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Differences in the lower troposphere in two- and three-dimensional cloud-resolving model simulations of deep convection

J. C. Petch*[1], P. N. Blossey[2] and C .S. Bretherton[2]
[1]*Met Office, UK*
[2] *University of Washington, Seattle, Washington, USA*

Abstract: This short note discusses key deficiencies in two-dimensional (2D) cloud resolving model (CRM) simulations. Results differ significantly from three-dimensional (3D) simulations in the low level humidity structure and associated fields. These differences are consistent across two different CRMs which differ substantially in their thermodynamic and microphysical formulations. Our analysis suggests than the near-surface humidity structure depends on moisture transport in clouds, and we suggest that differences in entrainment between 2D and 3D simulations lead to substantial differences in both cloud amount and moisture transport by the clouds at low levels. When compared to 3D, less entrainment in 2D reduces the likelihood that convective updraughts terminate and moisten the lower troposphere. The differences between the 2D and 3D are significant if the CRM is to be used as a reference for comparison against numerical weather prediction (NWP) or climate models. ©Crown Copyright 2008

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1 Introduction

Cloud-resolving models (CRMs) are considered a key tool in the process of developing and improving parametrizations in numerical weather prediction (NWP) and climate models; this is discussed in some detail in the GEWEX[†] Cloud System Study (GCSS) science and implementation plan (Randall *et al.*, 2002). CRMs complement observations, both by being able to provide details which cannot be observed but also because they can be driven by identical forcing to a single-column version of an NWP or climate model (SCM) (see Randall *et al.* (1996) for full details). It is important that the processes we are trying to improve in an NWP or climate model are well represented by the CRM, and the experimental design and the focus of our analysis of the CRM should reflect this.

Assessing the quality of any CRM simulation is very difficult because they can only respond to the forcing they are given. While forcing for CRMs can be derived from observations, the accuracy of the forcing is limited by the spatial and temporal sampling of the observations. Typically it is very difficult to attribute an error in CRM output to deficiencies in the model itself, or deficiencies in the forcing data. Two methods can be employed to better understand the quality of CRM simulations. Firstly, we can use a case study which is part of a multi model comparison (e.g. Grabowski *et al.*, 2006). Secondly we can carry out a range of sensitivity experiments with a given CRM (e.g. Donner *et al.*, 1999; Petch and Gray, 2001). Both these methods help identify the typical spread of a given diagnostic across different CRMs. Also, in both cases, we can gain some understanding of the physical processes leading to the differences in model behaviour.

Running CRMs in 2D is still very common because it is attractive to invest the saved computational expense associated with 2D simulations in other areas (e.g. better microphysics; more sensitivity studies; more resolution; bigger domain; etc.). It has also become popular to embed 2D CRMs in climate models to act as 'superparametrizations' (e.g. Randall *et al.*, 2003). While it has recently been noted that 2D simulations may have significant problems when modelling the development of convection (Grabowski *et al.*, 2006; Petch, 2006), it has often been suggested that 2D runs are acceptable for more strongly forced and persistent convection such as TOGA-COARE (e.g. Grabowski *et al.*, 1998). However, a key point is that the acceptability of simulation depends very much on the goals of the study. This quite possibly explains the mixed comments about 2D/3D differences in recent papers. Phillips and Donner (2006) have compared 2D and 3D simulations for a variety of cases and stress the large differences between in the dynamics in 2D and 3D convective cores, and the impacts this has on microphysics. Zeng *et al.* (2007) suggested that the sensitivity of buoyancy damping to dimensionality can give rise to fluctuations in precipitation in 2D that are not present in 3D simulations. Donner *et al.* (1999) and Petch and Gray (2001) both noted stronger interactions between radiation and dynamics in 3D, and Petch and Gray (2001) stressed this was sensitive to the microphysics used in the tests. Tompkins (2000) noted a strong impact of using a third

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*Correspondence to: Met Office, FitzRoy Road, Exeter. EX1 3PB, UK. email: jon.petch@metoffice.gov.uk
[†] Global Energy and Water Cycle Experiment

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dimension on thermodynamic structures and suggested the long times scales associated with radiative convective equilibrium experiments led to this large difference. However, other papers (e.g. Grabowski *et al.*, 1998; Xu *et al.*, 2002) which focused more on the domain-mean thermodynamic and cloud-cover profiles suggested that differences between 2D and 3D are not so important.

In this short paper we focus on one current issue being addressed using a CRM; this is the thermodynamic structure of the lower troposphere in the Met Office NWP model during an active period of TOGA-COARE (as discussed in Petch *et al.* (2007)). Here we compare two CRMs and carry out an analysis to better understand possible reasons for differences between the 2D and 3D runs. Section 2 describes the models used in this study. Section 3 describes the experimental design and shows some basic results. Section 4 highlights the key differences between 2D and 3D in terms of the lower-troposphere structure and in section 5 we summarise our results.

2 The models involved

The paper describes results from two different CRMs, both of which have been run in 2D and 3D. It is useful to use more than one CRM for this work to give some feel of the robustness of any 2D/3D difference. Also, as noted in Petch and Gray (2001) and Phillips and Donner (2006) the impacts of 2D 3D differences can be influenced by parametrizations in the CRM such as microphysics.

The *Met Office* CRM, hereafter referred to as the MetO model, is based on the Large Eddy Model first described in Shutts and Gray (1994) and more recently in Petch and Gray (2001). The configuration of its parametrizations was exactly as described in Petch *et al.* (2007) and references within. The 2D simulations used a horizontal domain of 525 km and an horizontal grid length of 350 m. A vertical domain of 20 km was used with the number of vertical levels chosen to give a vertical grid length of 250 m in the free troposphere stretched to give shorter grid lengths in the lowest 2 km; there were 17 levels in the lowest 2 km. The 3D model used a 256 km by 256 km horizontal domain with a 1 km grid length. The vertical domain was 20 km and the vertical grid length was double that of the 2D run in the free troposphere; there were 7 levels in the lowest 2 km. It should be stressed that a large number of 2D simulations with a variety of domain sizes as well as a range of horizontal and vertical resolution have been carried out with the Met Office model, and while resolution and domain can impact some results, none of the issues discussed in this paper were significantly impacted by changes in resolution or domain size.

The second CRM used in this paper, the System for Atmospheric Modelling (SAM) version 6.3, is described in detail in Khairoutdinov and Randall (2003). The model parametrizations used in this study are identical to those used in the BASE case presented in Blossey *et al.* (2007). Both the two- and three-dimensional simulations in this paper use the same vertical grid as the two-dimensional simulations with the MetO model, described above, except that extra layers are added so that the model top is at 30.3km. The top boundary condition of the model is a rigid lid, and damping is applied between 21 and 30km to prevent the spurious reflection of vertically-propagating gravity waves. The horizontal grid spacing is 500m for both the two- and three-dimensional simulations. The two-dimensional simulations have a domain size of 256km, while the three-dimensional domain is 64x64 km^2. While this three-dimensional domain is limited in size, previous simulations of KWAJEX (Blossey *et al.*, 2007) showed that most properties of the simulation do not differ strongly between domains of this size and larger domains. We also note here that like the Met Office model, non of the issues discussed in this paper were significantly impacted by changes in horizontal resolution.

While the general construction of the two models is similar, i.e. both models use finite difference methods for momentum and finite volume methods for energy and moisture, the two methods differ notably in their (1) choice of thermodynamic variable, (2) microphysical parametrization, (3) subgrid-scale parametrization and (4) choice of domain size and grid spacing. The thermodynamic variable used by SAM is liquid water–ice static energy, which is conserved under microphysical transformations but not by falling precipitation. The MetO CRM uses potential temperature as its thermodynamic variable. While both models use single-moment bulk microphysical schemes, the MetO model has prognostic equations for each water category (vapour, cloud water, cloud ice, rain, snow and graupel), and SAM has only two prognostic equations, for total water (vapour, cloud water and cloud ice) and precipitating water (rain, snow and graupel). In SAM, the phases of water and different types of ice precipitation are distinguished using temperature-dependent diagnostics. In the MetO model, however, freezing and melting are explicitly represented. Both models use a Smagorinsky-Lilly subgrid turbulence parametrization, but the choice of the eddy length scale near the surface differs, with SAM choosing the local vertical grid spacing and the MetO using a fixed length scale near the surface of 70 m. The domain sizes used in the MetO model are larger than those used in SAM. The 2D simulations use the same vertical grid spacing and similar horizontal grid spacings (350m in MetO model, 500m in SAM). The grid spacings in the 3D SAM simulations are smaller than those in the MetO model by a factor of two in the horizontal and approximately a factor of two in the vertical. While the models differ in these respects, many aspects of the simulations — including the dependence of certain statistics on the dimensionality of the simulation (2D versus 3D) – are similar, as is shown in the following.

3 Experimental design and basic results

The experiment used in this paper is a part of the GCSS precipitating cloud systems working group case 5 study. The experimental design is discussed Petch *et al.*

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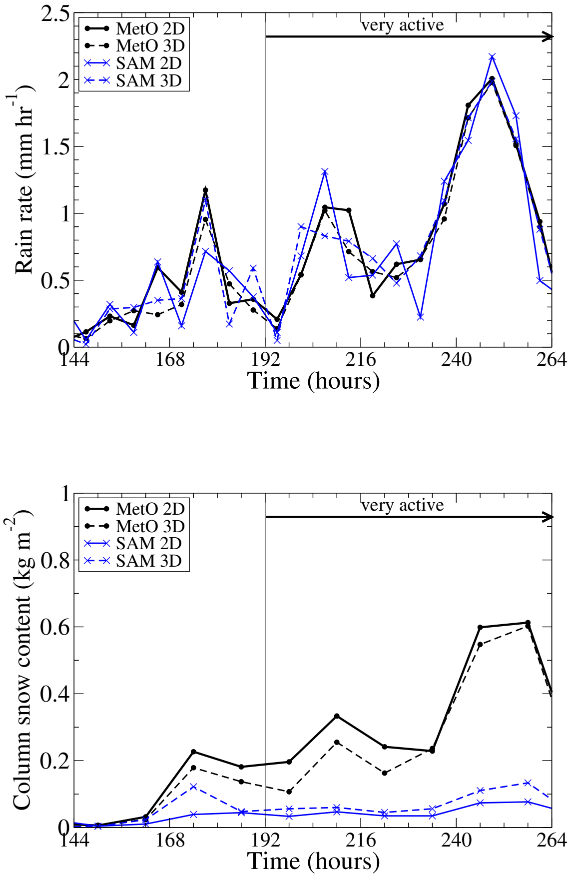

Figure 1. Time series of rain rate and vertically integrated snow content.

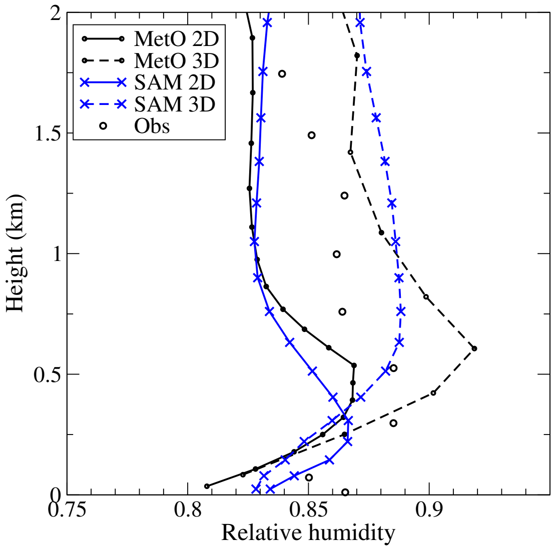

Figure 2. Profiles of relative humidity averaged over the very active period for the Met Office (MetO) CRM and SAM, both run in 2D and 3D.

(2007) and a comparisons of NWP models is described in Willett *et al.* (2008).The CRM simulations are of a 12 day period of TOGA-COARE starting on 8 January 1993 (case B of the GCSS model comparison). Full details of the initialisation and forcing of the CRMs are provided in Petch *et al.* (2007) and for brevity are not reproduced here. The analysis carried out here focuses on the lower tropospheric humidity biases in the NWP model which was discussed in Petch *et al.* (2007) and is most prominent during strong convection. Two issues related to the relative humidity were raised in Petch *et al.* (2007). Firstly, the near surface relative humidity was too low in the NWP model. Secondly, the relative humidity was too large in the NWP model above 600 m. In this paper we will show the CRM humidity used in this work differed notably above 600 m when the CRM was run in 3D and attempt to explain why. To support this work we carry out the 2D/3D comparison with two CRMs.

Figure 1 shows time series of 12 hourly averaged values of rain rate and vertically integrated snow content focused on the active period defined in Petch *et al.* (2007). There is good agreement between the models in rainfall (as expected since the forcings essentially dictate rainfall through large-scale moistening). On the other hand there are significant differences in snow content between the two models, most likely due to their differing microphysical parametrizations. The smaller snow content may be related to the amount of anvil cloud in SAM, which Lopez *et al.* (2008) found to be much smaller than that of observations when considered as a function of precipitation rate. While the microphysical differences between the MetO and SAM model are not the focus of this work, they are shown here to stress that even with these differences across models the 2D/3D differences we will show are robust.

4 Key differences between the 2D and 3D simulation

In this short paper, we focus on the lowest 2 km, as these lower levels were of key interest for addressing deficiencies in the NWP model in Petch *et al.* (2007). Figure 2 shows the relative humidity profile of both CRMs run in 2D and 3D. There are large differences in the humidity profile between 2D and 3D which are consistent for both the MetO and SAM CRM. The clearest signal is above 400 m, where the 3D models have a relative humidity of about 5 percent more than the 2D models. These differences between 2D and 3D are large enough to impact the interpretation the key deficiencies in the NWP model discussed in Petch *et al.* (2007). While not shown, it is worth noting that the larger relative humidity in the 3D models above cloud base is due mainly to larger water content ($\sim$1 g/kg), although they are also slightly cooler ($\sim$0.3 K).This result is entirely consistent with the results of Donner *et al.* (1999) who found that their CRM also exhibited a moister, cooler layer below 2 km in 3D when modelling tropical oceanic convection.

Figure 3 shows the mass flux from both CRMs, defined as the mass flux of upward moving, buoyant,

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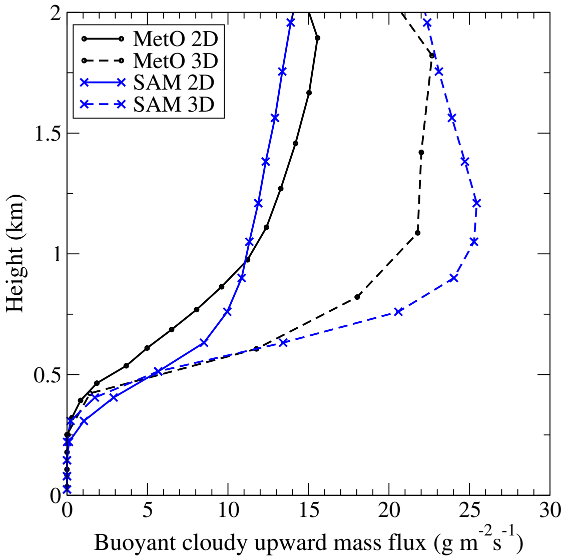

Figure 3. Profiles of the mass flux for upward moving, buoyant cloudy points averaged over the very active period. A point is defined as cloudy if it has a liquid water content above 0.01g/kg.

cloudy air. It can be seen that both models have a similar mass flux in a given dimension (i.e. in 2D or 3D) and both have large differences in this quantity between 2D and 3D simulations. Most notable are the larger values of mass flux in 3D. The decrease in mass flux and buoyant cloudy updraught area (not shown) above 1 km in the 3D simulations suggests that these updraughts are more likely to lose their buoyancy or terminate in 3D than in 2D. This is consistent with the simple argument that a plume in 3D has a greater surface area available for entrainment (both resolved and sub-grid) and that the plume is exposed to a greater variety of conditions over this surface area. One may also explain the dependence on dimensionality by noting that the evolution of a self-similar buoyant plume differs markedly whether one considers a plane plume (analogous to 2D) or an axisymmetric plume (analogous to 3D) (Tennekes and Lumley, 1972, p. 142). While not an exact analogue for buoyant updraughts in clouds — heat release due to condensation is neglected, for example — the fractional entrainment rate (defined below) for an axisymmetric plume exceeds that of a plane plume by a factor of 5/3, suggesting that the updraughts in 3D will be more strongly entraining than in 2D.

To understand how the humidity differences relate to differences in buoyant cloudy updraught area and mass flux, the fractional entrainment and detrainment rates of buoyant cloudy updraughts are plotted in figure 4. The fractional entrainment and detrainment rates are computed for each hour as:

$$\frac{\partial h_{bcu}}{\partial z} = -\epsilon(h_{bcu} - \bar{h}) \qquad (1)$$

$$\frac{1}{M}\frac{\partial M}{\partial z} = \epsilon - \delta \qquad (2)$$

where h is moist static energy, M is the vertical mass flux in buoyant cloudy updraughts, ϵ is the fractional entrainment rate and δ is the fractional detrainment rate. The quantities h_{bcu} and $\bar{h}$ refer to an average of h over buoyant cloudy updraughts and to a horizontal average of h, respectively. This approach for computing entrainment and detrainment closely follows that in equations 10 and 11 in Siebesma *et al.* (2003), except that moist static energy is used as the conserved variable and that buoyant cloudy updraughts are considered rather than just buoyant cloudy locations. The average fractional entrainment and detrainment rates are computed over the very active period using the buoyant cloudy mass flux as a weight, similar to the approach in Siebesma and Cuijpers (1995). The fractional entrainment rate represents the incorporation of environmental air into these updraughts as the updraughts penetrate farther above cloud base. The weakening of buoyant cloudy updraughts — through exchange of momentum with weaker updraughts or downdraughts in the environment — and their termination — through the loss of buoyancy due to evaporative cooling or overshooting of the height of neutral buoyancy or some other process — is represented by the fractional detrainment rate.

While there are notable differences in the entrainment between the two CRMs, it is clear that for both CRMs the 3D runs have larger entrainment rates than the 2D runs for the first few hundred meters above cloud base. The fractional detrainment rates are more similar for the two CRMs and the 2D 3D differences are more striking; the detrainment is up to four times larger in 3D than in 2D in the region above 900m. The increase in fractional detrainment suggests the more strongly entraining buoyant cloudy updraughts in 3D are more likely to terminate, on average, than such an updraught in 2D. The remaining population of buoyant cloudy updraughts at 2 km have similar entrainment rates in 2D and 3D, when weighted by their mass flux. Note that negative values of the fractional detrainment rate below 900m (not plotted in figure 4) indicate that buoyant cloudy updraughts are initiated at a variety of heights and are joining the updraught population leading up to that height.

Finally, it is worth showing that for some diagnostics there are significant differences between the two different CRMs, as is often seen in model comparison papers (e.g. Grabowski *et al.*, 1998; Xu *et al.*, 2002). Figure 5 shows the cloud fraction from the MetO CRM and SAM in 2D and 3D. Here it is clear that the two models have quite different cloud fractions from each other in both 2D and 3D with the SAM producing notably larger cloud areas. As both models have similar buoyant cloudy areas (not shown), this tells us that SAM has more non-buoyant cloud than the MetO CRM. However, even for this diagnostic, it is clear that the differences between 2D and 3D are very similar for the two models with the 3D version of each model producing less cloud than the 2D as we go up from about 1 km.

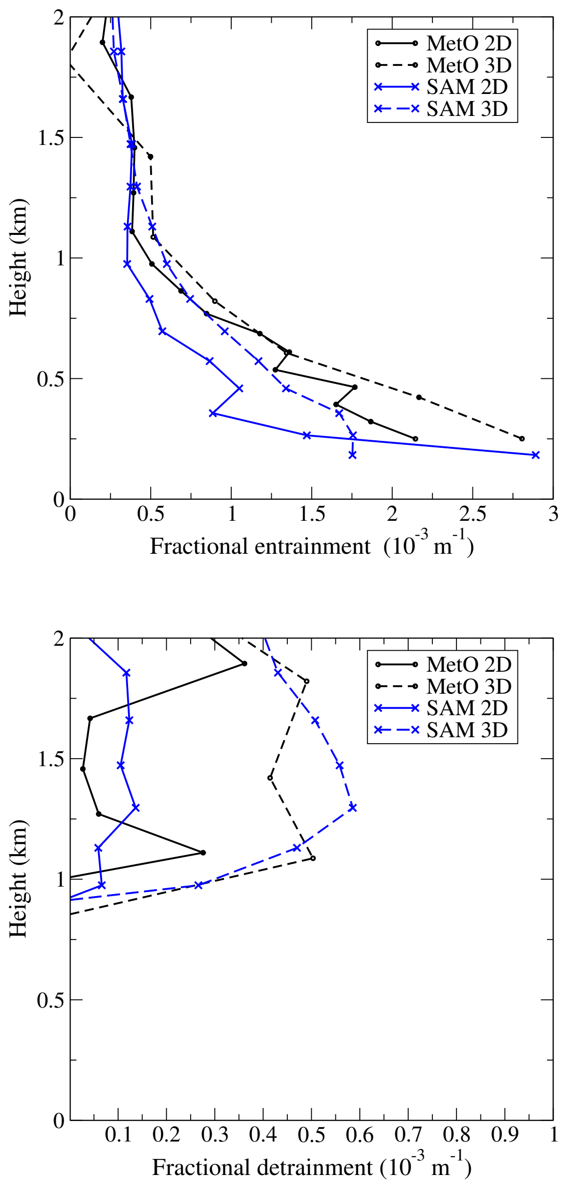

Figure 4. Profiles of weighted averages of fractional entrainment and detrainment over the very active period.

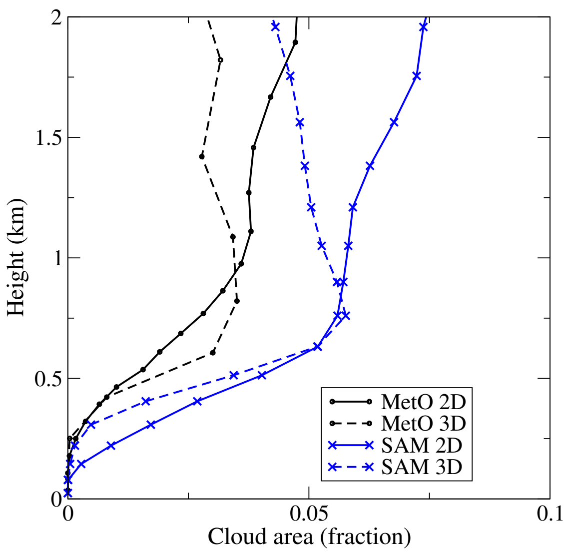

Figure 5. Profiles of cloud fraction from the very active period. A point is defined as cloudy if it has a cloud water content greater than 0.01g/kg.

5 Summary

There are mixed messages in the literature as to whether 2D and 3D CRM simulations differ significantly. It is likely that the conclusions differ because work which has investigated 2D 3D differences have focused on different aspects of a simulation and used different diagnostics to describe the simulations. They may also have reached different conclusions because they used different CRMs to address the issue and these will have used different parametrizations. Petch and Gray (2001) showed that some aspects of 2D/3D differences depended on the choice of parametrizations in a CRM such as the microphysics. Recently, Phillips and Donner (2006) have shown consistency in 2D/3D differences across several case studies, again using just a single CRM. In this short note we have used two different CRMs and focused on 2D/3D differences in the thermodynamic structure and moisture budgets in the lower troposphere. We have focused on the lower troposphere as this has been identified as poorly represented in some NWP and climate model (Petch *et al.*, 2007) and we aim to use information from CRMs to make improvements to their parametrizations.

Results showed great consistency in the key differences between 2D and 3D across the two different CRMs used in this study. Both models had quite different profiles in 2D and 3D. For many diagnostics such as the relative humidity profile and the buoyant cloudy mass flux, the 2D/3D differences were much larger than the differences between the two models. For other diagnostics, such as the total cloudy area, the two models differed by more than the 2D/3D differences. However, even with diagnostics such as these, the impact of going from 2D to 3D in both models was very similar. This suggested that in terms of the key processes occurring in the lower troposphere, the impact of the third dimension was independent of significant differences in the CRMs (such as the microphysics parametrization and the dynamical cores of the models).

Analysis of fractional entrainment and detrainment rates suggested that buoyant cloudy updraughts in 3D entrain more strongly than in 2D, leading to larger fractional entrainment rates near cloud base and larger detrainment rates between 1 and 2 km. This suggested that the 3D updraughts were able to entrain more at lower levels but as this mixing in of environment air would reduce the buoyancy of the cloud, more clouds remained shallow in 3D. This in turn implies that the 3D simulations are able to moisten the region above cloud base more efficiently than the 2D where the clouds continue to deepen. The increase in the mass flux of buoyant cloudy updraughts appears to

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be a response to the changed stability of the lower troposphere in 3D, where enhanced detrainment of cloudy air leads to a cooling and moistening of the layer above cloud base. The change to 3D is also associated with a warming of the subcloud layer.

Many of the differences between 2D and 3D seen in these two CRMs are consistent with previous work in this area. For example, the 2D/3D humidity profile differences are actually similar to those seem in Tompkins (2000) even though he carried out radiative convective equilibrium simulations. Also, while not shown here, the mean updraught velocities are higher in 3D as discussed in Phillips and Donner (2006). In addition, their observation that the strongest updraughts occur in 3D might be explained by the increased moistening of the lower troposphere in 3D, so that these strongest updraughts entrain relatively moister air than they would in 2D. The smaller lower tropospheric relative humidities seen in 2D by Zeng *et al.* (2007) could be explained in part by the mechanisms presented here, although the whole troposphere was drier in 2D than in 3D in that case.

Perhaps the most significant differences between 2D and 3D simulations have been in studies of the development of deep convection though. Notably 2D simulations develop from shallow to deep convection much quicker (e.g. Grabowski *et al.*, 2006; Petch, 2006). The comparison of entrainment and mass fluxes carried out in this paper are not possible in these cases, because 2D and 3D runs quickly diverge from each other, as soon as cloud is formed. However, it seems quite reasonable to believe that the arguments presented here explain these differences. That is, larger entrainment rates in 3D are leading to more shallow clouds and thus a slower development and more moistening of the atmosphere as convection deepens. The key point we want to stress with this short note is that the use of 2D CRM simulations may be acceptable for some experiments but results must be treated with some caution. The acceptability of the results depends very much on the questions being addressed and the diagnostics used to understand the issues.

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