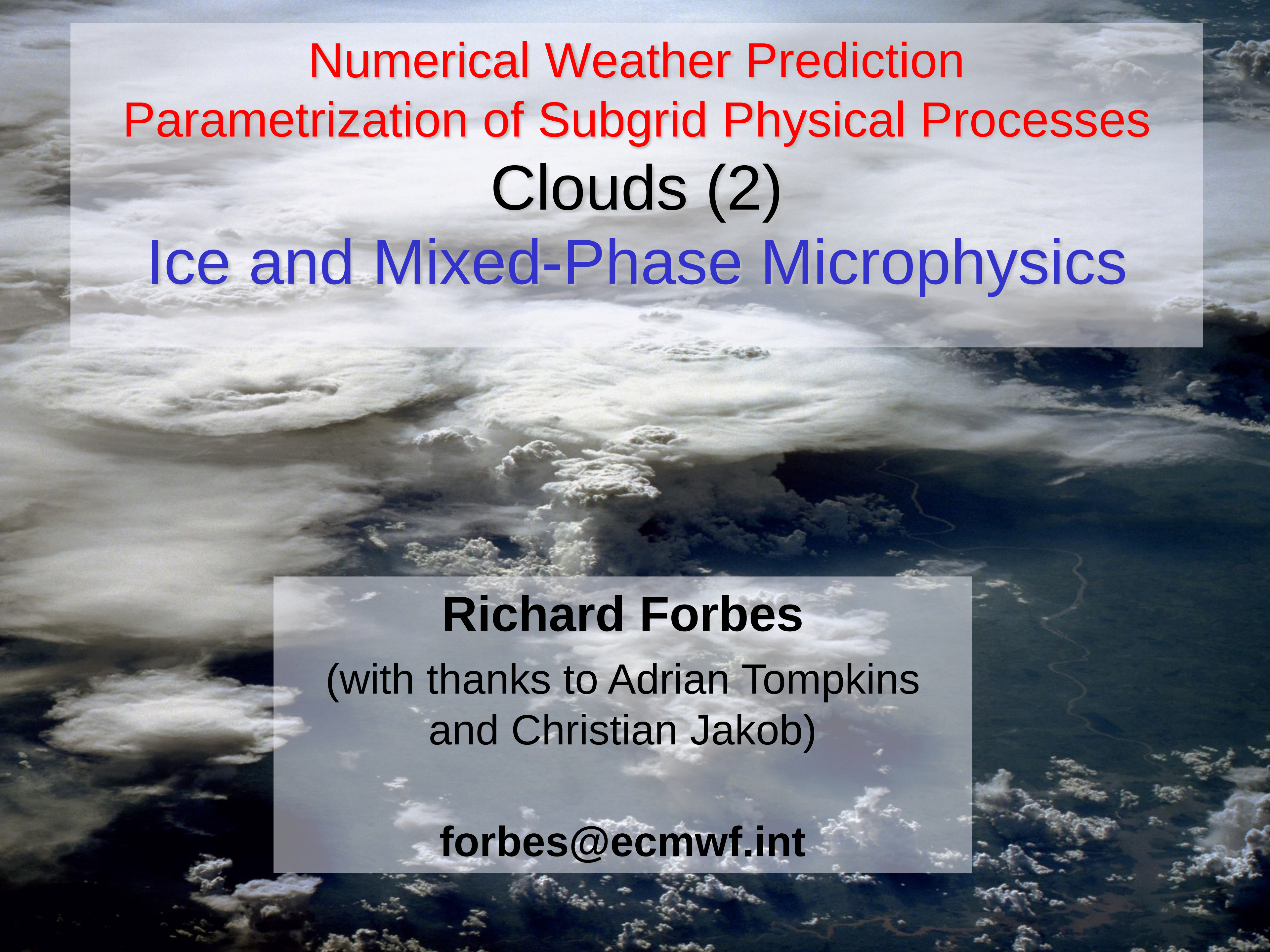


Numerical Weather Prediction
Parametrization of Subgrid Physical Processes
Clouds (2)
Ice and Mixed-Phase Microphysics

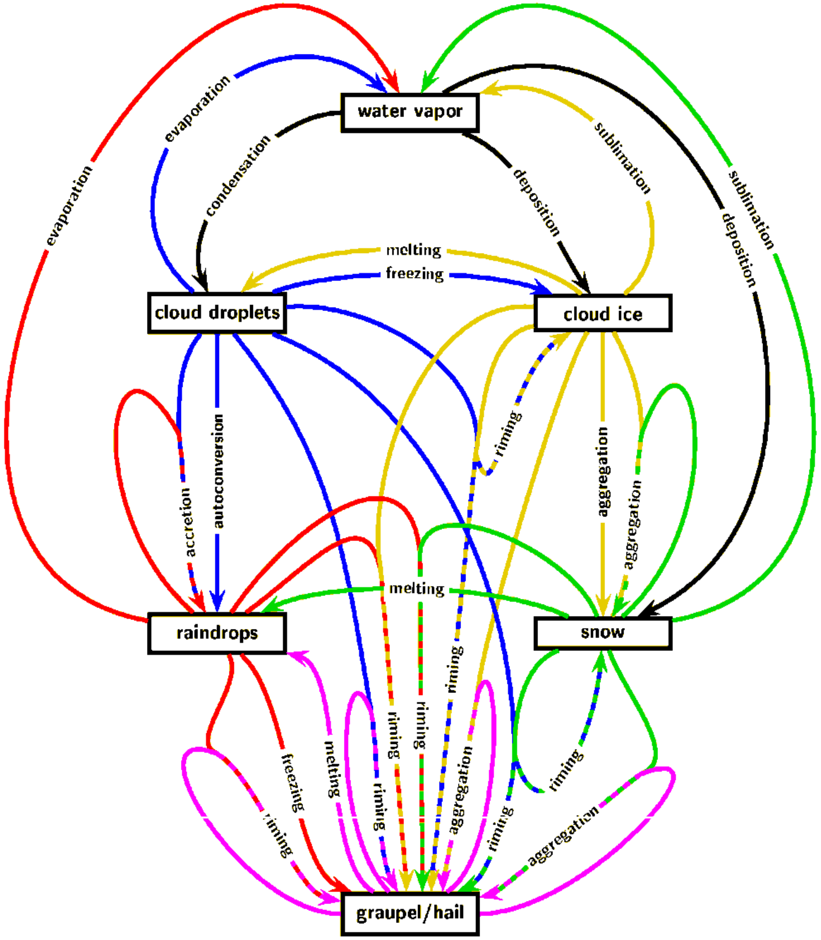
Richard Forbes

(with thanks to Adrian Tompkins
and Christian Jakob)

forbes@ecmwf.int

Cloud Parametrization Issues:
Which quantities to represent ?

- Water vapour
- Cloud water droplets
- Rain drops
- Pristine ice crystals
- Aggregate snow flakes
- Graupel pellets
- Hailstones



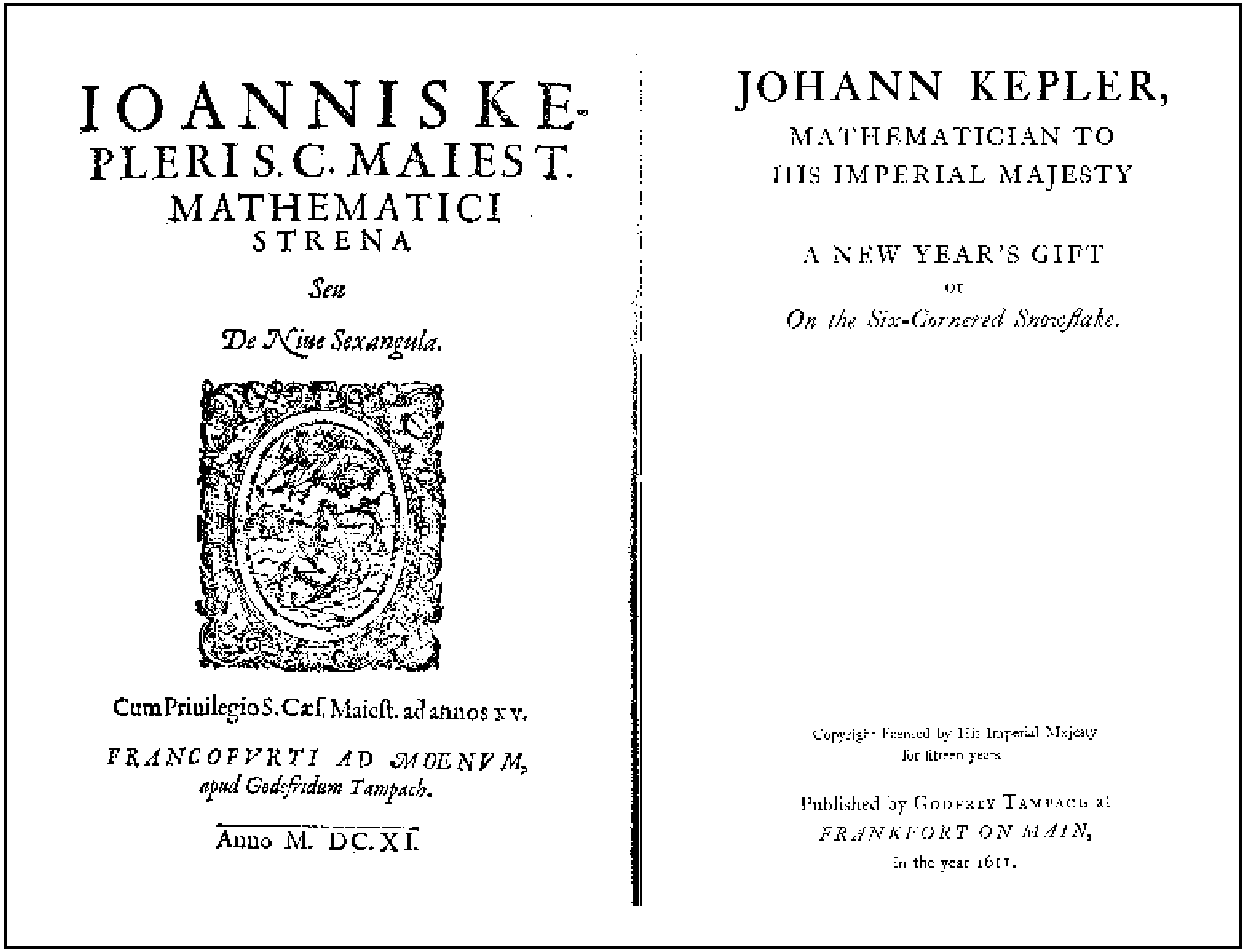
From: Axel Seifert

- Note for ice phase particles:
    - Additional latent heat.
    - Terminal fall speed of ice hydrometeors significantly less.
    - Optical properties are different (important for radiation).

Ice and mixed-phase microphysical processes

- To describe ice-phase cloud and precipitation processes in our models we need to represent:
  - Nucleation of ice crystals
  - Diffusional growth/sublimation of ice crystals
  - Collection processes for ice crystals (aggregation), for ice and liquid droplets (riming)
  - Breakup processes for ice crystals (splintering, Hallett-Mossop)
  - The advection and sedimentation (falling) of particles
  - Melting and freezing processes

First recorded mention of the "six-cornered snowflake" - Kepler (1611)



IOANNIS KEPLERI S.C. MAIEST.
MATHEMATICI
STRENA
Seu
De Niue Sexangula.

Cum Priuilegio S. Cæſ. Maieſt. ad annos XV.
FRANCOFVRTI AD MOENVM,
apud Godefridum Tampach.
Anno M. DC. XI.

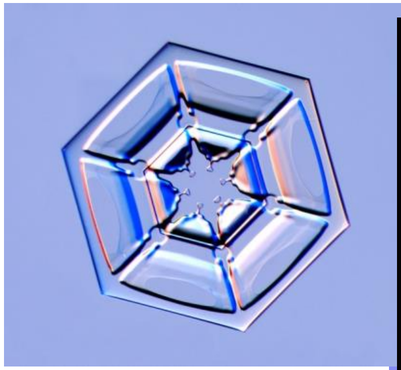
JOHANN KEPLER,
MATHEMATICIAN TO
HIS IMPERIAL MAJESTY

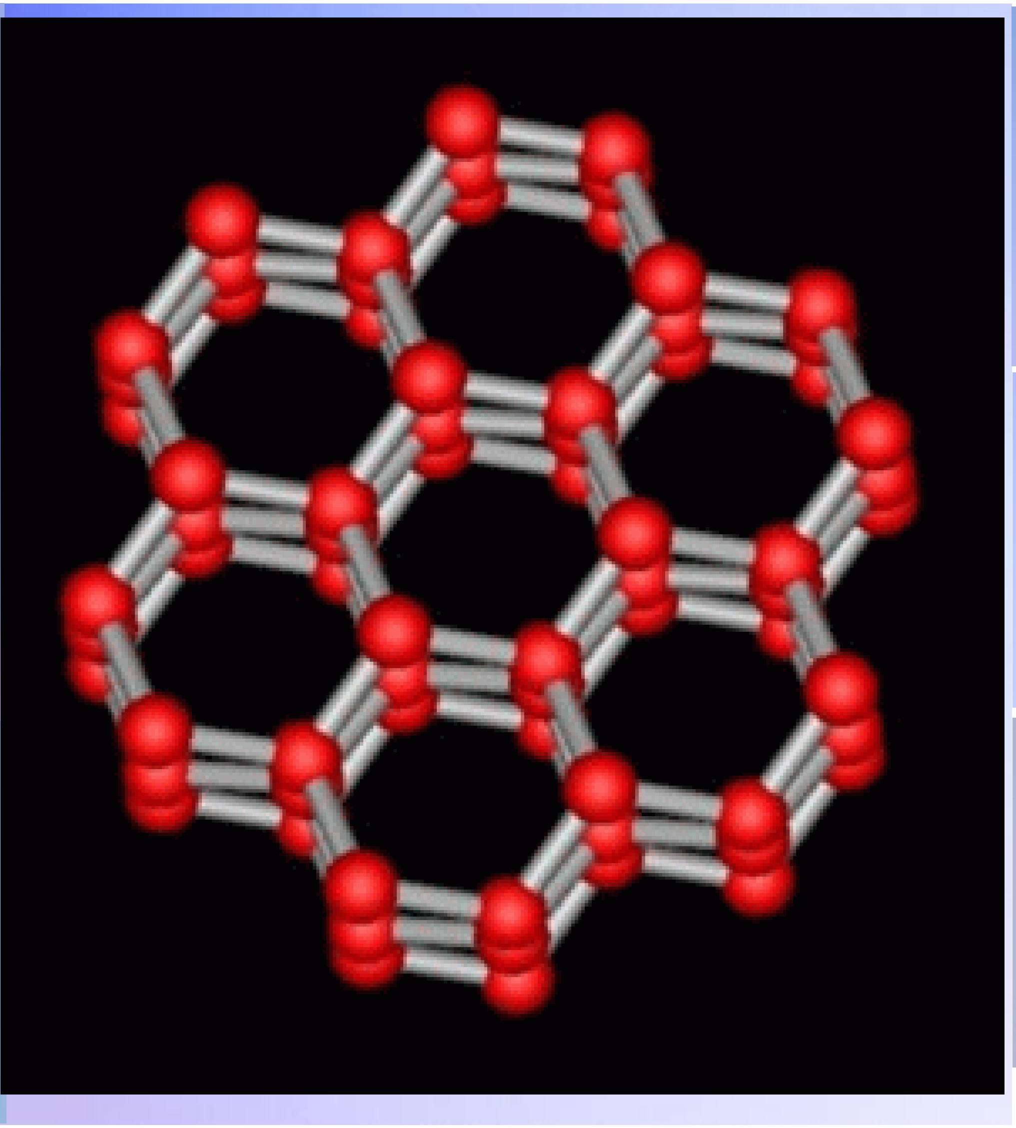
A NEW YEAR'S GIFT
or
On the Six-Cornered Snowflake.

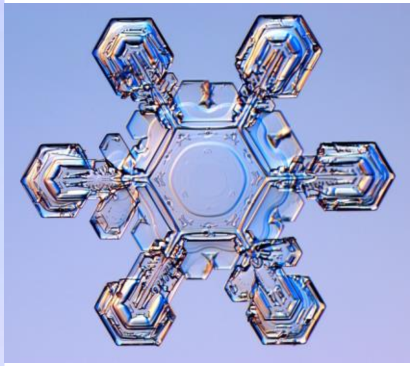
Copyright Granted by His Imperial Majesty
for fifteen years

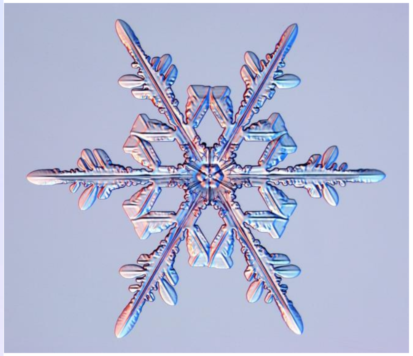
Published by GODFREY TAMPACH at
FRANKFORT ON MAIN,
in the year 1611.

“The Six-Cornered Snowflake”









www.snowcrystals.com
Ken Libbricht

Ice Microphysical Processes

- Ice nucleation
- Depositional Growth (and sublimation)
- Collection (aggregation/riming)
- Splintering
- Melting

Ice Nucleation

- Droplets do not freeze at 0^{o}C !
- Ice nucleation processes can be split into homogeneous and heterogeneous processes

Homogeneous nucleation

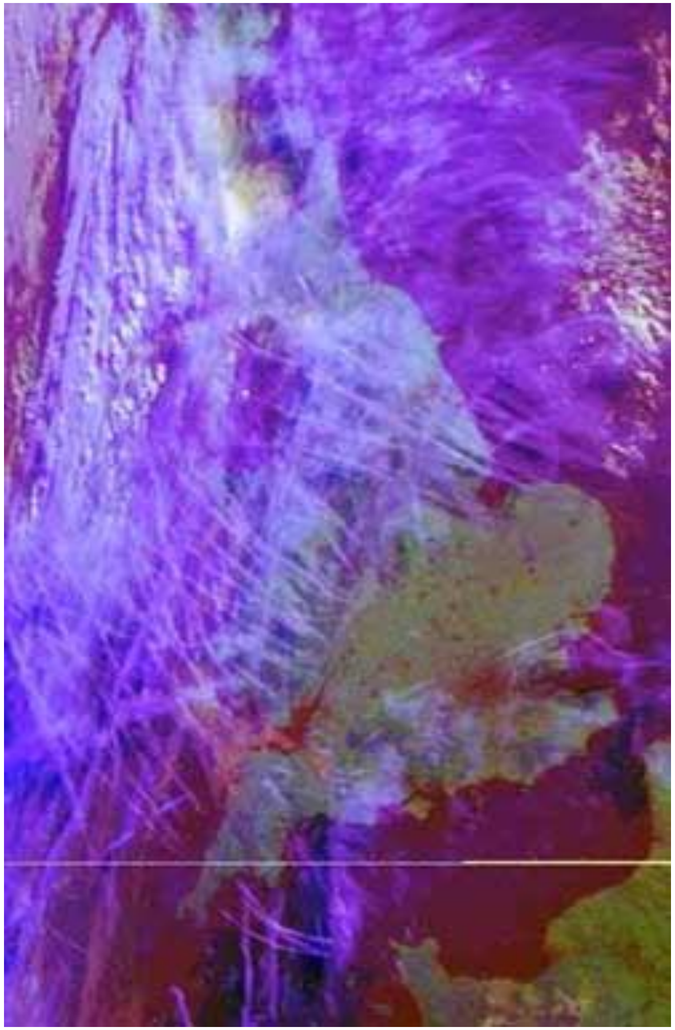
- No preferential nucleation sites (i.e. pure water or solution drop)
- Homogeneous freezing of cloud water droplets occurs below about -38^{o}C, so all ice below this temperature (e.g. water droplets carried upward by convective updraughts).
- Homogeneous nucleation of ice crystals from small aqueous solution drops (haze particles), which have a lower freezing temperature, is dependent on a critical relative humidity above saturation (function of temperature). So new ice cloud formation needs high supersaturations.
- Observations of clear air supersaturation are common…

Ice Nucleation:
Homogeneous Nucleation

- At cold temperatures (e.g. upper troposphere) ratio between liquid and ice saturation vapour pressures is large (can support large ice supersaturations).

- If air mass is lifted, and does not contain significant liquid particles or ice nuclei, high supersaturations with respect to ice can occur, reaching 160%.

- Long lasting contrails are a signature of supersaturation.

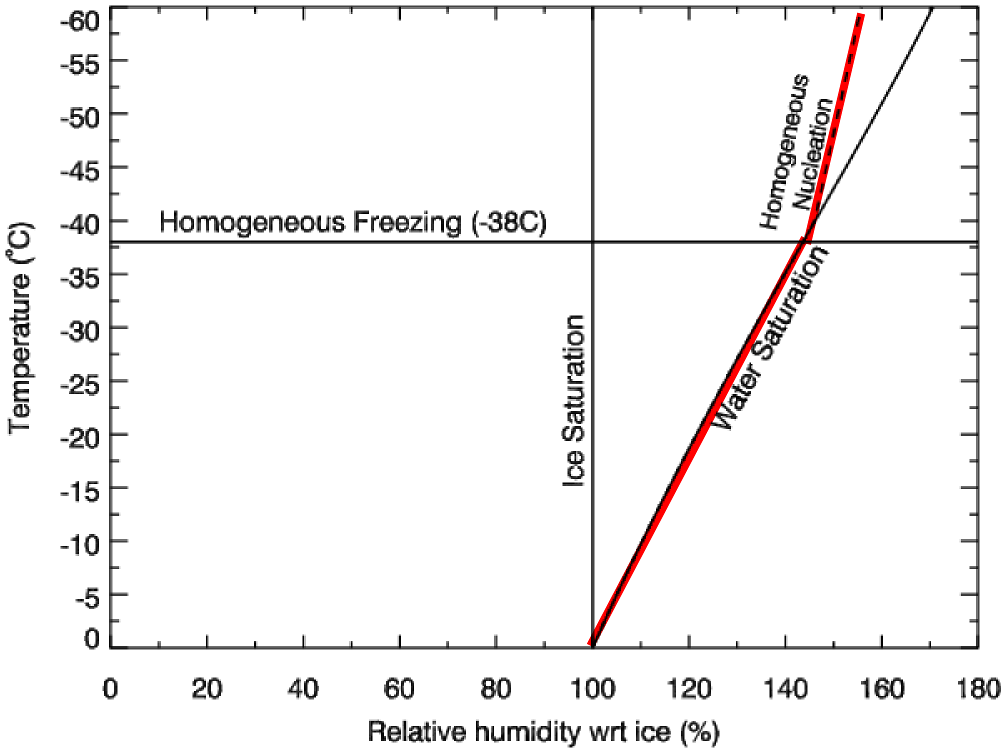


Ice supersaturation and homogeneous nucleation

- What is the maximum ice supersaturation?

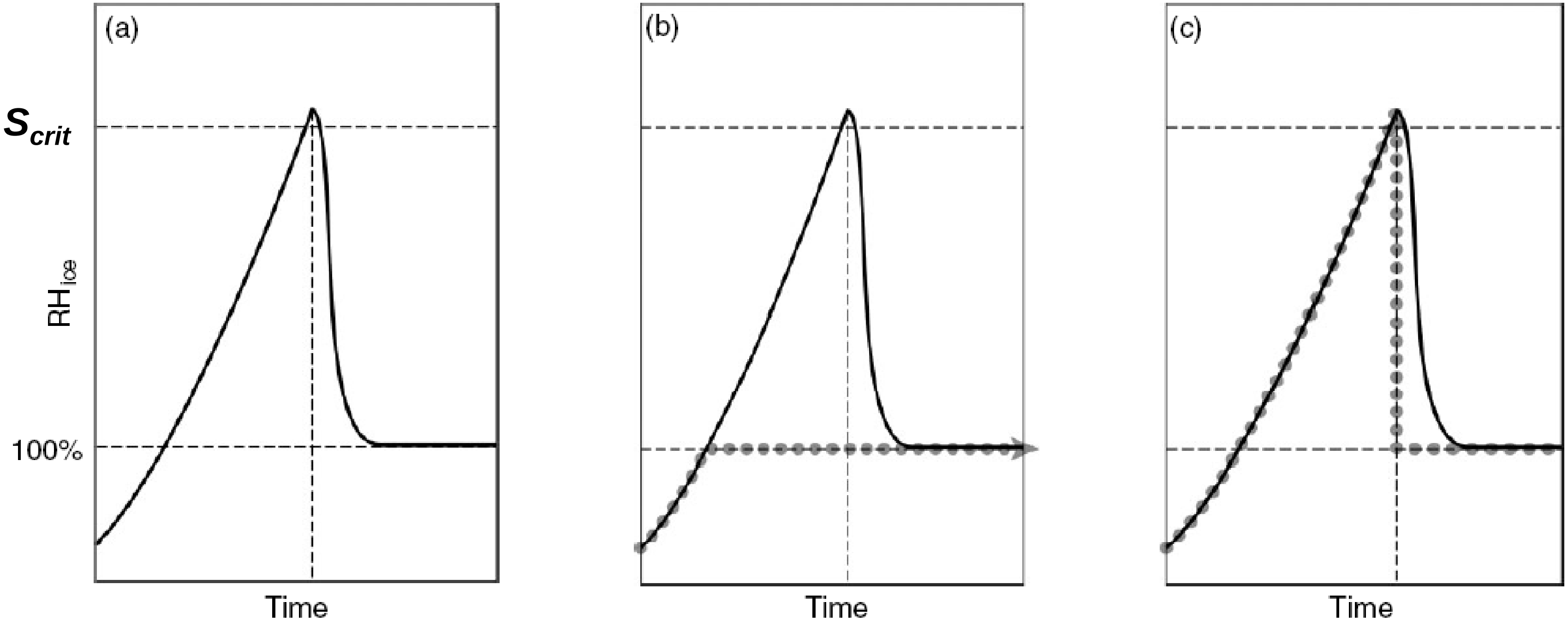
- Classical theory and laboratory experiments document the critical vapour saturation mixing ratio with respect to ice at which homogeneous nucleation initiates from aqueous solution drops (Pruppacher and Klett, 1997; Koop et al., 2000).

- Leads to supersaturated RH threshold S_{crit} as a function of temperature (Koop et al., 2000, Kärcher and Lohmann, 2002).



Parametrizing ice supersaturation and homogeneous nucleation

Evolution of an air parcel subjected to adiabatic cooling at low temperatures



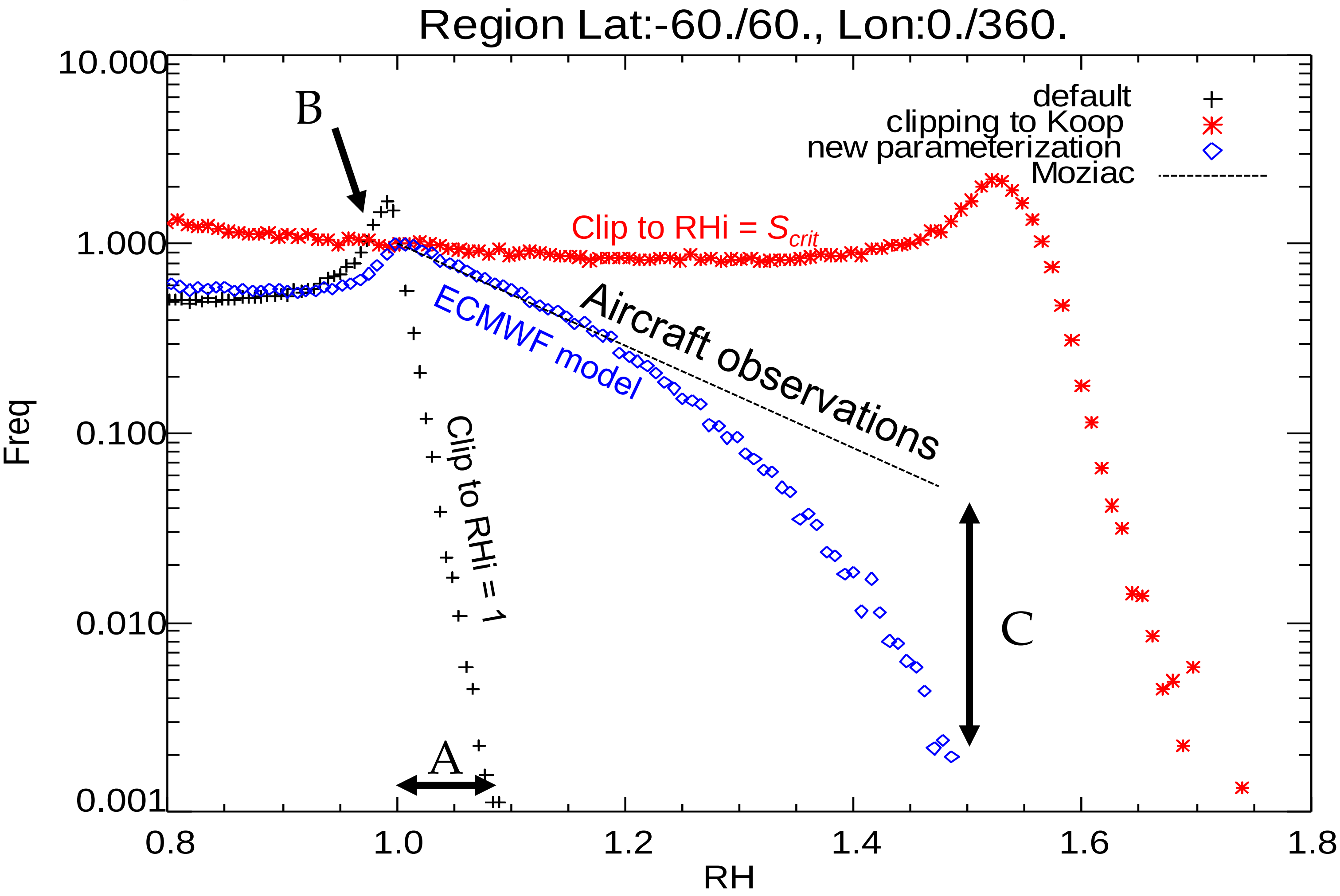
Evolution of an air parcel subjected to adiabatic cooling at low temperatures

Dotted line: Evolution if no ice supersaturation allowed (many models)

Dotted line: Evolution if ice supersaturation is allowed until reaches S_{crit} then all supersaturation converted to ice (ECMWF model)

From Tompkins et al. (2007) adapted from Kärcher and Lohmann (2002)

Supersaturation
Aircraft obs and ECMWF model



RH wrt ice PDF at 250hPa

one month average

A: Numerics and interpolation for default model

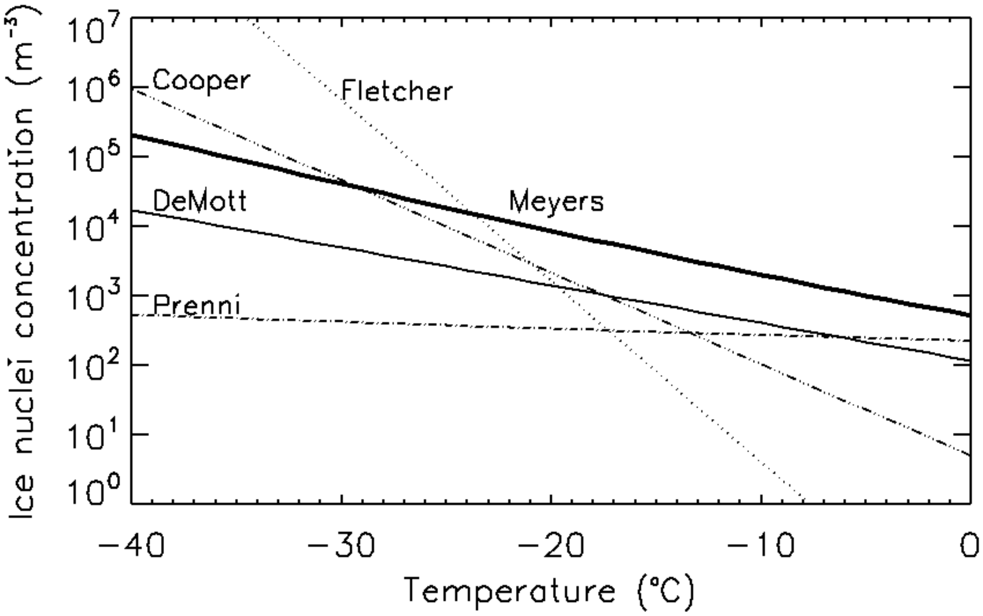
B: The RH=1 microphysics mode

C: Drop due to GCM assumption of subgrid fluctuations in total water

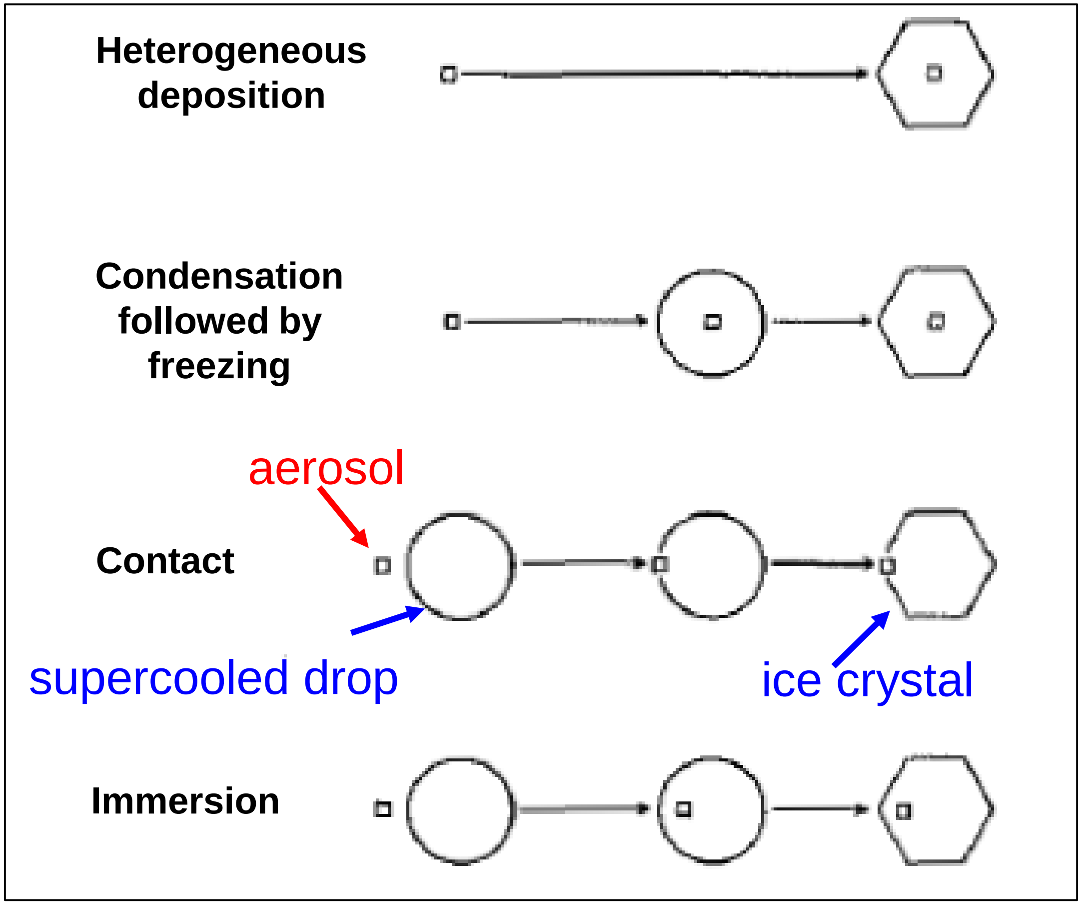
Ice Nucleation: Heterogeneous nucleation

Heterogeneous nucleation

- Preferential sites for nucleation (interaction with solid aerosol particles – ice nuclei)
- Frequent observation of ice between 0°C and colder temperatures indicates heterogeneous processes are active.
- Number of activated ice nuclei increases with decreasing temperature so heterogeneous nucleation more likely with increasing altitude, e.g. Fletcher (1962); Cooper (1986), Meyers (1991); Prenni et al. (2007) DeMott et al (2010).
- Lots of uncertainty!



Ice Nucleation: Heterogeneous nucleation



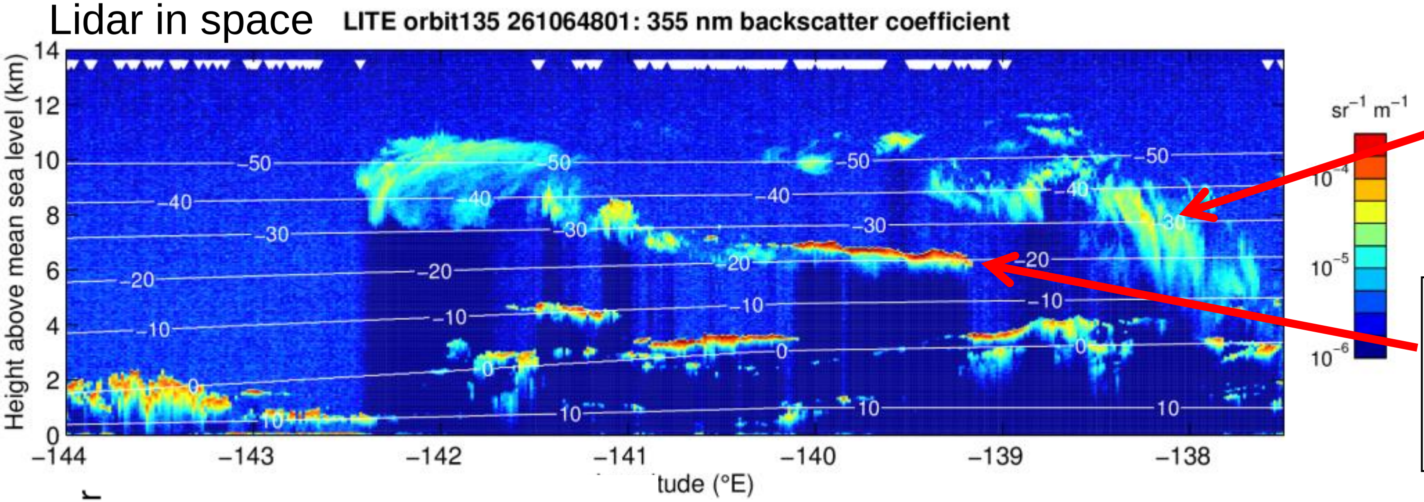
Schematic of heterogeneous ice nucleation mechanisms
(from Rogers and Yau, 1996)

Still many uncertainties in heterogeneous ice nucleation processes in the atmosphere and their impacts!

Mixed-phase clouds:

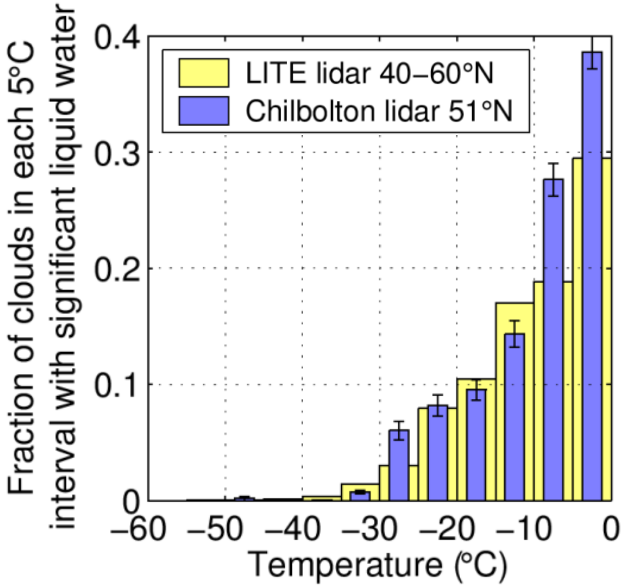
Observed supercooled liquid water occurrence

Lidar in space



Lidar: lower backscatter from ice cloud

Lidar: high backscatter from liquid water layers



(Hogan et al., GRL, 2004)

Observations:

- Colder than -38^{o}C, no supercooled liquid water.
- Supercooled liquid water increasingly common as approach 0^{o}C.
- Often in shallow layers at cloud top, or in strong updraughts associated with convection
- Often mixed-phase cloud – liquid and ice present
- Convective clouds with tops warmer than -5^{o}C rarely have ice.

Diffusional growth of ice crystals

Deposition/sublimation

Equation for the rate of change of mass for an ice particle of diameter D due to deposition (diffusional growth), or sublimation if subsaturated air:

$$\frac{\partial m}{\partial t} = \frac{4\pi sCF}{\left(\frac{L_s}{RT} - 1\right)\frac{L_s}{k_a T} + \frac{RT}{\chi e_{si}}}$$

$$\propto s\ C\ F$$

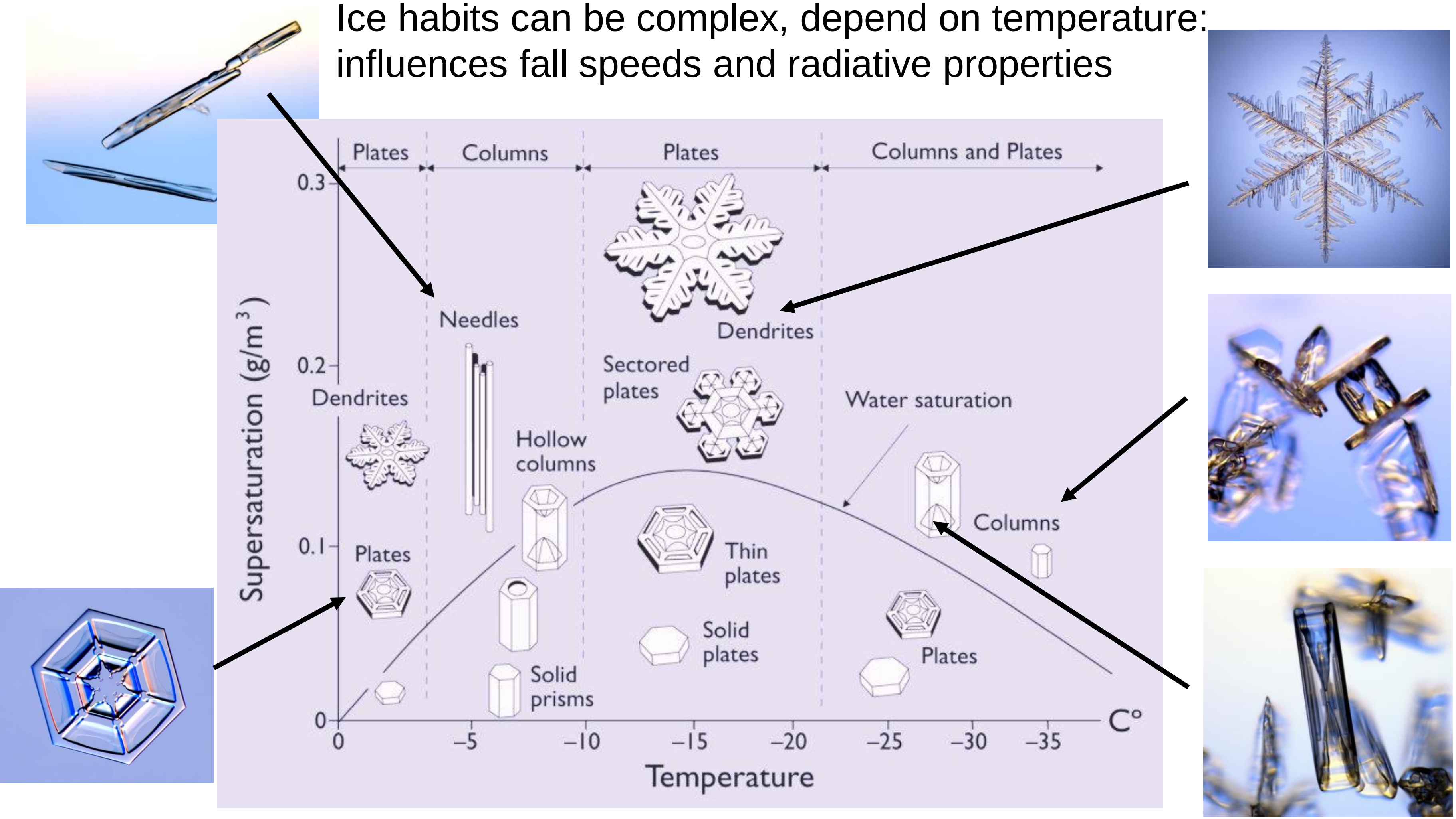
Integrate over assumed particle size spectrum to get total ice mass growth

- Deposition rate depends primarily on
  - the supersaturation (or subsaturation), *s*
  - the particle shape (habit), *C* (*plate, column, aggregate*)
  - the ventilation factor, *F* (*particle falling through air*)
- The particular mode of growth (edge growth *vs* corner growth) is sensitive to the temperature and supersaturation

Diffusional growth of ice crystals

Ice Habits

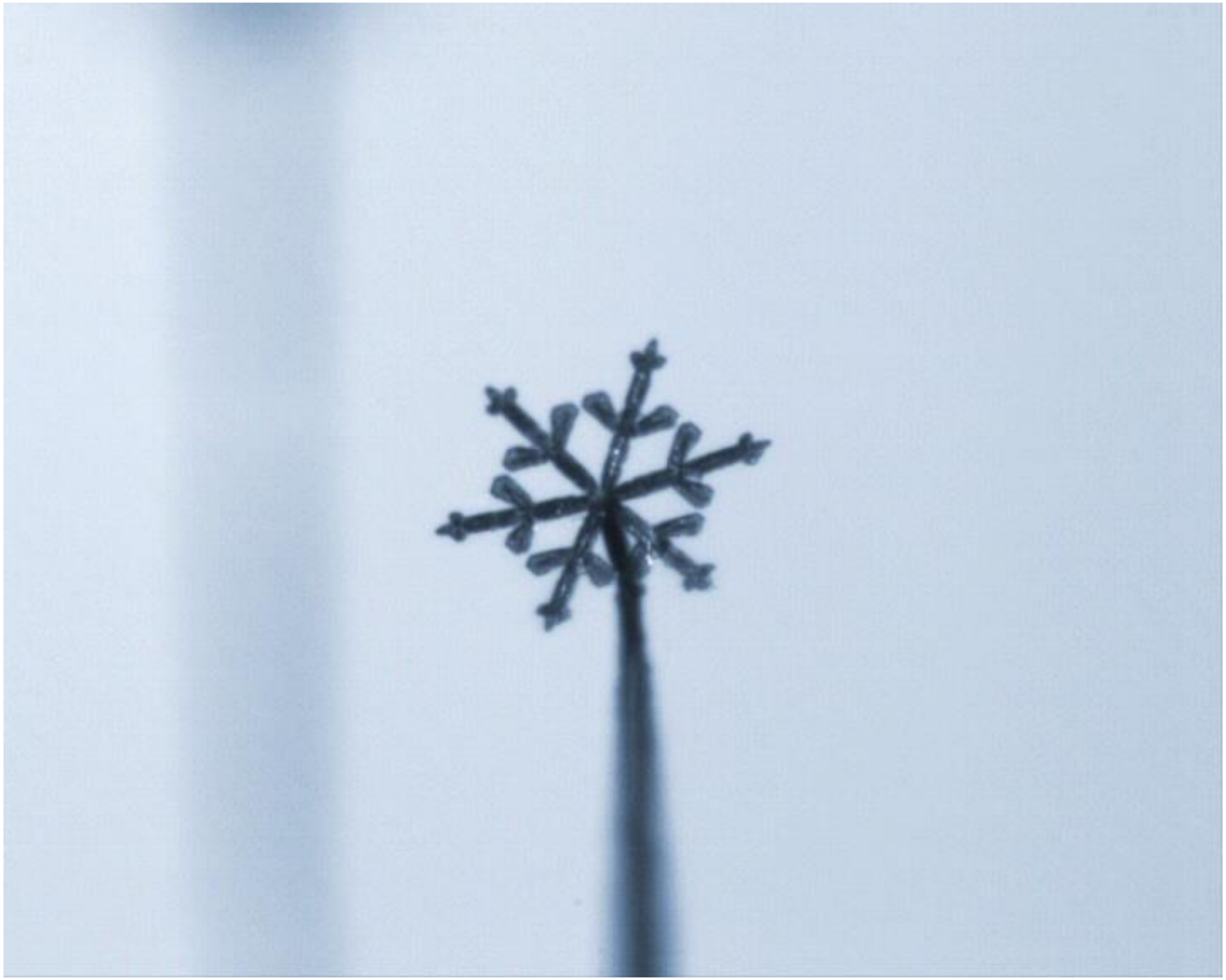
Ice habits can be complex, depend on temperature:
influences fall speeds and radiative properties



http://www.its.caltech.edu/~atomic/snowcrystals/

Diffusional growth of ice crystals

Animation of crystal growth



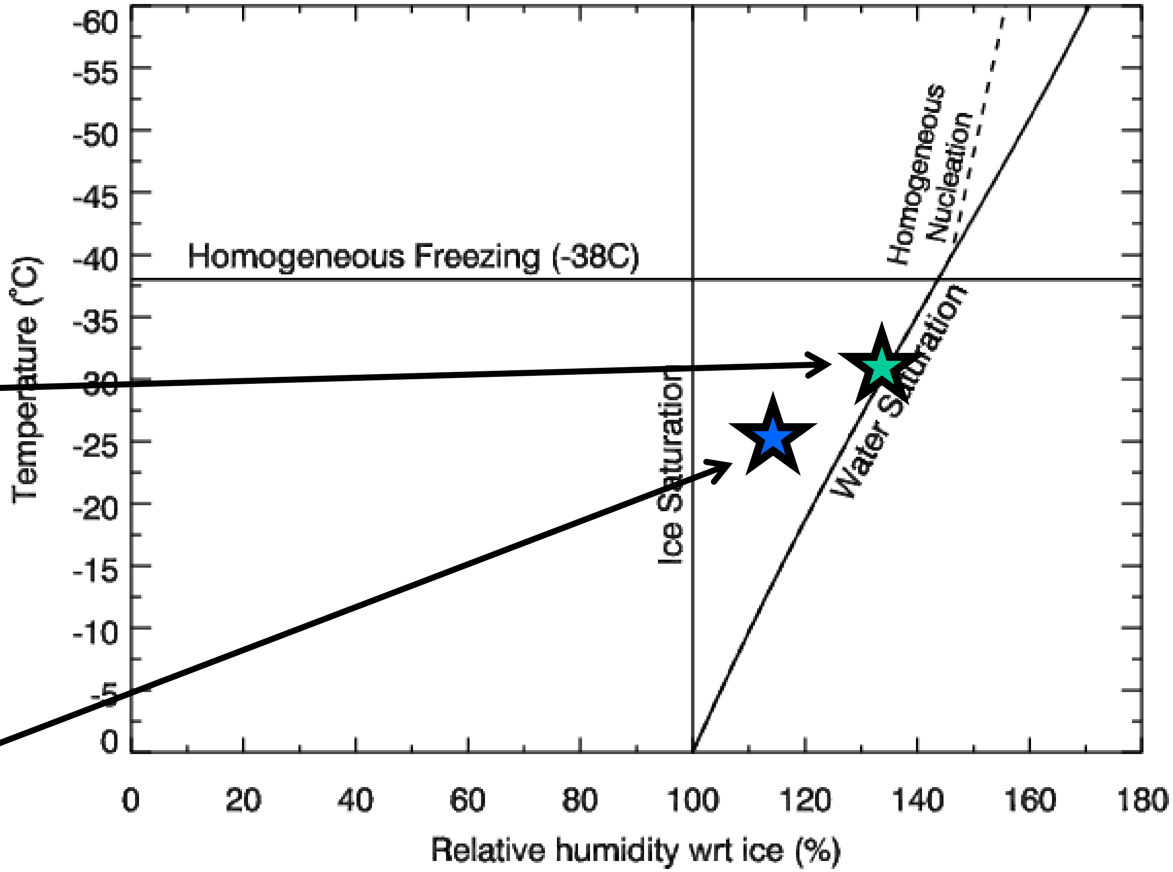
Diffusional growth of ice crystals

Mixed Phase Clouds: Bergeron Process (I)

The saturation vapour pressure with respect to ice is smaller than with respect to water.

A cloud which is saturated with respect to water is supersaturated with respect to ice.

A cloud which is sub-saturated with respect to water can be supersaturated with respect to ice.



Diffusional growth of ice crystals
Mixed phase cloud Bergeron process (II)

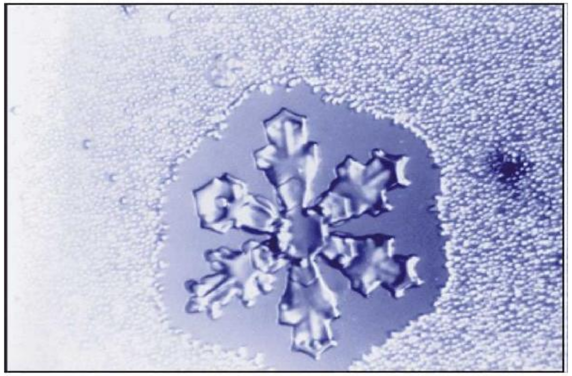
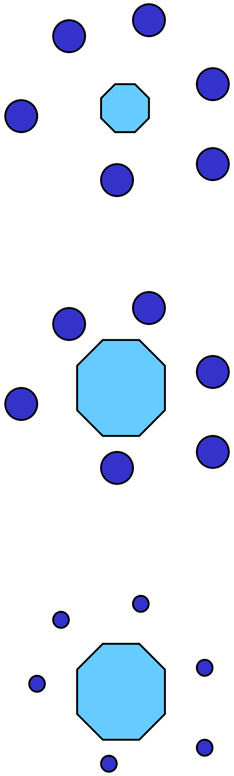


Photo by R. Pitter

Ice particles grow at the expense of water droplets

(Bergeron-Findeisen-Wegener process)



Ice particle enters water cloud →

↓

Cloud is supersaturated with respect to ice

↓

Diffusion of water vapour onto ice particle →

↓

Cloud will become sub-saturated with respect to water

↓

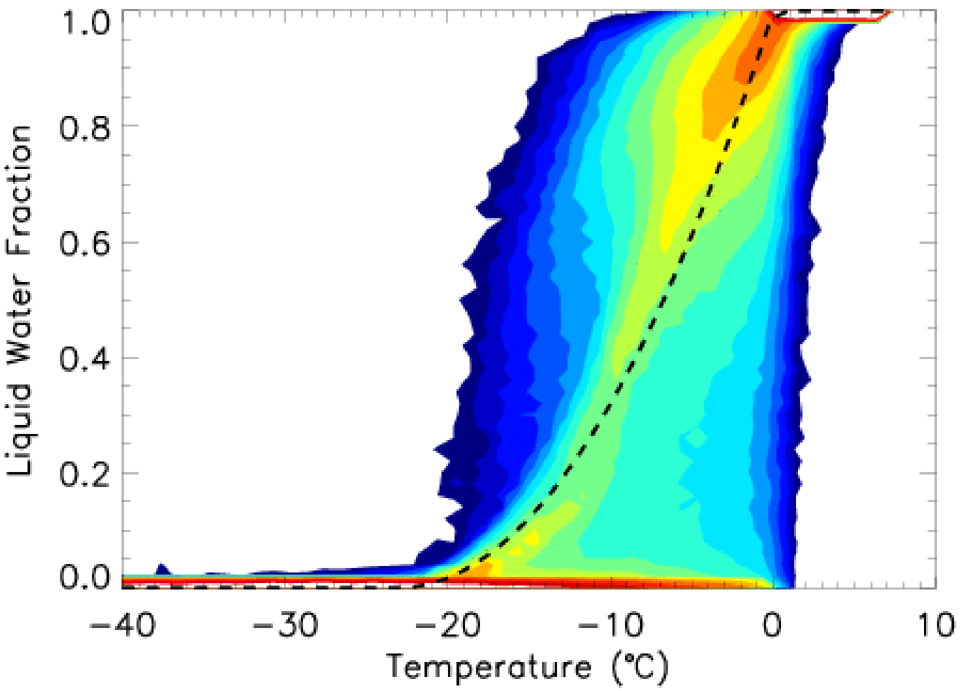
Water droplets evaporate to increase water vapour →

Parametrizing cloud phase

Diagnostic vs prognostic

- Many (global) models with a single condensate prognostic parametrize ice/liquid phase as a diagnostic function of temperature (see dashed line for ECMWF model pre-2010 below).
- Models with separate prognostic variables for liquid water and ice, parametrize deposition allowing a wide range of supercooled liquid water/ice fraction for a given temperature (see shading in example below).

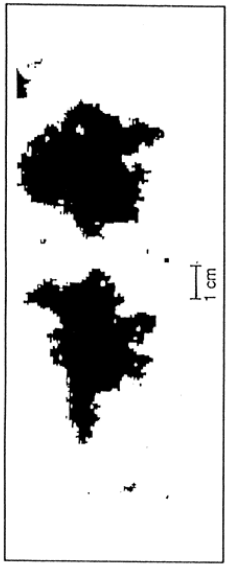
$$\frac{\partial m}{\partial t} = \frac{4\pi s C F}{\left(\frac{L_s}{RT} - 1\right)\frac{L_s}{k_a T} + \frac{RT}{\chi e_{si}}}$$



PDF of liquid water fraction of cloud for a diagnostic mixed phase scheme (<u>dashed line</u>) and prognostic ice/liquid scheme (shading)

Collection processes:
Ice Crystal Aggregation

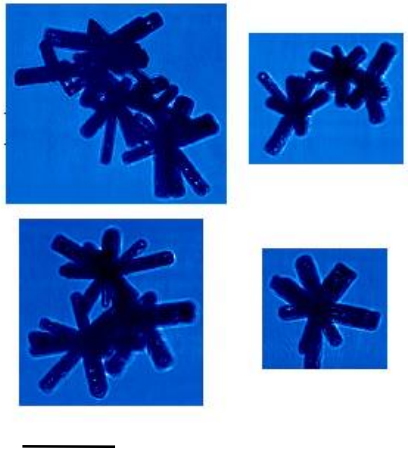
- Ice crystals can aggregate together to form “snow”
- “Sticking” efficiency increases as temperature exceeds –5^{o}C
- Irregular crystals are most commonly observed in the atmosphere (e.g. Korolev et al. 1999, Heymsfield 2003)



Lawson, JAS’99

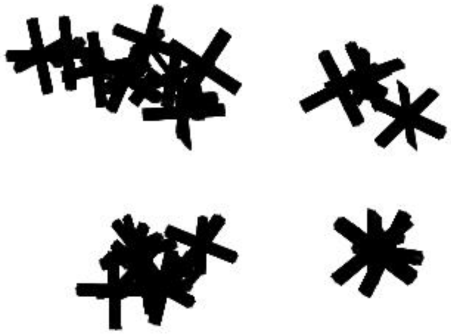
Field & Heymsfield ‘03

CPI



T=-46^{o}C

Model

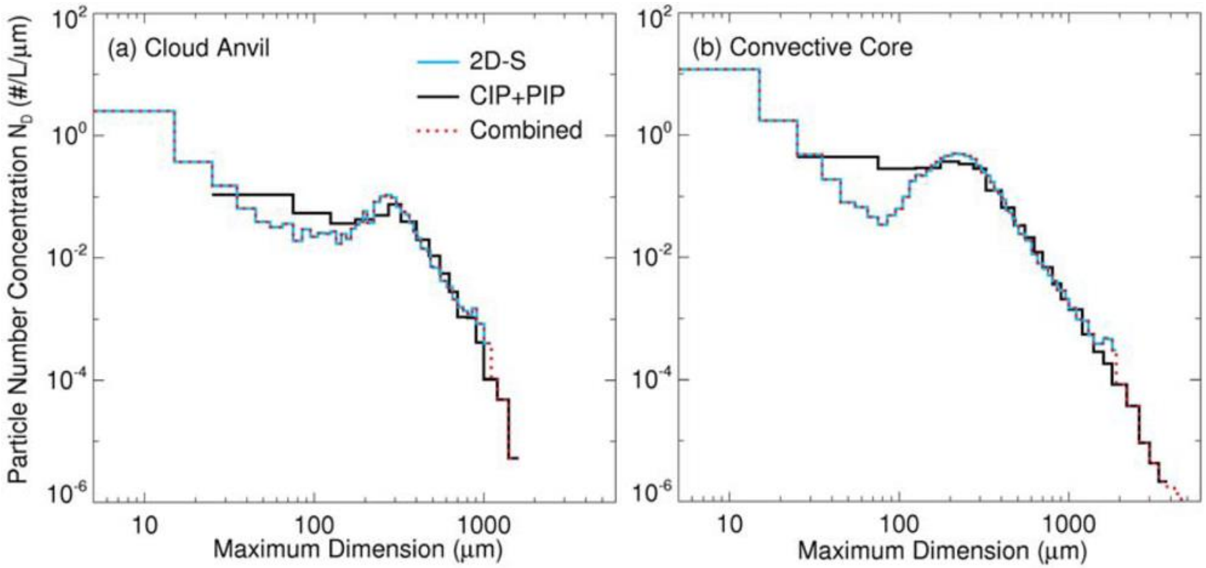


Westbrook et al. (2008)

Parametrization of aggregation

- Many models still have separate variables for ice and snow with a parametrization for aggregation, represented as an autoconversion.

- But any separation in the particle size spectra between ice and snow is much less clear than for cloud droplets and e.g. Minnis et al. 2012

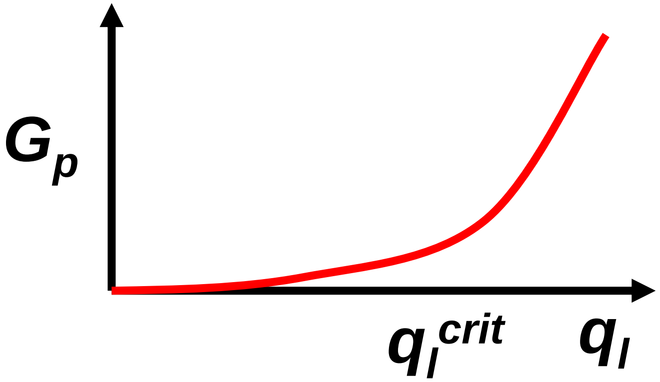


- Some schemes represent aggregation as an evolving particle size distribution, either prognostic number concentration (i.e. q_i, N_i) or as a diagnostic function (e.g. fn(q_i,T)).

Precipitation generation
Ice clouds

Representing aggregation in the ice phase with separate ice and snow variables (conversion ice-to-snow) analogous to warm-phase autoconversion, e.g. in ECMWF model:

$$G_P = c_0 q_i \left(1 - e^{-\left(\frac{qi}{qi_{crit}}\right)^2}\right)$$

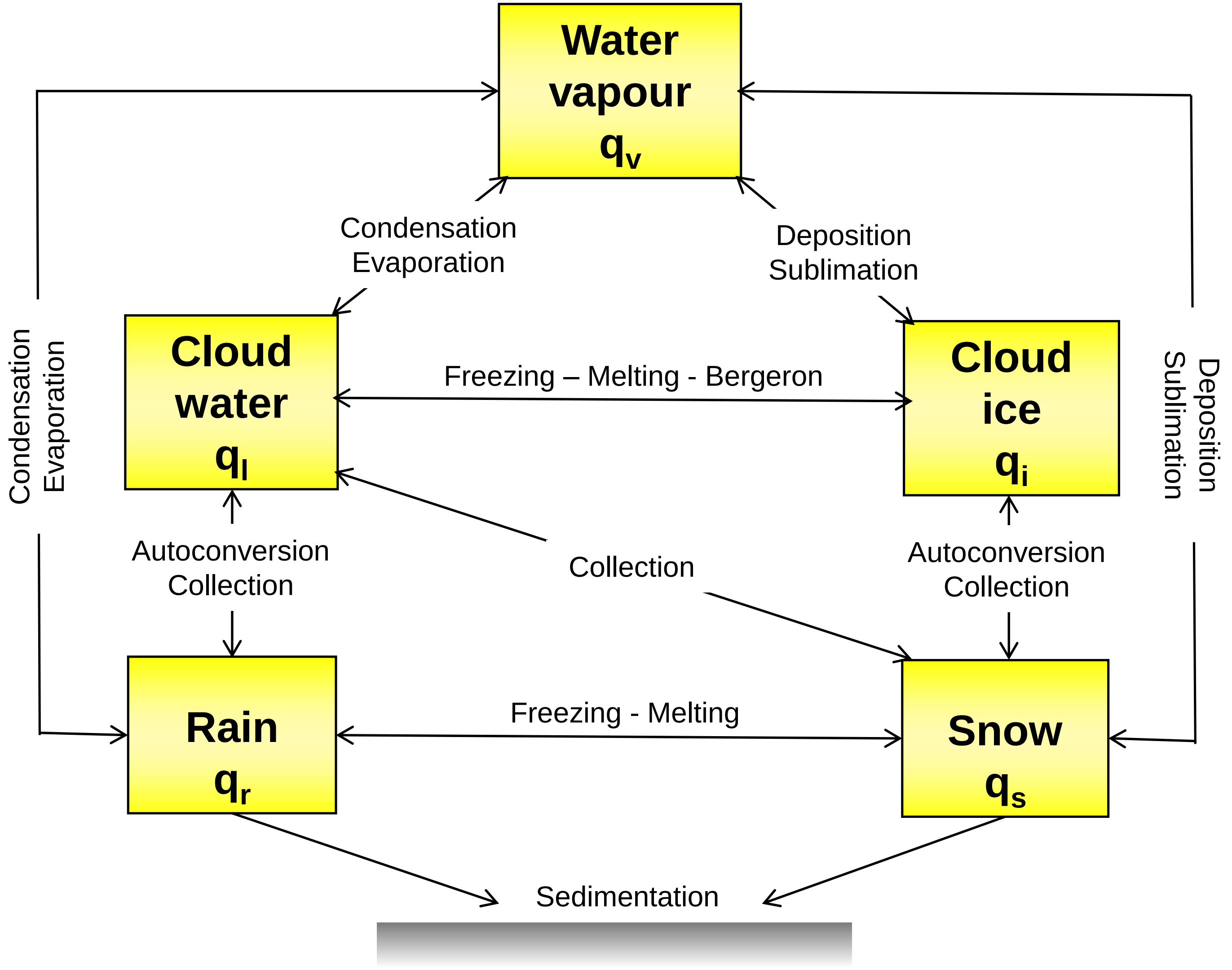


$c_0 = 10^{-3}\, e^{0.025(T - 273.15)}\ s^{-1}$ → Rate of conversion of ice (small particles) to snow (large particles) increases as the temperature increases.

$qi_{crit} = 3.10^{-5}$ kg kg^{-1}

Microphysics Parametrization:

The “category” view: Ice and Snow (ECMWF scheme)



Water vapour q_v

Condensation Evaporation

Deposition Sublimation

Cloud water q_l

Freezing – Melting - Bergeron

Cloud ice q_i

Condensation Evaporation

Deposition Sublimation

Autoconversion Collection

Collection

Autoconversion Collection

Rain q_r

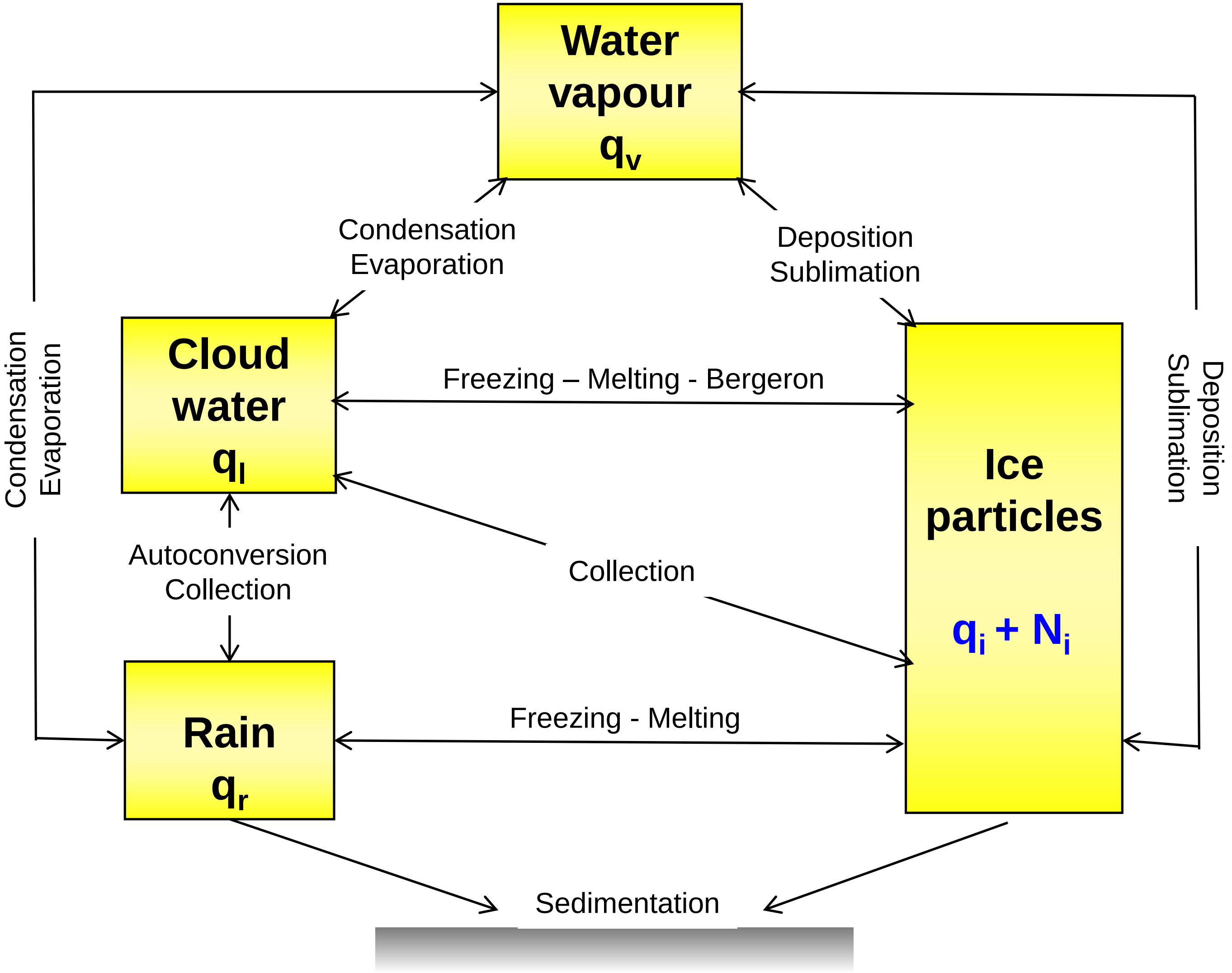
Freezing - Melting

Snow q_s

Sedimentation

Microphysics Parametrization:

The “category” view: Ice particle mass and number conc.



Water vapour q_v

Condensation
Evaporation

Deposition
Sublimation

Cloud water q_l

Freezing – Melting - Bergeron

Ice particles

$q_i + N_i$

Condensation
Evaporation

Deposition
Sublimation

Autoconversion
Collection

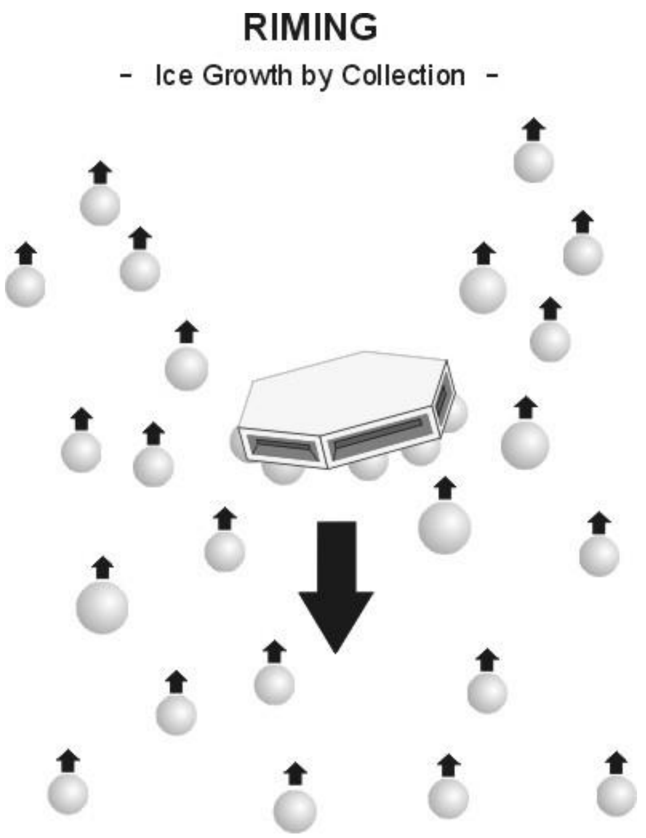
Collection

Rain q_r

Freezing - Melting

Sedimentation

Collection processes:
Riming – capture of water drops by ice

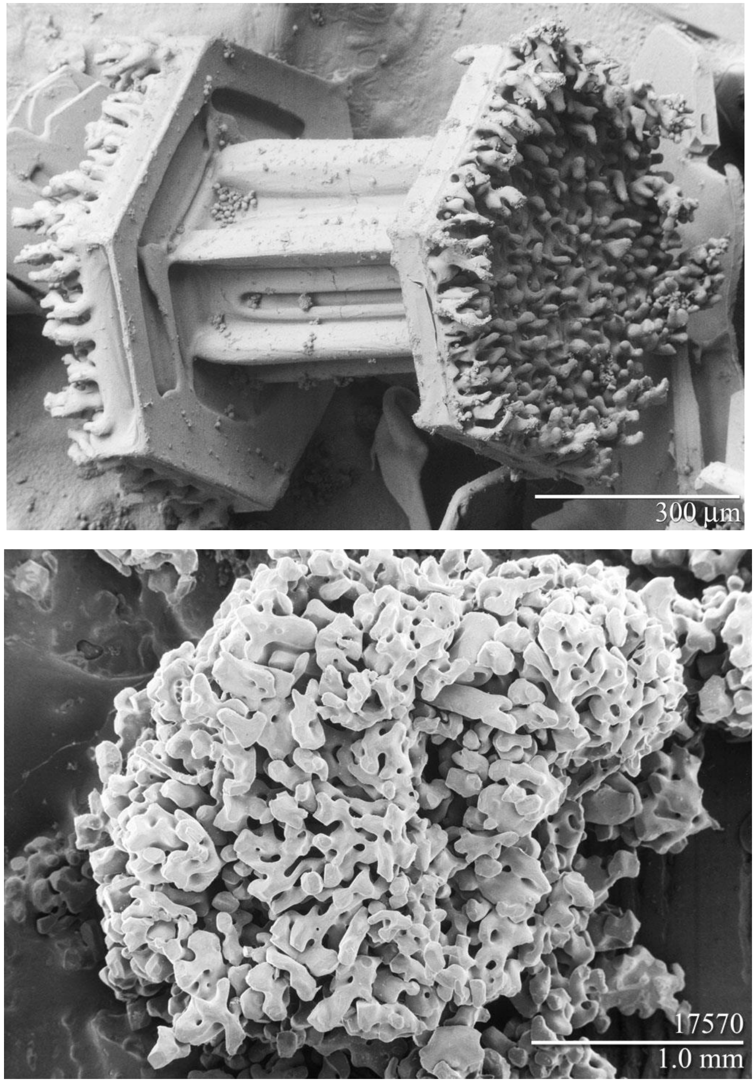


- Graupel formed by collecting liquid water drops in mixed phased clouds (“riming”), particulaly when at water saturation in strong updraughts (convection). Round ice crystals with higher densities and fall speeds than snow dendrites.

- Hail forms if particle temperature close to 273K, since the liquid water “spreads out” before freezing. Generally referred to as “Hail” – The higher fall speed (up to 40 m/s) imply hail only forms in convection with strong updraughts able to support the particle long enough for growth.

Rimed Ice Crystals

http://www.its.caltech.edu/~atomic/snowcrystals



Electron micrographs (emu.arsusda.gov)

Parametrization of rimed ice particles

- Most GCMs with parametrized convection don't explicitly represent graupel or hail (too small scale)
- In cloud resolving models, traditional split between ice, snow and graupel and hail as prognostic variables, but this split is rather artificial.
- Degree of riming can be light or heavy, particle density can vary smoothly.
- Alternative approach is to have ice particle properties as the prognostic variables, e.g.
  - Morrison and Grabowski (2008) have 3 ice variables: deposition mass, rime mass and number.
  - Morrison and Milbrandt (2015) have 4 ice variables to also represent hail-type particles: total ice mass, rime mass, rime volume and number.
  - Avoids artificial thresholds between different categories.

Other ice-phase microphysical processes

- Splintering of ice crystals, Hallet-Mossop splintering through riming around -5ºC. Leads to increased numbers of smaller crystals.
- Sedimentation due to gravity. Fall speed depends on particle size (and habit/density for ice).

Numerics: Explicit vs Implicit

$$\boxed{\frac{d\phi}{dt} = -D\phi}$$

ϕ = e.g. cloud water/ice
Process = e.g. autoconversion, sedimentation

Upstream forward in time solution (n = current time level, n+1 = next time level)

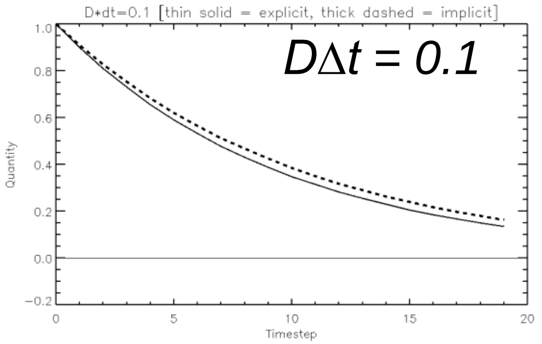
Explicit solution

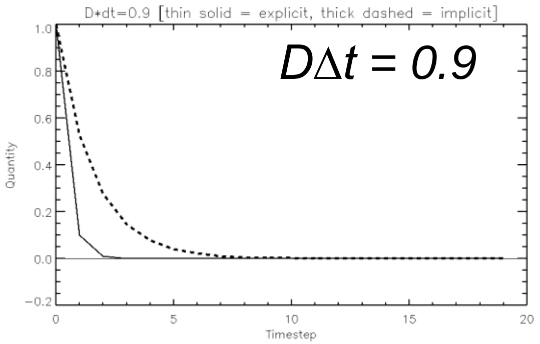
$$\boxed{\frac{\phi^{n+1}-\phi^{n}}{\Delta t} = -D\phi^{n}} \xrightarrow{\text{Rearrange}} \boxed{\phi^{n+1} = (1-D\Delta t)\phi^{n}}$$

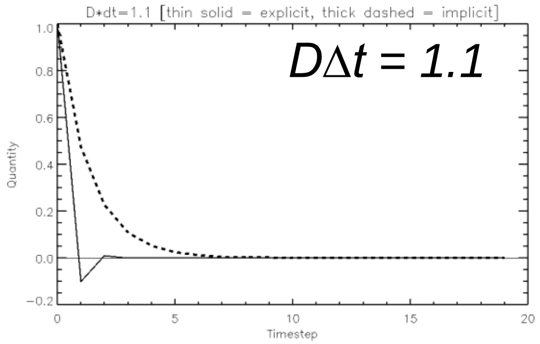
For long timesteps $D\Delta t$ maybe >1 so explicit Φ^{n+1} becomes negative!

Implicit solution

$$\boxed{\frac{\phi^{n+1}-\phi^{n}}{\Delta t} = -D\phi^{n+1}} \xrightarrow{\text{Rearrange}} \boxed{\phi^{n+1} = \frac{\phi^{n}}{(1+D\Delta t)}}$$







Numerics and sedimentation

Advected quantity (e.g. ice)

Sedimentation term

$$\boxed{\frac{d\phi}{dt} = C + D\phi + \frac{1}{\rho}\frac{d}{dz}\left(\rho v_X \phi\right)}$$

Constant
Explicit Source/Sink

Implicit Source/Sink
(not required for short timesteps)

what is short?

Options for sedimentation

(1) semi-Lagrangian
(2) time splitting
(3) implicit numerics

Implicit:
Upstream forward in time,
k = vertical level
n = time level
ϕ = cloud water (q_x)

$$\boxed{\frac{\phi_k^{n+1}-\phi_k^n}{\Delta t} = C + \frac{\rho_{k-1}V_{k-1}\phi_{k-1}^{n+1}}{\rho_k \Delta Z} + \left(D - \frac{\rho_k V_k}{\rho_k \Delta Z}\right)\phi_k^{n+1}}$$

Solution

$$\boxed{\phi_k^{n+1} = \frac{C\Delta t + \frac{\rho_{k-1}V_{k-1}\phi_{k-1}^{n+1}}{\rho_k \Delta Z}\Delta t + \phi_k^n}{1 - D\Delta t + \frac{V_k \Delta t}{\Delta Z}}}$$

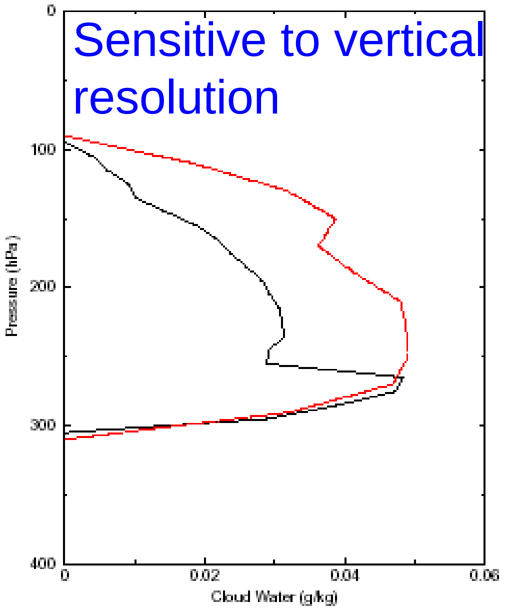
Ice Sedimentation:
Improved numerics in SCM cirrus case

- Important to have a sedimentation scheme that is not sensitive to vertical resolution and timestep.

Vertical profile of ice water content

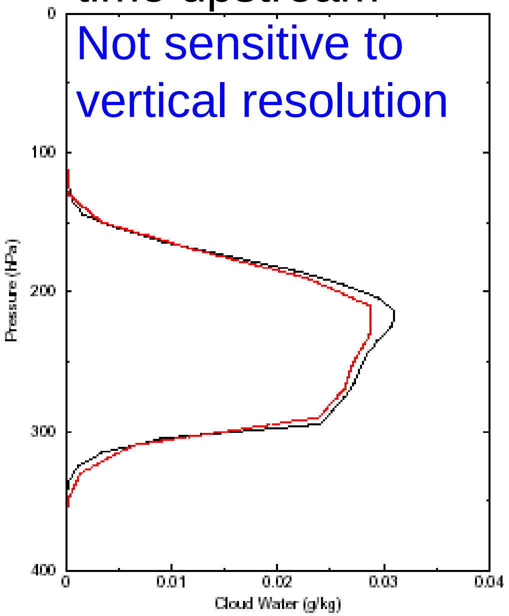
100 vertical levels (black) versus 50 vertical levels (red)

Old numerics before CY29R1



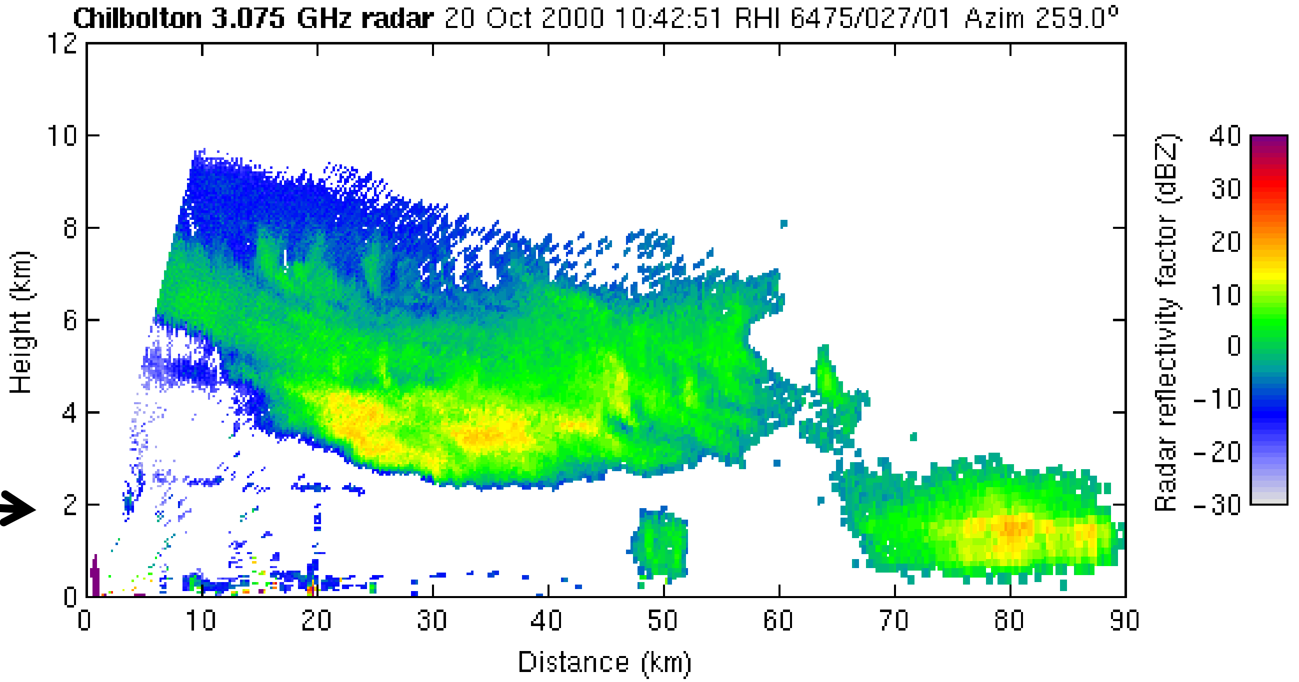
Sensitive to vertical resolution

Implicit forward-in-time upstream



Not sensitive to vertical resolution

Falling Precipitation



Ice

Snow

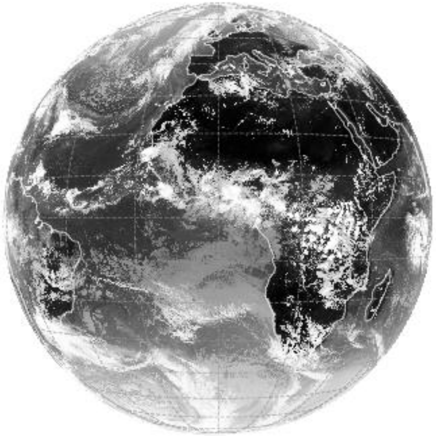
Melting layer

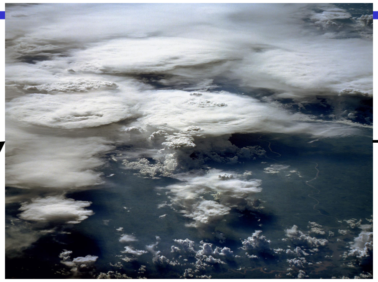
Rain

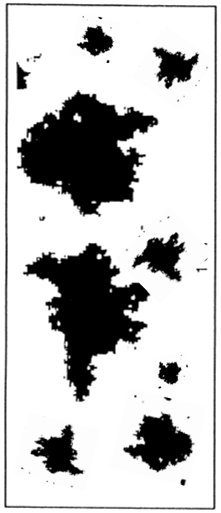
Courtesy R Hogan, University of Reading, www.met.rdg.ac.uk/radar

Microphysics - Summary

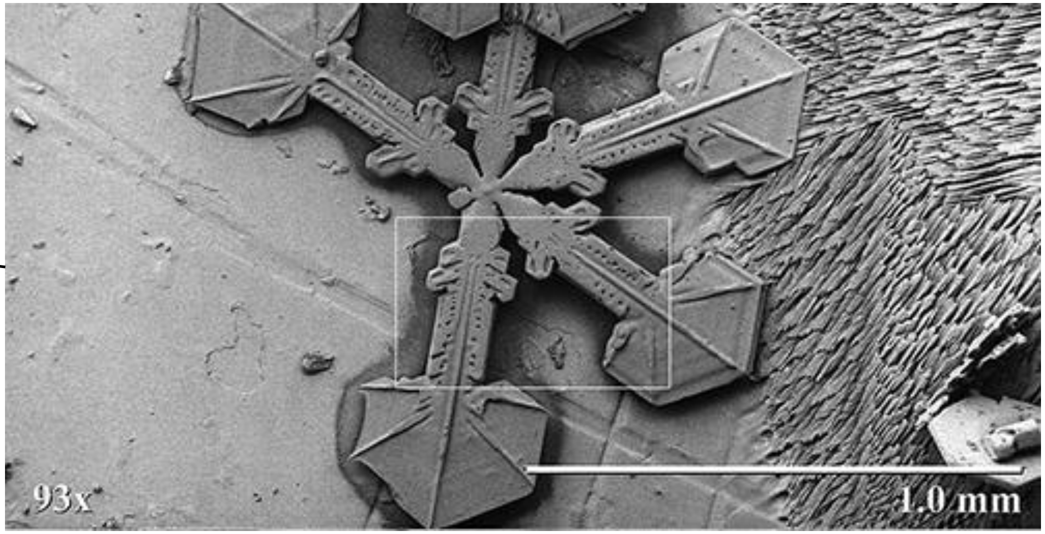
From global to micro-scales







Hugely complex system.
Need to simplify!



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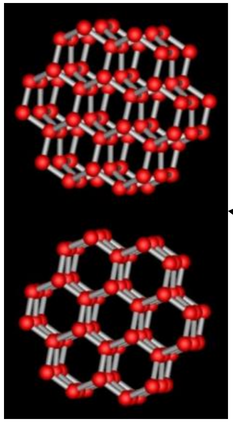

Summary

- Parametrization of cloud and precipitation microphysical processes:
  - Need to simplify a complex system
  - Accuracy vs. complexity vs. computational efficiency trade off
  - Appropriate for the application and no more complexity than can be constrained and understood
  - Dynamical interactions (latent heating), radiative interactions
  - Still many uncertainties (particularly ice phase)
  - Particular active area of research is aerosol-microphysics interactions.
  - Microphysics often driven by small scale dynamics – how do we represent this in models…..
- Next lecture: Cloud Cover
  - Sub-grid scale heterogeneity
  - Linking the micro-scale to the macro-scale

References

Reference books for cloud and precipitation microphysics:

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