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THE EFFECTS OF GIANT CCN ON CLOUDS AND PRECIPITATION: A CASE STUDY FROM THE SAUDI ARABIA PROGRAM FOR THE ASSESSMENT OF RAINFALL AUGMENTATION

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1. INTRODUCTION

One of the most important challenges in current cloud physics research is to evaluate and quantify the impact of different types of aerosols on the formation of precipitation. The eastern Mediterranean and Arabian Peninsula is a natural laboratory for studying the interactions between clouds and aerosols. This region is affected by a wide variety of aerosol sources. These include air masses containing anthropogenic pollution from eastern and western Europe; marine aerosols and biogenic material from various land and marine sources; aged smoke particles from biomass burning in Africa; and mineral dust particles from the North African and Arabian deserts and local sources.

Scarcity of freshwater is one of the largest problems facing the Kingdom of Saudi Arabia. The Presidency of Meteorology and Environment (PME) in Saudi Arabia has taken action to assess the feasibility and potential benefits of rainfall enhancement by cloud seeding.

One of the major recommendations in the recent National Academy of Sciences report dealing with weather modification (NAS, 2003) is to use detailed cloud simulation in order to gain better understanding on the cloud microphysical processes and the effect of different seeding methods on these processes.

The high concentration and significant effect of mineral dust particles on cloud systems in the Arabian Peninsula add importance to the study of the effects of these particles on precipitation formation. In general, mineral dust particles can have a role in cloud processes by serving as giant Cloud Condensation Nuclei (GCCN with diameter > 2 μm) or as Ice Nuclei (IN) that form ice crystals by different processes (van den Heever et al., 2006).

In this study, data from ground and airborne measurements collected during the rainfall enhancement assessment project in Saudi Arabia were used and compared with two detailed cloud model simulations (TAU-2D and new WRF bin microphysics scheme) in order to investigate the effects of air pollution and mineral dust particles, typically present in that region, on cloud development and precipitation formation processes.

A major objective of this study was to use the measured data in two similar cloud models in order to compare their performances in one particular case study.

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Some of the results of this preliminary study are shown in this paper. The WRF bin microphysics scheme will be used in the next stages of the research.

2. THE CLOUD MODELS

2.1 *The TAU-2D model*

The TAU-2D slab symmetric single cloud model contains detailed treatment of the cloud microphysics (Yin et al., 2000a) and uses the Spectral Method of Moments (Tzivion et al., 1987; Reisin et al., 1998) for calculating the change in the distribution of water drops and ice particles by various cloud processes. In this model the method is used to calculate the evolution of the droplets' spectrum by condensation/evaporation, collision/coalescence and binary breakup. Deposition, sublimation, aggregation and riming of ice particle are also treated using this method.

In the model, drops are nucleated based on the supersaturation and critical diameter following the classical Köhler theory (Pruppacher and Klett, 1997). The drops grow by condensation and then by collision-coalescence processes.

As the cloud develops vertically, reaching subfreezing temperatures, ice crystals begin to form by freezing of cloud drops containing efficient IN. Ice nucleation is formed by using the parameterization of Meyers et al. (1992) in which the concentration of IN in the atmosphere is proportional to the supersaturation when dealing with deposition or condensation-freezing processes, and it is proportional to the supercooling temperature when dealing with contact nucleation.

Ice particles also form through ice multiplication process induced by collisions of large drops and ice particles (Hallett and Mossop, 1974). The ice crystals grow by deposition and aggregation to form snow and by riming to form graupel particles. The large graupel particles and the large ice crystals eventually descend, melting on their way down to form raindrops. Large raindrops collide with other raindrops and break up to form smaller drops based on the algorithm of Reisin et al. (1998).

The model simulates the development of single clouds only, and potential effects of downdrafts and cold pools below cloud base on the formation of neighboring clouds is ignored. Furthermore, in the present study the clouds developed in an environment with no wind shear. Further details on the model and its components are discussed in Yin et al. (2000a), Yin et al. (2002) and Teller and Levin (2006).

It should be noted that this model and a similar axisymmetric version of it were validated and used in many studies related to cloud seeding research (Tzivion et al., 1994; Reisin et al., 1996; Yin et al., 2000b)

For this particular study the cloud is initiated with a short pulse of temperature and humidity just below cloud base. We used 300 m height and 300 m lateral resolutions and a 2 s time step. The grid size was 101X61 points corresponding to a domain of 18 km height vs. 30 km width.

2.2 The WRF_bin-microphyscics scheme

The use of the TAU-2D model as a tool for analyzing the effect of seeding on mixed phase convective cloud is limited because this tool is not able to treat complex cases where interaction between clouds should be considered. For that purpose, one needs to use a model that can treat larger domains including complex terrain profiles and secondary cloud formation.

The Weather Research and Forecasting (WRF) Model, is commonly used for the simulation of meteorological events. This model was designed to allow researchers to improve forecast accuracy and investigate weather features on a variety of scales, from cloud to synoptic. The model has the ability to to be used both for real time forecast and for research applications. Current WRF version enables the user to select between microphysics schemes which are based on bulk parameterizations.

The new bin microphysics scheme coupled with WRF was described in detail in Geresdi and Rasmussen (2005) and in Rasmussen et al. (2002). This scheme uses the spectral method of moments (Tzivion et al. 1987) as in the TAU-2D model to calculate the evolution of the size and mass spectrum of the different cloud particles for each time step.

The simulation calculates the distribution of the water droplets and 3 ice species (pristine ice, graupel and snow). Thirty-six size bins are used to describe the size and mass distributions for each of these four hydrometeor types. Since both TAU-2D and WRF_bin schemes use the same numerical method to calculate the changes in the cloud particles' number and mass distribution profiles, comparison between the two simulations done on the same conditions may add valuable information on the role of cloud microphysical processes in the conversion of aerosol particles to precipitation.

An important feature of the above mentioned microphysics scheme which is currently under development is the ability to track the aerosol masses within the droplets and the ice particles. This feature will enable the user to investigate the effects of in-cloud processes on the aerosol characteristics and these effects on secondary clouds. Another advantage of the new scheme is in its ability to simulate large domains using the WRF dynamics and the potential to simulate 3-dimensional domains.

For this study we used the same setup used for the TAU-2D simulations. The cloud is initiated with a short pulse of temperature and humidity below cloud base. As in the TAU-2D run, we used 300 m height and 300 m lateral resolutions and a 2 s time step. The grid size was 201X61 points corresponding to a domain of 18 km height vs. 60 km width.

In the current stage of the study we give attention mainly on the differences between the schemes in order to be able to compare future results from the WRF_bin with previous studies with the TAU-2D.

3. INITIAL CONDITIONS AND SIMULATION SETUP

We used the measurements that were carried out on 9 April 2007 above central Saudi Arabia during the rain enhancement project.

On this day a dust storm passed over the region and caused high Aerosol Optical Depth values of about 0.9. AErosol RObotic NETwork (AERONET) measurements that were carried out during that day and MODIS satellite observations show that a large fraction of the aerosol population was composed of dust aerosol. This case can be used to study the the interaction of the dust with cloud microphysical processes.

As initial conditions we used the aerosol size distribution that was measured by Differential Mobility Analyzer (DMA), Passive Cavity Aerosol Spectrometer Probe (PCASP) and Forward Scattering Spectrometer Probe (FSSP) that were mounted on the research airplane. These three instruments characterize the aerosol in large range of diameters between 0.01-45 μm. Figure 1 show the aerosol size distribution that was measured below cloud base. The aerosol distribution was fit to a three mode log-normal distribution in order to be used in WRF simulation. TAU-2D used the exact values of number concentrations in each bin. Lack of measurements of the particles' chemical composition caused us to assume that the fraction of CCN within aerosol > 1 μm was 0.2. These aerosols were regarded as GCCN. We run few cases with different CCN fraction for aerosol < 1 μm (accumulation mode particles) in order to study the sensitivity of the cloud to clean and polluted cases.

In addition, we assumed an exponential decrease of the aerosol concentration with height.

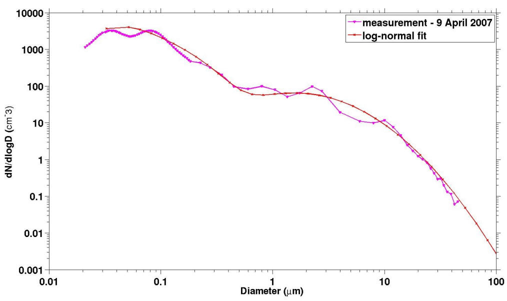


Figure 1: Initial aerosol size distribution below cloud base used in TAU-2D and WRF_bin simulation based on the airborne measurements of 9 April 2007.

The initial sounding used in the simulation is shown in Figure 2. One can see the potential for convection at altitude of 4 km above the ground where the relative humidity is above 95%. From Figure 2 we can also conclude about the very dry (RH=20%) and hot (~ 40°C) ground conditions on 9 April 2007.

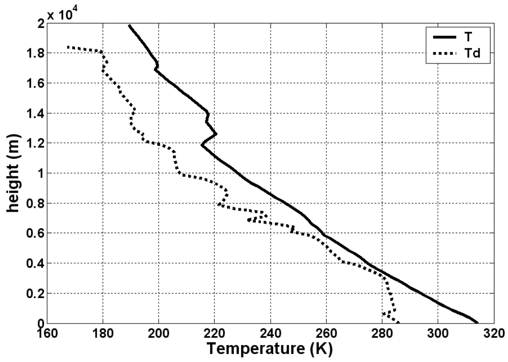


Figure 2: Initial sounding used in TAU-2D and WRF_bin simulation, taken from Riya'd, Saudi Arabia on 9 April 2007.

The sensitivity of precipitation and cloud microphysical processes to different concentration was examined by varying the total aerosol concentration between 160 to 970 cm^{-3} without changing the shape of the size distribution. The role of dust was tested by adding additional giant CCN particles with concentration 20 cm^{-3} to the CCN population larger than 1 μm in diameter.

4. RESULTS

4.1 *The sensitivity of total precipitation to aerosol concentrations and size distributions – TAU-2D study*

The total precipitation on the ground as a function of initial CCN concentration and the presence or absence of GCCN is shown in figure 3.

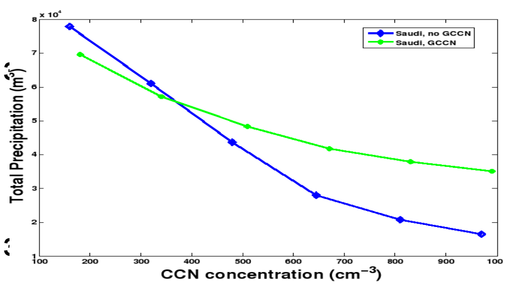


Figure 3: Total precipitation on the ground as function of initial CCN concentration and presence or absence of dust serving as GCCN for the 9 April 2007 case

Figure 3 shows that in polluted conditions where high CCN concentration are present the total precipitation is suppressed in agreement with the current scientific paradigm on the effect of aerosol on precipitation (e.g. Rosenfeld, 2000; Andreae et al., 2004, Jirak et al., 2006). In the polluted case (CCN > 500 cm^{-3}), injection of additional GCCN increase precipitation due to the fast initiation of large droplets at the first stages of the cloud development and in accordance with past modeling studies on mixed phase convective clouds (Yin et al., 2002; Teller and Levin, 2006).

In the clean case the additional GCCN reduce the total precipitation. This result requires some clarifications since it is in disagreement with previous studies that conclude that in clean condition dust serving as GCCN will not change precipitation yield from convective cloud (Teller and Levin, 2006) .

Figure 4 shows the accumulation of precipitation on the ground as function of time for the most clean (160-180 cm^{-3}) and the most pollute cases (970-990 cm^{-3}).

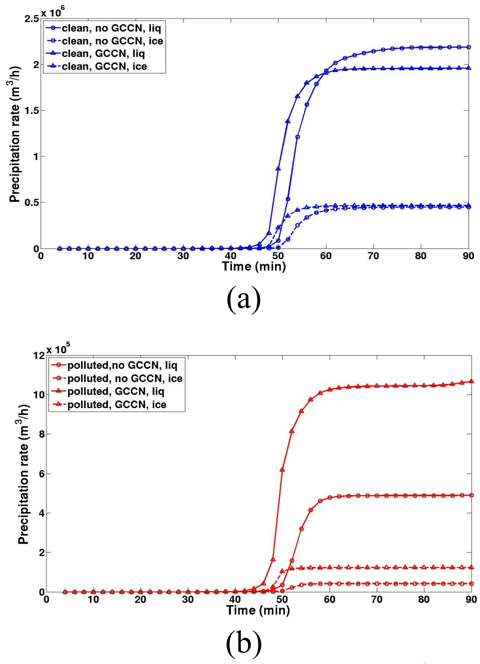
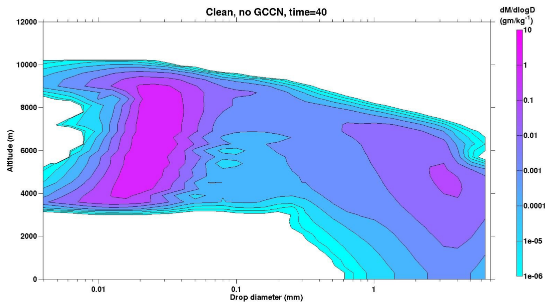


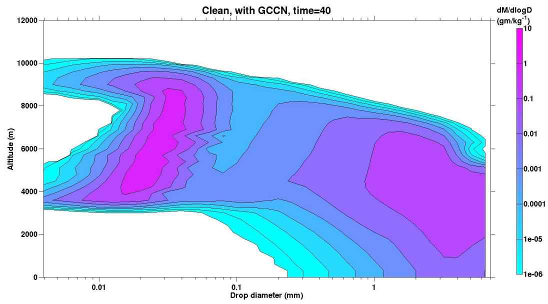
Figure 4: Accumulation of precipitation as function of time for the: (a) most clean (160-180 cm^{-3}) and (b) most polluted (970-990 cm^{-3}) cases

In Figure 4 the precipitation accumulation is divided between liquid and ice precipitation. Liquid precipitation refers to raindrops while ice precipitation refers to ice, graupel and snow particles reaching the ground. This way of presentation shows that in the clean case additional dust serving as GCCN contribute to fast initiation of precipitation as in the polluted case. The total precipitation when GCCN are added is less than in the case with no GCCN (as already shown in Figure 3). The fast initiation of precipitation due to warm processes in the GCCN case leaves less water in the mixed phase region which result in reduced formation of graupel particles and ice crystals, therefore the total precipitation is lower from the no GCCN case.

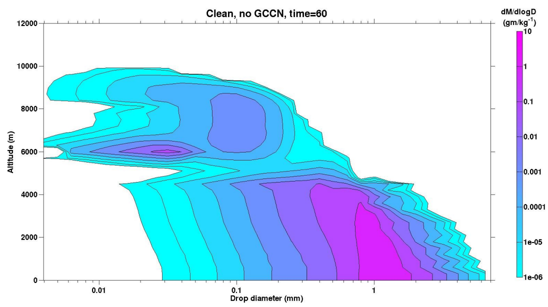
In order to demonstrate the difference between the case where GCCN are added and the case where they are not present, Figure 5 shows the drop mass distribution profile after 40 and 60 minutes from the beginning of the simulation. 60 min is the time where accumulated precipitation from the two cases is identical.



(a)



(b)



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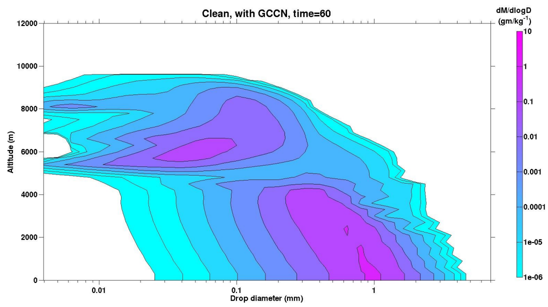


(d)

Figure 5: Droplet mass distribution height profiles for clean cloud simulation with/without GCCN. (a) without GCCN, 40 min, (b) with GCCN, 40 min, (c) without GCCN, 60 min, and (d) with GCCN, 60 min.

The results shown in Figure 5 reveal that most of the rainfall in the final stages of the precipitation period is formed in the mixed phase region of the cloud. The increase of water content below 4 km above the ground after 60 min (Figures 5c and d) is due to melting ice and graupel particles and this contribution is larger in the case where GCCN were not added.

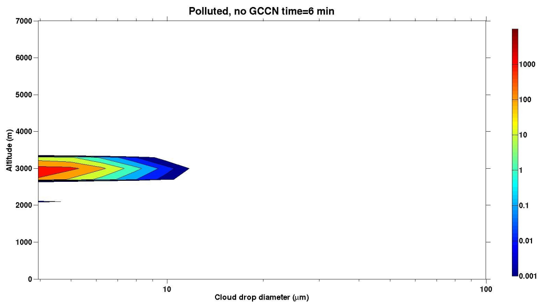
In the polluted case, the effect of the droplets that are formed at the early stages on precipitation is negligible so the production of droplets is mainly due to melting of graupel particles that are formed in the mixed phase region. The graupel content in the case with GCCN is higher since larger droplets ascend to the mixed phase regions (not shown, see discussion in Teller and Levin, 2006).

4.2 *The sensitivity of precipitation to changes in mixed-phase cloud microphysics schemes – preliminary results from WRF-bin microhysics study*

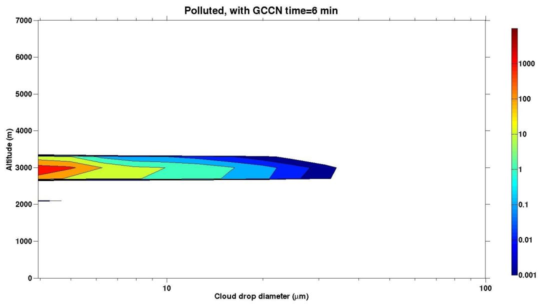
Simulations were carried out using the WRF_bin scheme for the same sounding and aerosol profiles that were used in the TAU-2D runs. At the current development stage of the WRF_bin scheme the major objective is to validate the tool by comparing its performance and results with the TAU-2D model that uses the same numerical method to treat the cloud processes.

Few runs with the WRF_bin simulation showed that GCCN did not have an effect on the characteristics of the hydrometeors either in clean or polluted cases. A careful look on the differences between the two schemes used in this study reveals that the efficiency of formation of large droplets due to collision and coalescence of smaller droplets is different between the two models. In the TAU-2D model the kernel of Low and List (1982a,b) are used for raindrops larger than 0.6 mm; the coalescence efficiencies of Ochs et al. (1986) are employed as collection efficiencies (assuming that the collision efficiencies in this region are close to unity) in the region 0.1-0.6 mm and the collision efficiencies of Long (1974) are adapted for smaller drops. In the WRF_bin the collection efficiencies are calculated using the method of Hall (1980).

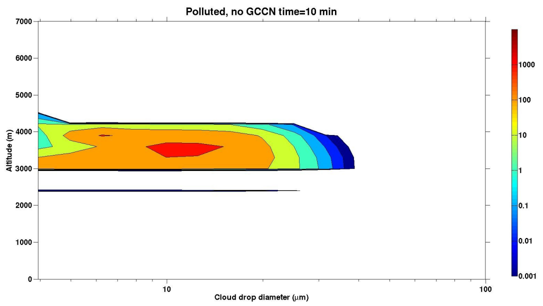
Figure 6 shows comparison between the evolution of the droplets size distribution profiles between the two polluted simulations in the WRF_bin model. Figure 6a and b show the profile at the time droplets are formed after 6 min while Figure 6c and d show the profile 4 min later. In both cases the total concentration of the cloud droplets were similar and the only difference that can be seen by comparing Figure 6a and b is that in one of the cases (Figure 6b and d) GCCN were added so the activated GCCN increase the width of the droplets size distribution profile. After 10 minutes the droplet size distribution for the cases with/without GCCN is similar so the contribution of these aerosol is insignificant.



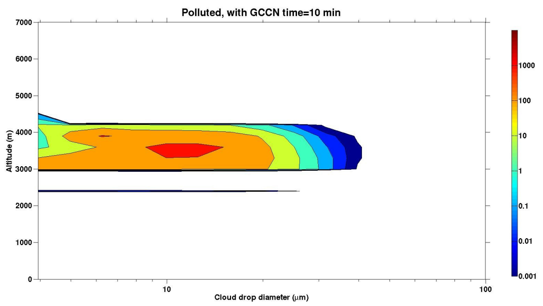
(a)



(b)



(c)



(d)

Figure 6: Droplet size distribution height profiles for polluted cloud simulation with WRF_bin model. (a) no GCCN, after 6 min, (b) with GCCN, after 6 min, (c) no GCCN, after 10 min, and (d) with GCCN, after 10 min.

In the WRF_bin simulations injection of GCCN did not have any effect on the cloud (although one can detect that these particles were activated). This suggests that the effect of injection of GCCN in the two models is supposed to be different. In the TAU-2D model the growth of droplets due to collection is slow, therefore injection of only few GCCN contribute significantly to the production of large droplets (see Figure 5) while in the WRF_bin model, the same aerosol and atmospheric characteristics lead to production of large droplets so GCCN contribution is negligible in all the cases.

5. SUMMARY AND CONCLUSIONS

In this study we used measurements of aerosol concentrations and size distribution profiles that were carried out during the weather modification program in Saudi Arabia to study the possible effect of the presence of mineral dust particles on precipitation formation in mixed phase convective clouds. In the study we used two cloud simulation tools containing detailed description of the cloud microphysics based on the bin approach: the Tel Aviv University 2D cloud model and the new WRF_bin microphysics scheme.

The results from the TAU-2D simulations show that for the particular atmospheric conditions studied, the contribution of mineral dust acting as giant CCN depends on the characteristics of the entire aerosol population. In polluted environment where aerosol concentration is large, additional GCCN may increase the total precipitation while in clean cases where the aerosol loading is low, additional GCCN reduced the total precipitation due to the reduced amount of water vapor in the mixed phase region of the cloud and the early onset of precipitation. The WRF_bin simulations have not shown any effect of GCCN probably due to the larger collection efficiencies of small droplets by large drops. Currently, by using this scheme we are not able to demonstrate the effect of the giant CCN.

One of the conclusions that may be a consequence of this study is that injecting hygroscopic material to the cloud, as part of **cloud seeding**, in order to increase the concentration of GCCN might have a negative effect on precipitation in certain conditions where it may speed up the formation of large droplets in the warm regions of the cloud. This effect prevents much of the water vapor from reaching higher altitude so graupel and ice production will be suppressed. In addition, the way we understand and implement the microphysics in the cloud model has of course large influence on the conclusions as shown by the comparison the two cloud simulations in this study.

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