Numerical Weather Prediction
Parametrization of sub-grid physical processes

Clouds (3)
The ECMWF Cloud Scheme

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The ECMWF Cloud Scheme

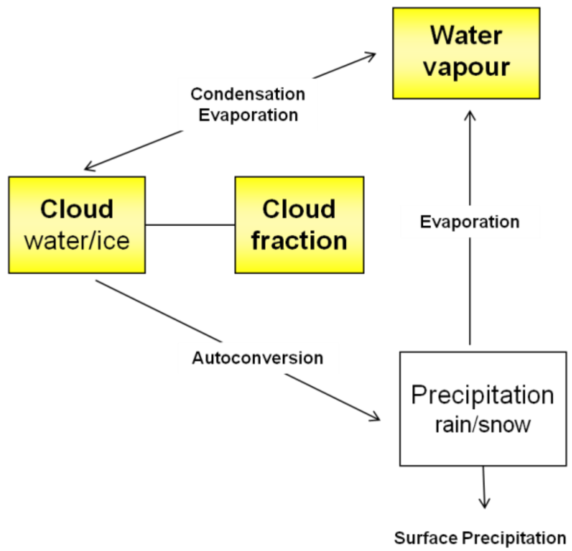
Outline

1. Basic approach
2. Sources and Sinks
   - Convective detrainment
   - Stratiform cloud formation and evaporation
   - Precipitation generation, melting and evaporation
   - Ice sedimentation
   - Ice supersaturation
3. Summary

ECMWF IFS Cloud Scheme Developments

Previous Cloud Scheme

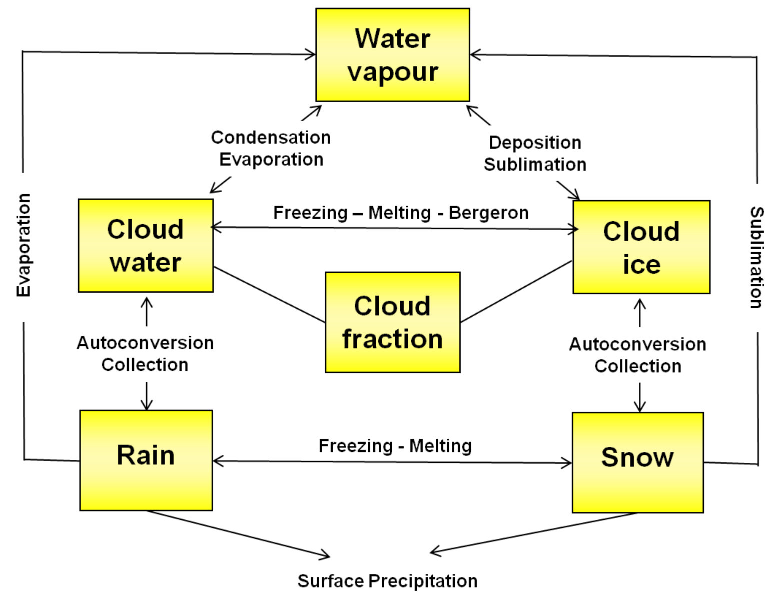
(operational until 08 Nov 2010)



- Based on Tiedtke (1993)
- Prognostic condensate (single moment) & cloud fraction
- Diagnostic liquid/ice split as a function of temperature between 0ºC and -23ºC
- Diagnostic representation of precipitation

Current Cloud Scheme

(operational from 09 Nov 2010)



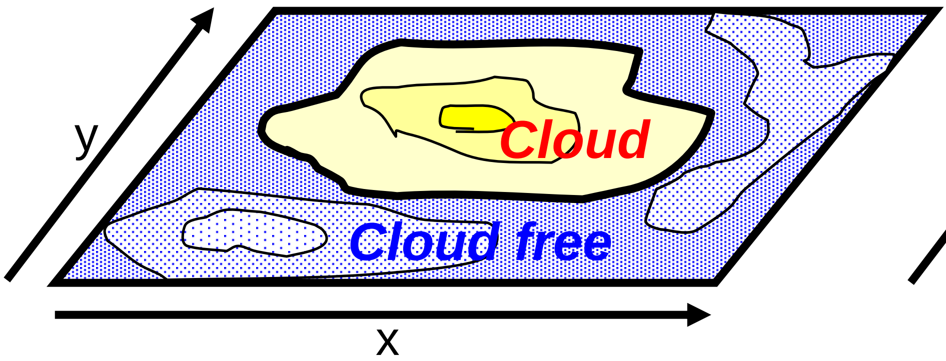
- Prognostic liquid & ice & cloud fraction
- Prognostic snow and rain (sediments/advects)
- Single moment microphysics (mass)
- New additional sources and sinks
- Existing sources and sink formulation retained (cond/evap/autoconv)

The ECMWF Cloud Scheme
Basic assumptions

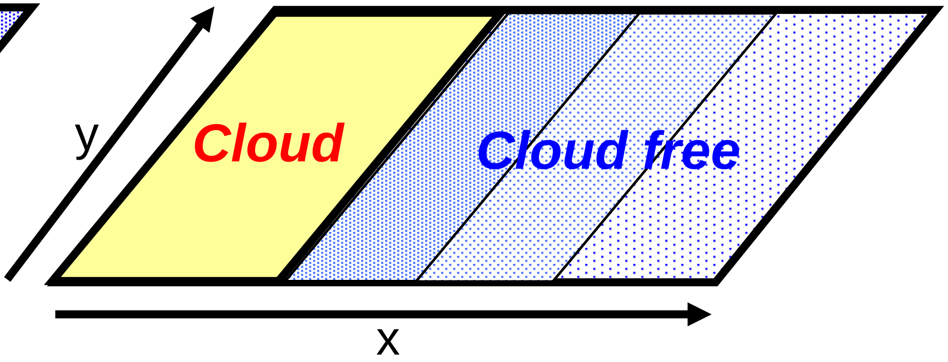
- Clouds fill the whole model layer in the vertical (fraction=cover).
- Clouds have the same thermal state as the environmental air (homogeneous T).
- Sub-grid variability represented with a cloud fraction prognostic variable and assumptions about the PDF of water vapour and cloud condensate (prognostic statistical cloud scheme).
- Considers the physical processes and derives source and sink terms for cloud fraction, ice and liquid cloud condensate and precipitating rain and snow.

The ECMWF Cloud Scheme
Representing sub-grid heterogeneity

In the real world



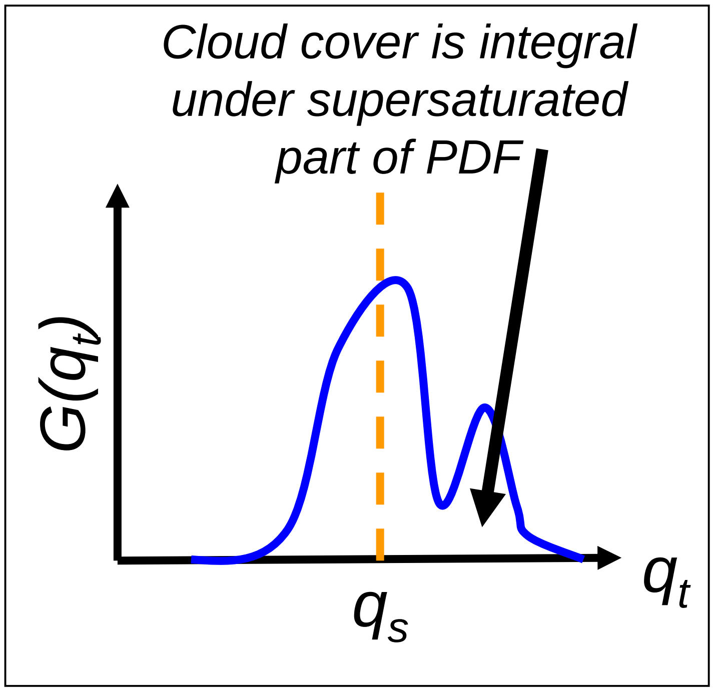
ECMWF cloud parametrization



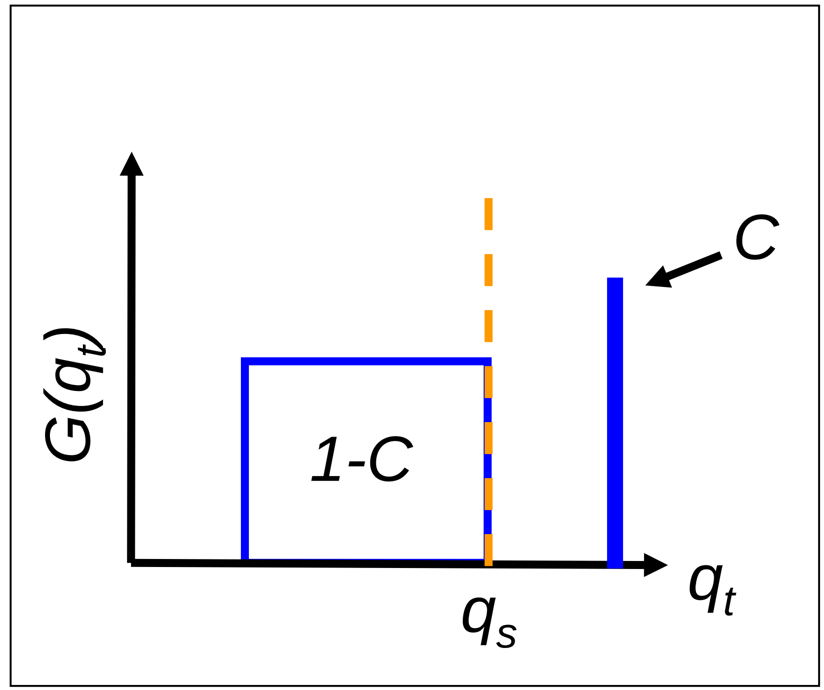
Humidity variations in cloud-free air but,
No in-cloud variability

The ECMWF Cloud Scheme
Representing sub-grid heterogeneity

In the real world



ECMWF cloud parametrization

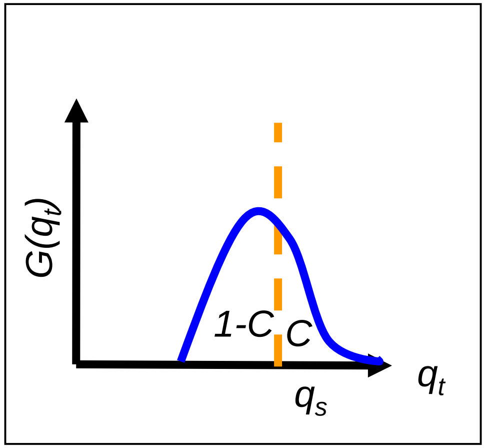


A mixed ‘uniform-delta’ total water distribution is assumed

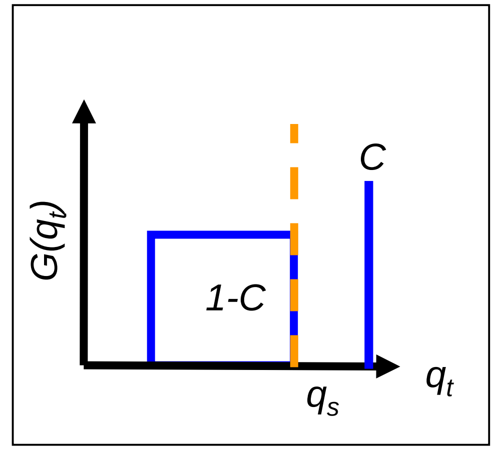
The ECMWF Cloud Scheme

Comparison with Tompkins prognostic PDF scheme

Tompkins (2002)



Tiedtke(1993) in ECMWF IFS



A bounded beta function with positive skewness.

Effectively 3 prognostic variables:

Mean q_t

Variance of PDF

Skewness of PDF

A mixed 'uniform-delta' total water distribution is assumed for the condensation process.

3 prognostic variables:

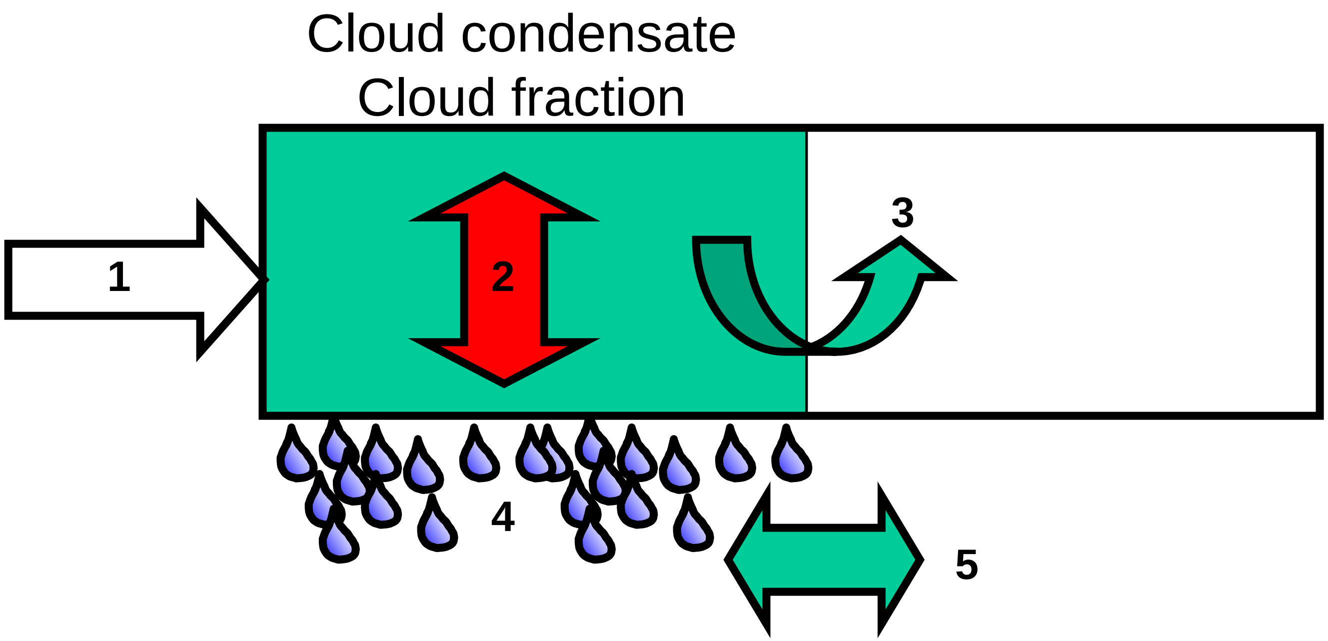
Humidity, q_v

Cloud condensate, q_c

Cloud fraction, C

Same degrees of freedom ?

The ECMWF Cloud Scheme
Schematic of sources and sinks



Some (not all) of these are derived from a pdf approach

1. *Convective Detrainment (deep and shallow)*
2. *(A)diabatic warming/cooling (radiation/dynamics)*
3. *Subgrid turbulent mixing (cloud top, horiz eddies)*
4. *Precipitation generation*
5. *Precipitation evaporation/melting*
6. *Advection/sedimentation*

The ECMWF Cloud Scheme
Sources and sinks

Cloud liquid water q_l
(similar for ice)

$$\frac{\partial q_l}{\partial t} = A(q_l) + S_{CV}(q_l) + S_{BL}(q_l) + c - e - G_P(q_l)$$

Cloud fraction C

$$\frac{\partial C}{\partial t} = A(C) + S_{CV}(C) + S_{BL}(C) + c - e - G_P(C)$$

Rain q_r
(similar for snow)

$$\frac{\partial q_r}{\partial t} = A(q_r) + G_P(q_l) + M - E$$

A:	*Transport of Cloud (Advection + Sedimentation)*
S_{CV} :	*Detrainment from Convection*
S_{BL}:	*Source/Sink Boundary Layer Processes*
c:	*Source due to Condensation*
e/E:	*Sink due to Evaporation*
G_p:	*Precipitation Sink*
M:	*Melting*

$$\frac{\partial q_l}{\partial t} = A(q_l) + S_{CV}(q_l) + S_{BL}(q_l) + c - e - G_P(q_l)$$

Convective Source Term

Convective source term
Linking clouds and convection

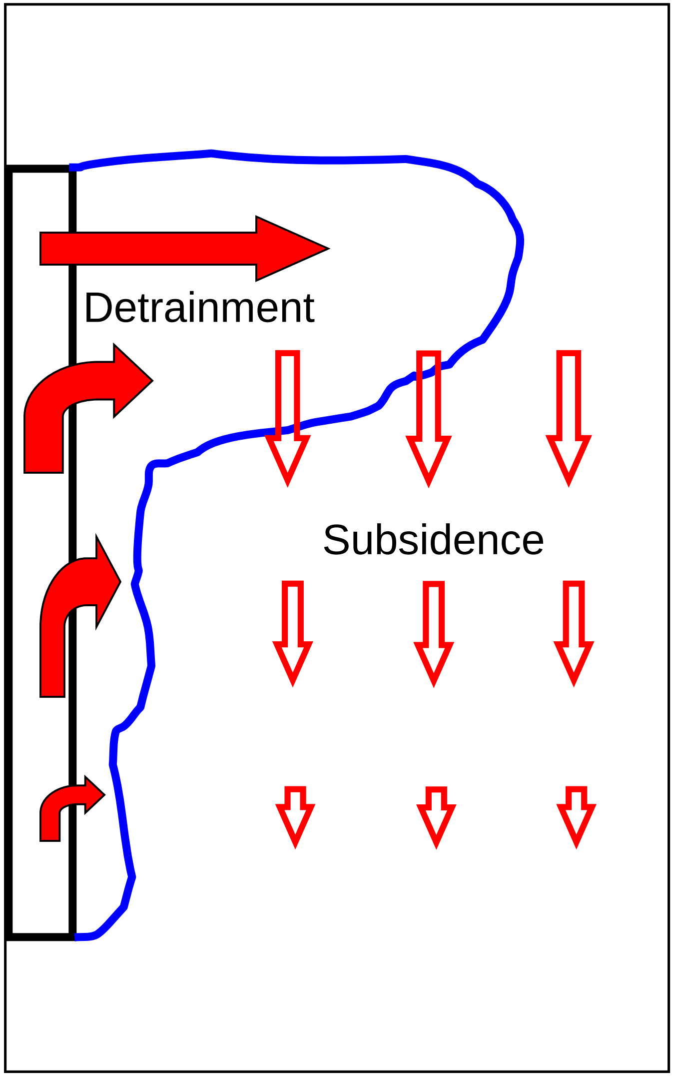
Basic idea:

Use detrained condensate as a source for cloud water/ice

Examples:

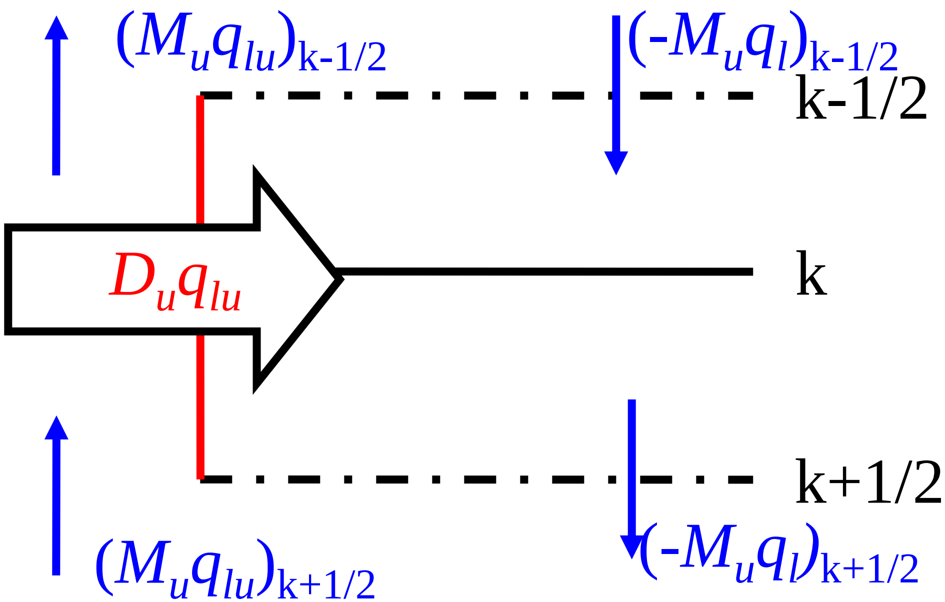
Ose (1993), Tiedtke (1993), Del Genio et al. (1996), Fowler et al. (1996)

Source terms for cloud condensate and fraction can be derived using the mass-flux approach to convection parametrization.



Convective source term

Source of water/ice condensate



Detrainment of mass from cumulus updraughts

Vertical advection due to environmental subsidence

$$S_{CV} = \frac{D_u q_{lu}}{\rho} + \frac{M_u}{\rho}\frac{\partial \overline{q_l}}{\partial z}$$

Standard equation for mass flux convection scheme

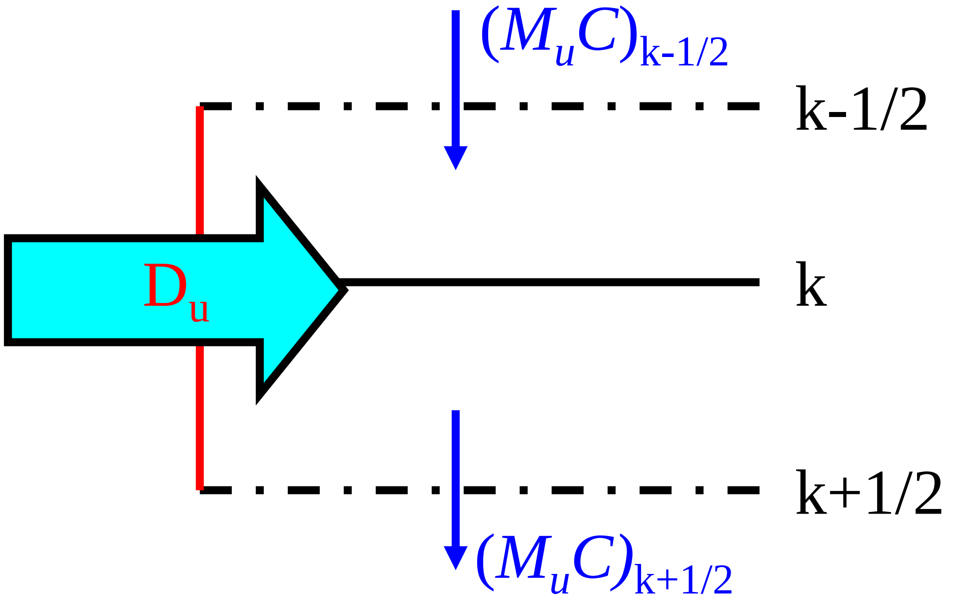
ECHAM, ECMWF and many others...

M_u = convective updraught mass flux
= environmental subsidence mass flux

Convective source term
Source of cloud fraction

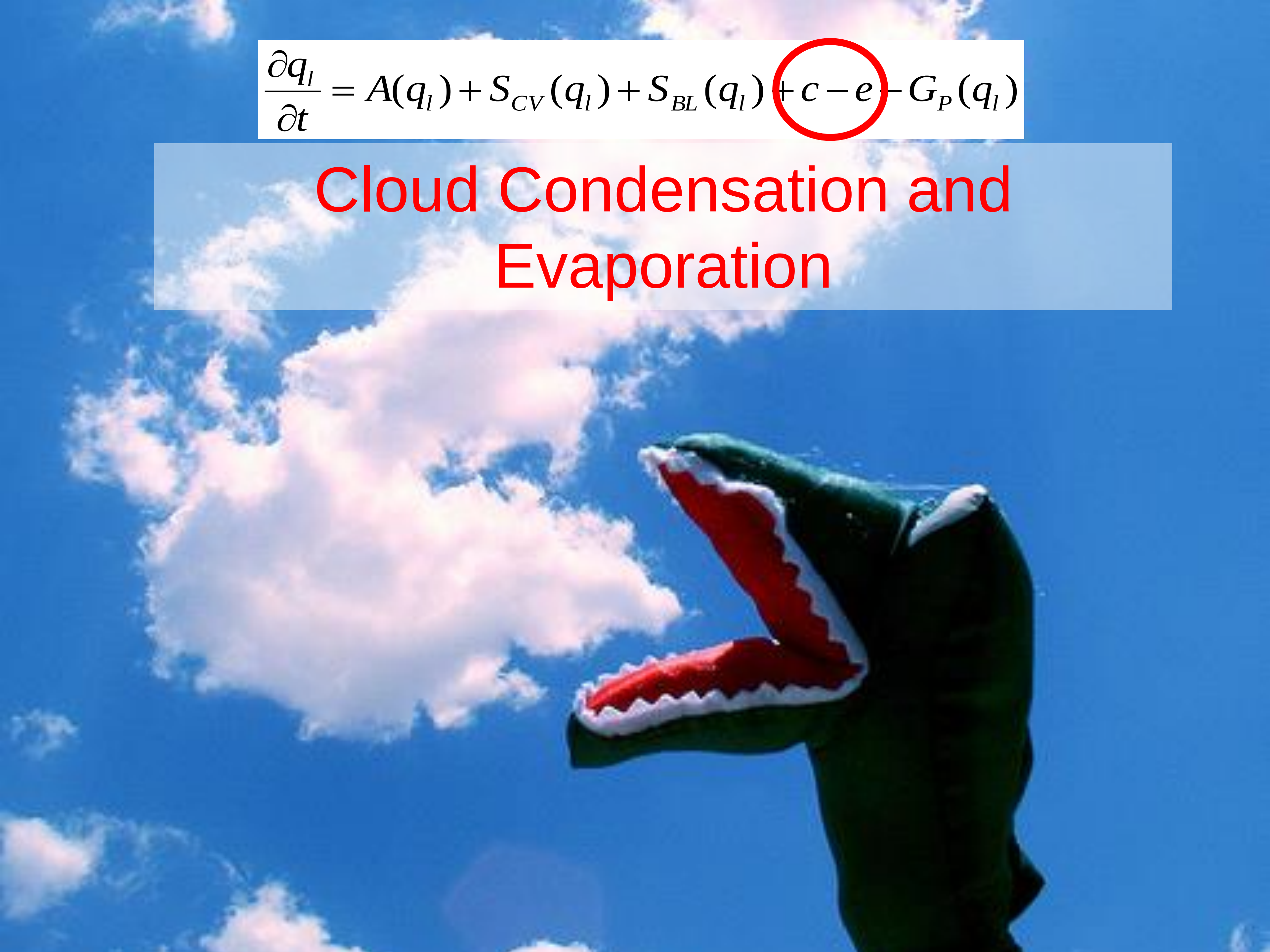
Similar equation for the cloud fraction

$$S_{CV}(C) = \frac{D_u}{\rho} + \frac{M_u}{\rho}\frac{\partial C}{\partial z}$$



$$\frac{\partial q_l}{\partial t} = A(q_l) + S_{CV}(q_l) + S_{BL}(q_l) + c - e - G_P(q_l)$$

Cloud Condensation and Evaporation



Stratiform cloud formation
Changes in water vapour, *q*

Local criterion for cloud formation: $q > q_s(T,p)$

Two ways to achieve this in an unsaturated parcel:

1. Increase q
2. Decrease q_s

Processes that can increase q in a gridbox

Convection	Cloud formation dealt with separately
Turbulent Mixing	Cloud formation dealt with separately
Advection	

Stratiform cloud formation
Changes in saturation, q_s

Postulate:

The main (but not only) cloud production mechanisms for stratiform clouds are due to changes in q_s. Hence we will link stratiform cloud formation to dq_s/dt (i.e. changes in p, T).

$$\frac{dq_s}{dt} = \left(\frac{dq_s}{dt}\right)_{adiab} + \left(\frac{dq_s}{dt}\right)_{diab} = \left(\frac{dq_s}{dp}\right)\frac{dp}{dt} + \frac{dq_s}{dT}\left(\frac{dT}{dt}\right)_{diab}$$

$$\frac{dp}{dt} = \omega \quad \text{(vertical velocity)}$$

Stratiform cloud formation:

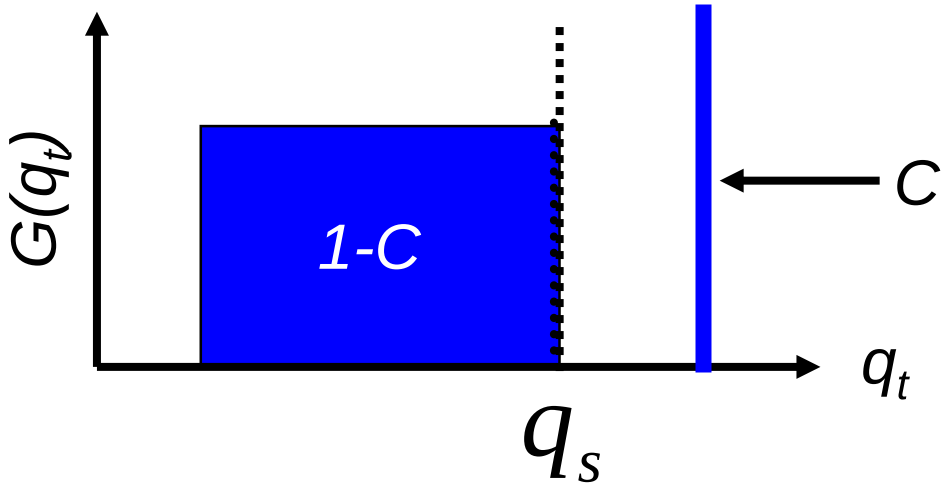
$$\frac{\partial q_l}{\partial t} = A(q_l) + S_{BL}(q_l) + c - e - G_P(q_l) - D(q_l)$$

The cloud generation term is split into two components:

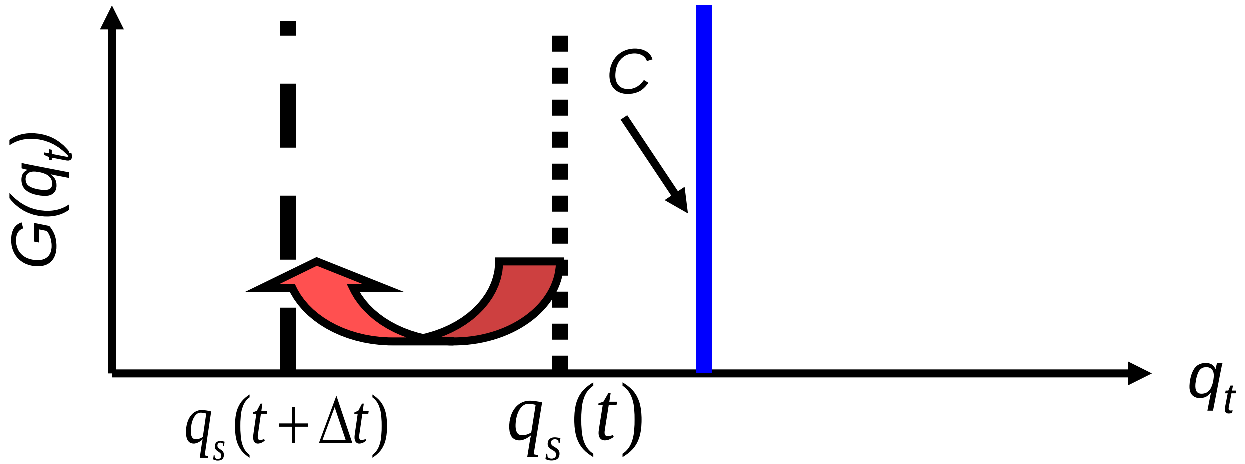
$$c = c_1 + c_2$$

Existing clouds "New" clouds

and assumes a mixed 'uniform-delta' total water distribution



Stratiform cloud formation:
Increase of existing clouds, c_1



Already existing clouds are assumed to be at saturation at the grid-mean temperature. Any change in q_s will directly lead to condensation.

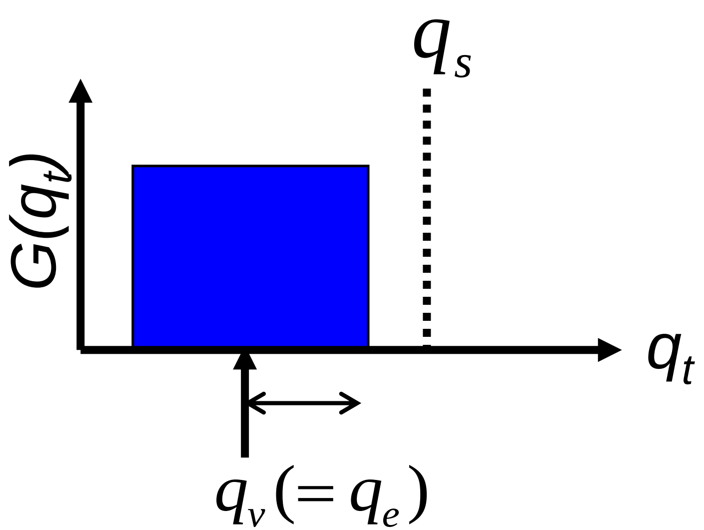
$$c_1 = -C\frac{dq_s}{dt} \qquad \frac{dq_s}{dt} < 0$$

Note that this term would apply to a variety of PDFs for the cloudy air (e.g. uniform distribution)

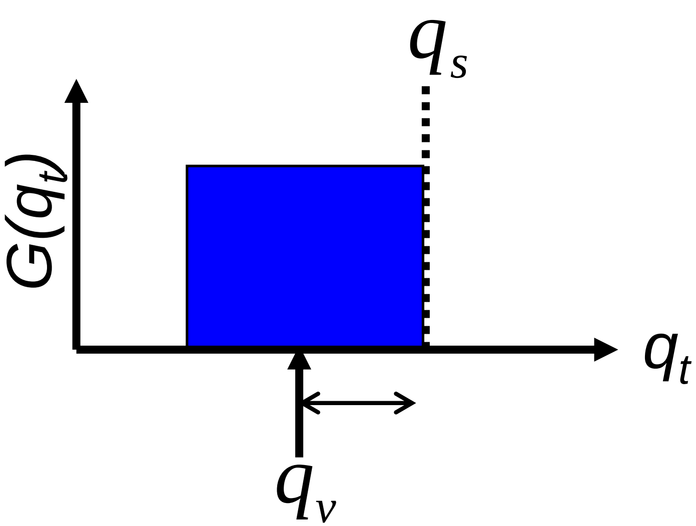
Stratiform cloud formation:
Formation of new clouds, c_2

Due to lack of knowledge concerning the variance of water vapour in the clear sky regions we have to resort to the use of a critical relative humidity, RH_{crit}

$$\frac{q_v}{q_s} < RH_{crit}$$



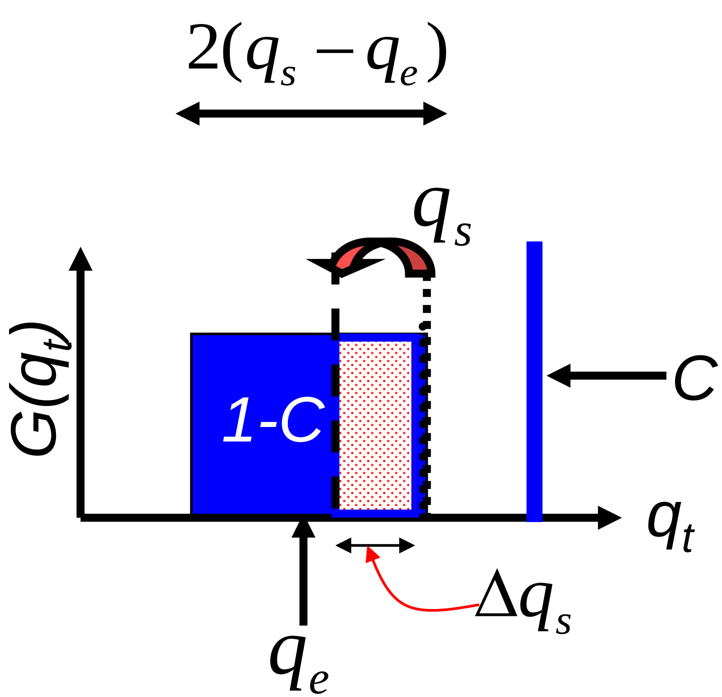
$$\frac{q_v}{q_s} = RH_{crit}$$



RH_{crit} = 0.8 is used throughout most of the troposphere

Stratiform cloud formation:
Formation of new clouds, c_2

For the case of $RH > RH_{crit}$



$$\Delta C = -(1-C)\frac{\Delta q_s}{2(q_s - q_e)}$$

We know q_e from

$$q_v = Cq_s + (1-C)q_e$$

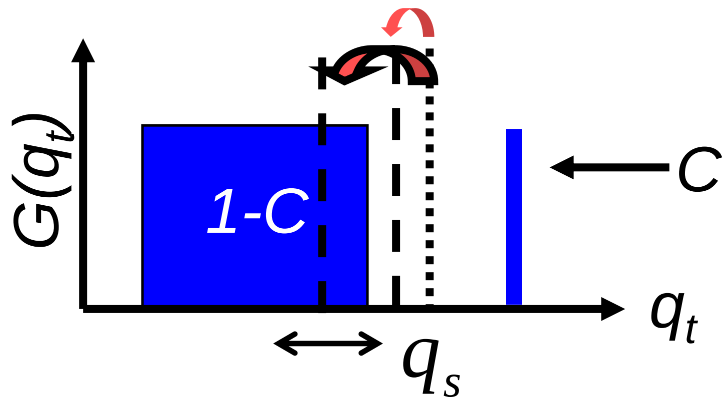
$$\Delta C = -(1-C)^2 \frac{\Delta q_s}{2(q_s - q_v)}$$

similarly

$$\Delta q_l = -\frac{1}{2}\Delta C \Delta q_s$$

Stratiform cloud formation:
Formation of new clouds, c_2

For the case of $RH<RH_{crit}$



Term inactive if $RH<RH_{crit}$

Perhaps for large cooling this is inaccurate?

As stated in the statistical scheme lecture:

1. With prognostic cloud water and here cover we can write source and sinks consistently with an underlying distribution function

2. But in overcast or clear sky conditions we have a loss of information. Hence the use of RH_{crit} in clear sky conditions for cloud formation

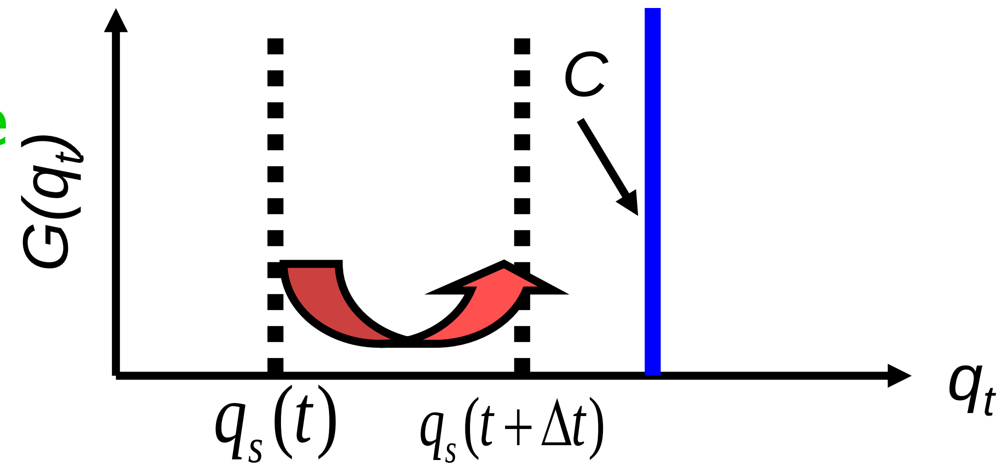
Evaporation of clouds

Processes: $e = e_1 + e_2$

No effect on cloud cover

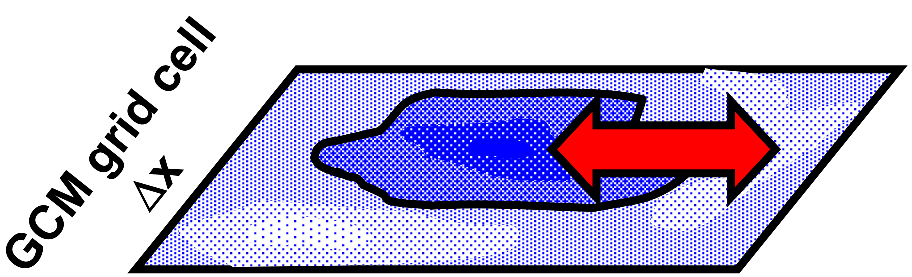
$$e_1 = C\frac{dq_s}{dt} \qquad \frac{dq_s}{dt} > 0$$

- Large-scale descent and cumulus-induced subsidence
- Diabatic heating



- Turbulent mixing (e_2)

Diffusion process proportional to the saturation deficit of the environmental air

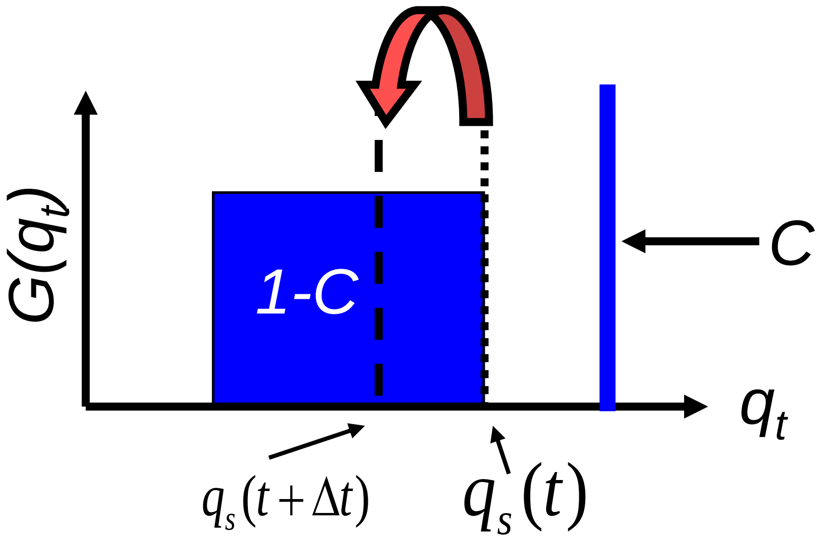


$$e_2 = CK(q_s - q_v)$$

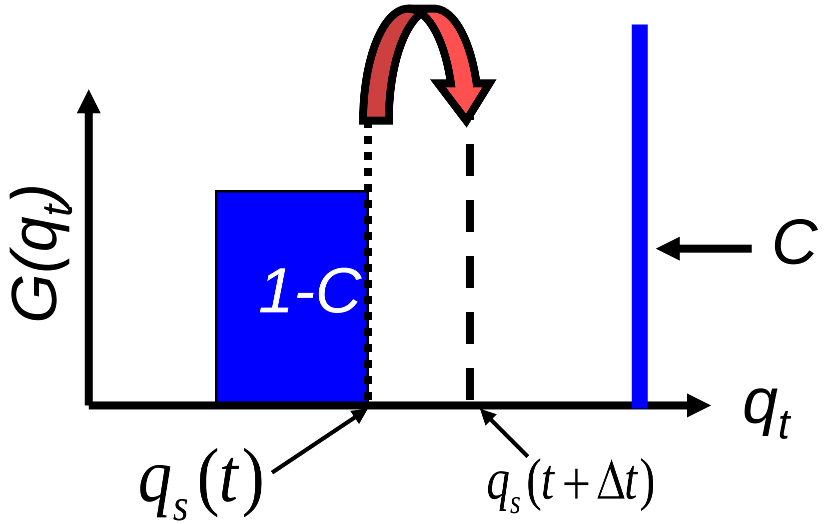
where $K = 3.10^{-6}\ s^{-1}$

Cloud cover also reduced to keep in-cloud condensate constant

Problem: Reversible Scheme?



Cooling: Increases cloud cover

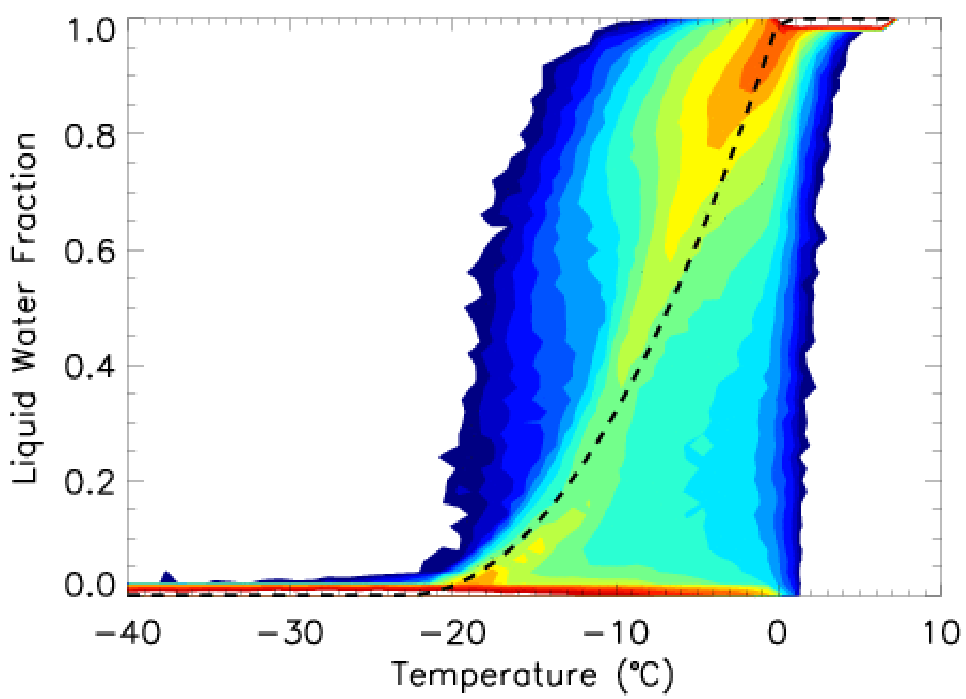


Subsequent warming of same magnitude: No effect on cloud cover

Process not reversible

Mixed-phase cloud

- The previous cloud scheme had a single prognostic variable for cloud condensate. The ice/liquid fraction was diagnosed as a function of temperature between 0°C and -23°C (see dashed line below).
- The new cloud scheme has separate prognostic variables for liquid water and ice allowing a wide range of supercooled liquid water for a given temperature (see shading in example below).



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

Mixed-phase cloud

- The conversion of liquid water to ice is controlled by ice nucleation and ice deposition processes.
- Ice nucleation is treated very simply; heterogeneous ice nucleation occurs at temperatures between 0°C and -38°C whenever there is liquid water present (Meyers et al., 1992).
- Freezing of water drops occurs below -38°C, so no liquid water below -38°C.
- If cloud contains water, then assumed to be at water saturation and Bergeron-Findeison mechanism evaporates water and ice grows through deposition:

Equation for the rate of change of mass for an ice particle of diameter D due to deposition (diffusional growth), or evaporation

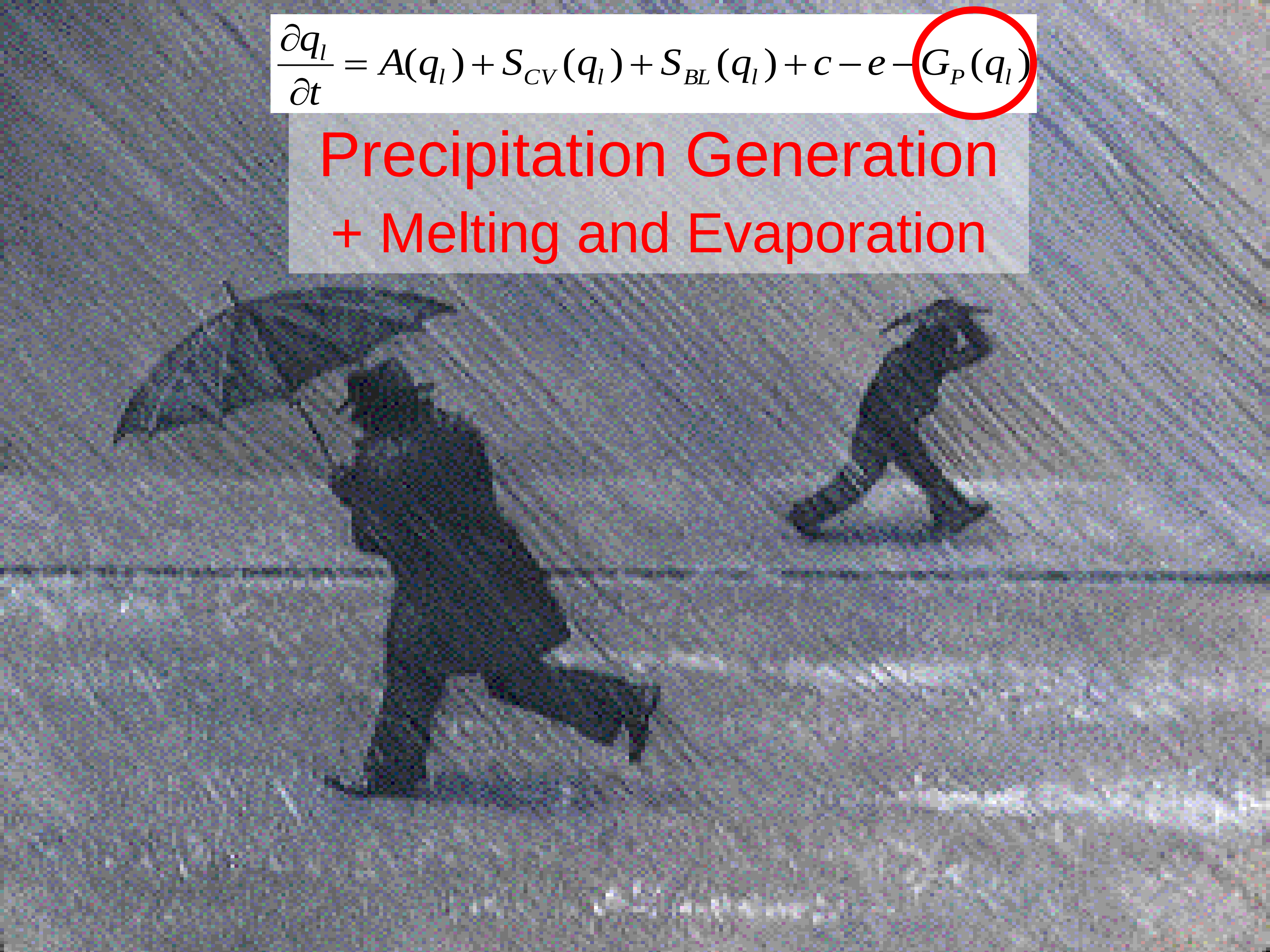
$$\frac{\partial m}{\partial t} = \frac{4\pi s C F}{\left(\frac{L_s}{RT} - 1\right)\frac{L_s}{k_a T} + \frac{RT}{\chi e_{si}}} \propto sCF$$

Deposition rate depends primarily on
- s = supersaturation
- C = particle shape (habit)
- F = ventilation factor

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

$$\frac{\partial q_l}{\partial t} = A(q_l) + S_{CV}(q_l) + S_{BL}(q_l) + c - e - G_P(q_l)$$

Precipitation Generation
+ Melting and Evaporation



Precipitation generation
Liquid water clouds

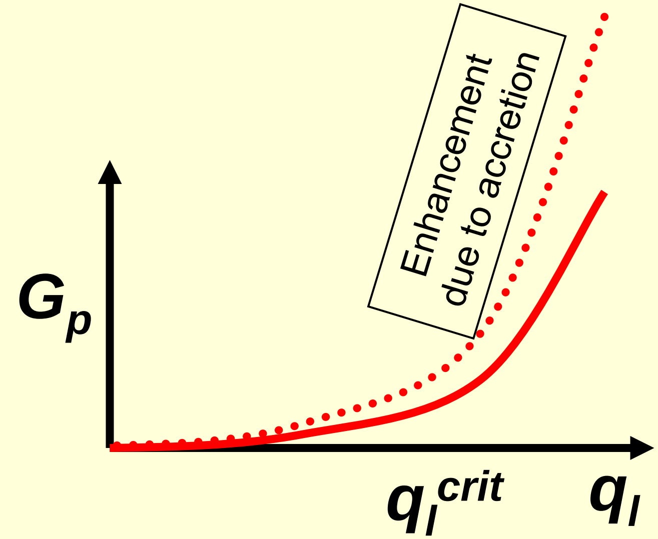
Representing autoconversion and accretion in the warm phase (liq. to rain).

Sundqvist (1978, 1989)

$$G_P = c_0 F_1 q_l \left(1 - e^{-\left(\frac{ql}{ql_{crit}} F_1\right)^2} \right)$$

G_p = autoconversion rate
P = precipitation rate

$$F_1 = 1 + c_1 \sqrt{P}$$ Accretion



Khairoutdinov and Kogan (2000)

$$G_{aut} = 1350 q_l^{2.47} N_c^{-1.79}$$

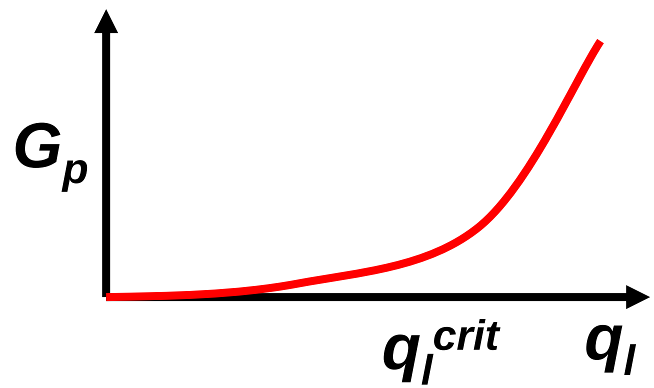
$$G_{acc} = 67 q_l^{1.15} q_r^{1.15}$$

- Functional form is different
- More non-linear process
- Slower autoconversion initially, then faster
- With prognostic rain, have memory in q_r
- Then faster accretion for heavier rain.

Precipitation generation
Ice clouds

Representing aggregation in the ice phase (conversion ice-to-snow).

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



$c_0 = 10^{-3}\, e^{0.025(\boldsymbol{T} - 273.15)}\ s^{-1}$

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

Rate of conversion of ice (small particles) to snow (large particles) increases as the temperature increases.

Precipitation melting

- The part of the grid box that contains precipitation is assumed to cool to T_{melt} over a timescale *tau*

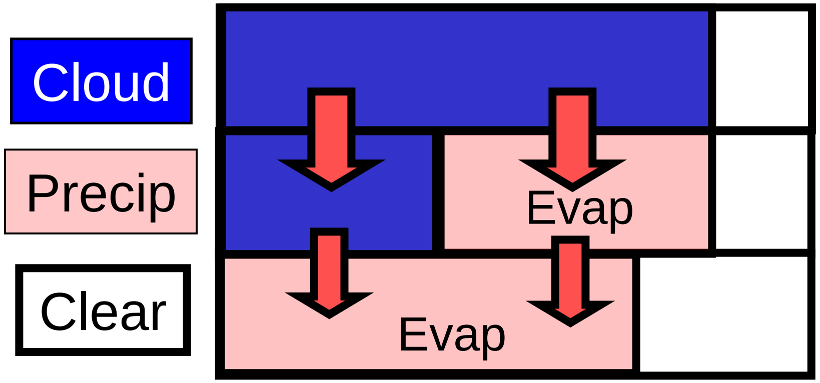
$$M = \frac{c_p}{L} \frac{\left(T - T_{melt}\right)}{\tau}$$

- Converts snow to rain
- Occurs whenever wet bulb temperature $T_w > 0°C$
- Is limited such that cooling does not lead to $T<0°C$

Precipitation evaporation

Evaporation (Kessler 1969, Monogram)

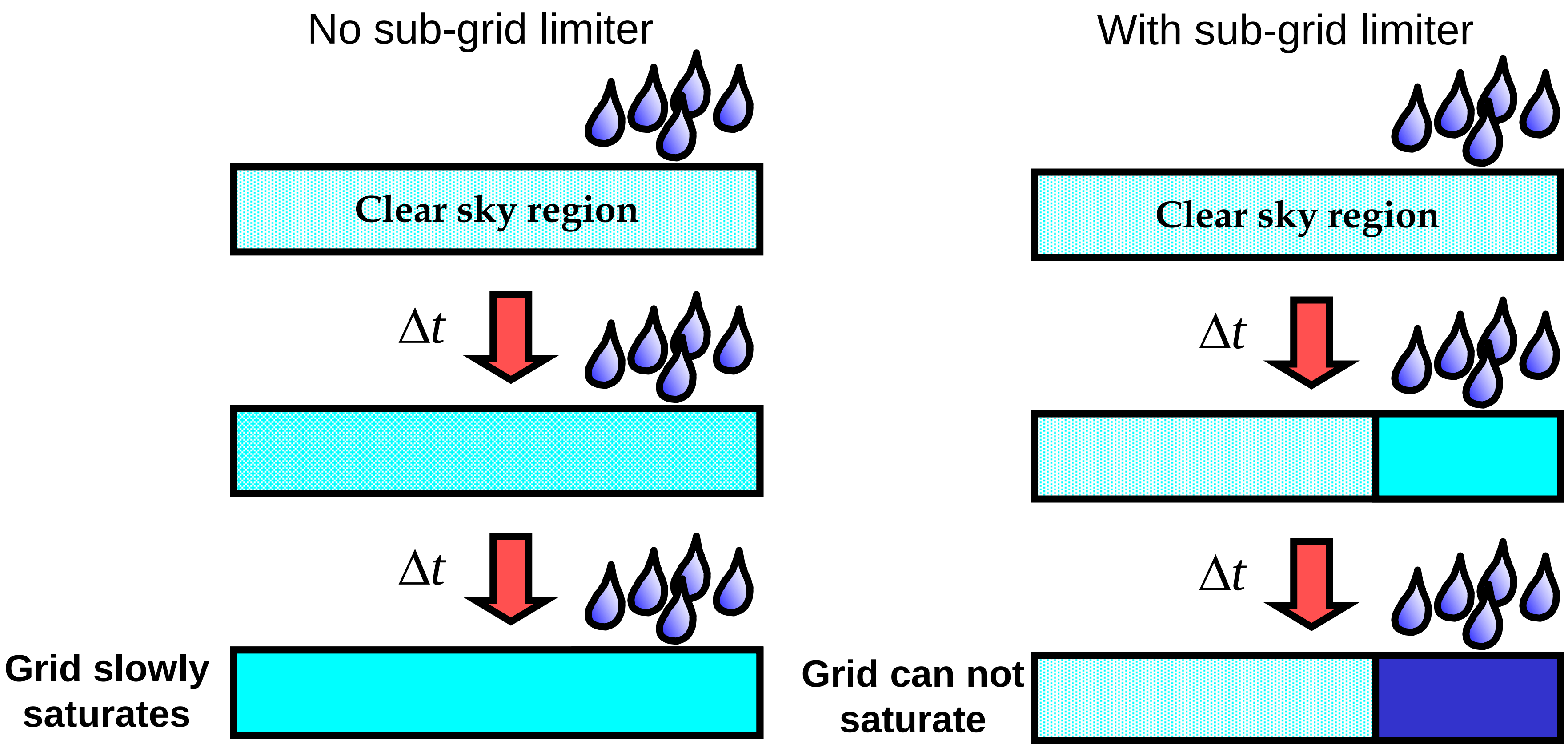
$$E_P = C_P^{clr} \alpha_1 (q_s - q_e) \rho_{rain}^{clr\ 0.577}$$



- Evaporation is proportional to the saturation deficit and dependent on the rain mass (g m^{-3}), $\rho_{rain}{}^{clr}$, in the clear air fraction of the grid box, $C_P{}^{clr}$.
- A diagnostic total precipitation fraction is calculated using a maximum-random overlap treatment of the cloud fraction.
- The clear sky fraction is the total precipitation fraction minus the cloud fraction in each layer.
- Evaporation reduces the precipitation (implicitly assumes sub-grid precipitation variability).

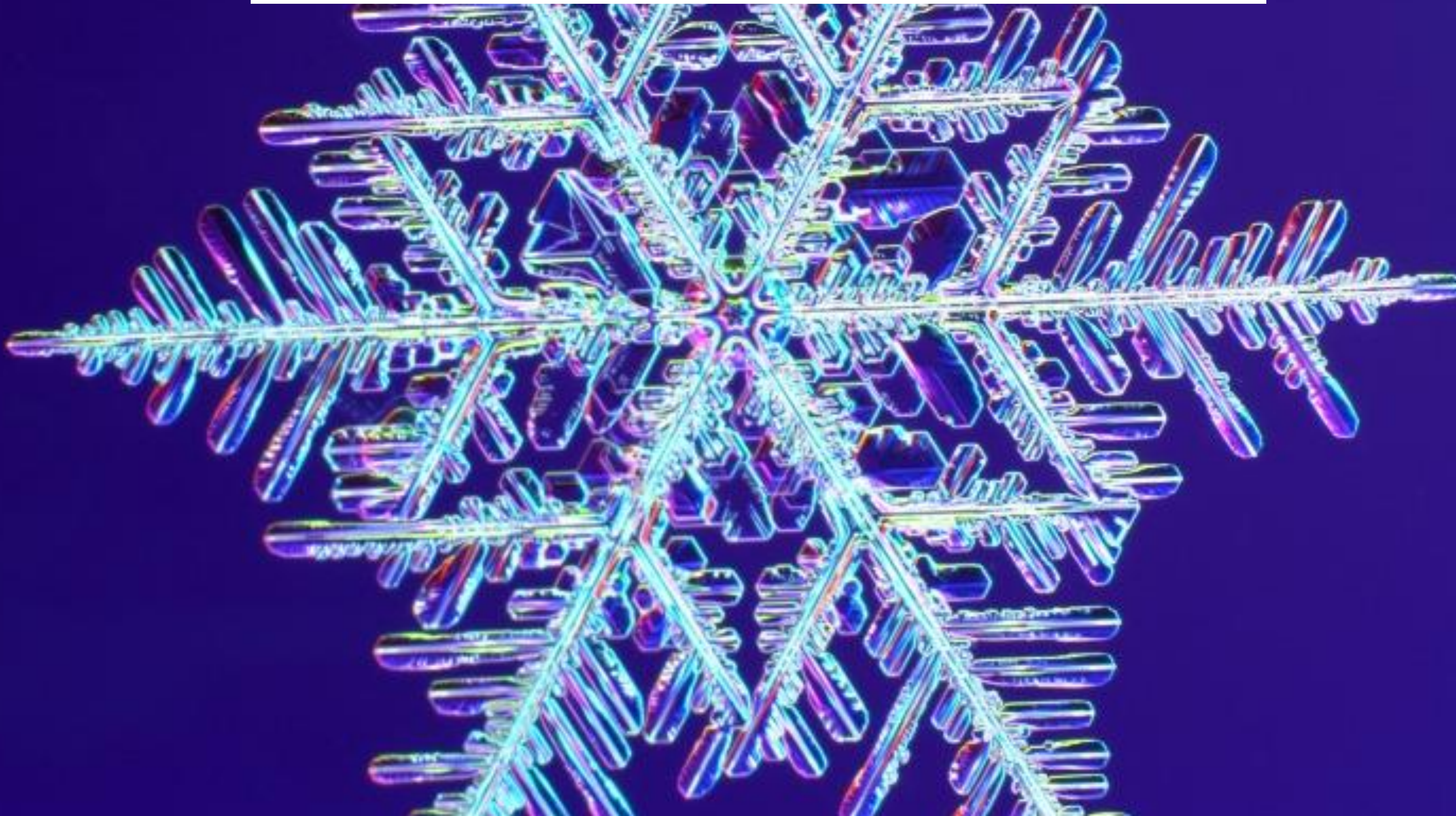
Precipitation Evaporation

Numerical "Limiters" have to be applied to prevent grid scale saturation when precipitation fraction is less than 1



$$\frac{\partial q_l}{\partial t} = A(q_l) + S_{CV}(q_l) + S_{BL}(q_l) + c - e - G_P(q_l)$$

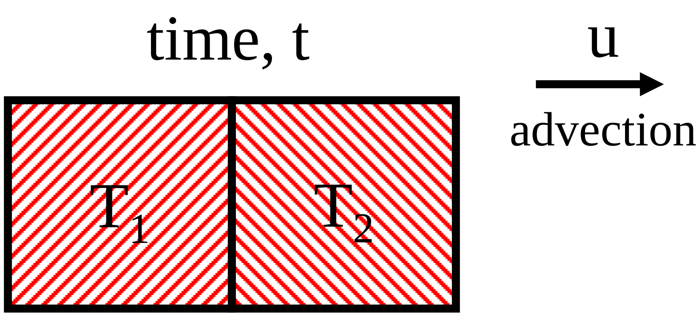
Numerical Issues and Sedimentation

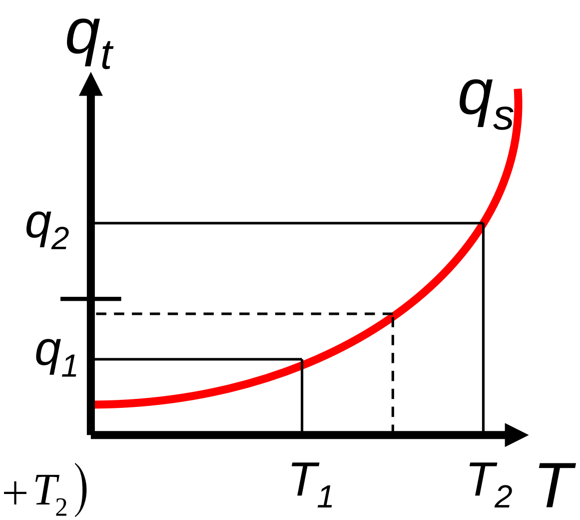


Stratiform cloud formation
Numerical advection

Advection does not mix air !!! It merely moves it around conserving its properties, including clouds.

but……… there are numerical problems in models





$q_1 = q_s(T_1) \quad q_2 = q_s(T_2)$

$T_1 < T_2$

$T_2^{t+\Delta t} = 0.5(T_1 + T_2)$

$q_2^{t+\Delta t} = 0.5(q_1 + q_2)$

Because of the non-linearity of $q_s(T)$, $q_2^{t+\Delta t} > q_s(T_2^{t+\Delta t})$ so cloud forms

This is a numerical problem and should not be used as cloud producing process!

Would be preferable to advect moist conserved quantities instead of T and q

Numerics: Explicit vs Implicit

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

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

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

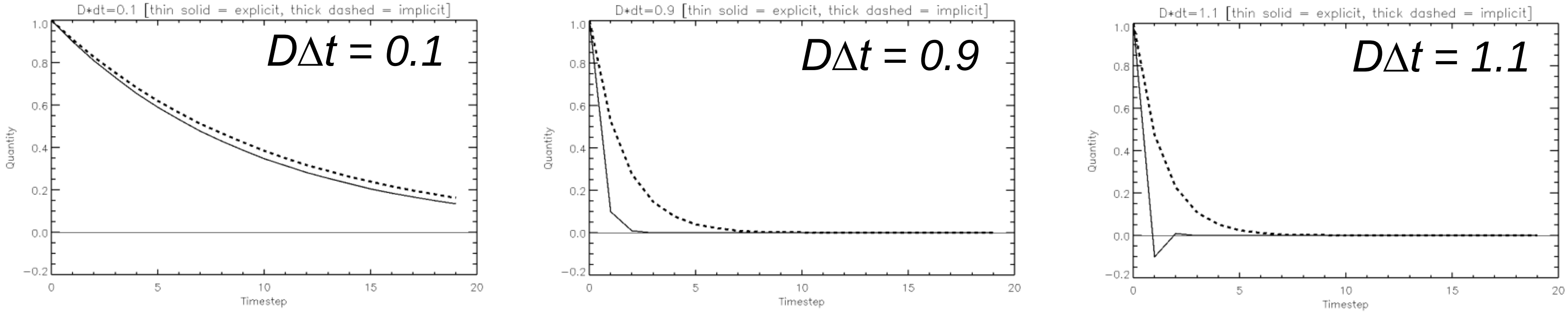
Explicit solution

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

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

Implicit solution

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



Numerics and sedimentation

Advected quantity (e.g. ice)

Sedimentation term

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

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)

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

Solution

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

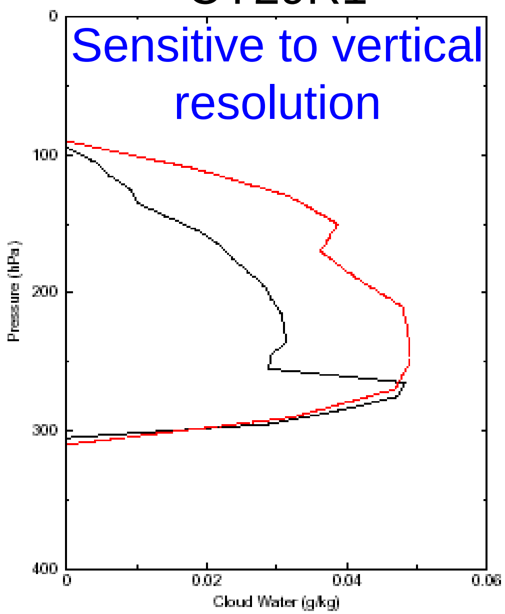
Ice Sedimentation:
Improved numerics in SCM cirrus case

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

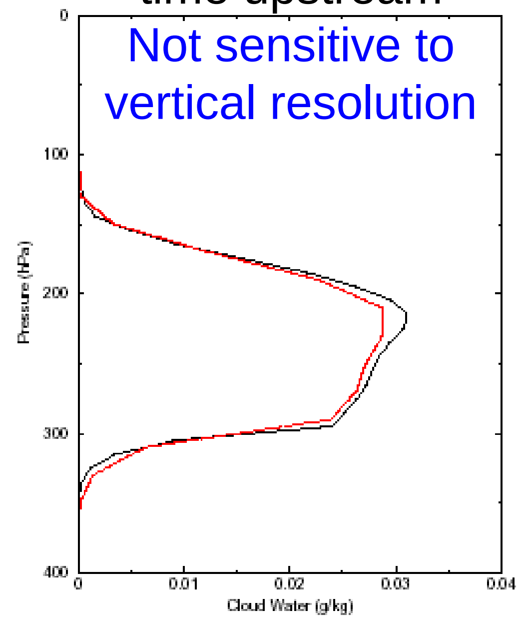
Vertical profile of ice water content

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

Old numerics before CY29R1

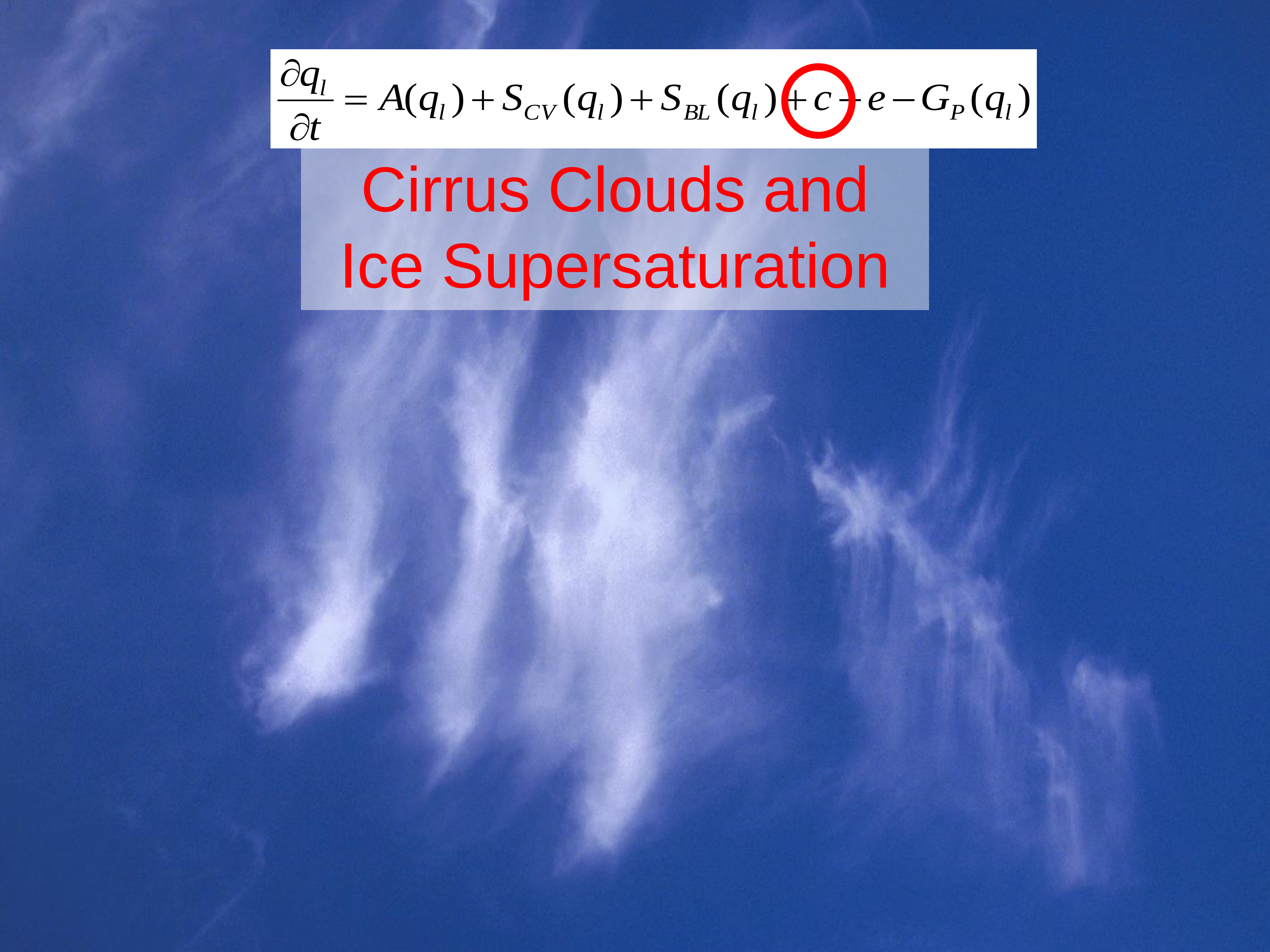


Implicit forward-in-time upstream



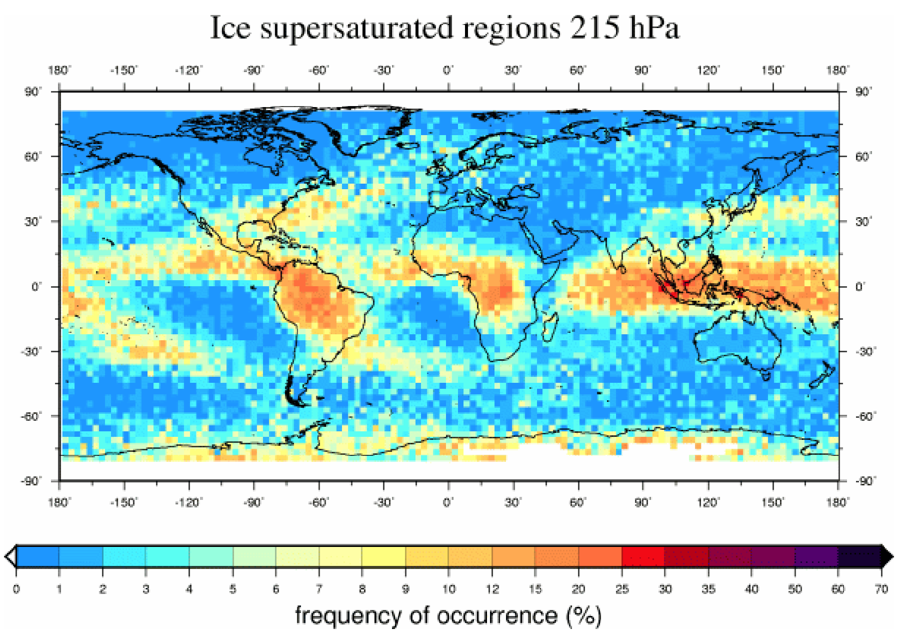
$$\frac{\partial q_l}{\partial t} = A(q_l) + S_{CV}(q_l) + S_{BL}(q_l) + c - e - G_P(q_l)$$

Cirrus Clouds and Ice Supersaturation



Air that is supersaturated with respect to ice is common

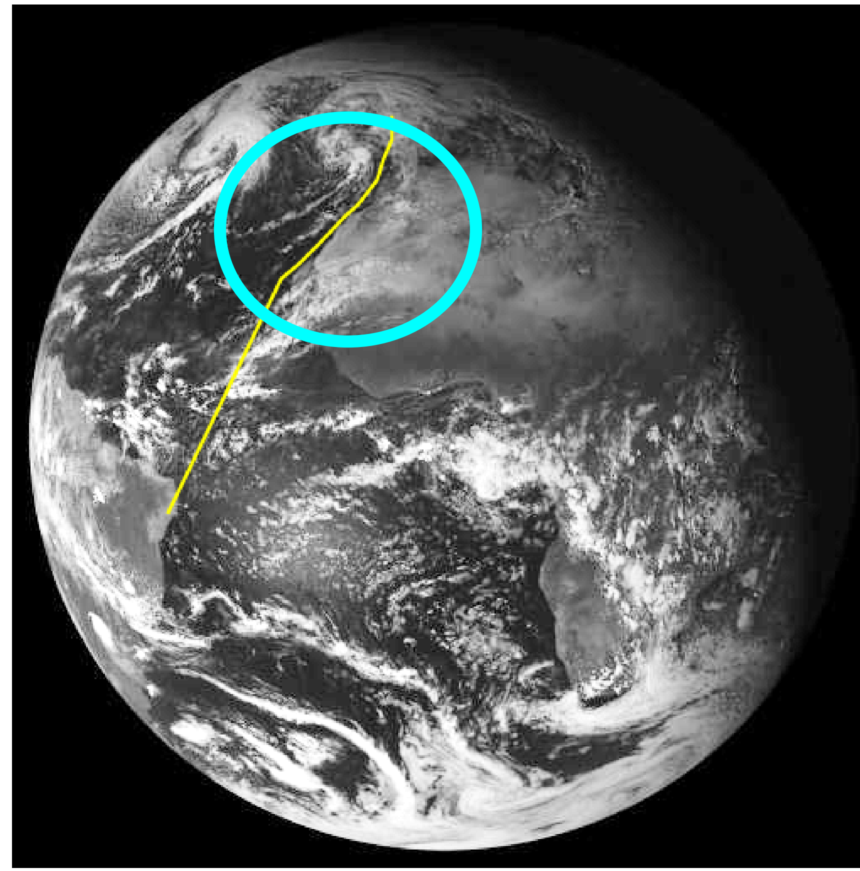
(Pictures courtesy of Klaus Gierens and Peter Spichtinger, DLR)



Microwave limb sounders

Aircraft flight data

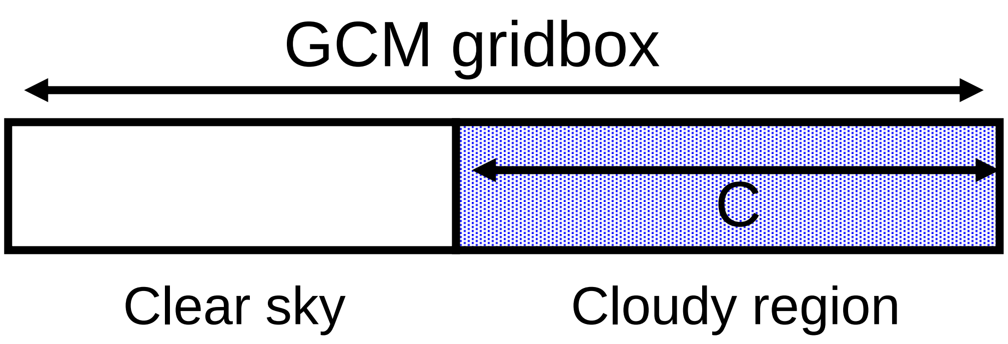
Meteosat visible channel, 18 Dec 1995, 15UTC, MOZAIC flight M5121803



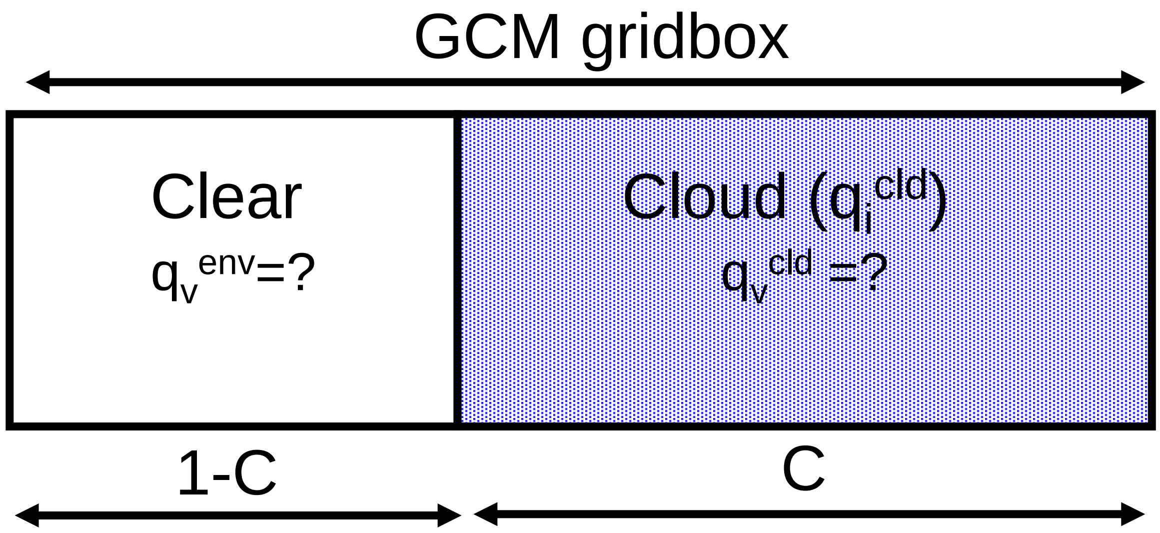
3000 km ice supersaturated segment observed ahead of front

Cirrus Clouds
Homogeneous nucleation

- Want to represent super-saturation and homogeneous nucleation
- Include simple diagnostic parameterization in existing ECMWF cloud scheme
- Desires:
  - Supersaturated clear-sky states with respect to ice
  - Existence of ice crystals in locally subsaturated state
- Only possible with extra prognostic equation ?



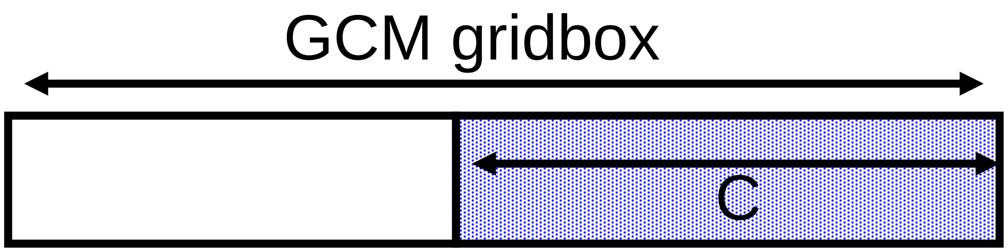
Unlike "parcel" models, or high resolution LES models, we have to deal with subgrid variability



We have three items of information: q_v, q_i, C (grid-box mean vapour, cloud ice and cloud cover)

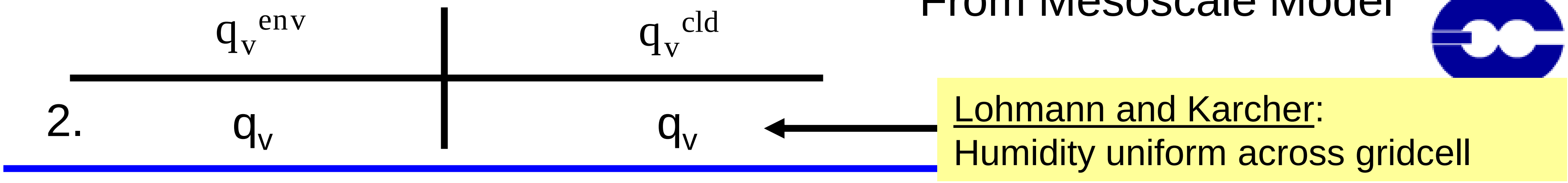
- We know q_i occurs in the cloudy part of the gridbox
- We know the mean in-cloud cloud ice ($q_i^{cld}=q_i/C$)
- What about the water vapour? Assuming no ice supersaturation:
    - Clouds: $q_v^{cld}=q_s$
    - Clear sky: $q_v^{env}=(q_v-Cq_s)/(1-C)$

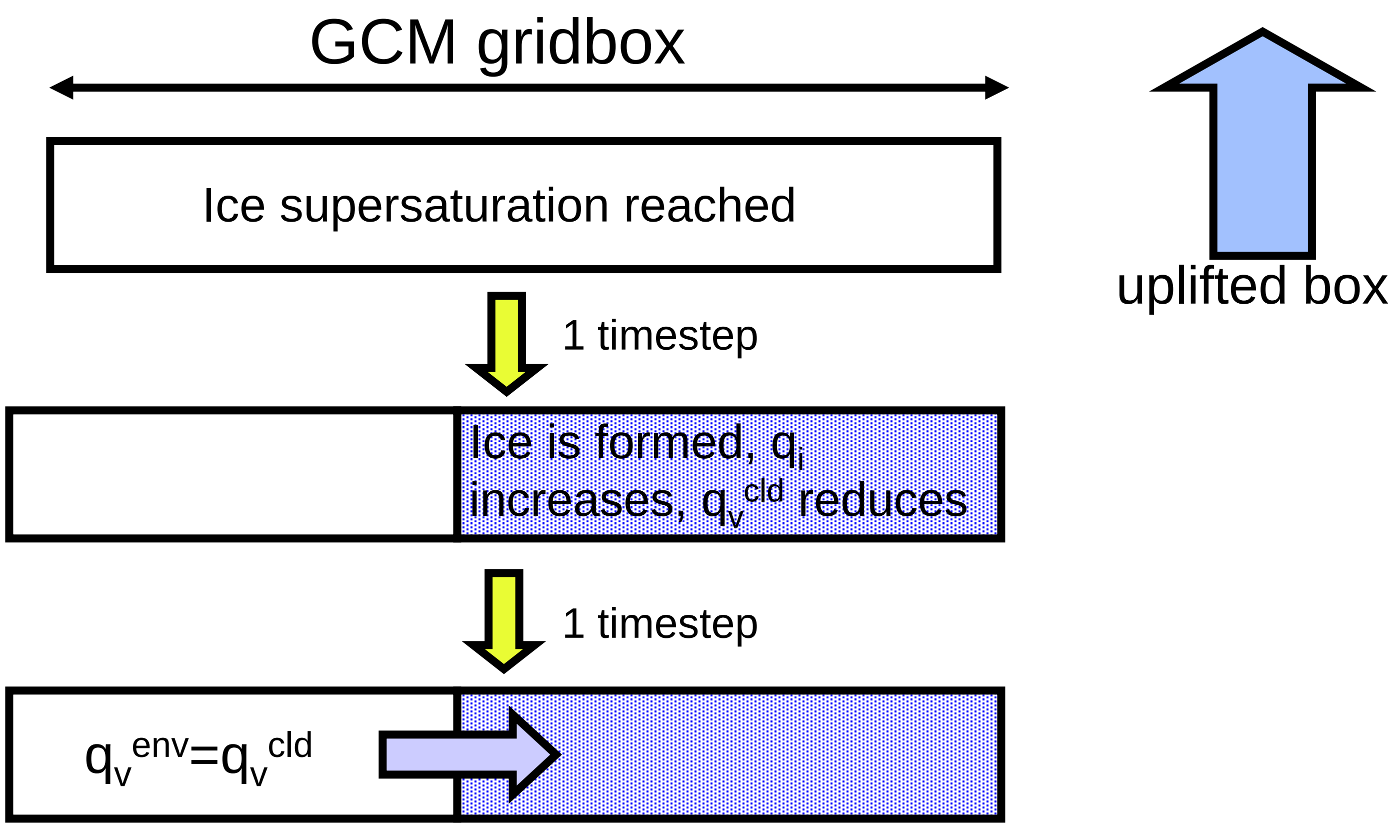
Different approaches to represent clear sky and cloudy humidity



	q_v^{env}	q_v^{cld}	
1.	$(q_v-Cq_s)/(1-C)$	q_s	In the bad old days No supersaturation
2.	q_v	q_v	Lohmann and Karcher: Humidity uniform across gridcell

From Mesoscale Model

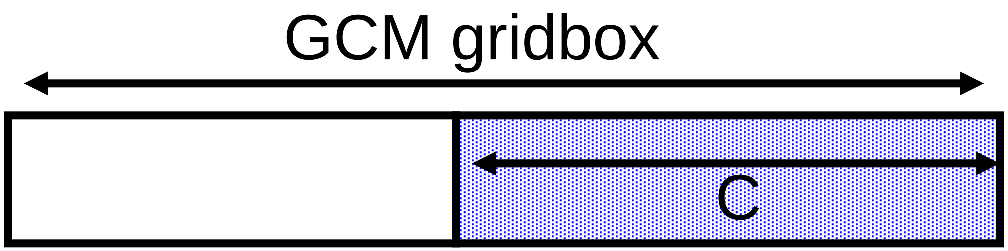




Artificial flux of vapour from clear sky to cloudy regions!!!

Assumption ignores fact that difference processes are occurring on the subgrid-scale

Different approaches to represent clear sky and cloudy humidity



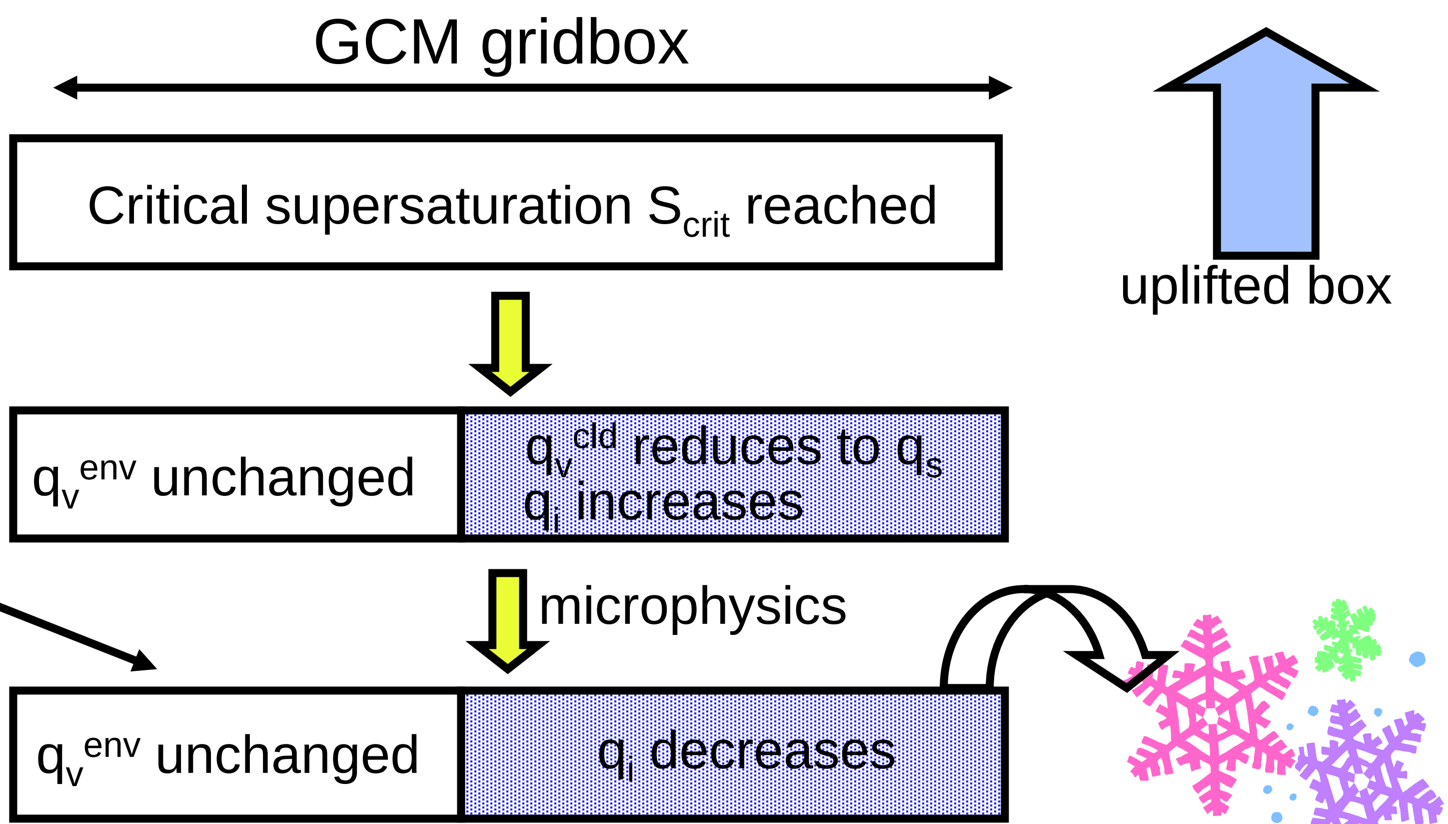
	q_v^{env}	q_v^{cld}	
1.	$(q_v - Cq_s)/(1-C)$	q_s	In the bad old days No supersaturation
2.	q_v	q_v	Lohmann and Karcher: Humidity uniform across gridcell
3.	$q_v + q_i$	$q_v - q_i(1-C)/C$	Klaus Gierens: Humidity in clear sky part equal to the mean total water
4.	$(q_v - Cq_s)/(1-C)$	q_s	Current assumption including supersaturation: Hang on… Looks familiar???

From GCM perspective

	q_v^{env}	q_v^{cld}
4.	$(q_v - Cq_s)/(1-C)$	q_s

← Current assumption:

Difference to standard scheme is that environmental humidity must exceed S_{crit} to form new cloud (rather than just exceeding ice saturation)

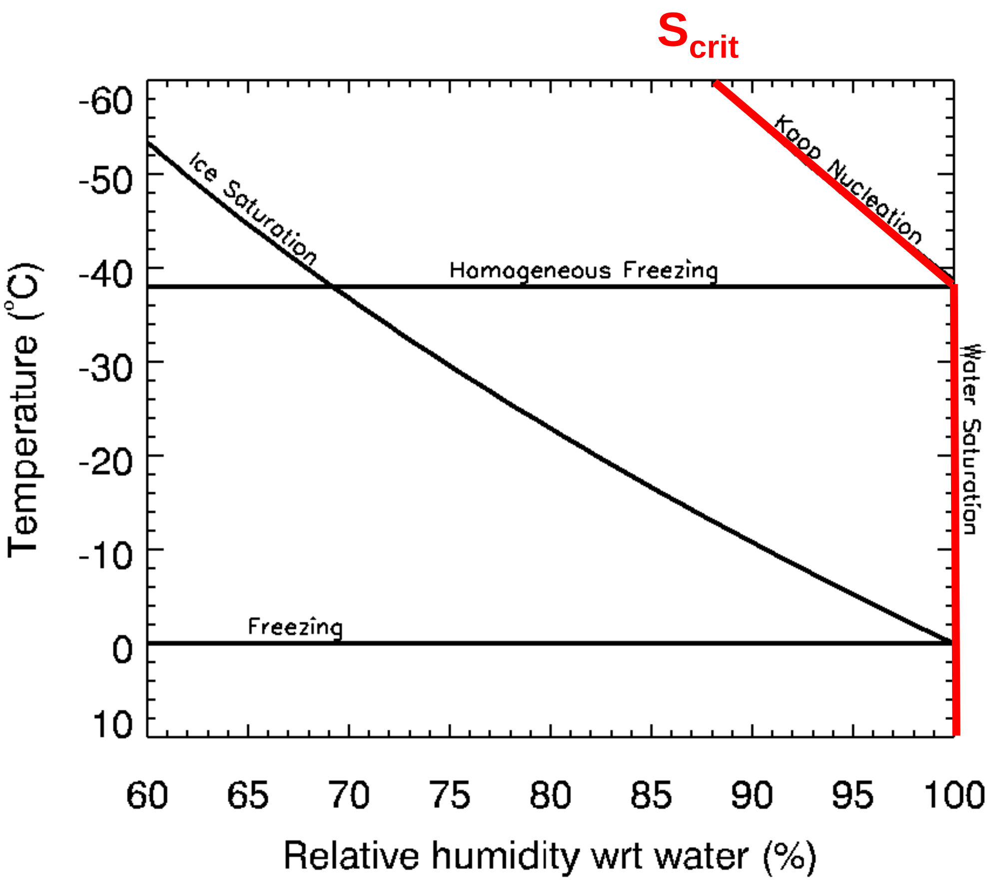


No artificial flux of vapour from clear sky to cloudy regions

Assumption seems reasonable: BUT! **Does not allow nucleation or sublimation timescales to be represented, due to hard adjustment to ice saturation in the cloud**

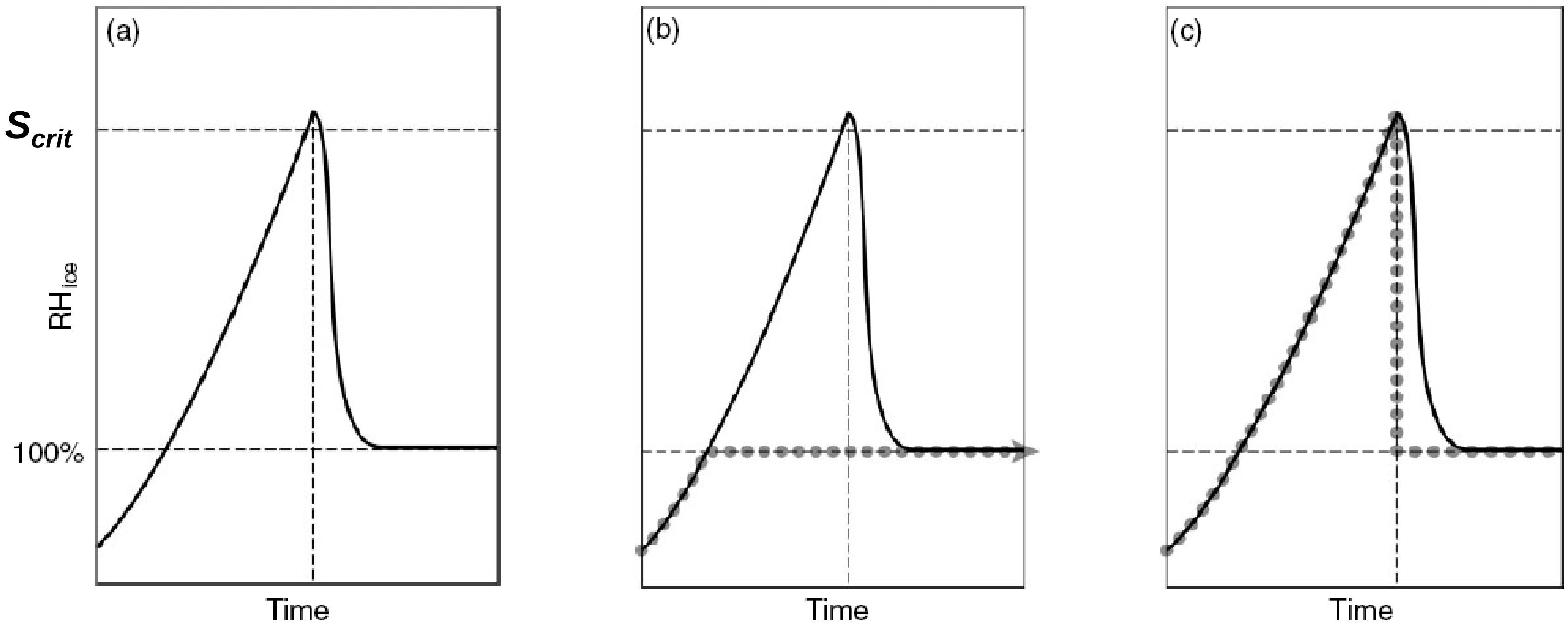
Ice supersaturation and homogeneous nucleation

- What is the critical ice supersaturation S_{crit} ?
- 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 as a function of temperature (Koop et al., 2000, Kärcher and Lohmann, 2002).



Ice supersaturation and homogeneous nucleation

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

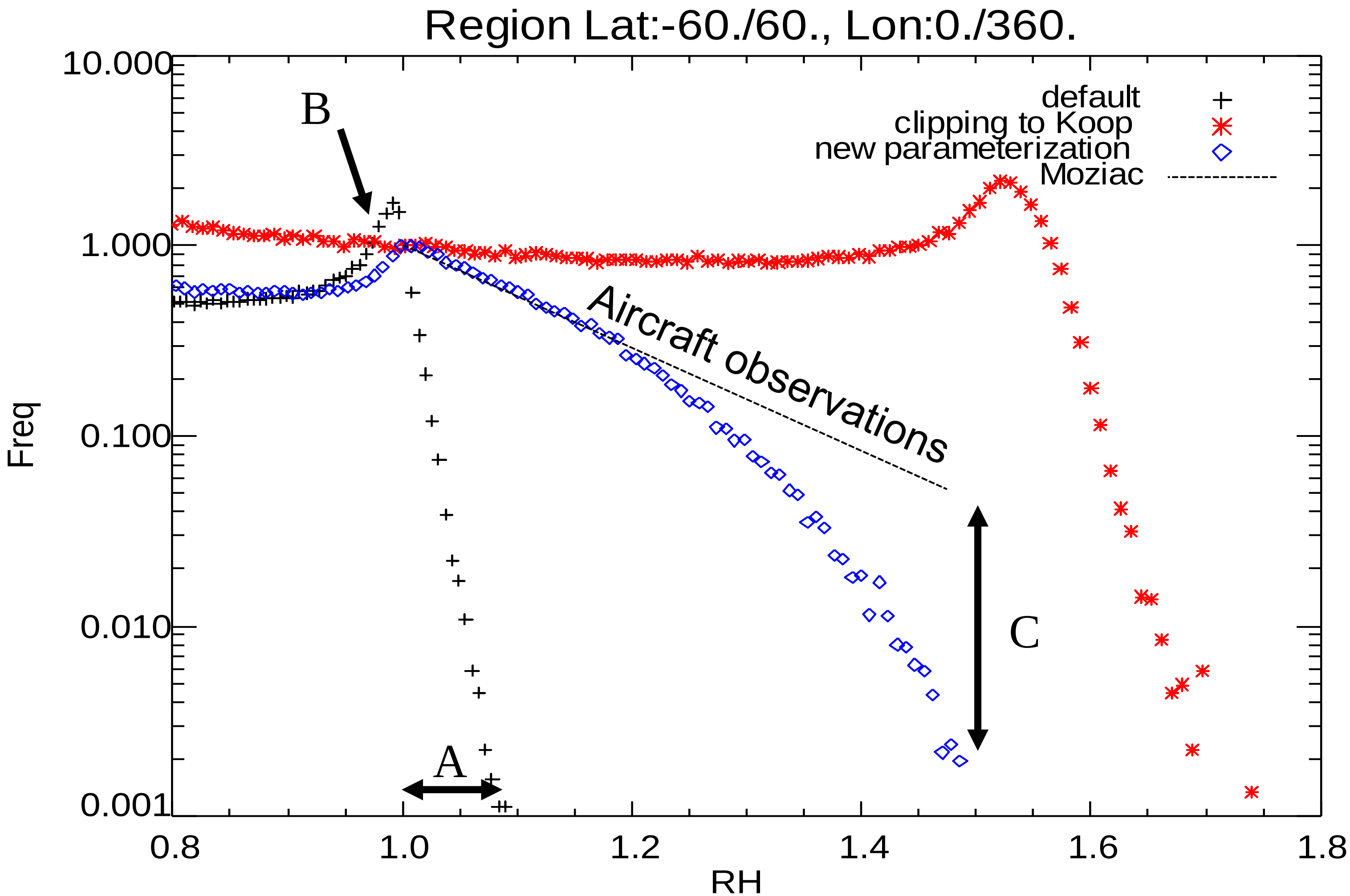


Evolution of an air parcel subjected to adiabatic cooling at low temperatures

Dotted line: Evolution if no ice supersaturation allowed

Dotted line: Evolution if ice supersaturation is allowed until reaches S_{crit}

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



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

Summary of ECMWF Scheme

- Scheme introduces prognostic equations for cloud fraction, cloud liquid water, cloud ice, rain and snow.
- Sources and sinks for each physical process.
- Some derived using assumptions concerning subgrid-scale PDF for vapour and clouds.

☺ More simple to implement than prognostic variance/skewness in a statistical PDF scheme. Also nicer for assimilation since prognostic quantities directly observable.

☹ Loss of information (no memory) in clear sky (a=0) or overcast conditions (a=1) (critical relative humidities necessary etc).

☹ Nothing to stop solution diverging for cloud cover and cloud water. (eg. q_l>0, a=0). Unphysical “safety switches” necessary.

☹ Artificial split between prognostic ice and snow variables.

☹ Many microphysical assumptions are empirically based.

Next time: Cloud Scheme Validation…..

Observations,

Observations,

Observations !

References

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