Modeling Aerosol Impacts on Convective Storms in Different Environments

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ABSTRACT

Aerosols are known to have both direct and indirect effects on clouds through their role as cloud condensation nuclei. This study examines the effects of differing aerosol concentrations on convective storms developing under different environments. The Regional Atmospheric Modeling System (RAMS), a cloud-resolving model with sophisticated microphysical and aerosol parameterization schemes, was used to achieve the goals of this study. A sounding that would produce deep convection was chosen and consistently modified to obtain a variety of CAPE values. Additionally, the model was initiated with varying concentrations of aerosols that were available to act as cloud condensation nuclei. Each model run produced long-lived convective storms with similar storm development, but they differed slightly based on the initial conditions. Runs with higher initial CAPE values produced the strongest storms overall, with stronger updrafts and larger amounts of accumulated surface precipitation. Simulations initiated with larger concentrations of aerosols developed similar storm structures but showed some distinctive dynamical and microphysical changes because of aerosol indirect effects. Many of the changes seen because of varying aerosol concentrations were of either the same order or larger magnitude than those brought about by changing the convective environment.

1. Introduction

Convective clouds are an important part of the climate system, contributing significantly both to cloud radiative feedbacks and global precipitation. One factor that influences the properties of convective clouds is the presence of nucleating aerosols. It has been stated that anthropogenic aerosols can have a significant impact on the radiative properties of clouds and on regional precipitation patterns (Ramanathan et al. 2001; Rotstayn and Lohmann 2002). However, the Fourth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC) points out that the full range of processes involved in cloud–aerosol interactions are not yet well understood and lists aerosol indirect effects as one of the key uncertainties in our changing climate (Solomon et al. 2007). It is therefore important to understand even small changes in the properties of these convective clouds due to aerosol forcing, because such differences could become quite significant when summed over large spatial and temporal scales.

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The first and second aerosol indirect effects combine to explain the basic theory of how increased concentrations of cloud condensation nuclei (CCN) will affect the properties of clouds. First, assuming equal liquid water contents, an increase in aerosol available to act as CCN will lead to the formation of more cloud droplets that are smaller in diameter. This in turn will increase the albedo of clouds formed in polluted areas, thus significantly impacting the radiation budget (Twomey 1974, 1977). The second aerosol indirect effect (Albrecht 1989) explains a reduction in warm rainfall due to high concentrations of CCN. The larger number of small cloud drops present in these polluted clouds means that fewer droplets grow to larger sizes and hence the droplet size distribution is narrower. This leads to a less effective collision and coalescence process, and hence the formation of warm rain is hindered in polluted clouds. Albrecht also found that the reduction of warm rain can lead to longer cloud lifetimes, which also would enhance cloud albedo.

Many have followed these original studies with attempts to better understand how such indirect effects can change the properties of clouds; however, this response is still not well understood. For example, the reduction in precipitation in polluted clouds due to the second aerosol indirect effect has been shown in many cases (e.g., Khain et al. 1999, 2005; Phillips et al. 2002; Andreae et al. 2004; Cohen and McCaul 2006; Lin et al. 2006; van den Heever et al. 2006; van den Heever and Cotton 2007; Lebsock et al. 2008) to result in an increase in liquid water path (LWP) and in cloud lifetime. However, several situations have been studied in which this is not the case (Jiang et al. 2002; Ackerman et al. 2004; Lu and Seinfeld 2005). Often, the differences in the response of mixed-phase clouds to higher CCN concentrations can be attributed to the presence of ice within the clouds examined.

Polluted clouds have been shown (e.g., Cohen and McCaul 2006; Khain et al. 1999, 2005; Andreae et al. 2004; Carrió et al. 2007; Lynn et al. 2007) to contain more pristine ice, because more small cloud droplets are available to be lofted into the colder regions of the clouds. Several studies (Phillips et al. 2002; van den Heever et al. 2006; van den Heever and Cotton 2007; Lynn et al. 2007; Khain 2009) have found that high aerosol concentrations may affect mixed-phase clouds differently than warm clouds. It has also been noted (e.g., Khain et al. 2005; van den Heever et al. 2006; van den Heever and Cotton 2007; Lynn et al. 2007; Lee et al. 2008; Ntelekos et al. 2009) that high concentrations of aerosols can invigorate convection (because of the latent heat released by both condensational processes and the freezing of cloud droplets) and influence secondary convection. In addition, differences in cloud type and environment can change the response (e.g., Matsui et al. 2004, 2006; Khain et al. 2005; Cohen and McCaul 2006; Seifert and Beheng 2006; Lynn et al. 2007; Lebsock et al. 2008; Khain 2009). When looking at convective clouds, the picture is much more complicated than what was originally described by the first and second aerosol indirect effects, which considered only stratocumulus clouds. Understanding the aerosol indirect effects on convective clouds is important, given their production of heavy rainfall and other severe weather. Pollution can lead to important changes in the cold pools produced by storms (e.g., van den Heever and Cotton 2007) and appear to even have a role in determining storm organization and the possibility of tornadogenesis (e.g., Lerach et al. 2008; Snook and Xue 2008).

Both modeling and observational studies have been used to examine the effects of increased CCN concentrations in warm clouds. Each method has its own advantages and disadvantages. For example, idealized modeling studies can be used to isolate the response of clouds to changes in aerosol concentration while keeping environmental conditions constant. However, these findings are dependent on the model's parameterization schemes and aspects such as model resolution. On the other hand, satellite data can be used to infer information about atmospheric properties (e.g., aerosol optical depth, cloud coverage, and precipitation) with good spatial and temporal coverage, but the information typically gained is about integrated quantities and hence shows only part of the picture. Also, as with model parameterization schemes, many assumptions are made within remote sensing algorithms. Recently, *CloudSat* (Stephens 2002) has offered the opportunity to penetrate clouds and gather information about vertical structure in the atmosphere. Some studies (Berg et al. 2008; Lebsock et al. 2008) have attempted to combine these data with other available remote sensing data or with model results. However, a weakness when using satellite data is the complexity that exists in observing the details of the ice phase, making it difficult to study the effects of aerosols on mixed-phase clouds.

This study seeks to examine the impacts of varying CCN concentrations on convective storms developing in different environments, utilizing an idealized modeling study. The convective environment will be varied to determine the relative importance of changes in CAPE and aerosol concentration. Results will be presented that show the significant changes that occur in convective storms characteristics because of an increase in aerosol concentration within varying CAPE environments. It will be shown that many of these changes are on the same order as or even larger than changes brought about by increasing CAPE in the initial storm environment for the range of aerosol concentrations and CAPE examined here. Results also show differences in the response to increased aerosols that depend on the initial environmental conditions.

The structure of this paper is as follows: section 2 will provide a description of the model used in this study and outline the initial conditions of the idealized simulations. Section 3 will be divided into three parts describing aerosol impacts on general storm development, storm microphysics, and dynamics. Section 4 describes a few simulations that were run to test the sensitivity of the results to changes in the initial model setup. Finally, section 5 will summarize the conclusions of this study.

2. Methods

a. Model description

The model chosen for this study was the Regional Atmospheric Modeling System (RAMS) (Pielke et al. 1992; Cotton et al. 2003). RAMS is appropriate for this numerical study because of its ability to resolve convective processes and its sophisticated microphysical and aerosol parameterization schemes, both of which

TABLE 1. RAMS options utilized in the model simulations.

Parameter	Model option used
Horizontal domain size	300 km × 500 km
Horizontal grid spacing	$dx = dy = 1$ km
Vertical grid spacing	35 levels up to a 23-km model top; stretched from 50 m to 2-km spacing
Time step	4 s
Duration of model runs	5.5 h
Model physics	Nonhydrostatic
Model microphysics	Two-moment bulk microphysics scheme with prognostic aerosols (Meyers et al. 1997; Saleeby and Cotton 2004)
Lateral boundary condition	Radiative lateral boundary conditions (Klemp and Wilhelmson 1978)
Upper boundary condition	Rayleigh friction layer over top four model levels topped with a rigid lid
Surface scheme	Land Ecosystem–Atmospheric Feedback (LEAF-2; Walko et al. 2000)
Radiation model	Two-stream radiation parameterization (Harrington 1997; Harrington et al. 1999)
Coriolis force	Off

are necessary to understand cloud–aerosol interactions. The two-moment bulk microphysics scheme (Meyers et al. 1997) was utilized in these simulations to allow for a more accurate representation of the microphysical processes that would be affected by changes in the concentration of aerosols that can act as CCN. The two-moment scheme predicts both the mass mixing ratio and number concentration of cloud water, rain, and five ice species (pristine ice, snow, aggregates, graupel, and hail). The size distribution of each of the hydrometeors is represented using a generalized gamma function. The RAMS two-moment microphysics scheme uses a bulk approach for prediction but attempts to emulate a bin microphysics scheme for several important microphysical processes through the use of lookup tables and offline parcel calculations (Feingold and Heymsfield 1992). In this way, the scheme can retain some of the sophistication of a bin model while keeping computational costs relatively low. Processes such as CCN activation (Saleeby and Cotton 2004), cloud droplet collection (Feingold et al. 1988), and drop sedimentation (Feingold et al. 1998) are represented in such a way.

An initial profile for the number concentration of aerosols that are available to act as CCN is specified at the start of the simulations. These aerosols are then activated by the model based on environmental conditions and can be advected throughout the model domain and eventually scavenged by precipitation. They are returned to the atmosphere following evaporation. The number of CCN that are activated to form cloud droplets is determined by an activation function that depends on vertical velocity, temperature, water supersaturation, and aerosol properties (Saleeby and Cotton 2004). The use of this aerosol scheme thus allows for a more realistic simulation of aerosols in an environment than schemes in which the number of cloud droplets is simply initially specified to represent clean or polluted conditions. The initial aerosol field that is specified represents the maximum number of aerosols that can be activated as CCN.

All simulations were run on the same model domain, which spanned 500 km × 300 km. The horizontal grid spacing of the runs was 1 km, which was chosen to be small enough to explicitly resolve storm scale motion while remaining reasonably inexpensive computationally. The model setup included 35 vertical levels, reaching to just over 23 km in height. Sensitivity tests concluded that the number of levels was sufficient to represent deep convection. The vertical resolution is stretched with height, with the highest resolution (~100 m) in the boundary layer. A Rayleigh friction layer of four model layers was implemented at the model top, which was used to relax conditions to the original horizontally homogeneous environment to avoid the problems of gravity waves reflecting off of the top boundary of the model. Lateral boundary conditions were implemented using the Klemp–Wilhelmson scheme (Klemp and Wilhelmson 1978). Because the experiments are run for a relatively short time period, the Coriolis force was turned off. Table 1 provides a summary of the model options utilized.

b. *Experiment design*

The model simulations were initialized with a horizontally homogeneous but vertically varying temperature and moisture profile. A temperature perturbation was used to initiate convection. Sensitivity tests led to the value of 2 K being used for the perturbation, which was 10 km × 10 km in size and extended over a depth of roughly 2.5 km. The simulations were run out for 5.5 h to capture a large portion of the convective life cycle.

The temperature and moisture profiles used for the control simulation came from a well-used idealized sounding originally utilized by Weisman and Klemp (1982). This sounding is representative of a typical

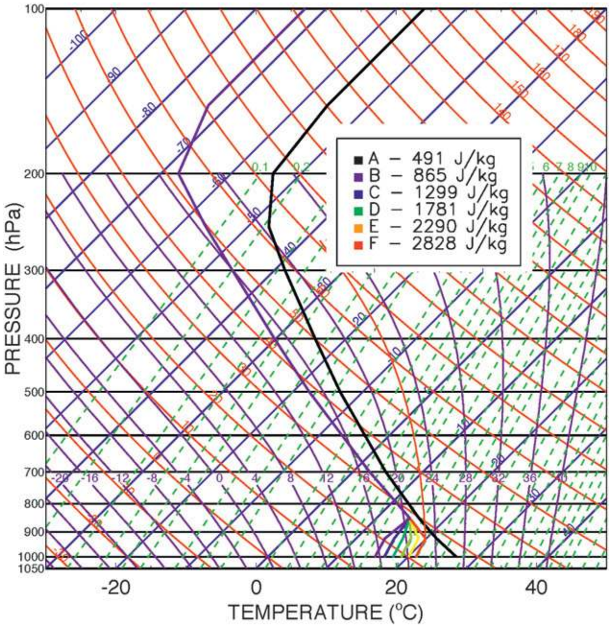

FIG. 1. The six soundings that were used to initialize the model (Weisman and Klemp 1982).

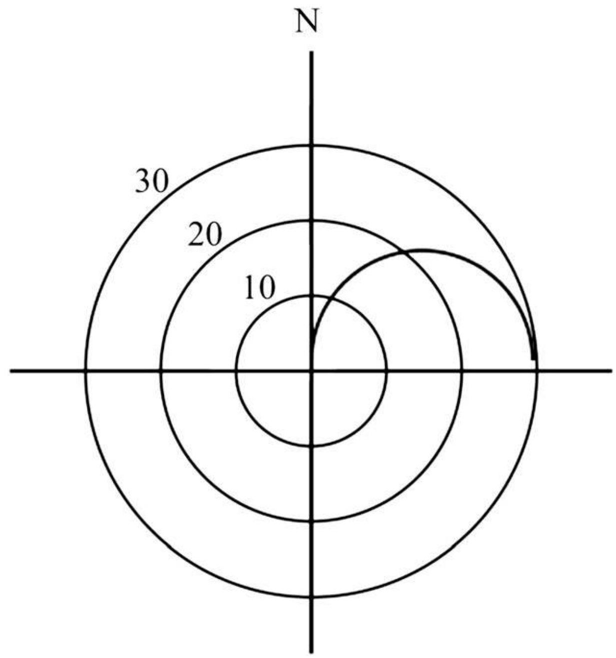

FIG. 2. Hodograph of initial winds used in all model simulations (Weisman and Klemp 1984).

midlatitude deep convective storm environment. The sounding has a constant mixing ratio over the lowest 750 m thus representing a well-mixed boundary layer. To create a set of model simulations with different updraft strengths but similar storm evolution, the original sounding was consistently modified to change the available energy in the prestorm environment. This was accomplished by changing the value of the mixing ratio in the surface layer. The mixing ratio was set to range from 11 to 16 g kg^{-1}, which resulted in a set of six soundings with CAPE values ranging from ~500 to ~2800 J kg^{-1}. Figure 1 shows the initial soundings that were used. Weisman and Klemp (1982) altered their sounding in a similar manner.

The wind profile that was chosen for use in this study was a semicircle hodograph, as in Weisman and Klemp (1984). The magnitude of the shear was the largest from their study, with Us = 50 m s^{-1}, as shown in Fig. 2. In the Weisman and Klemp study, the authors showed that simulations using this high shear value produced a splitting storm in which the right mover becomes dominant and long lived while the left flank leads to the production of multicellular convection. This allows for the possibility of studying differences in aerosol effects on different types of convection within the same simulation.

In the simulations conducted for this study, the number of aerosol available to act as CCN was progressively doubled from one simulation to the next to allow for the examination of the effects of a wide range of aerosol concentrations. The initial profile of aerosol available to act as CCN has a maximum value N at the surface, decreases linearly up to a height of approximately 4 km, and then has a constant value of 100 cm^{-3} above that. Seven values for the initial surface CCN concentration were chosen, starting at a relatively pristine 100 cm^{-3} and doubled in each model simulation up to a relatively polluted value of 6400 cm^{-3}. All seven aerosol profiles had the same vertical shape but differed in N. In Table 2, the combinations of aerosol concentration and CAPE are shown along with the naming conventions that will be used throughout this paper. Individual model simulations will be referred to by a label that includes the initial aerosol number concentration and a letter (A–F) representing the initial CAPE of the environment. The combined changes in both aerosol concentrations and CAPE allow for an examination of the relative contributions of each of these factors on the developing storm characteristics.

3. Results

a. Storm development

The general storm development was similar in all 42 simulations. As an example, a time series of simulation A-100 (that with the lowest CAPE and lowest aerosol concentration) is depicted in Fig. 3. The figure includes the updraft vertical velocity at 5.4 km, the accumulated

TABLE 2. Naming conventions used for the 42 numerical experiments performed, showing the initial CAPE and aerosol concentrations used in each experiment.

Surface mixing ratio (g kg^{-1})	CAPE (J kg^{-1})	N (cm^{-3})						
		100	200	400	800	1600	3200	6400
11	491	A-100	A-200	A-400	A-800	A-1600	A-3200	A-6400
12	865	B-100	B-200	B-400	B-800	B-1600	B-3200	B-6400
13	1299	C-100	C-200	C-400	C-800	C-1600	C-3200	C-6400
14	1781	D-100	D-200	D-400	D-800	D-1600	D-3200	D-6400
15	2290	E-100	E-200	E-400	E-800	E-1600	E-3200	E-6400
16	2828	F-100	F-200	F-400	F-800	F-1600	F-3200	F-6400

precipitation at the surface, and the outline of the surface cold pool at six time steps throughout the course of the simulation. The cold pool was defined using the technique described by Tompkins (2001). This involves calculating a buoyancy difference between the cold pool and the environment and choosing a threshold value (in this case, this threshold value was chosen as -0.05 m^2 s^{-1}) such that those points with buoyancy much less than that of the environment get counted as the cold pool. The storm development is similar to what has been observed previously in studies using the same initial sounding (e.g., Weisman and Klemp 1984). The warm bubble introduced at model start triggers a convective updraft almost immediately. Approximately 1 h into the simulation precipitation develops and around the same time the storm splits into two separate updrafts. The right mover is a long-lasting storm that persists for the entire model run, moving out of the model domain in the last few time steps. For the most part, the right mover remains isolated, though some secondary convection does occasionally occur along the boundary of the cold pool associated with this storm. The left mover exists as an individual storm for about an hour after the original split occurs, but it is followed by fairly widespread multicellular

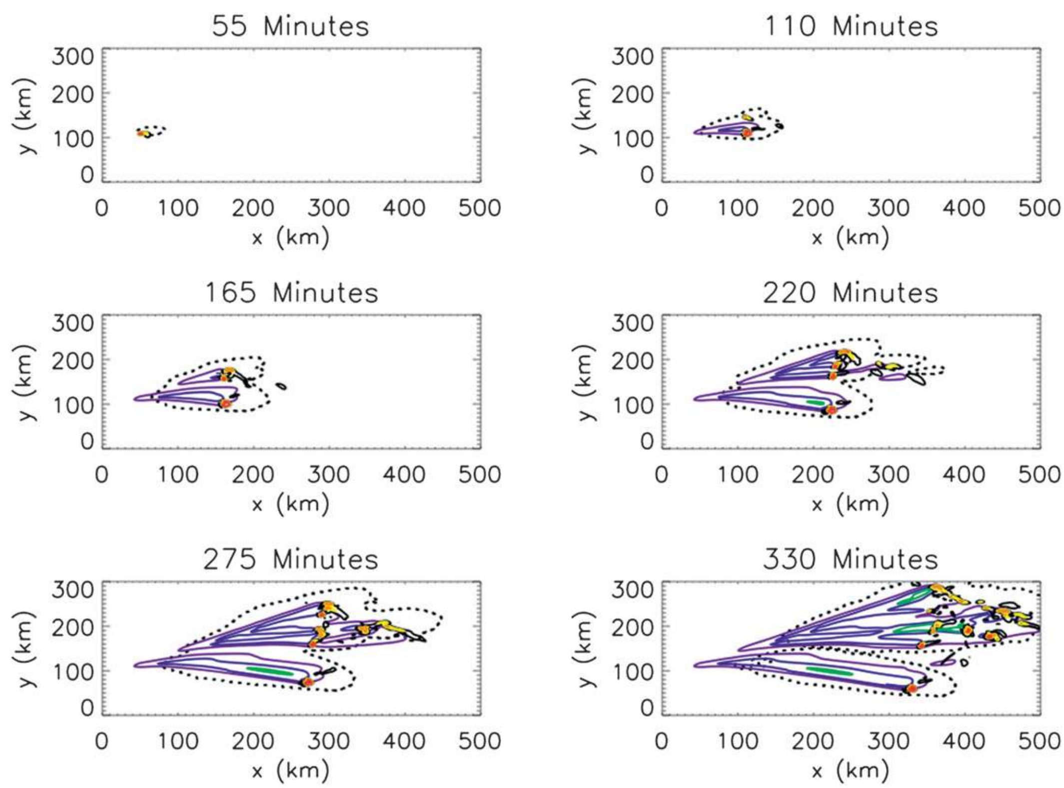

FIG. 3. Time series of model run A-100. The yellow, orange, and red contours are vertical velocity (5, 10, and 20 m s^{-1}, respectively) at 5.4 km. Purple, blue, and green contours represent total accumulated precipitation up to the current time (1, 10, and 20 mm, respectively). The dotted line is the outline of the cold pool at the surface.

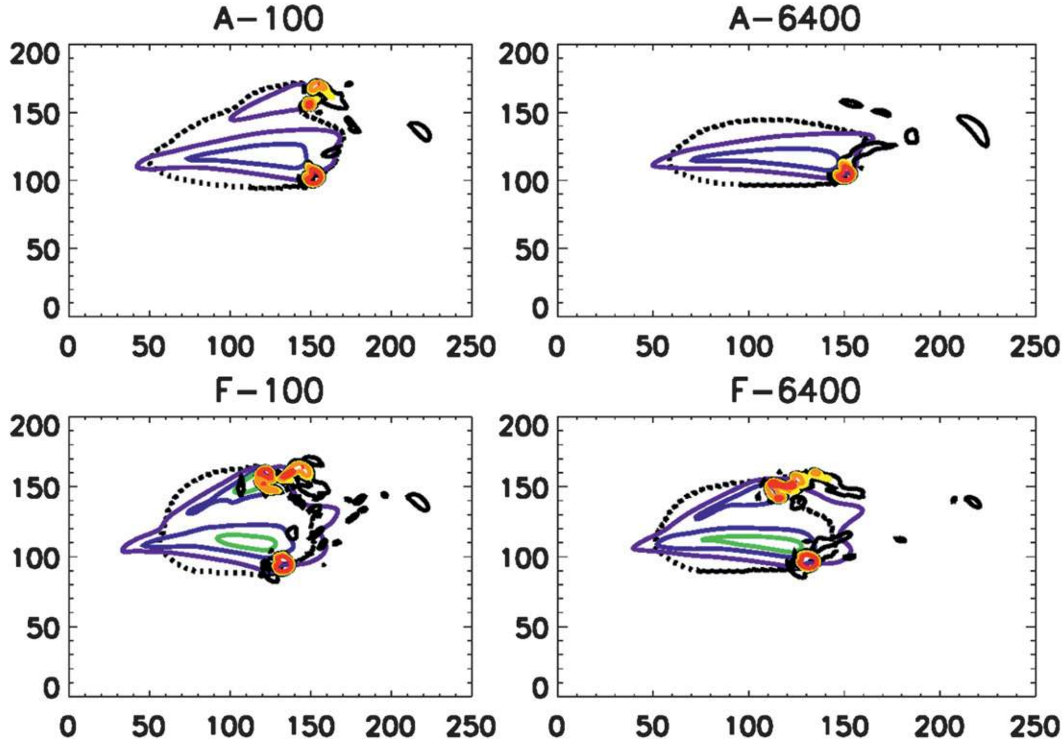

FIG. 4. A single time step of four model runs, shown 2 h into the simulation. The contours are as in Fig. 3.

convection that is initiated along the cold pool boundary. Although all of the 42 simulations produced comparable storm structure and evolution, the differences in CAPE and aerosol concentrations led to differences in aspects such as precipitation timing and amount, storm strength and longevity, and the placement and timing of storm splitting.

The exact timing and location of the left mover and also of the convection that follows from the left mover vary between simulations. A selection of model simulations (representing the lowest and highest values of both CAPE and aerosol concentration) is shown in Fig. 4 as an example of how different the storm evolution can be. The variables shown are the same as in Fig. 3, but this illustration shows a subset of the domain, 2 h into the simulation. By comparing these four model runs, some significant differences become apparent. The higher CAPE storms (F-100 and F-6400) have more widespread convection and larger amounts of accumulated precipitation. This difference is especially evident in the secondary convection triggered by the cold pool of the left-moving storm. When looking at differences due to aerosol loading, it is apparent that the convective development of the storms and the associated surface precipitation are delayed in the polluted simulations. This again can be seen most dramatically in the case of the left mover. In simulation A-6400 (lowest CAPE and highest aerosol concentration), the left mover has not even developed, whereas, in the A-100 simulation, the left mover has produced significant precipitation by this point in the simulation. It is interesting to note that many of the differences due to changes in aerosol concentration are much more pronounced in the lower CAPE scenarios over the range of CAPE and aerosol concentrations simulated.

b. Microphysics

Significant differences exist between the microphysical properties of the simulations. These differences are due to some extent to the value of CAPE used to initialize the model run, but the largest differences occur between simulations with different background aerosol concentrations. Figure 5 demonstrates evidence of the first aerosol indirect effect. Shown are the mean cloud droplet number concentration and mean cloud droplet diameter as a function of aerosol concentration. These properties are averaged temporally and spatially over cloudy grid points (those with nonzero values). As predicted by the first aerosol indirect effect, simulations with high initial aerosol concentrations produce clouds containing a significantly larger number of smaller cloud drops. Some differences occur in these properties based on the initial CAPE, because changes in CAPE will translate to differences in cloud properties such as

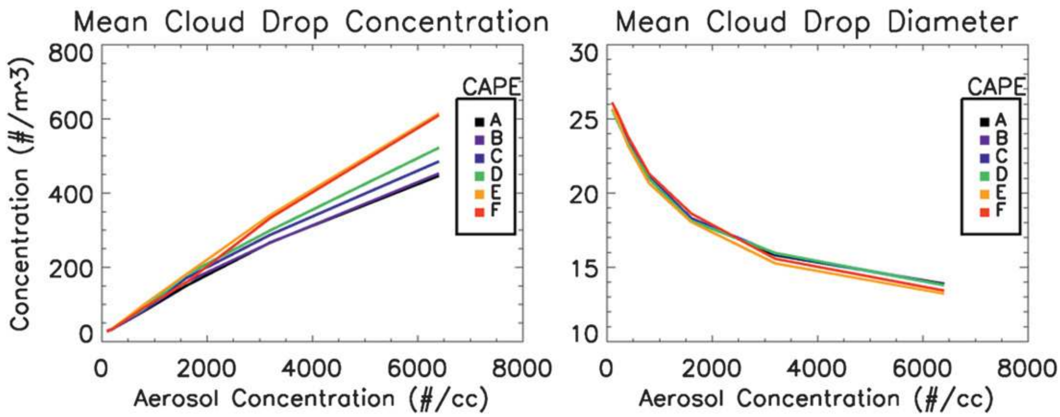

FIG. 5. Mean cloud droplet (left) number concentration and (right) diameter (μm), plotted as a function of aerosol concentration for the six values of CAPE.

vertical velocity, which will affect the activation of aerosols as cloud condensation nuclei. The differences due to the initial convective environment, however, are small and inconsistent compared to differences due to the aerosol indirect effect. Over the range of values simulated here (i.e., aerosol concentration increasing from 100 to 6400 cm^{-3}), changing the aerosol concentration leads to a 500%–600% increase in average cloud droplet number concentrations and a decrease of roughly 40% in mean cloud droplet diameter. Changing CAPE by 575% leads to changes of about 30% to these properties. To compare changes over ranges in aerosol that are more similar in magnitude to the range in CAPE, increasing the aerosol concentration from 400 to 1600 cm^{-3} (a 400% change) leads to an over 300% increase in cloud droplet number concentrations and a decrease of roughly 25% in mean cloud droplet diameter.

As described by the second aerosol indirect effect, the high number of small cloud drops in the polluted storms results in suppressed precipitation. In Fig. 6, it can be seen that CAPE is the more dominant factor in determining the total surface precipitation amount; the highest CAPE storms produce over twice the precipitation of those formed in the lowest CAPE environments. However, the precipitation is reduced significantly for storms formed in the most polluted environments (on the order of 30%–40% for the whole range of aerosols simulated but closer to ~15% for a 400% change in aerosol concentration).

From the reduction in precipitation, it follows that in the polluted simulations more water will be retained within the clouds for longer periods of time. Figure 7 shows the cloud water path, averaged spatially and temporally over columns that contain clouds. This increase in cloud water path over the range of aerosol concentrations simulated is on the order of 60%, significantly larger than the increase due to changes in CAPE (over a range in aerosol concentrations of 400%, the change is more like 20% due to aerosols, whereas changing CAPE by 575% leads to an increase in cloud water on the order of <10%). From Fig. 8, it can be seen that increasing the CAPE by 575% leads to an increase in ice water path on the order of 30%–50%. Changes in aerosol concentration have much stronger effects. Over the whole range simulated, the ice water path increases by over 200%; even with a range of aerosol concentrations of 400%, the changes are still around the same order (~50%) as those due to changes in CAPE. The polluted storms contain a larger mean ice water path due to the higher availability of cloud drops that can be lofted into the glaciating region of the storms. Although several studies have found similar trends in responses to aerosol forcing (e.g., Khain et al. 1999, 2005; Phillips et al. 2002; Andreae et al. 2004; Cohen and McCaul 2006; Lin et al. 2006; van den Heever et al. 2006; van den Heever and Cotton 2007; Carrió et al. 2007; Lynn et al. 2007; Lebsock

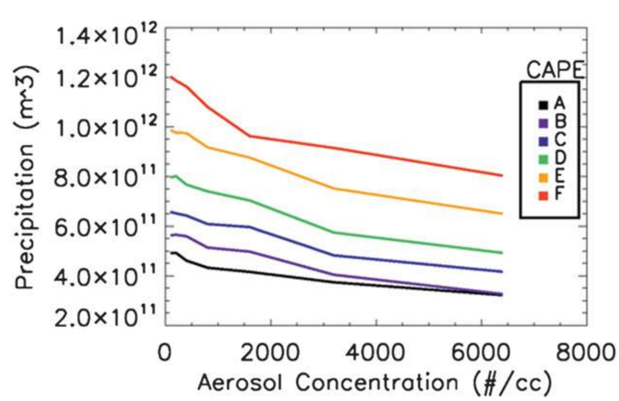

FIG. 6. Total volumetric precipitation, plotted as a function of aerosol concentration for the six values of CAPE.

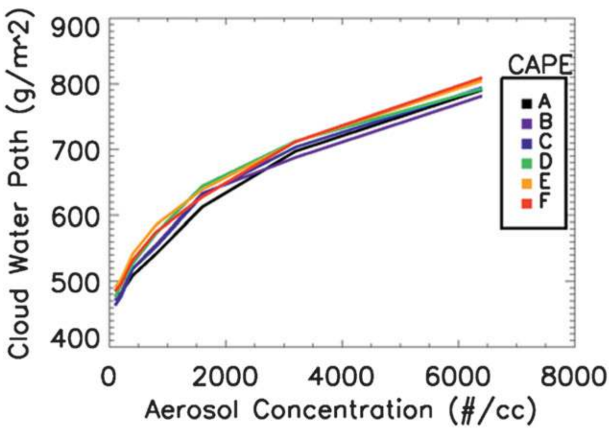

FIG. 7. Mean cloud water path, plotted as a function of aerosol concentration for the six values of CAPE.

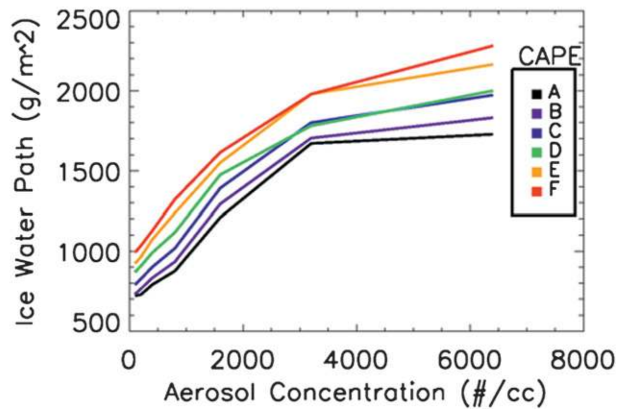

FIG. 8. Mean ice water path, plotted as a function of aerosol concentration for the six values of CAPE.

et al. 2008), the strong dependence of these microphysical quantities on the initial aerosol concentration when compared to the dependence on initial CAPE has not previously been demonstrated.

The size and number concentration of rain drops are also affected significantly by the initial aerosol concentration. In polluted simulations, the less efficient collision and coalescence processes act to reduce the number of drops that fall as rain. However, the enhanced availability of ice water and cloud water content in the polluted clouds results in the formation of larger precipitation hydrometeors throughout the cloud once they do eventually begin to grow, and hence those hydrometeors that reach the surface as rain are also larger than those formed in pristine environments. These results (Fig. 9) are similar to those found by others (e.g., Altaratz et al. 2008; Berg et al. 2008). The same trends exist for hail (not shown); that is, fewer hail stones are produced in the polluted storms, but those that do form grow larger than in pristine storms. Such changes in the size of precipitation particles can have a significant impact on storm dynamics (e.g., van den Heever and Cotton 2004).

c. *Dynamics*

Many previous studies (e.g., Khain et al. 2005; van den Heever et al. 2006; van den Heever and Cotton 2007; Lynn et al. 2007; Ntelekos et al. 2009) have shown that increased aerosol concentrations can lead to greater updraft speeds due to the increasing release of latent heat of condensation and freezing associated with the activation and freezing of more cloud droplets. In this way, aerosols can affect the dynamics of convective storms. A clear trend between aerosol concentration and updraft strength is not obvious in these simulations; however, the dynamics of the storms are affected through changes in precipitation and the subsequent cold pools that are formed. The reasoning behind this link is as follows: the polluted storms produce less total surface precipitation, and in addition the precipitation that is produced is made up of fewer larger rain drops and larger hail stones compared with storms formed in more pristine environments. The larger precipitation hydrometeors evaporate less efficiently than smaller hydrometeors as they fall because of the higher fall speeds and decreased surface area. These differences in the amount of precipitation produced and the hydrometeor sizes lead to a reduction in evaporative cooling near the surface, and hence the cold pools produced in the polluted experiments are smaller in area and weaker (warmer). This difference was alluded to when discussing Fig. 4 in section 3a, where a qualitative difference could be seen in the area covered by the cold pool between simulations A-100 and A-6400 especially. We can examine the cold pool quantitatively, using the technique described by Tompkins (2001). This technique was described in section 3a. There exists a fairly consistent decrease in cold pool size with increasing concentration of available aerosols. Figure 10 shows the change in maximum cold pool area achieved throughout the experiments and also in minimum average cold pool temperature. The trends in temperature are less coherent but do show that polluted storms generally have warmer cold pools.

There are several possible dynamic feedbacks that may result from the differences in cold pool size and strength associated with variations in both aerosol concentrations and CAPE. For instance, smaller and weaker cold pools may provide less forcing for the formation of secondary convection thereby leading to an overall reduction in convective coverage, intensity, and total

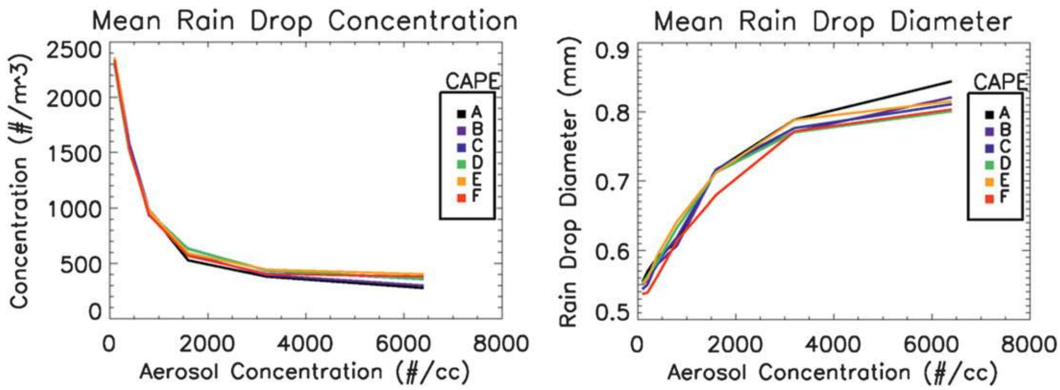

FIG. 9. Mean rain drop (left) number concentration and (right) diameter, plotted as a function of aerosol concentration for the six values of CAPE.

precipitation. This would be a positive feedback, because the reduction in precipitation would then lead to even smaller cold pools. Conversely, because cold pool propagation speed is directly related to temperature, warmer cold pools will move more slowly and may show a tendency to remain coupled to the convective storms rather than propagating away from them. This would be a negative feedback with enhanced precipitation being associated with increased aerosol concentrations, because such a setup can lead to an increase in storm lifetime (and subsequent precipitation) in individual convective cells. The full dynamic implications of pollution resulting in smaller and weaker cold pools are difficult to isolate in this study after the formation of the extensive secondary convection that develops. However, it can be concluded that a strong link does exist between the microphysical properties of convective storms and their dynamics. Both microphysical and dynamical properties must be considered for their sensitivity to concentrations of aerosols available to act as CCN.

A NOTE ON THE ROLE OF THE ENVIRONMENT ON CLOUD–AEROSOL INTERACTIONS

It was mentioned in section 3a that differences in the response to aerosols were found based on the initial CAPE in the environment. For the early time period shown in Fig. 4, precipitation is notably more delayed in the lowest CAPE case than in the highest, though the total precipitation trends tend to be similar by the end of the simulations. In addition, other variables such as cloud water path show a slightly steeper slope in the more stable environments. It is suggested here that, in the more unstable environments, the storm dynamics are strong enough to overwhelm aerosol effects, whereas aerosols appear to play a more significant role in more stable environments with weaker dynamics in play. Environment has been shown to play a role in previous studies as well. For example, Khain and Lynn (2009) also simulated a storm-splitting event and found a decrease in precipitation in polluted storms in a less humid environment, whereas the precipitation

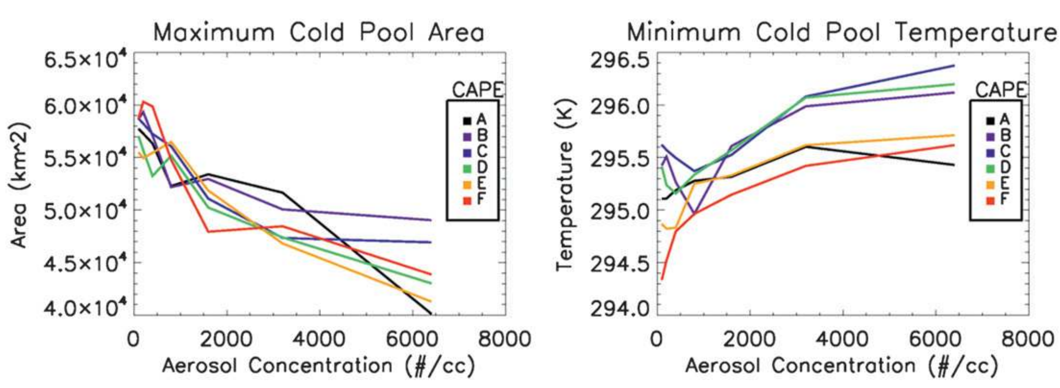

FIG. 10. (left) Maximum cold pool area and (right) minimum cold pool temperature, plotted as a function of aerosol concentration for the six values of CAPE.

in polluted storms actually increased in the more humid atmosphere.

The authors note that only one method out of many possible was chosen to alter the initial model sounding. CAPE can be changed in other ways, such as changing the temperature lapse rate or the humidity throughout the depth of the troposphere rather than just near the surface. It is possible that such changes in the environmental sounding would in fact lead to some differences in the trends shown; however, such tests are beyond the scope of this study.

4. Sensitivity tests to simulation setup

A number of model simulations were performed to test the sensitivity of the trends found to different model conditions. The first test looked at the sensitivity of storm development to the initial temperature perturbation used to initialize convection in the model. A perturbation of 1 K was tested for the initial warm bubble. The simulations with only a 1-K temperature perturbation produced convection that was weak and short lived. It was concluded that, to study the effects of aerosols on a long-lived convective storm, it was necessary to use a temperature perturbation of 2 K. A number of other studies (e.g., van den Heever and Cotton 2004; Lerach et al. 2008) have successfully simulated convective storms using a temperature perturbation of similar magnitude.

The sensitivity of the simulations to model vertical resolution was also tested. A test run was performed with 70 levels in the vertical, which is double that of the simulations presented here. The storm development and structure was similar in the high-vertical-resolution run, and the total precipitation differed by only 13% from the original simulation. In light of the computational expense of running the simulations with more vertical levels and the number of runs that were needed for this study, it was decided that the 35 levels were sufficient to simulate realistic convective storms.

Because the goal was to study long-lived convection, it was useful to include a high value of vertical shear, such that convection would remain organized for a significant time period. However, previous studies have certainly demonstrated the importance of vertical wind shear on various storm characteristics (e.g., Weisman and Klemp 1982, 1984), particularly the rate at which the cold pool may propagate away from its convective updraft. The sensitivity of the results was tested for a low and moderate value of vertical shear. The shape of the shear hodograph that was used was the same half circle, with values of Us = 10 m s^{-1} and Us = 30 m s^{-1} used for the arc length (corresponding to low and moderate shear cases), rather than the Us = 50 m s^{-1} that was used for the high shear case. The low and moderate shear profiles were simulated using a moderate CAPE case and all aerosol concentrations. Results are presented in Fig. 11. Although the storm structure and the total precipitation produced in the simulations are dependent on the shear profile chosen, the trends in total accumulated precipitation for increasing aerosol concentrations are robust. It is expected that a change in the shape of the shear profile may have a stronger effect, largely because of the differences in storm structure that would ensue. However, it is the changes in aerosol concentration that have the largest impacts on the storm microphysics.

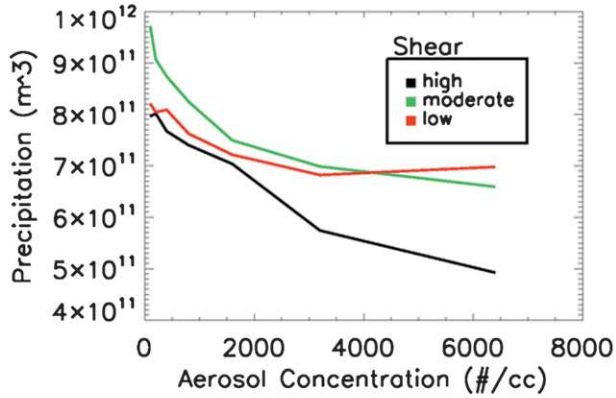

FIG. 11. Total volumetric precipitation for low, moderate, and high shear, with CAPE value D.

5. Conclusions

A series of simulations was run in which both the initial CAPE and the initial concentration of aerosols available to act as CCN were simultaneously and progressively varied to investigate their relative effects on deep convection. The development of the convective storms in all of the simulations was similar, but differences in precipitation and storm microphysics were observed because of variations in both CCN and CAPE. It is not an unexpected finding that changes in the model CAPE produced significant changes in the properties of the convective storms that formed. Storms that formed in higher CAPE environments contained more cloud and ice water, produced more precipitation, and generally had larger and stronger cold pools. However, the results of this study show that significant changes in storm properties also occur when higher concentrations of aerosols are available to act as CCN. Polluted storms had higher concentrations of smaller cloud droplets, reduced precipitation, and increased cloud and ice water. They also produced fewer rain drops that were larger in diameter, which, in combination with the reduction in precipitation, led to smaller and weaker cold pools. The changes in the cold pool characteristics of the storms led to dynamic feedbacks in the secondary convection. These effects are not well understood and will be studied further in future work but can have strong impacts on the organization of convection and feed back on precipitation effects.

The results presented here have shown that differences both in the initial CAPE and in the available aerosol concentration will lead to important changes in both microphysical and dynamic properties of convective storms. The relative importance of these differences is something that has not previously been examined. For the range of CAPE (491–2828 J kg^{-1}) and aerosol concentrations (100–6400 cm^{-3}) examined here, the total precipitation produced by the storms is primarily driven by CAPE, but an increase in the concentration of available aerosols from 100 to 6400 cm^{-3} leads to a decrease in total precipitation amount by 30%–40% (if considering only a 400% change in aerosol concentration to better compare with the range in CAPE, the decrease is still ~15%). It is interesting to note that an increase in cloud water path over the range of aerosol concentrations simulated is of much larger magnitude (on the order of 60%) than the increase due to changes in CAPE (over a range in aerosol concentrations of 400%, the change is more like 20% due to aerosols, whereas changing CAPE by 575% leads to an increase in cloud water on the order of <10%). Increasing the CAPE by 575% leads to an increase in ice water path on the order of 30%–50%, whereas, over the whole range of aerosol concentrations simulated, the ice water path increases by over 200% and even with a range of aerosol concentrations of 400% the changes are still around the same order (~50%) as those due to changes in CAPE. Certain microphysical parameters (such as mean rain drop diameter) demonstrated very little response to changes in CAPE when compared to the response to differences in aerosol loading. Differences in rain drop diameter are an essential part of determining the size and strength of cold pools, leading to changes of similar magnitude as those brought about by differences in CAPE.

This study has demonstrated the relative importance of available aerosol concentrations when compared with environmental changes. Several important properties in the simulated storms (e.g., changes in cloud and rain drop sizes and numbers and cloud and ice water paths) are much more sensitive to changes in aerosol concentration than changes in CAPE, leading to significant subsequent differences in storm evolution and total precipitation. On the other hand, characteristics such as storm strength and accumulated surface precipitation are more sensitive to changes in CAPE. It is important to note that several of the aerosol indirect effects in this study were modulated by the amount of CAPE available in the prestorm environment. Many of the aerosol effects were found to be stronger in environments of weaker CAPE. Finally, when studying deep convective storms over the midlatitudes, changes in both CAPE and CCN concentrations should be taken into account when examining the dynamical and microphysical properties of these storms.

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