A Review on the Uses of Cloud-(System-)Resolving Models

Jeffrey D. Duda

Since their advent into the meteorological modeling world, cloud-(system)-resolving models (CRMs or CSRMs) have become very important to the study of convection and clouds. Cloud resolving models are generally defined to be models with horizontal grid spacing low enough to be able to explicitly simulate individual clouds, but also large enough to contain cloud systems, as well as being run long enough to cover a multitude of cloud life cycles (Randall et al. 2003). Due to less than ideal computer technology, this has usually put researchers in an optimization problem – being able to best simulate clouds and convection using as high of horizontal grid spacing as possible while also using reasonable computer resources to make the use of CRMs feasible (i.e., not having to run the model for one month to do a simple 24 hour simulation). This has put a general range of horizontal grid spacing considered to be "cloud resolving" of 4 km or less (Cheng and Cotton 2004; Guichard et al. 2004).

Since CRMs are at the forefront of advancing modeling research, they have a number of uses, most of which revolve around their key feature – high resolution. Specifically, tests of dimensionality, an advance in cumulus parameterization – cloud resolving convection parameterization, aids to operational weather forecasting, and the use of model intercomparisons to study traits of shallow convection and the shallow to deep convection transition will be the focus of this literature review. Although each topic will be covered individually, it is important to recognize that they are interrelated. For example, a study of the dimensionality of CRMs usually involves sensitivity tests of resolution and microphysics. As another example, intercomparison studies are used to study just about every aspect of convection and cloud systems, including studying shallow convection, sensitivity to domain size and resolution, and testing the skill of cumulus parameterization schemes.

Since it is computationally less expensive to run CRMs in two dimensions instead of three, many studies have attempted to determine whether 2D CRMs have sufficient skill in simulating convection and cloud systems so that they can be used instead of 3D CRMs. Overall, many studies show that, with a few exceptions, there are not many significant differences between 2D and 3D CRM simulations. However, the exceptions are notable. For example, the lack of a third-dimension in 2D CRM simulations enables higher resolutions to be used. Since higher resolution models can resolve larger vertical motions, one difference between 2D and 3D CRMs (assuming the 3D CRM is run at a lower horizontal resolution than the 2D CRM) is that larger values of cloud mass flux are computed in high-resolution 2D CRMs (Grabowski and Wu 1998). As another example, when measured by precipitable water, or by vertical profiles of relative humidity (dewpoint), 2D CRMs have been shown to be drier than 3D CRM simulations that use the same parameters (Tompkins 2000; Khairoutdinov and Randall 2003). Tompkins (2000) also showed 2D CRM simulations to be warmer than 3D CRM simulations throughout most of the troposphere. This warmth does not explain the lower relative humidity described just earlier because a composite sounding also showed that dewpoint temperatures were also lower throughout a large portion of the troposphere. Another notable difference is in the representation of convection between 2D and 3D CRMs. It is much easier to accurately simulate two-dimensional convection (like squall lines) using a 2D CRM. However, 2D CRMs suffer greatly in simulating convection that is three-dimensional, such as scattered, random convection, or convection from non-linear mesoscale convective systems (like mesoscale convective complexes and isolated supercell thunderstorms) (Tompkins 2000). Grabowski et al. (2006) noted that the transition from shallow to deep convection occurred too quickly and cloud cover increased much faster in 2D CRMs compared to 3D CRMs. This was also shown for the 2D CRMs in the intercomparison study of Xu et al. (2002). In his search for a "minimum benchmark simulation" that best simulates convection while using the minimum computational expense, Petch (2006) determined that using a 3D CRM performed better than the same CRM in two-dimensions since convection simulated in that study was suppressed to much less of an extent when three-dimensional simulations were used. His minimum benchmark simulation included three-dimensions for the model, a grid length of 200 meters, and a domain size of at least 25 km. Despite these potentially significant differences between 2D and 3D CRMs, Grabowski and Wu (1998) noted that it is difficult to separate the statistics and physics of 2D and 3D CRM simulations for a given scenario, so some differences should be expected anyway. However, Xu et al. (2002) concluded that 2D and 3D CRMs simulated continental deep convection very similarly. Therefore, there remains good reason to use 2D CRMs when running one in three dimensions would not be feasible.

Since operational numerical weather prediction (NWP) models like the current National Centers for Environmental Prediction's (NCEP) North American Mesoscale (NAM) model have now reached the 12 km grid spacing range, and will soon be at 4 km, then this model will soon be considered to be a CRM due to the criterion mentioned in the introduction (Guichard et al. 2004). Therefore, CRMs are starting to be used for weather forecasting purposes. Cheng and Cotton (2004) and Derbyshire et al. (2004) showed how CRMs can be used to test the sensitivity of convection to moisture either in the soil or in the atmosphere. In Cheng and Cotton (2004), high soil moisture anomalies were shown to indirectly cause convection to be supressed despite greater amounts of surface latent heat flux, surface dewpoint temperature, and convective available potential energy (CAPE). Perhaps the supression was related to the lower surface sensible heat flux, and subsequently the lower Bowen ratio. However, convection was found to be favored over the edges of the soil moisture anomalies due to the presence of non-classical mesoscale circulations (NCMCs) which resulted in greater upward motion in these areas, thus leading to enhanced convective activity. The point here is that CRMs were used to determine that convection was favored over dry soil, and that the circulations set up over soil moisture gradients caused enhanced convective activity. This study occurred in Texas and Oklahoma. Other studies referenced in Cheng and Cotton (2004) suggest that the suppression or enhancement of convection may be oppositely related to soil moisture in other parts of the United States. Therefore, the results of their study are unique to the Texas and Oklahoma panhandle region. However, in Findell and Eltahir (2003a), a mnemonic of sorts was created to gauge the direction of the relation of soil moisture to convective activity (Fig. 1).

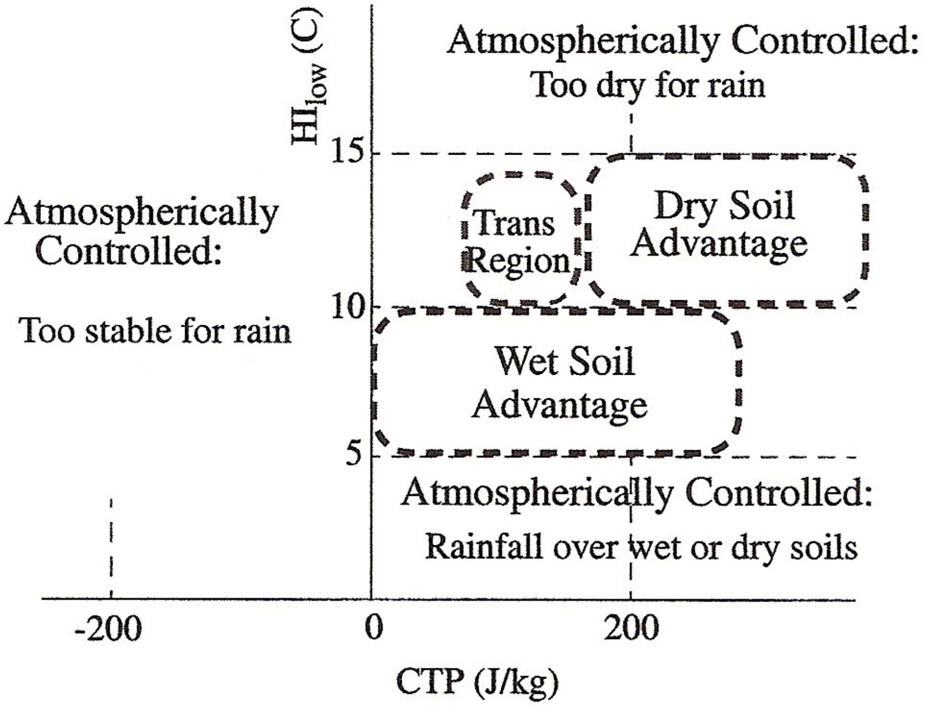

Fig. 1. Mnemonic for the relation between soil moisture and convective activity (From Fig. 15 of Findell and Eltahir (2003a). CTP – or convective triggering potential – is a measure of instability comparable to low-level CAPE. HI_{low} is the sum of the dewpoint depressions 50 and 100 hPa above the surface. Therefore, higher areas of the chart refer to drier conditions, and right areas of the chart refer to more unstable conditions.

Derbyshire et al. (2004) investigated the sensitivity of convection to environmental relative humidity (RH) using 3D CRMs. The results of the sensitivity tests agreed with the theory of a buoyant entraining plume: convective activity, measured by cloudy updraft mass flux (defined as the average mass flux for all points that had cloud and upward velocity), was shown to be greatly sensitive to environmental relative humidity. Higher values of RH in the troposphere resulted in profiles of updraft mass flux that resembled those of deep convection, whereas simulations run with low RH showed profiles of updraft mass flux that resembled only shallow convection. These results do not contradict those of Khairoudinov and Randall (2006), who showed that moistening the free troposphere had little effect on the characteristics of the transition from shallow to deep convection, because the initial conditions in that case were already very moist, and thus is comparable to the difference between the cases of RH = 70% to RH = 90% cases in Derbyshire et al. (2004).

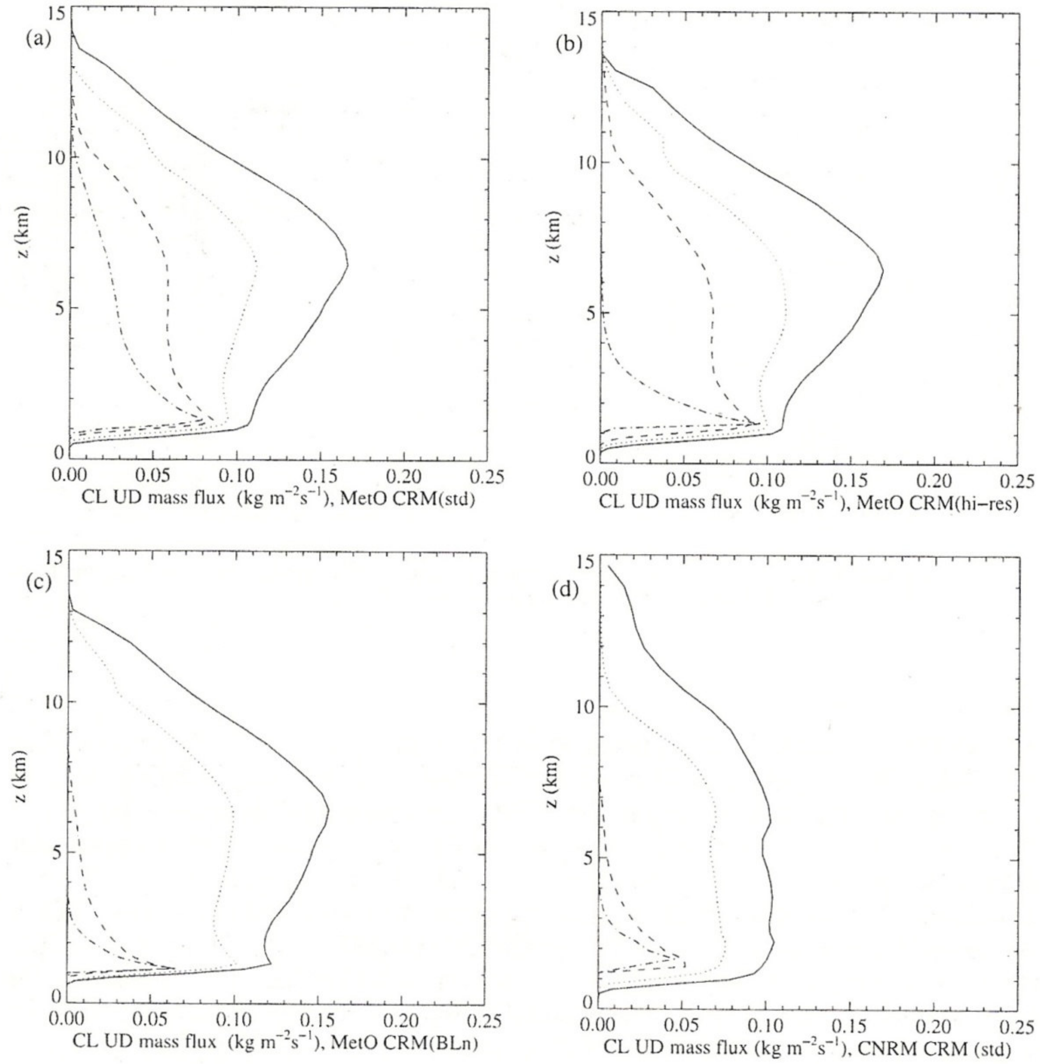

Figure 4. Cloudy updraught mass flux profiles for the four RH_t values in the cloud-resolving models (CRMs): the Met Office CRM at (a) 500 m, (b) 250 m, (c) 500 m with boundary-layer nudging (see text), and (d) the CNRM–GAME CRM at the standard 500 m horizontal resolution (line definitions as in Fig. 1). Note that all four plots are on the same scales.

Fig. 2. From Fig. 4 of Derbyshire et al. (2004). The dark, solid line represents the RH = 90% case, the light dotted line represents RH = 70%, the dashed line represents RH = 50%, and the dashed-dotted line represents RH = 25%.

The entrainment of unsaturated environmental air into a plume obviously will reduce its buoyancy and thus will weaken upward motion to the point of restricting deep convection. From Derbyshire et al. (2004), there is some critical RH value (RH was held constant with height) that separates only a shallow convective scenario from a deep convective scenario. The operational forecasting implications gained from this study are wonderful – with a climatology study to build a database of relative humidity profiles, the ability to forecast whether certain initial conditions (specified forcing was a warm bubble in this study, but surface heat fluxes have been used in other studies (e.g., Guichard et al. 2004 and Khairoutdinov and Randall 2006) as well as advective tendencies (Grabowski and Wu 1998; Su et al. 1999), and radiative forcing (Grabowski 2001; Grabowski 2004)) will spawn deep convection or merely shallow convection will increase. A forecasting aid from Cheng and Cotton (2004) is simply to have soil moisture data (resolution of the data was found not to matter) and to apply the lessons learned from that study.

Recently, the idea of cloud resolving convection parameterization (CRCP), or superparameterization, was suggested by Grabowski and Smolarkiewicz (1999). The idea behind CRCP is that a 2D CRM is inserted into individual columns of a large scale model (usually a GCM) so that the GCM can effectively resolve smaller scale features while using less computer resources than would be required to run that same model at the same resolution as the embedded CRMs (also termed *small-scale models*). In fact, using a GCM with embedded 2D CRMs is about 10^3 to 10^4 times less expensive computationally than running the same GCM at cloud resolving resolution (Randall et al. 2003). Cloud resolving convection parameterization is an improvement over current GCMs because it allows for more detailed studies of climate to be performed (CRCP models can explicitly resolve deep convection, fractional cloudiness on a smaller scale, and surface precipitation accumulation patterns for example (Randall et al. 2003)) and is seen as an intermediate or temporary solution to explicitly resolving small scale processes in large scale models models while the computer technology required to run those models at high enough resolution is developed. Grabowski (2001) said it was the assumption of scale separation - that the embedded CRMs can resolve features on a smaller scale than those that can be resolved by the GCM - that made CRCP possible. The embedded CRMs are run at resolutions similar to other CRMs, around 2 to 4 km (Khairoutdinov and Randall 2001), or finer if computational expenses are not too great.

CRCP has been used to model cumulus and mesoscale processes over a very large domain (that typical of GCMs). The link between the large scale and embedded small scale models is described in Grabowski (2004). The essence of the link is as follows. Since there exists a CRM within each column of the large scale model (with the CRM having obviously higher resolution than the large scale model), the horizontal average of the values of a field variable at each level in the CRM is *required* to match the single value of that variable at each level of the corresponding column of the large scale model. The large scale model is integrated forward (uncentered) in time. The tendencies for the variables are given from advective and source terms of the large scale variables as well as from a forcing term that is computed from the CRM from the previous time step (or set to zero for the initial time step). Once that integration is completed, the CRM integrates forward (in smaller time steps) to meet up with the time of the large scale model. The tendencies in the CRM are also given from advective and source terms (from the small scale variables, i.e., from the variables within the CRM only, which is run in a non-hydrostatic mode. This is opposed to the large-scale model, which is usually run in hydrostatic mode.), as well as a forcing term computed as the difference between the large scale model and the small scale model divided by the time step.

This assures that, after the CRM has integrated all the way up to the large scale model, the requirement initially listed is always met. The same method is used to determine the forcing for the large scale model from the CRM, and the process is repeated.

In a study of mesoscale and cloud processes (Grabowski 2001), it was found that the results from CRCP were somewhat sensitive to the horizontal resolution of the embedded CRMs, and that mesoscale organization suffered in the runs since the small scale models within each column of the large scale model do not interact, and thus cold pools could not travel between small scale models. This effectively stopped the mesoscale convective systems from propagating correctly through the large scale model domain.

Since 2D CRMs being inserted into a 3D GCM (or other large scale model) highlights the key component of CRCP, the issue of orientation of the embedded CRMs was visited by Grabowski (2004). He ran sensitivity tests wherein the embedded CRMs were oriented either west-east or along the lower troposphere mean wind vector. Whereas the first orientation was a standard, the second orientation was intended to be able to incorporate topological effects into the embedded CRMs. The results of the sensitivity tests were all very similar – an MJO like westerly wind burst was simulated in all runs – but the simulation with variable CRM orientation had weaker westerly winds. These results corroborate the assumption made in Grabowski (2001), in that the orientation of the CRMs shouldn't matter in most cases, especially when modeling two-dimensional convection. In an attempt to bypass the issue altogether, Randall et al. (2003) suggested a method of superparameterization in which a second set of 2D CRMs were inserted at right angles to the first set within each column of the large-scale model. Although computational cost increases, this enables the 2D CRMs to essentially become three-dimensional where the two domains intersect within each large-scale grid column. Using three-dimensions to model 3D convection is obviously preferred where available.

Cloud resolving models are frequently used to model shallow convection and the shallow-to-deep convection transition, both over land and over water. Model intercomparisons are frequently becoming useful means for researching these cloud systems and cumulus parameterization schemes (Derbyshire et al. 2004). Model intercomparison studies are frequently conducted not to determine which models perform the best in a given scenario (many intercomparison studies also involve single column models (SCMs) and comparisons between CRMs and SCMs are usually made), but instead are used somewhat as an ensemble to investigate various aspects of cloud systems and cumulus parameterization schemes. A number of these intercomparison studies focused on shallow convection and the transition. Simulations that studied this topic had remarkably high horizontal and vertical resolution (Table 1). This is likely due to using a smaller model domain since the modeled features were of shallow convection, and thus the domains did not need to extend as high as they do for simulations of deep convection. In the search for sufficient horizontal resolution to simulate convection fully, Guichard et al. (2004) noted that 2 km in the horizontal and 100 m in the vertical is not good enough to be able to resolve all of the features of cumulus convection, whereas Grabowski et al. (2006) and Bryan et al. (2003) suggest that grid spacings of 500 m or better are sufficient to accurately simulate cumulus convective processes. Thus the studies referenced in the

Table 1. Studies of shallow convection.

Reference	Horizontal grid spacing(s) used	Vertical grid spacing(s) used
Stevens et al. (2001)	100 m	20 m
Brown et al. (2002)	66.7 m, 100 m	40 m
Siebesma et al. (2003)	100 m	40 m
Guichard et al. (2004)	250 m	47 m, 75 m, 102 m
Grabowski et al. (2006)	50 – 400 m	25 – 100 m
Kuang and Bretherton (2006)	100 m	50 (below 12 km)

table should be considered of sufficiently high resolution to explicitly simulate all of the convective processes.

In studies of just shallow convection, many different simulations represented similar scenarios. That is to say, similar vertical profiles of entrainment rate and cloud mass flux were obtained by Stevens et al. (2001), Brown et al. (2002), and Siebesma et al. (2003). Although the exact numbers in Brown et al. (2002) were off from those in the other two studies (which agreed well with each other, and they also agreed in that around 50% of the cloudy areas were "core" areas, which they defined to be cloudy areas with positive buoyancy and upward vertical motion), it was found that a simple ratio was able to make up the difference between values of many variables. Stevens et al. (2001), Siebesma et al. (2003), and Kuang and Bretherton (2006), agreed that modeled shallow cumulus systems behaved as if their entrainment rate was about 2.0 km^{-1}.

The transition from shallow to deep convection will now be discussed. Grabowski et al. (2006) noted that a small delay in the development of the first clouds in a shallow-to-deep convection transition was due primarily to horizontal grid spacing. Indeed, the average size of the first clouds to develop were usually on the order of the grid spacing since at least a few grid points are needed to resolve an individual cloud. These results were obtained by comparing CRM simulations with a set of benchmark simulations that used the highest horizontal and vertical resolutions this author found during his research (Table 1). The benchmark simulatons started at 50 m and 25 m vertical resolution, but only covered an area of (6.4 to 9.6 km)^2 due to computational limitations. However, after the first two hours of the simulation, the domain dimensions were doubled and the grid spacings halved, so that by 4 to 4.5 hours into the simulation, the domain had a size of (51.2 to 76.8 km)^2, at which size a cloud system could be reliably simulated. The idea was to start with grid spacings small enough to simulate and resolve the formation of the first few small clouds, and then to enlargen the domain to capture the evolution of the boundary layer as the transition began.

Kuang and Bretherton (2006) found that undilute parcels are rare and don't comprise a significant component of the transition from shallow to deep convection. However, Khairoutdinov and Randall (2006) found that the least diluted parcels were experiencing an entrainment rate of about 0.1 km^{-1}. They also found that the boundary layer, despite mixing throughout the transition, was still quite thermodynamically heterogeneous. Consequently, first deep convective development originated from the areas of highest moist static energy in the boundary layer. Despite the heterogeneity, low amounts of entrainment, and the usually high amounts of atmospheric instability (measured by CAPE), as well as the low amounts of low level stability (measured by convective inhibition (CIN)), studies of the shallow-to-deep convection transition commonly noted that deep convection did not initiate even though the atmospheric profile was largely supportive of it (e.g., low CIN, high CAPE, and low level of free convection). The reason for this was a combination of entrainment – the smaller clouds earlier in the transition suffered from a larger entrainment rate, and thus were diluted and lost buoyancy to the point of neutrality – and dynamics – the cold pools that managed to form under the bigger clouds that did form provided convergence and lift to initiate deep convection nearby (Khairoutdinov and Randall 2006). The transition to deep convection is usually marked by a rapid increase in cloud mass flux above cloud base, liquid and ice water path, and obviously precipitation rate, as well as a widening of cloud base and increase in height of center of mass of cloud and maximum cloud height (Grabowski et al. 2006; Khairoutdinov and Randall 2006). Some studies have alluded to the sensitivity of the timing of the transition to the moisture field. A slight moistening of the boundary layer was noted before deep convection formed in Khairoutinov and Randall (2006), Grabowski et al. (2006), and Guichard et al. (2004), although in the latter study, the moistening occurred in the free atmosphere. Perhaps this moistening reduces entrainment rates to the point where a few larger clouds can form and use the dynamics suggested by Khairoutdinov and Randall (2006) to further initiate deep convection.

A CRM was used to study the sensitivity of cumulus convection to various parameters such as dimensionality, resolution, domain size, and microphysics (Khairoutdinov and Randall 2003). While some of the results of this study have been mentioned in other sections, an additional outcome of this study that has not yet been revealed bears mentioning. The authors tested the sensitivity of the CRM to microphysics changes such as changing intercept parameters and removing graupel, and determined that there were significant differences in simulations that used different microphysics. Xu et al. (2002) also showed that the differences in microphysics parameterizations resulted in significant differences in vertical profiles of various species of hydrometeor concentrations, and also that there were differences in vertical profiles of cloud mass flux. However, in the former study, the actual spread of the results was within that of an ensemble of simulations in which only random perturbations in the initial conditions were allowed. Thus it was deemed impossible to fully separate the differences due to changes in microphysics. Also mentioned in Khairoutdinov and Randall (2003) was the fact that the large scale forcing for this case was relatively large, and that could have masked some of the differences due to changes in microphysics. Lesser large scale forcing would not cover up these differences as much, a fact that holds true for any CRM simulation.

Although CRCP has already been discussed, CRMs have also been used to verify other cumulus parameterization schemes. However, results are mixed. Guichard et al. (2004) alluded to needing to use an ensemble of parameterizations for cumulus convection to encompass differing regimes, such as dry and moist non-precipitating, precipitating, and deep and shallow convection. Contrary to that, Kuang and Bretherton (2006) concluded that a single representation of cumulus convection would be sufficient to represent both deep and shallow convection.

As has been shown throughout this literature review, cloud resolving models have been used as a venue for research of many aspects of meteorology on a fine scale, with grid spacings of such models in the range of 50 m to 4 km. They have been used to model shallow and deep convection, test cumulus parameterization schemes, and advance cloud system studies by giving researchers and modelers a chance to zoom in on smaller scale details than have ever been studied before. 2D and 3D CRMs have been shown to perform similarly, and intercomparison studies have revealed that the for the most part, many CRMs simulate the same things in a given scenario. Therefore, researchers can now make conclusions about cloud systems that they could not make without cloud resolving models.

REFERENCES

Brown, and Coauthors, 2002: Large-eddy simulation of the diurnal cycle of shallow cumulus convection over land. *Quart. J. Roy. Meteor. Soc.,* **128,** 1075 – 1094.

Bryan, G. H., J. C. Wyngaard, and J. M. Fritsch, 2003: Resolution requirements for the simulation of deep moist convection. *Mon. Wea. Rev.*, **131**, 2394 – 2416.

Cheng, W. Y. Y., and W. R. Cotton, 2004: Sensitivity of a cloud-resolving simulation of the genesis of a mesoscale convective system to horizontal heterogeneities in soil moisture initialization. *J. Hydrometeor.*, **5**, 934 – 958.

Derbyshire, S. H., I. Beau, P. Bechtold, J.-Y. Grandpeix, J.-M. Piriou, J.-L. Redelsperger, and P. M. M. Soares, 2004: Sensitivity of moist convection to environmental humidity. *Quart. J. Roy. Meteor. Soc.,* **130,** 3055 – 3080.

Findell, K. L., and E. A. B. Eltahir, 2003a: Atmospheric controls on soil moisture–boundary layer interactions. Part I: Framework development. *J. Hydrometeor.,* **4,** 552 – 569.

Grabowski, W. W., and X. Wu, 1998: Cloud-resolving modeling of cloud systems during phase III of GATE. Part II: Effects of resolution and the third spatial dimension. *J. Atmos. Sci.*, **55**, 3264 – 3281.

----, and P. K. Smolarkiewicz, 1999: CRCP: A cloud resolving convection parameterization for modeling the tropical convecting atmosphere. *Physica D,* **133,** 171 – 178.

----, 2001: Coupling cloud processes with the large scale dynamics using the cloud-resolving convection parameterization (CRCP). *J. Atmos. Sci.*, **58**, 978 – 997.

----, 2004: An improved framework for superparameterization. *J. Atmos. Sci.*, **61**, 1940 – 1952.

----, and Coauthors, 2006: Daytime convective development over land: A model intercomparison based on LBA observations. *Quart. J. Roy. Meteor. Soc.,* **132,** 317 – 344.

Guichard, F., and Coauthors, 2004: Modeling the diurnal cycle of deep precipitating convection over land with cloud-resolving models and single-column models. *Quart. J. Roy. Meteor. Soc.*, **131,** 3139 –3172.

Khairoutdinov, M. F., and D. A. Randall, 2001: A cloud resolving model as a cloud parameterization in the NCAR community climate system model: Preliminary results. *Geophys. Res. Lett.*, **28,** 3617 – 3620.

----, ----, 2003: Cloud resolving modeling of the ARM summer 1997 IOP: Model formulation, results, uncertainties, and sensitivities. *J. Atmos. Sci.,* **60**, 607 – 625.

----, ----, 2006: High-resolution simulation of shallow-to-deep convection transition over land. *J. Atmos. Sci.*, **63**, 3421 – 3436.

Kuang, Z., and C. S. Bretherton, 2006: A mass flux scheme view of a high-resolution simulation of a transition from shallow to deep cumulus convection. *J. Atmos. Sci.*, **63**, 1895 – 1909.

Petch, J. C., 2006: Sensitivity studies of developing convection in a cloud resolving model. *Quart. J. Roy. Meteor. Soc.*, **132**, 345 – 358.

Randall, D. A., M. F. Khairoutdinov, A. Arakawa, and W. W. Grabowski, 2003: Breaking the cloud parameterization deadlock. *Bull. Amer. Meteor. Soc.* **84**, 1547 – 1564.

Siebesma, and Coauthors, 2003: A large eddy simulation intercomparison study of shallow cumulus convection. *J. Atmos. Sci.,* **60,** 1201 – 1219.

Stevens, and Coauthors, 2001: Simulations of trade wind cumuli under a strong inversion. *J. Atmos. Sci.,* **58,** 1870 – 1891.

Su, H., S. S. Chen, and C. S. Bretherton, 1999: Three-dimensional week-long simulations of TOGA COARE convective systems using the MM5 mesoscale model. *J. Atmos. Sci.*, **56**, 2326 – 2344.

Tompkins, A. M., 2000: The impact of dimensionality on long-term cloud resolving model simulations. *Mon. Wea. Rev.*, **128**, 1521 – 1535.

Xu, K.-M., and Coauthors, 2002: An intercomparison of cloud-resolving models with the Atmospheric Radiation Measurement summer 1997 intensive observation period data.

Quart. J. Roy. Meteor. Soc., **128**, 593 – 624.