P1.66: DOES THE INTRODUCTION OF A SIMPLE CLOUD-AEROSOL INTERACTION IMPROVE THE REPRESENTATION OF DRIZZLE IN THE OPERATIONAL MET OFFICE UNIFIED MODEL?

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1. Introduction

Over-production of drizzle in cloudy situations is a common problem in NWP models, and significant input from the human forecaster is required to convert the model output into an operational product. Editing of these fields takes up valuable time of duty forecasters that could be better spent elsewhere.

The Met Office Unified Model Cullen (1993); hereafter MetUM is no exception to this, and the microphysics scheme (an advanced version of Wilson and Ballard, 1999) frequently suffers from overproduction of drizzle in stratocumulus boundary layers.

One particular problem area is a land-sea split, that commonly occurs in the MetUM. An example of this is shown in figure 1, where light rain in a warm front crossing the UK virtually disappears over the land, but yet is present over the sea. However, precipitation is clearly located over the south west peninsula of the UK, as seen in figure 2. This is a result of the microphysics scheme assuming one value for droplet number concentration over land and one over sea. In the UM, this is usually chosen as 100 per cm^3 for sea and 300 per cm^3 for land for the Global, 12 km North Atlantic and Europe (NAE) model and UK 1.5 km model. The 4km UK model uses the values of Bower and Choularton (1992): 150 per cm^3 for sea and 600 per cm^3 for land. Land-sea splits are frequently observed in all models, but are most commonly seen in the higher-resolution UK area models. The use of a different droplet number for sea and land stems from early modelling studies, (e.g. Bower and Choularton, 1992) and was traditionally used in older versions of the climate model, where horizontal grid spacing was often greater than 250 km. In these cases, the use of a different number drop for land than over the ocean was considered to bring a more realistic assumption of the cleanliness of an air mass. However, despite models have gone to higher resolutions, this assumption has been retained, resulting in the rather unrealistic land-sea split we see in figure 1.

This paper examines progress made to improve drizzle using a simple cloud-aerosol interaction for NWP forecasting. In section 2 we examine how the autoconversion scheme within the MetUM is dependent on cloud droplet number. Section 3 compares drizzle rates within the MetUM to relations derived from observational field campaigns. Section 4 describes the links made between the aerosol and the cloud droplet number and 5 shows the results of including this within the operational MetUM. Section 6 provides a summary to the paper.

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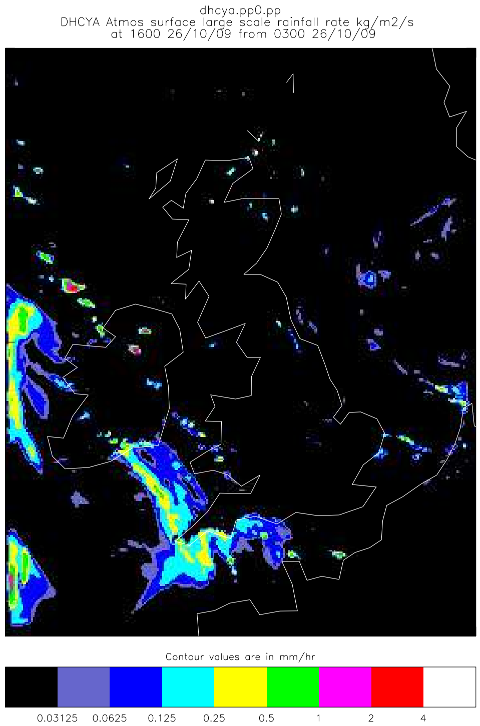

FIG. 1: Land-Sea split in light rain as observed in the UK4 MetUM model at 16Z on 26 October 2009. A front is crossing the South-West peninsula of the UK, but only rain is observed over the sea, and not over land.

2. Sensitivity of the UM microphysics to Cloud droplet number

The microphysics scheme used at present in the MetUM is based on Wilson and Ballard (1999), but with several improvements to the additional scheme. In particular, there is the option to treat the rain in the model as a prognostic variable in the higher resolution models.

The autoconversion scheme used consists of the

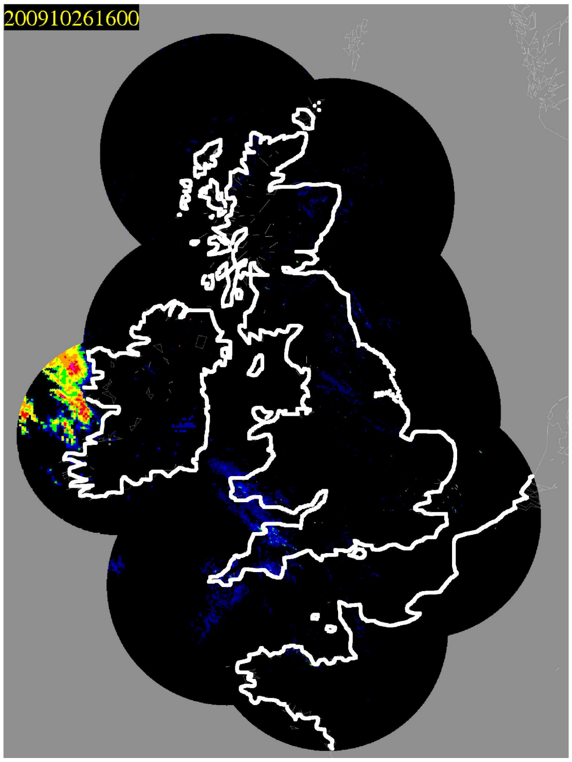

FIG. 2: UK network radar image taken at the same time as in figure 1. The blue colouring indicates a rain rate of 0.25–0.5 mm hr^{-1}.

rate, as specified by Tripoli and Cotton (1980), but autoconversion only becomes active when the liquid water content (q_{cl}) for a single gridbox exceeds some threshold value. In the MetUM, this is when the liquid water content is such that the number of droplets of radius above 20 μm is 1000 m^{-3}. This is defined, as in Pruppacher and Klett (1997) to give cloud droplet number, N_d as

$$N_d = \left(\frac{A}{B}\right) r^2 e^{-Br} + \left(\frac{2A}{B^2}\right) re^{-Br} + \left(\frac{2A}{B^3}\right) e^{-Br}, \qquad (1)$$

where $A = \frac{B^3 N_d}{2}$, $B = \frac{3}{r_{mean}}$ and mean radius $r_{mean} = \left(\frac{27\rho q_{cl}}{80\pi\rho_w N_d}\right)^{\frac{1}{3}}$. This can be inverted for a threshold radius of 20 μm and a threshold concentration of 1000 m^{-3} to give a cloud liquid content threshold for autoconversion as a function of air density (ρ) and N_d as

$$q_{clo} = \frac{1}{\rho}\left(6.20 \times 10^{-31} N_d^3 - 5.53 \times 10^{-22} N_d^2 + 4.54 \times 10^{-13} N_d + 3.71 \times 10^{-6} - \frac{7.59}{N_d}\right). \qquad (2)$$

The relationship between cloud droplet number and threshold liquid water content is shown in figure 3. This shows that for an increase in droplet number from 150 per cm^3 to 600 per cm^3, the liquid cloud threshold for autoconversion increases by roughly a factor of 3.5 (from 0.062 to 0.212 g m^{-3}). In light rain situations, this has the effect of switching off autoconversion over the land, but

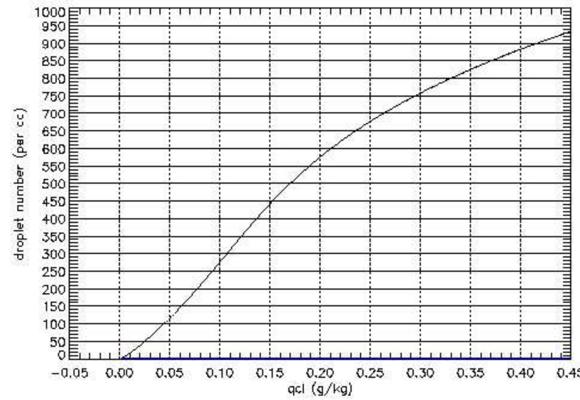

FIG. 3: The MetUM threshold for autoconversion expressed as the number concentration of cloud droplets required to stop a model grid box of a given liquid content from raining out in the MetUM. Above the black line, the combination of cloud liquid content and droplet numbers mean that the cloud will not autoconvert, but beneath the line, the cloud will autoconvert and rain out.

still allowing light rain to form over the seas, causing the land-sea effect shown in figure 1.

3. Comparison to climatologies produced in the literature

Recent field studies have suggested relations between the liquid water path (LWP) of stratocumulus, the droplet number concentration and the associated rain rate falling out of the base of the cloud (R_{CB}). Using data from the EPIC (East Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System) field campaign Comstock *et al.* (2004) suggested that cloud base rain rate should be related to droplet number and liquid water path as

$$R_{CB} = 0.0156\left(\frac{LWP}{N_d}\right)^{1.75}, \qquad (3)$$

where R_{CB} is in mm hr^{-1}, LWP is in g m^{-2} and N_d is in cm^{-3}.

Using observational data from the DYCOMS-II (Second field study into the Dynamics and Chemistry of Marine Stratocumulus) campaign, Geoffroy *et al.* (2008) suggested an alternative, relation, which when expressed using the same units is

$$R_{CB} = 3600 \times \left(21.5 \times 10^3 \frac{(LWP/1000)^{1.5}}{N_d} - 2.3 \times 10^{-6}\right) \qquad (4)$$

The Comstock *et al.* (2004) study was derived from ship-based observations, with LWP data from microwave radiometers and cloud base rain rate derived from radar. The Geoffroy *et al.* (2008) relation was derived from aircraft observations. They also used radar to derive cloud base rain rate, but assumed an adiabatic cloud along with in-situ and lidar measurements of cloud thickness.

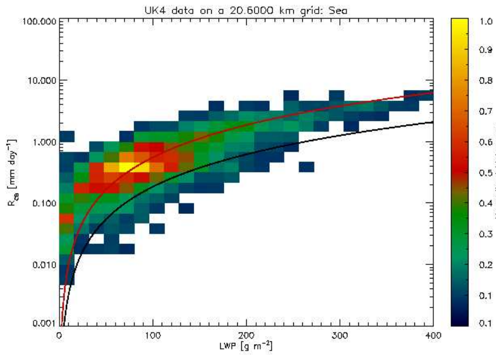

FIG. 4: Histograms of stratocumulus liquid water path versus cloud base, averaged over 21 hours of MetUM data and normalised to the maximum number of points in each bin. Overplotted are the curves generated from the Comstock *et al.* (2004) relationship (equation 3) assuming cloud droplet concentrations of 80 (red line) and 150 (black line), the latter being the assumed MetUM value for the points in question.

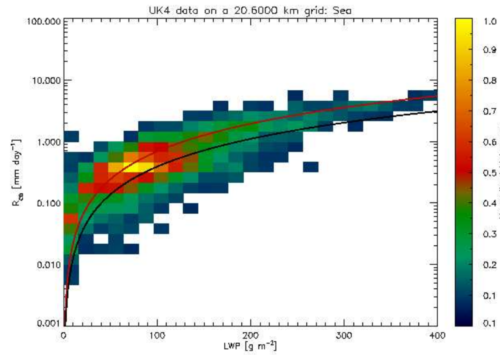

FIG. 5: As figure 4, but with the Geoffroy *et al.* (2008) relationships plotted. The assumed cloud droplet concentrations are 85 (red line) and 150 (black line).

The Geoffroy *et al.* (2008) relation used in-cloud measurements of droplet number; however, the Comstock *et al.* (2004) relation derived droplet number from cloud transmission measurements, where night time values of droplet number were derived from linear interpolation between the day time observations. We have been able to compare these two relations to values of cloud base rain and liquid water path from the model. To to this, we have extracted columns of MetUM forecast data over 20-hour forecasts (T+0 to T+20) according to the following criteria:

- Only data in the lowest 30 model levels (beneath 6400 m) was selected.
- Only points with a diagnosed stratocumulus boundary layer type (following the scheme of Lock *et al.*, 2000 were chosen).
- Only sea points were chosen, as there was little rain data over the land (see figure 1).
- Only points where the rain was falling out of cloud base were chosen.
- Ice cloud data was excluded.
- The model columns were averaged up to 20.6 km from the original 4.0 km grid spacing. This was to try and take account of the fact that the Comstock *et al.* (2004) is applicable to length scales of around 75 km and the Geoffroy *et al.* (2008) relation was averaged over flights of around 500 to 900 km. It was not possible to average the model grid boxes to these length scales as the stratocumulus area within model domain is patchy and is much smaller in scale than the stratocumulus decks of the DYCOMS-II or EPIC campaigns. In fact, averaging to larger length scales simply removes the lowest-numbered points from the data histogram. The points that remain are unaffected by the smoothing and the best fit curves do not change significantly with any smoothing value up to 100 km.
- The liquid water path data were divided into 25 linear bins, whilst the rain rate at cloud base were divided into 3 bins, dependent on $\log_{10}$ of the data. A histogram of the number of points in each bin was generated, normalised to the maximum (i.e. the number of points in the most populated bin).
- Cloud base was assumed to occur at the altitude of the first model grid box where the model bulk cloud fraction diagnostic was above zero.

The results of the analysis performed using both relations are shown in figures 4 and 5.

By overlaying the curves generated from equations 3 and 4, we find that the 4km MetUM is producing too much precipitation at cloud base for a given liquid water path when compared to the relations of both Comstock *et al.* (2004) and Geoffroy *et al.* (2008). In fact, for the Comstock *et al.* (2004) relation, the spread of data lies close to the N_d = 80 cm^{-3} curve, when in fact, the assumed droplet number for these points is 150 cm^{-3}. For the Geoffroy *et al.* (2008), relation, the spread of data lies roughly on top of the N_d = 85 cm^{-3} curve.

The key point that can be made by looking at both data sets, is that for any given value of LWP, the MetUM cloud base rain rate is excessive. The spread of data should lie close to the black line in each plot, but instead, it lies on the red line, which would signify a much smaller droplet number concentration. This excessive drizzle at cloud base implies that the autoconversion rate within the model is too large. This agrees with the findings of Wood (2005), who showed that when the autoconversion threshold used in Tripoli and Cotton (1980) was exceeded, the resulting autoconversion rate was too large.

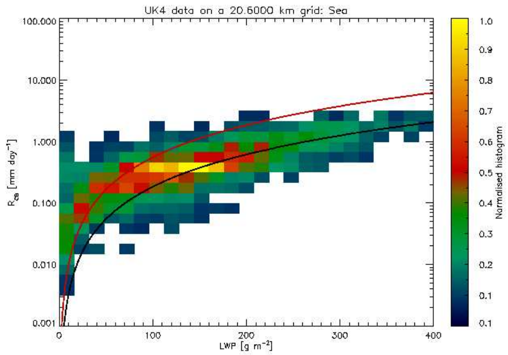

FIG. 6: As for figure 4, but with autoconversion efficiency reduced to 0.15.

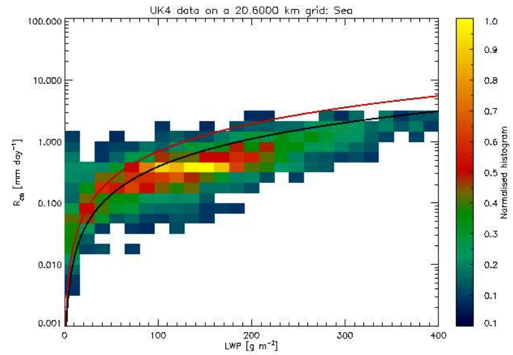

FIG. 7: As figure 6, but with the Geoffroy *et al.* (2008) relationships plotted.

The value of autoconversion rate used in the MetUM is based on Tripoli and Cotton (1980) and is specified as

$$AR = A_1 \left[E_{auto} (\rho q_{cl})^{A_2 - 1} \left(\frac{qcl}{n_d^{A_3}} \right) \right], \qquad (5)$$

where E_{auto} is the autoconversion efficiency, $A_2 = \frac{7}{3}$, $A_3 = \frac{1}{3}$ and A_1 is

$$A_1 = \frac{4\pi g}{18 \left(\frac{4}{3}\pi\right)^{\frac{4}{3}} \mu \rho_w^{\frac{1}{3}}} \qquad (6)$$

where g is the acceleration due to gravity and μ is the dynamic viscosity of air. In order to try and reduce the excessive drizzle at cloud base, we have altered the value of autoconversion efficiency assumed in the MetUM. In the default UK4 MetUM, it is defined as 0.55. The MetUM simulations were then re-run for exactly the same time period. However, in this model run, the autoconversion efficiency was reduced to 0.15. The regenerated histograms for this new data are shown in figure 6 for the Comstock *et al.* (2004) data and figure 7 for the Geoffroy *et al.* (2008) data.

As can be seen in the data where the autoconversion efficiency was reduced to 0.15, the fit to the Comstock *et al.* (2004) data is much better. However, at LWP values of 30 g m^{-2} or less, there is still a tendency for the model to autoconvert cloud water into precipitation too readily. Compared to the Geoffroy *et al.* (2008) data, the model is now showing a slight negative bias in the amount of drizzle production, especially for LWP values greater than 150 g m^{-2}. However, from the perspectove of an operational model, a slight underprediction in the amount of light rain would be more useful than a large over-prediction, and with the present MetUM configuration, any increase in autoconversion efficiency from the 0.15 value would result in spurious drizzle forming out of low LWP clouds in the MetUM.

In the future, we intent to investigate using a different autoconversion scheme other than Tripoli and Cotton (1980). Results of Wood (2005) suggest that better autoconversion schemes to try would be Khairoutdinov and Kogan (2000) or running with Liu and Daum (2004), but with a reduced autoconversion efficiency value.

4. Use of the visibility aerosol and the link to cloud microphysics

In order to forecast visibility, the MetUM contains a single prognostic variable of aerosol mass. Full details of the scheme are given in Clark *et al.* (2008). The aerosol has climatological sources and is scavenged out by falling precipitation and settling cloud droplets. Above the boundary layer top, the aerosol mass reverts to climatological values. The relation of aerosol number to aerosol mass is given as

$$N_{aer} = N_0 \left(\frac{A_{mass}}{m_0} \right)^{\frac{1}{2}}, \qquad (7)$$

where N_0 is the standard number density and m_0 is the 'standard' mass-mixing ratio of the aerosol in unpolluted conditions.

Following research flights to measure aerosol around the UK, Haywood *et al.* (2008) examined the Clark *et al.* (2008) scheme and suggested that the values in the visibility code be set as $N_0 = 2.0 \times 10^9$ m^{-3} and $m_0 = 1.896 \times 10^{-8}$.

Although this provides aerosol number, a link needs to be established between this and cloud droplet number, N_d. For this, we have chosen to follow the same route as the climate version of the MetUM and use the parametrization of Jones *et al.* (1994) as

$$N_d = 3.75 \times 10^8 \left(1 - \exp\left(-2.5 \times 10^{-9} N_{aer}\right)\right). \qquad (8)$$

This has the clear advantage that it asymptotes to a maximum droplet number concentration of 375 cm^{-3}. Over sea, sea-ice and ice sheets, the minimum value of droplet number is 5 cm^{-3}, whilst over the land the minimum number is 35 cm^{-3}, although over the UK area, the droplet numbers rarely drop below 100 cm^{-3}.

The result of applying the visibility scheme to the aerosol number can be seen in figure 8. It can be seen from the conversion process that where the air is polluted, such as across the South of England and off the East coast of Scotland, the droplet number asymptotes to its maximum value of 375 cm^{-3}. Allowing a very high droplet concentration within the MetUM causes the autoconversion process to shut off, except where in very heavy rain areas (such as ana frontal rain bands and heavy showers). It is likely that the 600 cm^{-3} used in the operational MetUM over the land surface is unrealistically too high, as in cases like that shown in figure 1, no light rain is allowed to fall over the land. Closer to the surface, the air is more polluted and more points in the model domain asymptote to the 375 cm^{-3} upper limit. Higher in the free troposphere, the aerosol concentrations decrease significantly and the droplet numbers reduce. Although there are a few points shown in figure 8 where the droplet number concentration drops below 270 cm^{-3}, these are where the air is clean, such as over the sea to the West of France.

5. Results of applying the scheme improvements to the operational MetUM

The droplet number concentration formulae assumed in section 4 has been included in the MetUM and trials have been performed on the case study shown in figure 1. Figure 9 shows the effect of including the new droplet number concentration and reducing the autoconversion efficiency to the 0.15 value. It can be seen that before, where the high droplet number over the land prevent the clouds from autconverting to produce rain, except in a few situations, the new code allows similar amounts of rain to fall over the south-west peninsula of the UK and over the nearby oceans. This closely matches the location of the light precipitation seen on the radar image in figure 2. It can be seen that the rain now falling over the peninsula is of similar intensity to the observations. When the autoconversion efficiency is reduced to 0.15, the rain rates remain at a similar rate to the radar, but the falling precipitation becomes more patchy in nature, which is in better agreement with the nature of the falling precipitation, as seen in figure 2.

6. Summary and Future Work

Introduction of a simple function to convert the visibility aerosol used in the MetUM into a cloud droplet number has removed the artificial land-sea split seen within the model, that has existed for some years, an artefact of when the MetUM resolution was much lower than it is now. It has allowed a fairly realistic assumption of where the air is dirty and where it is clean.

Comparing the MetUM to stratocumulus climatologies (Comstock *et al.*, 2004; Geoffroy *et al.*, 2008), we find that for a given liquid water path, the cloud base rain

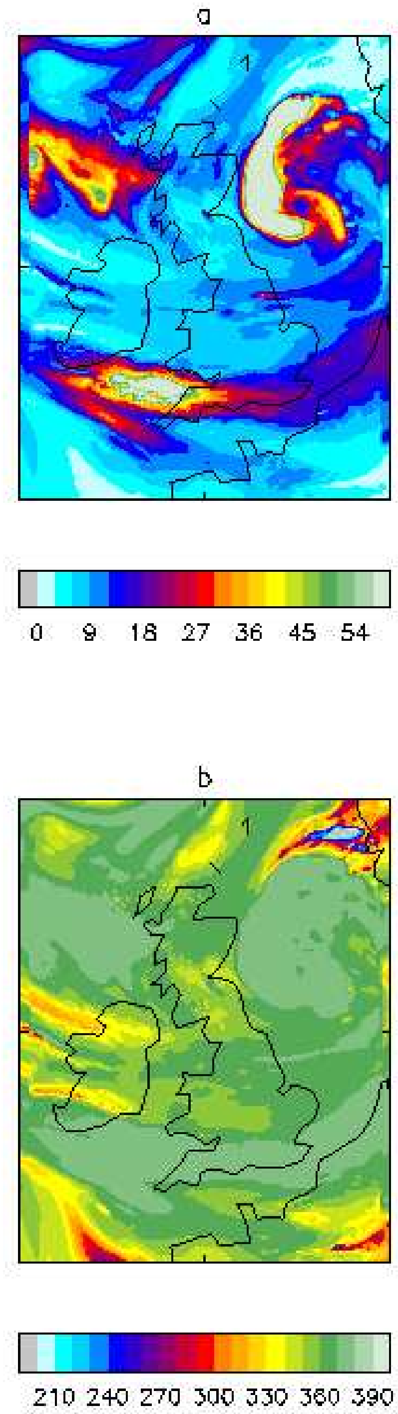

FIG. 8: The process of by converting aerosol concentrations into a droplet number, shown at an altitude of around 600 m for 03Z on 26 Oct 2009. (a) Shows the mass concentration of the visibility aerosol, in μg kg^{-1}. (b) Droplet number (per cm^3 after equations 7 and 8 have been applied to the data.

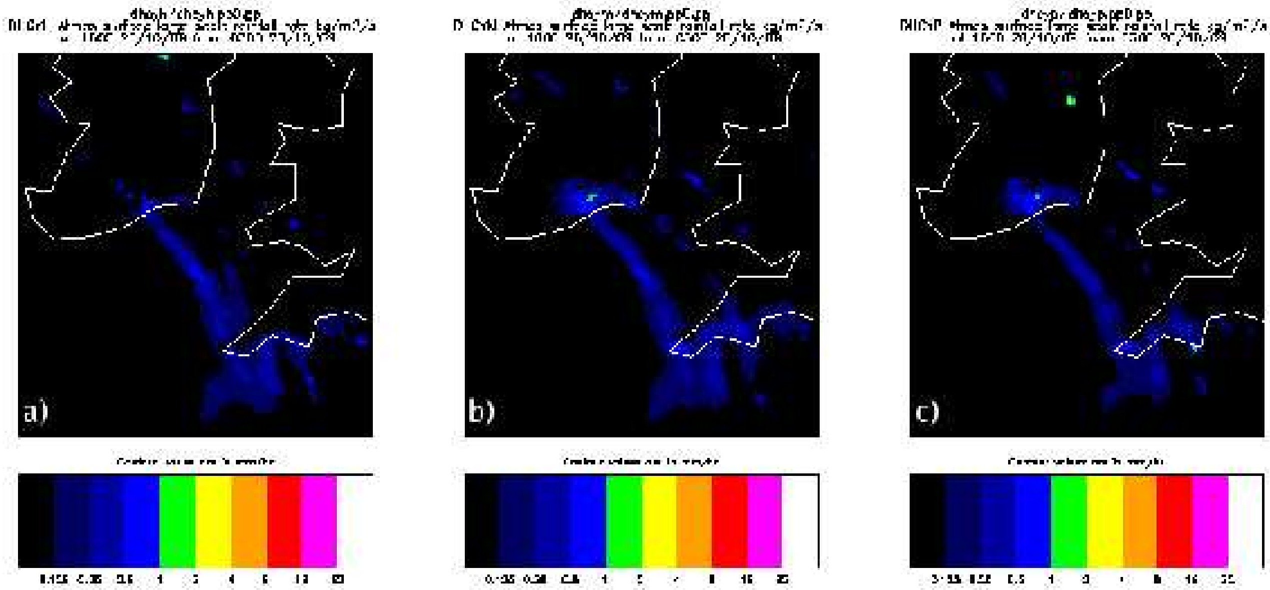

FIG. 9: a) The initial MetUM scheme, as shown in figure 1, but on the same colour scale as figure 2. b) The MetUM with the new autoconversion scheme producing cloud droplet number from the relations of Haywood *et al.* (2008) and Jones *et al.* (1994). c) The MetUM with the new autoconversion scheme, but with autoconversion efficiency reduced to 0.15.

rate is too large. Reducing the autoconversion efficiency of the scheme used in the MetUM results in better agreement with the climatologies, although the model has still a tendency to drizzle excessively at very low values of liquid water path. This is under investigation for the future.

Although the importance of cloud-aersol interactions has long been known for climate models, the importance of this topic for NWP forecasting is not yet known. However, in many operational models, and autoconversion relations, there is a strong dependence on cloud droplet number. This study shows the impacts of using aerosol amounts to look at this process. We hope to be able to extend this work further by coupling the UKCA model to the MetUM microphysics scheme. This will allow the investigation of important questions about cloud-aerosol interaction within NWP forecasting, such as the level of complexity required to improve forecasts of rain but without hindering the quick run-time of an operational model.

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