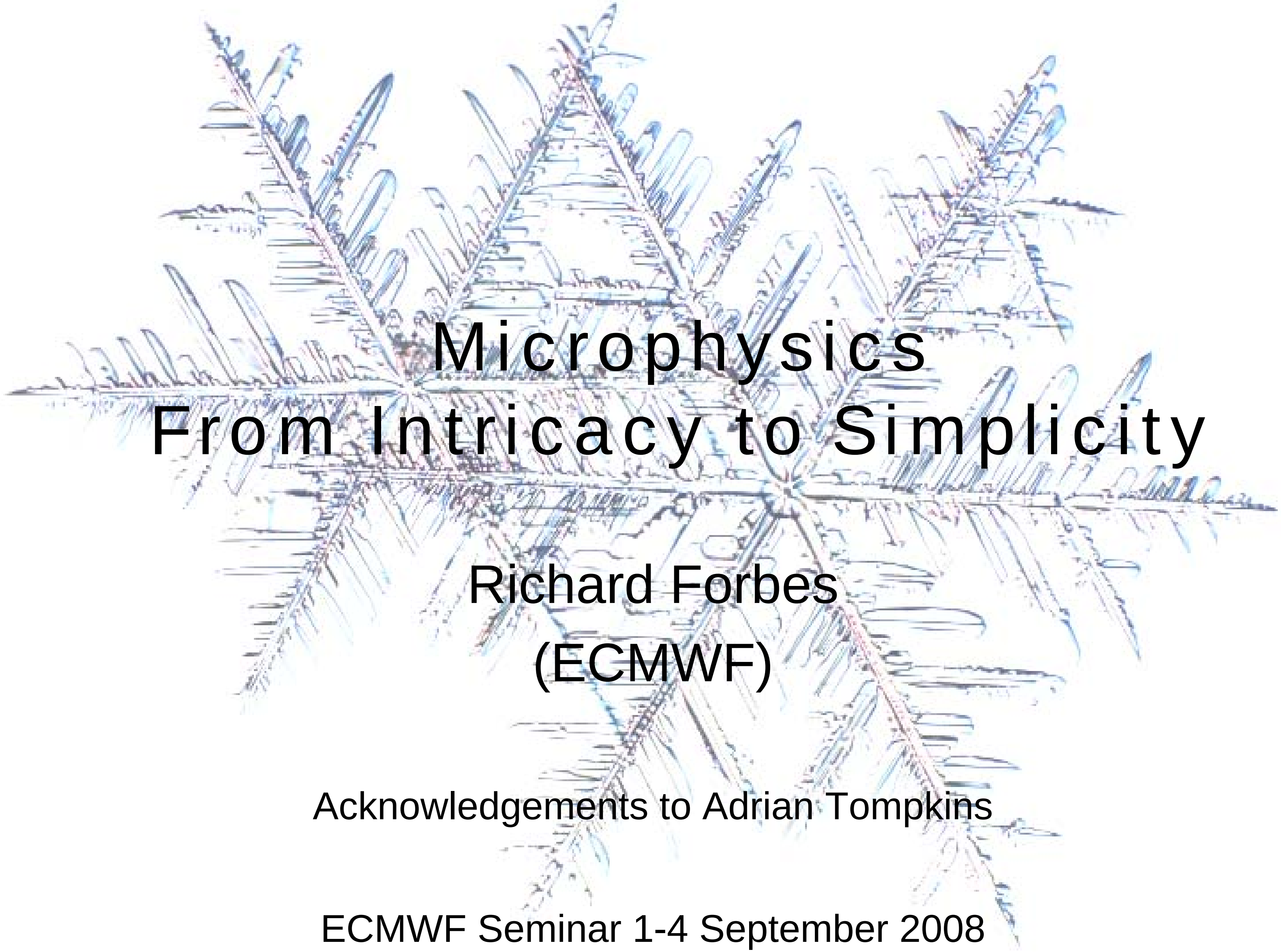


Microphysics
From Intricacy to Simplicity

Richard Forbes
(ECMWF)

Acknowledgements to Adrian Tompkins

ECMWF Seminar 1-4 September 2008

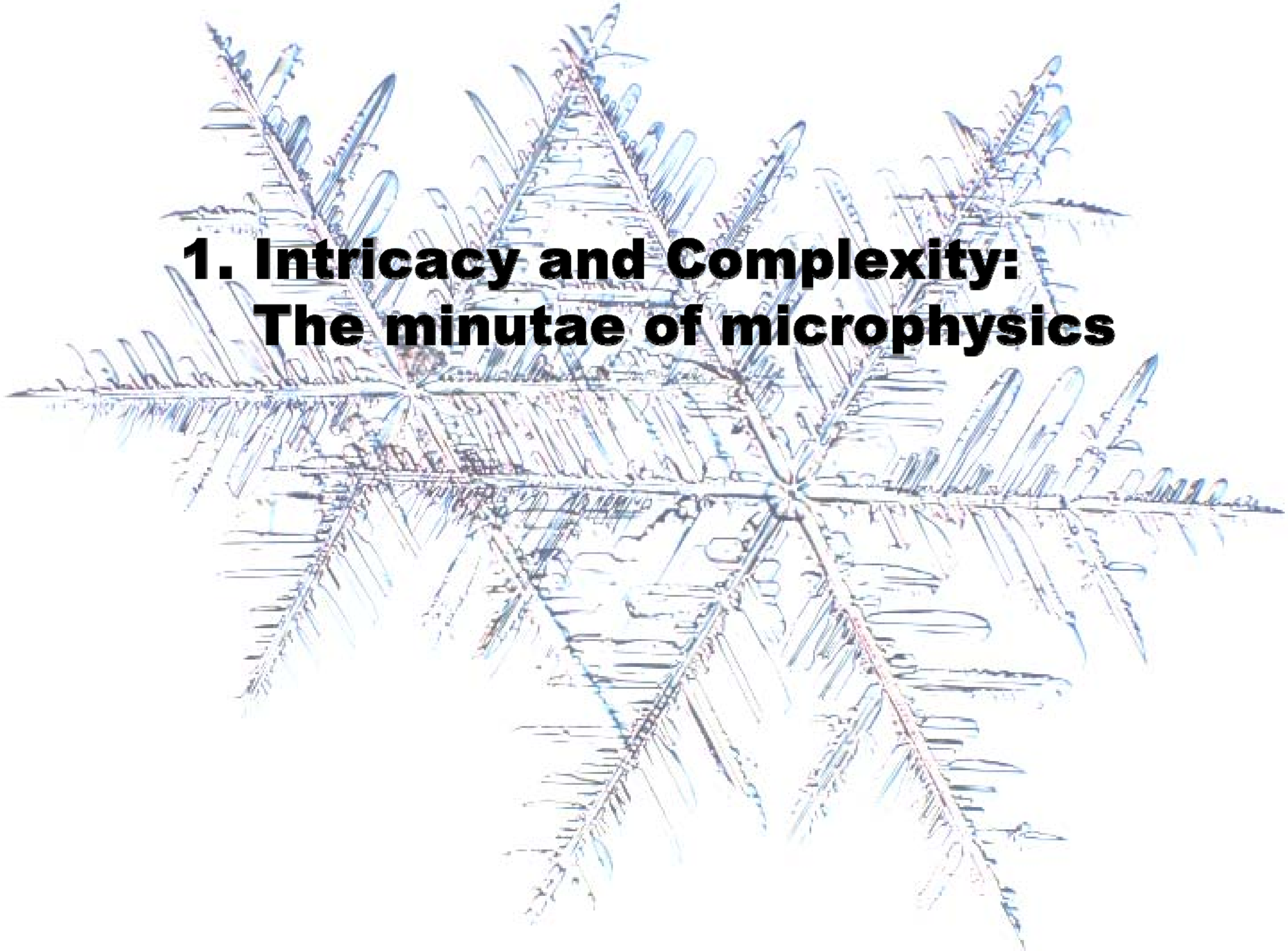
Talk Outline

1. **Intricacy and Complexity:** The minutiae of microphysics

2. **Simplicity and Approximation:** Parametrizing microphysics

3. **Microphysics and Atmospheric Dynamics**

1. Intricacy and Complexity: The minutae of microphysics



Kepler (1611) “On the Six-Cornered Snowflake”

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apud Godefridum Tampach.

Anno M. DC. XI.

JOHANN KEPLER,

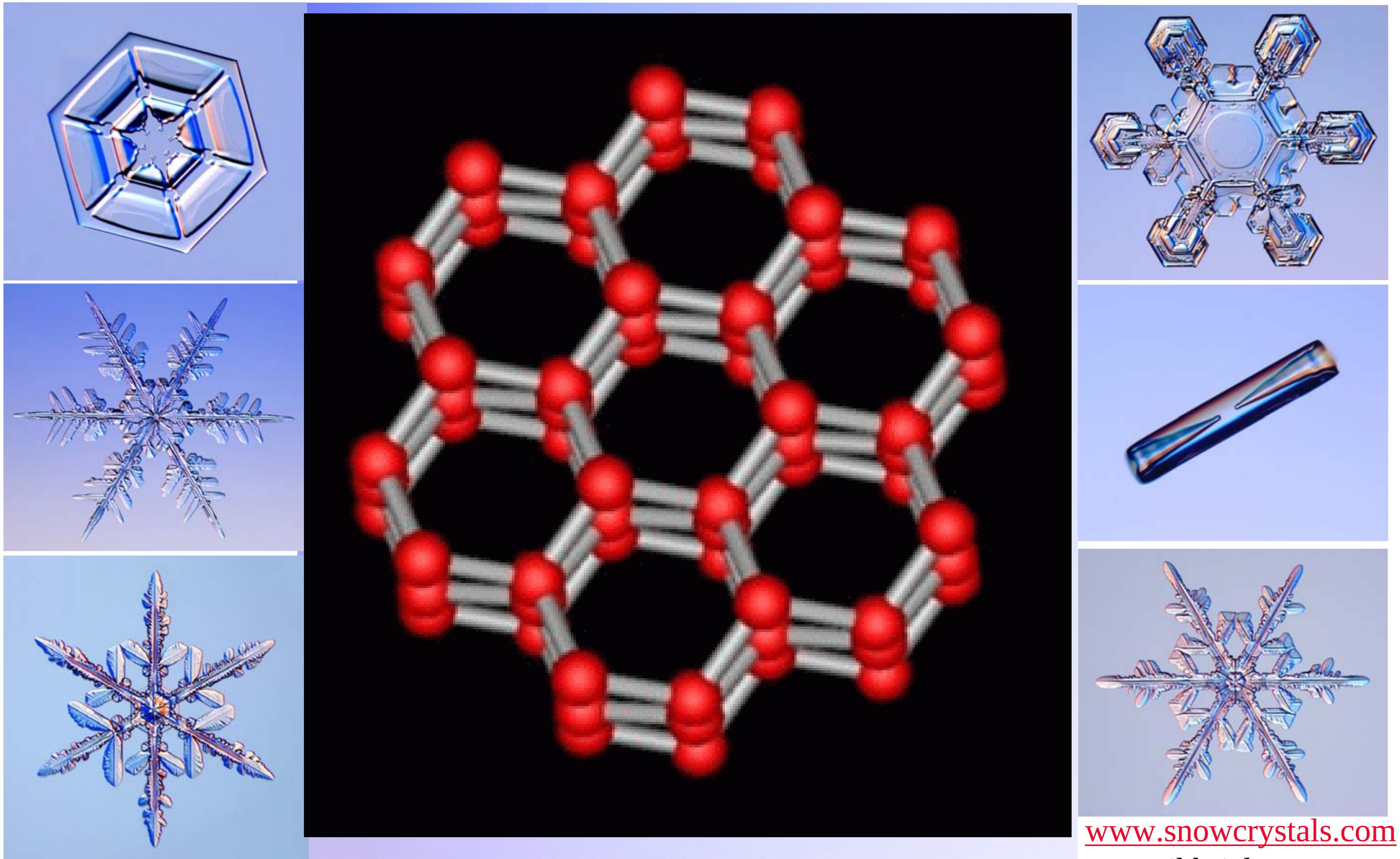
MATHEMATICIAN TO
HIS IMPERIAL MAJESTY

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

Copyright licensed 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

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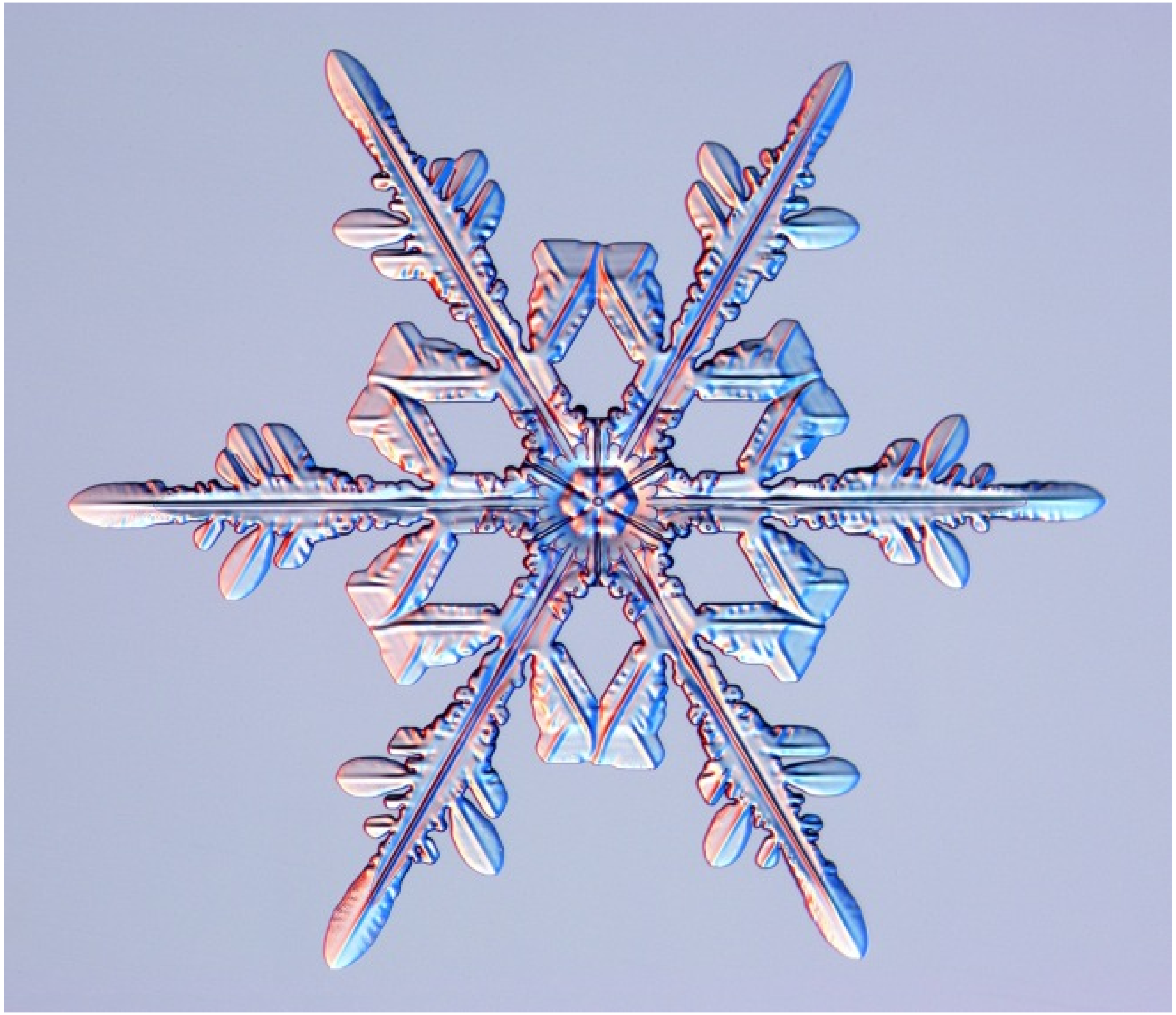
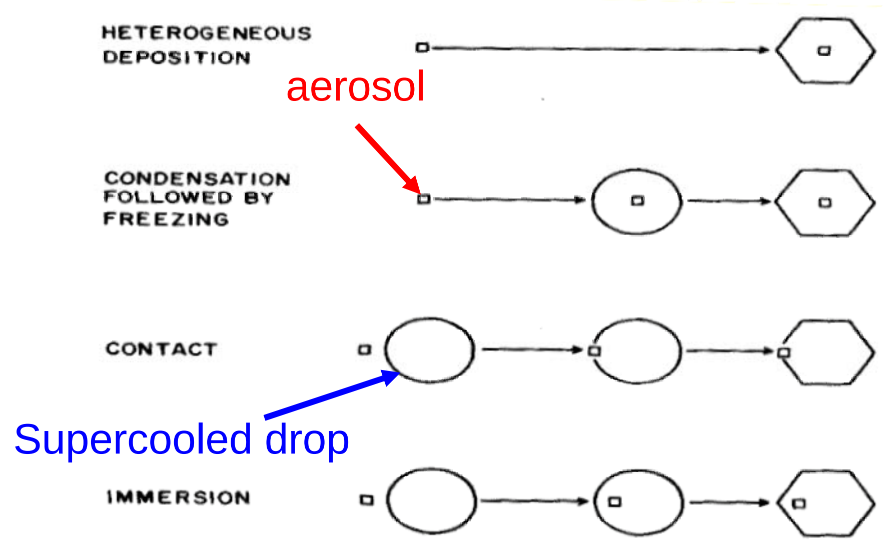


Ice Nucleation

- Droplets do not freeze at 0^{o}C !
- Ice nucleation processes can be split into Homogeneous and Heterogeneous processes, but complex and not well understood.
- Homogeneous freezing of water droplet occurs below about -38^{o}C, dependent on a critical relative humidity (fn of T, Koop et al. 2000).

- Frequent observation of ice between 0^{o}C and colder temperatures indicates heterogeneous processes active.
- Number of activated ice nuclei increases with decreasing temperature.



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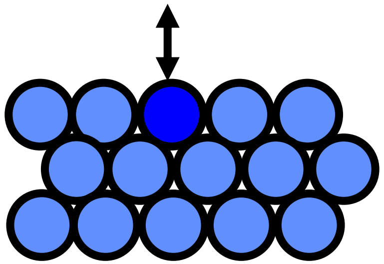
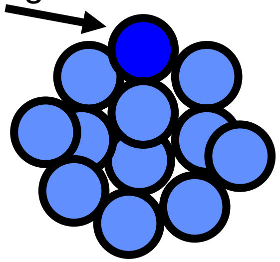
Nucleation of water drops

- **Homogeneous nucleation**
  - Drop of pure water from vapour
  - Would require several hundred percent supersaturation (not observed in the atmosphere)
- **Heterogeneous nucleation**
  - Collection of water molecules on a foreign substance, RH > ~80% (haze particles)
  - These (hydrophilic) soluble particles are called Cloud Condensation Nuclei (CCN)
  - CCN always present in sufficient numbers in lower and middle troposphere
  - Nucleation of droplets (i.e. from stable haze particle to unstable regime of diffusive growth) at very small supersaturations.

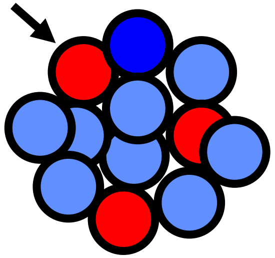
Nucleation of water drops
Important effects for particle activation



Planar surface: Equilibrium when $e=e_s$ and number of molecules impinging on surface equals rate of evaporation



Curved surface: saturation vapour pressure increases with smaller drop size since surface molecules have fewer binding neighbours.
Effect proportional to r^{-1}



Presence of dissolved substance: saturation vapour pressure reduces with smaller drop size due to solute molecules replacing solvent on drop surface (assuming $e_{sollute}<e_v$)
Effect proportional to r^{-3}

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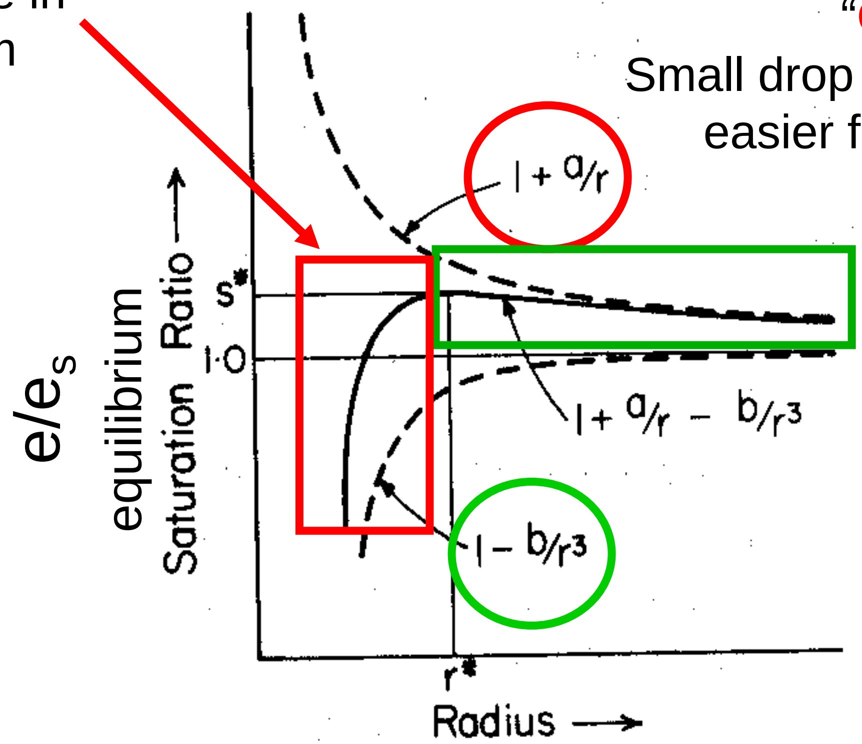
Nucleation of water drops
Heterogeneous Nucleation

Haze particle in equilibrium

"Curvature term"
Small drop – high radius of curvature easier for molecule to escape



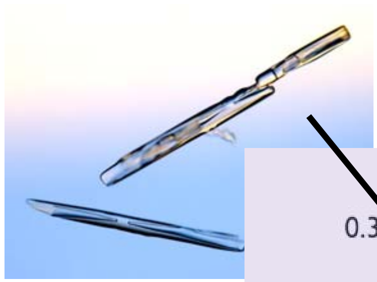
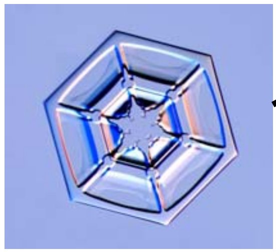
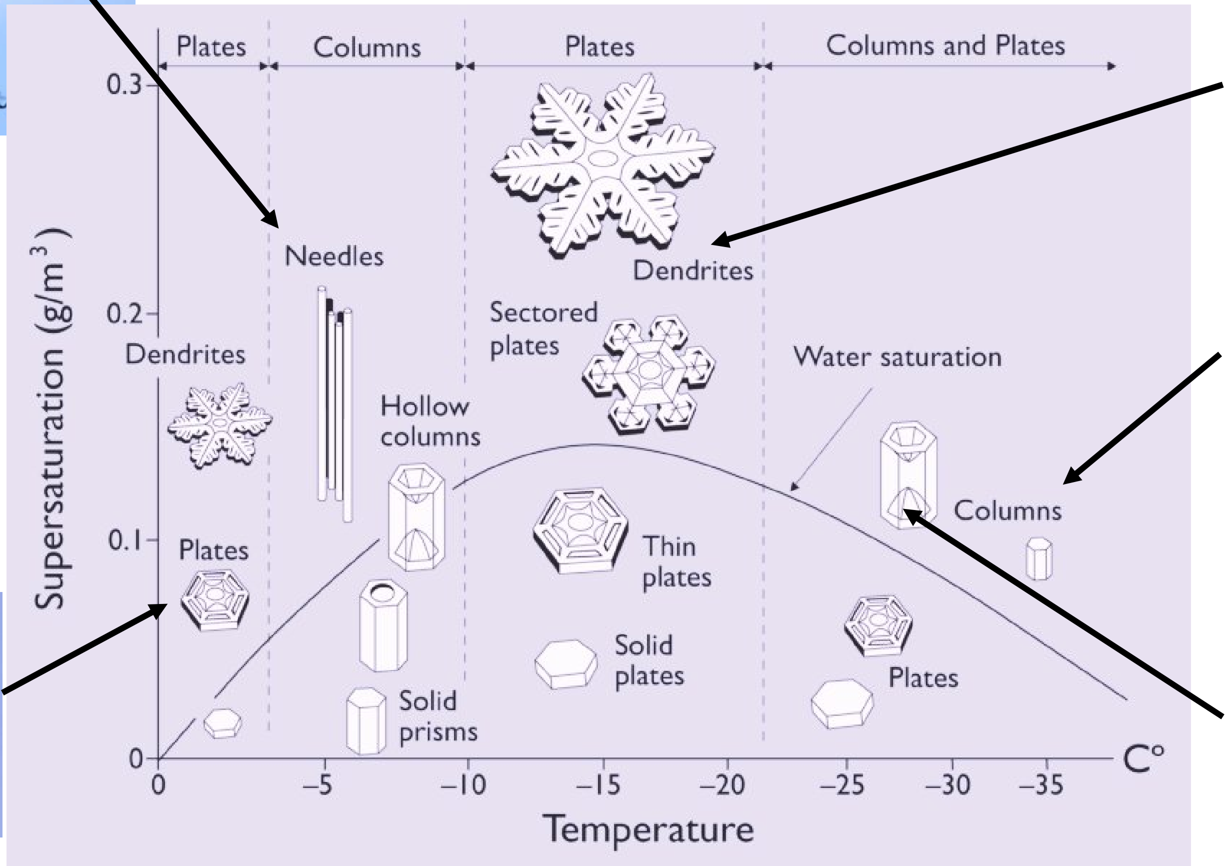
"Solution term"
Reduction in vapour pressure due to dissolved substance

$$e / es = 1.01,$$

$$r > 0.12 \mu m \text{ "activated"}$$

Diffusion Growth
Ice Habits

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



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

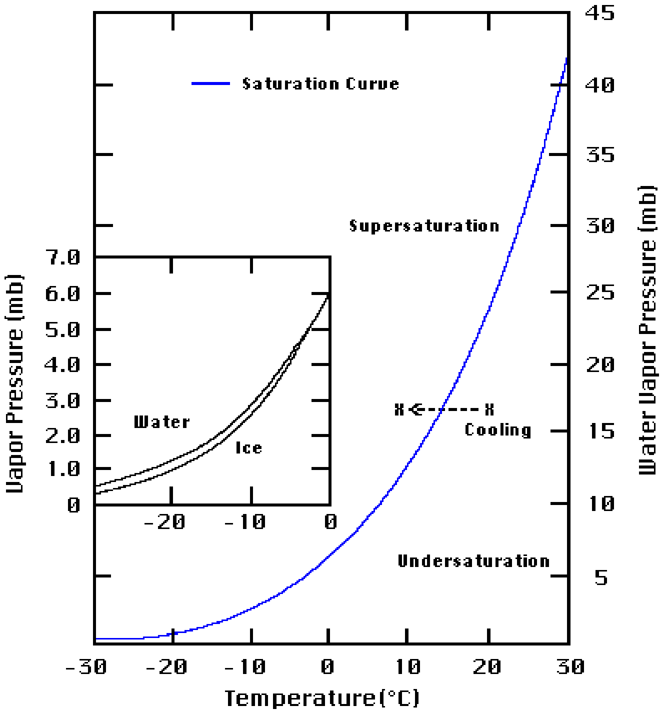
Diffusion growth

Diffusion Growth

Bergeron-Findeison-Wegener process

- Saturation vapour pressure with respect to ice is smaller than with respect to water.
- A cloud that is subsaturated wrt water can therefore be supersaturated wrt ice
- Ice particles grow at the expense of water droplets

The vapor pressure of ice and water between -30° and 30° (mb = millibar). (Berner and Berner 1987)



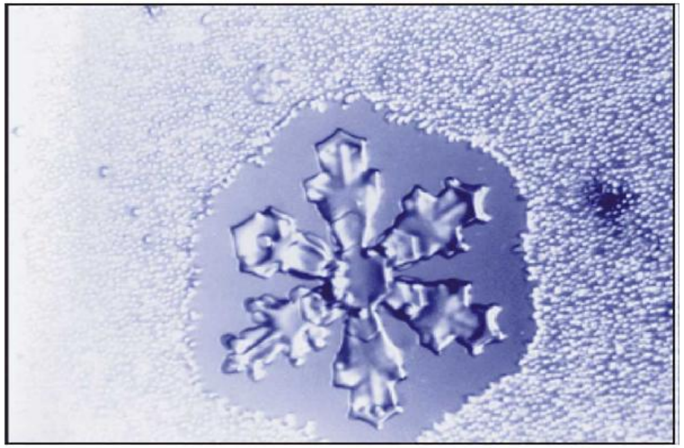


Photo by R. Pttler

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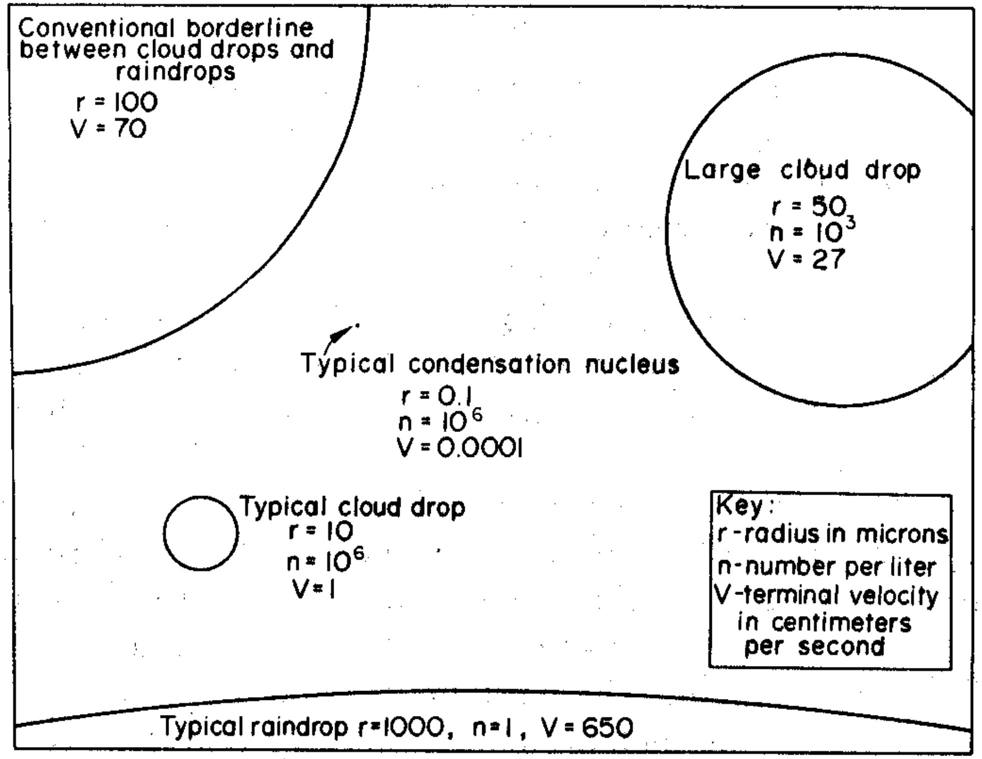
Diffusion Growth
Water droplets

- Once droplet is activated, water vapour diffuses towards it = condensation
- Droplets that are formed by diffusion growth attain a typical size of 0.1 to 10 μm
- Rain drops are much larger

  -drizzle: 50 to 100 μm

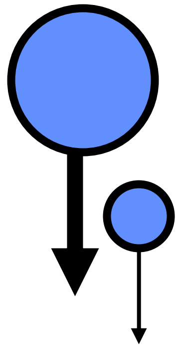
  -rain: >100 μm
- Other processes must also act in precipitating clouds



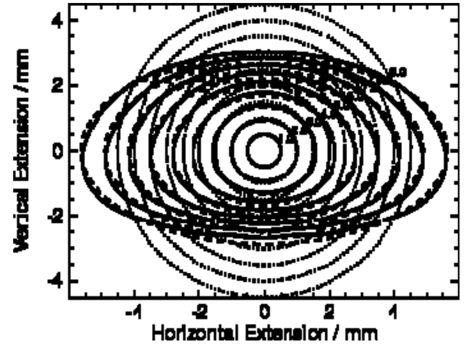
From McDonald (1958)

Collection
Collision-Coalescence of water drops

- Drops of different size move with different fall speeds - collision and coalescence
- Large drops grow at the expense of small droplets
- Collection efficiency low for small drops
- Process depends on width of droplet spectrum and is more efficient for broader spectra – paradox
- Large drops can only be produced in clouds of large vertical extent – Aided by turbulence, giant CCNs ?



Rain drop shape
Chuang and Beard (1990)



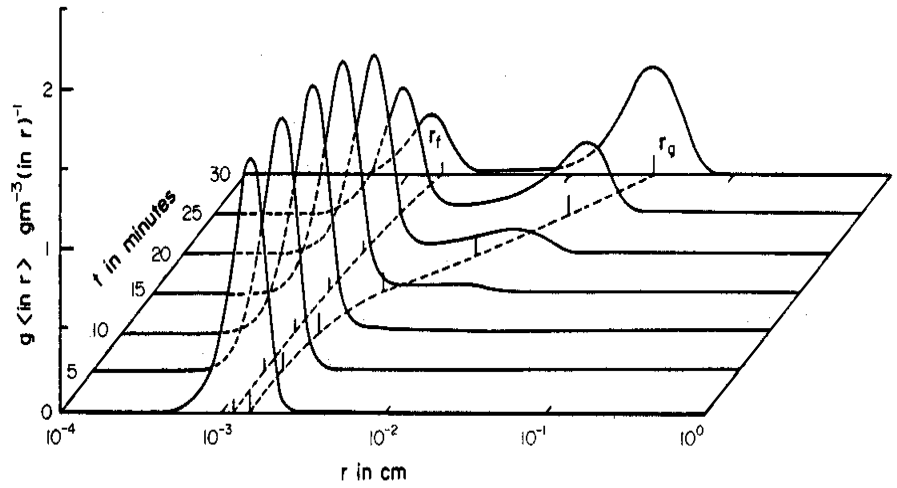
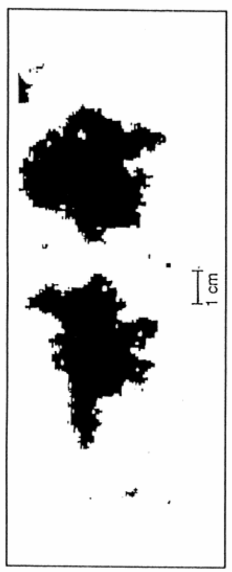


FIG. 8.10. Example of the development of a droplet spectrum by stochastic coalescence. (From Berry and Reinhardt, 1974b.)

Collection
Ice Crystal Aggregation

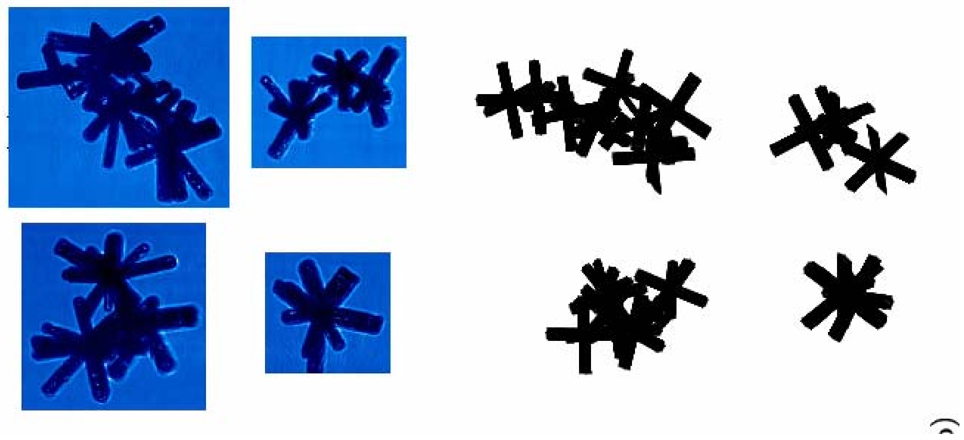
- Ice crystals can aggregate together to form “snow”
- “Sticking” efficiency increases as temperature exceeds –5C
- Irregular crystals are most commonly observed in the atmosphere (e.g. Korolev et al. 1999, Heymsfield 2003)



Lawson, JAS’99

Field & Heymsfield ‘03

CPI Model

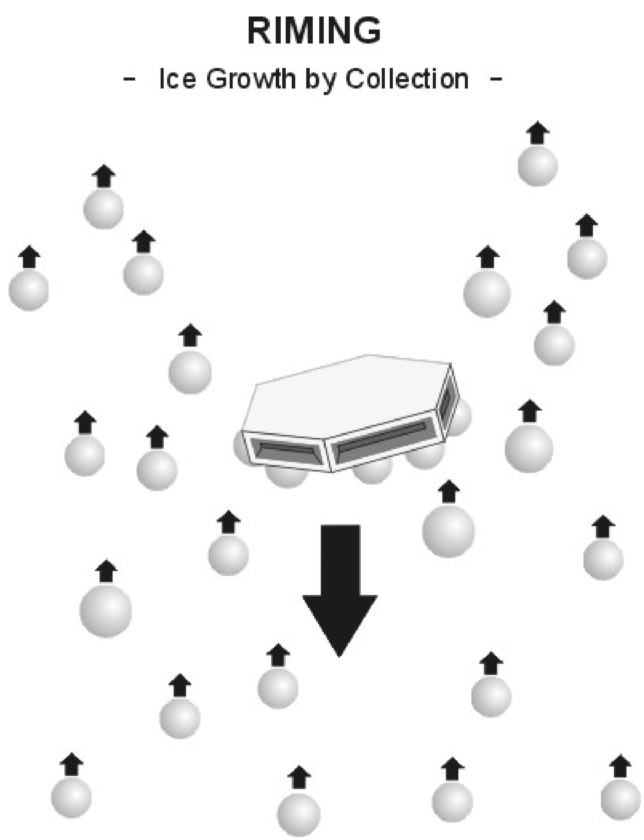


500 μm

T=-46°C

Westbrook et al. (2008)

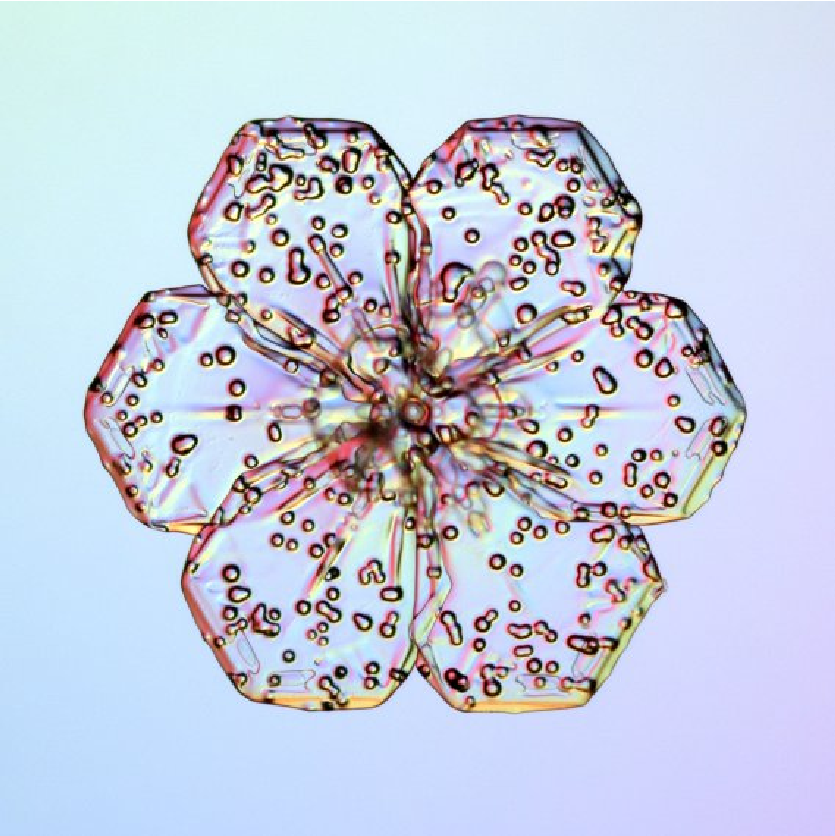
Collection
Riming



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

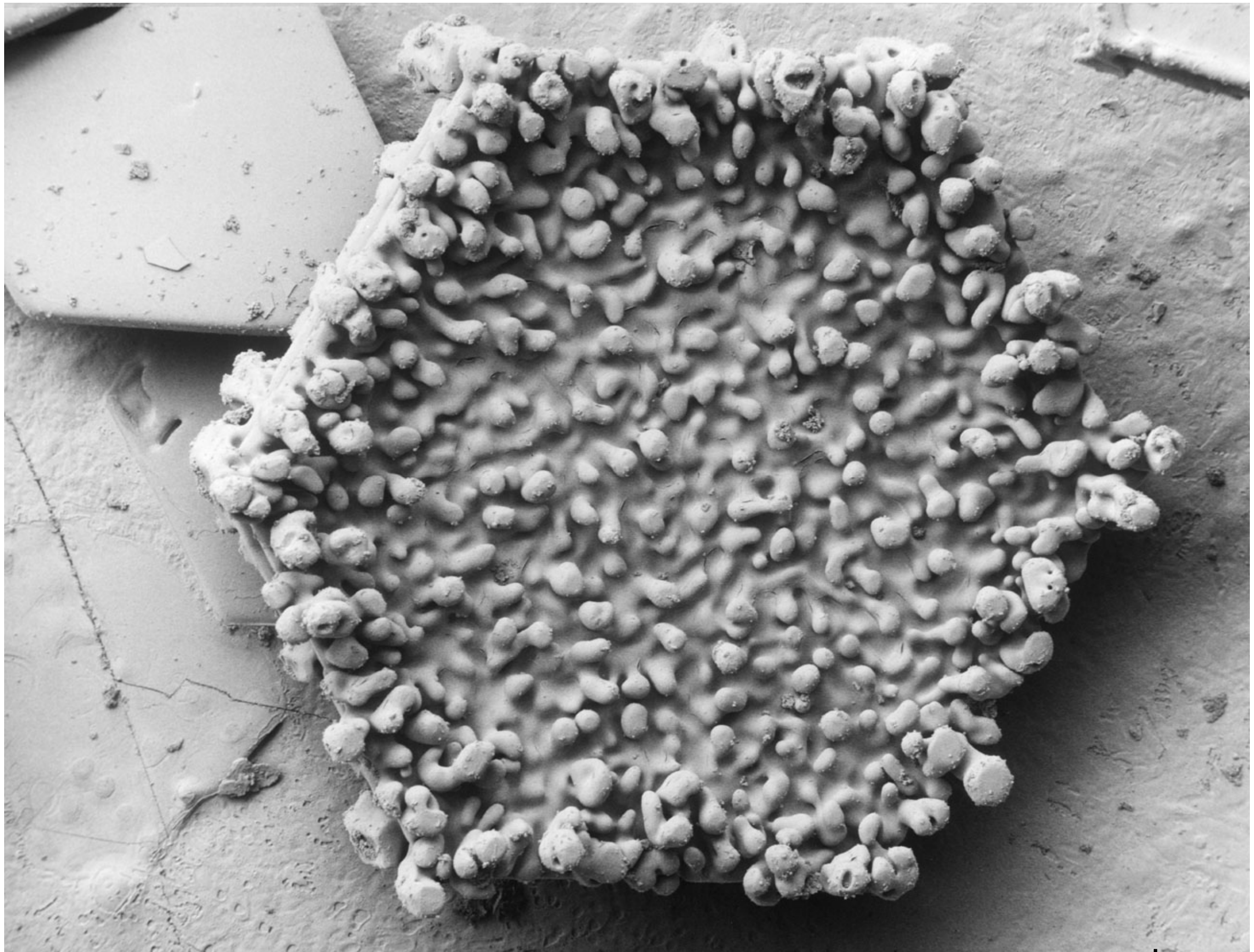
- Hail forms if particle temperature close to 273K, since the liquid water “spreads out” before freezing. Generally referred to as “Hail” – The higher fall speed (up to 40 m/s) imply hail only forms in convection with strong updraughts able to support the particle long enough for growth

Rimed Ice Crystals



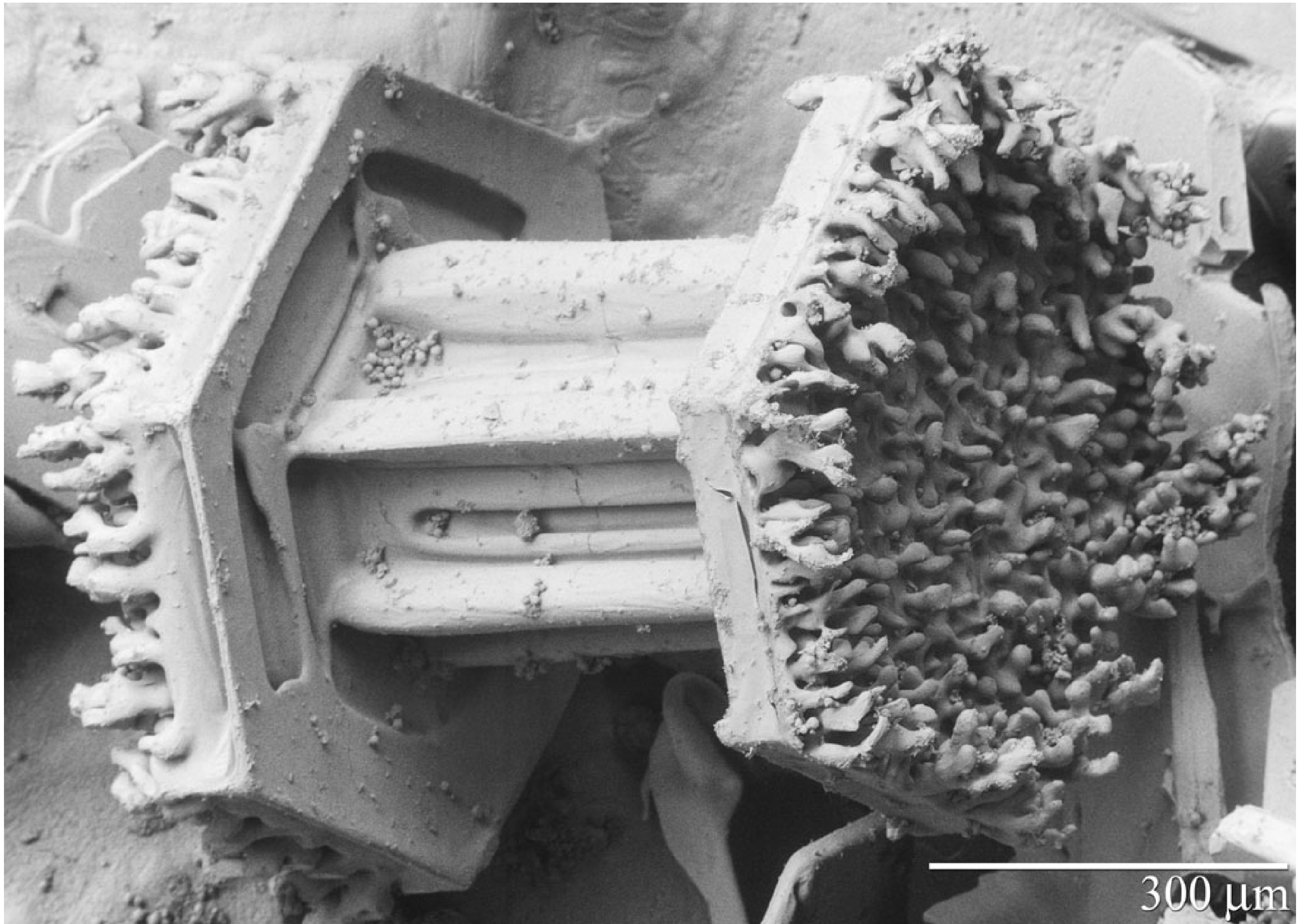
http://www.its.caltech.edu/~atomic/snowcrystals

Rimed Ice Crystal



emu.arsusda.gov

Rimed Ice Crystal



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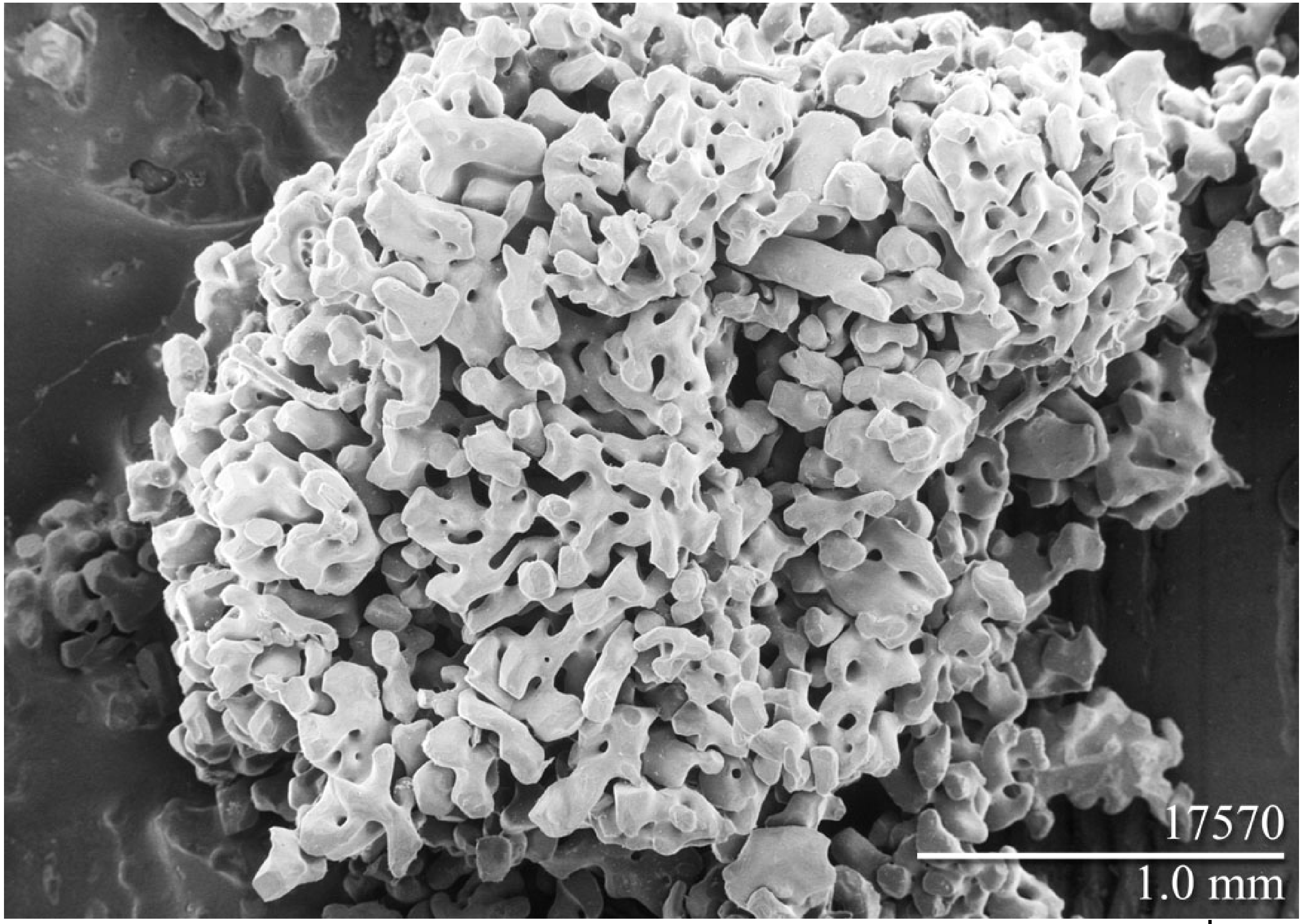
Heavily Rimed Ice Crystal



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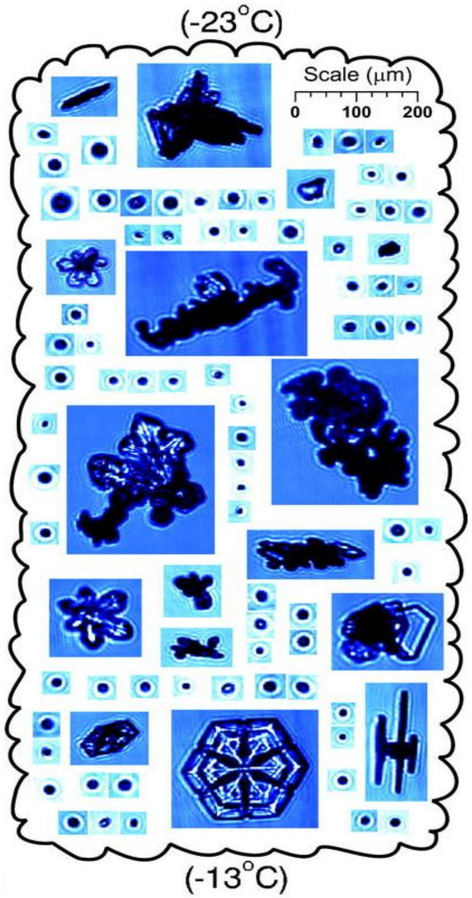
Splintering, Shedding Evaporation, Melting

- Other processes include evaporation/sublimation and melting.

- Large rain drops break up – shedding to form smaller drops, places a limit on rain drop size.

- Splintering of ice crystals, Hallet-Mossop splintering through riming around -5°C. Leads to increased numbers of smaller crystals.

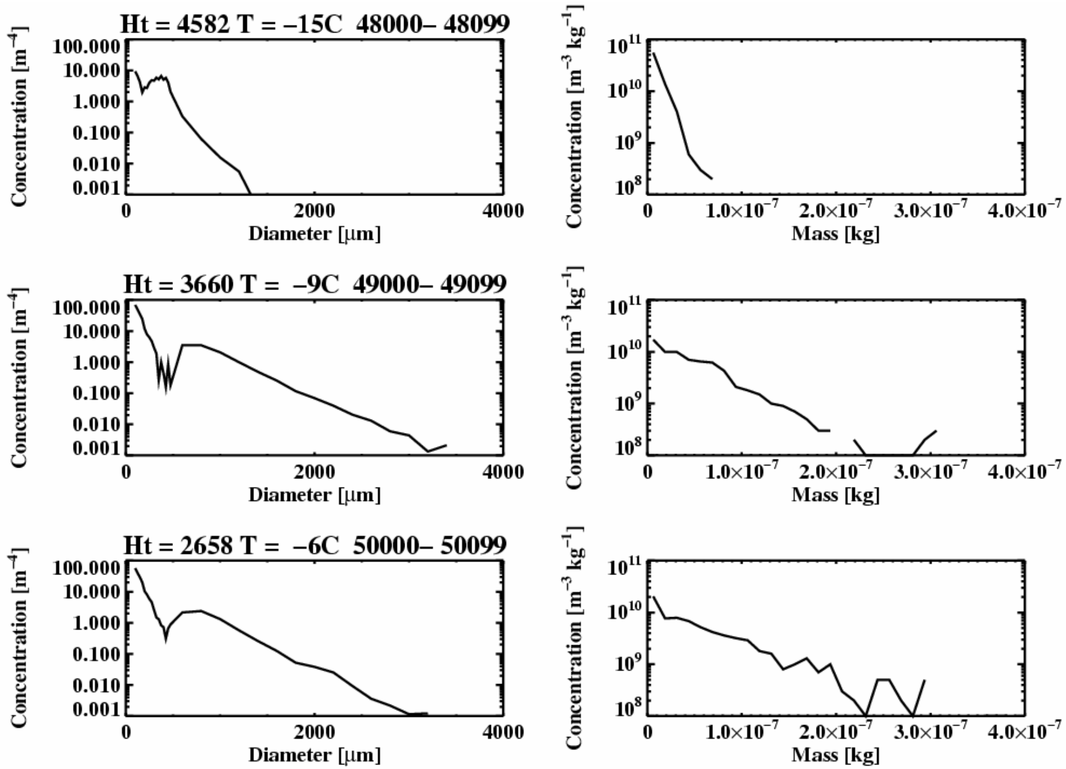
Particle Size Distributions



From Fleishauer et al (2002, JAS)

Size Distribution

Mass Distribution



Field (2000), Field and Heymsfield (2003)

Microphysics at the Cloud Scale

Typical time-height cross section of a front from the vertically pointing 94GHz radar at Chilbolton, UK

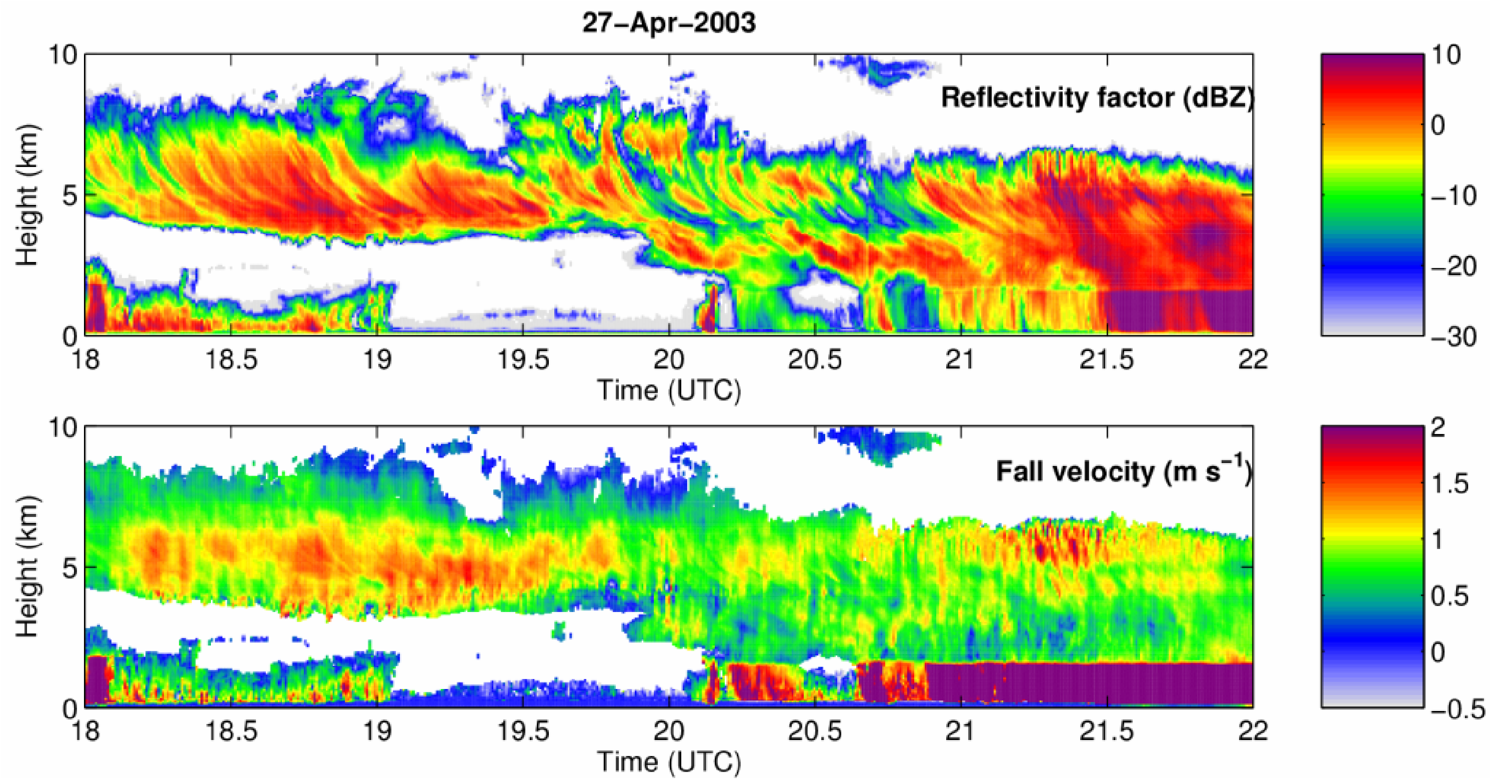
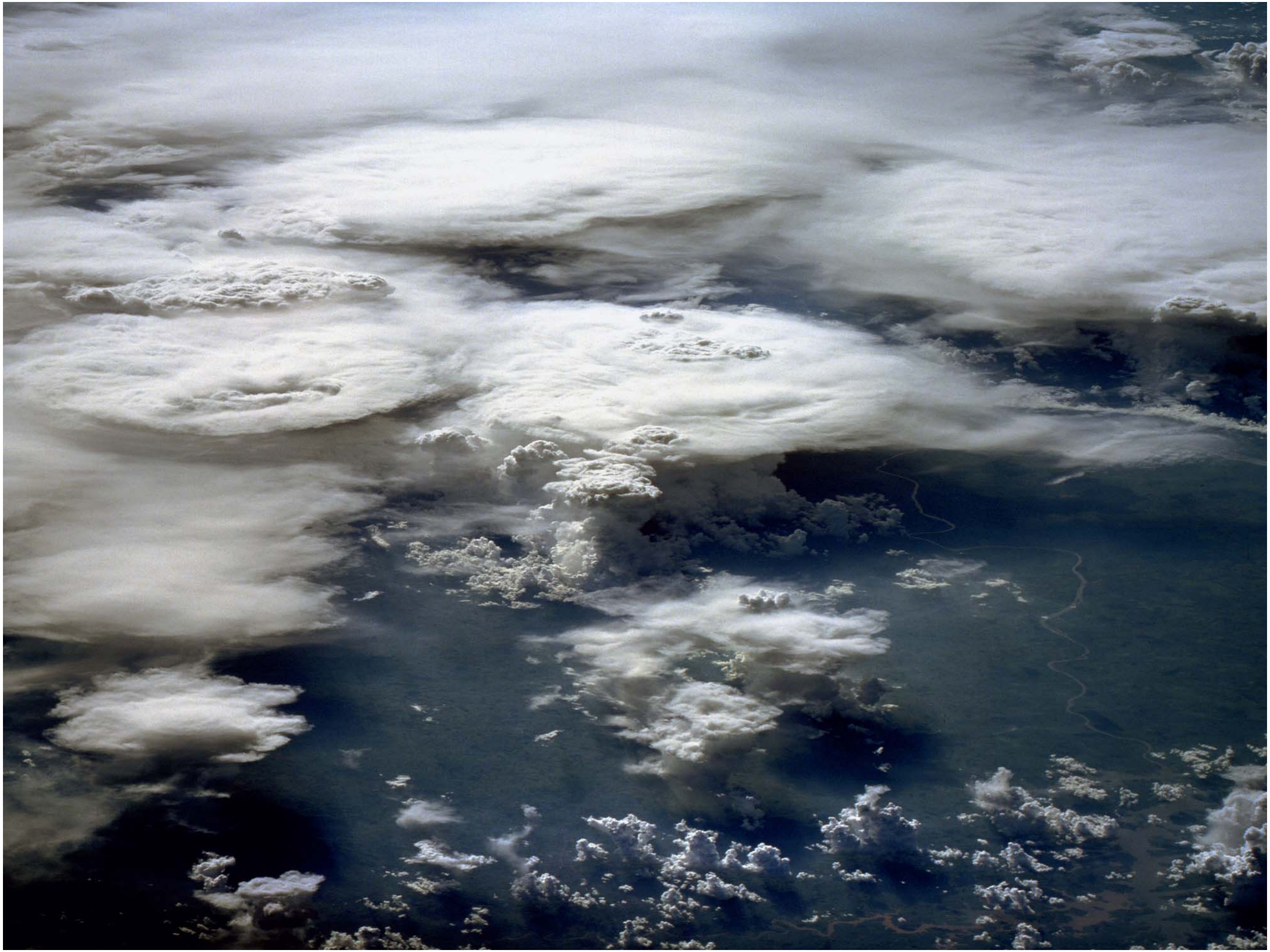
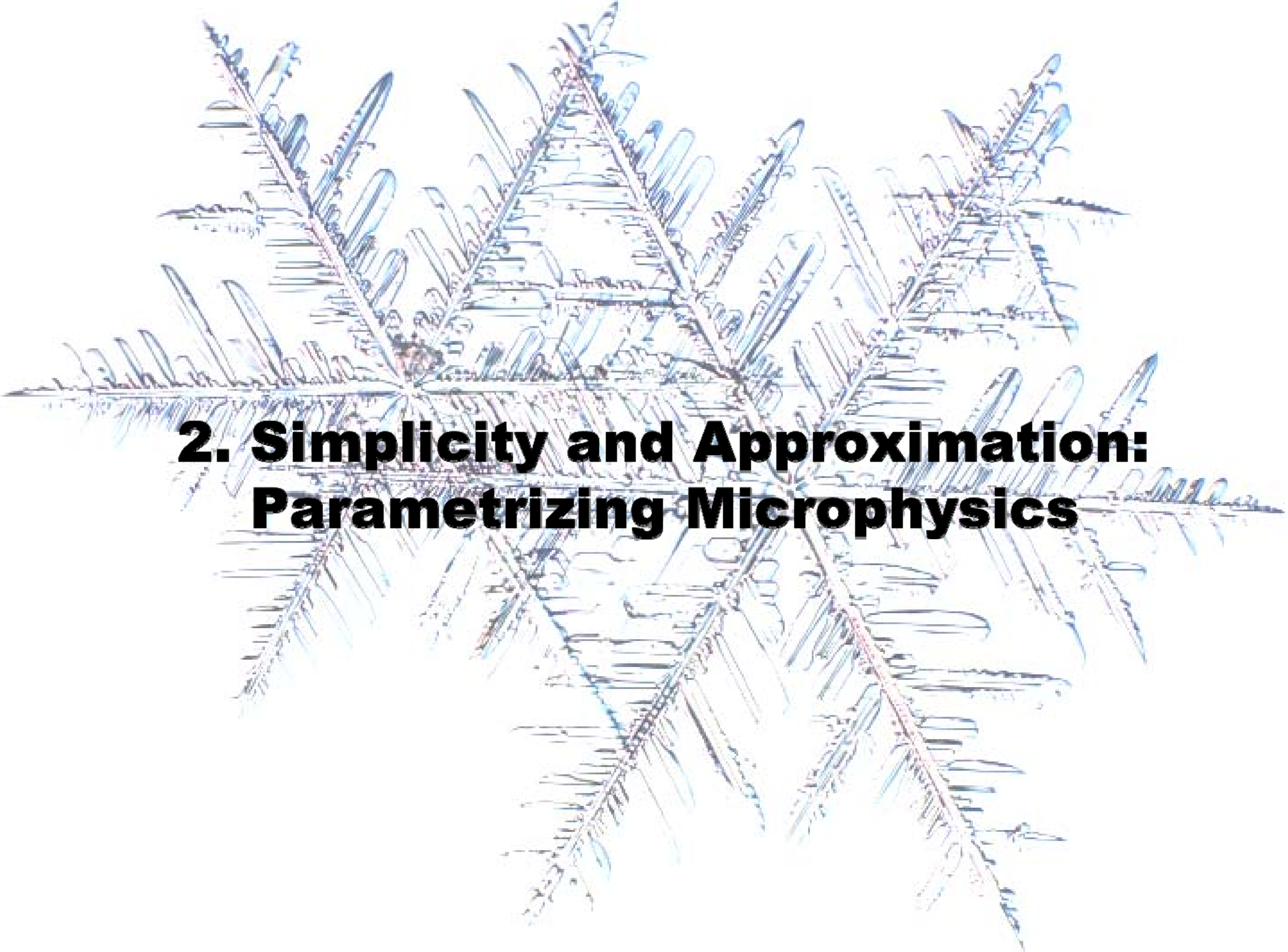


Image from Robin Hogan. Data from RCRU RAL.

Summary 1: Intricacy and Complexity

- **Molecular Scale**
  - **Nucleation/activation, Diffusion/condensation/evaporation**
- **Particle Scale**
  - **Collection/collision-coalescence/aggegation, Shedding/splintering**
- **Parcel Scale**
  - **Particle Size Distributions**
- **Cloud Scale**
  - **Heterogeneity**
  - **Interaction with the dynamics**





2. Simplicity and Approximation: Parametrizing Microphysics

Why do we need microphysics in GCMs?

- **Water Cycle**
  - Representation of clouds
  - Surface precipitation (rain, snow, hail)
- **Radiative Impacts**
  - Absorption
  - Emissivity
- **Dynamical Impacts**
  - Vertical profile of latent heating/cooling
  - Water loading
- **Validation and Assimilation (e.g. satellite, radar)**

Representing microphysics

- **Perfect knowledge, “infinite” computing power**: Track individual aerosols and particles, location, history, shape, size, mass, etc.
- **Imperfect knowledge and a “very big” computer:** Group particles together and treat all in the same way, e.g. “bin” microphysical models (different liquid/ice categories, size bins).
- **Even less knowledge and a slightly smaller computer:** Different liquid/ice categories, simple functional representation of size spectra with gridbox mass (single moment) and number concentration (double moment).
- **Still less knowledge and a slightly smaller computer:** Fewer particle categories, no explicit assumptions about particle sizes, one variable per category (usually mass).

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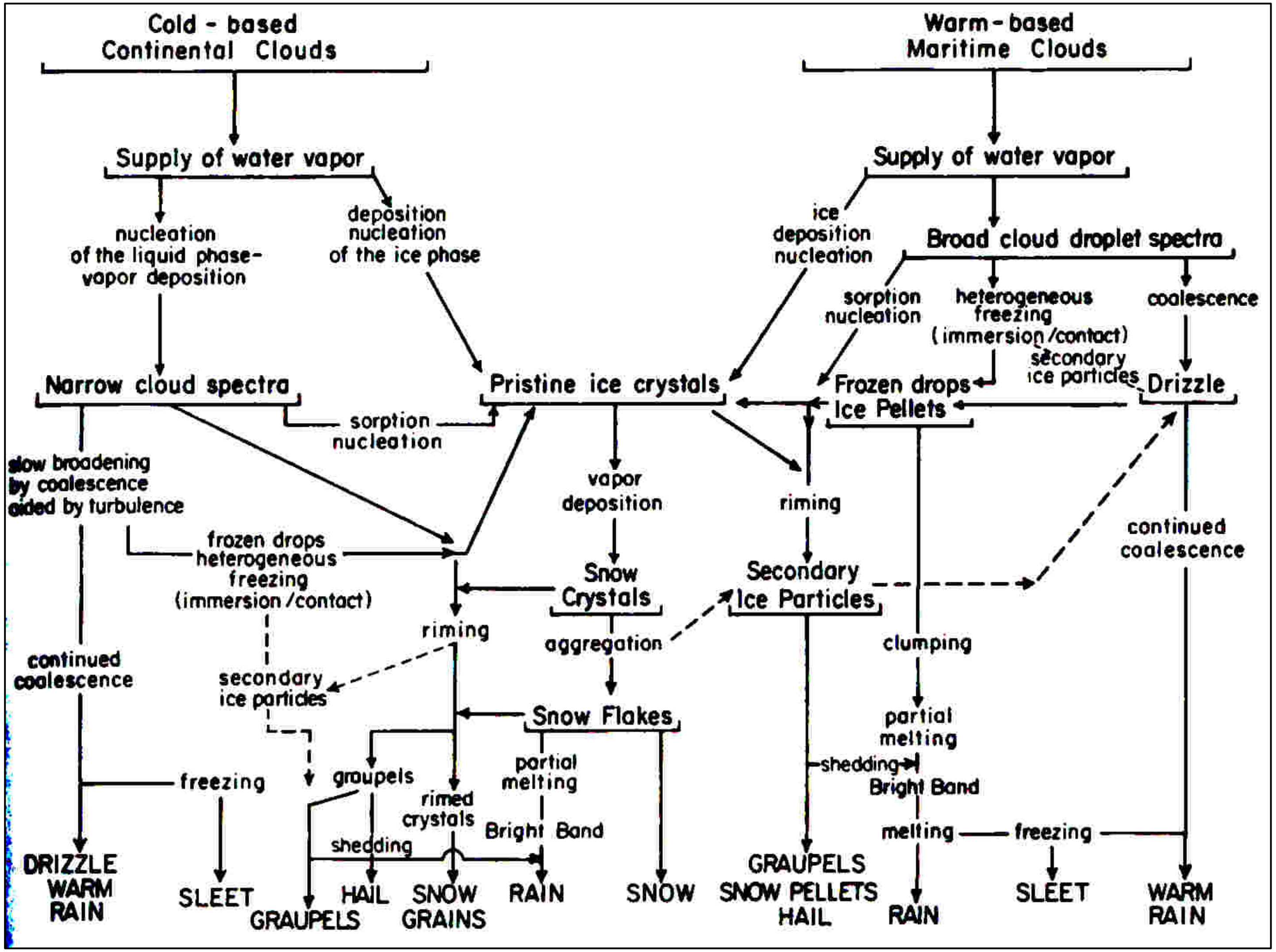
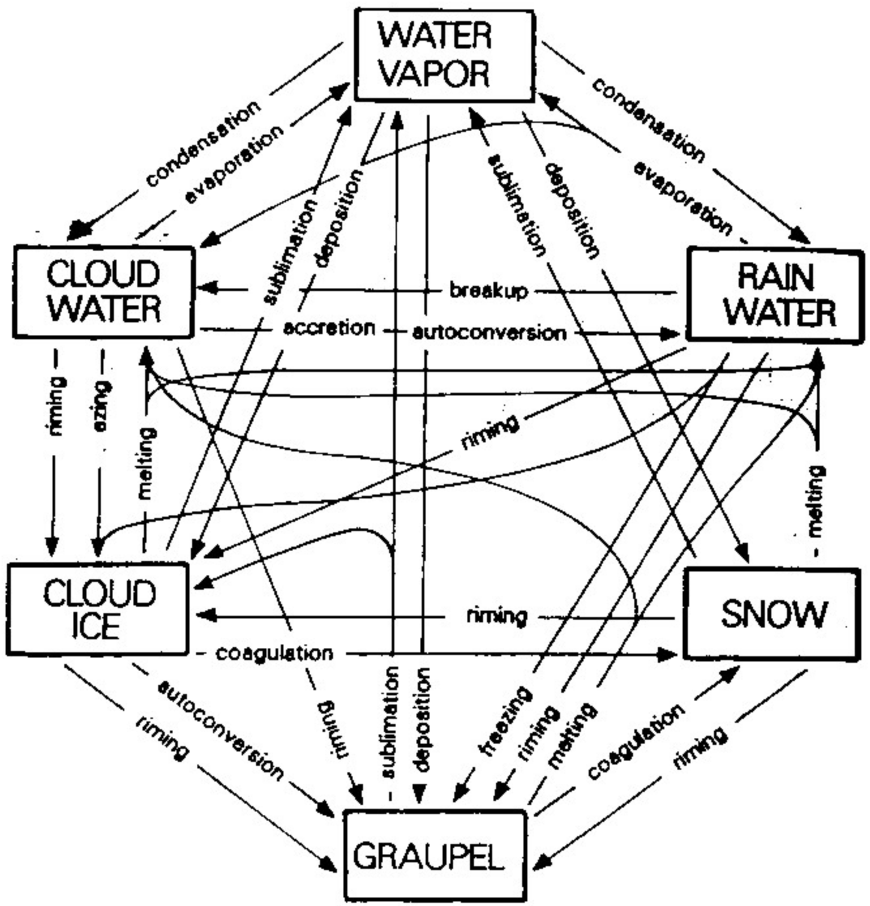
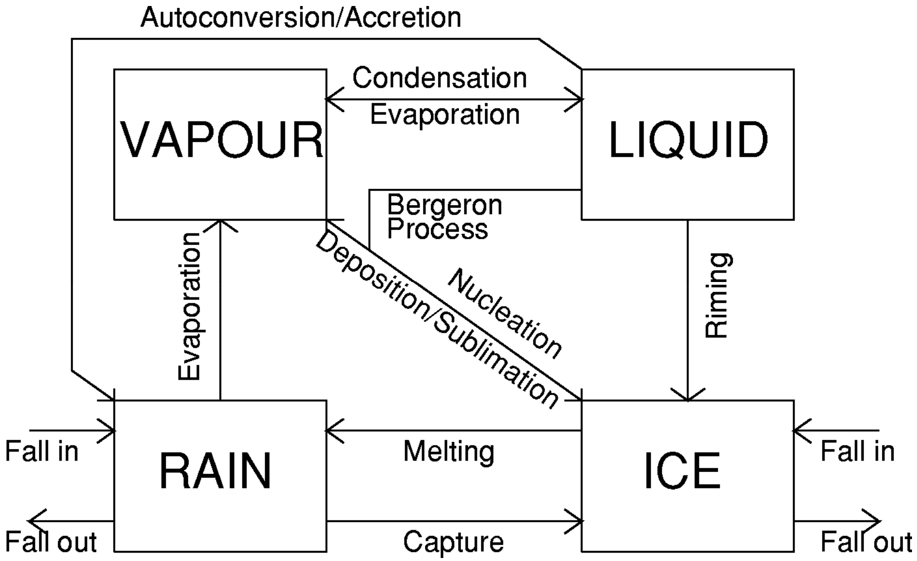
Complexity vs. Efficiency



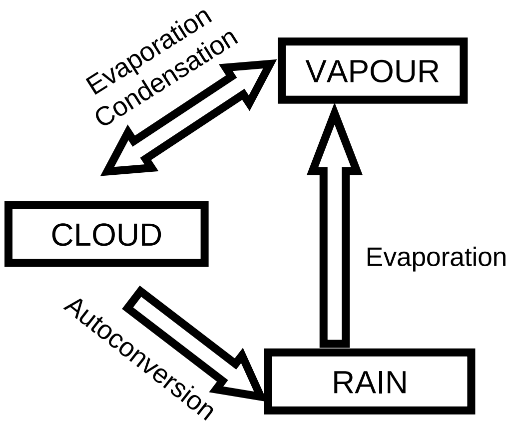
Complexity vs. Efficiency



Complexity vs. Efficiency



Complexity vs. Efficiency



Categorising particle types

- Warm phase microphysics
  - Water vapour / Cloud liquid water drops / Rain drops
  - Clear split between water drops and rain
  - Prognostic vs diagnostic

Rain droplet spectrum

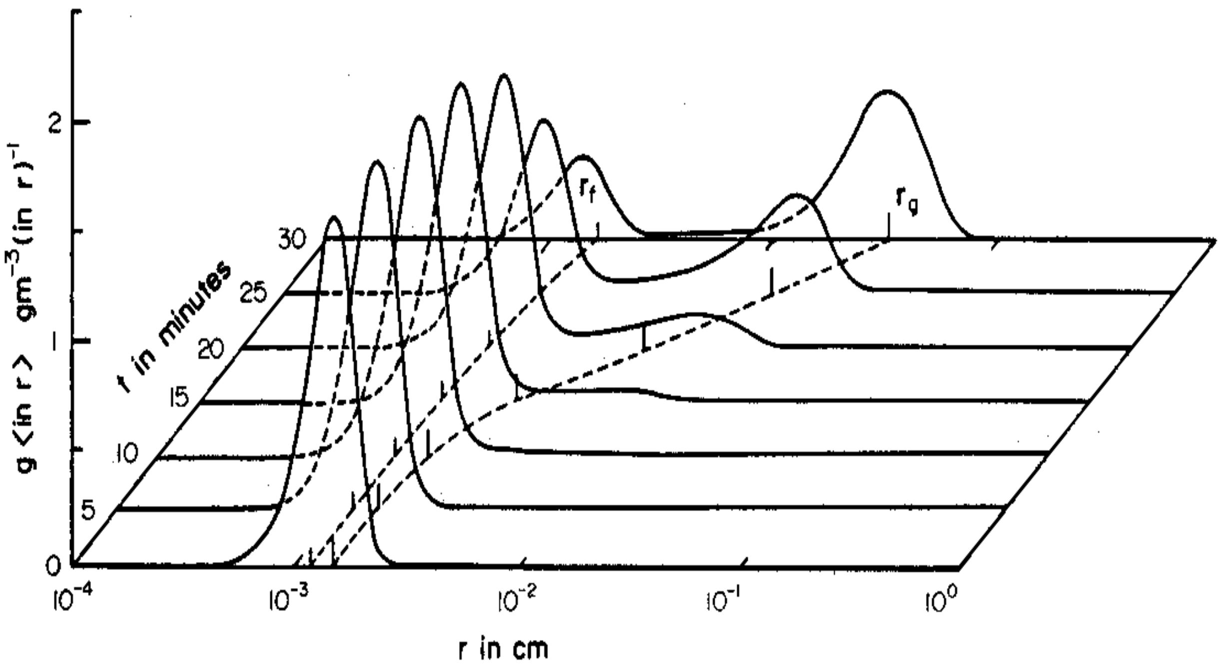


FIG. 8.10. Example of the development of a droplet spectrum by stochastic coalescence. (From Berry and Reinhardt, 1974b.)

Categorising Particle Types

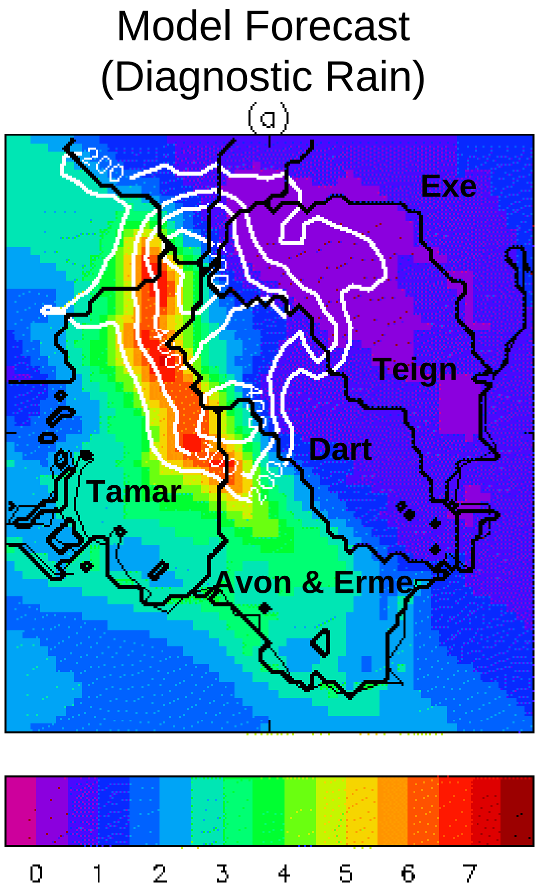
What determines the number of prognostic variables ?

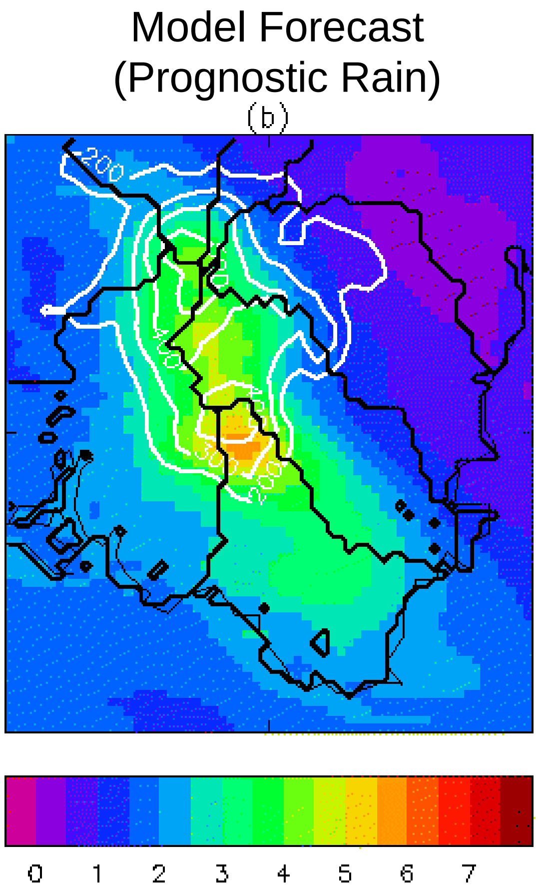
Particle	Fall Speed	Height Scale	Time Scale	Horizontal Scale
Cloud drop 10 μm	0.01 ms^{-1}	5 km	few days	1000+ km
Raindrop 5 mm	10 ms^{-1}	1 km	1 minute	1 km

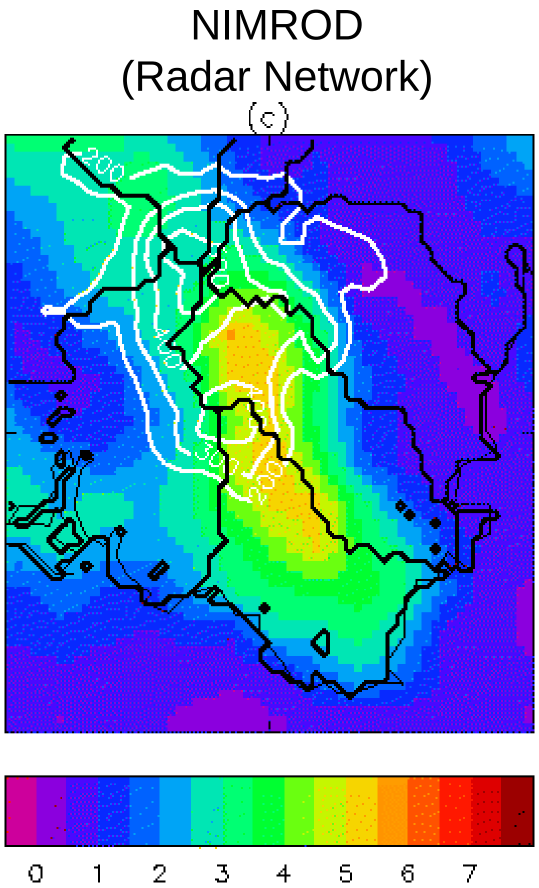
Categorising Particle Types

Prognostic vs. diagnostic rain

Model (MetUM, 2km grid res.) Case Study of Dartmoor River Catchment Rainfall (9 Hour Accumulations)







Categorising particle types

- Warm phase microphysics
  - Water vapour / Cloud liquid water drops / Rain drops
  - Prognostic vs diagnostic

- Ice phase microphysics
  - Ice crystals / snow aggregates / graupel / hail
  - Prognostic vs. diagnostic
  - No clear split between ice and snow
  - No clear split between ice/snow and graupel

Categorising particle types
Differences between warm and ice phase microphysics

- Reversible transformation between liquid and ice is accompanied by a significant latent heat release (10% of the cond/evap).

- Terminal fall speed of ice hydrometeors significantly less (lower density) - longer time scale for the life cycle of e.g. convection, due to longer residence time and modified redistribution of precipitation (not all falling in same column)

- Optical properties are different (important for radiation).

Categorising Particle Types

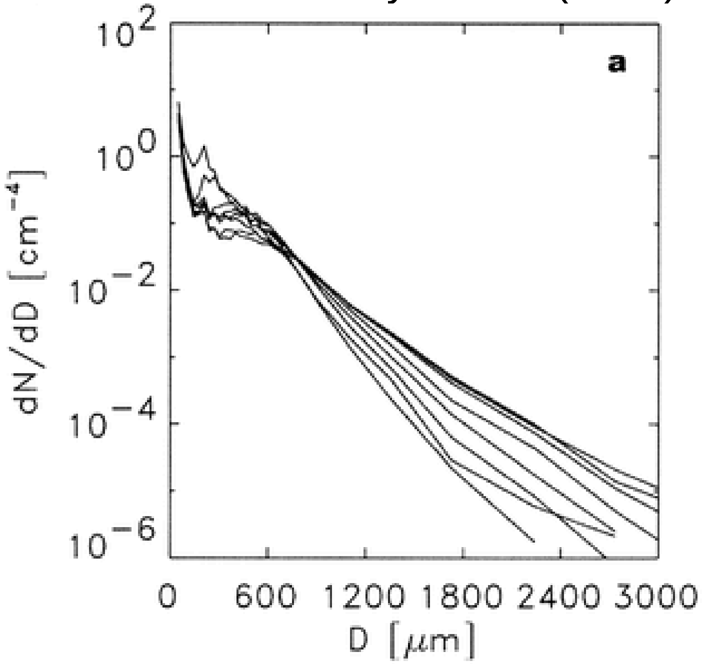
What determines the number of prognostic variables ?

Particle	Fall Speed	Height Scale	Time Scale	Horizontal Scale
Cloud drop 10 μm	0.01 ms^{-1}	5 km	few days	1000+ km
Ice crystal 100 μm	0.1 ms^{-1}	5 km	1 day	100-1000 km
Ice aggregate 5 mm	1 ms^{-1}	5 km	1 hour	10-100 km
Raindrop 5 mm	10 ms^{-1}	1 km	1 minute	1 km

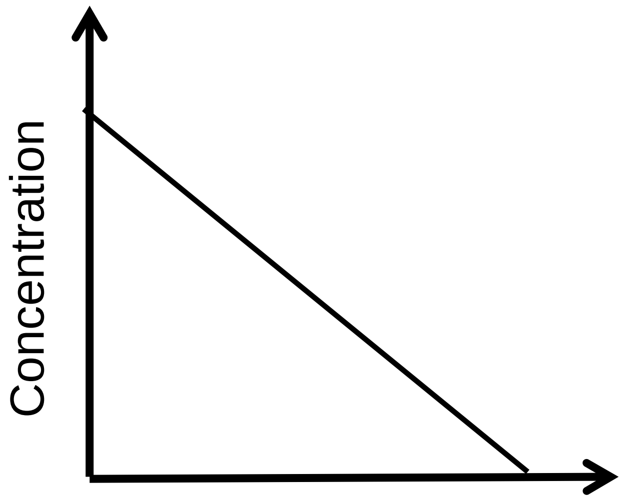
Categorising Particle Types

Ice particle size distributions

Observed PSDs from
Field and Heymsfield (2003)



Often approximated by an exponential
or gamma function



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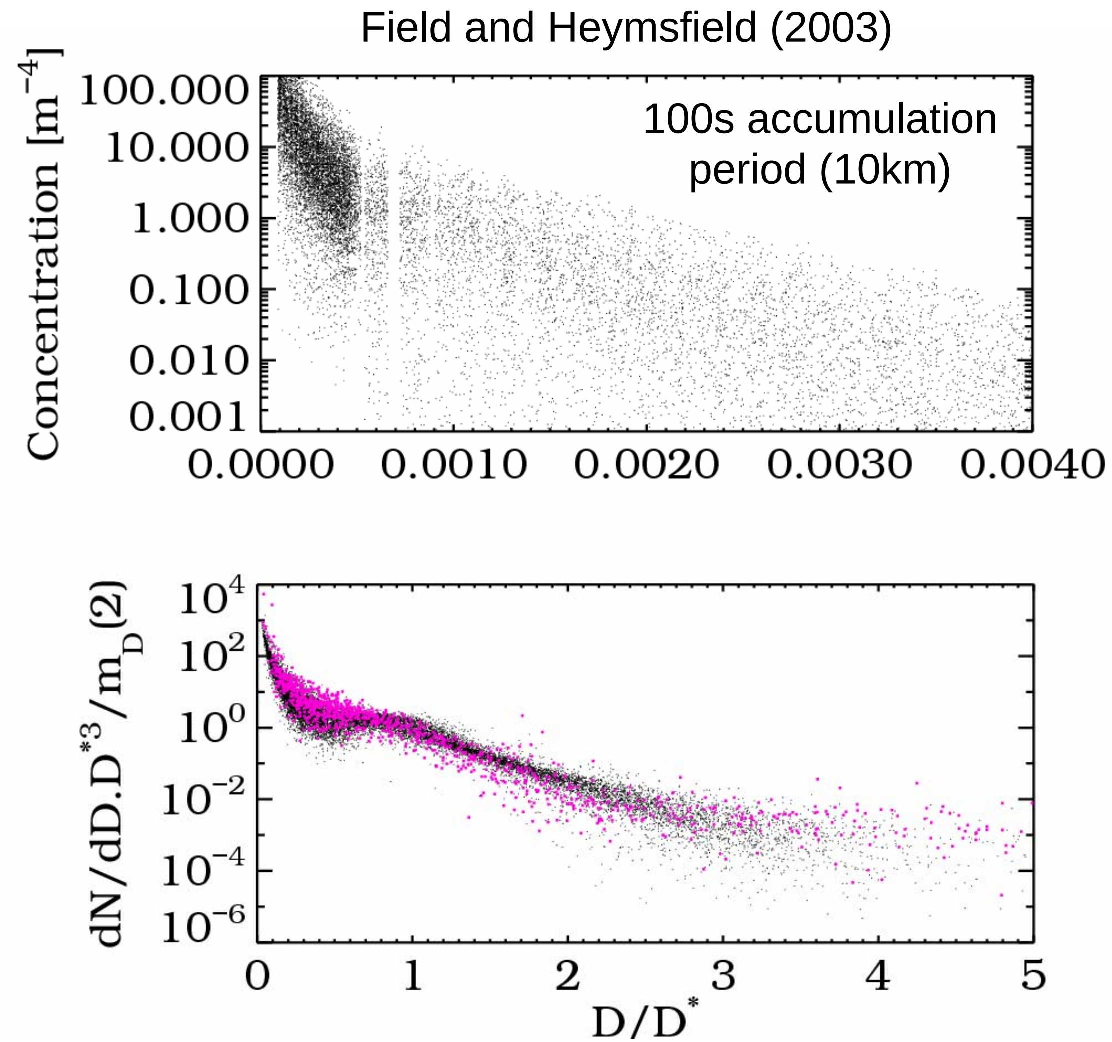
Categorising Particle Types

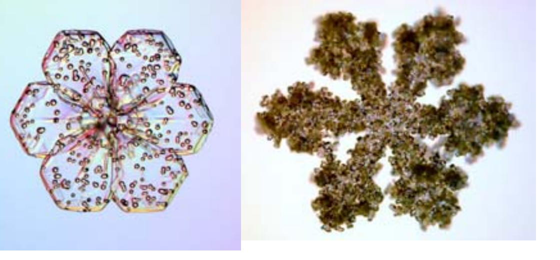
Ice particle size distributions



- Size spectrum has no clear break (like cloud drops/rain)
- Aggregation results in size and mass distributions that are scalable.
- Require only 2 variables to describe distribution.
- Characteristic size or mass and IWC, for example.

Categorising Particle Types
Representing rimed particles (graupel)

- Traditional split between ice, snow and graupel (rimed ice) but this split is rather artificial.
- Degree of riming can be light or heavy.



- Alternative approach:
  - Morrison and Grabowski (2008) have three ice phase prognostics: ice number concentration, mixing ratio from deposition, mixing ratio from riming.
  - Avoids artificial thresholds between different categories.

Microphysical processes

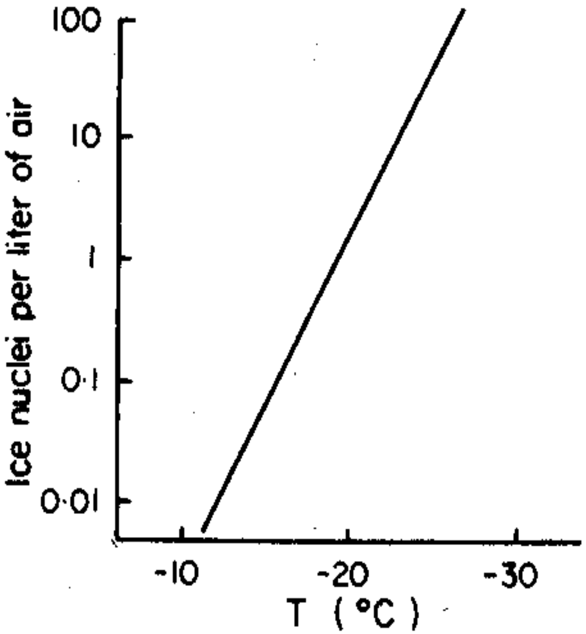
- Depends on the number of particle categories and representation of the particle size distributions (bin, double moment, single moment)
  - Formation of clouds
  - Release of precipitation
  - Evaporation of both clouds and precipitation

$$\frac{\partial q_l}{\partial t} = A(q_l) + S(q_l) - D(q_l)$$

- Therefore we need to describe
  - the change of phase from water vapour to water droplets and ice crystals (nucleation, condensation, diffusion)
  - the transformation of small cloud droplets/ice crystals to larger rain drops/ice particles (collection)
  - the advection and sedimentation of these species
  - the evaporation/sublimation of cloud and precipitation size particles

Microphysical Processes
Ice Nucleation parametrization

- Water drop nucleation: Assume no supersaturation with respect to water.
- Homogeneous ice nucleation: Models generally assume all water drops freeze at temperatures colder than around -40°C.
- Heterogeneous nucleation: Complex processes highly simplified in GCMs, nucleation dependent on temperature/RH dependent (Fletcher, 1962; Meyers et al. 1992).
- Note: In “diagnostic mixed phase” schemes (e.g. Tiedtke 1993), no need for an ice nucleation parametrization.



Fletcher (1962)

Microphysical Processes
Ice deposition/sublimation

- Assumption of no grid box supersaturation (Tiedtke, 1993)
- Assumption of no in-cloud supersaturation (Tompkins et al., 2007)
- In-cloud supersaturation allowed and solve diffusional growth equation

Evaporation rate for a particle of diameter D

$$S(D) = \frac{4\pi C s F}{\left(\frac{L_s}{RT} - 1\right)\frac{L_s}{k_a T} + \frac{RT}{X e_{si}}}$$

Evaporation rate for a spectrum of particle sizes

$$\overline{S} = \int_{D=0}^{\infty} S(D) N(D) dD$$

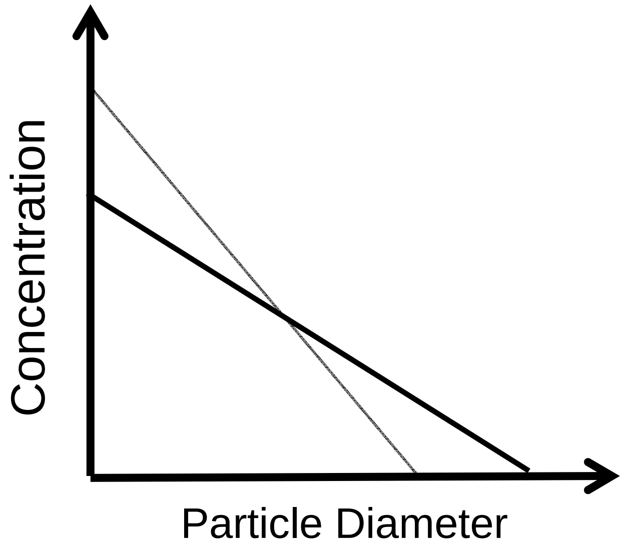
Microphysical Processes
Parameterizing Ice Aggregation

- Not relevant if no assumption of particle size distribution (e.g. Tiedtke, 1993)

- Ice to snow category

- Diagnostic function of temperature, (e.g. Wilson and Ballard, 1999)

- Double moment schemes – increase number of particles, without changing ice water content.



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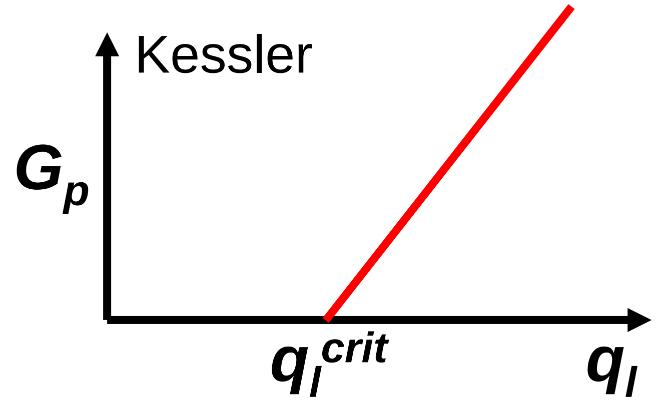
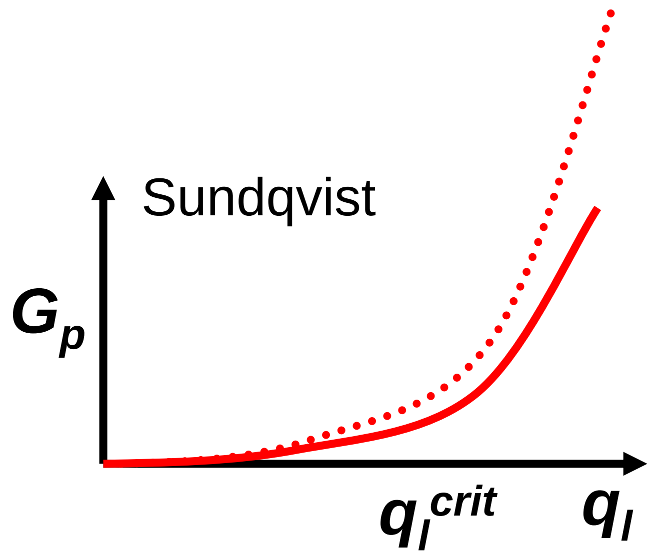
Microphysical Parametrization
"Autoconversion" of cloud drops to raindrops

- Linear function of ql (Kessler, 1969)
- Function of ql with additional term to avoid singular threshold and non-local precipitation term (Sundqvist 1978)
- Seifert and Beheng (2001), a double-moment parameterization derived directly from the stochastic collection equation.





Microphysics Parametrization
Uncertainty and Sensitivity

- **Uncertainty (particularly for the ice/mixed phase)**
  - in our knowledge of the real system e.g. the evaporation rate of ice aggregates
  - in the parametrization process, e.g. representing the spectrum of particles
  - in the numerical discretization

- **Example: Ice Deposition/Evaporation Rate/Terminal Fall Speed**
  - Could vary by a factor of two

Evaporation rate for a particle of diameter D

$$S(D) = \frac{4\pi CsF}{\left(\frac{L_s}{RT} - 1\right)\frac{L_s}{k_a T} + \frac{RT}{X e_{si}}}$$

Integration over the particle size spectrum

$$\overline{S} = \int_{D=0}^{\infty} S(D)N(D)dD$$

Fall Speed for a particle of diameter D

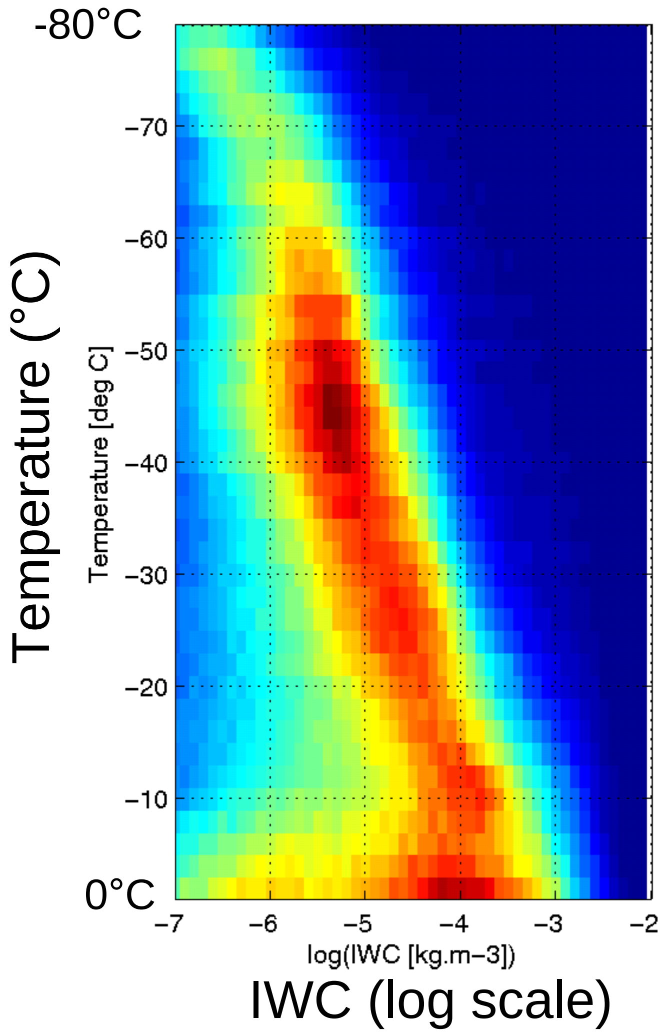
$$v_t(D) = cD^d$$

$$\overline{v_t} = \frac{\int_{D=0}^{\infty} v_t(D)m(D)N(D)dD}{\int_{D=0}^{\infty} m(D)N(D)dD}$$

Frequency diagrams IWC vs. T

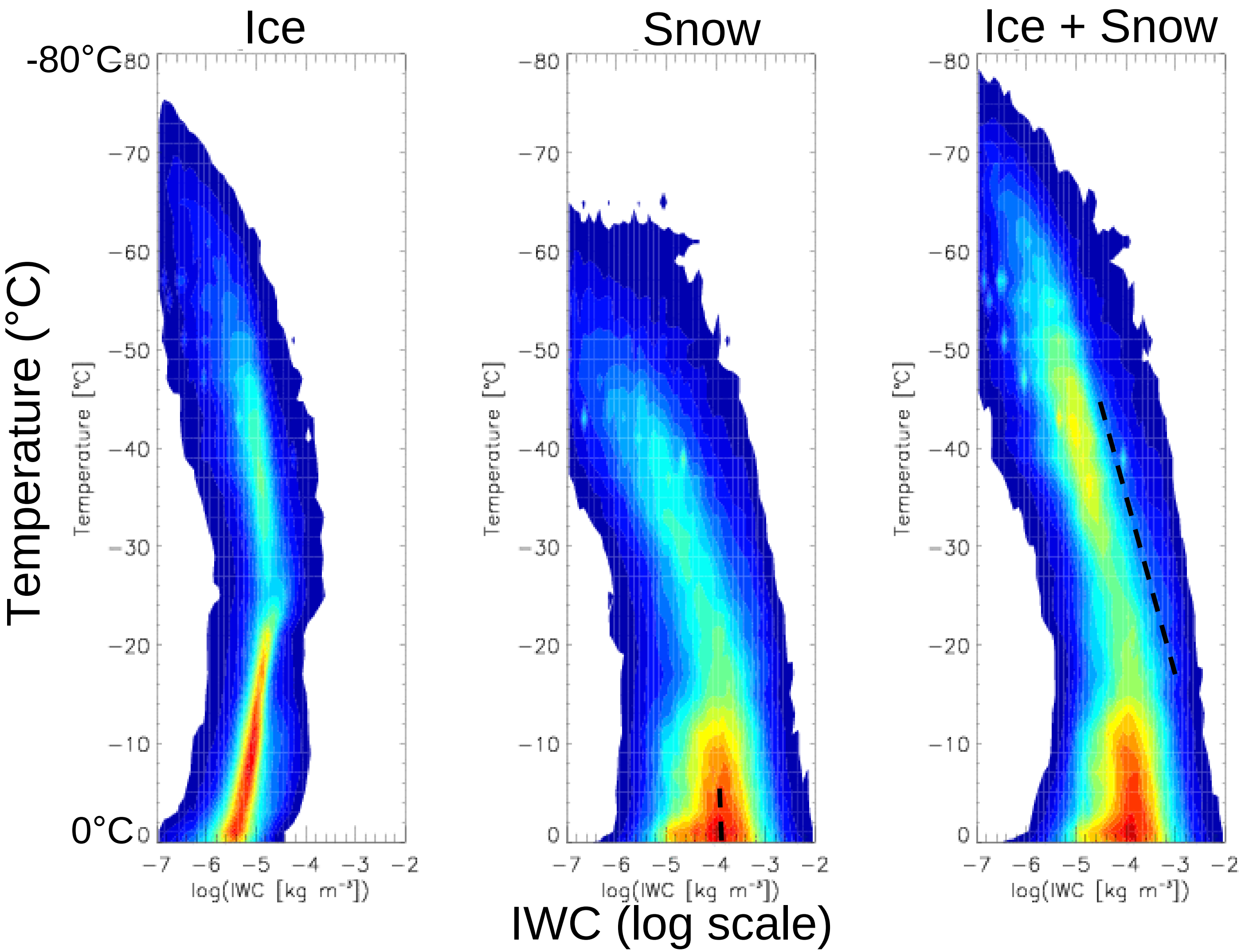
CloudSat/Calipso retrieved IWC
From Julien Delanoe (Reading Univ.)

- Data averaged along the satellite track on the ECMWF grid for three weeks in July 2006.
- IWC retrieval method as described in Delanoe and Hogan (2008)
- Following plots from the model are from a reduced period.



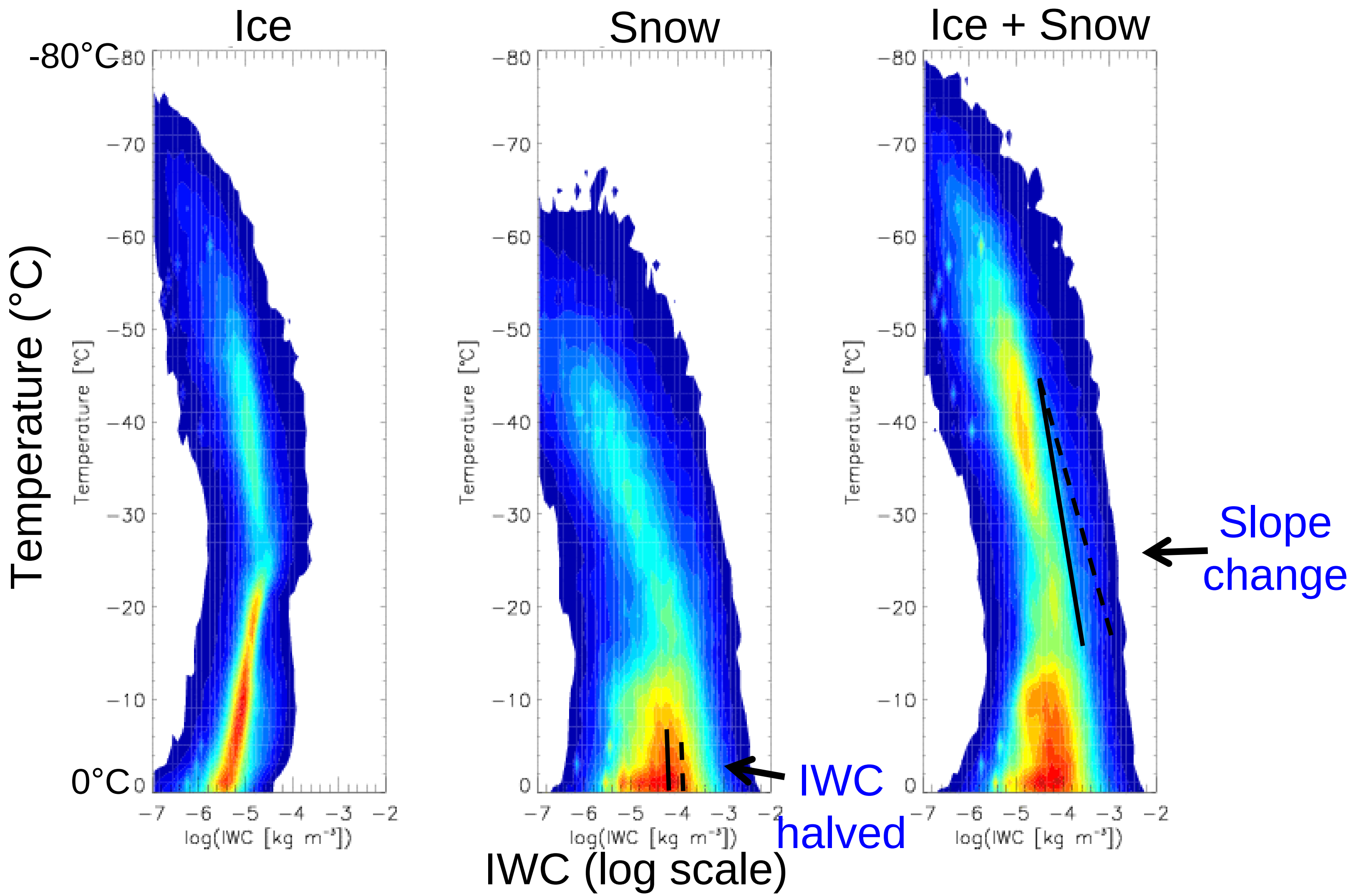
ECMWF

Frequency diagrams IWC vs. T
ECMWF model “Control”



Frequency diagrams IWC vs. T

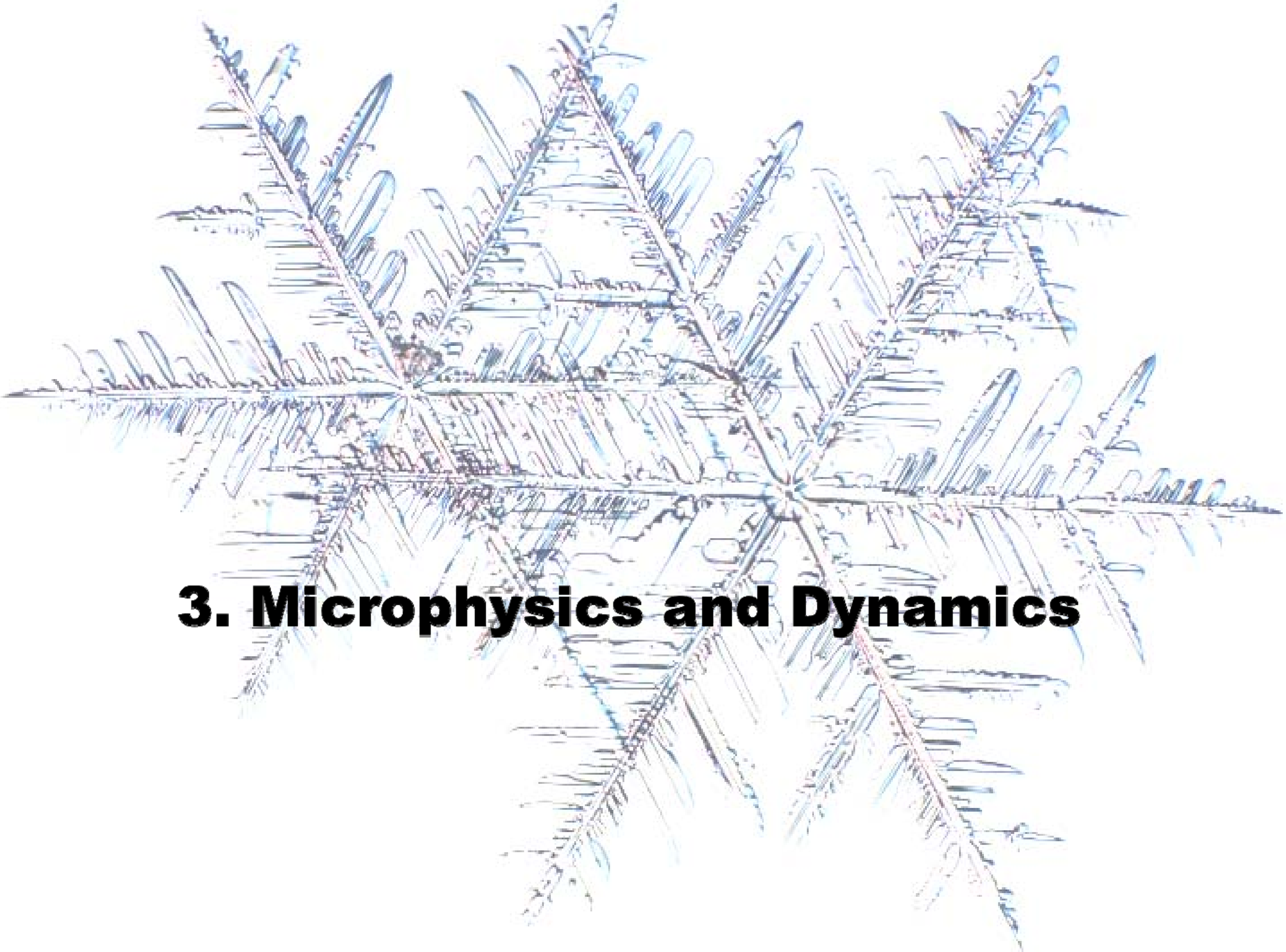
ECMWF model "Sensitivity Expt"
Deposition Rate x1.5, Snow Fallspeed x2



ECMWF

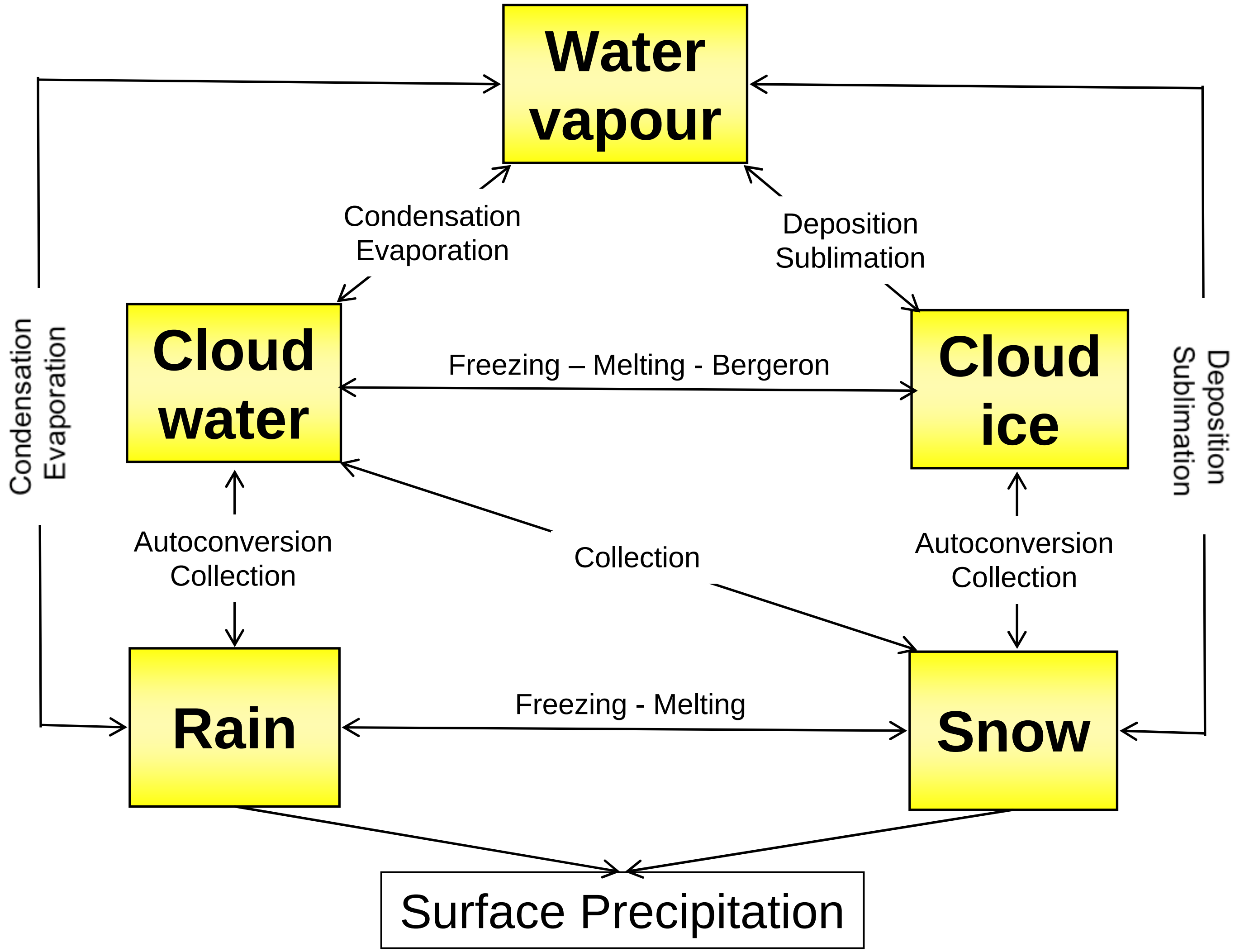
Summary 2: Simplicity and Approximation

- Accuracy vs. complexity vs. efficiency
  - appropriate for the application
  - no more complexity than can be constrained and understood
- Traceability
  - to observations (and more complex models)
  - an approximation of reality
- Quantifying uncertainty
  - and model sensitivity to this uncertainty
- Understanding impacts and feedbacks
  - dynamical, radiative, hydrological
- Appropriate numerical formulation



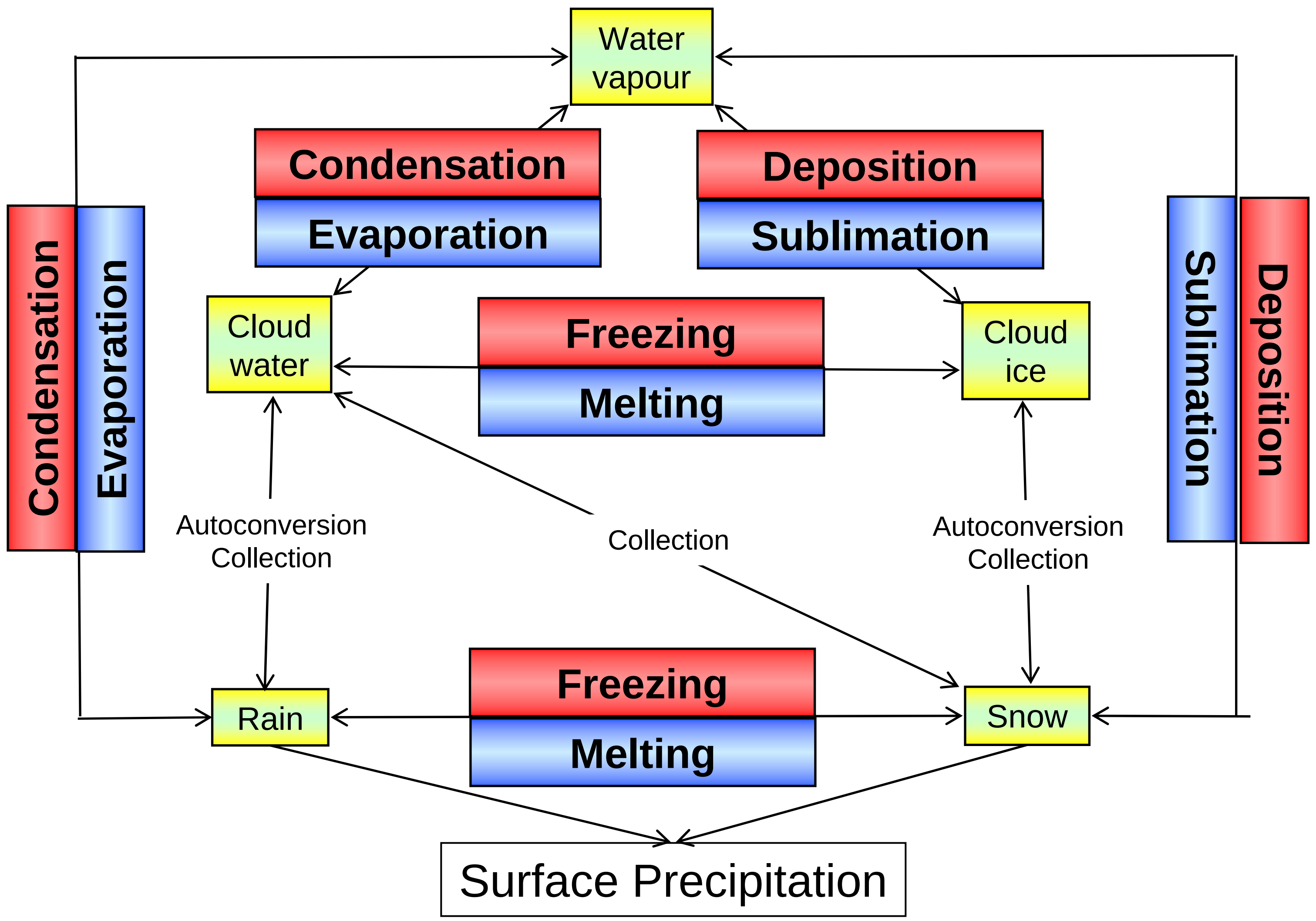
3. Microphysics and Dynamics

Microphysics Parametrization:
The “category” view



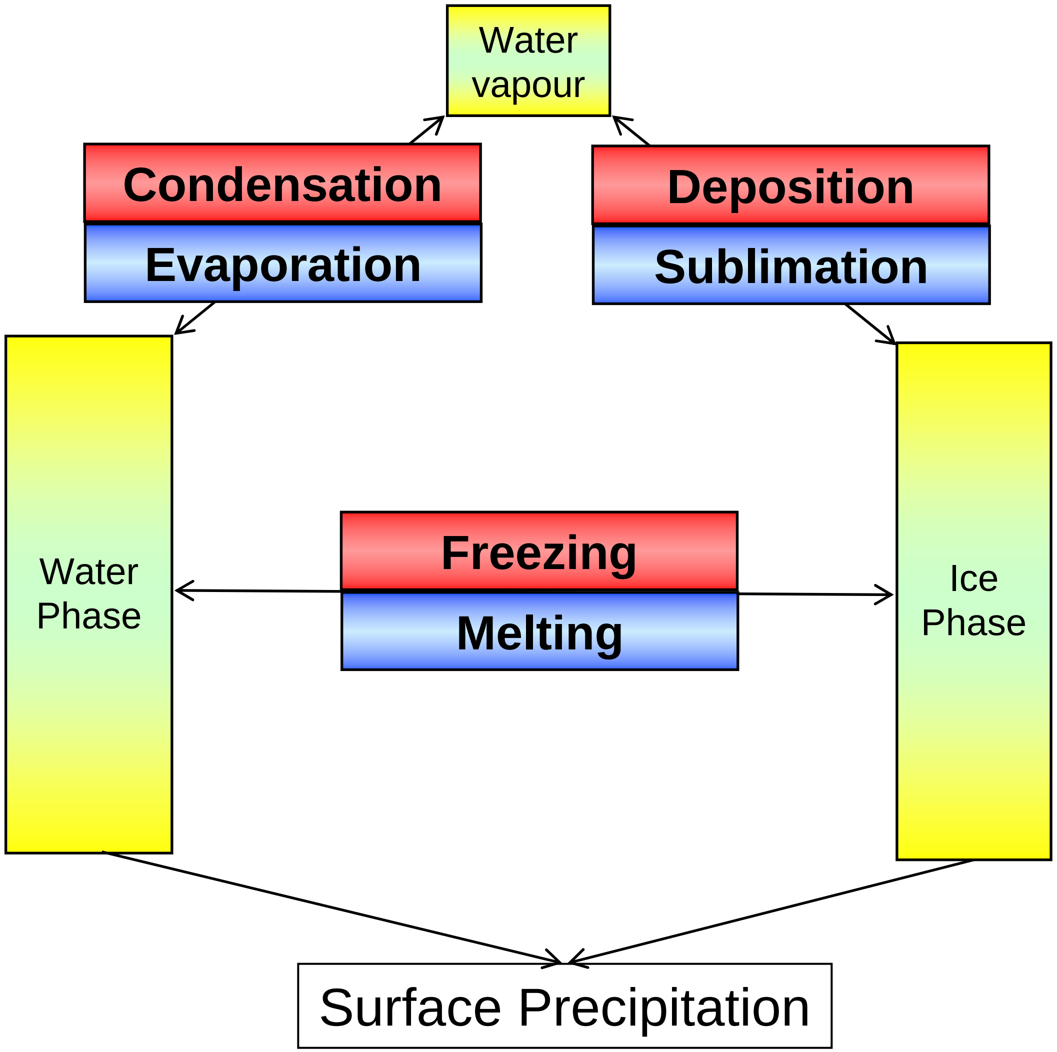
ECMWF

Microphysics Parametrization:
The “diabatic process” view

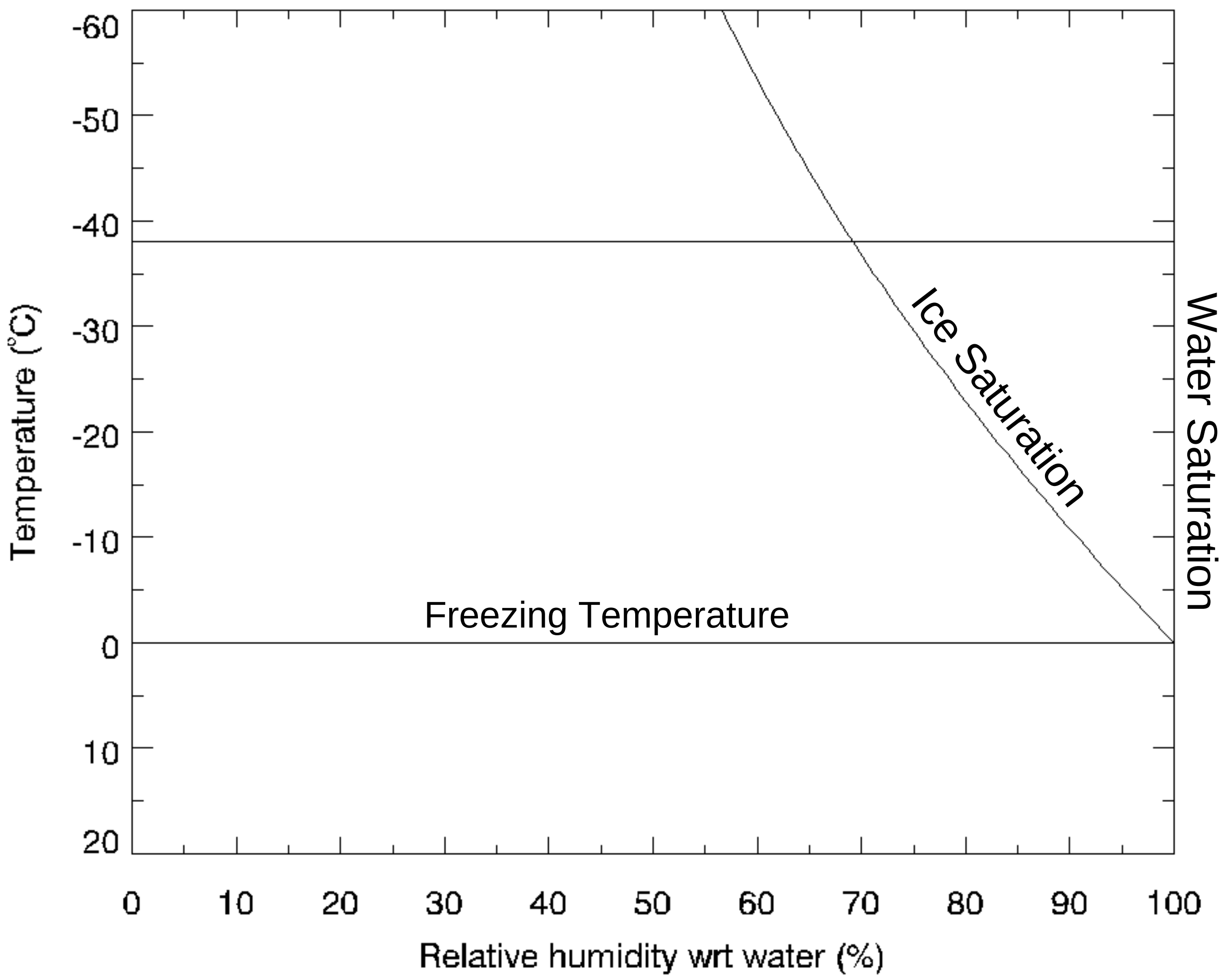


ECMWF

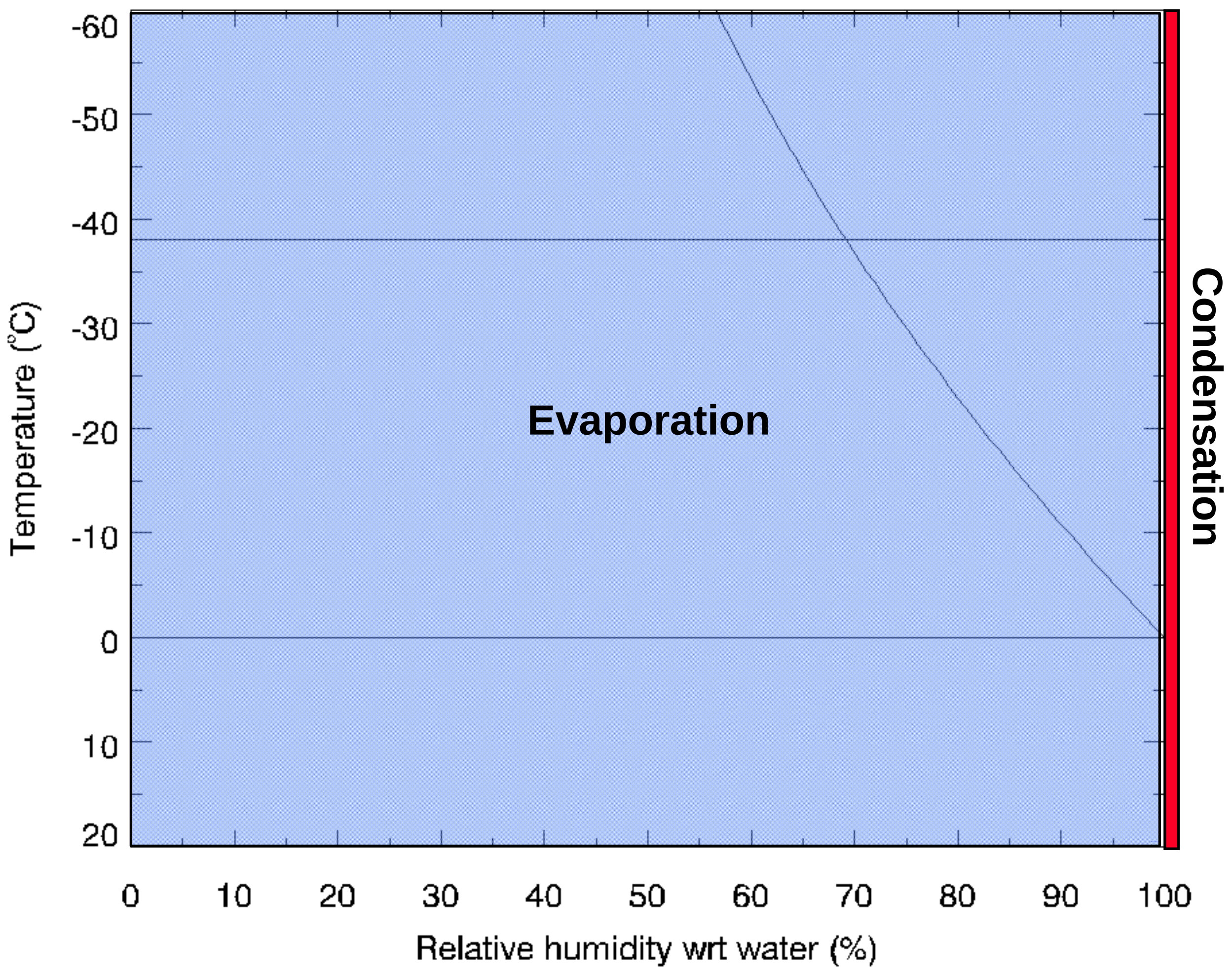
Microphysics Parametrization:
The "diabatic process" view



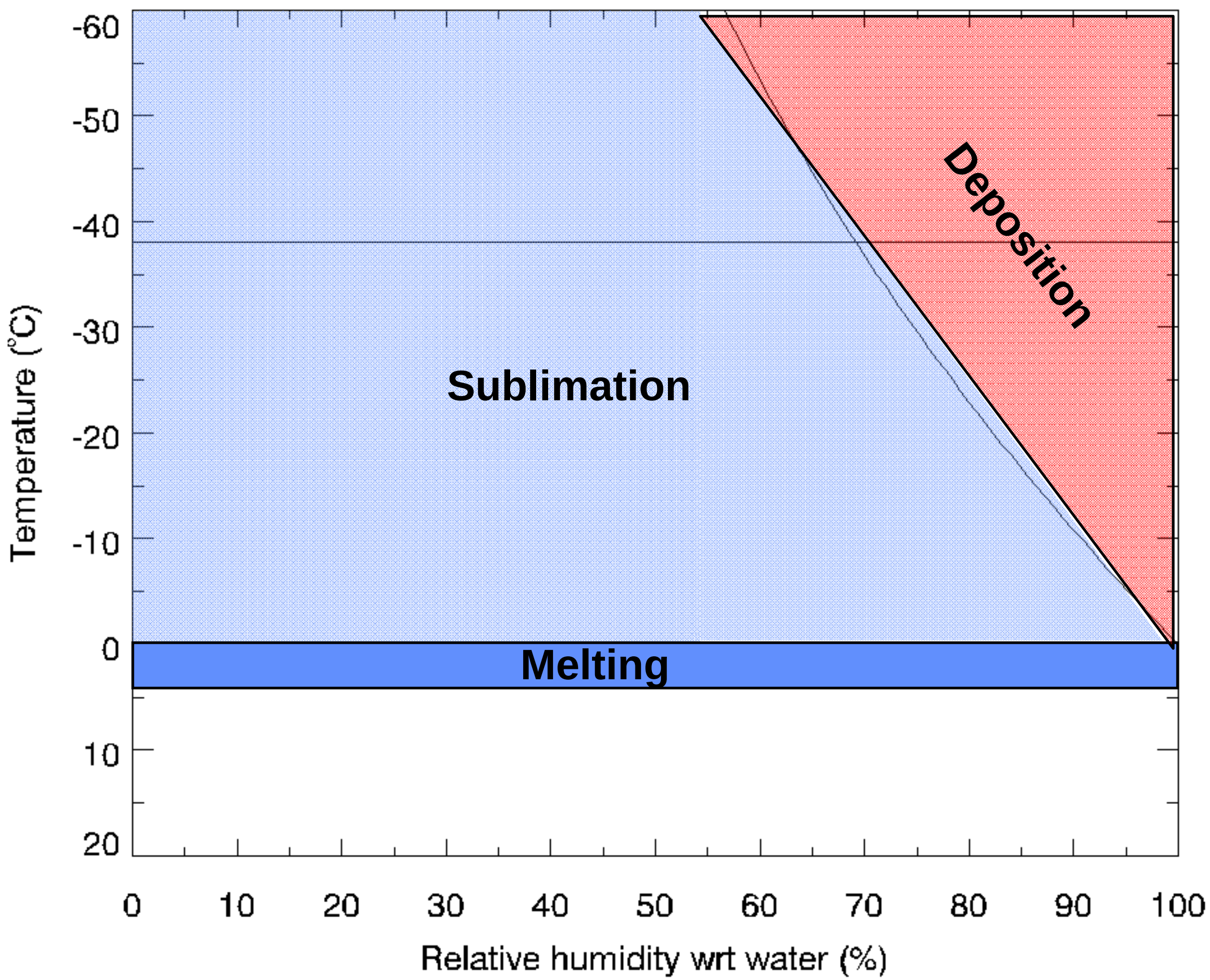
Microphysics Parametrization:
The “diabatic process” T-RH view



Microphysics Parametrization:
The “diabatic process” T-RH view: Warm phase

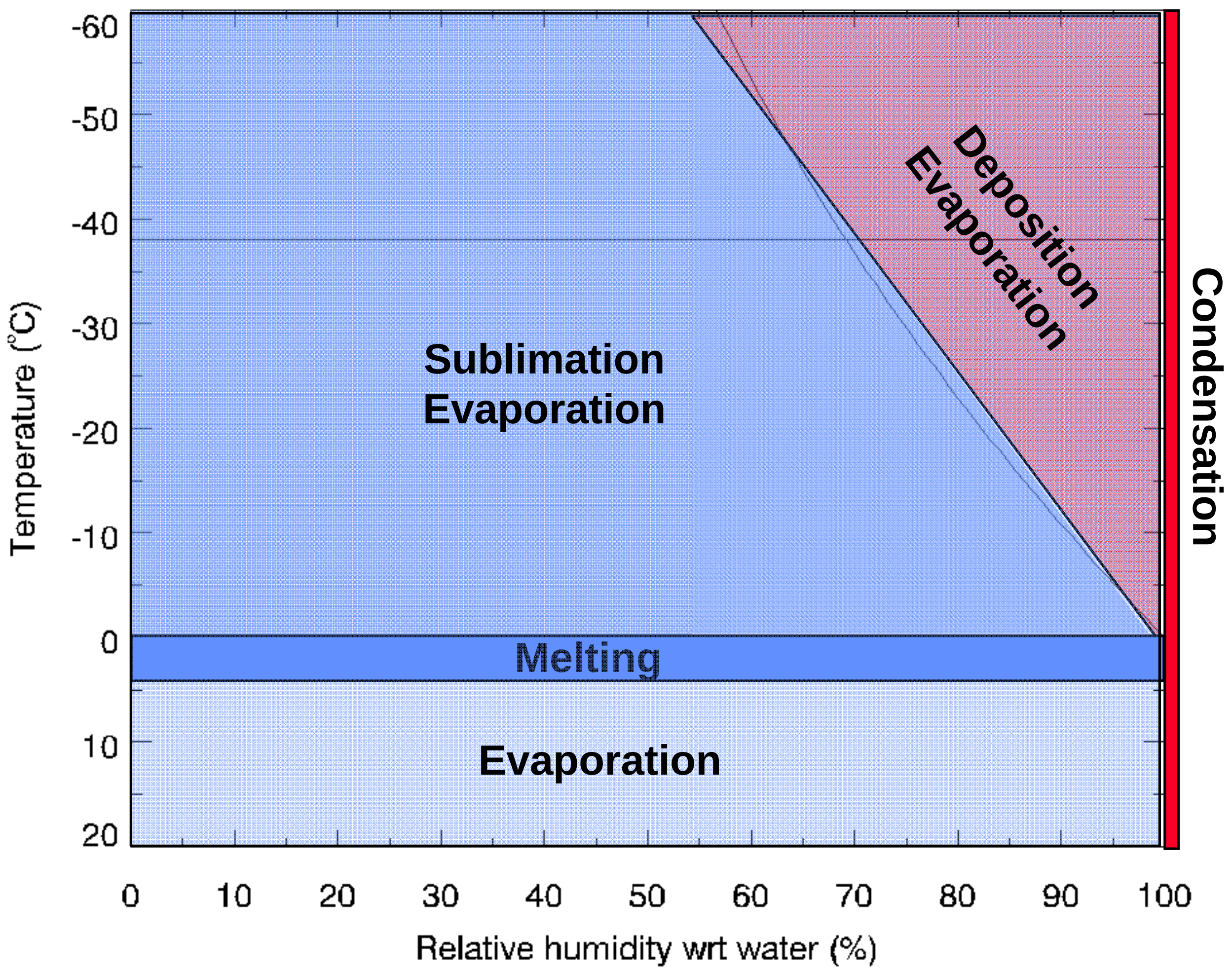


Microphysics Parametrization:
The “diabatic process” T-RH view: Ice phase



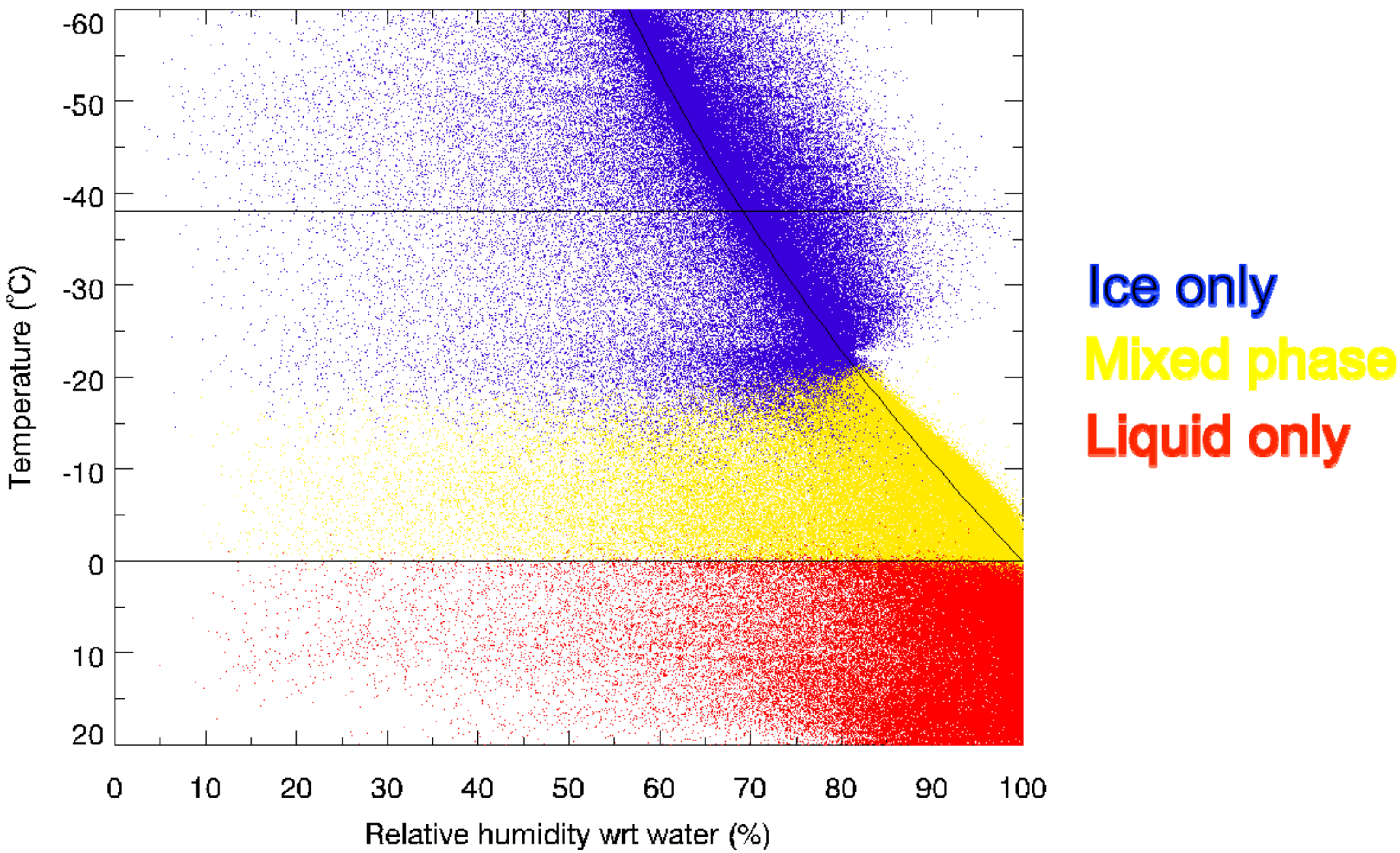
ECMWF

Microphysics Parametrization:
The "diabatic process" T-RH view

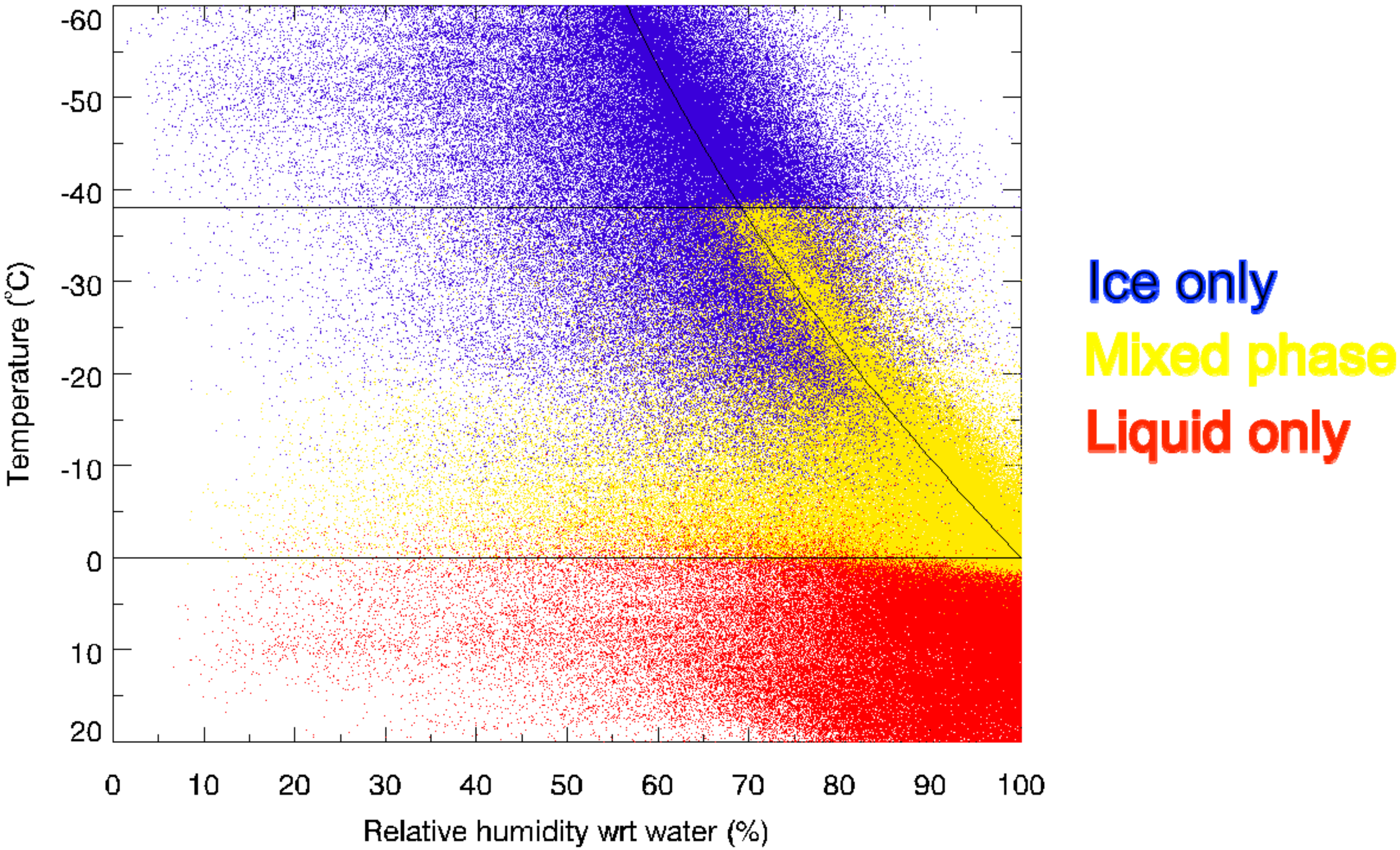


ECMWF Model Cloudy Points

Standard 2-prognostic microphysics scheme



ECMWF Model Cloudy Points
New 5-prognostic microphysics scheme



ECMWF

Latent Heating/Cooling and Dynamics

- **Water condensation heating**: Enhanced ascent in convective storms, fronts and cyclones (e.g. Thorpe and Emanuel 1985, Mallet et al. 1999).
- **Ice deposition heating**: Additional 10% heating gives further kick to ascent (e.g. Liu and Moncrieff 1997, Gao et al 2006).
- **Rain evaporative cooling**: Enhanced descent in convective storms and fronts (e.g. Huang and Emanuel 1991). Most significant in tropical convection (high 0°C level).
- **Ice evaporative cooling**: Enhanced descent. Lower fallspeeds and lower densities lead to evaporation in much shallower depths than rain. Significant impact on strong downdraughts in convection/fronts (e.g. Clough and Franks 1991, Tao et al 1995, Forbes and Clark 2003, Browning 2005).
- **Cooling due to melting**: Confined to a narrow layer just below 0°C in saturated or sub-saturated air. Can lead to decoupling across stable layer, instability, mesoscale circulations (e.g. Willis and Heymsfield 1989, Szeto et al 1988)

Microphysics and Frontal Dynamics
Cross-Section

Schematic

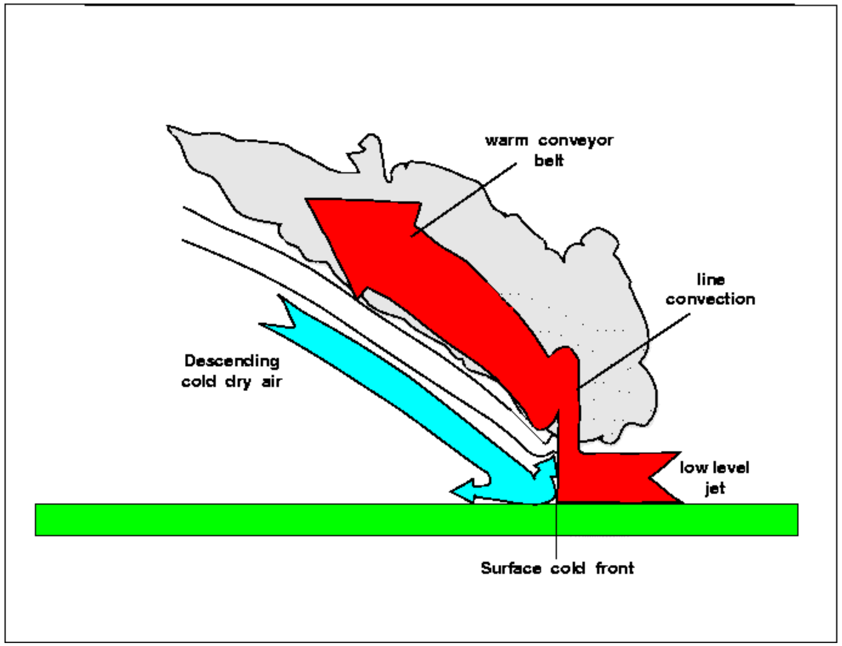


Image provided by A. Semple

Radar Obs

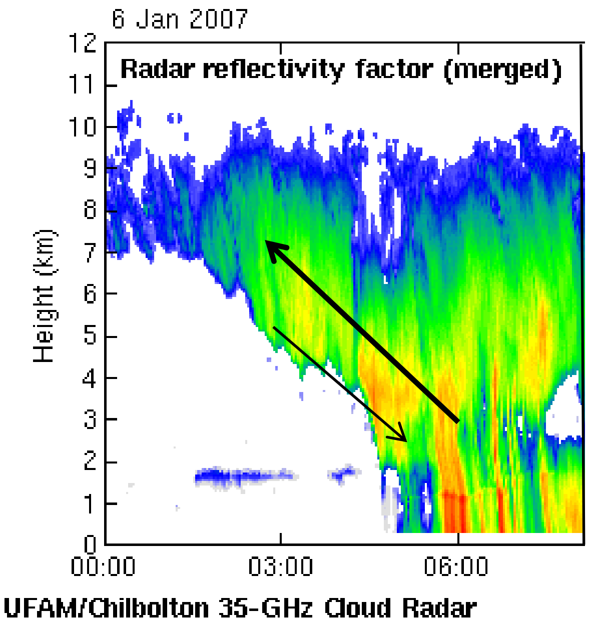
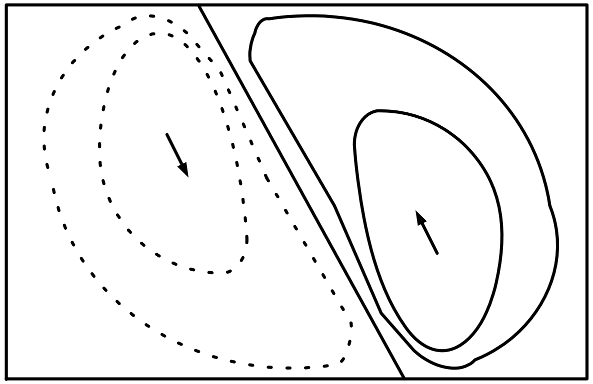


Image provided by RAL/RCRU

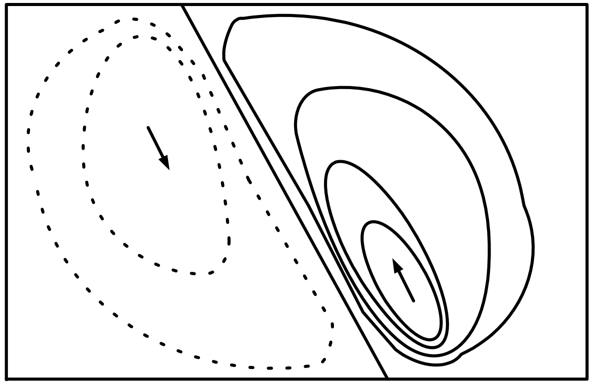
ECMWF

Microphysics and Frontal Dynamics

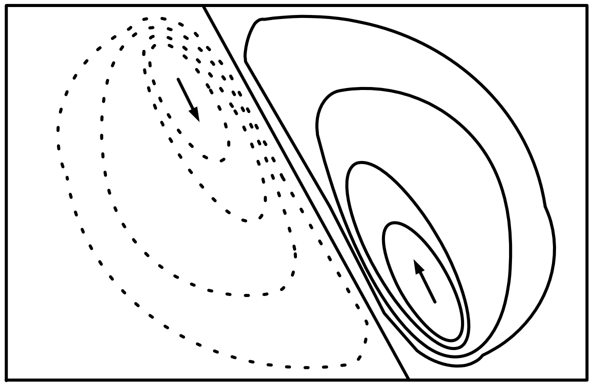
2D semi-geostrophic model cross section:
Impact of latent heating/cooling



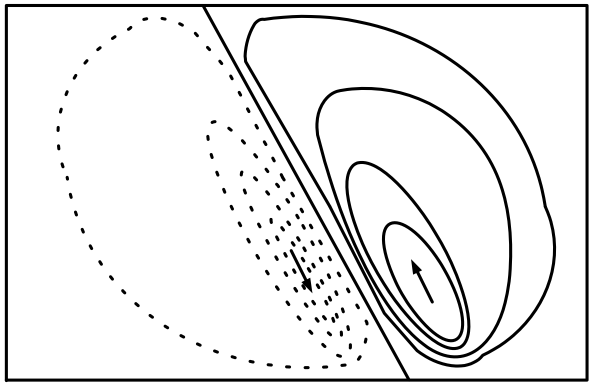
Dry Up Dry Down



Moist Up Dry Down



Moist Up Moist Down



Moist Up
Moist Down in Precipitation

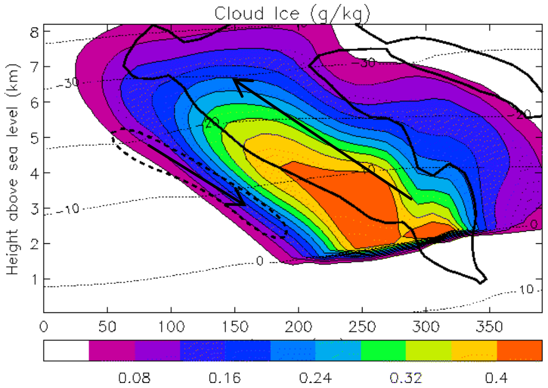
Parker and Thorpe (1995)

Microphysics and Frontal Dynamics

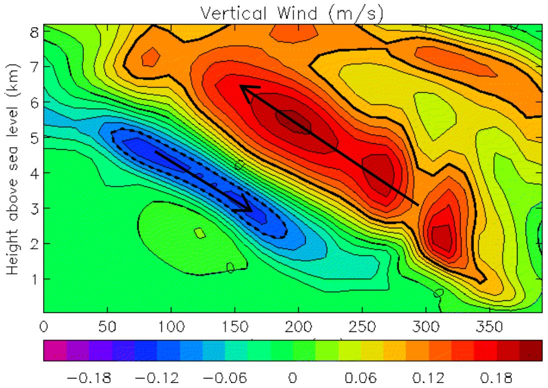
3D NWP model (UM) Idealised Front Cross Section

Reference forecast

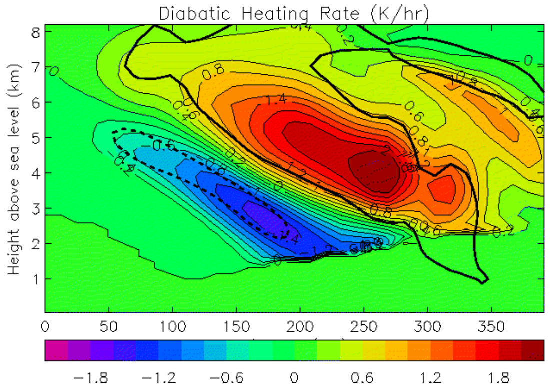
Cloud Ice (g/kg)



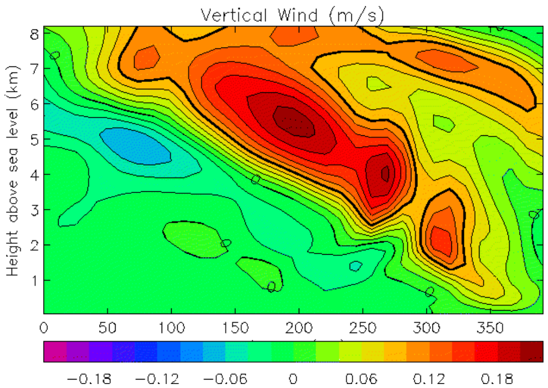
Vertical Wind (m/s)



Diabatic Heating Rate (K/hr)



Downdraught is significantly weaker when there is no ice evaporative cooling



Forbes (2002)

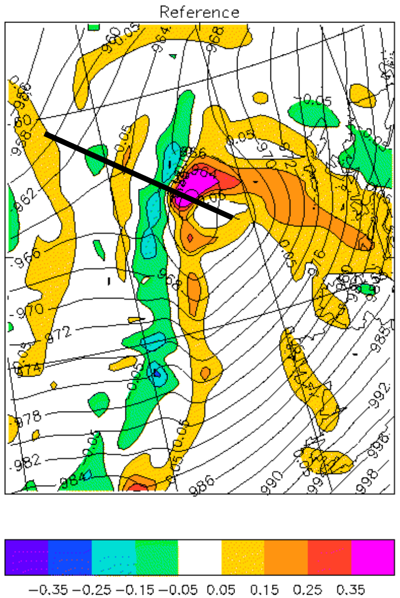
(Met Office)

ECMWF

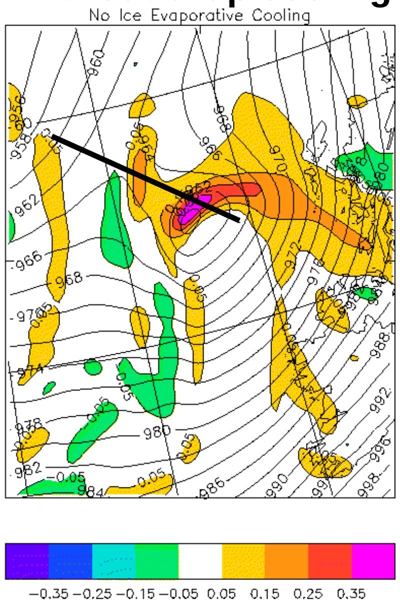
Microphysics and Frontal Dynamics

NWP model (UM) case study from FASTEX: Impact of ice evaporative cooling

Control

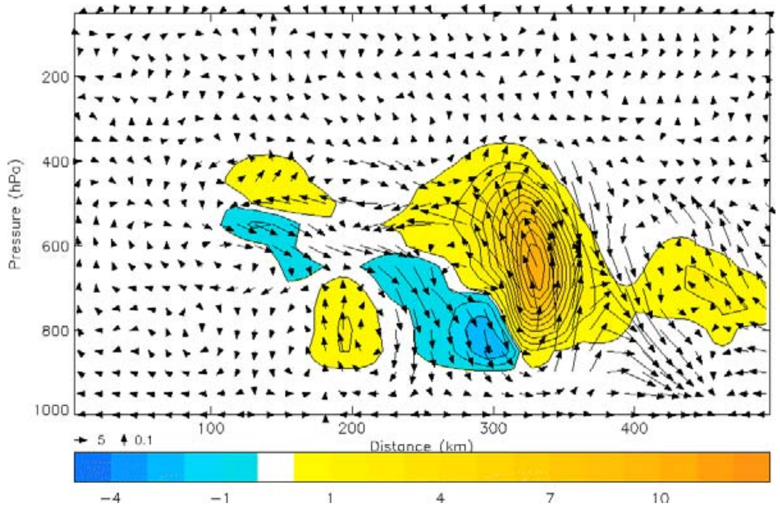


Without evap cooling



Plan view of vertical velocity at 800hPa with and without ice evaporative cooling

Cross section – difference in vertical velocity between the two simulations



Evaporative cooling leads to enhanced descent beneath the frontal cloud band **and** enhanced ascent in the frontal updraught

Forbes and Clark (2003)

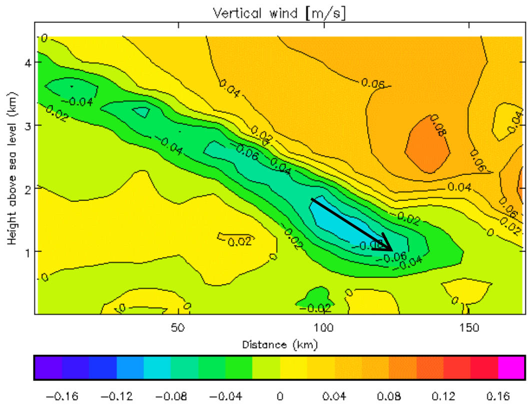
(Met Office)

Microphysics and Frontal Dynamics

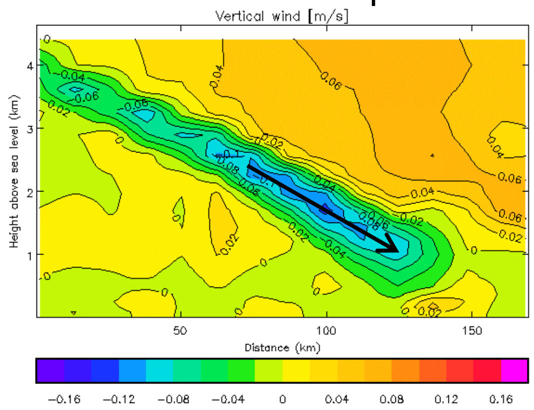
3D NWP model (UM) idealised front:
Impact of uncertainties in the ice evaporation rate

- Increasing the ice evaporation rate increases the strength of the downdraught beneath the frontal surface. Secondary front enhancement ?

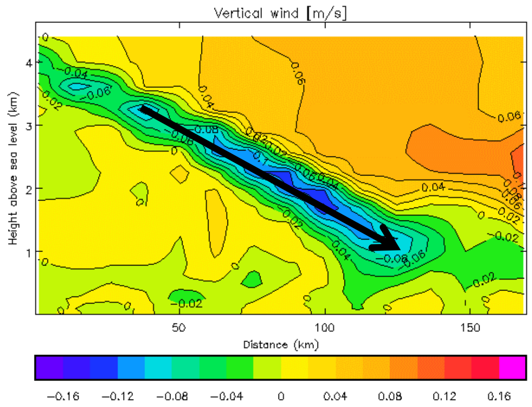
Vertical Wind Speed



0.5 x Evaporation rate



1 x Evaporation rate



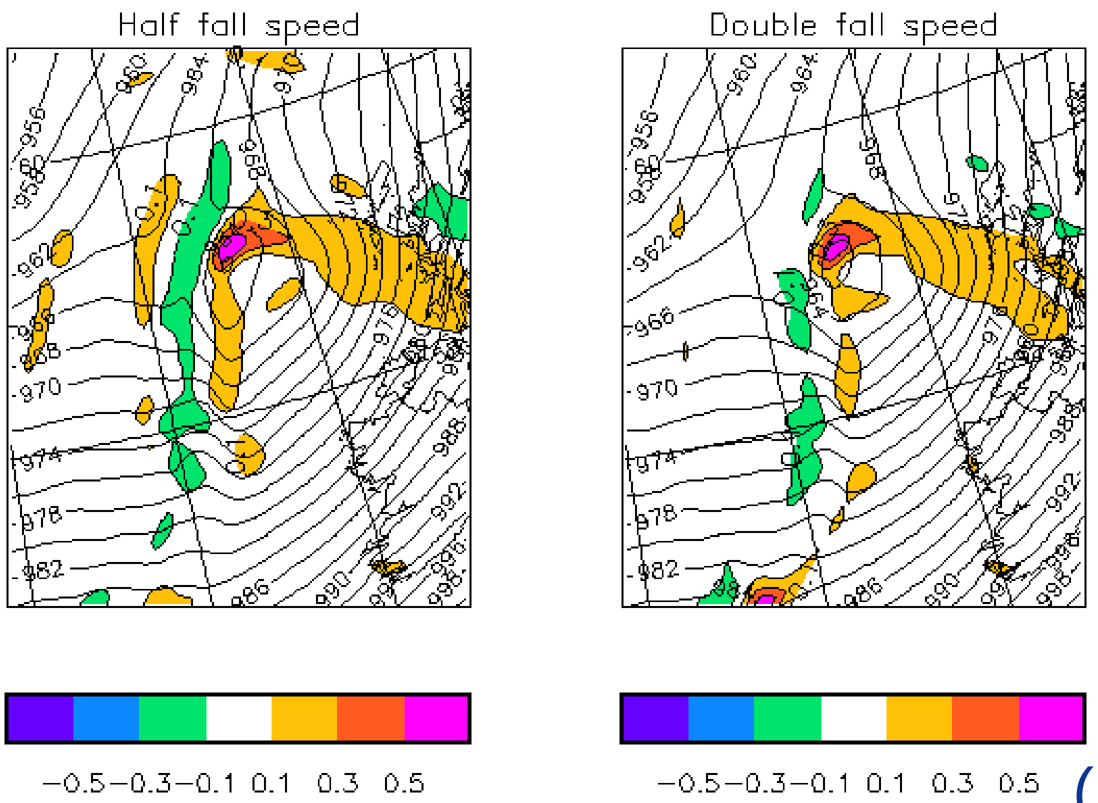
2 x Evaporation rate

(Met Office)

Microphysics and Frontal Dynamics

3D NWP model (UM) case study idealised front:
Impact of uncertainties in the ice fall speed

- **850hPa vertical velocity**
- **Increasing ice terminal fall speed <u>decreases</u> frontal development**



(Met Office)

Summary 3: Microphysics and Dynamics

1. **The details of the microphysics affect the dynamics.**

2. **There is uncertainty in the microphysical parametrization. What is the dynamical sensitivity of the model to this uncertainty ?**

3. **We should try and understand changes in the microphysics in terms of dynamical impacts, (i.e. changes in the latent heating/cooling profile).**

Conclusion
From intricacy to simplicity

- It is a challenge to understand and simplify a complex system of interactions over 9 orders of magnitude !

- But parametrizations are successful !

- We can and will do better and should strive to refine cloud and precipitation microphysics parametrizations keeping in mind:

    - accuracy vs. appropriate complexity vs. computational efficiency

    - traceability to observations and across an hierarchy of models.

- We should quantify uncertainty and model sensitivity to this uncertainty and understand the impacts of microphysics on the model system as a whole (dynamical, radiative, hydrological).

Future Issues
for model parametrization

- Many microphysical issues, from drizzle processes to ice crystal aggregation.
- Small scale dynamics drives the microphysics, yet this is not represented or is represented in a crude way in large scale models. Can we do better – improved sub-grid heterogeneity, linking to pdfs of vertical velocity ???
- Interaction of aerosols and microphysics (particularly ice nucleation), climate interest in aerosol feedbacks.
- Data assimilation of remote sensing observations, dependent on microphysics representation for forward modelling of the observations.
- Unifying cloud microphysical assumptions across model parametrizations (cloud/convection/radiation)

THE END