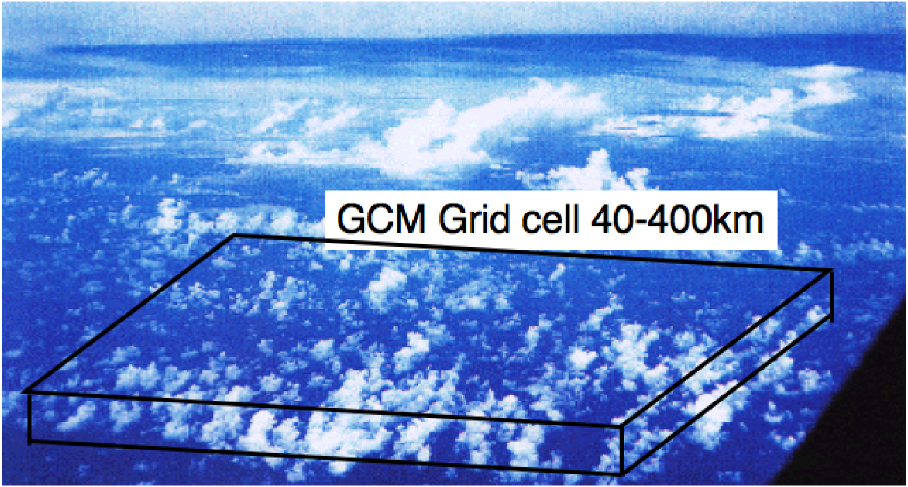
Parameterizations of large-scale clouds



Courtesy Adrian Tompkins, ECMWF, 2005

Gravity waves (GWs)

- GWs are generated either in a fluid media or at the interface between two media when the force of gravity or buoyancy tries to restore equilibrium.
- In the troposphere GWs are generated by frontal systems, violent thunderstorms or flow over mountains.
- GWs transfer momentum from the troposphere to the stratosphere.
- Wavelengths of GWs: up to thousands of kilometers. Periods of GWs: a few minutes to days.

www.atoptics.co.uk/highsky/hgrav.htm

Aspects to consider

The parameterization of large-scale clouds includes parameterizations of microphysical processes and/or fractional cloud cover:

Scheme	GCM	NWP
Fractional cloud cover scheme:		
Cloud microphysics parameterization:		

A fractional cloud cover parameterization is needed for:

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Parameterization of large-scale cloud cover

- Clouds range in size from hundreds of meters to hundreds of km. I.e. most clouds are smaller horizontally than the typical grid resolution of GCMs and must be parameterized
- Unlike other climate variables (e.g., momentum, T, specific humidity), there is no fundamental prognostic equation for cloud fraction
- Assumptions:
  - Local criterion for formation of cloud: $q_v > q_s \leftrightarrow RH > 100\%$
  - Condensation process is fast (compared to a GCM timestep), so that $q_v = q_s^{new}$ and $q_c = q_v - q_s^{new}$.
  - No supersaturation is allowed to exist (saturation adjustment)
  - Both assumptions are suspect in ice clouds
  - New schemes avoid these simplifications

Partial cloud cover

- Partial coverage of a grid-box with clouds is only possible if there is an inhomogeneous distribution of T and/or q_v
- Here concentrate on humidity fluctuations which are more important for water cloud formation
- Then relate cloud amount to large-scale relative humidity RH (e.g. Sundqvist et al., 1989):

$$C = 1 - \sqrt{\frac{1 - RH}{1 - RH_{crit}}} \tag{1}$$

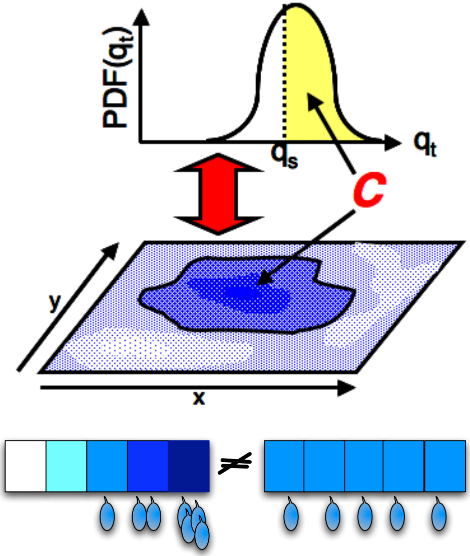
  where RH_{crit} is a critical relative humidity above which clouds fill the entire grid box.
- RH_{crit} is a tunable constant. It ECHAM, it depends on height and model resolution. It is highest near the surface to avoid excessive fog.

Cloud blinking

- Some of these cloud cover schemes result in cloud "blinking". When condensation occurs a cloud is formed at that time step of the model.
- In the next time step RH may be less than RH_{crit} and the cloud fraction will be 0. Thus, a time series of cloud amount from this approach indicates high-frequency "on-off" cloud activity.
- Cloud blinking can be avoided by using:
  - Statistical cloud schemes
  - Prognostic cloud cover C:

$$\frac{dC}{dt} = sources - sinks \tag{2}$$

Statistical cloud schemes [Tompkins, ECMWF lecture, 2006]



Statistical cloud schemes

- Define a single cloud variable s as the difference between the total water $q_t = q_v + q_c$ within the grid volume and that which would exist if the air were just saturated (e.g. Smith, 1990):

$$s = a_l(q_t - q_{sl}) \tag{3}$$

- q_{sl} is the saturation vapor mixing ratio with respect to the condensed water temperature $T_l = T - \frac{L_v}{c_P} q_l$
- The local deviation from the mean is:

$$s' = a_l(q_t' - \alpha_l T_l');\ \alpha_l = \frac{\partial q_{sl}}{\partial T};\ a_l = \left[1 + \frac{L}{c_p}\alpha_l\right]^{-1} \tag{4}$$

- The cloud water content is calculated on the assumption that sufficient CCN are present to remove any supersaturation.

Statistical cloud schemes

- The fluctuations represented here are not necessarily due entirely to turbulence, but rather to all unresolved processes. The grid-box mean of $s^{'}$ =0 as $\overline{q_t^{'}}$ and $\overline{T_l^{'}} = 0$.
- The standard deviation of $s^{'}$ is:

$$\sigma_s = a_l \sqrt{\overline{q_t^{'2}} + \alpha_l^2 \overline{T_l^{'2}} - 2\alpha_l \overline{q_t^{'} T_l^{'}}} \tag{5}$$

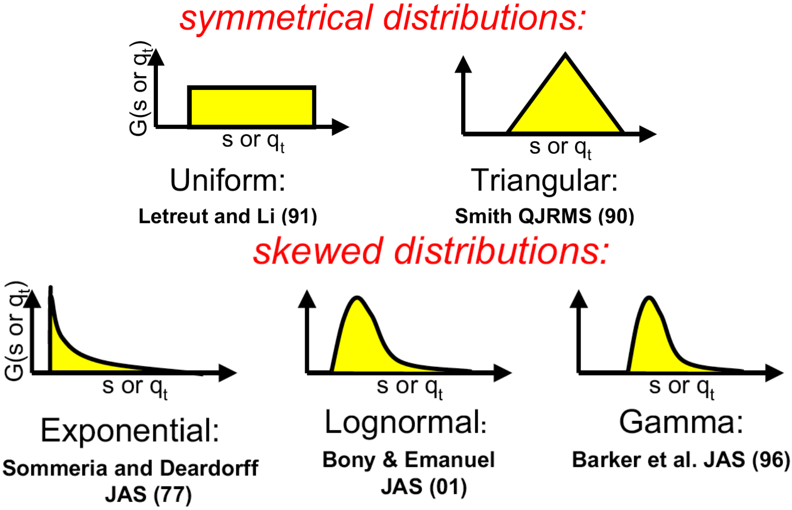
- C and ensemble mean cloud water content q_c are expressed in terms of a distribution function G for the normalized variable $t = s^{'}/\sigma_s$:

$$C = \int_{-Q_1}^{\infty} G(t)dt \tag{6}$$

$$q_c = 2\sigma_s \int_{-Q_1}^{\infty} (Q_1 + t)G(t)dt \tag{7}$$

where $Q_1(= a_l[\frac{q_t - q_s}{\sigma_s}])$ is the normalized mean saturation deficit (condensation occurs if $t > -Q_1$).

Choice of probability density function (PDF)



(Tompkins, ECMWF lecture, 2006)

Prognostic cloud scheme

- Introduced by Tiedtke (1993):

$$
\begin{aligned}
\frac{\partial q_c}{\partial t} &= A(q_c) + S_{CV} + S_{BL} + C - E - G_p - \frac{1}{\rho}\frac{\partial}{\partial z}(\rho \overline{w' q_c'})_{entr} \\
\frac{\partial C}{\partial t} &= A(C) + S(C)_{CV} + S(C)_{BL} + S(C)_C - D(C)
\end{aligned} \tag{8}
$$

- where A = transport, S = source by convection (CV), boundary layer turbulence (BL) and stratiform condensation (C), D = decrease of cloud area due to evaporation (E), G_p = generation of precipitation, and $\frac{1}{\rho}\frac{\partial}{\partial z}(\rho \overline{w' q_c'})_{entr}$ = flux divergence due to cloud top entrainment of stratocumulus.
- Also a combination of both, prognostic scheme schemes (Tompkins, 2002), exist

What microphysics scheme to choose?

- One-, two- or higher moment scheme?
- Prognostic equations for how many species? Cloud liquid water, drizzle, rain, ice crystals, snow, graupel, hail?
- Coupling to aerosol particles wanted? If so, at which level of detail?
  - Climatological, 3D monthly mean values of cloud condensation nuclei (CCN) and ice nuclei (IN) or the major aerosol species (sulfate, sea salt, mineral dust, black and organic carbon, nitrate)
  - On-line calculation of the major aerosol species in a one-, two- or higher moment scheme

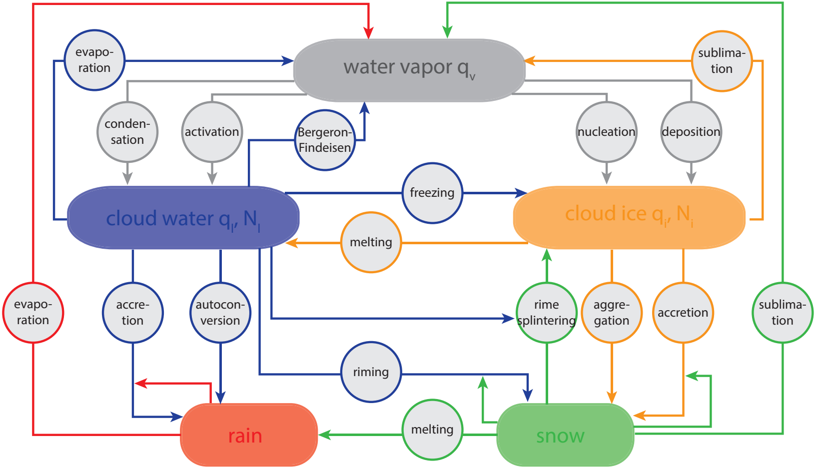
Typical approaches in NWPs:

- Solve prognostic equations for the mass mixing rations of q_l, q_i, rain, snow, and sometimes graupel and/or hail (one-moment scheme)
- Use a two-moment scheme with number concentrations of these hydrometeors only when the skill score improves (disadvantage: higher CPU demand)
- For a two-moment scheme: prescribe the aerosol number/mass concentrations or prescribe CCN/IN
- For a one-moment scheme: prescribe the cloud droplet and ice crystal number concentrations

Typical approaches in GCMs:

- Solve prognostic equations at least for the mass mixing rations of cloud liquid water q_l and cloud ice q_i
- Treat precipitation diagnostically, i.e. assume that it reaches the Earth' surface within one time step
- To study aerosol-cloud interactions:
  - Solve additional prognostic equations for the number concentrations of cloud droplets and ice crystals
  - Couple to an aerosol microphysics scheme that solves prognostic equations for the number and mass mixing ratios of the most important aerosol species in different size modes (nucleation, Aitken, accumulation and coarse mode)
  - Choose parameterizations of cloud droplet activation and ice crystal nucleation that depend on the aerosol species, their sizes and number concentrations

Cloud microphysics in the ECHAM GCM



based on Lohmann et al. (2008); figure from Fabian Mahrt

Aerosols in the ECHAM GCM

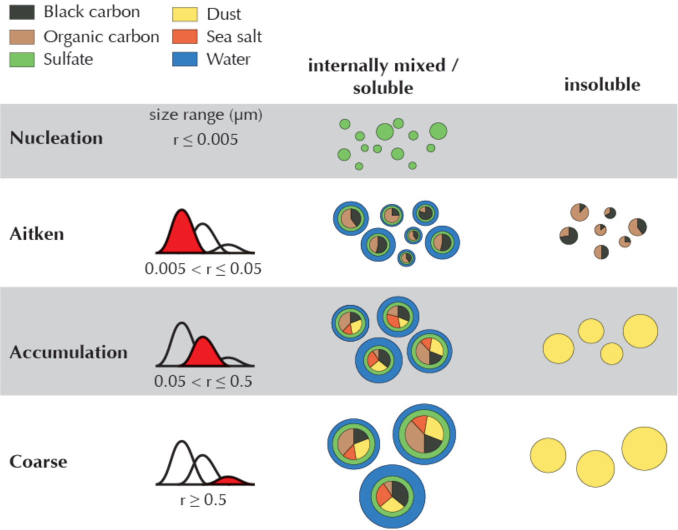
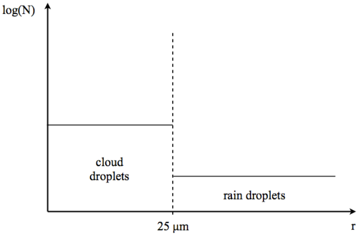


Figure from Elias Zubler based on Stier et al., ACP, 2005

Simplest microphysics scheme: Kessler (1969)

One-moment scheme (mass mixing ratios) for cloud water and rain

- Cloud water (q_l): droplets (5 - 30 μm) have negligible velocity
- Rain: rain drops that reach the surface within one model time step
- Autoconversion rate (AU): $= \alpha(q_l - q_{l,c})$, where $q_{l,c}$ is a threshold, e.g. 0.1 g kg^{-1} that needs to be exceeded



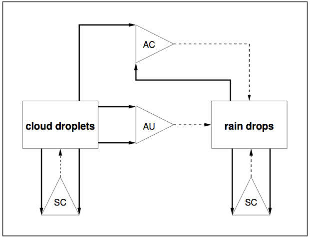
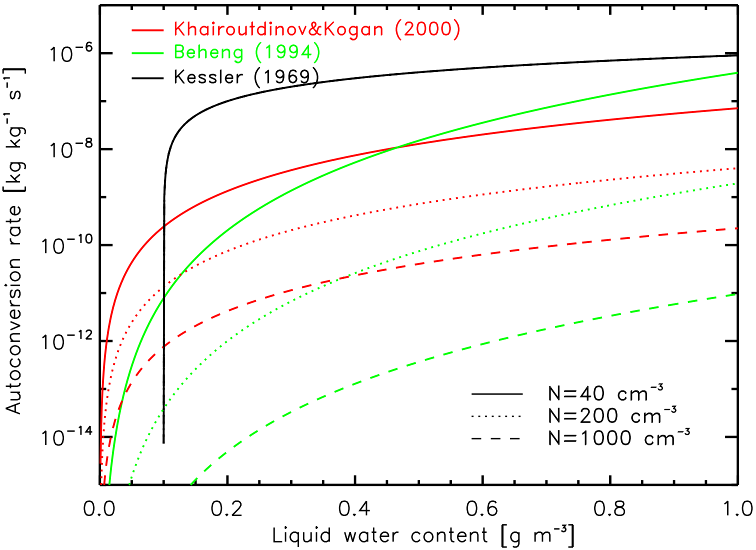
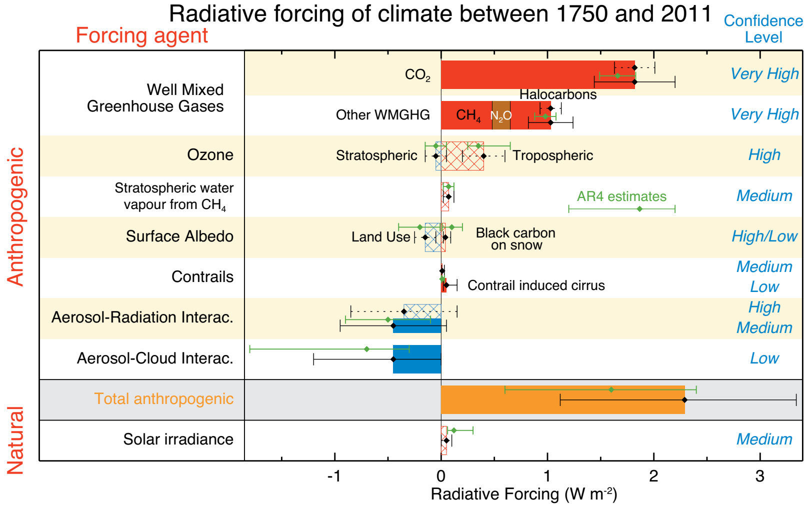


figure from V. Sant

Example of different autoconversion rates



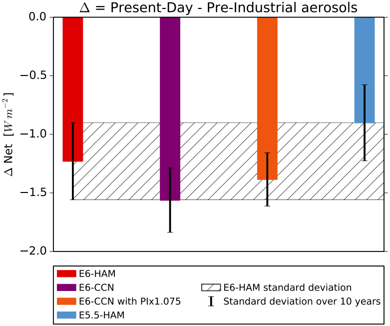
Aerosol radiative forcing (ARF): AR4 vs. AR5



Stocker et al., IPCC 2013, Fig. TS 6

CCN climatology simulations

- E6-HAM: coupled 2-moment cloud - aerosol microphysics schemes with params for cloud droplet activation and freezing that depend on properties of the aerosol particles
- E6-CCN: Use monthly mean CCN and IN concentrations from a multi-year simulation E6-HAM as input.



Take-home messages: large-scale cloud param.

- Cloud cover parameterization is needed for coarse resolutions as in climate models, but not in high-resolution NWP models
- The level of detail of a cloud microphysics (CMP) parameterization and the coupling to aerosols depends on the question being asked

Comparison of typical CMP params in GCMs and NWPs:

CMP param:	GCM	NWP
Prognostic species:	liquid water, ice	+ rain, snow (graupel, hail)
Order of scheme:	two-moment (mass, number)	one or two-moment
Coupling to aerosols:	online	prescribed CCN, no IN