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Evaluating the effects of microphysical complexity in idealised simulations of trade wind cumulus using the Factorial Method

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Abstract

The effect of microphysical and environmental factors on the development of precipitation in warm idealised clouds are explored using an idealised process modelling framework. A simple one-dimensional column model is used to drive a suite of microphysics schemes including a flexible multi-moment bulk scheme (including both single and dual moment liquid water) and a state-of-the-art bin-resolved scheme with explicit treatments of liquid and aerosol. The Factorial Method is employed to quantify and compare the sensitivities of each scheme under a set of controlled conditions, in order to isolate the effect of additional microphysical complexity in terms of the impact on surface precipitation. For the schemes considered, and in the absence of entrainment, surface precipitation totals were found to depend increasingly on the meteorological conditions as the level of microphysical complexity is increased. The dual-moment liquid bulk scheme was shown to provide the best agreement with the bin scheme when the cloud base updraught speeds are relatively weak. At higher updraughts, all schemes show that the sensitivity to the magnitude of vertical velocity reduces dramatically, and any subsequent change in precipitation is governed almost entirely by the change in aerosol concentration. However the effect of changes in temperature were found to be underestimated in the bulk schemes compared to the bin scheme; this can be accounted for through differences in the depletion of rain below cloud base by evaporation. Collectively, these results demonstrate the usefulness of the Factorial Method as a model development tool for quantitatively comparing and contrasting the behaviour of microphysics schemes of differing levels of complexity within a specified parameter space.

1 Introduction

Shallow convective clouds play an important role in the global circulation and the hydrological cycle of the Earth system. Sub-tropical marine shallow cumuli, capped by the

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD

10, 23497–23537, 2010

Evaluating the effects of microphysical complexity using the Factorial Method

C. Dearden et al.

trade wind inversion, transport moisture vertically within the cloud layer, where it is subsequently detrained and transported to the tropics by the trade winds to fuel deep convection within the Inter Tropical Convergence Zone (ITCZ). Furthermore, warm clouds are particularly sensitive to cloud condensation nuclei (CCN) concentrations by virtue of aerosol-cloud interactions (Twomey, 1977; Albrecht, 1989), and changes in aerosol concentration could have important consequences for weather and climate through modification of the liquid water content of trade wind cumulus. Thus the treatment of precipitation processes associated with warm convection is an important consideration in Numerical Weather Prediction (NWP) and climate modelling. Field campaigns in recent years have strived to enhance our understanding of the relevant microphysical processes and have, for example, focused on precipitation development in the Caribbean as part of the Rain In shallow Cumulus over the Ocean project (RICO, Rauber et al., 2007), and the indirect effects of aerosols on shallow convection in the INDian Ocean EXperiment (Heymsfield and McFarquhar, 2001). An important part of such projects is to compliment the in-situ observations with cloud-resolving model studies (e.g., Abel and Shipway, 2007; Wang and McFarquhar, 2008), the results from which can feed into improving the microphysics of warm convection in larger-scale models.

However the representation of warm convection in General Circulation Models (GCMs) remains a major source of uncertainty. At the heart of the uncertainty in GCMs is the reliance upon dedicated mass flux-based convection schemes to parameterize the effects of convective cloud unresolved by the model grid. Such mass flux parameterizations have traditionally lacked the necessary microphysical detail to enable any sort of coupling between aerosol concentrations and cloud droplet number; this is a major obstacle in reducing the uncertainty surrounding global estimates of the 1st indirect effect (IPCC, 2007) and the climate sensitivity (Bony and Dufresne, 2005). Yet in recent years it has at least become feasible to include indirect effects on warm convective clouds in limited-area models, for instance via the Convective Cloud Field Model (CCFM) for use in regional climate studies (Graf et al., 2009), and in mesoscale models with convection-permitting resolutions based on bulk microphysics. Bulk schemes

ACPD
10, 23497–23537, 2010

assume a functional form of the hydrometeor size distribution and solve prognostic equations representing the moments of the distribution, namely the mass mixing ratio for single-moment (1-m) schemes and additionally number concentration for dual-moment (2-m). Bulk schemes are much cheaper to run than explicit bin schemes, but must make simplifying assumptions in order to ensure computational efficiency. As the reliance on bulk microphysics schemes is likely to continue in the future, it is necessary to validate their performance relative to more explicit bin-resolved microphysics. Studies such as those by Morrison and Grabowski (2007) have assessed the performance of 2-m bulk microphysics in terms of simulating warm clouds within an idealised 2-D framework using an explicit bin scheme as a benchmark, where both schemes assume a fixed background aerosol size distribution. They considered idealised representations of a shallow cumulus regime and a stratocumulus regime. However such regimes can themselves cover a broad range of environmental conditions, and it is important to assess the sensitivity of the microphysics to variations in the meteorological conditions as well. It is fair to say that in general, the need to account for changes in meteorology when evaluating aerosol effects on clouds has been somewhat overlooked. Recent exceptions include the work of Wang and McFarquhar (2008) and Teller and Levin (2008). In the case of the latter, the Factorial Method (FM) was used to quantify the sensitivity of precipitation in simulations of mixed-phase convective cloud when both meteorological and microphysical factors occur synergistically. Dearden (2009) proposed to expand the use of the FM across a hierarchical suite of microphysics schemes within a one dimensional framework, consisting of a bulk scheme with the choice of both 1-m and 2-m liquid water, and an explicit bin scheme with prognostic treatment of aerosol, capable of accounting for the effects of aerosol composition. Such a method allows the environmental conditions to be easily constrained, and is adopted here in relation to identifying the key factors that govern precipitation development in sub-tropical marine shallow cumulus cloud. The sensitivity of the bulk schemes can be quantified and compared to that of the bin scheme such that it will be possible to isolate those meteorological regimes where the additional microphysical complexity is warranted. Equally

ACPD
10, 23497–23537, 2010

as important given the computational cost of running models, is to identify any meteorological regimes within which the additional microphysical complexity has little or even negligible impact on the simulation of precipitation.

This paper is organised as follows. A description of the microphysics and the idealised driver model are presented in Sect. 2. Section 3 considers the details of the experimental design based on the FM. The results from each microphysics scheme are analsyed and compared in Sect. 4, and the potential implications of these findings are addressed in Sect. 5.

2 Model configuration

The suite of microphysical schemes considered for testing are embedded within a 1-D column framework, within which the initial temperature and humidity profiles are prescribed, along with the vertical velocity field responsible for producing the supersaturation necessary for cloud formation. The hierarchy of microphysical complexity ranges from a fully explicit treatment of liquid water and aerosol to a bulk parameterization of warm rain processes with the option of both 2-m and 1-m cloud liquid water. A detailed description of each of the schemes considered is now given, starting with the bin microphysics.

2.1 Bin microphysics

The bin scheme used in this study is the Aerosol-Cloud-Precipitation-Interaction-Model (ACPIM), developed at the University of Manchester. ACPIM is a state-of-the-art process model that has been created primarily to study the effects of aerosol on mixed-phase cloud as part of the core modelling suite for the Aerosol Properties Processes And InfluenceS on the Earth's climate (APPRAISE) project. For the purpose of this study its use is restricted to liquid-only processes. The ACPIM model supports a prognostic treatment of aerosol, allowing the effects of the aerosol size distribution and also

ACPD
10, 23497–23537, 2010

composition to be explored. Activation of droplets in ACPIM is based on Kohler theory. 147 size bins are used to resolve the liquid drop size distribution, and 154 are used for aerosol. The ambient supersaturation is resolved using a variable sub-step to ensure it is captured to a sufficient level of accuracy, regardless of the choice of the main model timestep. Each aerosol size bin solves prognostic equations for the mass and number of aerosols. Condensation occurs continuously via the droplet growth equation (Pruppacher and Klett, 1997), where the equilibrium vapour pressure is supplied by Kohler theory using data from a thermodynamic model (ADDEM, Topping et al., 2005). The growth equation is solved explicitly using the Variable-coefficient Ordinary Differential Equation solver (VODE) available from the netlib repository (www.netlib.org). Initial growth of the cloud droplets is dominated by the diffusional growth equation, and subsequent growth to rain drop size through the collision-coalescence process is handled by explicitly solving the 2-D stochastic collection equation (Bott, 2000), with the collision efficiency based on the look up table by Hall (1980). In the version of ACPIM used for this study, the efficiency of coalescence is taken to be unity, such that the overall collection efficiency is equal to the Hall collision efficiency. In terms of gas kinetic effects, the condensation coefficient in all cases is taken to be unity, based on Laaksonen et al. (2005).

For this study, a single log-normal aerosol size distribution is used with a geometric standard deviation of 1.28, and a geometric mean diameter of 0.06 microns. These values are based on the bimodal distribution defined in the RICO model intercomparison study; the giant mode was found to have minimal impact on precipitation for the range of CCN concentrations considered. In terms of the aerosol composition, pure sea-salt was assumed in all cases. Tests with ammonium sulphate were also performed, although the effect on precipitation was found to be small, with only a slight increase in rain at lower updraught speeds.

ACPD
10, 23497–23537, 2010

2.2 Bulk microphysics

The bulk scheme is based on a liquid-only version of the scheme described in Morrison et al. (2005), such that the two classes of hydrometeor considered are cloud liquid water and rain. The scheme is a flexible multi-moment scheme, allowing the choice of either a 1-m or 2-m treatment for liquid droplets. The scheme also contains different options for the treatment of droplet activation in the 2-m liquid case.

Saturation adjustment is used in the bulk schemes, such that any water vapour present above 100% relative humidity is assumed to instantaneously condense onto existing cloud droplets. Such an assumption is valid for model timesteps greater than one second. The autoconversion scheme in all cases is based on the scheme of Khairoutdinov and Kogan (2000), henceforth referred to as the KK scheme. The KK scheme was tuned to bin microphysical simulations of marine boundary layer clouds and so is considered to be an appropriate choice for this study.

In all cases, a 2-m scheme is used for rain. Dearden (2009) had originally proposed to include a 1-m treatment for rain as well, but this was not included in the final experimental design because it was not possible to identify a single value of the rain intercept parameter that was appropriate for different values of droplet number. The benefits of 2-m rain over 1-m rain have been well documented recently, e.g. in the studies by Morrison et al. (2009), although Shipway and Hill (2010) and references therein suggest that 2-m rain schemes with an invariant shape parameter can suffer from the problem of excessive size-sorting.

The particle size distribution for both rain and liquid is defined by a gamma distribution of the form

$$N(D) = N_0 D^{\mu} e^{-\lambda D} \tag{1}$$

where N is the number concentration as a function of particle diameter D. N_0 is the intercept parameter, λ is the slope parameter and μ is the shape parameter. N_0 is

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD

10, 23497–23537, 2010

Evaluating the effects of microphysical complexity using the Factorial Method

C. Dearden et al.

determined as a function of the number concentration

$$N_0 = \frac{N\lambda^{\mu+1}}{\Gamma(\mu+1)} \tag{2}$$

For rain, μ is set to zero, which reduces equation 2 to an exponential distribution, such that $N_0 = N\lambda$.

Terminal fall speeds for rain are given by the following

$$V_r(D) = (\rho_0/\rho)^{g_r} a_r D^{b_r} e^{f_r D}, \tag{3}$$

where ρ_0 is the density of air at sea level, and the constants a_r,b_r, f_r and g_r are set to 841, 0.8, 0.0 and 0.54 respectively, following Liu and Orville (1969).

The different combinations of the bulk scheme are now presented, starting with the simplest level of complexity.

2.2.1 1-m liquid, 2-m rain

In the simplest treatment considered here, only one prognostic variable is used to represent cloud liquid water (the mass mixing ratio), and the droplet number concentration is taken as a constant in the calculation of the intercept parameter in Eq. (2).

2.2.2 2-m liquid (Twomey activation), 2-m rain

Moving from 1-m to 2-m liquid grants the ability to predict droplet number, thus requiring an explicit term representing activation of cloud droplets. The first treatment of droplet activation considered is based on the parameterization of Twomey (1959), which in Rogers and Yau (1989) is approximated as:

$$N \approx 0.88 c^{2/(k+2)} [7.10^{-2} w^{3/2}]^{k/(k+2)} \tag{4}$$

where w is the grid-scale vertical velocity in cm/s and the droplet number concentration N is in cm^{-3}. The variables c and k are activation parameters where c represents the

ACPD
10, 23497–23537, 2010

number of CCN active at 1% supersaturation and k represents the ease with which droplets form. In this study, a value of 0.4 is used for k based on measurements of tropical maritime airmasses (Pruppacher and Klett, 1997).

2.2.3 2-m liquid (Abdul-Razzak activation), 2-m rain

The second option for droplet activation is based on the parameterization of Abdul-Razzak et al. (1998), henceforth identified as A-R, which assumes a single log-normal aerosol size distribution for a given chemical composition, requiring knowledge of the geometric mean radius of aerosol particles and the standard deviation. This information is then used to parameterise the maximum supersaturation in the rising air parcel given the vertical velocity, which in turn determines the fraction of aerosols activated to form cloud droplets. The aerosol log-normal parameters used are the same as those employed to initialise the bin model, as is the assumed chemical composition. By repeating the 2-m liquid simulations using the A-R scheme for droplet activation, it will be possible to quantify the benefits of explicitly specifying the aerosol log-normal parameters, albeit assuming a fixed form. Dearden (2009) had originally proposed the option of a prognostic treatment of aerosol for the bulk scheme; however this was not considered due to time constraints. The possibility of a 2-m aerosol scheme coupled to the 2-m bulk microphysics will be revisited in future work on the subject.

2.3 Driver model configuration

The bulk microphysics are driven using the 1-D Kinematic Driver Model, KiD (Shipway and Hill, 2010) whilst the ACPIM microphysics is currently embedded within its own 1-D column model. To obtain consistency with ACPIM, some changes have been made to the standard KiD model to ensure consistency between driver models, thus ensuring that both bin and bulk microphysics schemes can be compared safely. The details of the necessary changes in the KiD model are now presented.

ACPD
10, 23497–23537, 2010

2.3.1 Advection

The advection scheme common to both driver models is a 4th order, positive definite, monotonic scheme (Bott, 1989, 1992). The Bott scheme is used to advect vapour and liquid water. The default advection scheme in the KiD model is the Total Variance Diminishing (TVD) scheme of Leonard et al. (1993) known as ULTIMATE, but for the purpose of this study the Bott scheme is used for consistency with ACPIM. There is no advection of potential temperature in the column; indeed the potential temperature and pressure fields are held fixed such that the microphysics is not permitted to influence the evolution of the dynamics. This was deemed necessary such that the pure microphysical behaviour of each scheme could be compared fairly, in the absence of feedbacks. A slight caveat is in the handling of sedimentation. In ACPIM, precipitation is advected using the 4th order Bott scheme, whereas in KiD, sedimentation of cloud liquid water and rain is handled implicitly within the bulk microphysics scheme.

2.3.2 Initialisation of thermodynamics

Both models accept inputs for potential temperature and vapour mixing ratio at specified height levels; this defines the initial thermodynamic profiles. These points are then linearly interpolated onto the model vertical grid at every level. The model then converts from potential temperature to absolute temperature to pass to the microphysics, for which it needs the pressure field. Pressure is obtained by solving the following first-order differential based on the hydrostatic equation and the ideal gas law:

$$\frac{dp}{dz} = \frac{-pg}{RT} \tag{5}$$

Equation (5) is solved based on Press et al. (2007) in both KiD and ACPIM.

ACPD
10, 23497–23537, 2010

3 Experimental design

3.1 Initial conditions and idealised forcing

The forcing for the idealised warm shallow cumulus case is based on the "warm1" configuration as defined in the KiD documentation which can be downloaded from http://appconv.metoffice.com/microphysics/doc.html. It consists of a single updraught, constant in height and sinusoidal in time:

$$w(z,t) = \begin{cases} w_1 \sin(\pi t/t_2) & \text{if } t < t_2, \\ 0.0 & \text{if } t > t_2 \end{cases} \tag{6}$$

The timescale t_2 is dependent upon the peak updraught speed, w_1, such that $t_2 = 1200/w_1$. For a peak updraught speed of 0.5 m/s, this would result in the vertical velocity field reducing to zero after 2400 s. Thus values of w_1 greater than 0.5 m/s would reduce the timescale over which the updraught is applied. The evolution of the updraught velocity with time for different values of w_1 is plotted in Fig. 1, as applied equally at every vertical level.

The warm1 case is based on the composite profile used to initialise models for the GCSS RICO intercomparison. However, as noted in Shipway and Hill (2010), there is a slight issue with simulations based on the warm1 profile in that the resulting profile of liquid water content decreases with height after reaching a maximum above cloud base, which is not necessarily realistic for a warm shallow convective cloud. Despite this, and given the highly idealised nature of the 1-D framework to begin with, the warm1 profile still acts as a suitable basis upon which to conduct a comparison of different microphysics schemes. The reader is made aware that in the 1-D intercomparison of Shipway and Hill (2010), the warm1 profile is modified to produce a slightly drier surface, which leads to a liquid water content profile that increases with height and an overall reduction in liquid water path. This produces reduced surface precipiation totals relative to the original warm1 profile, given the same peak updraught velocity.

ACPD

10, 23497–23537, 2010

Changes in temperature are considered such that the warm1 profile is shifted to cooler temperatures resulting in a constant cooling with height whilst keeping the relative humidity fixed. The result is such that changes in the dynamics do not affect the cloud height or depth. The temperature profile used in this study is plotted in Fig. 2. In all cases, the simulations are left to run for long enough until they have finished precipitating (typically two hours) and diagnostic output is available at the end of each timestep (every 5 s). The vertical resolution in both models is set to 30 m, with 100 levels giving a domain height of 3 km.

3.2 Experimental design for the Factorial Method

The experimental design based around the FM is now presented. It should be noted that changes in meteorological factors, namely the temperature profile and updraught velocity, are treated consistently in each scheme; however the choice of microphysical factors to explore depends on the level of complexity of the microphysics scheme in question. The factorial design is based around the 2^n design, meaning two values, arbitrarilly labelled "low" and "high", are assigned to n number of factors, and the effect of changing from the "low" to the "high" value is calculated for each factor. Values for each factor are chosen such that the effect of moving from the "low" value to the "high" value acts to reduce the amount of precipitation reaching the surface. Thus each factor can be evaluated in terms of its percentage contribution to precipitation suppression. In some cases, repetitions of the 2^n design are considered to allow the effect of more than one "high" value to be explored.

3.2.1 General example: 2^3 design

Consider the following general example based on 3 factors, labelled A, B and C respectively, each at two levels, yielding a 2^3 design. Thus eight treatment combinations (experiments) would be necessary to fulfill the requirements of the study. To denote low and high values, the geometric notation system is used such that "–" indicates low

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD

10, 23497–23537, 2010

Evaluating the effects of microphysical complexity using the Factorial Method

C. Dearden et al.

and "+" indicates high, and the eight runs required in the 2^3 design are given in Table 1. Table 1 also writes the treatment combinations based on the labelling system of lowercase letters, which in standard order is written as (one), *a*, *b*, *ab*, *c*, *ac*, *bc* and *abc*. In this system, the presence of a lowercase letter represents the high value of that factor, and the absence of a letter denotes the low value. The label (one) is used for the case when all factors are at their low value. Using the lowercase letter labels, it is possible to write down expressions for the main effects; that is, the average effect of each factor due to the change in value from low to high. Similar expressions for the interactions between main effects can also be derived. For full details on the calculation of the main effects and interaction terms based on a general 2^3 design, the reader is referred to Dearden (2009) and references therein.

3.2.2 Factorial design for bin microphysics

Table 2 summarises the factorial design for the ACPIM model. A 2^3 design is used, giving three factors in total, two of which, namely w_1 and T, are meteorological in nature and represent vertical velocity and the ambient temperature respectively. The remaining factor, CCN, is a microphysical factor which represents the number concentration of the aerosol present within the column at each vertical level. 36 numerical simulations are required to fulfill the design presented in table 2. The CCN factor is designed to explore the effect of increasing the aerosol number concentration from a starting value of 50/cc, whilst the geometric mean radius and standard deviation as defined in Sect. 2.1 are held constant.

3.2.3 Factorial design for bulk microphysics

Table 3 summarises the factorial design for the bulk microphysics, also based around a 2^3 design and requiring 135 simulations in each case. The reduced computational burden of the bulk parameterizations compared to the bin scheme is exploited to perform a more thorough exploration of the parameter space. The meteorological factors w_1

ACPD
10, 23497–23537, 2010

Evaluating the effects of microphysical complexity using the Factorial Method

C. Dearden et al.

and T are defined to be the same as in the bin scheme, although the w_1 factor covers a greater range of values. In the 2-m bulk scheme, the CCN factor relates to the maximum droplet number concentration permitted. For 2-m Twomey, this is equal to the value of c in Eq. (4). For 2-m A-R, the CCN factor relates to the aerosol number concentration based on the unimodal log-normal distribution, as in the bin scheme. In the 1-m scheme, the CCN factor is simply the prescribed value of droplet number, which implicitly assumes that all available aerosol have activated to form cloud droplets. It should be noted that no attempt was made to tune the bulk schemes to the bin scheme prior to running the experiments.

4 Results

4.1 Initial analysis of cloud fields

To illustrate the equality of the driver models, tests were performed based on both the bulk and bin microphysics with precipitation and sedimentation processes switched off, such that the only microphysical processes permitted are condensation and evaporation. The resulting liquid water paths from each scheme are plotted in Fig. 3. It can be seen that the curves agree so closely that they appear to be coincident, which confirms the consistency of the forcing conditions between driver models. It can also be concluded from this result that, once precipitation and sedimentation are permitted to occur, any subsequent differences in cloud liquid water path can be attributable to the treatment of these processes.

Figure 4 shows time-height plots from the bin and 2-m A-R schemes with precipitation and sedimentation enabled, for w_1=2 m/s, T=RICO and CCN=100/cc. In both cases, the dynamical forcing conditions produce a cloud whose base is around 500 m and a top at 2 km. As the prescribed updraught reduces to zero, and in the absence of any parameterised entrainment effects, a small fraction of cloud remains by the end of the simulations. To allow comparison of rain mixing ratios, the bin scheme defines rain as those liquid drops greater than 40 microns in diameter. Comparing the plots of droplet number concentration and rain mass shows that the bin simulation converts more of the cloud to rain than the bulk scheme; this is confirmed by the plots of cloud liquid and rain water path, also in Fig. 4. Given that the cloud liquid water paths are essentially the same in the absence of precipitation processes as shown in Fig. 3, this suggests that the collision-coalescence process in the bin scheme is more efficient at forming rain compared to the KK autoconversion scheme. The implications of the larger rain water path in the bin scheme are addressed later in Sect. 4.3.

It should also be remembered that the bulk scheme uses an exponential size distribution for rain, which implicitly assumes a shape parameter of zero. It is possible to test the validity of this assumption using the bin scheme; this is accomplished by fitting a gamma function to the resolved size distribution and diagnosing μ for rain through consideration of those drops greater than or equal to 40 microns in diameter. Figure 5 plots the evolution of the diagnosed shape parameter with height and time from the bin scheme. The value of μ varies considerably through the evolution of the cloud; around the onset of rain formation, μ is small but then increases as a mode is formed at later times. This result is important since a varying shape parameter has implications for rates of sedimentation (Milbrandt and McTaggart-Cowan, 2010) and hence evaporation, which could be significant in full 3-D simulations when feedbacks between microphysics and dynamics can influence the temperature of the sub-cloud layer.

4.2 Comparison of total precipitation

Table 4 shows the total precipitation amounts (in mm) for a subset of the total number of experiments from all four schemes. The nature of the table allows for comparison of each scheme as a function of changing CCN concentrations, cloud base updraught speeds and temperature profiles. Before a more rigorous analysis of this data is performed using the FM, some broad observations can first be made. The general pattern is for the total precipitation to increase as a function of increasing microphysical complexity, although it should be noted that this differs from the study of Shipway and Hill

ACPD
10, 23497–23537, 2010

(2010), where no trend is obvious. With regard the 1-m scheme, the total precipitation is essentially insensitive to vertical velocity; however in the other schemes, an increase in the magnitude of vertical velocity generally produces a reduction in the total amount of precipitation produced, with some minor exceptions to this pattern at low updraught speeds. This is a consequence of the ability of the other three schemes to predict droplet number; not all droplets are necessarily activated for a given updraught. The reduction of precipitation towards larger updraughts can be attributed to aerosol indirect effects, since stronger vertical velocities activate more CCN which in turn reduces the precipitation efficiency. It can also be seen that as vertical velocity is increased in the 2-m schemes, the total precipitation amounts begin to converge on those from the 1-m scheme. It is worthy of note that in some instances, an increase in w_1 from 0.5 ms^{-1} to 1 ms^{-1} actually results in a slight increase in precipitation. This is because some of the 0.5 ms^{-1} simulations are still producing small amounts of drizzle at the end of the integrations, and so have not quite finished precipitating by the time the simulations are stopped. Thus precipitation totals appear slightly underestimated in these cases. All four schemes agree, at least in a qualitative sense, on a reduction in precipitation amount as a function of cooling temperature. This is because under a fixed relative humidity, the available source of water vapour that is converted to liquid water during condensation is reduced as the temperature profile cools.

Figure 6 plots the precipitation rate and accumulated precipitation totals as a function of time, for those experiments highlighted in bold in Table 4. Figure 6 reveals that all four schemes show a delay in the onset of precipitation as a function of reducing vertical velocity. Precipitation reaches the surface slightly earlier in the bulk schemes; this is particularly noticeable towards lower updraught speeds. It is of interest that the results of Shipway and Hill (2010) and Morrison and Grabowski (2007) also demonstrate this feature despite different set-ups being used in each case, and so the tendency for bulk schemes to precipitate sooner appears to be a robust result. There is a relatively large jump in the peak precipitation rates between the 2-m bulk schemes and the bin scheme. It is interesting to note that in the KiD intercomparison study by Shipway

ACPD
10, 23497–23537, 2010

Evaluating the effects of microphysical complexity using the Factorial Method

C. Dearden et al.

and Hill (2010), the 1-m Morrison scheme was found to overestimate precipitation as validated against the explicit TAU bin model (Tzivion et al., 1987) in the same idealised framework. This is in contrast to the results shown here when comparing the Morrison bulk scheme with ACPIM, suggesting that differences between bin schemes can be as large as those between bulk schemes. A possible explanation for this difference is that the TAU-bin model accounts for the coalescence efficiencies of droplets based on the work of Ochs et al. (1986), which acts to reduce the number of successful collisions involving collector drops in the size range 0.1 to 0.6 mm, whereas the version of ACPIM used in this study assumes a coalescence efficiency of unity for all drop sizes. A detailed investigation into the impact of coalescence efficiencies on surface precipitation in bin schemes is beyond the scope of this study; however this should be considered in future work to determine the extent to which the choice of collection kernel can account for differences in behaviour between bin schemes.

4.3 Factorial analysis: quantifying the effects of CCN, w_1 and T (2^3 design)

The FM is now used to quantify the sensitivity of the schemes to the choice of microphysical and meteorological factors based on the data provided in Table 4. This section explores the relative importance of each factor as a function of time throughout the evolution of the cloud, and compares the sensitivities of each scheme to illustrate differences in behaviour. Calculation of the relative contributions for each factor and their interactions follows the methodology explained in Sect. 3.2.

Figure 7 considers the effect of changes in each factor, such that they all produce a reduction in surface precipitation, and the relative importance of each factor in reducing precipitation is expressed as a percentage of the total variance as a function of time. Specifically, an increase in w_1 is considered from 0.5 m/s to 2 m/s, along with a cooling of the temperature profile, T, from RICO to RICO-2, and an increase in CCN from 50/cc to 100/cc. Figure 7 shows that, in all four schemes, the suppression of precipitation is dominated by the change in vertical velocity in the early stages of cloud development. Beyond 40 minutes, the relative importance of the vertical velocity effect reduces and

ACPD
10, 23497–23537, 2010

by the end of the simulations, the change in temperature produces the largest effect on the suppression of precipitation. However the schemes disagree on the extent to which the temperature effect dominates the response. It can be seen that as the complexity of the microphysics increases, the relative contribution of CCN to the suppression of rainfall becomes less significant (blue lines in Fig. 7), and the effect of temperature (in red) becomes increasingly more dominant. In the case of the bulk schemes, this can be explained as follows. For slowly increasing updraught speeds such as the 0.5 ms^{-1} case, the ability to predict droplet number results in competition for water vapour between growth of existing droplets and activation of new droplets; this is demonstrated by Dearden (2009) using a simple lagrangian parcel model. The presence of CCN that activate at relatively low updraught speeds act as a sink of water vapour through growth by condensation, resulting in fewer droplets being activated overall compared to the 1-m scheme where the change in droplet number is prescribed to a fixed value regardless of the change in vertical velocity. This explains why the 1-m scheme has the largest relative contribution from the effect of CCN according to Fig. 7. However the 2-m A-R scheme, which includes a parameterization for the maximum supersaturation based on the vertical velocity and the properties of the aerosol size distribution, shows less of a change in droplet number at low updraught speeds and therefore less of an impact on precipitation. Consequently Fig. 7 shows that the 2-m A-R scheme improves the comparison with the bin scheme. However in more rapidly increasing updraughts, Fig. 8 shows that the benefit of diagnosing the maximum in-cloud supersaturation is lost and the 2-m A-R scheme produces largely the same sensitivity as the 1-m scheme.

The remaining difference in sensitivities between the bin and 2-m A-R bulk scheme as shown in Figs. 7 and 8 can be explained by considering the effects of evaporation below cloud base. It has already been shown that the rain mass falling out of the cloud in the bin scheme is greater than in the bulk schemes (Fig. 4), and that the bin scheme also produces consistently larger amounts of surface precipitation. This is consistent with larger rain drops which fall faster and therefore reduce the amount of

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD
10, 23497–23537, 2010

Evaluating the effects of microphysical complexity using the Factorial Method

C. Dearden et al.

rain evaporation. It is therefore hypothesised that differences in rates of sedimentation between the bulk and bin scheme are contributing to the different sensitivities to temperature and CCN. To explore this hypothesis, a sensitivity test was performed with the 2-m A-R scheme where the rain fall speed parameter b_r is increased from the default value of 0.8 to 0.825 to facilitate faster falling rain drops, in order to reduce evaporation and increase the amount of rain reaching the surface. Table 5 confirms that the effect of increasing the fall speeds for rain in the bulk scheme reduces the depletion of rain by evaporation, and in turn increases the surface precipitation totals. Figure 9 shows the effect of this change on the relative contributions in the bulk scheme, and illustrates how the effect of temperature becomes relatively more dominant in accordance with the bin scheme.

4.4 Factorial analysis: the effect of increasing vertical velocity for a fixed temperature (2^2 design)

It is now prudent to explore the sensitivity of surface precipitation to different levels of change in the vertical velocity field. The sensitivities of each scheme can be compared through consideration of the total effect on precipitation suppression, as described in Sect. 3.2; the sign and magnitude of the result indicates the direction and significance of the induced change. In this case the factors considered are the effect of CCN and w_1, with a fixed background temperature and humidity based on the RICO profile, yielding a 2^2 design. The results from the following FM analysis are based on values of surface precipitation accumulated at the end of the model simulation. Following the logic from Sect. 3.2, the 2^2 design has three degrees of freedom, such that the total effect is equal to the sum of the effects of the two main factors plus their interaction.

Figure 10 considers the total effect on precipitation resulting from repeated increases in w_1 from a low value of 0.5 m/s, plus the additional effect of an increase in CCN from 50/cc to 100/cc. For the 1-m scheme, Fig. 10 illustrates that the reduction in precipitation is due solely to the change in droplet number and is essentially insensitive to changes in updraught speed, which is clearly a limitation when comparing against the

ACPD
10, 23497–23537, 2010

bin scheme (solid black line) under the same conditions. Both 2-m schemes show an increase in suppression of rainfall as a function of increasing vertical velocity, which in a qualitative sense agrees with the bin scheme. However the 2-m Twomey scheme considerably overestimates the amount by which precipitation is suppressed. This can be understood by considering the total precipitation for the 50/cc case from Table 4. The 2-m Twomey scheme produces relatively more precipitation than the other schemes at low updraught speeds, suggesting that it activates fewer droplets at 50/cc. Thus when the value of CCN is increased to 100/cc, the suppression of precipitation appears to be exaggerated. The implications of this are that for this idealised case, a single value of k for different CCN concentrations is not appropriate, and that the value of k should change as a function of the assumed CCN concentration. This problem is alleviated in the 2-m A-R scheme due to the ability to diagnose the in-cloud supersaturation, and consequently the 2-m A-R scheme fares best in the comparison with the bin scheme.

For values of w_1 starting from 2 m/s (as shown in Fig. 11), all four schemes are in much better agreement in terms of the overall amount by which precipitation is suppressed. Thus it is difficult to justify the increased computational expense of a 2-m liquid scheme in this regime when a 1-m scheme performs in such a similar manner.

5 Summary and discussion

The Factorial Method has been used to compare the sensitivities of warm shallow cumulus cloud as simulated by four different microphysics schemes of increasing levels of complexity using an idealised 1-D column framework. The use of a simple driver model is intended to aid the comparison by removing the sensitivity to dynamical feedbacks, thus isolating the pure microphysical behaviour. The chosen factors include the magnitude of the cloud base vertical velocity, the ambient temperature profile, and the assumed number of aerosol available to act as CCN. The sensitivity of each scheme was assessed and quantified in terms of the suppression of precipitation at the surface, with the bin scheme used as a benchmark in order to validate the performance of the bulk schemes.

ACPD
10, 23497–23537, 2010

The reader is reminded that all of the results found in this study are strictly specific to the particular test case considered, and future work will be necessary using the tools presented in this paper to determine the generality of our results. With this in mind, the main conclusion to be drawn from this comparison is that for aerosol number concentrations typical of unpolluted sub-tropical maritime airmasses (i.e. between 50 and 100/cc), 2-m liquid schemes are shown to be preferable only within a certain meteorological regime, one where the cloud base vertical velocities are relatively weak. For the idealised case considered in this study, the benefits of being able to predict droplet number explicitly were demonstrated for cloud base updraught speeds up to 2 m/s, although the performance of the 2-m scheme was found to be dependent on the method of droplet activation used. Beyond this value, the 2-m schemes behaved much like the 1-m scheme and the additional complexity of an extra prognostic variable can no longer be justified. This suggests that for models with sufficient resolution, it is theoretically possible to optimise the balance between complexity and cost by allowing the model to choose the appropriate level of microphysical detail based on the magnitude of the cloud base updraught speed and knowledge of microphysical parameters such as aerosol number concentration and size. This stresses the importance of coupling the microphysics to a prognostic aerosol scheme to provide the necessary information.

Comparison of the schemes also highlighted some fundemental differences in behaviour worthy of comment. For instance, for the set of schemes considered and the particular case tested, a positive correlation was found between microphysical complexity and the amount of precipitation produced. A cooling of the temperature profile by 2 °C under a fixed relative humidity was also found to produce a relatively higher contribution to precipitation suppression in the bin scheme compared to the bulk schemes. The larger precipitation totals in the bin scheme are believed to be the main cause of the increased sensitivity to changes in temperature. It was possible to enhance the dominance of the temperature effect in the bulk scheme and thus improve the agreement with the bin scheme by modifiying the fallspeed parameters for rain, which acts to reduce the amount of evaporation and thus increase the surface

ACPD
10, 23497–23537, 2010

Evaluating the effects of microphysical complexity using the Factorial Method

C. Dearden et al.

precipitation. Differences in evaporation of rain between schemes may have important consequences in terms of dynamical feedbacks in full 3-D simulations, by modifying the extent of evaporative cooling of the sub-cloud layer. A consideration of such feedbacks is beyond the scope of this paper, but warrants further invesigation in future work.

It is important to note that separate intercomparison studies comparing bin and bulk microphysics with the same KiD framework do not necessarily support the conclusion that surface precipitation increases with microphysical complexity. Thus the enhanced sensitivity to temperature as seen in the ACPIM model may not be a general feature of bin schemes. Although it was shown that the bulk scheme could be effectively tuned to produce better agreement with this particular bin scheme, the same tuning may not necessarily improve the agreement relative to other bin schemes. Future work should therefore focus on investigating and understanding the origin of differences between bin schemes to increase confidence in their use as benchmarks against which simpler bulk parameterizations are validated. Suggested variables for investigation include the number of size bins used to resolve the liquid size distribution, the treatment of aerosol (whether a fixed log-normal mode or prognostic), the choice of collection kernel and vertical resolution.

A big caveat in producing these conclusions is the absence of any entrainment effects in the 1-D framework. Future work should also investigate how the results of this study are modified given more realistic dynamical forcing; to this end, work is currently ongoing to parallelise the ACPIM model for use on supercomputing platforms to enable 3-D simulations to be performed.

Acknowledgements. The first author would like to thank Ben Shipway and Adrian Hill of the Met Office for their advice and feedback in setting up the KiD model. Thanks also to Hugh Morrison of NCAR, USA for supplying the latest version of the bulk microphysics code used in this study.

ACPD

10, 23497–23537, 2010

References

Abdul-Razzak, H., Ghan, S. J., and Rivera-Carpio, C.: A parameterization of aerosol activation – 1. Single aerosol type, J. Geophys. Res.-Atmos., 103, 6123–6131, 1998. 23505

Abel, S. J. and Shipway, B. J.: A comparison of cloud-resolving model simulations of trade wind cumulus with aircraft observations taken during RICO, Q. J. Roy. Meteorol. Soc., 133, 781–794, 2007. 23499

Albrecht, B. A.: Aerosols, cloud microphysics, and fractional cloudiness, Science, 245, 1227–1230, 1989. 23499

Bony, S. and Dufresne, J. L.: Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models, Geophys. Res. Lett., 32, L20806, doi:10.1029/2005GL023851, 2005. 23499

Bott, A.: A positive definite advection scheme obtained by nonlinear renormalization of the advective fluxes, Mon. Weather Rev., 117, 1006–1015, 1989. 23506

Bott, A.: Monotone flux limitation in the area-preserving flux-form advection algorithm, Mon. Weather Rev., 120, 2592–2602, 1992. 23506

Bott, A.: A flux method for the numerical solution of the stochastic collection equation: Extension to two-dimensional particle distributions, J. Atmos. Sci., 57, 284–294, 2000. 23502

Dearden, C.: Investigating the simulation of cloud microphysical processes in numerical models using a one-dimensional dynamical framework, Atmos. Sci. Lett., 10, 207–214, 2009. 23500, 23503, 23505, 23509

Graf, H.-F., Yang, J., and Wagner, T. M.: Aerosol effects on clouds and precipitation during the 1997 smoke episode in Indonesia, Atmos. Chem. Phys., 9, 743–756, doi:10.5194/acp-9-743-2009, 2009. 23499

Hall, W. D.: A detailed microphysical model within a two-dimensional dynamic framework – Model description and preliminary-results, J. Atmos. Sci., 37, 2486–2507, 1980. 23502

Heymsfield, A. and McFarquhar, G.: Microphysics of INDOEX clean and polluted trade cumulus clouds, J. Geophys. Res.-Atmos., 106, 28653–28673, 2001. 23499

IPCC: Climate Change 2007 – The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the IPCC, Cambridge University Press., 2007. 23499

Khairoutdinov, M. and Kogan, Y.: A new cloud physics parameterization in a large-eddy simulation model of marine stratocumulus, Mon. Weather Rev., 128, 229–243, 2000. 23503

Laaksonen, A., Vesala, T., Kulmala, M., Winkler, P. M., and Wagner, P. E.: Commentary on cloud modelling and the mass accommodation coefficient of water, Atmos. Chem. Phys., 5, 461–464, doi:10.5194/acp-5-461-2005, 2005. 23502

Leonard, B. P., MacVean, M. K., and Lock, A. P.: Positivity-preserving numerical schemes for multidimensional advection, NASA Technical Memorandum, 1993. 23506

Liu, J. Y. and Orville, H. D.: Numerical modelling of precipitation and cloud shadow effects on mountain-induced cumuli, J. Atmos. Sci., 26, 1283–1298, 1969. 23504

Milbrandt, J. A. and McTaggart-Cowan, R.: Sedimentation in bulk microphysics schemes – considering alternatives to the standard two-moment approach, 13th American Meterological Society Conference on Cloud Physics, Portland, Oregon, 28 June–2 July, 2010. 23511

Morrison, H. and Grabowski, W. W.: Comparison of bulk and bin warm-rain microphysics models using a kinematic framework, J. Atmos. Sci., 64, 2839–2861, 2007. 23500, 23512

Morrison, H., Thompson, G., and Tatarskii, V.: Impact of Cloud Microphysics on the Development of Trailing Stratiform Precipitation in a Simulated Squall Line: Comparison of One- and Two-Moment Schemes, Mon. Weather Rev., 137, 991–1007, 2009. 23503

Ochs, H. T., Czys, R. R., and Beard, K. V.: Laboratory measurements of coalescence efficiencies for small precipiating drops, J. Atmos. Sci., 43, 225–232, 1986. 23513

Press, W. H., Teukolsky, S. A., Vetterling, W. T., and Flannery, B. P.: Numerical Recipes 3rd edition: The Art of Scientific Computing, Cambridge University Press., 2007. 23506

Pruppacher, H. R. and Klett, J. D.: Microphysics of Clouds and Precipitation, Kluwer Academic Publishers., 1997. 23502, 23505

Rauber, R. M., Stevens, B., Ochs, III, H. T., Knight, C., Albrecht, B. A., Blyth, A. M., Fairall, C. W., Jensen, J. B., Lasher-Trapp, S. G., Mayol-Bracero, O. L., Vali, G., Anderson, J. R., Baker, B. A., Bandy, A. R., Burnet, E., Brenguier, J. L., Brewer, W. A., Brown, P. R. A., Chuang, P., Cotton, W. R., Girolamo, L. D., Geerts, B., Gerber, H., Goke, S., Gomes, L., Heikes, B. G., Hudson, J. G., Kollias, P., Lawson, R. P., Krueger, S. K., Lenschow, D. H., Nuijens, L., O'Sullivan, D. W., Rilling, R. A., Rogers, D. C., Siebesma, A. P., Snodgrass, E., Stith, J. L., Thornton, D. C., Tucker, S., Twohy, C. H., and Zuidema, P.: Rain in shallow cumulus over the ocean – The RICO campaign, B. Am. Meteorol. Soc., 88, 1912, doi:10.1175/BAMS-88-12-1912, 2007. 23499

Rogers, R. R. and Yau, M. K.: A Short Course in Cloud Physics, 3rd edition, Butterworth and Heinemann, 1989. 23504

Shipway, B. J. and Hill, A. A.: A 1D modelling framework for a microphysics intercomparison study: Part I, Q. J. Roy. Meteorol. Soc., submitted, 2010. 23503, 23507, 23511, 23512

ACPD

10, 23497–23537, 2010

Teller, A. and Levin, Z.: Factorial method as a tool for estimating the relative contribution to precipitation of cloud microphysical processes and environmental conditions: Method and application, J. Geophys. Res.-Atmos., 113(13), D02202, doi:10.1029/2007JD008960, 2008. 23500

Topping, D. O., McFiggans, G. B., and Coe, H.: A curved multi-component aerosol hygroscopicity model framework: Part 1 – Inorganic compounds, Atmos. Chem. Phys., 5, 1205–1222, doi:10.5194/acp-5-1205-2005, 2005. 23502

Twomey, S.: The influence of pollution on shortwave albedo of clouds, J. Atmos. Sci., 34, 1149–1152, 1977. 23499

Twomey, S. A.: The Nuclei of Natural Cloud Formation. Part II: The Supersaturation in Natural Clouds and the Variation of Cloud Droplet Concentrations, Geofis. Pure Appl., 43, 227–242, 1959. 23504

Tzivion, S., Feingold, G., and Levin, Z.: An efficient numerical-solution to the stochastic collection equation, J. Atmos. Sci., 44, 3139–3149, 1987. 23513

Wang, H. L. and McFarquhar, G. M.: Modeling aerosol effects on shallow cumulus convection under various meteorological conditions observed over the Indian Ocean and implications for development of mass-flux parameterizations for climate models, J. Geophys. Res.-Atmos., 113(20), D20201, doi:10.1029/2008JD009914, 2008. 23499, 23500

ACPD

10, 23497–23537, 2010

ACPD
10, 23497–23537, 2010

Evaluating the effects of microphysical complexity using the Factorial Method

C. Dearden et al.

Table 1. Design matrix for the general 2^3 factorial design.

Run	A	B	C	Labels
1	–	–	–	(one)
2	+	–	–	*a*
3	–	+	–	*b*
4	+	+	–	*ab*
5	–	–	+	*c*
6	+	–	+	*ac*
7	–	+	+	*bc*
8	+	+	+	*abc*

Table 2. Summary of the factorial design for the bin microphysics.

Factor	Description	Values
w_1	Peak vertical velocity (m/s)	0.5, 1, 2, 4
T	Temperature Profile	RICO, RICO-2, RICO-5
CCN	Aerosol no. concentration (/cc)	50, 100, 200

ACPD
10, 23497–23537, 2010

Table 3. Summary of the factorial design for the bulk microphysics.

Factor	Description	Values
w_1	Peak vertical velocity (m/s)	0.5 to 4 in intervals of 0.25
T	Temperature Profile	RICO, RICO-2, RICO-5
CCN	Aerosol number concentration (2-m A-R) No. of droplets active at 1% supersaturation (2-m Twomey) Droplet number concentration (1-m)	50, 100, 200

ACPD
10, 23497–23537, 2010

Table 4. Surface precipitation totals (mm) for each scheme as a function of CCN and w_1 for three different temperature profiles, namely RICO (top); RICO-2 (middle); and RICO-5 (bottom). Those results highlighted in bold type are plotted in Fig. 6 as timeseries of surface precipitation rate and accumulated surface precipitation.

	CCN											
RICO		1-m			2-m (Twomey)			2-m (A-R)			Bin	
	50/cc	100/cc	200/cc	50/cc	100/cc	200/cc	50/cc	100/cc	200/cc	50/cc	100/cc	200/cc
$w_1 = 0.5$ m/s	1.38	**1.22**	1.00	1.48	**1.35**	1.18	1.39	**1.30**	1.24	1.63	**1.57**	1.47
$w_1 = 1.0$ m/s	1.40	**1.24**	1.02	1.44	**1.30**	1.13	1.41	**1.26**	1.09	1.67	**1.54**	1.34
$w_1 = 2.0$ m/s	1.40	**1.24**	1.02	1.41	**1.25**	1.08	1.41	**1.25**	1.04	1.67	**1.52**	1.27
$w_1 = 4.0$ m/s	1.40	**1.23**	1.02	1.41	**1.24**	1.03	1.40	**1.24**	1.03	1.65	**1.49**	1.25

RICO-2		1-m			2-m (Twomey)			2-m (A-R)			Bin	
	50/cc	100/cc	200/cc	50/cc	100/cc	200/cc	50/cc	100/cc	200/cc	50/cc	100/cc	200/cc
$w_1 = 0.5$ m/s	1.21	1.04	0.82	1.32	1.18	1.00	1.24	1.14	1.07	1.47	1.38	1.27
$w_1 = 1.0$ m/s	1.23	1.06	0.84	1.27	1.13	0.96	1.25	1.08	0.91	1.48	1.34	1.13
$w_1 = 2.0$ m/s	1.23	1.06	0.84	1.25	1.08	0.90	1.24	1.07	0.86	1.47	1.31	1.06
$w_1 = 4.0$ m/s	1.22	1.06	0.84	1.24	1.07	0.86	1.24	1.07	0.86	1.46	1.29	1.05

RICO-5		1-m			2-m (Twomey)			2-m (A-R)			Bin	
	50/cc	100/cc	200/cc	50/cc	100/cc	200/cc	50/cc	100/cc	200/cc	50/cc	100/cc	200/cc
$w_1 = 0.5$ m/s	0.97	0.80	0.58	1.08	0.93	0.76	1.02	0.90	0.82	1.22	1.12	0.99
$w_1 = 1.0$ m/s	0.99	0.81	0.60	1.04	0.89	0.72	1.01	0.84	0.66	1.21	1.06	0.84
$w_1 = 2.0$ m/s	0.98	0.81	0.60	1.01	0.84	0.66	1.01	0.83	0.62	1.20	1.03	0.78
$w_1 = 4.0$ m/s	0.98	0.81	0.60	1.01	0.83	0.62	1.00	0.83	0.61	1.18	1.01	0.76

ACPD
10, 23497–23537, 2010

Table 5. Top: Integrated rain evaporation (kgm^{-2}) for 2-m A-R scheme as a function of CCN, w_1 and T, and also for the 2-m A-R scheme with increased fallspeed parameter for rain, such that $b_r = 0.825$. Bottom: the corresponding total surface precipitation (mm).

w_1	RICO 2-m A-R 50/cc	RICO 2-m A-R 100/cc	RICO 2-m A-R ($b_r = 0.825$) 50/cc	RICO 2-m A-R ($b_r = 0.825$) 100/cc	RICO-2 2-m A-R 50/cc	RICO-2 2-m A-R 100/cc	RICO-2 2-m A-R ($b_r = 0.825$) 50/cc	RICO-2 2-m A-R ($b_r = 0.825$) 100/cc
0.5 m/s	−0.476	−0.448	−0.409	−0.389	−0.438	−0.406	−0.378	−0.352
1.0 m/s	−0.433	−0.414	−0.366	−0.349	−0.410	−0.391	−0.347	−0.331
2.0 m/s	−0.438	−0.424	−0.369	−0.356	−0.419	−0.402	−0.354	−0.339
4.0 m/s	−0.446	−0.431	−0.375	−0.362	−0.426	−0.408	−0.360	−0.345

w_1	RICO 2-m A-R 50/cc	RICO 2-m A-R 100/cc	RICO 2-m A-R ($b_r = 0.825$) 50/cc	RICO 2-m A-R ($b_r = 0.825$) 100/cc	RICO-2 2-m A-R 50/cc	RICO-2 2-m A-R 100/cc	RICO-2 2-m A-R ($b_r = 0.825$) 50/cc	RICO-2 2-m A-R ($b_r = 0.825$) 100/cc
0.5 m/s	1.39	1.30	1.49	1.41	1.24	1.14	1.33	1.25
1.0 m/s	1.41	1.26	1.51	1.38	1.25	1.08	1.34	1.21
2.0 m/s	1.41	1.25	1.51	1.38	1.24	1.07	1.34	1.20
4.0 m/s	1.40	1.24	1.51	1.37	1.24	1.07	1.34	1.20

ACPD
10, 23497–23537, 2010

Evaluating the effects of microphysical complexity using the Factorial Method

C. Dearden et al.

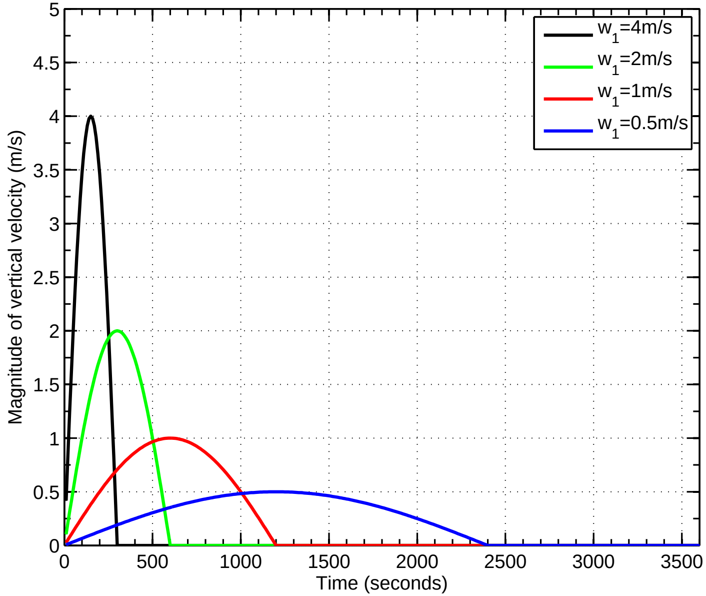

Fig. 1. Vertical velocity fields as a function of time, as applied to the 1-D column equally at every vertical level.

ACPD

10, 23497–23537, 2010

Evaluating the effects of microphysical complexity using the Factorial Method

C. Dearden et al.

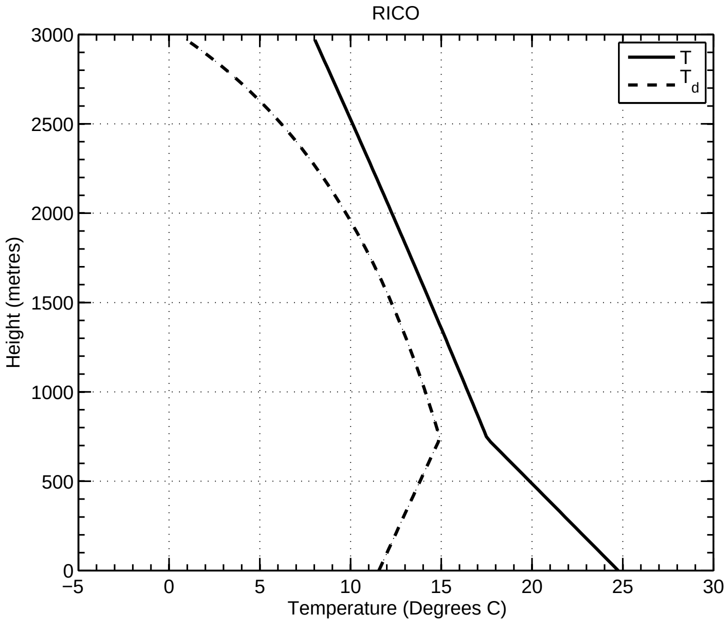

Fig. 2. Temperature (solid) and dew-point temperature (dashed) profiles in °C taken from the RICO model intercomparison, and used to initialise the models. The additional profiles, "RICO-2" and "RICO-5", are obtained by cooling the RICO profile uniformly in height by 2 °C and 5 °C respectively under a fixed relative humidity.

ACPD
10, 23497–23537, 2010

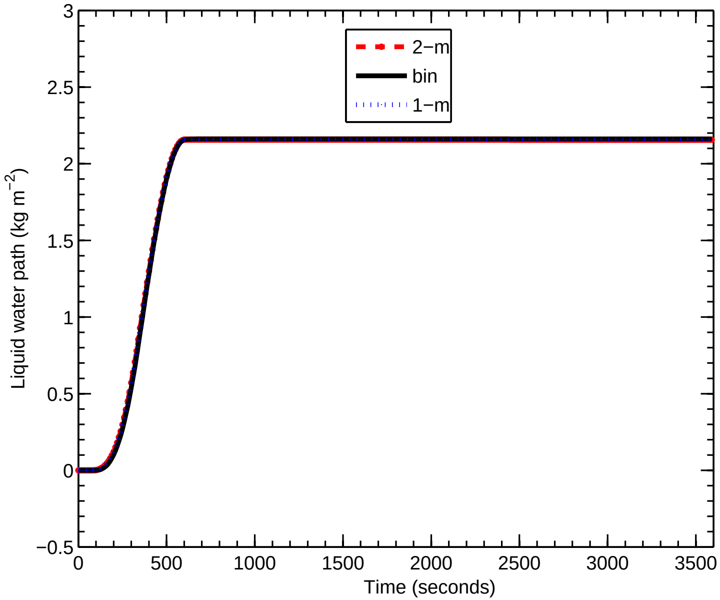

Fig. 3. Timeseries of liquid water path from the 1-m, 2-m A-R and bin schemes in the absence of precipitation and sedimentation, such that all condensed water stays in the cloud. The results shown were obtained with the following settings: w_1=2 m/s, T=RICO and CCN=100/cc.

ACPD
10, 23497–23537, 2010

Evaluating the effects of microphysical complexity using the Factorial Method

C. Dearden et al.

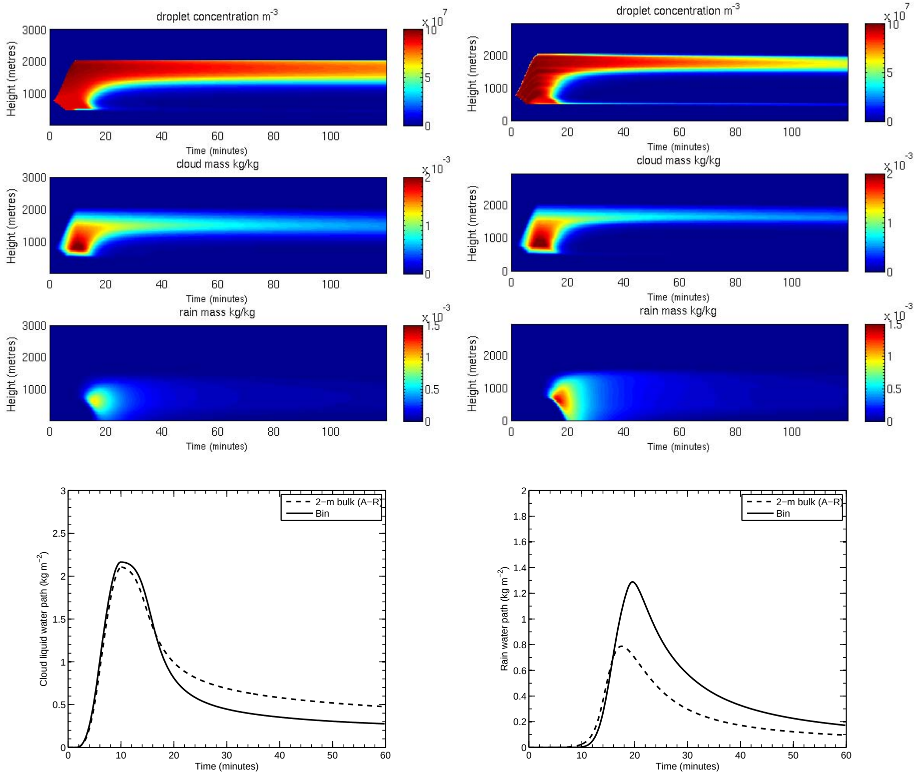

Fig. 4. Top row: comparison of cloud droplet number concentration (m^{-3}), cloud mass mixing ratio ($kgkg^{-1}$) and rain mixing ratio ($kgkg^{-1}$) from the 2-m A-R scheme (left) and the bin scheme (right). Bottom row: Comparison of cloud liquid water path (left) and rain water path (right) in kgm^{-2} from the 2-m A-R scheme (dashed) and bin scheme (solid). The results shown are taken from simulations with w_1=2 m/s, T=RICO and CCN=100/cc.

ACPD
10, 23497–23537, 2010

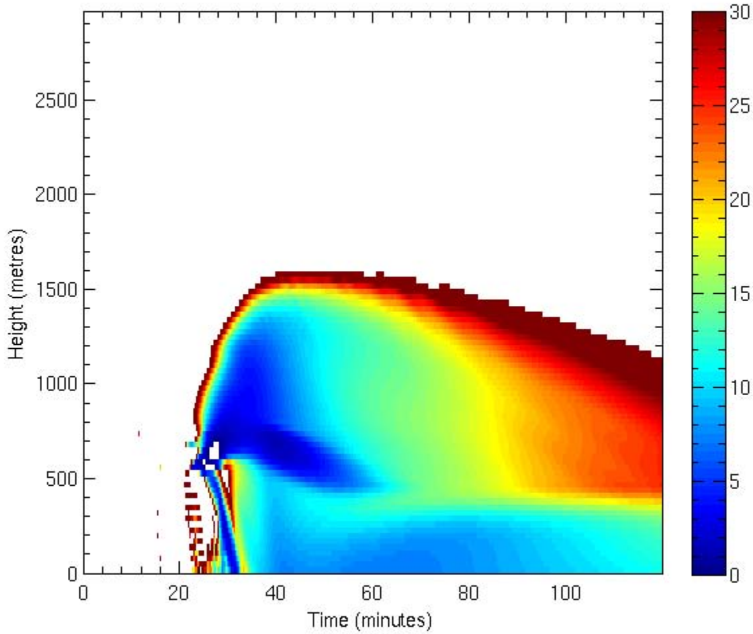

Fig. 5. Time-height plot of the diagnosed shape parameter from the bin scheme, obtained by fitting a gamma function to the resolved size distribution for rain, where rain is defined as those liquid drops greater than 40 microns in diameter. The plot shown is from the CCN=50/cc case, with w_1=0.5 m/s and T=RICO profile.

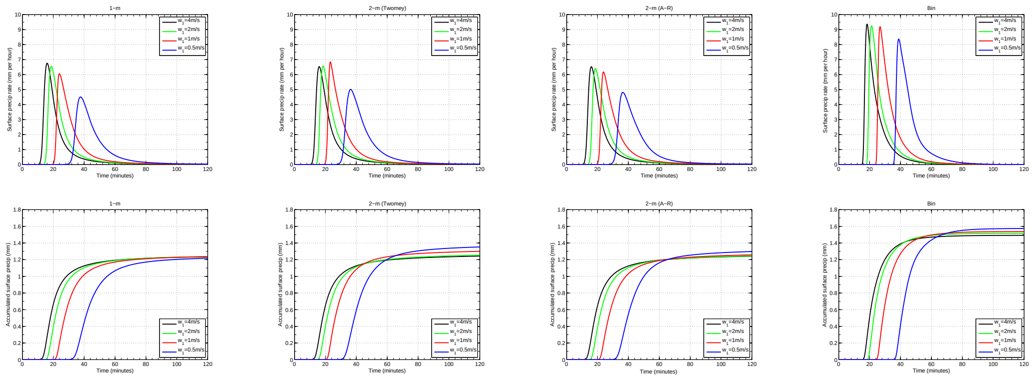

Fig. 6. Top row: timeseries of surface precipitation rates (mm/hr) from each scheme. From left to right: 1-m, 2-m Twomey, 2-m A-R, bin. Bottom row: the corresponding timeseries of accumulated surface precipitation (mm) from each scheme. Results are shown with CCN=100/cc and T=RICO, for four different values of w_1.

ACPD
10, 23497–23537, 2010

Evaluating the effects of microphysical complexity using the Factorial Method

C. Dearden et al.

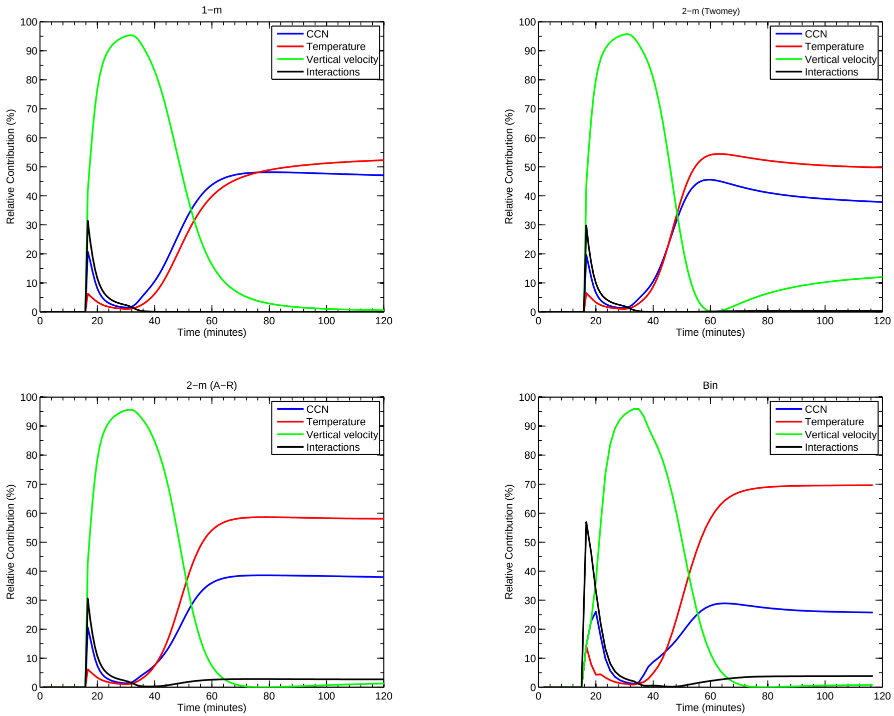

Fig. 7. Relative contribution (%) timeseries plots for each scheme, considering the effects of changes in CCN, vertical velocity and temperature, plus their combined interaction effects. The relative contribution is calculated in terms of the induced suppression of precipitation at the surface. The contributions shown are based on the following changes: w_1 from 0.5 m/s to 2 m/s; CCN from 50/cc to 100/cc, and T from RICO to RICO-2. Clockwise from top left: 1-m, 2-m Twomey, bin, 2-m A-R.

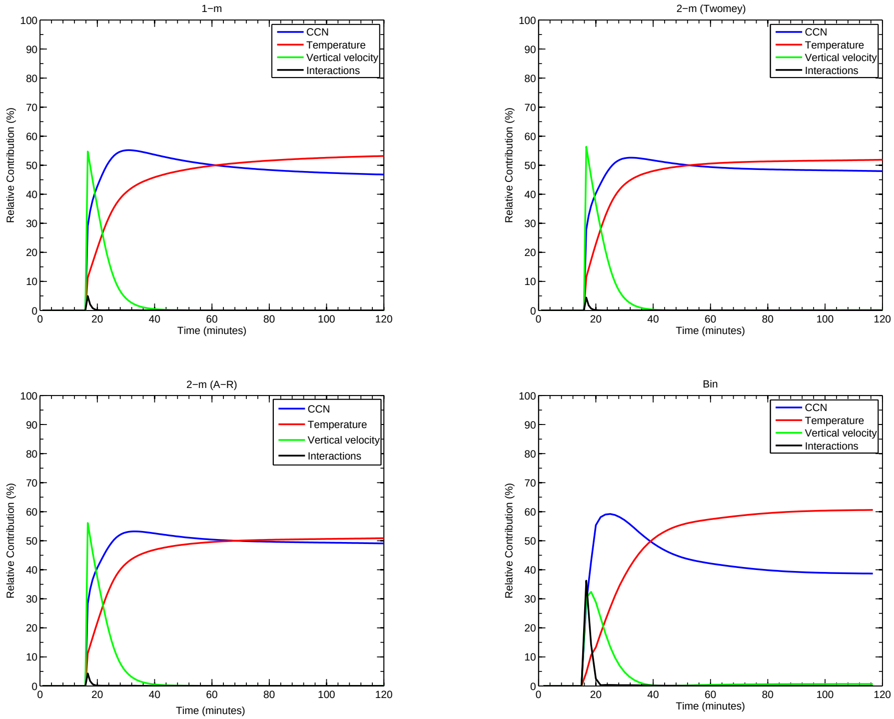

Fig. 8. As for Fig. 7 but for an increase in w_1 from 2 m/s to 4 m/s.

ACPD
10, 23497–23537, 2010

Evaluating the effects of microphysical complexity using the Factorial Method

C. Dearden et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
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Back | Close
Full Screen / Esc
Printer-friendly Version
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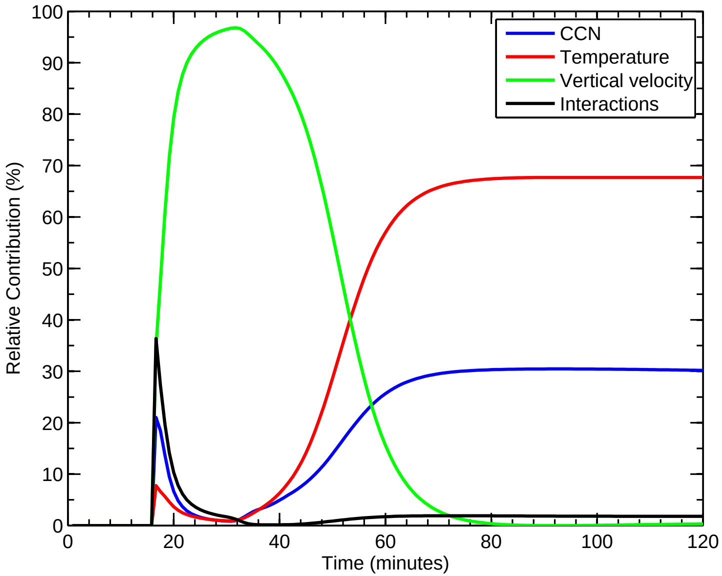

Fig. 9. As Fig. 7 but for the 2-m A-R scheme with modified fallspeed parameter for rain, such that b_r is increased from the default value of 0.8 to 0.825. All other fallspeed parameters are unchanged.

ACPD
10, 23497–23537, 2010

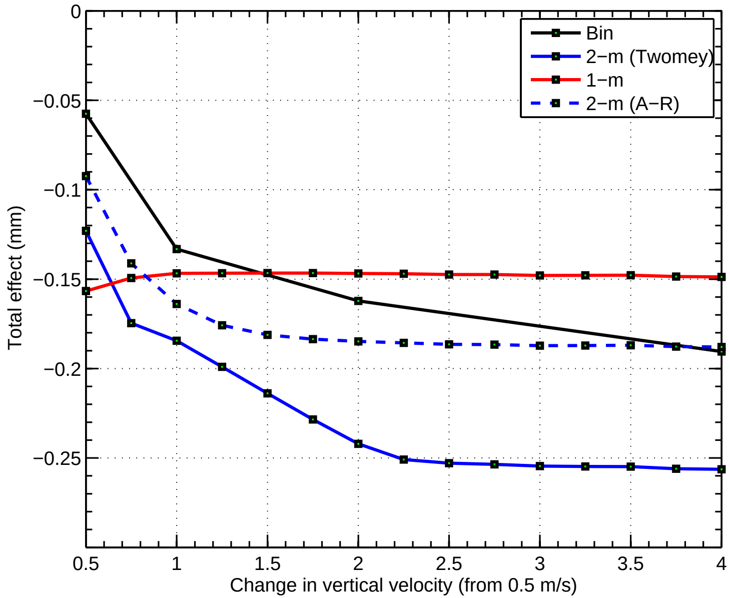

Fig. 10. Total effect on suppression of precipitation (in mm) from each scheme as a function of changes in w_1 and CCN, under a fixed temperature (T=RICO). Changes in w_1 are considered from 0.5 m/s up to 4 m/s, and the change in CCN is from 50/cc to 100/cc.

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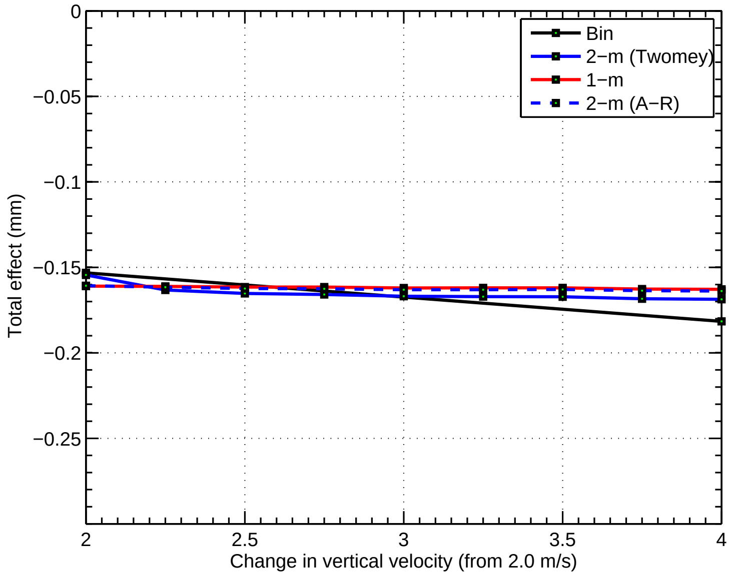

Fig. 11. As Fig. 10 but for changes in w_1 starting from 2 m/s.

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Evaluating the effects of microphysical complexity using the Factorial Method

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