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4 **The relationship between latent heating, vertical velocity, and precipitation**
5 **processes: The impact of aerosols on precipitation in organized deep convective**
6 **systems**
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44   Increasing aerosol number concentrations could either enhance or reduce surface

45   precipitation. Enhanced near surface cold pool strength is important in precipitation

46   enhancement. Other processes include modifications of latent heat release and ice

47   microphysics by aerosols.

48

49

50   **Abstract**

51

52   A high-resolution, two-dimensional cloud-resolving model with spectral-bin

53   microphysics is used to study the impact of aerosols on precipitation processes in both a

54   tropical oceanic and a midlatitude continental squall line with regard to three processes:

55   latent heating (LH), cold pool dynamics and ice microphysics. Evaporative cooling in the

56   lower troposphere is found to enhance rainfall in low cloud condensation nuclei (CCN)

57   concentration scenarios in the developing stages of a midlatitude convective precipitation

58   system. In contrast, the tropical case produced more rainfall under high CCN

59   concentrations. Both cold pools and low-level convergence are stronger for those

60   configurations having enhanced rainfall. Nevertheless, latent heat release is stronger

61   (especially after initial precipitation) in the scenarios having more rainfall in both the

62   tropical and midlatitude environment. Sensitivity tests are performed to examine the

63   impact of ice and evaporative cooling on the relationship between aerosols, LH and

64   precipitation processes. The results show that evaporative cooling is important for cold

65   pool strength and rain enhancement in both cases. However, ice microphysics play a

66   larger role in the midlatitude case compared to the tropical. Detailed analysis of the

67   vertical velocity governing equation shows that temperature buoyancy can enhance

68   updrafts/downdrafts in the middle/lower troposphere in the convective core region;

69   however, the vertical pressure gradient force (PGF) is the same order and acts in the

70   opposite direction. Water loading is small but on the same order as the net PGF-

71   temperature buoyancy forcing. The balance among these terms determines the intensity

72   of convection.

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74   **1.   Introduction**

75

76   Aerosols are a critical factor in the atmospheric hydrological cycle and radiation budget.

77   As a major reason for clouds to form and a significant attenuator of solar radiation,

78   aerosols affect climate in several ways. Current research suggests that aerosol effects on

79   clouds could further extend to precipitation, both through the formation of cloud particles

80   and by exerting persistent radiative forcing on the climate system. However, the various

81   mechanisms behind these effects, in particular the ones connected to precipitation, are not

82   yet well understood [see reviews by *Levin and Cotton,* 2008, *Khain,* 2009, and *Tao et al.,*

83   2012].

84

85   Compared to typical global circulation and climate models, cloud-resolving models

86   (CRMs) use more sophisticated and relatively realistic representations of cloud

87   microphysical processes, and they can reasonably well resolve the structure and life

88   cycles of clouds and cloud systems (with sizes ranging from about 2-1000 km). CRMs

89   also allow for direct interaction among clouds, outgoing longwave (cooling) and

90   incoming solar (heating) radiation, as well as ocean and land surface processes [see

91   reviews by *Tao,* 2003, 2007; *Randall et al.,* 2003; and *Tao and Moncrieff,* 2009]. There

92   are several major advantages in using CRMs to study the interactive processes between

93   clouds, precipitation and aerosols. For example, the use of a sophisticated microphysics

94   scheme (liquid and ice) and a fine horizontal resolution can provide relatively realistic

95   cloud optical properties, which are crucial for determining radiation budgets. With a high

96   spatial resolution, each atmospheric grid is considered either completely cloudy

97   (overcast) or clear; no partial cloudiness is assumed as with GCMs. In addition, the life

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98   cycle of clouds, precipitation and aerosols can be simulated by CRMs. CRMs can also

99   have better cloud dynamic processes in terms of aerosol transport [see reviews by

100   *Thompson et al.*, 1997; *Ekman et al.,* 2004, 2006; and *Yin et al.,* 2005].

101

102   Recently, many different studies have used CRMs to examine the role of aerosols on

103   mixed-phase convective clouds (c.f., Table 1). These modeling studies have many

104   differences in terms of model configuration (two- vs three-dimensional, single case study

105   vs ensemble simulations), domain size, grid spacing (150 – 3000 m), microphysics (i.e.,

106   two-moment bulk, simple or sophisticated spectral-bin), turbulence (1st or 1.5 order

107   turbulent kinetic energy), radiation, lateral boundary conditions (i.e., closed, cyclic or

108   radiative open), cases (isolated convection vs organized systems) and model integration

109   time (e.g., from 2.5 to 48 up to 100s of hours in order to reach convective-radiative

110   equilibrium). A simple metric, the percent change in time-integrated precipitation (dP =

111   100 * (P_{high} − P_{low}) / P_{low}) as a result of a set increase in the number concentration of

112   CCN (dN_0 = N_{high} − N_{low}), has been used to examine the impact of aerosol concentration

113   on surface rainfall. P_{high} − P_{low} is the difference in surface rainfall between the high and

114   low CCN concentrations, and N_{high} − N_{low} is the number concentration difference between

115   the high and low CCN. Among these modeling studies, the most striking difference is

116   that cumulative precipitation can either increase or decrease in response to higher

117   concentrations of CCN. *Phillips et al.* [2002], *Khain et al.* [2004, 2005], *Khain and*

118   *Pokrovsky* [2004], *Teller and Levin* [2006], *Cheng et al.* [2010], *Fan et al.* [2013],

119   *Saleeby et al.* [2010], *Storer et al.* [2010], *Seigel et al.* [2013], and *Grant and van den*

120   *Heever* [2015] changed the number concentrations of CCN gradually and found robust

121   decreases in cumulative precipitation for higher concentrations of CCN. This is

122   completely opposite from the results from *Wang* [2005], *Khain et al.* [2005], *Lee et al.*

123   [2009], *Fan et al.* [2007b], *Lebo and Morrison* [2014], and *Igel et al.* [2013]. Variations

124   in the microphysics scheme, vertical wind shear, atmospheric static stability and relative

125   humidity (dry vs. moist) could lead to different aerosol impacts on precipitation [*Storer et*

126   *al.,* 2010; *Fan et al.*, 2012a,b; *Storer and van den Heever,* 2013; *Kalina et al.,* 2014;

127   *Grant and van den Heever,* 2015]. Also, the different stages of a convective system's life

128   cycle may also respond differently to changes in aerosols in terms of precipitation [*Tao et*

129   *al.,* 2007; *van den Heever and Cotton,* 2007]. Note that these modeling studies are for

130   different convective systems that developed in different environments, and the results are

131   based on different models and microphysical schemes

132

133   Different physical processes have been proposed to explain aerosol impacts on deep

134   convective precipitation. These processes include latent heating (LH), cold-pool

135   dynamics and ice microphysics. However, these hypotheses were based on different

136   models and different cases. *In this paper, three different hypotheses are examined using*

137   *the same model with the same microphysics scheme and same cases*. The relationships

138   between LH, convective updrafts and downdrafts and precipitation processes with

139   different aerosol concentrations, and the different physical processes responsible for the

140   aerosol impact on precipitation are also examined. CRM simulations based on two deep

141   convective precipitation systems from vastly different environments, one tropical oceanic

142   and one midlatitude continental, and that have differing surface rainfall responses to

143   changes in aerosols, will be used for this study.

144

145   The physical processes hypothesized to invigorate convection are reviewed in section 2.

146   Section 3 describes the model and cases used in this study.   The results including

147   sensitivity tests on evaporative cooling, and the summary, are presented in sections 4 and

148   5, respectively.

149

150   **2. Physical Processes Responsible for the CCN Effect on Precipitation**

151

152   In general, three mechanisms have been proposed to explain the enhancement of

153   precipitation due to changes (increased or decreased) in the aerosol concentration and are

154   described in the following subsections.

155

156   *2.1   Latent Heating Effect*

157

158   The first mechanism is the creation of stronger updrafts/downdrafts resulting from

159   enhanced latent heat release for high-CCN scenarios. This effect can be termed *the latent*

160   *heat – dynamic effect*, which includes LH from both condensational growth and the

161   freezing of water drops. *Wang* [2005], *Rosenfeld et al.,* [2008] and *Li et al.* [2013]

162   indicated that precipitation increases in tropical deep convection due to higher CCN

163   concentrations through this latent heat effect. *Khain et al.* [2005] also found that for

164   cases where there were enhanced precipitation with higher CCN concentrations, clouds

165   were associated with stronger updrafts/downdrafts as well as stronger convergence in the

166   boundary layer, which increases the chance to trigger secondary clouds and prolong the

167   lifetime of convective systems. *Van den Heever and Cotton* [2007], *Lee et al.* [2008] and

168 *Storer et al.* [2010] also demonstrated the influence of aerosols on secondary storm

169 development and its effect on increasing precipitation.

170

171 *2.2   Cold Pool Effect*

172

173 The second mechanism is based on the potential for stronger evaporative cooling due to

174 more but smaller cloud droplets under high CCN concentration conditions. Stronger

175 evaporative cooling can enhance the strength of the near surface cold pool. When the

176 enhanced cold pool interacts with low-level wind shear, convergence can become

177 stronger, producing more vigorous convection that ultimately leads to enhanced surface

178 precipitation [i.e., *Khain et al.,* 2005, *Tao et al.,* 2007]. This positive feedback

179 mechanism is termed the *cold pool effect*. Note that stronger evaporative cooling occurs

180 in the *developing stages of convective cloud systems*. *Lee et al.* [2009] also demonstrated

181 that stronger evaporative cooling occurred under higher aerosol concentrations and

182 consequently lead to enhanced surface precipitation. *Lebo and Morrison* [2014] showed

183 that changes in aerosol loading could alter raindrop size and number concentration, which

184 can affect cold pool strength via changes in evaporation. The balance between the cold

185 pool and low-level wind shear–induced vorticity [*Rotunno et al.,* 1988] can therefore be

186 changed by an aerosol perturbation. However, there are other studies (both modeling and

187 observational) in the literature that find that under higher CCN concentrations there are

188 fewer but larger raindrops, reduced evaporation rates and therefore warmer cold pools

189 [e.g., *Altaratz et al.,* 2007, *Storer et al.,* 2010; May *et al.,* 2011; *Saleeby et al.,* 2010,

190 *Khain et al.,* 2011, *Morrison,* 2012, *Loftus and Cotton,* 2014, *Grant and Van den Heever,*

191 2015].

192

193   *2.3   Cold Microphysics Effect*

194

195   The third mechanism is the CCN effect on ice-phase microphysics. For example, *Wang*

196   [2005] and *Rosenfeld et al.* [2008] suggested that with higher CCN concentrations, there

197   is a greater increase in total water content consisting of numerous small liquid particles.

198   This leads to less efficient collision-coalescence and hence less raindrop formation,

199   which allows for more droplets to be carried above the freezing level and become

200   supercooled where they can then enhance riming. This can then enhance latent heat

201   release via freezing. Among the major microphysical conversion processes, riming is

202   found to be most sensitive to aerosol concentration [*Cheng et al.,* 2010]. As a result, rain

203   production is mainly from ice phase microphysics. *Cheng et al.* [2010] further showed

204   that increasing the CCN concentration leads to more cloud droplets and cloud ice. *Storer*

205   *and van den Heever* [2013] also showed that the collision and coalescence processes and

206   the production of rain from ice are sensitive to aerosol concentrations. The impact of

207   changes in cloud droplets and cloud ice on the resulting surface precipitation is termed

208   the cold microphysics effect.

209

210   The three physical mechanisms can affect each other, making it difficult to isolate each

211   mechanism independently. For example, stronger evaporative cooling (the cold pool

212   effect) can be due to more evaporation associated with stronger convective downdrafts

213   (the latent heating effect). The cold microphysics effect can affect both the latent heating

214   and the cold pool effect and vise-versa. More numerous cloud droplets (due to more

215   CCN) can also lead to more ice nucleation and thus a higher number of snow and graupel

216   particles which, when melted, form more but smaller raindrops that cause stronger

217   evaporative cooling below the cloud base. Convection may be strengthened due to either

218   the latent heating effect or the cold pool effect with the induced stronger updrafts then

219   leading to higher super-saturation and thus enhanced ice deposition and nucleation.

220

221   **3.   Numerical model and cases**

222

223   *3.1   Model*

224

225   The model used in this study is the same as in *Tao et al.* [2007]. It is the two-

226   dimensional (2D) version of the Goddard Cumulus Ensemble (GCE) model.   The

227   equations that govern the cloud-scale motion are anelastic by filtering out sound waves.

228   The subgrid-scale turbulence used in the model is based on *Klemp and Wilhelmson*

229   [1978]. The effect of condensation on the generation of subgrid-scale kinetic energy is

230   also incorporated into the model [*Soong and Ogura*, 1980].   The model includes

231   interactive solar [*Chou et al.*, 1998] and thermal infrared [*Chou and Suarez*, 1994]

232   radiation parameterization schemes.

233

234   The spectral-bin microphysics developed by *Khain et al.* [2005] has been implemented

235   into the GCE model [*Tao et al.*, 2007 and *Li et al.*, 2009]. Its ice-phase collection

236   coefficients have been modified based on comparisons with radar observations [*Li et al.*,

237   2010].   The collisional growth formulation is based on solving stochastic kinetic

238   equations for the size distributions of water droplets (cloud droplets and raindrops), and

239   six types of ice particles: pristine ice crystals (columnar and plate-like), snow (dendrites

240   and aggregates), graupel, and frozen drops/hail. In the scheme, hail is high density and

241   originates from the direct freezing of water drops and grows via the collection of super-

242   cooled water while graupel is moderate density and forms when snow aggregates collect

243   super-cooled water droplets. Each hydrometeor type is described by a size distribution

244   using 33 categories (mass bins). Size spectra of atmospheric aerosols are also described

245   using 33 bins. The initial aerosol size distribution is represented by the sum of 3

246   lognormal distributions [*Jaenicke, 1993*]:

$$n(logD) = \sum_{i=1}^{3} \frac{N_i}{(2\pi)^{\frac{1}{2}} log\sigma_i} \exp\left(-\frac{(logD - log\overline{D}_i)^2}{2log^2\sigma_i}\right)$$

247   where D is the particle diameter, N is the number concentration, and σ is the standard

248   deviation of the log-normal distributions. The subscript i represents three different size

249   modes in atmospheric aerosols: the Aitken mode, the accumulation mode and the coarse

250   mode. This size distribution (activation) is different from that used in *Tao et al*. [2007].

251   The marine background spectrum (N_i=133, 66.6, and 3.1 cm^{-3}; D_i = 0.008, 0.266 and 0.58

252   μm, and $log\sigma_i$= 0.657, 0.210 and 0.396) is used for the TOGA COARE control case, and

253   the remote continental spectrum (N_i=3200, 2900, and 0.3 cm^{-3}; D_i = 0.02, 0.116 and 1.8

254   μm, and $log\sigma_i$= 0.161, 0.217 and 0.380) is used for the PRESTORM control case. In the

255   high CCN scenarios, the background number concentrations are simply increased by 10

256   fold. Aerosol concentration is held constant with height for particles with radius smaller

257   than 2μm. The large aerosol concentration is constant from the surface to 1 km, and then

258   decreases exponentially with an e-folding factor of 2 km.

259

260   The aerosol spectra were taken from *Jaenicke* [1993] and are compilations of ground

261   measurements at various locations. These spectra are based on data from different

262   observations and are normalized consistently. Since aerosol observations are not

263 available for either PRESTORM or TOGA COARE cases, these observation-based

264 aerosol concentrations were used to represent aerosol concentrations in different

265 environmental conditions (oceanic vs. continental).   The high values in the remote

266 continental spectrum are mainly in the Aitken mode and accumulation mode.   There are

267 two pieces of evidence that suggest that these values are not saturating the aerosol effect.

268 First, only the coarse mode and the tail (large sizes) of the accumulation mode become

269 activated in the PRESTORM case.   The actual cloud droplet concentrations are

270 comparable to the previous study [*Tao et al.,* 2007] where an idealized CCN=C*S^k

271 spectrum was used.   Second, similar small aerosol effects were presented in *Tao et al.*

272 [2007] for the same PRESTORM case with C=600 cm^{-3} for the low-CNN scenario and

273 6000 cm^{-3} for the high-CNN scenario.   The vertical aerosol distributions of aerosols are

274 based on field observation results [i.e., *Fridlind et al.*, 2012].   Aerosols enter and exit via

275 the open lateral boundaries.   The lower boundary is held constant.   Aerosol wet

276 deposition is included in the simulations, but dry deposition is ignored.   The environment

277 becomes cleaner after precipitation passes through.

278

279 All scalar variables (potential temperature, mixing ratio of water vapor, turbulence

280 coefficients, and all hydrometeor classes) use forward time differencing and a positive

281 definite advection scheme with a non-oscillatory option [*Smolarkiewicz and Grabowski*,

282 1990]. The dynamic variables, u and w, use a fourth-order accurate advection scheme

283 and leapfrog time integration. Details of the GCE model description and improvements

284 can be found in *Tao and Simpson* [1993] and *Tao et al.* [2014].

285

286   Radiative open lateral boundary conditions are used [*Klemp and Wilhelmson*, 1978]. A

287   large horizontal domain is used in this study to simulate the large convective system and

288   minimize the reflection of convectively-generated gravity waves at the lateral boundaries

289   [see *Fovell and Ogura*, 1988]. The top boundary condition is free slip (i.e., the vertical

290   velocity is assumed to be zero as are the vertical gradients of horizontal wind velocity

291   and other scalar variables). In addition, a Rayleigh relaxation (or damping) layer is

292   applied above 15 km to damp convectively-generated gravity waves near the top of the

293   model domain, which is above 20 km. There are 1024 horizontal grid points with a

294   resolution of 1 km in the center 720 points and laterally-stretched grids on either side.

295   Use of the stretched horizontal grid makes the model less sensitive to the choice of

296   gravity wave speed associated with the open lateral boundary conditions [*Fovell and*

297   *Ogura*, 1988]. For the present study, a stretched vertical coordinate with 33 levels is

298   used. The model has finer resolution (80 and 40 meters for the PRESTORM and TOGA

299   COARE cases, respectively) in the boundary layer and coarser resolution (about 1000

300   meters) at upper levels. The model time step is 5 s. Convection is initiated by imposing

301   a cold air mass at the beginning of the simulation, imitating the cold pool dynamics that

302   generate new convection at the leading edge of the respective squall lines.

303

304   *3.2   Cases*

305

306   Two cases from vastly different environments, a tropical oceanic squall system observed

307   during TOGA COARE (the Tropical Ocean and Global Atmosphere Coupled Ocean-

308   Atmosphere Response Experiment, which occurred over the Pacific Ocean warm pool

309   from November 1992 to February 1993), and a midlatitude continental squall system

310 observed during PRESTORM (the Preliminary Regional Experiment for STORM-

311 Central, which occurred in Kansas and Oklahoma during May-June 1985), are used to

312 identify the physical processes that are responsible for enhancing the precipitation

313 processes associated with deep convective systems as a result of changing CCN

314 concentrations.

315

316 The 22 February 1993 TOGA COARE squall line has been well studied [*Jorgensen et al.*,

317 1997; *Redelsperger et al.,* 2000; *Trier et al.,* 1996, 1997; *Wang et al.,* 1996, 2003]. The

318 sounding used to initialize the model is from *LeMone et al.* [1994]. Surface fluxes are

319 included in the model for this case using the TOGA COARE flux algorithm [*Fairall et*

320 *al.,* 1996; *Wang et al.,* 1996]. The 10-11 June 1985 PRESTORM case has also been well

321 studied [e.g., *Johnson and Hamilton*, 1988; *Rutledge et al.*, 1988; *Tao et al.,* 1995, 1996;

322 *Yang and Houze,* 1995; *Lang et al.*, 2003]. The PRESTORM environment is fairly

323 unstable and relatively dry. The model is initialized with a single sounding taken at 2330

324 UTC from Pratt, KS, which was taken ahead of the squall line. Radiation is included but

325 not surface fluxes. The freezing level is approximately 4.5 km for the TOGA COARE

326 case and 3 km for the PRESTORM case. Both the TOGA COARE and PRESTORM

327 cases are well-organized, long-lived mesoscale convective systems. These two cases

328 were also simulated by *Tao et al.* [2007] and found to have different responses to changes

329 in CCN concentration.

330

331 The two cloud systems presented in this study formed into organized, linear structures

332 (i.e., squall lines). A 2D simulation, therefore, can provide a reasonable approximation

333 of their line-normal structure. Since the real atmosphere is 3D, further 3D cloud-

14

334   resolving simulations are still needed to address aerosol-precipitation interactions. In

335   addition, a finer resolution and large domain are required to solidify interactive aerosol-

336   cloud-precipitation processes further.

337

338   *3.3   Numerical Experiments*

339

340   A total of ten numerical experiments are conducted; Table 2 shows the numerical

341   experiments (names), their descriptions and domain mean rainfall amount. The first two (P-

342   low and P-high) experiments are for the PRESTORM case using low and high CCN

343   concentrations, respectively. The third and fourth (T-low and T-high) are for the TOGA

344   COARE case using low and high CCN concentrations, respectively. The next four

345   experiments (P-low-warm, P-high-warm, T-low-warm, and T-high-warm) are the same as the

346   first four experiments except that they use warm rain physics only. The P-low-evap and T-

347   high-evap cases are used to examine the impact of evaporation processes on aerosol-

348   precipitation interaction. More discussion on the numerical experiments is presented in the

349   following section.

350

351   **4.   Results**

352

353   Figure 1 shows time sequences of the model-estimated domain mean surface rainfall rate

354   for the TOGA COARE and PRESTORM cases. Note that there are some minor

355   differences between these and previous results published in *Tao et al.* [2007]. These

356   differences are due to the use of a different CCN activation. Nevertheless, the main

357   results are the same between this and the *Tao et al.* [2007] study. For example, rain

358   suppression in the high CCN concentration (i.e., polluted environment) runs is evident in

359   both studies for both cases but only during the first hour of the simulations, while rain

360   reaches the ground early in both studies for low CCN situations for both cases. Also,

361   during the mature stage of the simulations, the effect of increasing the CCN concentration

362   ranges from rain suppression in the PRESTORM case to rain enhancement in the TOGA

363   COARE case (see Table 2 for the detailed amounts for this study). These results still

364   indicate that model simulations of the whole life cycle of convective system are needed in

365   order to assess the impact of aerosols on precipitation processes. Please see *Tao et al.*

366   [2007, 2012] for more discussion.

367

368   *4.1   Latent heating and evaporative cooling effects*

369

370   Total LH consists of condensation, deposition, and freezing. Time series of total LH for

371   the high- and low-CCN scenarios are shown in Fig. 2 for the TOGA COARE case. The

372   model results clearly show that the total LH in the T-high scenario is much larger than

373   that for the T-low during the 12 h model integration. In addition, the mean total LH

374   profiles show that heating reaches higher in altitude, indicating taller cloud tops and

375   stronger convection for the T-high simulation. Figures 2(c) and (d) also indicate that the

376   low-level evaporative cooling is quite different between the T-low and T-high scenarios.

377   The high CCN scenario shows stronger, deeper evaporative cooling profiles than the low

378   (also see Fig. S1 in the supplement). Stronger evaporative cooling can enhance the near

379   surface cold-pool strength. When the cold pool interacts with the low-level wind shear,

380   the convergence could become stronger, producing stronger convection in the T-high

381   case (see Fig. S2 in the supplement). This can lead to more vigorous precipitation and

382   therefore enhanced surface precipitation (i.e., a positive feedback).

383

384   Rain suppression in the PRESTORM high CCN concentration (i.e., polluted

385   environment) run is evident for the P-high scenario (Fig. 1b). The total LH in the P-high

386   scenario is slightly weaker than in the P-low at upper levels (~ above 7 km) during the

387   12-h model integrations (Figs. 3a and b). The evaporative cooling is also slightly weaker

388   at low altitude (surface to 3 km) for the high-CCN run (Figs. 3c and d). These results are

389   completely opposite to the TOGA COARE case wherein stronger evaporative cooling

390   and LH occur in the high-CCN run. In addition, the total LH and evaporative cooling are

391   much stronger in the PRESTORM case than those in the TOGA COARE case. This

392   result is due to the high convective available potential energy (CAPE) and drier

393   environmental in the PRESTORM case (see Table 3 in *Tao et al.* 2007).

394

395   More rain reaches the surface after an hour and a half of model integration in the T-high

396   simulation as compared to the T-low simulation (Fig. 1a). During this period, more

397   evaporative cooling in the T-high simulation is already evident from the model results

398   (Fig. 2d). Figures 4(a) and (b) show the vertical profiles of the time and domain mean

399   LH and evaporative cooling during the early stage of the simulated TOGA COARE high

400   and low CCN scenarios. During the first hour of model integration, evaporative cooling

401   is stronger (2-3 K/day), and LH is also slightly stronger (less than 0.5 K/day) for the T-

402   high scenario. Evaporative cooling is still stronger and occurs in a narrow area near the

403   leading edge of the system for the T-high run for the first two hours of model integration

404   (see Fig. S1 in the supplement). The strongest evaporative cooling for the T-low run is

405   not at the leading edge of the system.   The strongest LH occurs in a narrow region and at

406   the leading edge of the system for both the T-high and T-low scenarios (see Fig. S1 in the

407   supplement), but LH is much stronger for the T-high scenario than the T-low after 1.5 h

408   model integration. Peak LH is between 2 and 5 km and indicates development of low-

409   level cloud (warm-rain) during the first two hours of model integration (Fig. 2). Note

410   that the strongest LH occurs between 2 and 3 hours of model integration for the T-high

411   scenario (Fig. 2a).

412

413   The total LH profiles, especially above 5 km, are quite similar for the low and high-CCN

414   scenarios during the first 1 to 2.5 hours of model integration for PRESTORM case (Fig.

415   4c). But, the total LH is stronger (1-2 K/day) between 2 and 4 km for the P-low scenario.

416   The evaporative cooling is also stronger at lower levels in the P-low run for the

417   PRESTORM case (Fig. 4d). This could be related to the early onset of rainfall in that run

418   and because rain evaporation dominates the lower levels for this case. Note that the

419   results show that there are less small rain (< 2 mm) droplets for the P-high scenario than

420   the P-low. In addition, the strongest evaporative cooling is located in a very narrow

421   region at the leading edge after 3.5 hours of model integration in the P-low run in contrast

422   to the P-high (see Fig. S3 in the supplement). The results also show that strong LH

423   occurs within a narrow region and at the leading edge of each system for both the P-high

424   and P-low runs as with the TOGA COARE runs (see Fig. S3 in the supplement)

425

426   The role of total LH and evaporative cooling with regard to enhancing surface rainfall is

427   examined during the developing/early stages of the TOGA COARE and PRESTORM

428   cases. For TOGA COARE, LH is slightly larger for the high-CCN scenario than the low;

429   however, low-level evaporative cooling is stronger for the high-CCN scenario. The low-

430   level evaporative cooling and its interaction with the low-level convergence zone could

431   be the key physical process that enables more surface rainfall to be generated for the

432   TOGA COARE squall line under high aerosol loading. For the PRESTORM case, P-low

433   does have more small raindrops. It also has more low-level evaporative cooling compared

434   to P-high. Also, with the dry environment in the PRESTORM case, evaporation rates

435   will be high in both the clean and polluted scenarios, and hence the impact of aerosols

436   may be reduced. In contrast, the moist environment limits the evaporation rates in the

437   TOGA COARE case such that aerosols may be required to make droplets sufficiently

438   small in order to achieve reasonable evaporation rates [*Tao et al.*, 2007].

439

440   Figure 5 shows Hovmoller diagrams of low-level convergence and low-level equivalent

441   potential temperature perturbations for the P-low and P-high simulations. The low-level

442   equivalent potential temperature perturbations (averaged vertically from the lowest model

443   level to z=3 km) can be used as an indicator of the cold pool strength. Only the first 4

444   hours of data are plotted here in order to emphasize details of the cold pool structures

445   because the differences in surface rainfall (Fig. 1b) and evaporative cooling (Figs. 3c and

446   d) already emerged within this time. Figures 5e and 5f also show the vertical structure of

447   the equivalent potential temperature perturbations and convective updrafts (contour lines

448   at 1, 5 and 10 m/s). Both cases simulate a narrow, linear convective system. The low-

449   level convergence and cold pool are both stronger in the P-low scenario than in the P-

450   high scenario. These features are clearly shown after 1.5 hours of model

451   integration. Evaporative cooling at the lowest levels is also stronger in the P-low case

452   after 1.5 hours (Figs. 3c and 3d) as is the surface rainfall (Fig. 1b). The highest surface

453   rainfall rates are located in the low-level convergence zone. The vertical cold pool

454   structure is only slightly stronger in the P-low scenario than the P-high scenario. The

455   convective updrafts are located near and above the cold pool. There are also remnants of

456   convective cells above the cold pool and over a broad area that extends 100 km from the

457   leading edge of the system. This feature has been observed [i.e., *Rutledge et al.*, 1988

458   and *Johnson and Hamilton,* 1988] and simulated by many CRMs [i.e., *Dudhia et al.*,

459   1987; *Rotunno et al.*, 1988; *Lafore and Moncrieff*, 1989 and many others]. Note that the

460   maximum convective updrafts are quite similar between the P-high and P-low scenarios

461   [shown in Fig. 3 in *Tao et al.*, 2007]. The small differences in maximum updrafts are due

462   to the PRESTORM environment being fairly unstable with a CAPE of 2300 J/kg.

463

464   There are similarities and differences between the PRESTORM and TOGA COARE

465   cases in terms of low-level convergence, cold pools, and the vertical structures of the

466   simulated systems (Fig. 6). Both the PRESTORM and TOGA COARE cases have

467   narrow low-level convergence zones, cold pools at the leading edge of the system and

468   convective updrafts located above the cold pools. However, the cold pools and

469   convective updrafts are much weaker in the TOGA COARE case due to a weaker CAPE

470   (1776 J/kg) as compared with the PRESTORM case. Also, surface rainfall was enhanced

471   in the high CCN simulation, T-high, which was not the case for PRESTORM. Low-level

472   convergence is stronger in the T-high simulation than in the T-low (Fig. 6 a and b). It is

473   much stronger than in the T-low after 1.5 hours of model integration. The low-level cold

474   pool is also stronger in the T-high run than in the T-low between 0.5 and 1.5 hours of

475   model integration. This is consistent with the evaporative cooling shown in Fig. 2. There

476   is more rainfall (i.e., enhancement) in the T-high scenario than in the T-low after 1.5

477   hours of model integration (Fig. 1a). Figure 6 also shows that the cold pool is "warmer"

478   at the leading edge of the stronger convergence zone in the T-low scenario. The cold

479   pool is "colder" at the leading edge of or close to the stronger convergence zone in the T-

480   high scenario, especially after initial stage of model simulations. This feature is also

481   shown in the vertical structures (Figs. 6e and f) and is the reason for the more upright

482   vertical velocity structure shown in Fig. 6f. Therefore, the enhanced cold pool (driven by

483   evaporative cooling) interacting with convergence can allow for new (or secondary)

484   clouds to be deeper. This could also enhance rainfall in the T-high scenario (compared to

485   the T-low) in the TOGA COARE precipitation system.

486

487   *4.2   Warm Rain Only*

488

489   The third hypothesis regarding the invigoration of convective precipitation systems in

490   high CCN environments is the cold microphysics effect. Sensitivity experiments are

491   performed by turning off the ice processes to examine the impact of ice microphysics on

492   aerosol-precipitation interactions (similar tests were conducted in *Tao et al.,* [2007]). In

493   these sensitivity tests, the following microphysical processes are included: (1)

494   condensation/evaporation of liquid drops, (2) drop/drop collision/coalescence, (3)

495   turbulence effects on liquid drop collisions, (4) collisional breakup, and (5) sedimentation

496   of liquid. These warm-rain only tests still allow condensation to occur above the freezing

497   level in place of deposition. In addition, the warm rain scenario does not allow riming

498   and freezing processes, which result in more cold rain and melting. Therefore, the

499   differences between the pairs of control runs (low CCN vs. high CCN) and the warm-rain

500   only runs can be used to assess and examine the role of ice microphysics in producing the

501   sensitivities between the low-CCN and high-CCN environments.

502

503   Figure 7 shows time sequences of model-estimated domain mean surface rainfall rate

504   without ice processes (warm rain only). For the PRESTORM case, the mean surface

505   rainfall under both low CCN and high CCN conditions is quite similar. This suggests

506   that the ice processes are crucial in suppressing surface precipitation and increasing the

507   portion of light rain in a high-CCN environment. For TOGA COARE, rain suppression

508   due to a high CCN concentration is again only evident during the first hour or so of the

509   simulation. For the entire period, increasing CCN still enhances rainfall, the same as

510   with the full ice run. These results suggest that the main mechanisms for CCN enhancing

511   surface rainfall exist in warm rain microphysics. However, ice-phase microphysics can

512   further enhance the surface rainfall amount in the T-high scenario as compared with the

513   T-high-warm scenario, because the majority of surface rainfall in this case comes from

514   warm rain.

515
516   The total LH and evaporative cooling (Figs. 2 and 8) for the TOGA COARE case for the

517   low-CCN scenario are quite similar between the control and warm rain only simulations

518   and indicate that ice processes appear to play only a secondary role in terms of their

519   aerosol impact in this scenario. The total LH between the control and warm rain only

520   simulations for the high-CCN scenario is likewise similar for the first 1.5 hours of model

521   integration. Thus, during the development and early mature stages of the high CCN

522   simulations, ice processes again appear to have little impact on the aerosol effect as LH

523   and evaporative cooling are nearly identical to the full physics control run (Figs. 2b and

524   d).   However, after 2 hours of simulation, the total LH in the high CCN full physics

525   control run is larger and deeper, especially above the freezing level where there are more

526   episodes of deep, LH penetrations, than in the warm rain only simulation.   Likewise,

527   Figs. 2d and 8d indicate that the low-level evaporative cooling becomes quite different

528   with the warm rain run exhibiting much stronger and somewhat deeper (as evaporation

529   replaces sublimation above the freezing level in the warm rain run) low-level

530   evaporation, which in turn enhances the near surface cold-pool. The difference between

531   the low- and high-CCN simulations (Figs. 8c and d) is greater than that between the

532   control pair (Figs. 2c and d). As in the control run, evaporative cooling, which affects

533   cell regeneration in convective systems, is still determined mainly by warm rain

534   processes for the TOGA COARE case.

535

536   For the PRESTORM warm rain experiments, the differences in total LH and evaporative

537   cooling are not significant between the P-high-warm and P-low-warm cases (Fig. 9). The

538   differences are quite small during the first 3 hours (early stage) of the model simulations.

539   This could be the reason for the similar surface rainfall between the high and low CCN

540   situations.   Note that there is a jump in latent heat release around 4 and 5 hour,

541   respectively, for the low and high CCN cases.   Consequently, there is enhanced

542   evaporative cooling and surface rainfall. The difference in LH and evaporative cooling is

543   quite small because the PRESTORM environment is both fairly unstable with a

544   convective available potential energy (CAPE) of 2300 J/kg and relatively dry and

545   therefore already conducive for evaporation. In addition, these results also suggest that

546   ice microphysics play an important role in the aerosol impact for the PRESTORM case.

547

548   These warm-rain only sensitivity tests still allow condensation to occur above the

549   freezing level in place of deposition. These tests examine the water phase microphysics;

550   their associated latent heating and evaporative cooling are responsible for the greater

551   sensitivity shown in the TOGA COARE case in contrast to the PRESTORM case. *Khain*

552   *and Sednev* [1996] applied spectral bin microphysics to a precipitation event that

553   occurred in the eastern Mediterranean coastal zone. Their results also showed that ice

554   processes did not have a significant effect on the location of precipitation events, the

555   vertical velocity or rainfall accumulation. However, their results did show that ice

556   processes can delay precipitation formation and alter the spatial distribution of

557   precipitation.

558

559   *4.3   The effect of latent heating on vertical velocity*

560

561   With the LH effect, updrafts/downdrafts could be enhanced as a result of enhanced latent

562   heat release. The relationship between thermodynamic buoyancy (or latent heat release)

563   and convective updrafts and downdrafts is analyzed to identify whether or not LH is the

564   main physical process enhancing surface rainfall due to aerosol-precipitation interactions.

565   The vertical velocity equation is shown as follows:

$$\frac{\partial w}{\partial t} = -\frac{\partial}{\partial x}uw - \frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\bar{\rho}ww - C_p\bar{\theta}\frac{\partial \pi'}{\partial z} + g\left(\frac{\theta'}{\bar{\theta}} + 0.61q_v' - q_l\right) + D_w$$

566

567   where, u, and w are the horizontal and vertical velocity, the variables θ and q_v are

568   potential temperature and water vapor, $\bar{\rho}$ is the air density, $\bar{\pi} = (p/p_{00})^{R/c_p}$ is non-

24

569   dimensional pressure (where p and p_{oo} are dimensional and reference pressures,

570   respectively, with p_{oo} taken as 1000 hPa), c_p is the specific heat of dry air at constant

571   pressure, q_l is the liquid and ice water loading, and D_w is diffusion (turbulence term). The

572   prime means the deviation from the horizontal mean (represented by the bar over a

573   variable). Please see Soong and Ogura [1973, 1980] and Tao and Soong [1986] for

574   details on this equation. The turbulence term is very small and the advection term also

575   small in the middle and upper troposphere compared to the pressure gradient force and

576   buoyancy term. In the lower troposphere, the advection term is about 1/3 of the pressure

577   gradient force. It is positive (i.e., it acts to increase vertical velocity) beneath 1.5 – 2 km

578   and negative (i.e., it acts to decrease vertical velocity) above that.

579

580   Figure 10 shows the vertical pressure gradient force (PGF=$-C_p\bar{\theta}\frac{\partial \pi^{'}}{\partial z}$), buoyancy effect

581   due to temperature buoyancy forcing or latent heat release ($g\frac{\theta'}{\bar{\theta}}$), water vapor buoyancy

582   force ($0.61gq_v^{'}$), and water loading effect ($-gq_l$) for the PRESTORM case. Both

583   buoyancy due to water vapor and the loading effect are quite small compared to PGF and

584   LHR. LHR is positive (negative) in the middle (low) troposphere where the convective

585   updrafts (downdrafts) are located. This implies that latent heat release (heating by

586   condensation and/or deposition) will enhance updrafts in the middle troposphere while

587   negative LH (i.e., cooling by evaporation) will enhance downdrafts in the low

588   troposphere. The buoyancy due to water vapor change is positive (negative) in the

589   middle (low) troposphere (Fig. 10c). It has the same effect on convective drafts as the

590   LH effect except with one order smaller magnitude. It also has a smaller effect than the

591   loading effect.

592

593   Figure 11(a) shows the domain mean vertical profiles of PGF and the LH effect for the

594   low-CCN and high-CCN scenarios. Both PGF and LH are slightly larger in the low-CCN

595   scenario than in the high-CCN scenario. Their net effect on updrafts and downdrafts is

596   about the same (Fig. 11(b)). Their net effect is also about the same magnitude as the

597   loading effect. This suggests that the loading effect is quite important but in a negative

598   way with regard to convective updraft enhancement. The relative roles of the PGF, LH

599   effect, water vapor buoyancy force and water loading effect on the vertical velocity are

600   the same for the TOGA COARE case.

601

602   The relationship between thermodynamic buoyancy (latent heat release), vertical pressure

603   gradient force, and drag from water loading associated with convective updrafts and

604   downdrafts has been previously studied [*Soong and Ogura*, 1973; *Schlesinger*, 1980;

605   *Knupp and Cotton*, 1985; *Tao et al.,* 1995 and *Storer and van den Heever*, 2013]. For

606   example, *Soong and Ogura* [1973] showed the importance of the PGF on cloud

607   development. Their results also indicated that PGF is the same order of magnitude as the

608   thermal buoyancy force in the core regions of clouds. PGF acted in the opposite direction

609   of the net force due to the excess heat, moisture, and weight of liquid water (there were

610   no ice processes in their model). *The current modeling results are consistent with Soong*

611   *and Ogura [1973] except that the importance of the water loading effect has been*

612   *identified.*

613

614   *Tao et al.* [1995] also showed that PGF and buoyancy oppose each other and are larger

615   than the water loading. They suggested that the water-loading effect plays an important

616　role for initiating downdrafts. Their study was focused on cloud downdrafts and was

617　based on *trajectory analyses*. Recently, *Storer and van den Heever* [2013] indicated that

618　the drag associated with condensate loading is an important factor in determining the

619　*average updraft strength* for tropical deep convective clouds.

620　　　.

621　*4.4　Reduction of evaporative cooling*

622

623　Evaporative cooling from rain is one of the major microphysics processes that produce

624　cold pools in the lower troposphere. It is also one of the hypotheses associated with the

625　enhancement of precipitation and surface rainfall due to aerosols. Sensitivity tests in

626　terms of reduced evaporation are conducted. These tests aim to identify whether

627　evaporative cooling is the main physical process enhancing surface rainfall due to

628　aerosol-precipitation interactions. Note that in spectral-bin microphysics, water drops

629　and their interactions with one another span the whole size spectrum. There is no clear

630　distinction between cloud droplets and raindrops, and thus evaporative cooling comes

631　from the entire size spectrum (i.e., from small cloud droplets to large precipitating

632　raindrops). Reduced evaporation can impact surface rainfall in three ways. First, it could

633　allow more / larger raindrops to reach the surface. This could produce more surface

634　rainfall. Second, it could allow less cooling in the low troposphere and consequently

635　affect relative humidity (and reduce relative humidity due to a higher temperature), but it

636　could also allow for more evaporative cooling due to a lower relative humidly. This

637　could either favor or not favor the enhancement of precipitation processes and therefore

638　surface rainfall. Third, the cold pool strength could be weakened. This could affect

639　secondary convective generation and reduce the surface rainfall (the hypothesis discussed

640   in the 2nd section). Which factor dominates could depend on the large-scale (or

641   mesoscale) environment.

642

643   In the first sensitivity test, evaporation is completely removed from 1 to 3 hours of model

644   integration, from the surface to 3 km, for the PRESTORM P-low scenario. This is

645   because evaporative cooling is quite similar between the P-low and P-high simulations

646   during the first hour of model integration (see Fig. 3). Figure 12 shows time sequences of

647   the model-estimated domain mean surface rainfall rate for the three different scenarios

648   (P-low, P-high and P-low-evap, which is P-low without evaporation from 1 to 3 hours

649   from 0 to 3 km). The total rainfall amount is reduced from 58.4 mm for the (clean)

650   control simulation to 40.7 mm for the reduced evaporation simulation. In the P-low-evap

651   scenario, rainfall increased significantly after the first hour of model integration due to

652   the first impact (more/larger raindrops reach the surface). After 3 hours, when

653   evaporation is turned back on, rainfall is initially reduced due to the reverse of the first

654   impact (fewer/smaller raindrops reach the surface); however, rainfall continues at a

655   reduced rate until the cold pool is replenished (figure not shown) and eventually increases

656   back to a level similar to the clean scenario at around 7 hours.

657

658   For the TOGA COARE case, T-high is used to show the sensitivity to evaporation. P-

659   low and T-high have the most rainfall and evaporation for their respective cases and

660   therefore are likely to show the greatest response to changes in evaporation. For the T-

661   high case, the evaporation rate is reduced 100 % only for the first 1.5 hours of model

662   integration, from the surface to a height of 4 km. The results show that the total amount

663   of accumulated surface precipitation is reduced (from 33.0 mm to 26.6 mm) compared to

664   the T-high run (Fig. 13). The results also show that rainfall increased significantly for the

665   first one and half hours of model integration due to the first impact of reduced

666   evaporation (more rainfall reaches the surface) and are consistent with the PRESTORM

667   case.   The rainfall amount was also only slightly reduced compared to the T-high

668   scenario but is still more than the T-low after 1.5 hour of model integration. Eventually,

669   the rainfall amount and temporal variation of the surface rainfall is quite similar between

670   the simulation without evaporation and the clean run after 6.5 hours of model integration

671   (Fig. 13).   Different environmental conditions (moist vs. dry, differing stability or

672   convective available potential energy) could be the reason for this difference.

673   Evaporative cooling is quite efficient and could have more impact on convective systems

674   in a drier environment (i.e., the P-high scenario).

675

676   An additional run with evaporation reduced by 50% over the first 1.5 hours of model

677   integration was also conducted for the T-high scenario. Rainfall is almost identical

678   between these two runs even after the first 1.5 hours of model integration (plot not

679   shown). This is because the temporal domain-mean LH and evaporative cooling are quite

680   similar (Fig. 14). Both cases should have smaller-sized droplets due to high CCN

681   concentrations. By reducing evaporation, some of the smaller drops will remain, and

682   hence light rainfall will be possible. It should also reduce the relative humidly and

683   therefore allow more evaporative cooling to occur later on. This could explain why the

684   evaporative cooling does not change in these two cases. Consequently, the LH does not

685   change significantly either (Figs. 14b and c).

686

687   **5.   Summary**

688

689 A 2D CRM with detailed spectral-bin microphysics is used to examine and identify the

690 dominant physical processes that determine precipitation enhancement as a result of high

691 CCN concentrations. Two cases are simulated using idealized initial aerosol

692 concentrations: a tropical, linear convective system during TOGA COARE and a

693 summertime, midlatitude squall line during PRESTORM. A pair of model simulations,

694 an experiment with low (clean) and an experiment with high CCN concentrations

695 (polluted environment), is conducted for each case. The latent heating and evaporative

696 cooling associated with three different potential processes (i.e., latent heating, cool-pool

697 and ice microphysics) that could determine the aerosol impact on deep convective

698 precipitation are examined. The relationship between vertical velocities, vertical pressure

699 gradient force, buoyancy (latent heat and water vapor) and the water loading effect are

700 also examined to identify the important processes for convective development.

701 Sensitivity tests are performed to examine the impact of ice and evaporative cooling on

702 the relationship between aerosols and precipitation processes. The major highlights are

703 as follows:

704

705 • For the scenarios in which rainfall is enhanced (i.e., T-high and P-low), low-level

706 cold pools and convergence are stronger than in their counterpart scenarios (i.e., T-

707 low and P-high). The low-level evaporative cooling is also stronger in the T-high and

708 P-low cases, especially in the early stages (i.e., the first 1-3 hours of model

709 integration) of the convective systems. The results also suggest that latent heating

710 and evaporative cooling (and cold pools) are the key processes associated with the

711 enhanced rainfall during the *mature stage* of these two deep convective, precipitating

712   cloud systems (i.e., Figs. 2 and 3). The importance of latent heating and evaporative

713   cooling over the *whole life cycle* of convective cloud systems was also addressed in

714   *Khain* [2009].

715   • For the TOGA COARE (tropical) case, the T-high-warm scenario still produces more

716   rainfall than the T-low-warm as with the original full physics simulations. This is

717   because the latent heating and evaporative cooling are quite similar between the ice

718   and warm rain only simulations. This result suggests that the ice processes do not

719   have a major impact on aerosol-precipitation interaction for this case. For the

720   PRESTORM (midlatitude) case, the P-high-warm and P-low-warm simulations

721   produce similar total rainfall amounts. In contrast, the P-high and P-low simulations

722   have much larger differences. This suggests that ice processes are crucial in

723   suppressing surface precipitation in the high CCN environment.

724   • For both the PRESTORM (P-low) and TOGA COARE (T-high) high rainfall

725   scenarios, the total rainfall amount is reduced in sensitivity tests in which evaporation

726   is restricted (see Table 2). However, rainfall increased significantly during the period

727   in which evaporation was eliminated because more rain could reach the surface. The

728   simulated cold pools are also much weaker compared to the run with full evaporation

729   in the PRESTORM case. The results also show that overall rainfall was still more

730   than in the high (low) CCN scenario for the PRESTORM (TOGA COARE) case.

731   This is because the cold pool was replenished and eventually become stronger.

732   Similar to other studies [e.g., *Khain et al*., 2005; *Khain*, 2009], our results suggest

733   that evaporative cooling can affect the cold pool strength.

734 • For both the TOGA COARE and PRESTORM cases, the temperature buoyancy term

735   can enhance updrafts via heating due to condensation and deposition in the middle

736   troposphere and downdrafts via evaporative cooling in the lower troposphere in the

737   convective core region (see Fig. 10). However, PGF is the same order of magnitude

738   as the temperature buoyancy forcing and acts in the opposite direction. This suggests

739   that PGF is as important as the temperature buoyancy term in determining the cloud

740   velocity strength. The water loading and water vapor buoyancy terms are quite small

741   compared to PGF and temperature buoyancy forcing. *But, the water loading term is*

742   *the same order as the net difference between PGF and temperature buoyancy forcing.*

743   This suggests that the water-loading effect could be quite important for vertical

744   velocities associated with clouds. These results are consistent with previous

745   modeling results for isolated clouds [*Soong and Ogura*, 1973], from trajectory

746   analysis [*Tao et al.,* 1995], and for multi-cloud systems [*Storer and van den Heever*,

747   2013].

748

749 Almost all previous CRM studies (including the present one) used idealized chemical

750 compositions and CCN concentrations in the simulations [e.g., *van den Heever et al.,*

751 2006]. Furthermore, the spatial distribution of CCN was assumed to be uniform, at

752 least horizontally. A non-homogeneous CCN distribution (from observations or from

753 large-scale modeling/analyses), consistent with non-homogeneous initial

754 meteorological conditions, is needed to assess aerosol-precipitation interactions [i.e.,

755 *Shi et al.,* 2014]. A 2D simulation provides a good approximation to the observed

756 linear convective systems in this study; however, 3D CRM simulations are needed to

757 address aerosol-precipitation interactions more fully. Furthermore, CRM studies

758 need to compare model results with observed cloud features such as dynamical and

759 microphysical profiles, cloud extent, evolution of organization, radar reflectivity, and

760 rainfall. Combining observations and modeling can enable us to better understand the

761 response of clouds and precipitation to aerosols and their interactive feedbacks.

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Table 1: Summary of precipitation sensitivity (dP) to increases in the number of CCN (dN0) for different studies. Note that van den Heever et al. [2006] used a linear CCN concentration profile that ranged from 300 cm^{-3} at 4 km above ground level to 1000 cm^{-3} near the surface; GCCN and IN effects from *van den Heever et al.* [2006] and *Teller and Levin* [2006] are excluded from the table; only five of the total 30 cases from *Wang* [2005] are displayed in the table. Updated and modified from *Tao et al.* [2007]. The results from *van den Heever et al.* [2011, 2013] are based on 100-day integrations using a 10,000-km domain with cyclic lateral boundary conditions, whereas *Morrison and Grabowski* [2011] are based on 6-day integrations, a 240-km domain, and 240 ensembles with imposed large-scale advective forcing. Note that this list of papers is not complete. This table was adapted from *Tao et al.* [2007, 2012].

Reference	case		dN_0 (N_{clean}) [cm^{-3}] CNN #	dP (%)	Model specifications
Phillips et al. [2002]	New Mexico		1950 (800)	-14.	1D, bin
			4200 (800)	-30.	1D, bin
Khain and Pokrovsky [2004]	Texas		40 (10)	-16.	2D, bin
			90 (10)	-19.	2D, bin
			290 (10)	-53.	2D, bin
			1250 (10)	-88.	2D, bin
Khain et al. [2005]	GATE		1160 (100)	-3.	2D, bin
Khain et al. [2005]	PRESTORM		1160 (100)	+258.	2D, bin
Wang [2005]	ITCZ		400 (100)	+180.	3D, bulk
			800 (100)	+340.	3D, bulk
			1,200 (100)	+540.	3D, bulk
			1,500 (100)	+700.	3D, bulk
Lynn et al. [2005]	Florida		1,250 (10)	-5.	3D, bin, 400x199
Teller and Levin [2006]	Winter-time eastern Mediterranean		210 (100)	-27.	2D, bin
			510 (100)	-55.	2D, bin
			810 (100)	-73.	2D,bin
			1,260 (100)	-93.	2D, bin
van den Heever et al. [2006]	CRYSTAL		350 (300)	-22.	3D, bulk
Tao et al. [2007]	TOGA COARE		2400 (100)	+58.	2D, bin,1024 grid
	PRESTORM		1900 (600)	-24.	2D, bin, 1024 grid
	CRYSTAL		1900 (600)	-13.	2D, bin, >1024 grid
Fan et al. [2007a]	A sea-breeze induced convective event (Houston, TX)		30,000 (3000)	+9.	2D, bin
van den Heever and Cotton [2007]	METROMEX (St. Louis, June 8, 1999 convective storm)				3D, bulk
	GCCN = 0.01 cm^{-3}	Early stage	2000 (800)	-12	3D, bulk
		Late stage	2000 (800)	-1	3D, bulk
	GCCN = 0.1 cm^{-3}	Early stage	2000 (1200)	+5	3D, bulk
		Late stage	2000 (1200)	-2	3D, bulk
	GCCN = 0.2 cm^{-3}	Early stage	2000 (1200)	+26	3D, bulk
		Late stage	2000 (1200)	-1	3D, bulk
Lee et al. [2008a,b,2009]	ARM-A		900 (100)	+18.	2D, bulk
Fan et al. [2009]	TWP-ICE and China		1,100 (110)	+/- (Depends on the wind shear	2D, bin
Lee and Feingold [2010]	TWP-ICE		450 (50)	+9.	2D, bin
Cheng et al. [2010]	A front system (Northern Taiwan)		9,000 (1000)	-12	3D, bulk
			900 (100)	~0	
Saleeby et al. [2010]	Marine Warm Rain Events: January 22-23, 1998; February 2-3,		Observed AOD for each event, ranging from 0.02 to 0.7 optical depth		3D, bulk

	2004; April 2-3, 2007 (East China Sea)			
		¼ x OBS	-38	3D, bulk
		½ x OBS	-21	3D, bulk
		Observed AOD (OBS)	-	3D, bulk
		2 x OBS	-3.5	3D, bulk
Storer et al. [2010]	Idealized Super Cells	100 (6,400)	-30-40	3D, bulk
van den Heever et al. [2011]	TOGA COARE Tropical R-C Equilibrium	25 (375) 400-1,600	+2 -6	2D, bulk
Morrison and Grabowski [2011]	TWP-ICE	354, 2,780, 6,130	-0.4	2D, bulk
Fan et al. [2012a]	AMF-China	8600 (1600)	+18% for SBM -12% for Morrison	3D, bin, 251x201
Fan et al. [2012b]	AMF-China: weak and strong wind shear SGP: weak and strong wind shear	1700 (280)	Weak wind shear: +7% for AMF-China (warm cloud base) and +4% for SGP (cold cloud base) Stronger wind shear: +3% for AMF-China and -4% for SGP.	3D, bin
Fan et al. {2013}	Long-time (monthly) simulations at TWP, SGP and Southeast China	1700 (280)	+5 to +7% at TWP and SEC -2% at SGP (decrease and increase offset). Rain rate PDF changed significantly.	3D, bin, 300x300
Igel et al. [2013]	North American Extra-tropical Cyclone, (Warm Front Region)	800 (400)	+1.4	3D, bulk
		1600 (400)	+2.1	3D, bulk
Seigel et al. [2013]	Idealized Squall Line (Africa)	~30, 125, 175 (Vertical varied with Maximum value)	~ -20-30	3D, bulk
Storer and van den Heever [2013]	Tropical Deep Convection (TOGA COARE)	100 (900) 800 (2400)	-25 ~+10	2D, bulk
Grant and van den Heever [2014]	Idealized Sea Breeze Convection (Africa)	500 (200)	-15%	3D, bulk
		2000 (200)	-40%	3D, bulk
Lebo and Morrison [2014]	Idealized Squall Line	100 (900)	+20 Weak wind shear	3D, bulk
Kalina et al. [2014]	Idealized Super Thunderstorms	100 – 10,000 100 - 5,000	-50% (low RH) + <5 % (high RH) (Depends on moist/dry condition)	3D, bulk
Grant and van den Heever [2015]	Idealized Supercell (moist profile)	400 (100)	~ +10	3D, bulk
		1600 (100)	~ -5	~
	Idealized Supercell (low-level dry layer)	400 (100)	~ -2	~
		1600 (100)	~ -20	~
	Idealized Supercell (mid-level dry layer)	400 (100)	0	~
		1600 (100)	~ -20	~
	Idealized Multicell (moist profile)	400 (100)	~ -1	~
		1600 (100)	~ +1	~
	Idealized Multicell (low-level dry layer)	400 (100)	~ +20	~
		1600 (100)	~ +100	~
	Idealized Multicell (mid-level dry layer)	400 (100)	0	~
		1600 (100)	~ -15	~

Table 2: Numerical experiments performed in this study. "P" and "T" stand for the PRESTORM and TOGA COARE cases, respectively. "low" and "high" stand for low and high CCN concentration, respectively. "Warm" is for warm rain only, and "evap" indicates reduced evaporative cooling.

Case Name	Description	Domain mean rainfall (mm)
P-low	PRESTORM continental case clean/background CCN over land	58.4
P-high	10 times CCN concentration as P-low	40.7
P-low-warm	Same as P-low except for all ice microphysics are off	60.7
P-high-warm	Same as P-high except for all ice microphysics are off	61.8
P-low-evap	Same as P-low except for evaporation is turned off from the surface to 3km, between 1 and 3 hours	51.0
T-low	TOGA-COARE maritime case clean/background CCN over ocean	19.0
T-high	10 times CCN concentration as T-low	33.0
T-low-warm	Same as T-low except for all ice microphysics are off	18.0
T-high-warm	Same as T-high except for all ice microphysics are off	24.7
T-high-evap	Same as T-high except for evaporation is turned off from the surface to 4km, between 0 and 1.5 hours	26.4

List of Figures:
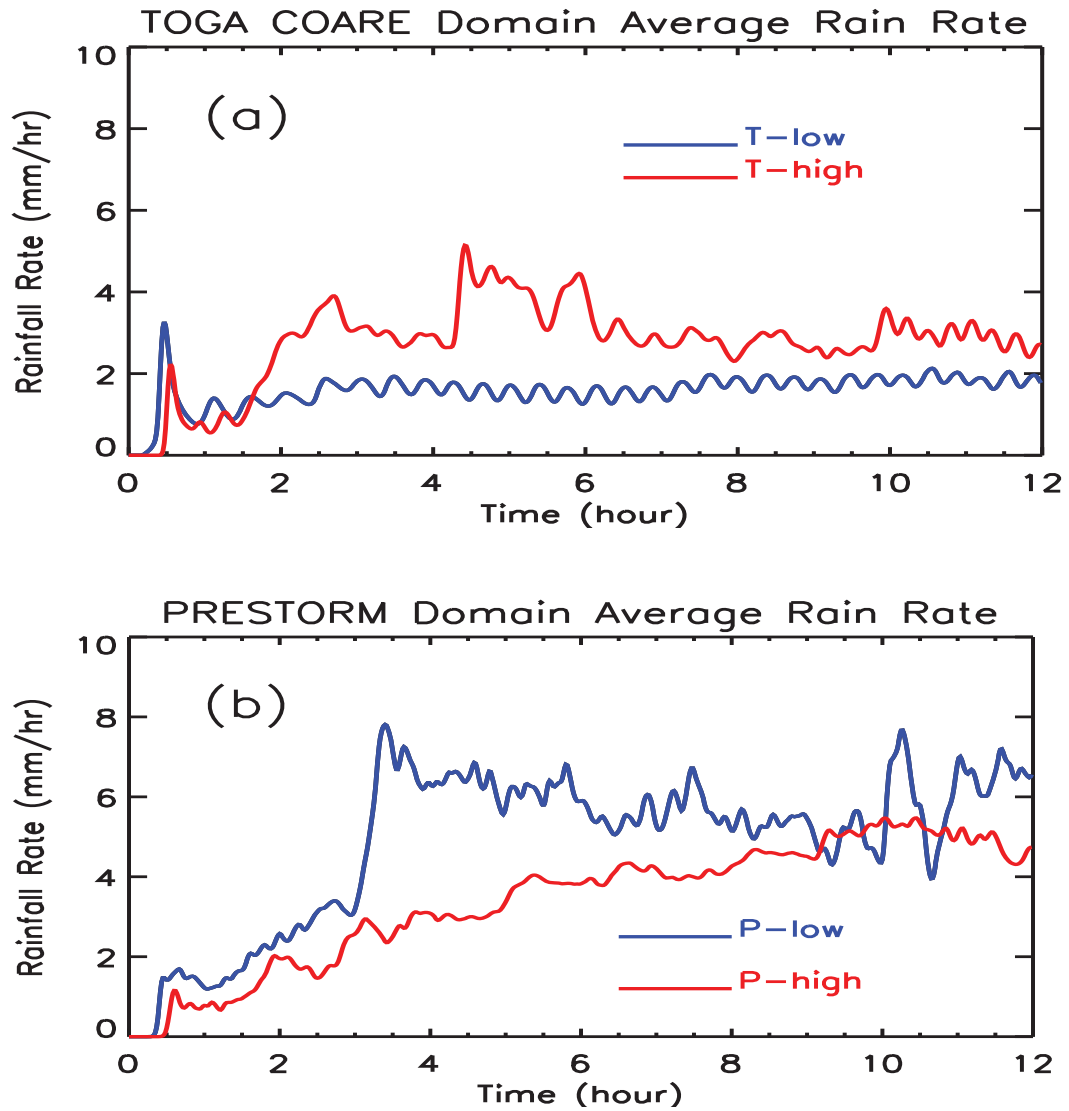
Figure 1: Time series of GCE model-simulated domain mean surface rainfall rate (mm h⁻¹) for the (a) TOGA COARE and (b) PRESTORM case. The blue and red lines represent the low CCN and high CCN scenario, respectively.
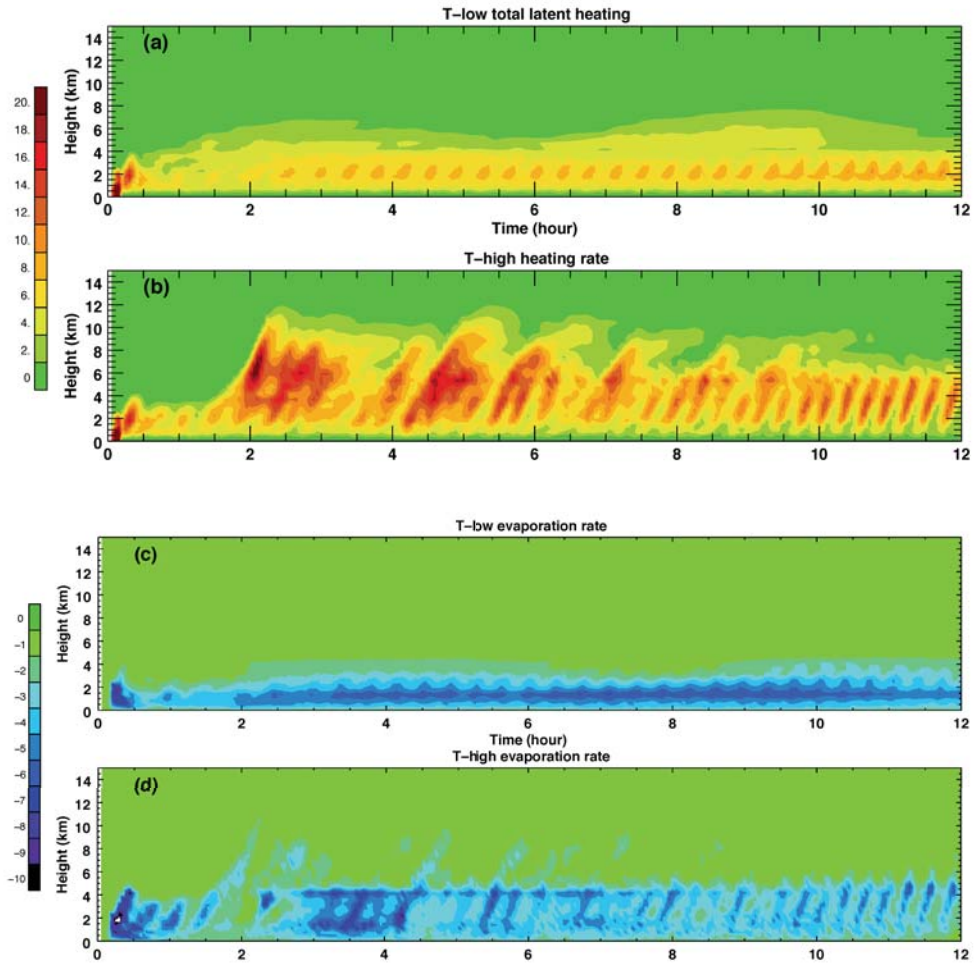
Figure 2: Time-height cross sections of model-simulated domain mean total heating (K h-1) for the TOGA COARE case for the (a) T-low and (b) T-high scenario. (c) and (d) are the same as (a) and (b) except for evaporative cooling (K h-1).
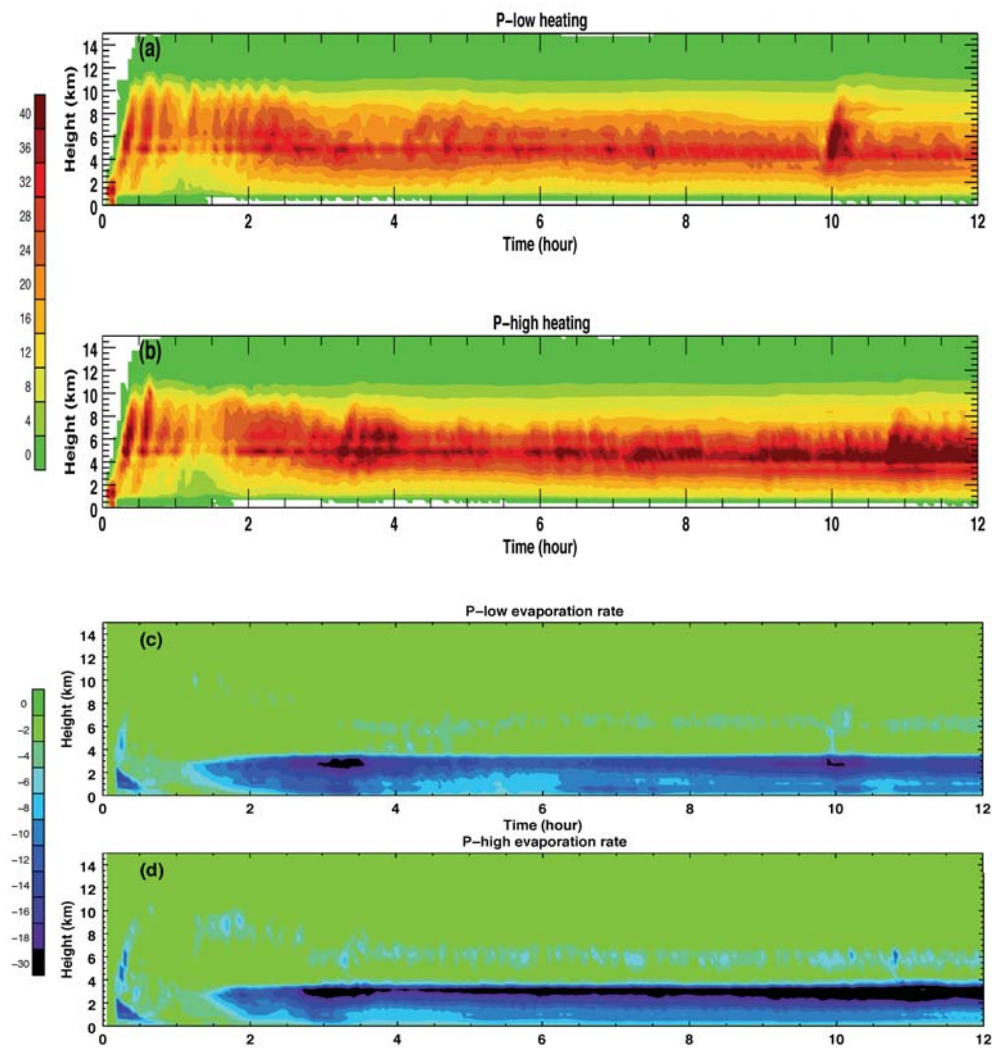
Figure 3: Time-height cross sections of model-simulated domain mean total heating (K h-1) for the PRESTORM case for (a) P-low (low CCN) and (b) P-high (high CCN) conditions. (c) and (d) are the same as (a) and (b) except for evaporative cooling (K h-1). Note the color bar scales are different from the TOGA COARE case in Figure 2.

Figure 4: Profiles of domain-average microphysical heating/cooling rates: (a) total heating between 0 and 60 minutes for the TOGA COARE experiments, (b) total evaporative cooling for the TOGA COARE experiments between 0 and 60 minutes, (c) total latent heating between 60 and 150 minutes for the PRESTORM experiments, and (d) total evaporative cooling for the PRESTORM experiments between 60 and 150 minutes. The solid and dashed lines represent the low and high CCN scenarios, respectively.

Figure 5: Near surface convergence and cold pool structures for the PRESTORM case. Near surface convergence (the average from the surface to z=3 km) for the P-low and P-high scenarios is plotted in 5(a) and 5(b), respectively. The thin black lines in 5(a) and 5(b) indicate 0.01 mm/hr of surface rainfall and the thick black lines 5 mm/hr of surface rainfall. The middle two panels are Hovmoller diagrams of near surface equivalent potential temperature perturbation (averaged from the surface to z=3 km) for the P-low 5(c) and P-high 5(d) scenarios. Vertical cross of instantaneous equivalent potential temperature perturbation at 3 hours are plotted in 5(e) for P-low and 5(f) for P-high. The black contour lines indicate vertical velocities of 1 m/s, orange contours 5 m/s, and red contours 10 m/s.

Figure 6: Same as Fig. 5 except for the TOGA-COARE case. (e) and (f) are the instantaneous equivalent potential temperature perturbations at 2 hours.

Figure 7: Same as Fig. 1 except for the warm rain only simulations.

Figure 8: Same as Fig. 2 except for the warm rain only simulation.

Figure 9: Same as Fig. 3 except for the warm rain only simulation.

Figure 10: Vertical cross sections of the (a) vertical pressure gradient force (PGF), (b) buoyancy effect due to latent heat release (LHR), (c) water vapor buoyancy force and (d) water loading effect for the P-low case at 3 hours. Note that there is a difference in scales.

Figure 11: Domain mean vertical profiles of PGF [solid lines in (a)] and the LHR effect [dashed lines in (a)] for the P-low (black) and P-high (red) scenario for the PRESTORM case at 3 hours. The net effect of the PGF and LH are shown in (b) (solid lines) together with the water loading term [dashed lines in (b)].

Figure 12: Time series of surface rainfall for the PRESTORM case. The solid blue line is for the P-low case; the red solid line is for the P-high case; and the blue dotted line is the sensitivity test P-low-evap where both cloud and rain evaporation term were turned off from the surface to 3km between 1 and 3 hours.

Figure 13: Time series of surface rainfall for the TOGA COARE case. The solid blue line is for the T-low case; the solid red line is for the T-high case; and the red dotted line is the sensitivity test T-high-evap where both cloud and rain evaporation term were turned off from surface to 4km, between 0 and 1.5 hours, for the T-high case.

Figure 14: Time-height cross sections of total latent heating for the TOGA COARE case for (a) T-low, (b) T-high, and (c) T-high-evap-0.5 case where the rain evaporation rate is reduced by 50% for the first 1.5 hours from 0 to 4km.

Figure 1: Time series of GCE model-simulated domain mean surface rainfall rate (mm h^{-1}) for the (a) TOGA COARE and (b) PRESTORM case. The blue and red lines represent the low CCN and high CCN scenario, respectively.

Figure 2: Time-height cross sections of model-simulated domain mean total heating (K h⁻¹) for the TOGA COARE case for the (a) T-low and (b) T-high scenario. (c) and (d) are the same as (a) and (b) except for evaporative cooling (K h⁻¹).

Figure 3: Time-height cross sections of model-simulated domain mean total heating (K h^{-1}) for the PRESTORM case for (a) P-low (low CCN) and (b) P-high (high CCN) conditions. (c) and (d) are the same as (a) and (b) except for evaporative cooling (K h^{-1}). Note the color bar scales are different from the TOGA COARE case in Figure 2.

Figure 4: Profiles of domain-average microphysical heating/cooling rates: (a) total heating between 0 and 60 minutes for the TOGA COARE experiments, (b) total evaporative cooling for the TOGA COARE experiments between 0 and 60 minutes, (c) total latent heating between 60 and 150 minutes for the PRESTORM experiments, and (d) total evaporative cooling for the PRESTORM experiments between 60 and 150 minutes. The solid and dashed lines represent the low and high CCN scenarios, respectively.

Figure 5: Near surface convergence and cold pool structures for the PRESTORM case. Near surface convergence (the average from the surface to z=3 km) for the P-low and P-high scenarios is plotted in 5(a) and 5(b), respectively. The thin black lines in 5(a) and 5(b) indicate 0.01 mm/hr of surface rainfall and the thick black lines 5 mm/hr of surface rainfall. The middle two panels are Hovmoller diagrams of near surface equivalent potential temperature perturbation (averaged from the surface to z=3 km) for the P-low 5(c) and P-high 5(d) scenarios. Vertical cross of instantaneous equivalent potential temperature perturbation at 3 hours are plotted in 5(e) for P-low and 5(f) for P-high. The black contour lines indicate vertical velocities of 1 m/s, orange contours 5 m/s, and red contours 10 m/s.

Figure 6: Same as Fig. 5 except for the TOGA-COARE case. (e) and (f) are the instantaneous equivalent potential temperature perturbations at 2 hours.

Figure 7: Same as Fig. 1 except for the warm rain only simulations.

Figure 8: Same as Fig. 2 except for the warm rain only simulation.

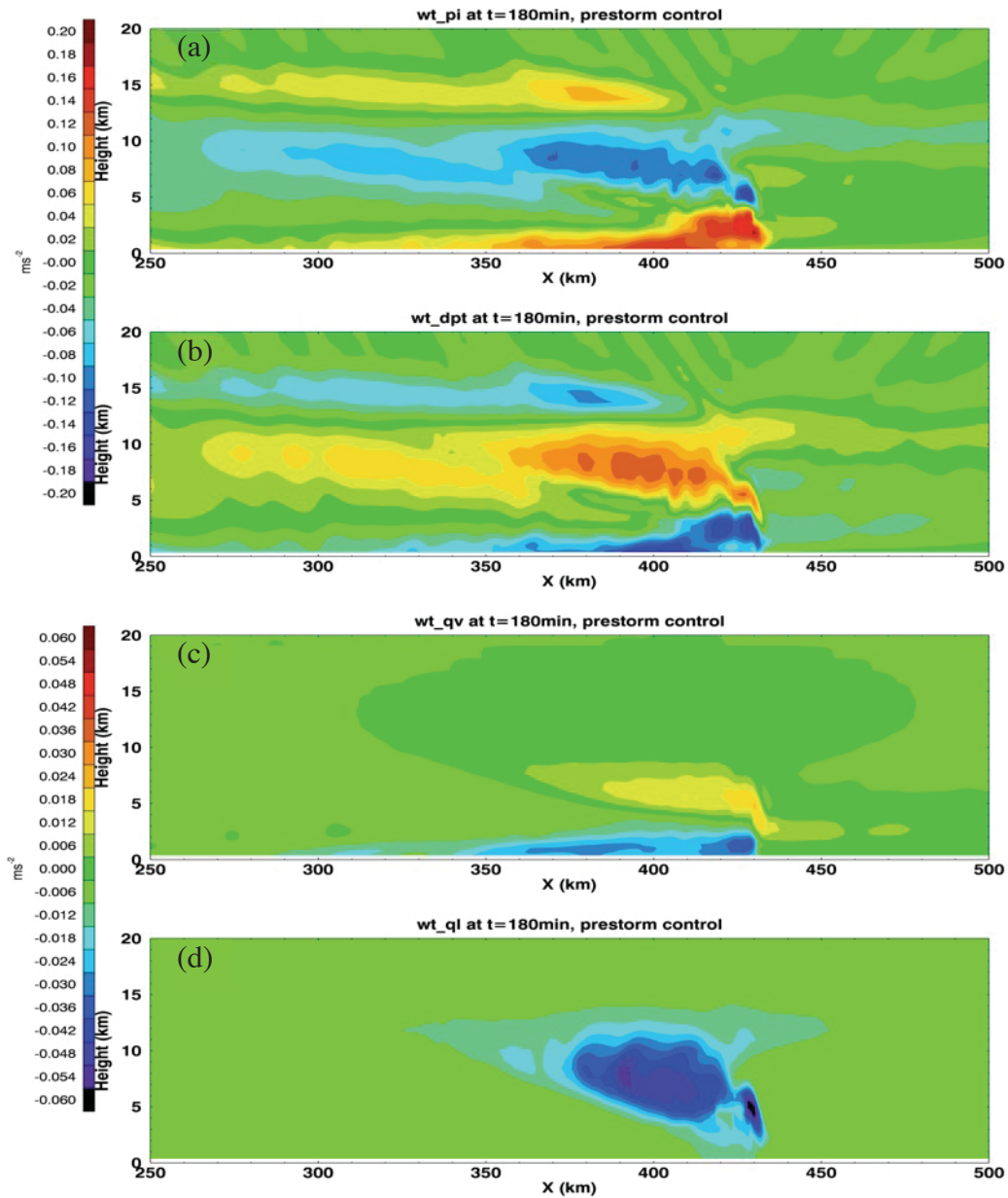Figure 9: Same as Fig. 3 except for the warm rain only simulation.

Figure 10: Vertical cross sections of the (a) vertical pressure gradient force (PGF), (b) buoyancy effect due to latent heat release (LHR), (c) water vapor buoyancy force and (d) water loading effect for the P-low case at 3 hours. Note that there is a difference in scales.

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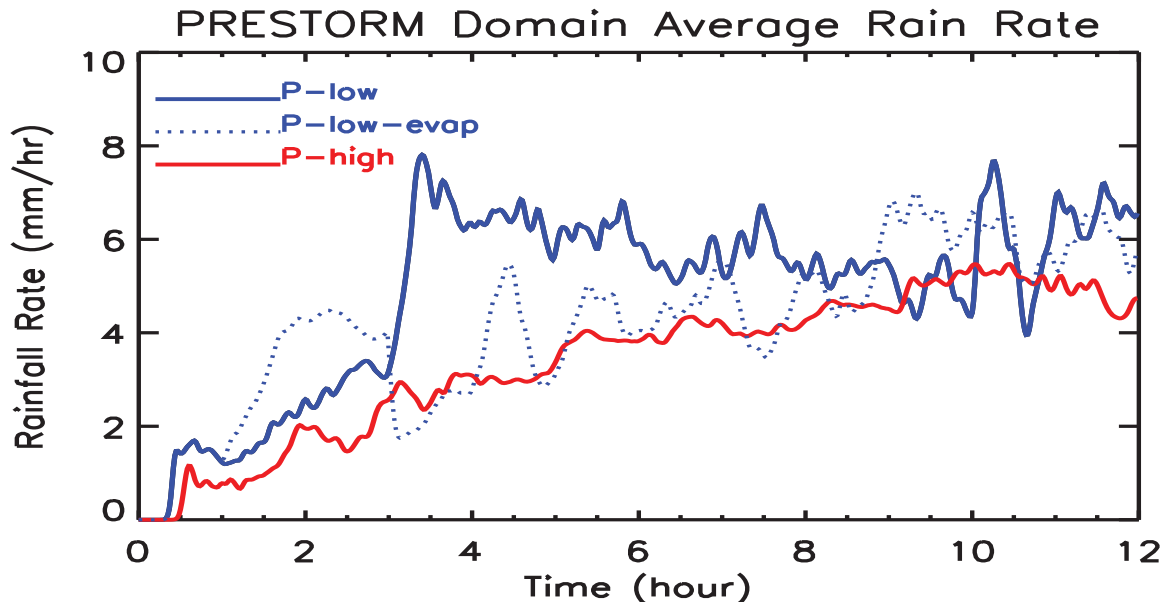
Figure 12: Time series of surface rainfall for the PRESTORM case. The solid blue line is for the P-low case; the red solid line is for the P-high case; and the blue dotted line is the sensitivity test P-low-evap where both cloud and rain evaporation term were turned off from the surface to 3km between 1 and 3 hours.
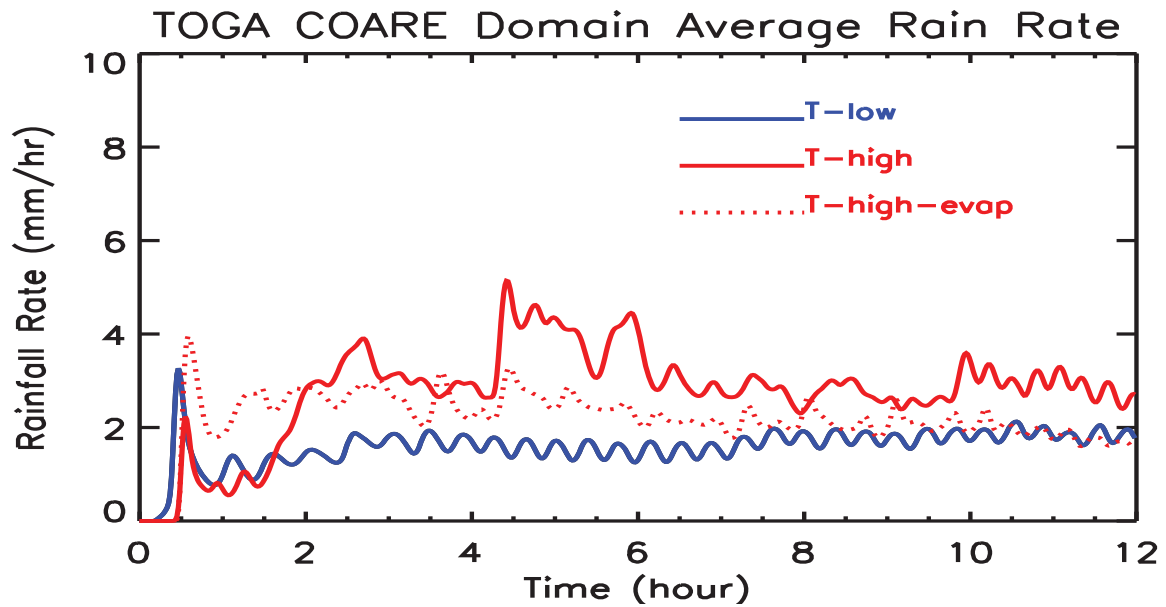
Figure 13: Time series of surface rainfall for the TOGA COARE case. The solid blue line is for the T-low case; the solid red line is for the T-high case; and the red dotted line is the sensitivity test T-high-evap where both cloud and rain evaporation term were turned off from surface to 4km, between 0 and 1.5 hours, for the T-high case.
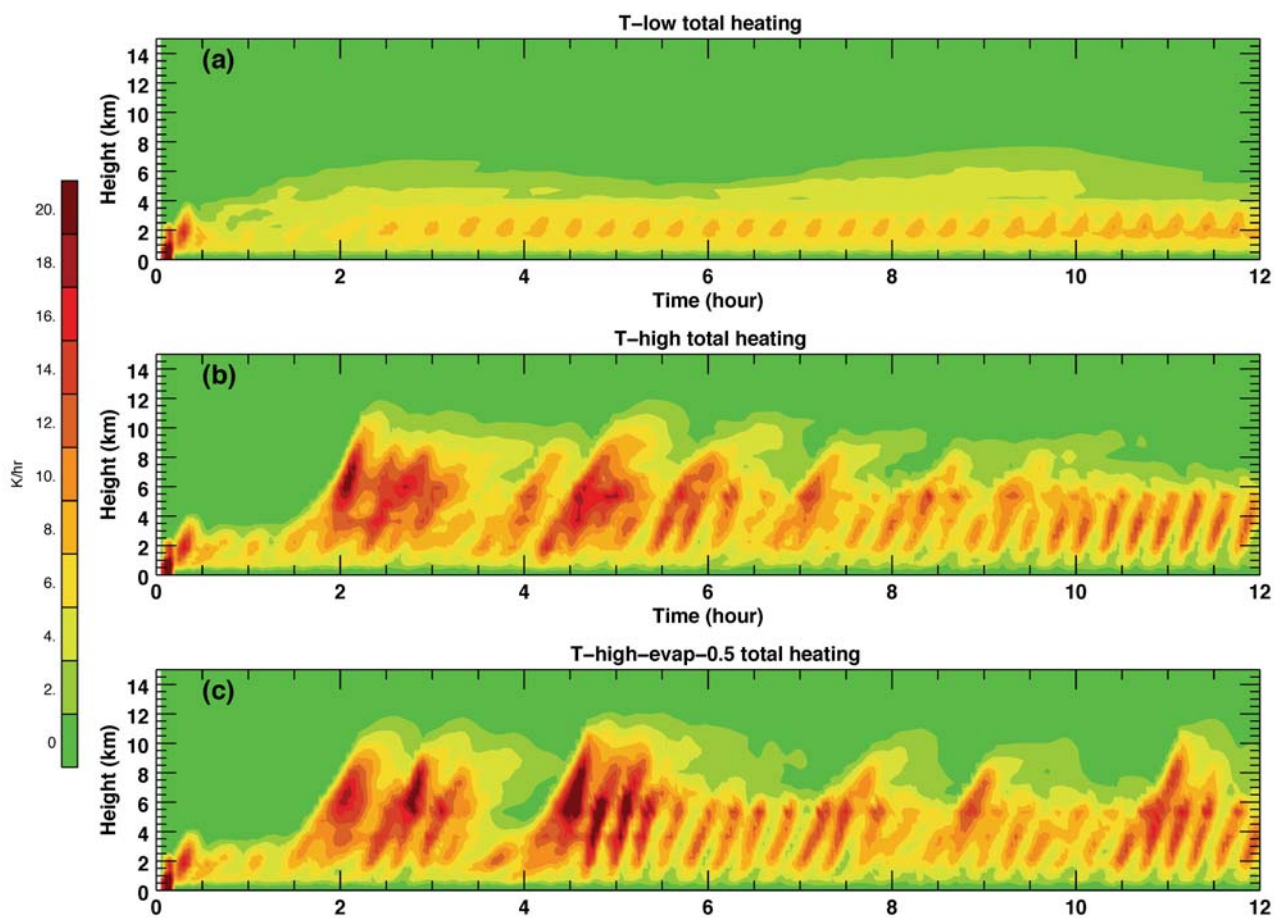
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