P2.1 Quantifying the benefits of microphysical complexity in a one-dimensional framework using the Factorial Method

C Dearden[1], PJ Connolly[1], TW Choularton[1] and PR Field[2]

[1]University of Manchester, United Kingdom
[2]Met Office, United Kingdom
(Christopher.Dearden@postgrad.manchester.ac.uk)

1. Introduction

The Factorial Method is used to explore the effects of microphysical and environmental variables on the development of precipitation in idealised representations of warm shallow cumulus clouds. A one-dimensional column model is used to drive a suite of microphysics schemes including a flexible multi-moment bulk scheme and a state-of-the-art bin microphysics model with explicit treatments of liquid water and aerosol, including the ability to account for the effects of CCN composition. The aim is to shed light on those meteorological regimes where the addition of extra microphysical complexity may be beneficial in terms of the ability of the model to capture aerosol indirect effects.

From a climatological perspective, 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 trade wind inversion, detrain cloud water which is transported to the deep tropics to fuel deep convection within the Inter Tropical Convergence Zone (ITCZ). Thus the treatment of precipitation processes in warm convection is an important consideration in Numerical Weather Prediction (NWP) and General Circulation Models (GCMs). The representation of trade wind cumuli in climate models is also believed to be crucial in determining the global temperature change in response to a doubling of CO_2 (Bony and Dufresne 2005), yet GCMs currently do not provide any sort of robust conclusion on the expected sign and magnitude of this change, and in most cases are at odds with the latest observational estimates (Clement et al 2009). Furthermore, warm clouds are particularly sensitive to modification through increased CCN concentrations by virtue of the 1st and 2nd indirect effects (Twomey 1977 and Albrecht 1989 respectively). Indeed, the latest findings from the Intergovernmental Panel on Climate Change (IPCC, 2007) suggest that the 1st indirect effect is the most uncertain of all the known processes in terms of global radiative forcing. One of the main reasons for this situation is the reliance upon convection schemes in existing GCMs. The need to parameterise convection at current GCM resolutions presents a barrier to calculating aerosol indirect effects, since convection schemes traditionally have contained very little microphysical detail and so have no means to account for the effects of changing CCN concentrations. 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 sub-tropical marine shallow cumulus in the Caribbean as part of the Rain In shallow Cumulus over the Ocean (RICO) project, and the indirect effects of aerosols on convective cloud in the INDian Ocean EXperiment (INDOEX). An important part of such projects is to compliment the in-situ observations with cloud-resolving model (CRM) studies (e.g. Abel and Shipway 2007; Wang and McFarquhar 2008), the results from which can feed into improving the parameterizations of warm convection in operational schemes. Typically, CRMs are based on bulk microphysics, which themselves are available at different levels of complexity. Thus it is necessary to validate the performance of bulk schemes relative to more explicit bin-resolved microphysics, to increase our understanding of the strengths and weaknesses of existing bulk parameterizations. It is fair to say that until recently, the need to account for changes in meteorological conditions when evaluating aerosol effects on clouds has been somewhat overlooked. Teller and Levin (2008) used the Factorial Method (FM) to quantify the sensitivity of precipitation in mixed-phase convective cloud when both meteorological and microphysical factors occur together. The aim of this study is to expand the use of the FM across a hierarchical suite of microphysics schemes within a one dimensional framework such that the effect of microphysical complexity can be quantified in terms of the impact upon surface precipitation.

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 based on the University of Manchester Aerosol-Cloud-Precipitation-Interaction-Model (ACPIM), to a bulk parameterization of warm rain processes with the option of both dual-moment and single-moment cloud liquid water. A detailed description of each of the schemes considered in this study are now given, starting with the bin microphysics.

a) Bin microphysics

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 the ability to treat aerosols explicitly, allowing the effects of aerosol concentration, mean diameter and also 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 model is initialised with an aerosol log-normal size distribution, and a prescribed vertical velocity field produces a supersaturation. The ambient supersaturation is resolved using a variable sub-step to ensure it is captured to a sufficient level of accuracy, independent of the choice of the main model timestep. Each aerosol size bin solves prognostic equations for the mass and number of aerosols. The resolved supersaturation is then compared against the critical supersaturation for each aerosol size bin, and activation of cloud droplets occurs in all aerosol bins where the resolved supersaturation exceeds the critical supersaturation. Initial growth of the cloud droplets is governed by the diffusional growth equation, and subsequent growth to rain drop size is handled by solving the stochastic collection equation, with the collision efficiency based on the Hall kernel (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).

b) **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. Both single moment and dual moment cloud liquid water are considered in the bulk scheme; in both cases rain is given dual-moment treatment. Saturation adjustment is used 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 a few seconds. In the single moment case, cloud droplet number is prescribed a fixed value. For dual-moment liquid, activation of cloud droplets at cloud base is parameterized by the Twomey relation (1959), where the number of droplets activated is based on the grid-scale vertical velocity and parameters *c* and *k*, where *c* represents the number of CCN active at 1% supersaturation, and *k* is a constant that determines how easily droplets form. Autoconversion is based on the scheme of Khairoutdinov and Kogan (2000), henceforth referred to as the KK scheme, in both the single and dual moment cases. The KK scheme was originally developed based on bin microphysical simulations of marine boundary layer clouds and so is considered to be an appropriate choice for this study.

c) 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. However necessary steps have been taken to ensure that both driver models are consistent such that both bin and bulk microphysics schemes can be compared safely.

The advection scheme common to both driver models is the 4th order, positive definite, monotonic version of the Bott scheme (Bott 1992). This scheme is used to advect vapour and liquid water. 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, using a time-split Euler step. However in a 1-D framework the difference does not have any significant impact on the results.

3. **Experimental Design**

3.1 **Initial conditions and idealised forcing**

The warm shallow cumulus case is based on the 'warm1' configuration as defined in the KiD documentation (obtained from http://appconv.metoffice.com/microphysics/doc.html). It consists of a single updraft, sinusoidal in time, constant in height and given as:

$$w(z,t)=w_1\sin(\pi t/t_2), \quad \text{for } t<t_2,$$

$$\text{and } w(z,t)=0, \quad \text{for } t>t_2.$$

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

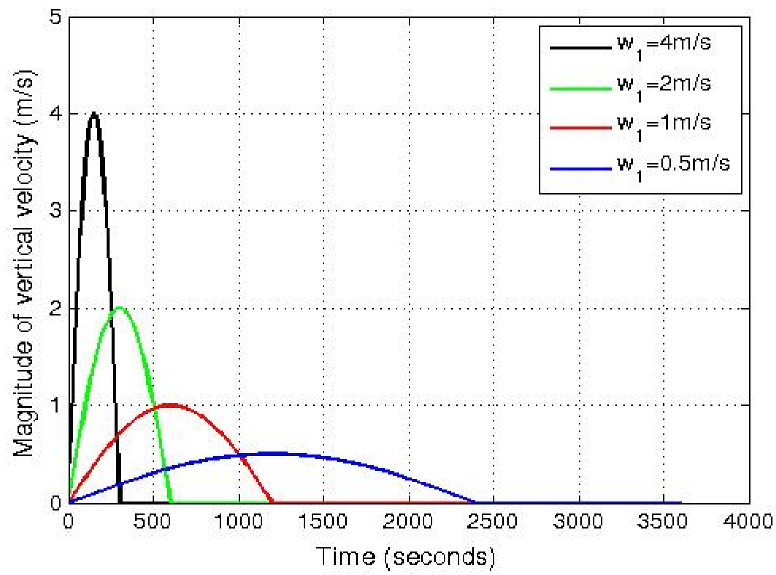

Figure 1: Vertical velocity fields as a function of time, as applied equally at every vertical level

The variation of temperature and humidity with height is based on the composite profiles taken from the RICO model intercomparison. Changes in temperature are considered such that the default RICO temperature profile is shifted to cooler temperatures resulting in a uniform cooling with height whilst keeping the relative humidity constant. The result is such that changes in the dynamics do not affect the cloud height or depth. The temperature profiles used in this study are plotted in figure 2.

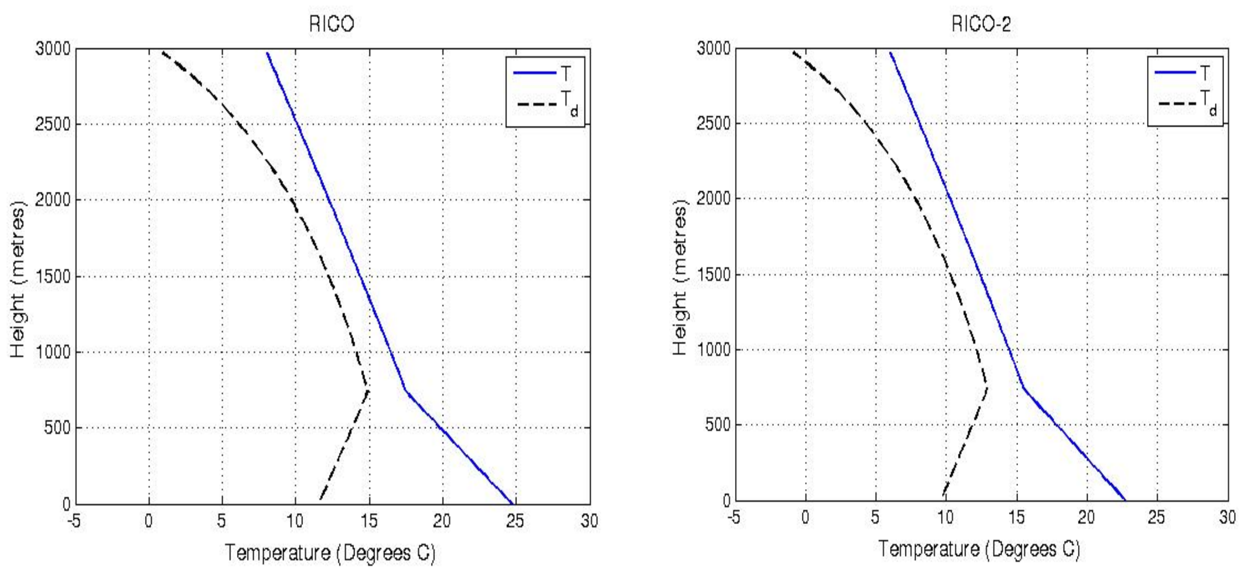

Figure 2: Temperature (blue) and dew-point temperature (dashed) profiles in degrees C as defined by (left): the RICO intercomparison; (right): RICO cooled by 2degC under a fixed relative humidity; henceforth referred to as 'RICO-2'.

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 seconds). The vertical resolution in both models is set to 30m, with 100 levels giving a domain height of 3km.

3.2 Experimental design for the Factorial Method

The experimental design based around the FM is now presented. It should be noted that the effect of changes in dynamical factors, namely temperature profile and magnitude of peak updraft velocity, is 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. Further details are given in Dearden (2009) and Teller & Levin (2008), and references therein. 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.

a) Factorial design for ACPIM microphysics

Table 1 summarises the factorial design for the ACPIM model. A 2^3 design in used, giving three factors in total, two of which, namely w_1 and T, are meteorological in nature and represent vertical velocity and temperature respectively. The remaining factor, 'CCN' is a microphysical factor which represents the number concentration of the background aerosol. 16 numerical simulations are required to fulfill the design presented in table 1.

Factor Label	Factor Description	Values
W_1	Magnitude of peak vertical velocity (m/s)	0.5, 1, 2, 4
T	Temperature Profile	RICO, RICO-2
CCN	Number concentration of background aerosol (/cc)	50, 100

Table 1: Summary of the Factorial Design for the ACPIM microphysics

Aerosols are initialised using a log-normal size distribution whose parameters are taken from the RICO model intercomparison. The default is to assume a unimodal size distribution, described by a geometric standard deviation of 1.28, and a geometric mean dry radius of 30nm. The factor 'CCN' is designed to explore the effect of increasing the aerosol number concentration from a starting value of 50/cc. In terms of the aerosol composition, the default is to use pure sea-salt for all runs described in table 1. Ammonium sulphate was also used as the inorganic component; however this was found to have little impact on the precipitation rates or precipitation totals.

b) Factorial design for bulk microphysics

Table 2 summarises the factorial design for the bulk microphysics, based around a 2^3 design and requiring 64 simulations for each scheme. The reduced computational burden of the bulk scheme compared to the bin scheme is exploited to perform a more thorough exploration of the parameter space. The meteorological factors w_1 and T are the same as in ACPIM, but covering a greater range of values. In the 2-m bulk scheme, the microphysical factor 'CCN' relates to the value of *c* in the Twomey (1959) approximation to the power-law relation, $N=cs^k$, where *c* is the number of CCN active at 1% supersaturation, and *k* is taken to be fixed at a value of 0.4 based on measurements of tropical maritime airmasses (Pruppacher and Klett, pg 287-288). In the single-moment 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.

Factor Label	Factor Description	Values
w_1	Vertical Velocity (m/s)	0.5 to 4 in intervals of 0.25
T	Temperature Profile	RICO, RICO-2
CCN	CCN (/cc) active at 1% supersaturation (2m); Droplet number /cc (1m)	50, 100

Table 2: Summary of the Factorial Design for the bulk microphysics

4. **Results: Factorial Analysis**

4.1 Quantifying the relative importance of each factor with time (2^3 design)

The Factorial Method is now used to quantify the sensitivity of the schemes to changes in the microphysical and meteorological factors. The relative importance of each factor is explored as a function of time throughout the evolution of the cloud, and the sensitivities of each scheme are compared to highlight any differences in behaviour.

Figure 3 plots the timeseries of relative contribution of CCN, w_1 and T plus their interactions to the overall change in surface precipitation at each model timestep. The effect of CCN considers an increase from 50/cc to 100/cc; the effect of w_1 is based on an increase from 0.5m/s to 2m/s, and finally the temperature effect explores the impact of a cooling induced by changing from the RICO profile to the RICO-2 profile.

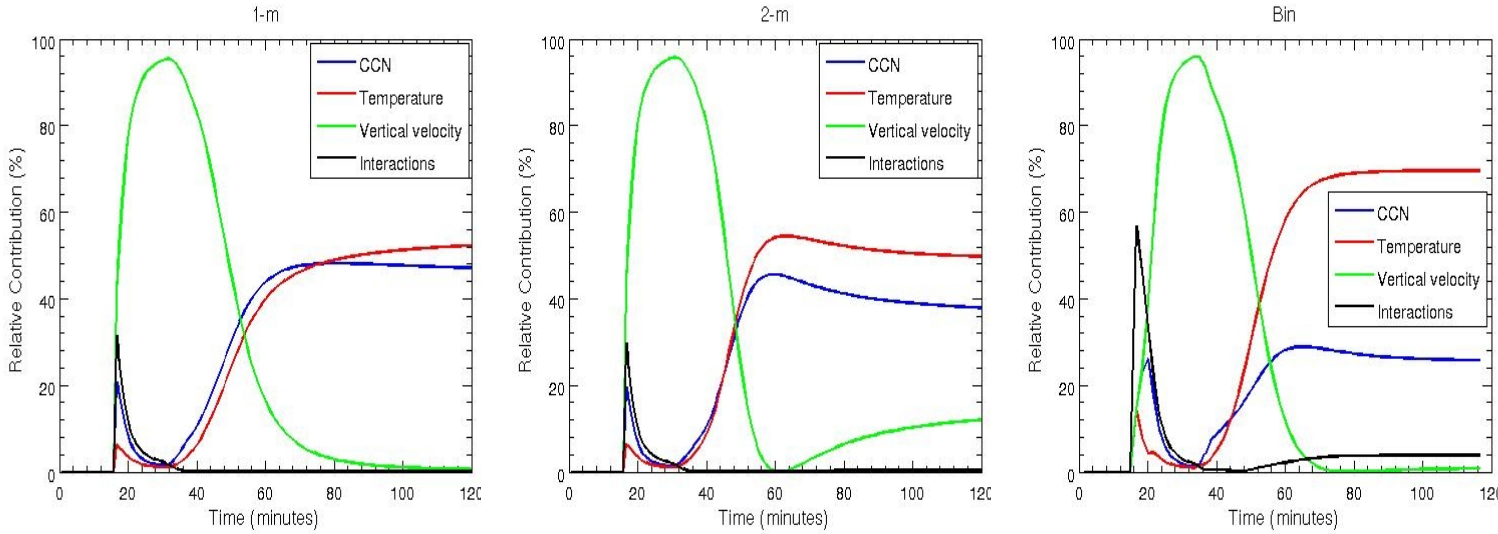

Figure 3: Relative contribution timeseries plots for each scheme, considering the effect of changes in CCN, vertical velocity, temperature plus their combined interaction. The relative contribution is calculated based on the induced suppression of precipitation at the surface. Left: 1-m bulk scheme; Middle: 2-m bulk scheme; Right: Bin scheme.

When all three factors are considered together, in the early stages of the cloud development the vertical velocity factor dominates the relative contribution in each scheme in a similar manner. Beyond 40 minutes, the schemes begin to disagree mostly in relation to the relative contributions from CCN and temperature. 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 figure 3), and the effect of temperature (in red) becomes increasingly more dominant. In the case of the bin scheme, this is at least partly due to the ability to resolve the in-cloud supersaturation. In slowly building updraft speeds such as the 0.5m/s case, increasing the CCN concentration in the bin scheme has less of an effect on rainfall compared to the bulk schemes because the largest CCN that activate at low supersaturations have more time to grow by condensation. This reduces the maximum supersaturation in the rising air parcel, and in turn reduces slightly the total number of droplets that would otherwise be activated relative to the saturation adjustment method. The effect is enhanced at warmer temperatures, where the amount of supersaturated water vapour available is larger than at colder temperatures.

It is also worthy of note that higher rain mass mixing ratios were produced in the bin scheme relative to the bulk schemes, and that the larger rain mixing ratios lead to larger evaporation rates. The different representations of the size distribution for rain between schemes could also contribute to the difference in evaporation rates. The bulk schemes use an exponential size distribution for rain, which implicitly assumes a shape parameter of zero and is known to suffer from the problem of excessive size-sorting (Wacker and Seifert 2001). By fitting a gamma function to the resolved drop size distribution from the bin scheme, it is possible to diagnose the shape parameter for rain through consideration of those drops greater than or equal to 80 microns in diameter. Figure 4 plots the evolution of the shape parameter with height and time from the bin scheme. Clearly the value of the shape parameter varies considerably through the evolution of the cloud, casting doubt on the validity of a zero shape parameter in bulk schemes.

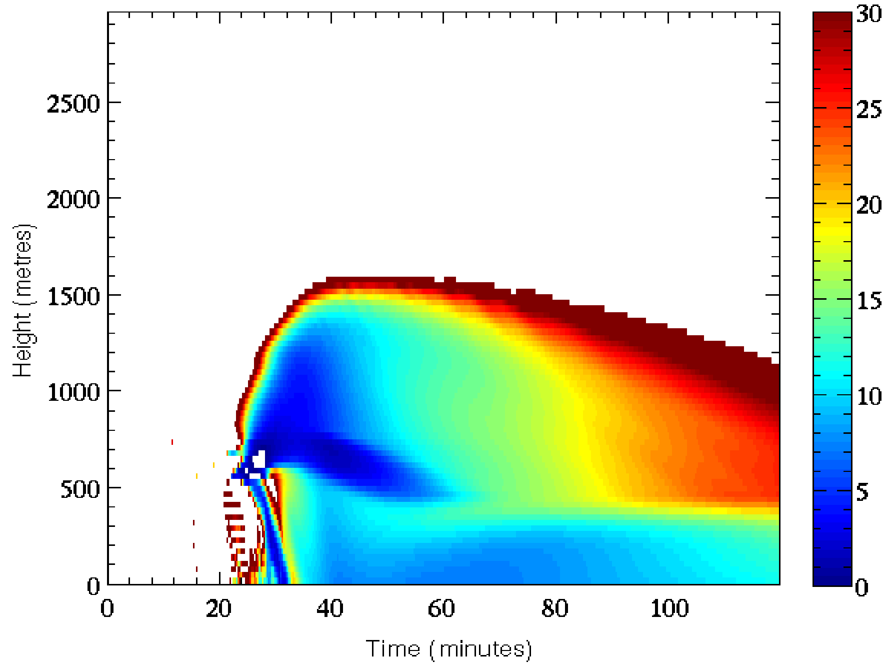

Figure 4: Diagnosed shape parameter from the bin scheme, obtained by fitting a gamma function to the resolved size distribution. Plot shown is from 50/cc case, with 0.5m/s updraft and RICO profile

4.2 The effect of increasing vertical velocity on precipitation suppression (2^2 design)

Consider a change in CCN from 50/cc to 100/cc, acting together with an increasing cloud base updraught speed, under a fixed background temperature. The FM can be used to compute the total effect on surface precipitation resulting from these changes, under a range of different updraught speeds. The sensitivities of each scheme can then be compared to see how the models differ in their response. The total effect is equal to the sum of the average effects of all factors including their interactions; the sign and magnitude of the result indicates the direction and significance of the induced change. In this case, the results from the FM are based on values of surface precipitation accumulated at the end of the model simulation. Figure 5 the total effect on precipitation as a function of increasing vertical velocity, assuming a starting value of 0.5m/s. The net effect on precipitation suppression in the 2-m scheme is overestimated relative to the bin scheme; this is because the effect of increasing the CCN concentration is weaker in the bin scheme for gradually building updraft speeds as discussed in the previous section. However only the 2-m scheme exhibits a similar range of sensitivity as compared to ACPIM. The limitations of a 1-m bulk scheme are clear in this case, since the suppression of precipitation is insensitive to change in updraft speed making it unsuitable for exploring aerosol indirect effects. However it can be shown that if the cloud base updraft speed is large enough to begin with, a 1-m scheme may suffice. For cloud base updraughts starting at 2m/s or more (as shown in figure 6), all three 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 the 1-m scheme performs in such a similar manner.

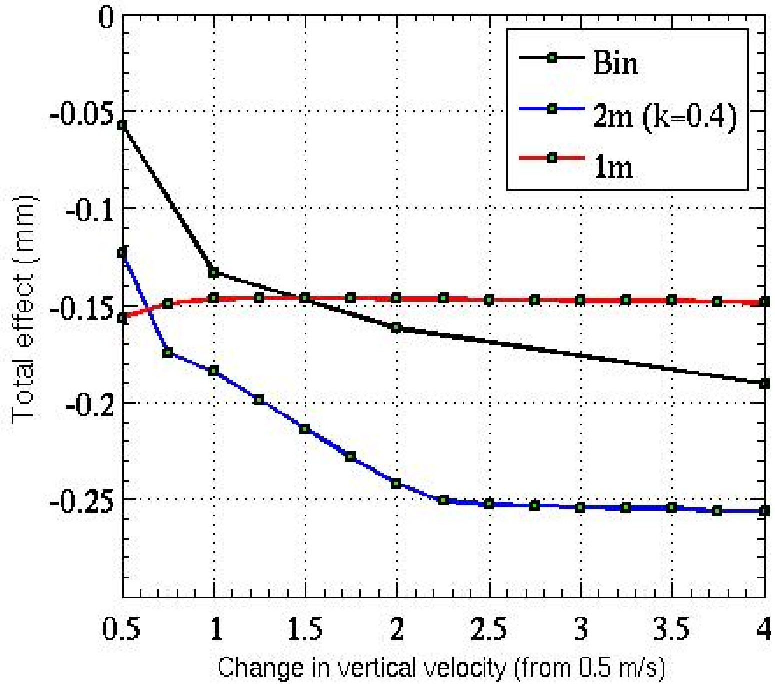

Figure 5: Total effect on suppression of precipitation for the 50-100/cc case, as a function of the change in vertical velocity (RICO profile)

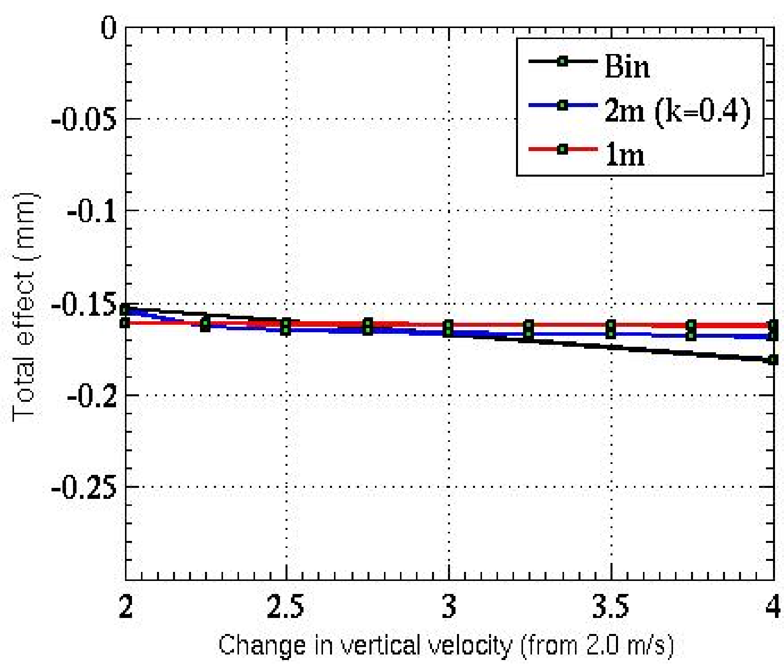

Figure 6: As figure 5 but starting from an updraft speed of 2m/s

5.Summary and Discussion

The Factorial Method has been used to compare the sensitivities of warm shallow cumulus cloud as simulated by three different microphysics schemes of increasing levels of complexity using an idealised 1-D column framework. 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. The main conclusion to be drawn from this comparison is that for droplet number concentrations typical of unpolluted sub-tropical maritime airmasses (i.e. between 50 and 100/cc), 2-m liquid schemes are preferable for simulating warm shallow cumulus only within a certain meteorological regime, one where the cloud base vertical velocity does not exceed 2 m/s. Beyond this value, 2-m schemes behave much like a 1-m scheme and the additional complexity of a prognostic droplet number variable can no longer be justified. However the bulk schemes were also found to underestimate the relative importance of changes in temperature compared to the bin scheme, and tended to overestimate the relative importance of changes in CCN concentration. The enhanced sensitivity to temperature in the bin scheme is a consequence of the ability to resolve the in-cloud supersaturation as opposed to the method of saturation adjustment. Differences in evaporation rates and the ability to resolve the drop size distribution explicitly were also identified as contributing factors. Collectively, these results demonstrate the usefulness of the Factorial Method as a model development tool for comparing the sensitivities and behaviour of different microphysics schemes within a specified parameter space. A big caveat in producing these conclusions is the absence of any entrainment effects in the 1-D framework. Future work should therefore investigate how the results of this study are modified given more realistic dynamical forcing, for example by repeating the experiments within a 3-D cloud resolving model. Work is ongoing to parallelise the bin scheme for use on supercomputing platforms such that 3-D simulations can be performed. Work is also in progress to exploit the ability of ACPIM to account for changes in aerosol composition, where the Factorial Method is being used to quantify the effect of increasing the organic fraction of internally mixed CCN relative to existing factors.

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