UKCA_ACTIVATE

Aerosol activation and indirect effects in UKCA (UM 8.4)

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Outline

Introduction

- From a bulk perspective, water vapour condenses to form cloud when the local relative humidity (RH) reaches 100%.
- This typically happens as an air parcel rises and cools adiabatically to its dew point.
- However, the droplet size distribution depends on microphysical processes and in particular the available aerosol particles on which droplets can form.
- Changes in the droplet size can affect both the albedo and lifetime of the cloud, affecting the radiation balance.

A brief review of Köhler theory

- Homogeneous nucleation of water droplets cannot occur until RH reaches several hundred percent, and is never seen in the atmosphere.
- Instead, cloud droplets form by condensation onto hygroscopic aerosol particles which act as *cloud condensation nuclei*.
- The condensational growth of such particles into cloud droplets is referred to as *activation* and usually described by Köhler theory.
- This considers the competing effects of droplet curvature and surface tension (the Kelvin effect) and the presence of dissolved aerosol particles (the Raoult effect).

The Kelvin (curvature) effect

- To grow a small droplet, work must be done against its surface tension.
- This increases the equilibrium vapour pressure relative to that over a plane surface, and can prevent growth even when RH is significantly above 100%.
- This is why homogeneous nucleation doesn't happen under atmospheric conditions: embryonic droplets of pure water have such a high equilibrium vapour pressure that they evaporate.

The Raoult (solute) effect

- The equilibrium vapour pressure of a solution is reduced proportionately to the mole fraction of solute.

- This allows hygroscopic aerosol particles (e.g. aqueous solutions of $(NH_4)_2\,SO_4$ or NaCl) to grow into cloud droplets at RH $\approx 100\%$, overcoming the Kelvin effect.

The Köhler equation

- These two effects combine to give the supersaturation ($S = \mathrm{RH} - 1$) at which a droplet or radius r, in which an aerosol particle of dry radius a is dissolved, is in equilibrium:

$$S = \frac{\overbrace{A}^{\substack{\text{curvature parameter} \\ \text{(depends on temperature)}}}}{r} - \underbrace{B}_{\substack{\text{hygroscopicity parameter} \\ \text{(depends on composition)}}} \frac{a^3}{r^3}$$

The Köhler curve

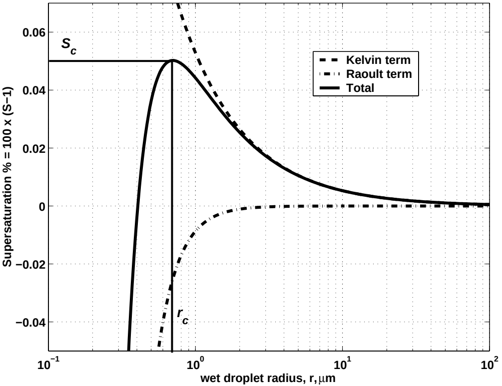

Figure : The Köhler curve shows how the supersaturation at which a droplet is in equilibrium varies according to its size. Its shape depends upon the quantity and composition of solute in the droplet. If the critical supersaturation S_c is reached, the droplet can grow without limit and is said to be *activated*. From McFiggans et al. (2006).

The supersaturation balance

- The key to calculating which aerosol particles activate is thus to find the maximum supersaturation S_{max} reached as the cloud forms.
- This is a balance between adiabatic cooling as the air parcel rises and condensation onto existing droplets:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \overbrace{\alpha \qquad \gamma}^{\text{size-invariant coefficients}} \underbrace{w}_{\text{updraught velocity}} - \gamma \underbrace{\frac{\mathrm{d}W}{\mathrm{d}t}}_{\text{condensation rate}}$$

- Settings $\frac{\mathrm{d}S}{\mathrm{d}t} = 0$ leads to a nonlinear integral equation for S_{max} which cannot be solved analytically, and hence a variety of parameterisations have been developed.

Parameterisation

- The parameterisation in UKCA (Abdul-Razzak and Ghan, 2000) uses an empirical fit to detailed numerical simulations with a parcel model to estimate S_{max}.
- This is formulated for multiple internally-mixed log-normal modes, as used in GLOMAP-mode, with all modes in competition for the available water vapour.
- Once S_{max} is known, the the Köhler equation can be used to find the critical radius above which aerosol particles in each mode will activate.
- It is then a simple matter of integrating the log-normal distributions to calculate the number of droplets formed.

Dependence on vertical velocity

- The supersaturation balance depends strongly on the vertical velocity.
- Within the turbulent environment at cloud base, the local vertical velocity varies considerably.
- Following West et al. (2014), the activation scheme is integrated over a 20-bin normal distribution of vertical velocity, truncated at zero.

$$W \sim \mathrm{N}\left(w_{\text{large-scale}}, \max\left(\frac{2}{3}\underbrace{\mathrm{TKE}}_{\substack{\text{turbulent kinetic energy}\\\text{from boundary layer scheme}\\\text{– this formulation assumes isotropic turbulence}}}, \Big(\overbrace{0.1\ \mathrm{m\,s^{-1}}}^{\substack{\text{in practice, this limit}\\\text{is hit too often...}}}\Big)^2\right)\right), \quad W > 0$$

Implementation in UKCA (West, 2012)

- The UM has a bulk cloud scheme with no prognostic cloud droplet number concentration (CDNC).
- At (the end of) each timestep, CDNC is diagnosed as the number concentration of activated droplets calculated by the activation scheme (with a hard minimum of $5\,\text{cm}^{-3}$).
- The CDNC diagnosed at cloud base is used as a uniform profile throughout any contiguous layers of liquid cloud above, as the bulk cloud scheme handles neither transport nor depletion by coalescence.

Aerosol activation

- Implemented in `UKCA_ACTIVATE`, which is called after the rest of GLOMAP-mode, directly from `UKCA_MAIN1`.
- Inputs are thus 3D (UM-style) rather than 1D (GLOMAP-style) arrays, and aerosol inputs are in tracer form (mass and number mixing ratios) rather than `ND` and `MD` arrays.
- Dry radius is obtained by pulling it back out of the `mode_diags` array.
- Due to shared heritage with other implementations, the arrays are internally reshaped to 2D.

Aerosol activation (2)

- UKCA_ABDULRAZZAK_GHAN is called to evaluate the actual parameterisation:
  - calculation of curvature and hygroscopicity parameters;
  - empirical fit to calculate max. supersaturation reached;
  - calculation of how many particles activate in each mode as a result;
  - all integrated over updraught PDF.
- The diagnosed CDNC is then output to D1 and section 34 via a reserved slot in the chem_diags array, for coupling to the radiation and precipitation schemes.
- Other diagnostics are output to section 38 via the mode_diags array, in a set of reserved elements left untouched by UKCA_AERO_CTL.

Indirect effects

- The indirect effects work via the CDNC dependence of processes in the radiation and precipitation schemes.

- The CDNC calculated in `UKCA_ACTIVATE` is passed through to these schemes via D1, much as for `UKCA_RADAER`, using the interface in `UKCA_CDNC_MOD`.

First indirect (albedo) effect: radiation coupling

- If this is enabled in the UMUI (`L_UKCA_AIE1=.TRUE.`), the CDNC from UKCA is passed down into the radiation scheme and used in the calculation of droplet effective radius in `R2_RE_MRF_UMIST`.
- There are many layers of forwarding routines, but it's passed through from `ATMOS_PHYSICS1` as `n_drop_pot`!
- This causes the effective radius, and hence the cloud albedo, to depend on the number of activated droplets, giving rise to the first indirect effect.

Second indirect (lifetime) effect: precip. coupling

- If this is enabled in the UMUI (`L_UKCA_AIE2=.TRUE.`), the CDNC is passed down into the precipitation scheme (`LS_PPN`) and used in the calculation of the droplet size distribution (`LSP_TAPER_NDROP`) used in the autoconversion parameterisation (`LSP_AUTOC`).
- This causes the autoconversion rate to respond to changes in the number of activated droplets, giving rise to the second indirect effect.
- The details of the CDNC dependence can be found in UMDP 26, which decribes the large-scale precipitation scheme in great detail.

Configuration via UMUI: activation

- In UKCA (Section 34) "MODE" sub-window, setting logicals in `UKCA_OPTION_MOD`:
  - Switch to use Abdul-Razzak and Ghan in place of the older empirical aerosol–CDNC relation. This sets `L_UKCA_ARG_ACT`.
  - Switch to calculate diagnostics of the CCN that would activate at a range of fixed supersaturations (hard-coded in `UKCA_ACTIVATE.F90`). Sets `L_UKCA_SFIX`.

Configuration via UMUI: indirect effects

- In UKCA "coupling" sub-window, setting logicals in `UM_INPUT_CONTROL_MOD`:
  - Switch for the first indirect (albedo) effect in the radiation scheme. This sets `L_UKCA_AIE1`.
  - Switch for the second indirect (lifetime) effect in the precipitation scheme. This sets `L_UKCA_AIE2`.
- If these are set to `.FALSE.`, fixed values of CDNC over land and ocean are used instead.

Diagnostics: section 34, in D1

Item	Description	Units
162	mean CDNC in cloudy portion of grid box	m^{-3}
163	mean $CDNC^{-1/3}$ in cloudy portion of grid box	m

Diagnostics: section 38

Item	Description	Units
469	Mean no. conc. of activated NUCSOL in cloudy portion	m^{-3}
470	Mean no. conc. of activated AITSOL in cloudy portion	m^{-3}
471	Mean no. conc. of activated ACCSOL in cloudy portion	m^{-3}
472	Mean no. conc. of activated CORSOL in cloudy portion	m^{-3}
473	S_{max}: max. supersaturation in strongest updraught bin	%
474	Cloud base flag (1 at base, 0 elsewhere)	1
475	σ_w: st. dev. of updraught PDF	$m\,s^{-1}$
476	Liquid cloud fraction as seen by activation scheme	1
477	Grid-box mean CDNC $= (34, 162) \times (38, 476)$	m^{-3}
478	Liquid cloud flag (1 if liquid present, 0 elsewhere)	1
479	Cloud-masked CDNC $= (34, 162) \times (38, 478)$	m^{-3}
480	Cloud-masked $S_{max} = (38, 473) \times (38, 478)$	%
481	Cloud-masked W_{char} (uniform updraught which would activate the same number of droplets as the full PDF)	$m\,s^{-1}$
482	Cloud-masked $\sigma_w = (38, 475) \times (38, 478)$	$m\,s^{-1}$
483	Cloud-masked TKE as seen by activation scheme	$m^2\,s^{-2}$
484	Surface CCN at fixed supersaturation (each level in diag. represents a different supersaturation) *only if enabled*	m^{-3}

Finally, a note on forcing

- The first indirect (albedo) effect can be studied using the instantaneous radiative forcing diagnostics in a "double-call radiation" run, just like the direct effect.
- This is not true for the second indirect (lifetime) effect, which only modifies the radiation budget via feedbacks from the hydrological cycle.
- Studies including the second indirect effect must use "single-call radiation" simulations in which the aerosol feedbacks are active.

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