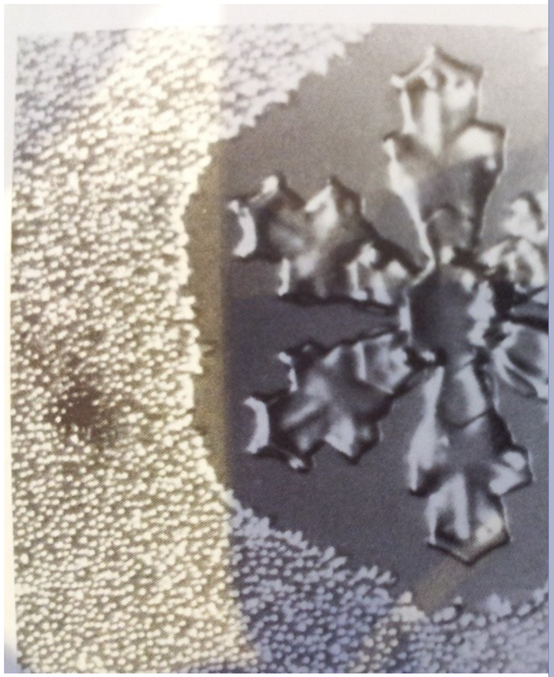
Wegener–Bergeron–Findeisen process



- While walking in the woods, Tor Bergeron observed that on cold days, fog didn't extend into the forest canopy, whereas it did on warmer days.
- Earlier theory developed by Alfred Wegener and later extended by Walter Findeisen, explains this phenomenon.

Wegener–Bergeron–Findeisen process

Images from Snowcrystals.com



- Ignoring solute and Kelvin affects for droplets and invoking the ideal gas law, we find that ice and liquid particles grow according to:

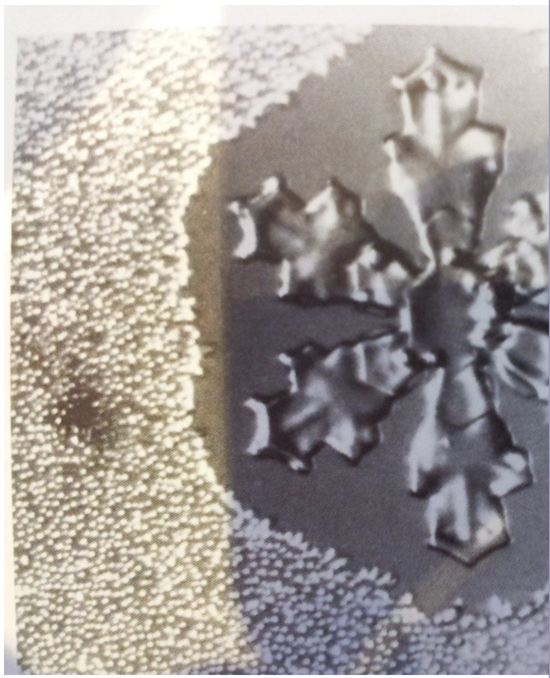
$$\frac{dm_l}{dt} \propto (e - e_{s,l})$$

$$\frac{dm_i}{dt} \propto (e - e_{s,i})$$

where es,l and es,i are respectively the equilibrium (or saturation) vapour pressures over liquid water and ice.

Wegener–Bergeron–Findeisen process

Images from Snowcrystals.com



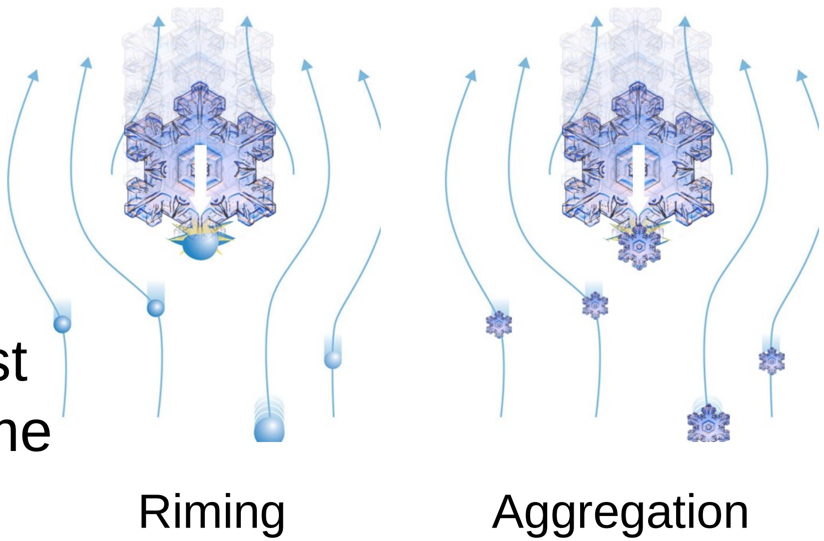
- Equilibrium vapour pressure over liquid, es,l, is greater than that for ice, es,i (since water molecules in ice are more tightly bonded).
- In conditions where the ambient vapour pressure, e, exceeds both es,l and es,i ,both droplets and ice will grow until e falls below es,l.
- If the ambient vapour pressure lies between the two, i.e. es,l> e >es,l, ice particles will grow and droplets will start to evaporate
- The evaporation of the droplets provides an additional source of vapour, accelerating the growth of the ice

Cold clouds

- Aggregation and Riming

Riming and Aggregation

- As with pure liquid clouds, particles of differing size or shape will fall at different speeds, resulting in collisions.
- Small plate-like crystals have very little variation in fallspeed, while needles fall very slowly.
- Riming of particles can result in greater differential fall speeds, and hence aggregation is more likely after riming has taken place
- The likelihood of two ice particles sticking together is increased at warmer temperatures
- 'Fernlike' dendrites are most likely to stick as they become interlocked.

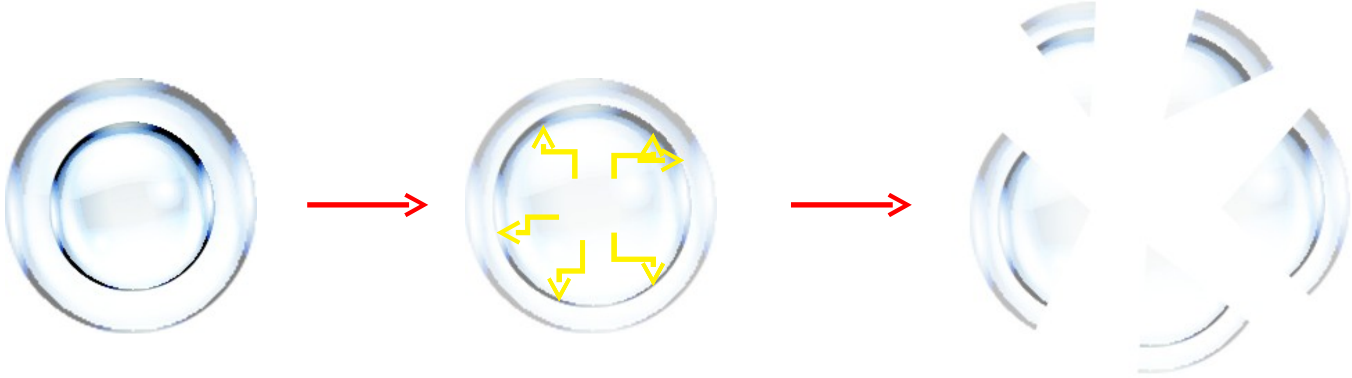


Cold clouds

- Ice multiplication

Ice multiplication (Hallet-Mossop)

- The process of freezing a supercooled droplet often first involves a thin shell of ice forming on the surface of the droplet, the subsequent freezing of the interior creates an outward pressure on this shell as it tries to expand.
- The resulting stresses can cause the particle to shatter, producing numerous small splinters
- Observations suggest that this process is most efficient at temperatures around -5°C, during the riming process



Cold clouds

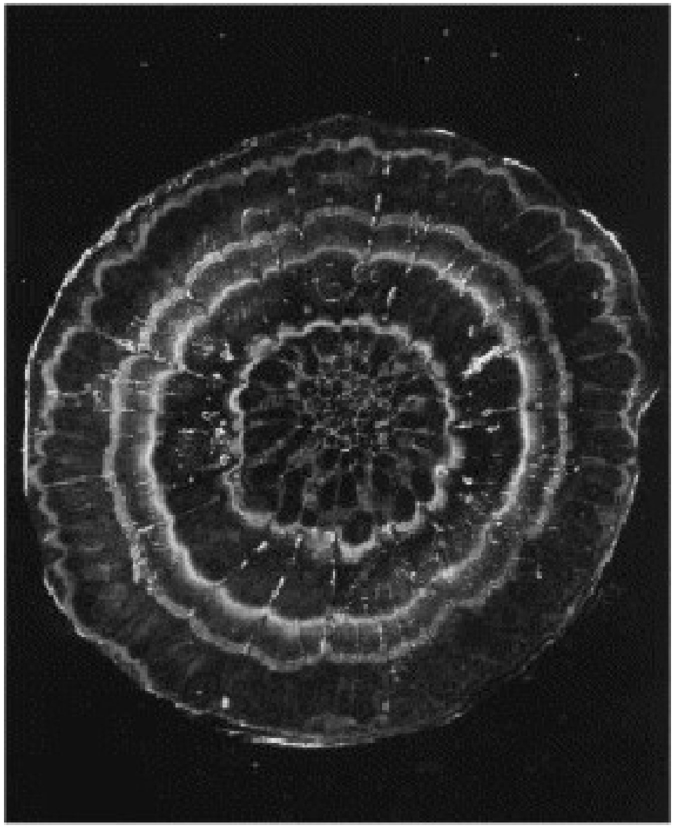
- Graupel and Hail

Growth of Hail and Graupel

- A heavily rimed ice particle is referred to as graupel (or soft hail)
- In vigorous convective clouds, graupel particles can be held up within the cloud, leading to further growth through riming until they become dense hailstones.
- Hailstones typically grow to around 1cm, but in extreme cases can grow to O(10cm), causing considerable damage to crops and property.

Growth of Hail and Graupel

- During the riming process, latent heat release due to the droplet freezing raises the temperature of the hailstone. If enough mass is collected (and frozen), the temperature of the surface of the hailstone can raise above 0°C
- In these conditions, some of the liquid remains unfrozen and the hailstone undergoes 'wet growth'.
- In this growth regime, numerous small liquid droplets may be shed in the wake of the hailstone
- Wet and dry growth history can be observed in the hailstone cross section: wet growth tends to result in clear ice; dry growth encases bubbles in the ice and appears opaque

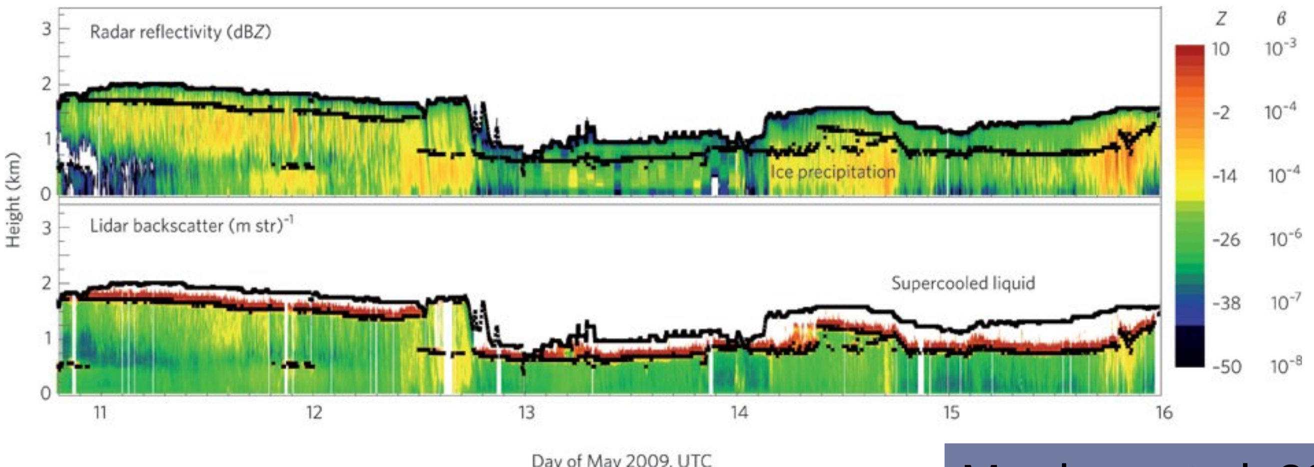


Cold clouds

- Supercooled liquid water and mixed-phase clouds

Supercooled liquid water layers

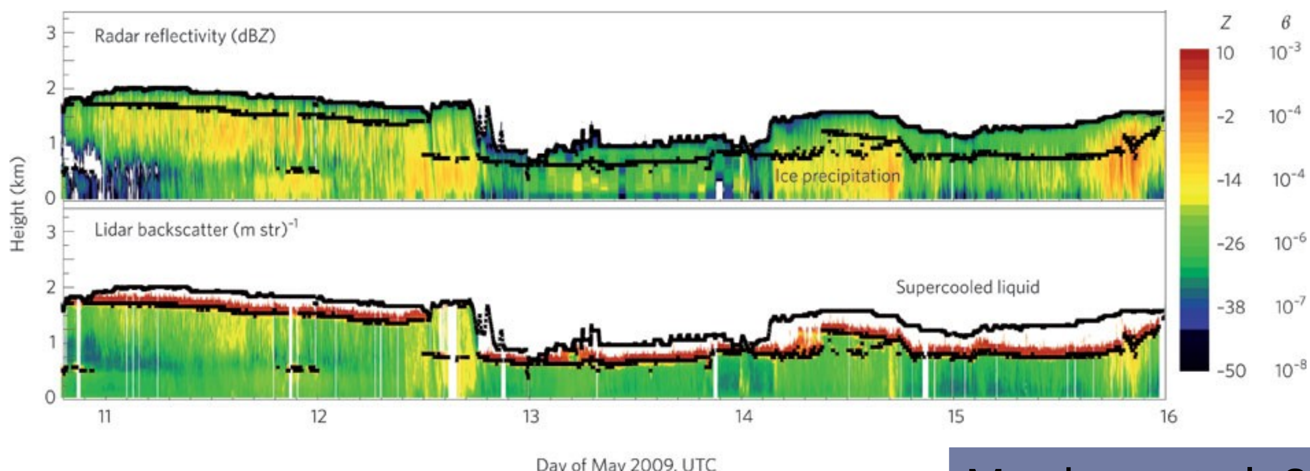
- In polar clouds and midlevel clouds, supercooled liquid water is often observed to co-exist with ice.
- This is important for the evolution of the clouds, but most significant is the radiative impact:
- Enhanced radiative cooling from the liquid droplets, generates turbulence which allows the system to persist
- Moreover, the persistence of the cloud has significant implications for the surface radiation budget in polar regions



Morrison et al, 2012

Supercooled liquid water layers

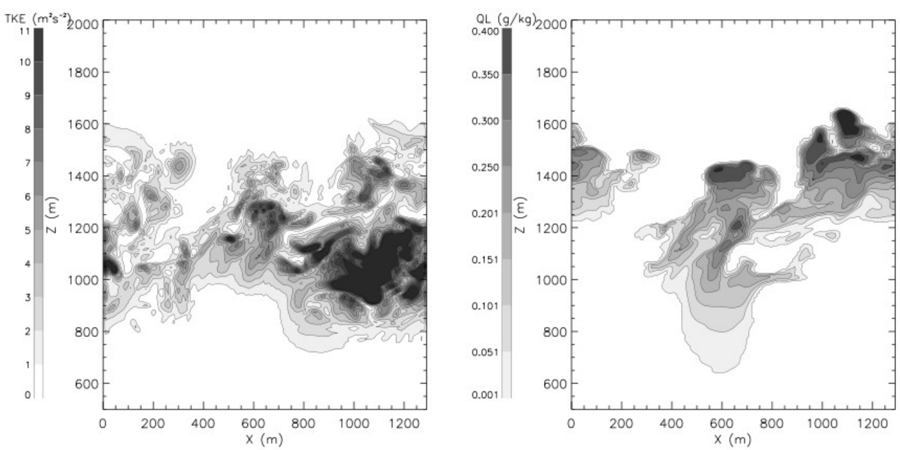
- Recall from WBF process, that ice will grow at the expense of liquid (since $e_{s,l} > e_{s,i}$)
- This would imply that for static clouds ice should grow and rapidly remove any liquid water (on the timescale of minutes)
- Yet liquid layers are observed to persist for several days.



Morrison et al, 2012

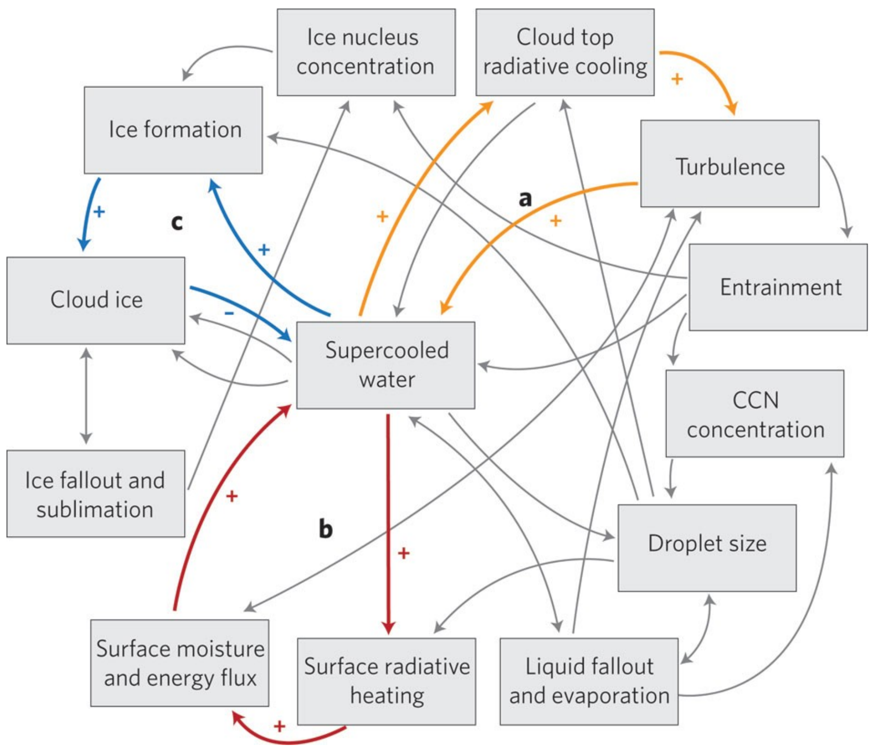
Supercooled liquid water layers

- Although the ambient vapour pressure is necessarily reduced by the growth of ice, adiabatic cooling of an air parcel will serve to further decrease the equilibrium vapour pressure.
- Thus if a parcel is lifted fast enough, the vapour pressure can remain above es,l and liquid water can persist.
- Where turbulent kinetic energy is strong enough, liquid water can be generated or maintained.



Supercooled liquid water layers

- But as with all clouds, the complete solution is a complex interaction between the cloud dynamics, the interaction with radiation and the microphysics...



Morrison et al, 2012

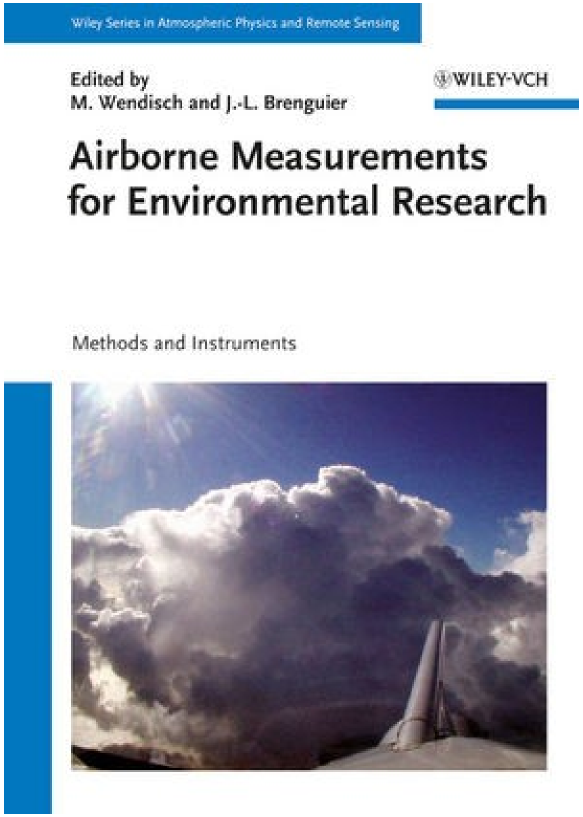
Observations, measurements

In-situ measurements

Remote sensing

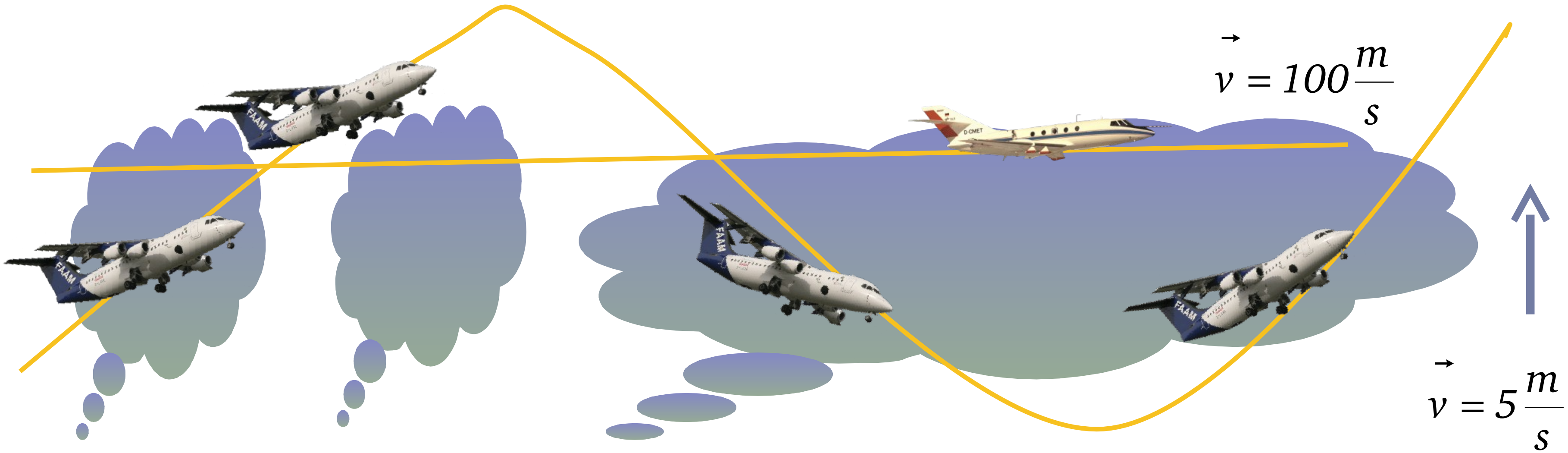
In-situ measurements

- Direct measurements in clouds
  - Instrumented aircrafts
  - Airborne laboratories (as ACTOS – Airborne Cloud Turbulence Observation System)



In-situ measurements
Instrumented aircrafts

EUFAR
European Facility
For Airborne Research



Vertical distance: 500 m, horizontal distance: 10 km

In-situ measurements
ACTOS – Airborne Cloud Turbulence Observation System

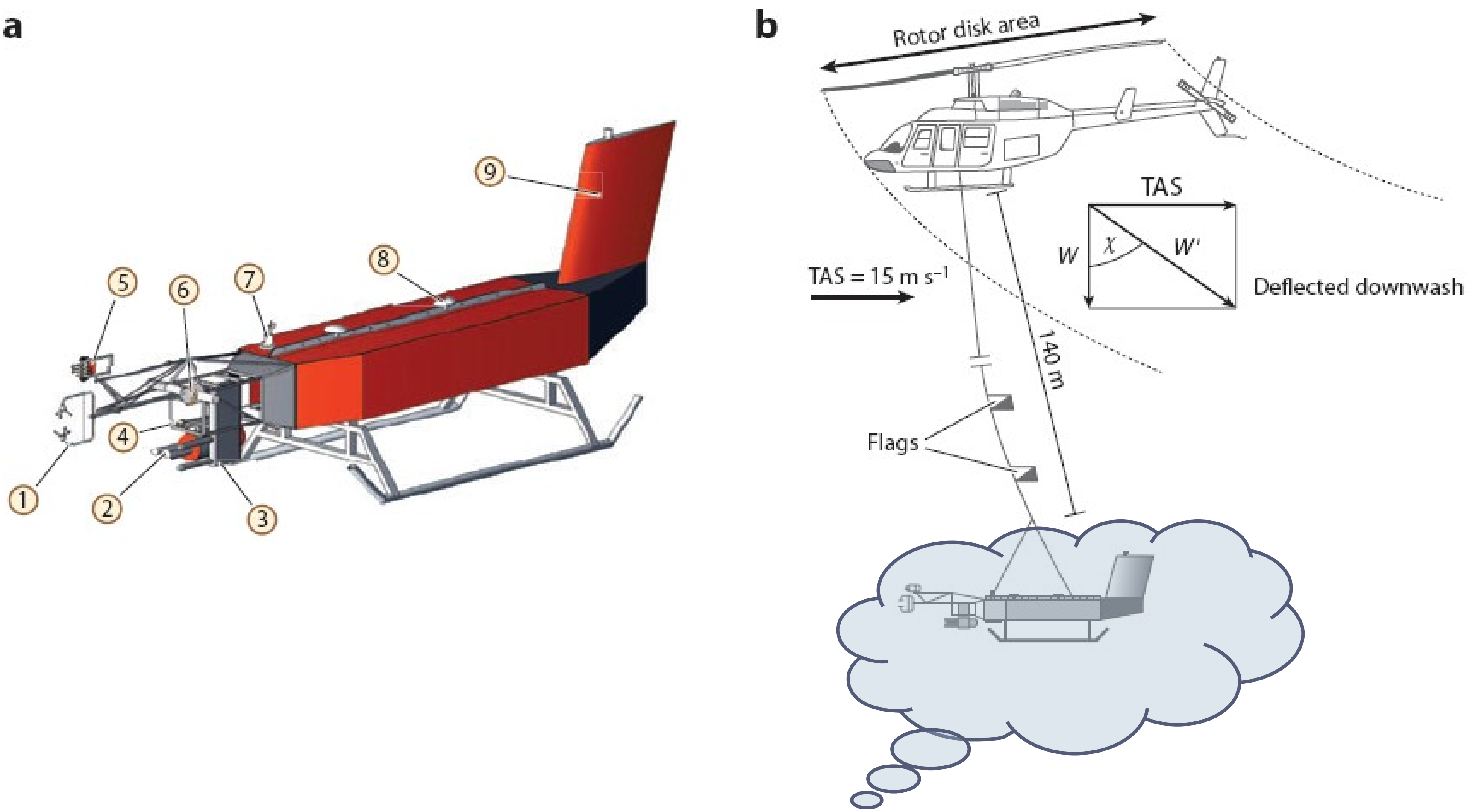


Figure: Siebert et al., 2006

Airborne measurements

- Aircraft-borne
- Observing the wide range of scales from an aircraft is challenging because of the aircraft speed (~100 m/s)
- This requires instruments with extremly fast response time
- They need to be located close to each other to

- Helicopter-borne
- Significantly lower horizontal speed
- Much better resolution
- Instruments have to be located closly
- Limited flight ceiling (helicopter are not allowed to fly through clouds)
- Measurements don’t represent large scale phenomena
- Very suitable to study turbulence processes

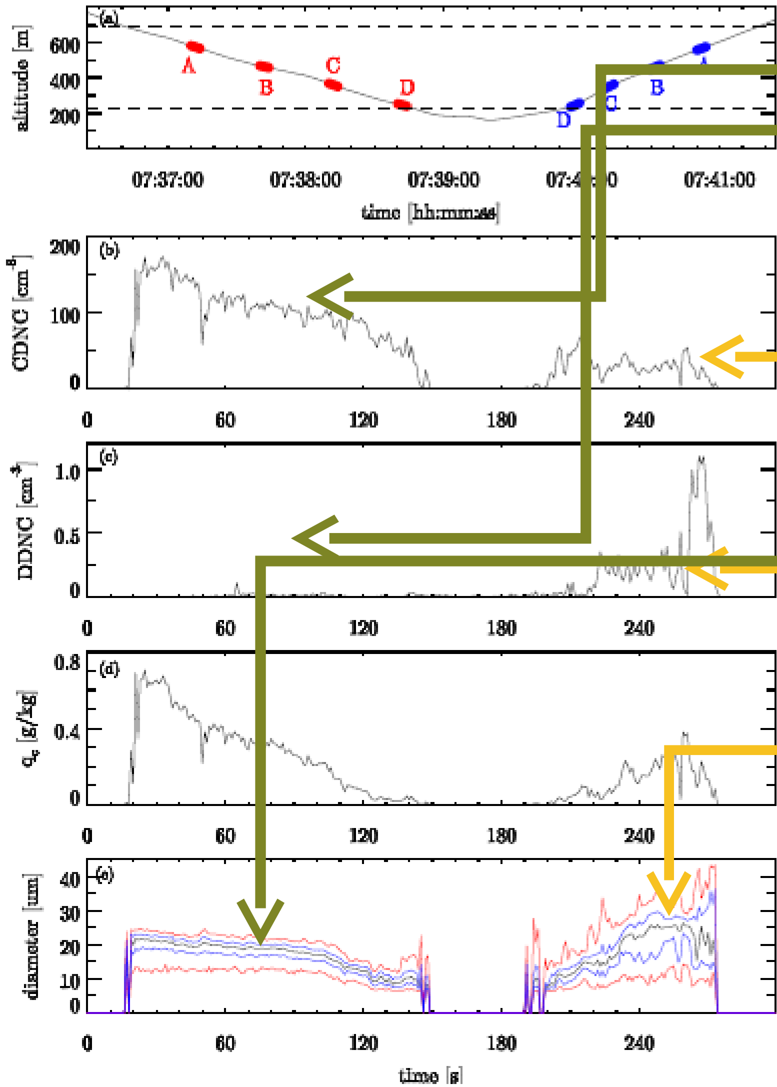
Cause and effect

Cloud droplets concentration

Drizzle drops concentration

Liquid water content

Droplets spectrum percentiles



High droplets concentration
No drizzle
Narrow spectrum

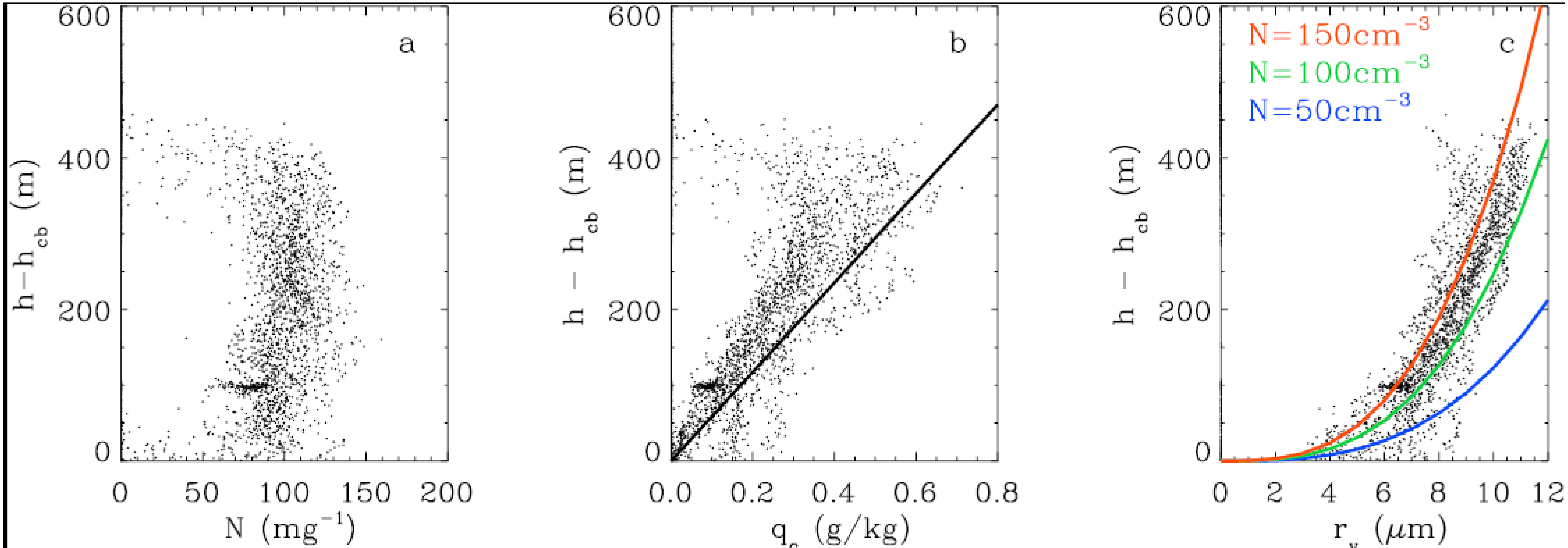
Low droplets concentration
Significant amount of drizzle
Wide spectrum

Time series of measurements taken during two ‘vertical traverses’ through stratocumulus layer during DYCOMS-II experiment (2001)

- The vertical stratification of droplet size must be resolved because it is central to both the cloud albedo and the precipitation process

‘Vertical’ profiles

EUCAARI – IMPACT experiment
SCu over the North Sea, 2008



Droplet concentration constant with height

Small values near the cloud base are due to instrument limitation (it misses small droplets)

Small values at the cloud top are due to entrainment and mixing

Liquid water content increases with height (solid line adiabatic value)

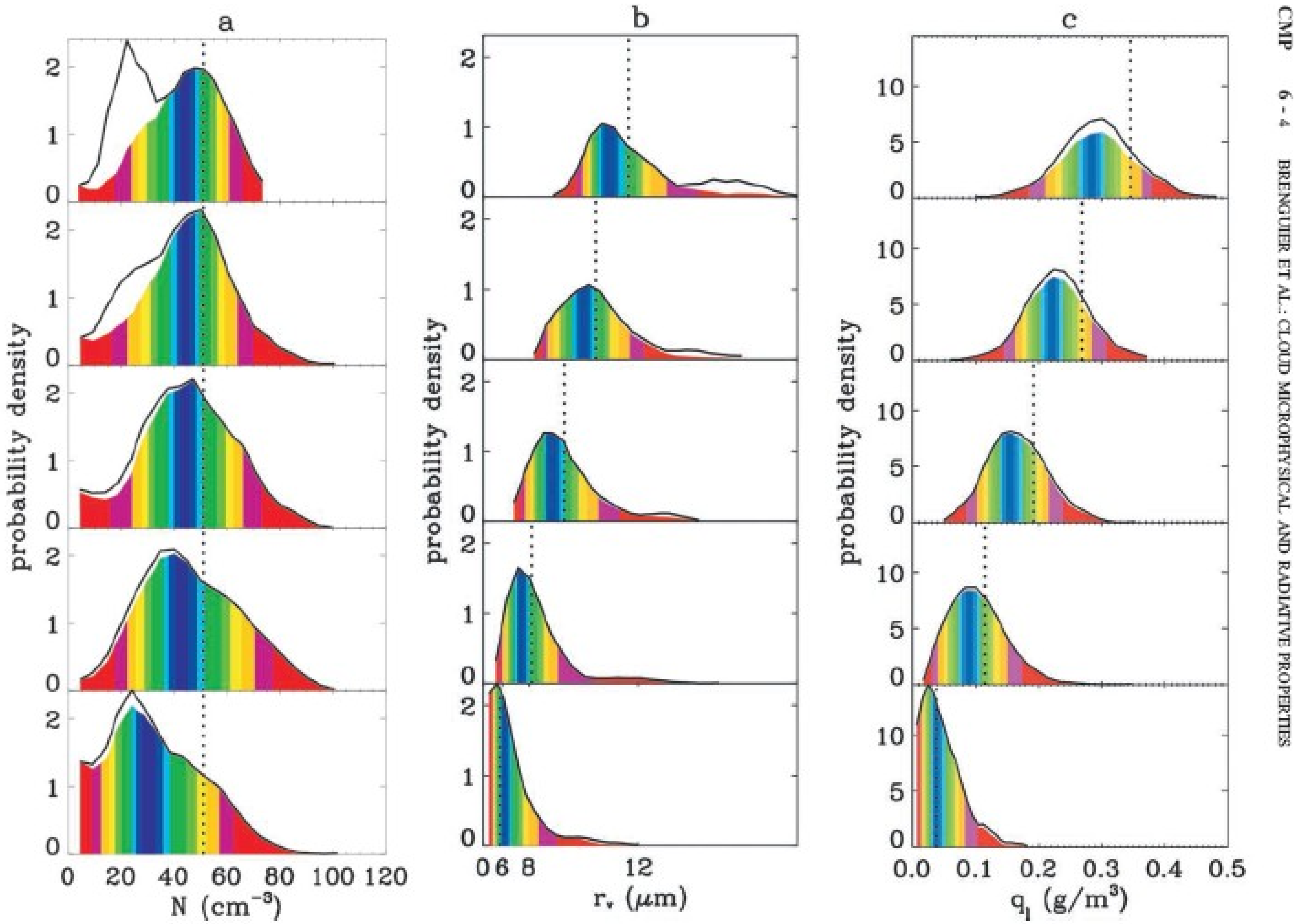
LWC values bigger than adiabatic belongs probably to cumulus that enter into Scu

LWC depletion at the cloud top due to entrainment

Mean volume radius follows adiabatic profile for N=100 cm-3

Jarecka et al., JAS 2013

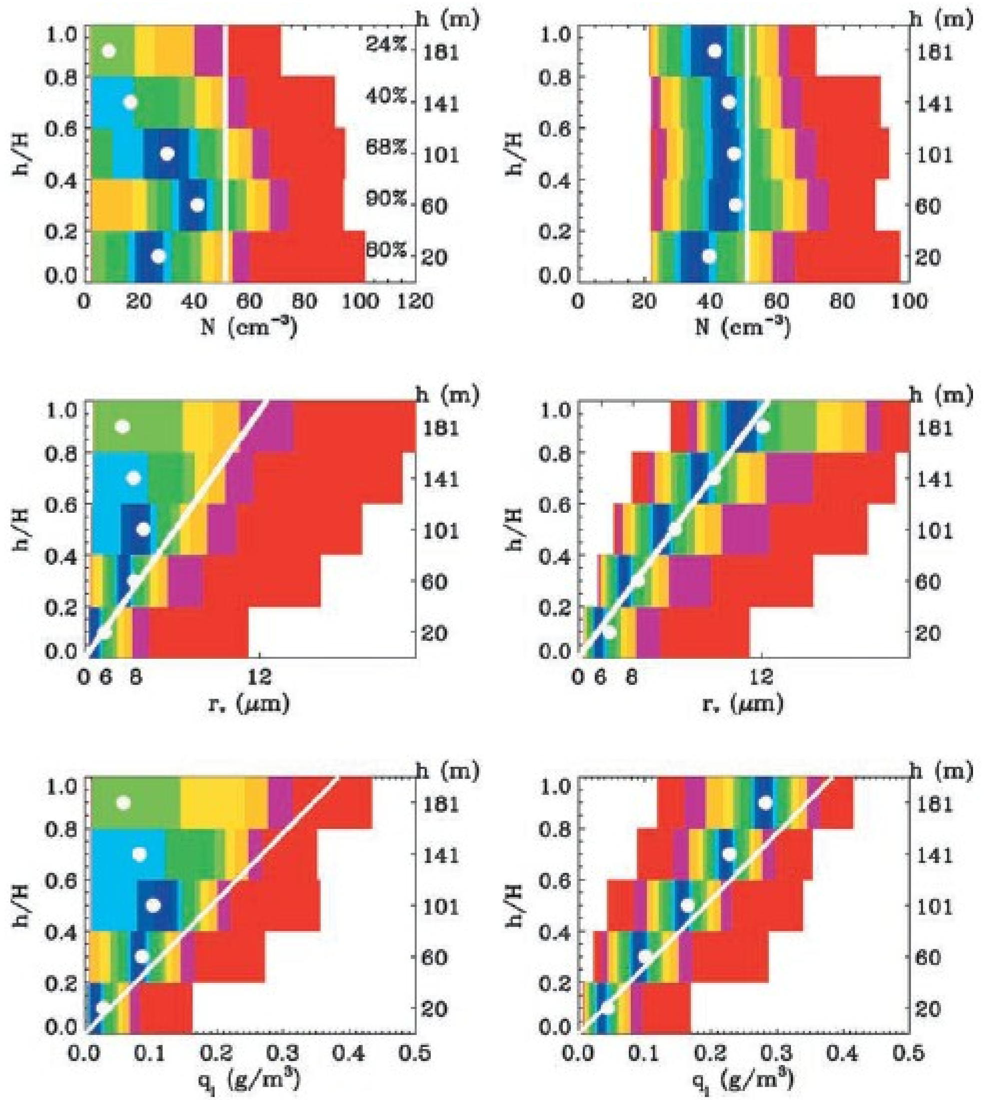
Scu during ACE 2



Brenguier et al., JGR 2003

Scu during ACE2

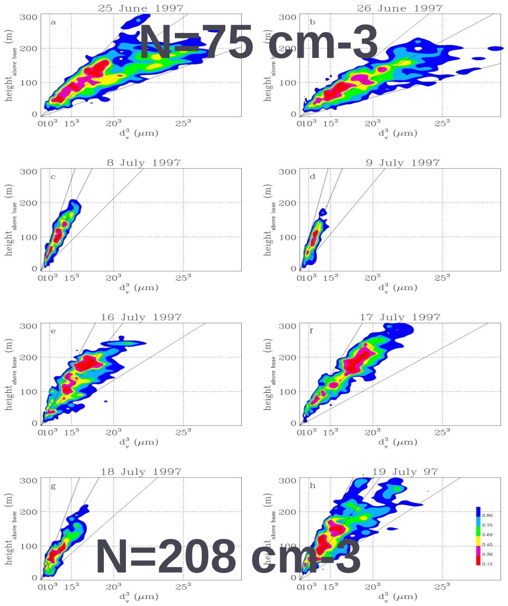
With drizzle



Without drizzle

Brenguier et al., JGR 2003

Scu, ACE 2, ‘vertical’ profiles



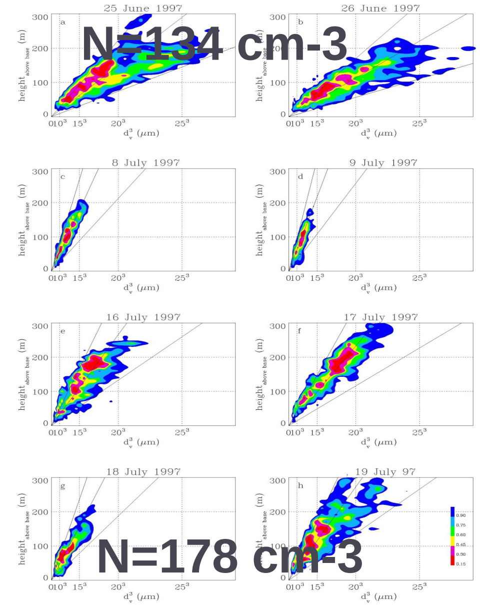
N=75 cm-3

N=51 cm-3

N=208 cm-3

N=256 cm-3

Fig.5



N=134 cm-3

N=114 cm-3

N=178 cm-3

N=134 cm-3

Fig.5

Shallow cumulus; RICO

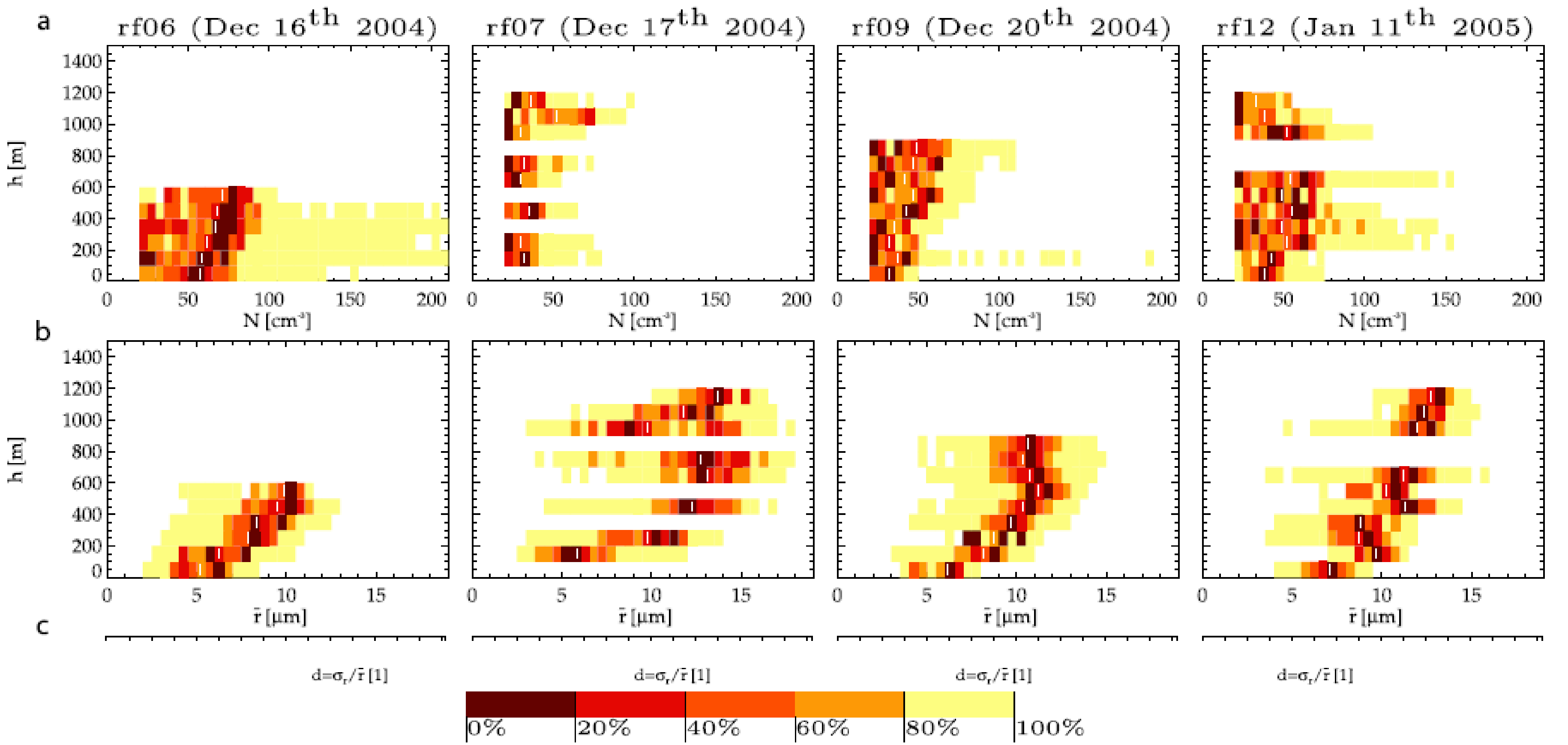


Figure 1. Statistics of droplet-spectrum and concentration measurements from RICO flights rf06, rf07, rf09, and rf12 as a function of height. (a) Droplet concentration N, (b) the mean radius $\overline{r}$, (c) the standard deviation of radius σ_r, and (d) the relative dispersion $d = \sigma_r/\overline{r}$. See text for details.

Arabas et al., GRL 2008

Shallow cumulus, RICO

L11803 ARABAS ET AL.: OBSERVATIONS OF CU MICROPHYSICS L11803

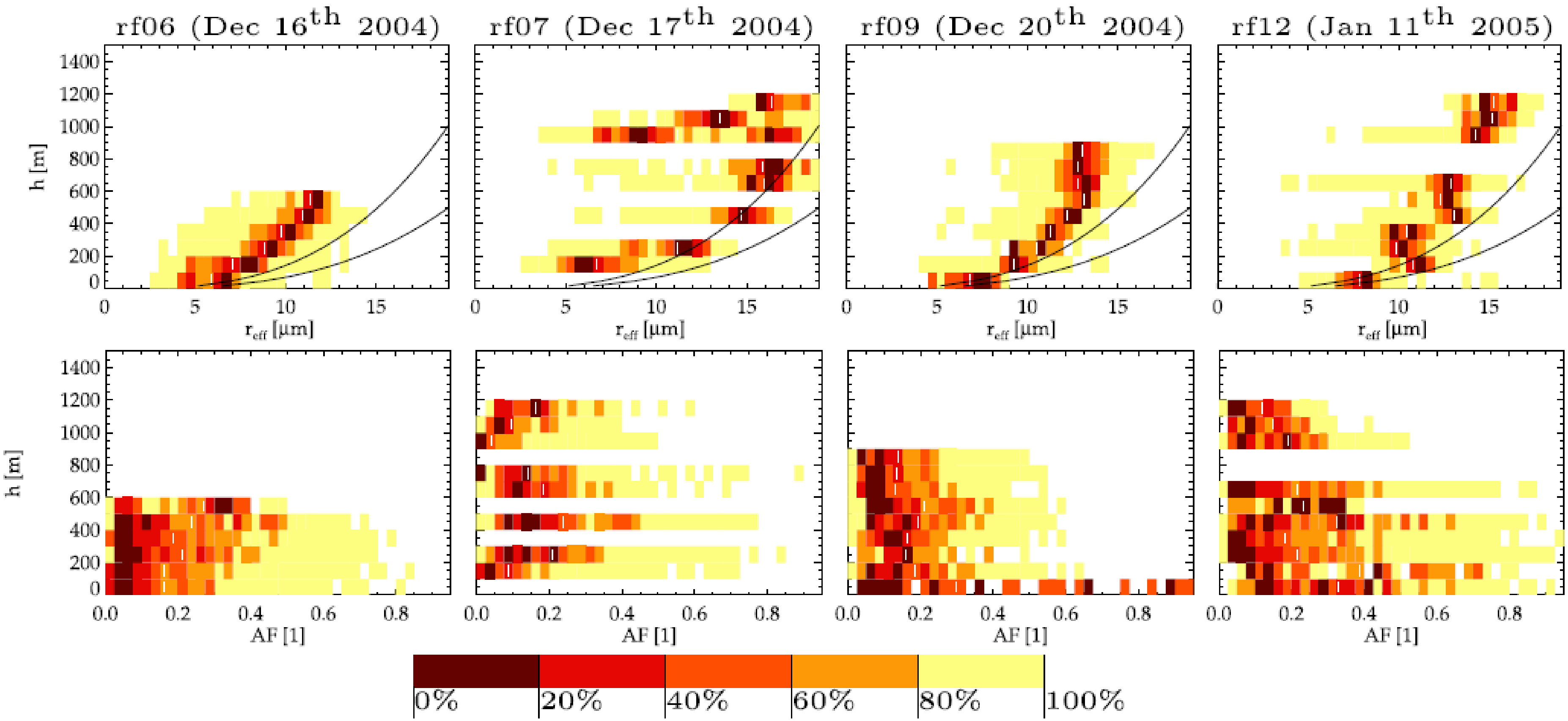


Figure 2. Same as Figure 1, but for the effective radius r_{eff} and adiabatic fraction *AF* values. Effective radius for adiabatic clouds with droplet concentrations of 50 and 100 cm^{-3} are shown by solid lines (larger r_{eff} values correspond to the concentration of 50 cm^{-3}).

Arabas et al., GRL 2008

- Although in situ measurements can resolve vertical profiles of droplet size, they cannot provide regional or global scale data sets for understanding and parameterization of aerosol effects on climate.

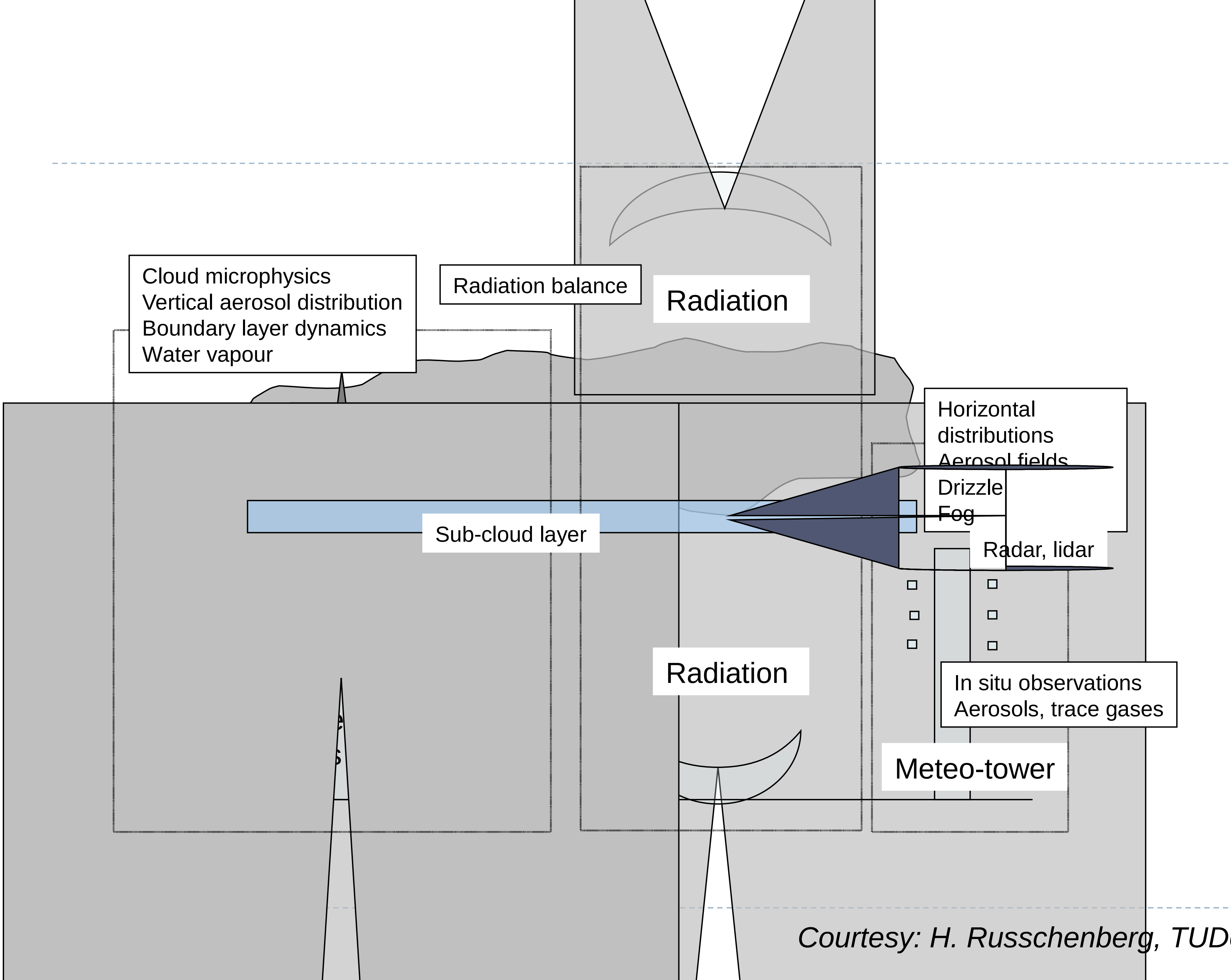
Ground-based remote sensing

- Ground-based remote sensing can retrieve droplet size profiles using millimeter cloud radar, with a constraint of microwave-derived LWP and assuming a droplet size distribution model, a fixed spectral breadth, and a constant droplet number concentration (Frisch et al., 1995).

Cesar Observatory

Delft University of Technology, KNMI, Wageningen University and Research
Utrecht University, RIVM, ECN, TNO , European Space Agency

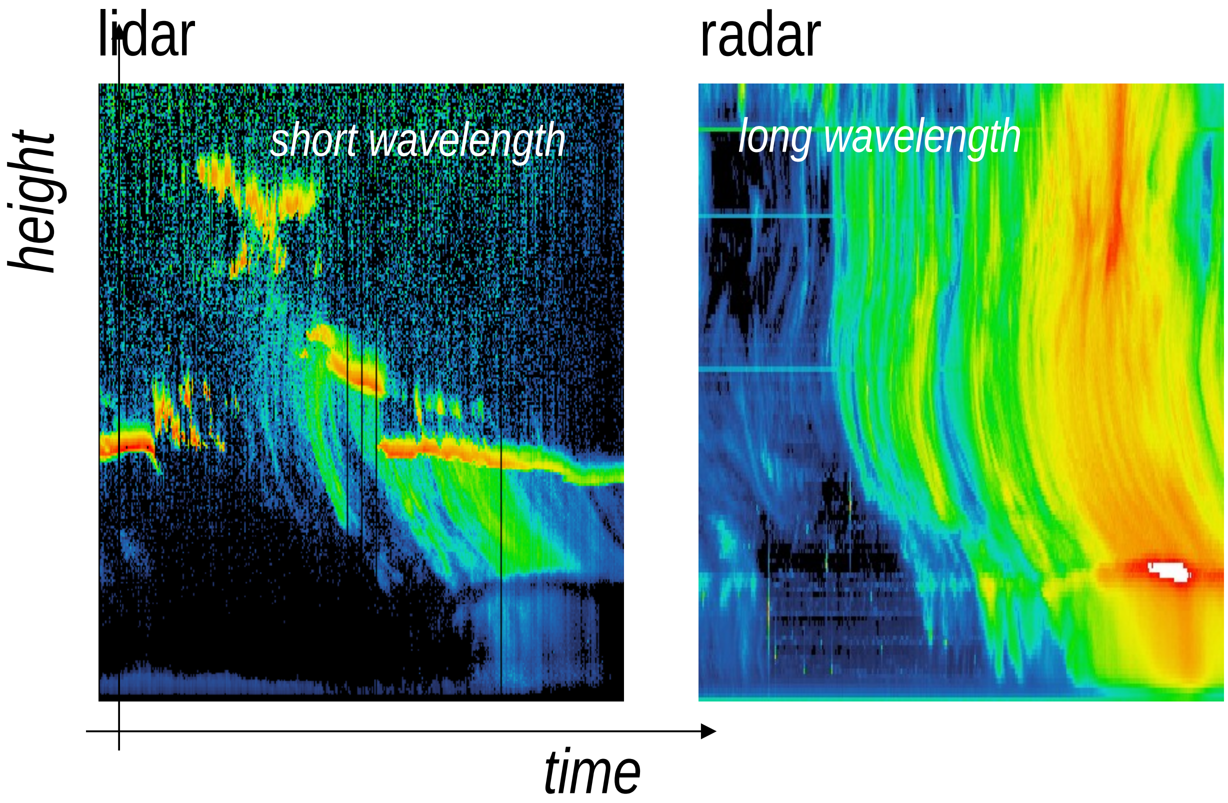
Courtesy: H. Russchenberg, TUDelft



Courtesy: H. Russchenberg, TUDelft

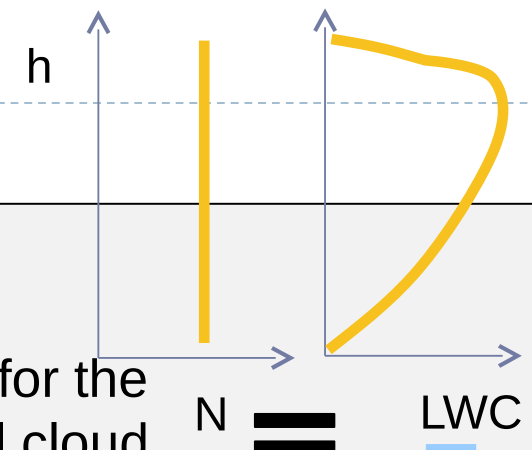
Why multi-sensors strategies?

Observation of light rain with different instruments



Courtesy: H. Russchenberg, TUDelft

Ground based observations and retrievals



Cloud Radar (Z) *cloud top*

Ceilometer *cloud base*

Microwave Radiometer (*LWP*)

Radiosondes

+ Model for the vertical cloud structure =

Boundaries – Thickness (H)

Liquid Water Content – Path (LWP)

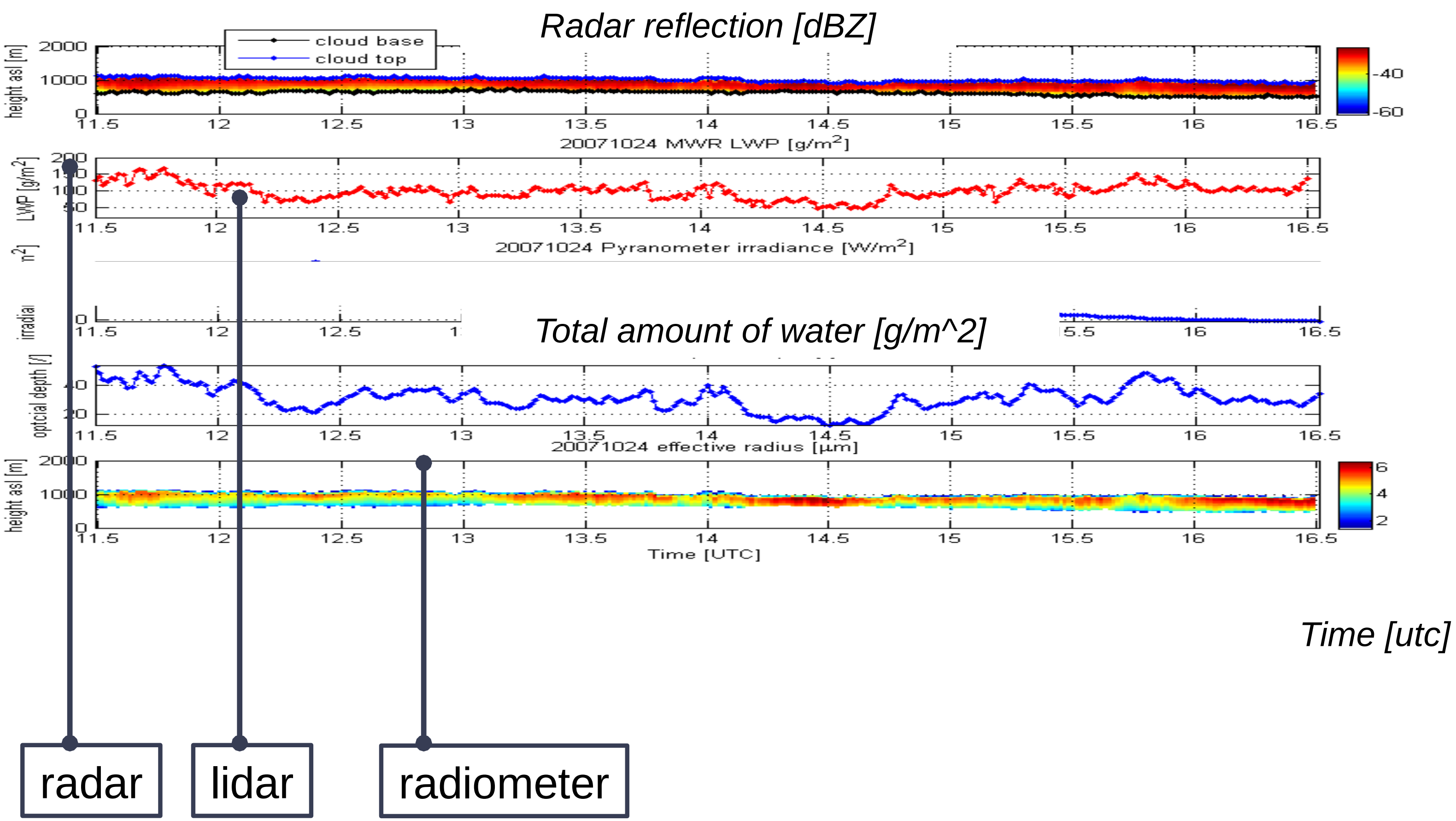
Extinction - Optical Thickness (τ)

Effective Radius – (re)

Droplet Number Concentration - (N)

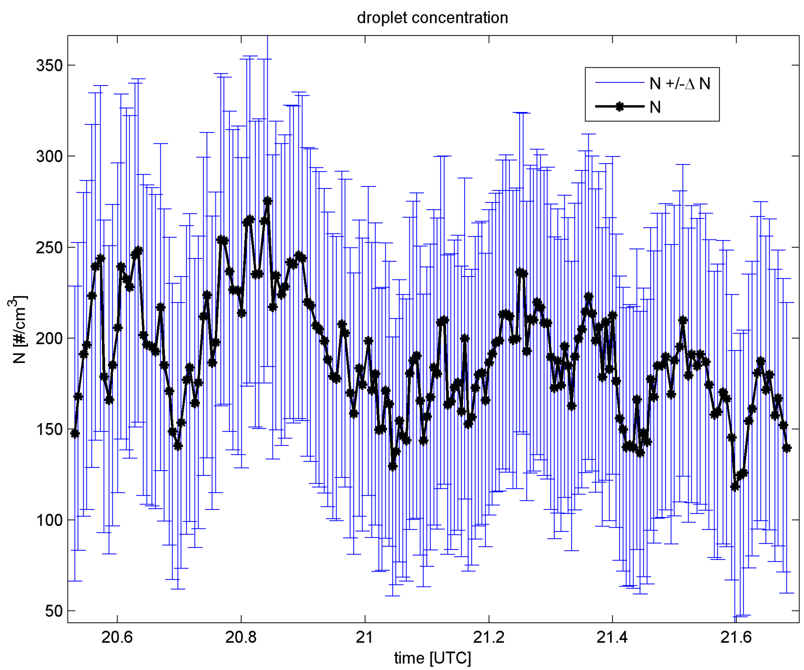
Courtesy: H. Russchenberg, TUDelft

Stratocumulus clouds

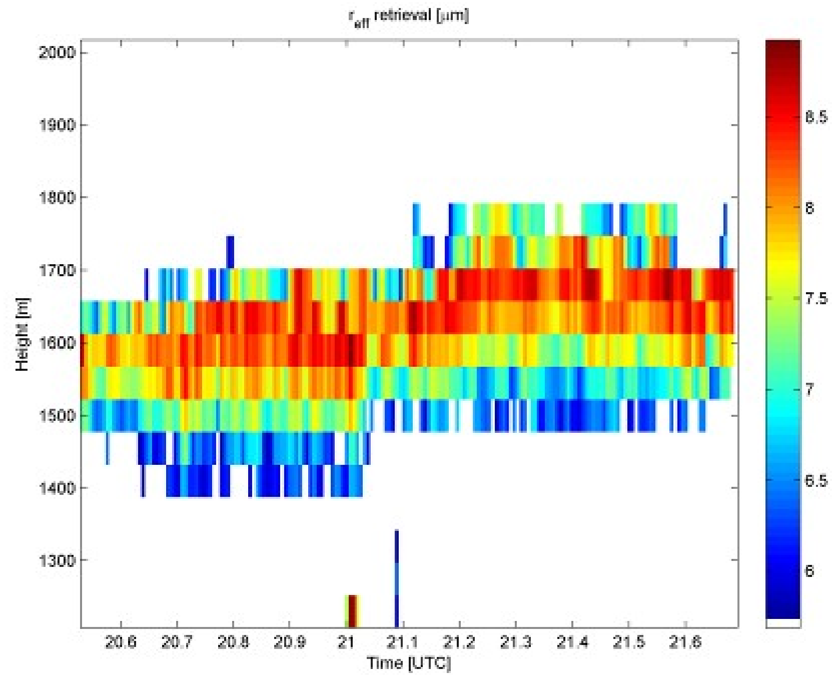


Estimates of cloud parameters

Droplet concentration



Profile particle size



Courtesy: Christine Brandau