Aerosol-cloud interaction studies using ATHAM

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We are developing a new cloud-aerosol microphysical module with explicit treatment of nucleation processes and user-controlled accuracy suitable for use across a range of scales.

We show the module works well for warm-rain processes. We have used it to show that adjustment schemes for temperature prognosis can introduce significant errors in the treatment of nucleation processes. Preliminary results from a mixed phase scheme and use of the the module within the LES-type model ATHAM are also presented.

Introduction

Cloud-aerosol interactions have an effect on cloud lifetime and cloud cover and consequently affect rainfall patterns and atmospheric circulation. It is therefore necessary to find ways to quantitatively account for these processes in atmospheric models in order to make robust predictions about future climate. Mixed-phase cloud modelling remains a challenge, due partly to the difficulty in incorporating them accurately within numerical models and also to a lack of knowledge of the relative importance of the various processes involved.

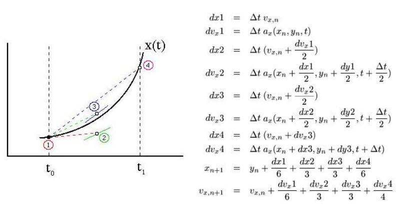
We are developing a new module combining existing aerosol microphysics, that simulates particle size distributions, with a synthesis of several existing cloud schemes that predict mass and number of various hydrometeor classes, including the formation of precipitation. It includes a numerical integrator with user-defined accuracy and adaptive time-stepping to enable accurate treatment of the short timescale processes involved.

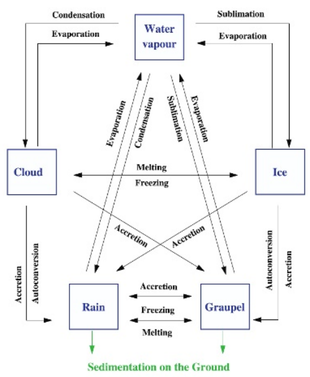
The method

A two-moment scheme to describe the mass (specific mixing ratio) and number concentration of the various hydrometeors has been developed. This involves two prognostic equations for each class of condensed water plus one for water vapour. As far as possible, the relevant dynamical and microphysical processes will be described from first principles.

In order to include a more complete description without incurring extra computational cost, the module features a new, dedicated numerical solver for the equations that describe the aerosol and cloud physics. The stability of numerical schemes can be rather questionable, and addition of new processes while retaining good numerical stability can be be a problem. The project aims to deliver a numerically stable, computationally efficient solver to allow for both improved efficiency and increased stability when new processes are added to the numerical scheme.

For the solver, we have chosen Runge-Kutta scheme with adaptive time-stepping [Press et al., 2003]. The scheme is illustrated schematically below. The new solver works well when the tendencies are large, such as in cloud activation, and is also applicable to longer timescale processes, such as coagulation.





Aerosol and cloud microphysics

We use the method of moments to develop expressions for the tendencies in aerosol, water vapor and liquid water. Further, a modal approach to the description of aerosol dynamics is employed [Whitby and McMurry, 1997].

The particle size distributions are described by Gamma distributions, which have been shown to be appropriate for cloud and rain distributions.

$$n(D) = N_i \frac{\alpha_i}{\Gamma(\nu_i)} \lambda^{\alpha_i \nu_i} D^{\alpha_i \nu_i - 1} \exp -(\lambda_i D)^{\alpha_i}$$

where Ni is the number concentration, α the shape and λ the width parameters. Tendencies are formulated in terms of the moments of the distribution - the k-th moment of the distribution is defined as

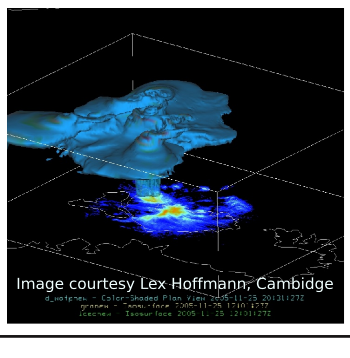
$$M^k(D_p) = \int_0^\infty D_p^k N(D_p) dD_p$$

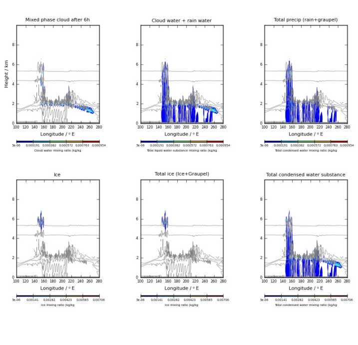
with two prognostic equations allowing prediction of mode mass and number, from which Ni and λ may be recovered if required. Future work will address the third parameter, by predicting modal surface area.

Active Tracer High-resolution Atmospheric Model (ATHAM)

The modules will be developed for use in both climate and mesoscale models. For initial work, the Active Tracer High Resolution Atmospheric Model (ATHAM) of Graf, Herzog and co-workers will be used to simulate cloud formation in both warm and mixed-phase clouds [Oberhuber et al., 1998].

ATHAM includes modules handling different aspects of the cloud dynamics: a dynamical core solves the equations of motion for gas and aerosol particles; turbulence is included, enabling the treatment of entrainment/detrainment processes; surface processes and cloud microphysics are included as stand-alone modules. The use of this model also permits the description of the phase transfer processes between water vapour, liquid water and ice and to estimate their influence on the energy budget of e.g. convective ascent.





First results

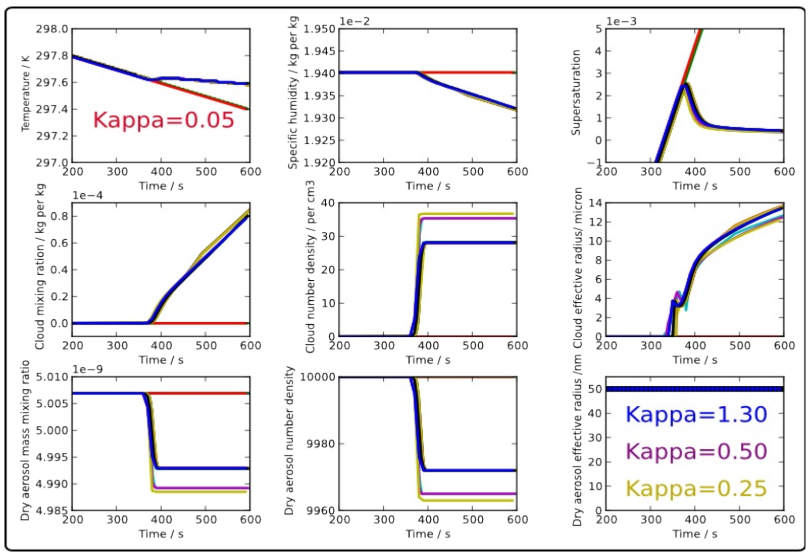
Initial runs have been performed in a 'single-box' configuration. The model uses a simple warm cloud microphysics to assess performance and to establish suitability for incorporation into ATHAM.

An underlying aerosol distribution was assumed of 1 x 10^4 particles per cc, with a mode effective radius of 50 nm. An effective variance of 0.3 was chosen. The vapor pressure over the particle surface described by Kappa-Koehler theory (Petters and Kreidenweis, 2007].

The critical supersaturation was diagnosed on the basis of the aerosol dry radius and solute effects described by the kappa parameter using a simple count-back procedure. The number of CCN activated was calculated from the underlying aerosol size distribution and the ambient supersaturation.

Once formed, the activated particles grow by condensation of water vapor. Formation of rain was described using the bulk parameterization of Kessler [Kessler, 1969].

The effect of Kappa and of the cooling rate was investigated. Moderate to small effects of Kappa were observed for cooling rates of 1 x 10^{-3} Ks^{-1} (corresponding to very slow ascent).

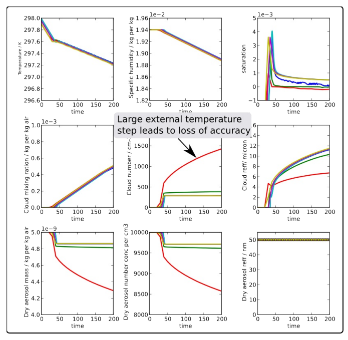


Effect of hygroscopicity parameter, Kappa, on cloud nucleation using explicit activation

Use of adjustment scheme introduces errors

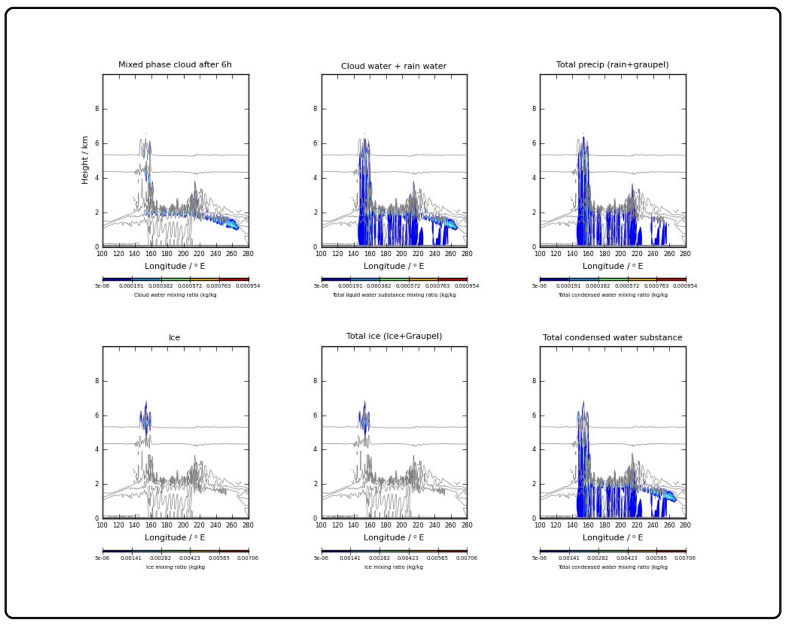
The effect of supplying the temperature to the microphysical module was assessed. If, instead of calculating the temperature change internally, the temperature is supplied to the model at each time step, as in an adjustment scheme, the error introduced becomes significant for timesteps greater than 10s.

The figure shows results for a cooling rate of 1 x 10^{-2} Ks^{-1}.



Adjustment with moderate cooling leads to significant discrepancies in activation tendencies

Aerosol and mixed phase cloud microphysics



Simulation of early stages of convective cloud using single moment scheme and RK4 module

Conclusions and outlook

Two-moment scheme has been developed using adaptive time-stepping routine applicable to a wide range of processes, enabling user-defined accuracy in the treatment of aerosol and cloud microphysical processes.

Further work will deploy the scheme within ATHAM, using the mixed-phase microphysics to study the effect of the underlying aerosol on cloud formation.