

Factorial method as a tool for estimating the relative contribution to precipitation of cloud microphysical processes and environmental conditions: Method and application

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[1] The factorial experiment method is presented as a tool for evaluating the sensitivity of precipitation to changes in atmospheric thermodynamic conditions and cloud microphysical characteristics in mixed phase convective clouds. As an example, the method is adopted here for analysis of the sensitivity of precipitation to changes in various parameters using simulations with the Tel Aviv University 2D (TAU 2D) cloud model. The cloud model was run in 80 scenarios in order to determine the relative sensitivity of precipitation in eastern Mediterranean winter mixed phase convective clouds to changes in cloud condensation nuclei (CCN) concentration, parameterization of ice formation mechanisms and initial atmospheric thermodynamic conditions. When these parameters act synergistically to suppress precipitation (by increasing the concentration of CCN and of small ice crystals and reducing the water vapor mixing ratio), for the cases simulated here, a decrease of about 2°C in the entire profile of the ambient temperature while keeping the relative humidity constant has the same contribution to precipitation suppression as an increase of about 400 cm⁻³ in the CCN concentration. It is shown that under the warmest and most humid atmospheric thermodynamic conditions simulated here, the suppression of precipitation is affected more by the increased CCN than by the ice generation processes, whereas in colder atmospheric conditions the reverse is true. For a given atmospheric sounding the time of rain initiation strongly depends on the CCN concentrations. The role of ice generation begins to affect precipitation at a later stage when the cloud is more mature.

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1. Introduction

[2] The recent IPCC reports [*Intergovernmental Panel on Climate Change*, 2001, 2007] have pointed out that the greatest uncertainty to global climate forcing is the indirect effects of aerosols on clouds. Furthermore, the WMO and the IUGG identified the effects of pollution aerosols on precipitation as an important and yet not clearly understood process that could have major implications to climate and water supplies [*Levin and Cotton*, 2007].

[3] One basic and unresolved problem in trying to understand the issue of aerosol-cloud interaction is to quantify the sensitivity of precipitation to variability in the aerosol properties as compared to its sensitivity to different atmospheric thermodynamic conditions.

[4] Many studies in cloud physics deal primarily with the effects of aerosols on clouds by conducting sets of simu-

lations for only one or a few types of atmospheric thermodynamic profiles without quantitatively discussing the sensitivity of the results to the modifications in the atmospheric thermodynamic conditions [*Phillips et al.*, 2002; *Yin et al.*, 2005; *Khain et al.*, 2005; *Teller and Levin*, 2006; *van den Heever et al.*, 2006; *Tao et al.*, 2007]. Only very few studies in cloud physics tried to quantify the response of the ground precipitation to variations in various microphysical parameters (such as concentration and size distribution of aerosol particles) as compared to the response of precipitation to changes in atmospheric properties such as temperature profile or water vapor mixing ratio.

[5] It is obvious that variations in one or a few of the above parameters will cause a change in rainfall from the cloud, however, it is not clear what would be the response of the ground precipitation to changes in these variables if they occur synergistically.

[6] The formation of precipitation in clouds is strongly affected by the properties of the aerosol population. *Seifert and Beheng* [2006] investigated these effects under different dynamical conditions. They concluded that the effect of cloud condensation nuclei (CCN) can be very different for different clouds and/or environmental conditions. They

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found that increasing CCN number concentration in small convective storms leads to a decrease in precipitation and in maximum value of the updraft velocity. For multicell cloud systems the effect of increased CCN concentration seems to lead to more intense secondary convection, more total precipitation and stronger updraft velocities. Supercell storms are least sensitive to CCN characteristics and concentrations. *Seifert and Beheng* [2006] did not show how the contributions of the various factors to the development of precipitation change with time.

[7] Recently, *Tao et al.* [2007] used 2D Cloud-Resolving Model (CRM) with detailed spectral bin microphysics to examine the effect of aerosols on three different deep convective cloud systems that developed in different geographic locations. They showed that rain was suppressed because of increased aerosol loading in all the atmospheric thermodynamic conditions only early in the simulation in agreement with other studies *van den Heever et al.* [2006] and *van den Heever and Cotton* [2007]. In all these studies the strengths of the cold pools produced by evaporation of raindrops determines whether high CCN reduces or enhances the total precipitation.

[8] In addition to the effect of CCN on precipitation, a number of studies dealt with the role of the ice processes in mixed phase convective clouds and their effects on precipitation. *Teller and Levin* [2006] used the TAU 2D cloud model to study the effect of different initial aerosol size distributions and ice forming mechanisms (ice nucleation) on total precipitation from single mixed phase convective cloud, typical for winter eastern Mediterranean conditions. They concluded that high concentrations of ice nuclei (IN) reduce precipitation amounts. In clean clouds, where CCN concentrations are low and where total precipitation is high, an increase in the concentration of IN tends to decrease the total precipitation, but the magnitude of this suppression is smaller than the suppression effects caused by polluting the cloud with high concentration of CCN. On the other hand, in the heavily polluted cloud the effect of increasing IN on precipitation was negligible. In the study of *Teller and Levin* [2006] no conclusions could be reached about the relative contribution of precipitation to simultaneous changes in the atmospheric thermodynamic conditions and aerosols characteristics.

[9] One of the methods that have been considered as suitable for the quantification and comparison of the relative contributions of aerosol to precipitation variability as compare to those of other atmospheric parameters is the factor separation (FS) method [*Stein and Alpert*, 1993]. For the purpose of explaining the method in a simple manner a factor was defined as a controlled independent parameter whose values are set by the experimenter such as initial CCN concentration or initial atmospheric relative humidity. Using FS one can isolate the contributions of the individual factors from the contributions of their interactions. It can also help to determine which of these factors has the strongest effect on different systems' properties such as precipitation from convective clouds.

[10] An example of the use of FS method using a numerical cloud model with bulk water microphysics is provided by *Reuter and Guan* [1995] and *Guan and Reuter* [1996]. They investigated the effect of sensible heat flux, water vapor and CCN emitted from oil refineries on cloud

development in two atmospheric thermodynamic regimes (typical for midlatitude and tropical environments). For the tested environments and for cases of industrial activity, they concluded that the sensible heat is the major factor affecting rainfall compared to the effects of vapor and CCN release.

[11] *van den Heever et al.* [2006] used the FS method to study the effect of dust originating from the Sahara on convective clouds in Florida. They showed that high CCN concentration due to dust reduces surface precipitation while the elevated concentrations of GCCN and IN enhances total surface rainfall at the beginning of the simulation. At the end of the simulation, total surface precipitation was largest in the clean case, where no additional CCN, GCCN or IN were introduced.

[12] One disadvantage of the FS method is that the relative contribution to the variability by any factor (for example, the contribution of CCN concentration to precipitation) cannot be determined and compared to the contributions of other factors (such as ice development).

[13] To overcome this difficulty, a different statistical tool is proposed; the 2^k factorial experiment (from here on it will be named the factorial method, FM). This tool is commonly used in many scientific fields, including numerical simulations, to evaluate the relative contribution of the entire set of possible interactions between the parameters as compared to the contribution of each parameter separately.

[14] This paper describes the FM and provides an example with a quantitative analysis of the relative sensitivity of surface precipitation to changes in the formation of ice, initial CCN concentrations and initial atmospheric soundings in mixed phase convective clouds.

[15] In order to carry out this type of evaluation, this study uses the same tools and framework used in the recent publications by *Yin et al.* [2002], *Levin et al.* [2005] and *Teller and Levin* [2006] but instead of using one set of atmospheric sounding and one or two sets of controlled parameters for the microphysical processes, the analysis consists of a large number of simulation runs.

2. Methods

2.1. Statistical Analysis of Factorial Experiment

[16] The experimental setup in this study is based on the unreplicated 2^k factorial design of experiments discussed in many statistical textbooks. Here we will use the method and the notation of *Montgomery* [2005].

[17] In this paper the relative contributions of single and multifactors to changes in surface precipitation from a single cloud were tested. The factors chosen for this study include the initial atmospheric sounding (affecting the bulk physical properties of the cloud, e.g., liquid water content, vertical velocity and cloud top height), initial CCN concentration and two ice forming processes; ice nucleation by deposition/condensation freezing and immersion freezing.

[18] The relative contributions of the two ice forming processes to the formation of rain vary during the lifetime of the cloud. Therefore their direct effect on precipitation and the indirect effects due to interactions between ice and cloud drops are rather complicated. For simplicity the contributions of the ice forming processes are lumped in some of the analyses into one single parameter named "ice." Another set of tests uses the FM to compare the relative contribution

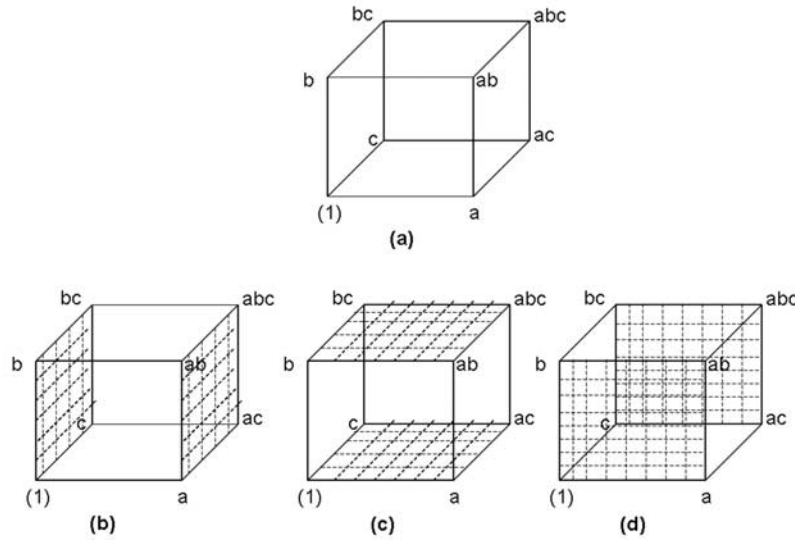


Figure 1. Graphical illustration of an experimental setup containing three factors with two values each (a 2^3 experimental design). (a) The eight experiments are placed at the corners of a cube where each dimension represents a single main effect (A, B, C). (b) The shaded faces represent the high and low values of factor A. (c) The shaded faces represent the high and low levels of factor B. (d) The shaded faces represent the high and low levels of factor C.

of the atmospheric thermodynamic conditions to that of the initial CCN concentration without considering any change in the ice forming processes.

[19] In this study it is assumed that the response of the surface precipitation to the different factors is a monotonic function containing no singular points. Under this assumption it is sufficient to test each factor with only two values. However, since some of the parameters have strong effects on precipitation four values were used to represent variations in the initial CCN concentration (from clean to extremely pollute conditions) and five values were used to represent the atmospheric sounding.

[20] The method of calculation will be illustrated for a case in which the sensitivity of precipitation to only three parameters (e.g., CCN concentration, atmospheric thermodynamic profile, and one of the ice forming processes) is evaluated. The factors are denoted by A, B and C, respectively. It is also assumed that each of these factors can be set to only two different values (high and low) where the high value denotes a condition in which precipitation is expected to be suppressed. For example, one can set the following cases for factor A: low initial CCN concentration (here set to 225 cm^{-3} , clean environment, low value) or high CCN (1530 cm^{-3} , high value, polluted environment).

[21] Each run of the simulation is labeled according to the value of the factors used such that a high value of any factor A, B or C is denoted by a lowercase letter a, b, c and the low value of each factor is denoted by the absence of the corresponding letter. Therefore in this example we have 8 simulation runs labeled by (1), a, b, c, ab, ac, bc and abc (the label (1) represents a reference, i.e., a run where all factors are set to their lower values).

[22] Figure 1 shows a graphical illustration of the experimental design with three factors where the eight experi-

ments can be presented on a cube with each experiment occupying one of the corners.

[23] In Figures 1b–1d, two faces are marked showing the effects of the factors A, B and C. The term “effect” (or “main effect” as defined by *Montgomery* [2005]) shows the average sensitivity of the result to a change in one factor and it is calculated by subtracting the average of the results when the factor is set to its low value from the average of the results when the factor is set to its high value. The “interaction” effect is the contribution of the combined changes by more than one factor within the experimental design. The two shaded faces illustrate the two values of each factor. For example one face in Figure 1b shows the cases where A is set to its high value (cases a, ac, ab and abc) and the other face shows the cases where A is set to its low value (cases (1), b, c, and bc).

[24] The difference between the averages of the simulations with A set high and low is calculated by:

$$\text{Eff}_A = \frac{1}{4} \cdot (a + ab + ac + abc) - \frac{1}{4} \cdot (b + c + bc + (1)) \quad (1)$$

[25] Similarly, the difference between the averages of the factors B and C are calculated by:

$$\text{Eff}_B = \frac{1}{4} \cdot (b + ab + bc + abc) - \frac{1}{4} \cdot (a + c + ac + (1)) \quad (2)$$

$$\text{Eff}_C = \frac{1}{4} \cdot (c + ac + bc + abc) - \frac{1}{4} \cdot (a + b + ab + (1)) \quad (3)$$

[26] The effect of the interactions between two factors is defined as half of the difference between the average effects

Table 1. Summary of Initial Conditions Used for the Cloud Simulations^a

Factor	Values	Symbol
Sounding	$T_{\text{ground}} = 19^{\circ}\text{C}$, $T_{\text{ground}} = 18^{\circ}\text{C}$, $T_{\text{ground}} = 17^{\circ}\text{C}$, $T_{\text{ground}} = 16^{\circ}\text{C}$, $T_{\text{ground}} = 15^{\circ}\text{C}$	Tg
Initial CCN concentration on the ground, cm^{-3}	225, 600, 900, 1530	CCN
Ice formation by deposition/condensation-freezing	off (0), on (1)	DP
Ice formation by immersion freezing	off (0), on (1)	IM

^aValues for each parameter and their corresponding labels are marked in bold letters and numbers.

of one factor when the second one is set to its high value to the average effects of the second factor when the first is set to its lower value.

[27] For example, the effect of the interaction AB in the above design is calculated by:

$$\text{Eff}_{A(B=\text{high})} = \frac{1}{2} \cdot (abc - bc) + \frac{1}{2} \cdot (ab - b) \quad (4)$$

$$\text{Eff}_{A(B=\text{low})} = \frac{1}{2} \cdot (ac - c) - \frac{1}{2} \cdot (a - (1)) \quad (5)$$

$$\begin{aligned} \text{Eff}_{AB} &= \frac{1}{2} (\text{Eff}_{A(B=\text{high})} - \text{Eff}_{A(B=\text{low})}) \\ &= \frac{1}{4} [abc + ab - bc - b - (ac + a - c - (1))] \\ &= \frac{1}{4} (abc + ab + c + (1) - bc - b - ac - a) \quad (6) \end{aligned}$$

[28] The effect of the interaction AB can be seen as the difference between two diagonal planes in the cube of Figure 1.

[29] To evaluate the relative contribution of each effect to the total variability (which is the most significant advantage of the FM), one needs to calculate the sum of squares of each effect and compare it to the total sum of squares (i.e., the total variance of the data).

[30] The sum of squares of the effect A is calculated by:

$$SS_A = \frac{1}{2^3} \cdot (a + ab + ac + abc - b - c - bc - (1))^2 \quad (7)$$

[31] The calculations of the sum of squares of the effects B, C and the interactions between the effects are performed in the same way.

[32] For the general case where more than three factors are evaluated the reader is referred to *Montgomery* [2005].

2.2. TAU-2D Cloud Model

[33] The TAU-2D slab symmetric single cloud model contains detailed treatment of the cloud microphysics [*Yin et al.*, 2000] and uses the Spectral Method of Moments [*Tzivion et al.*, 1987; *Reisin et al.*, 1998] for calculating the growth of water drops and ice particles by various processes such as nucleation of water and ice, condensation, collection, riming, melting, drop breakup and sedimentation. The

cloud is initiated with a short pulse of temperature and humidity just below cloud base. For the present study we used 300 m height and 300 m lateral resolutions and a 2 s time step. The grid size was 101×41 points corresponding to a domain of 12 km height versus 30 km width.

[34] In the model, drops are nucleated on the basis of 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.

[35] As the cloud develops vertically, reaching subfreezing temperatures, ice crystals begin to form by freezing of cloud drops containing efficient IN. Ice nucleation is accounted for 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. It should be noted that recent measurements [e.g., *Gultepe et al.*, 2001; *Korolev et al.*, 2003; *Field et al.*, 2005] show that the parameterization of *Meyers et al.* [1992] overestimates the rate of ice formation. 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 on the basis of 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 shear. Further details on the model and its components are discussed by *Yin et al.* [2000], *Yin et al.* [2002] and *Teller and Levin* [2006].

2.3. Initial Conditions and Experimental Setup

[36] A total of 80 runs were carried out in the present work. The studied factors were the atmospheric soundings (vertical temperature and humidity profiles), initial CCN concentrations and two ice formation mechanisms: (1) deposition/condensation-freezing which are parameterized according to *Meyers et al.* [1992] and (2) immersion freezing which is parameterized according to *Bigg* [1953]. On the basis of previous studies it was assumed that the sensitivity of precipitation to other processes such as contact nucleation and ice multiplication is weaker [*Yin et al.*, 2002]; therefore these processes were kept unchanged and were not included in the present experimental setup as parameters to be analyzed. Table 1 shows the values used for each of these parameters and their corresponding labels (marked in bold letters).

[37] Each run was labeled following the appropriate symbols in Table 1, For example in the simulation labeled Tg19_225_DP1_IM1, the ground temperature is 19°C , initial CCN concentration is 225 cm^{-3} , DP1 and IM1 means that ice formation by deposition/condensation freezing and by immersion freezing are included, respectively.

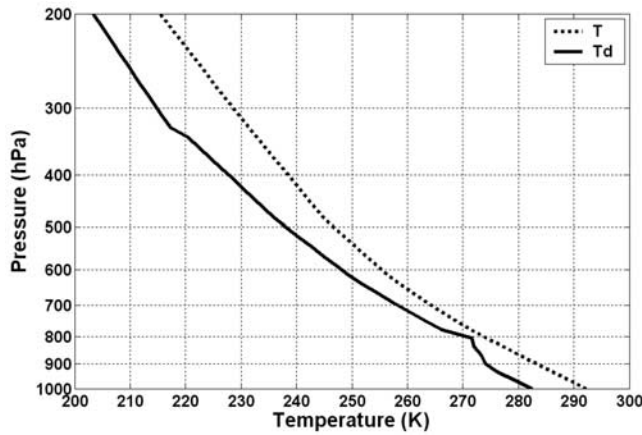


Figure 2. Profile of initial thermodynamic conditions ($T_{\text{ground}} = 19^{\circ}\text{C}$). The other profiles ($T_{\text{ground}} = 18^{\circ}\text{C}$, 17°C , 16°C and 15°C) were set by linear shifting of the entire curve.

2.3.1. Experimental Setup of Atmospheric Thermodynamic Conditions

[38] The initial thermodynamic profile (presented in Figure 2) was taken from *Levin et al.* [2005] and *Teller and Levin* [2006] and represents somewhat typical winter-like conditions in the eastern Mediterranean with ground temperature 19°C . It is a theoretical profile that enables the development of a mixed phase convective cloud.

[39] The sensitivity of the precipitation to a change in the atmospheric thermodynamic conditions was tested by shifting the entire thermodynamic sounding to colder temperatures (without changing the relative humidity). These modifications reduce the water vapor mixing ratio in the atmosphere and they caused suppression of the maximum liquid water content in the cloud and the total precipitation from the cloud. The profiles were labeled according to the ground temperatures tested ($T_g = 19^{\circ}\text{C}$, $T_g = 18^{\circ}\text{C}$, $T_g = 17^{\circ}\text{C}$, $T_g = 16^{\circ}\text{C}$ and $T_g = 15^{\circ}\text{C}$). A decrease of 2°C in the temperature profile while keeping the relative humidity constant leads to a decrease of about 0.4 g kg^{-1} in the maximum liquid water content (LWC) produced in the cloud. For the soundings tested (e.g., $T_g = 19^{\circ}\text{C}$, $T_g = 17^{\circ}\text{C}$ and $T_g = 15^{\circ}\text{C}$) the maximum LWC (taken from the entire set of simulations of each sounding) were 3.71 , 3.31 and 2.88 g kg^{-1} , respectively.

[40] In order to initiate the cloud, a temperature perturbation of 2°C is applied at the ground for one time step at $t = 0$, in the middle of the domain.

2.3.2. Experimental Setup of Initial Aerosol Properties

[41] The initial conditions of the CCN vertical size distribution profiles and their chemical compositions for the Mediterranean clouds were set according to the airborne physical and chemical measurements reported by *Levin et al.* [2005]. These measurements correspond to typical aerosol size distribution profiles for the Mediterranean region during winter dust storms. Since most of the small particles contained sulfate, it is assumed here that all aerosols up to $0.5 \mu\text{m}$ are CCN. In the present study the effect of large and giant CCN (GCCN) on precipitation was

not evaluated; therefore aerosols larger than $0.5 \mu\text{m}$ in diameter were not included.

[42] The simulations were run with initial surface CCN concentrations that varied between 225 cm^{-3} (“clean cloud”), 600 , 900 and 1530 cm^{-3} (“polluted cloud”). The use of CCN concentrations refers to the number of CCN active at 1% supersaturation. The shape of the size distribution profile was identical in all the cases and the initial aerosol concentrations remained constant from the surface to 1 km and then decreased exponentially with height with a decay factor of 2000 m (the concentrations decreased to $1/e$ of their values in 2000 m).

2.3.3. Experimental Setup of Ice Forming Processes

[43] Ice forming processes by deposition, condensation freezing and contact nucleation are parameterized on the basis of *Meyers et al.* [1992] in which the concentration of ice crystals per liter nucleated at a certain temperature and supersaturation with respect to ice is:

$$N_{ik} = \exp\{-0.639 + 0.1296 \cdot [100 \cdot (S_i - 1)]\} + \exp[-2.8 + 0.262(T_0 - T)] \quad (8)$$

where k is the bin number of the initial size of the nucleated ice crystal (assumed to be $5 \mu\text{m}$ in diameter), $(S_i - 1)$ is the supersaturation above ice, $T_0 = 273.15 \text{ K}$ and T is the temperature (in K).

[44] The first term accounts for the nucleation by deposition and condensation freezing. The second term represents the number of ice crystals produced by contact nucleation due to thermophoresis, diffusiophoresis, and Brownian motion, formulated according to *Cotton et al.* [1986].

[45] In regard to the deposition and condensation-freezing processes, the runs were divided into two sets of simulations: (1) simulations where *Meyers et al.* [1992] parameterization were used and (2) simulations in which deposition and condensation-freezing processes were eliminated.

[46] *Yin et al.* [2002] showed that the maximum rate of ice formation via the contact nucleation mechanism as parameterized by *Meyers et al.* [1992] is very low (below $0.02 \text{ m}^{-3} \text{ s}^{-1}$); therefore the experimental design in the present study did not contain analysis of the sensitivity of precipitation to this process.

[47] The immersion freezing of drops was formulated on the basis of the measurements by *Bigg* [1953]. In order to evaluate the relative contribution of immersion freezing to precipitation, simulations were performed with and without this process.

[48] The data from each run was recorded every 2 min. The runs were stopped after 90 min to allow precipitation to terminate.

3. Results

3.1. Total Precipitation

[49] The total precipitation from the entire set of simulations is summarized in Table 2.

[50] Figure 3 shows the accumulated precipitation as a function of time for ground temperatures of 19°C , 17°C , and 15°C with different initial CCN concentrations (Figures 3a, 3b, and 3c, respectively). The two other profiles (18°C and

Table 2. Total Precipitation on the Ground in the Entire Set of Simulations^a

	Tg19	Tg18	Tg17	Tg16	Tg15
225_DP1_IM1	30732.69	24319.83	19119.2	15011.89	11633.54
600_DP1_IM1	17552.09	10644.13	6794.83	4328.37	3033.7
900_DP1_IM1	8425.15	4044.99	2756.11	2511.58	2468.15
1530_DP1_IM1	1798.62	1851.96	1949.98	2024.05	2066.76
225_DP0_IM1	31806.44	26326.14	20771.28	16474.52	12709.86
600_DP0_IM1	17739.56	12364.33	8101.56	4895.8	2982.18
900_DP0_IM1	8161.29	4609.46	2570.98	1720.05	1397.34
1530_DP0_IM1	1194.71	985.67	1133.56	1293.2	1242.09
225_DP1_IM0	45724.77	39075.64	33730.47	28774.06	24105.74
600_DP1_IM0	31898.85	22443.79	17087.22	12735.92	9247.61
900_DP1_IM0	20626.41	12236.63	8403.15	5912.05	4439.71
1530_DP1_IM0	6194.52	3151.48	2764.55	3011.62	3022.64
225_DP0_IM0	67907.28	62425.37	56493.58	50685.68	45359.82
600_DP0_IM0	60335.74	53072.8	46328.81	40096.06	34354.76
900_DP0_IM0	51644.75	44611.22	38071.59	32079.76	26714.05
1530_DP0_IM0	36154.66	30054.91	24403.83	19469.14	15362.65

^aSee text for further explanation on the labeling of the runs. Bold indicates cases analyzed in Table 5.

16°C) produced similar shapes and were not included in Figure 3. It should be noted that in the present example, because of the limitation of the TAU-2D model the calculation of the accumulated precipitation does not contain precipitation from secondary clouds that could develop as a result of evaporative cooling from the main cloud.

[51] Figure 3 relates to simulations in which all the ice forming processes were included and are marked as DP1_IM1, rows 1–4 in Table 2. The model is two-dimensional; therefore the total precipitation was calculated assuming that the cloud has a horizontal thickness of one kilometer.

[52] It is apparent from Figure 3 that enhanced initial CCN concentrations reduce precipitation in each of the investigated atmospheric soundings. Figure 3 shows that the times for the initiation of rain and the times to reach

maximum precipitation rate are positively correlated to the CCN concentrations. In the clean cloud rain started around 30 min into the simulation and lasted for over 30 min. Initially the rain intensity was low ($<0.1 \text{ mm h}^{-1}$) reaching high value ($>10 \text{ mm h}^{-1}$) around 40 min. In the polluted case, rain started later and the accumulated amounts remained low until about 48 min. Total accumulated precipitation in this case was low and lasted about 40 min. Under the same environmental conditions, clouds formed in a cleaner environment produce lower droplet concentrations, thus forming larger drops that efficiently grow to precipitation by collision-coalescence. Furthermore, the larger drops formed in the cleaner clouds freeze more readily to form graupel particles, which contribute significantly to the total precipitation.

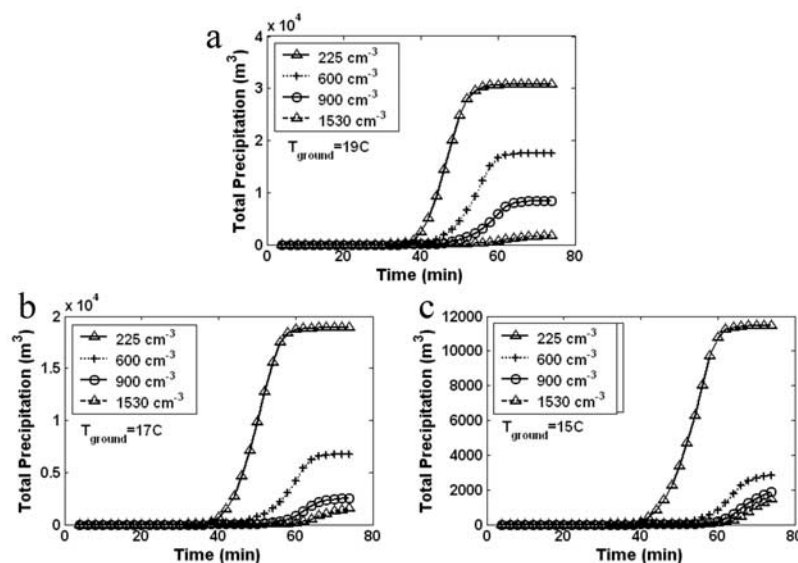


Figure 3. Total accumulated ground precipitation as a function of time for simulations with *Meyers et al.* [1992] and *Bigg* [1953] ice forming formulations. (a) Simulations with $T_g = 19^\circ\text{C}$, (b) $T_g = 17^\circ\text{C}$ and (c) $T_g = 15^\circ\text{C}$. These results correspond to the cases in rows 1–4 in Table 2.

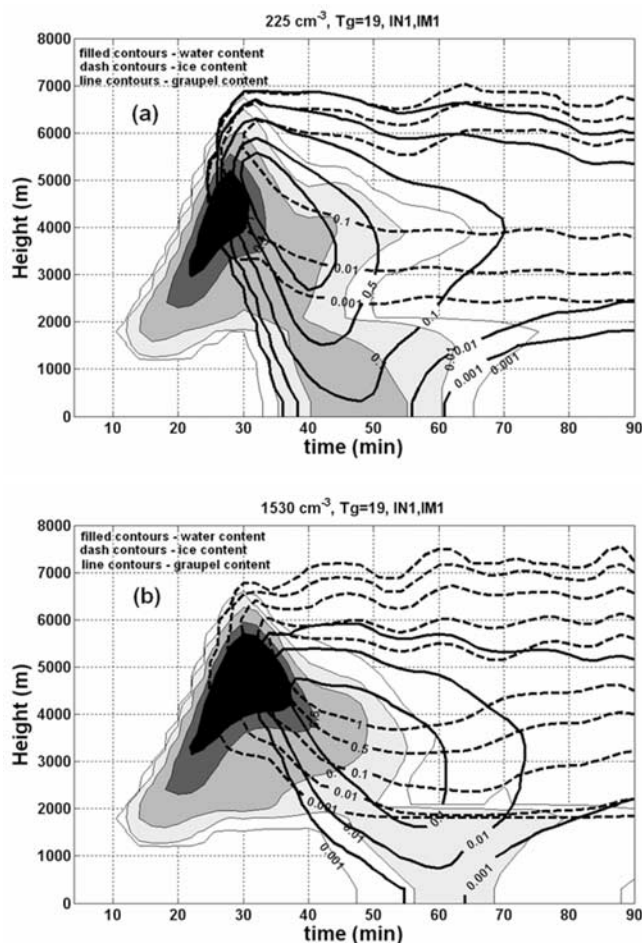


Figure 4. Horizontal averaged liquid water content (LWC), graupel content and ice crystals content (in g m^{-3}) as a function of time and height in the (a) clean (225 cm^{-3}) and (b) polluted (1530 cm^{-3}) clouds for simulations with Meyers *et al.* [1992] and Bigg [1953] ice forming formulations and $T_g = 19^\circ\text{C}$.

[53] Figure 4 shows for the case with $T_g = 19^\circ\text{C}$ the average liquid water content (LWC), graupel content and ice crystals (in g m^{-3}) as a function of time and height in the clean and polluted clouds; 225 and 1530 cm^{-3} , respectively. It shows that in the clean cloud (Figure 4a) at a height of 4000 to 5500 m the LWC and the graupel content are about equal; 1 g m^{-3} . Later on graupel particles descend and slowly melt. Below 2000 m ($\sim 0^\circ\text{C}$) a large fraction of the graupel particles melt, thus contributing to the rainfall on the ground. The graupel particles contribute about 65% of the total accumulated precipitable content. At lower altitudes the LWC increases because of the melting of the graupel particles.

[54] Figure 4b shows that the graupel content reaches a lower maximum value and at a later stage as compared to the clean case. The graupel particles begin to melt after falling below about 2000 m but their contribution to the total precipitation is only about 30%. As was pointed out by Teller and Levin [2006] the content of ice crystals in the

polluted case is much greater with a large fraction of the ice crystals remaining aloft.

[55] Figure 5 shows the total accumulated precipitation on the ground as a function of the initial CCN concentration for the cases shown in Figure 3 including the two profiles 18°C and 16°C . Figure 5 shows again the suppression effects of colder atmospheric thermodynamic condition and increased CCN on precipitation.

[56] The simulation runs shown in Figures 3 and 5 relate to the cases in which ice forming processes were not modified, namely, their representation was similar to previous studies [Levin *et al.*, 2005; Teller and Levin, 2006]. Evaluating the effects of modifying the ice forming processes, as discussed above, increased the number of simulations from 20 to 80 runs as shown in Table 2.

3.2. Relative Contribution of Atmospheric Sounding and Cloud Microphysics to Precipitation

[57] In this section the experimental set up presented in section 2 is used to calculate the relative contribution of the controlled factors and their interactions to the suppression of total precipitation. It is demonstrated how the factorial method can be used to quantify the relative importance of the different factors. Here, three examples for the use of the method are given: (1) An analysis of the relative contribution of CCN, ice forming processes and the atmospheric sounding when all are modified. (2) Only the contribution of the atmospheric sounding and the initial CCN concentration is included. (3) Analysis of the contribution of the ice forming processes and the initial CCN concentration in each of the atmospheric soundings separately. The calculation of the relative contributions and their interactions is based on the method that was presented in section 2.1.

[58] Table 3 shows the relative contributions of the atmospheric soundings, the initial CCN concentrations, and the ice forming processes and their interactions to the reduction in precipitation. The results from Table 3 are also shown graphically in Figure 6. The last two rows in

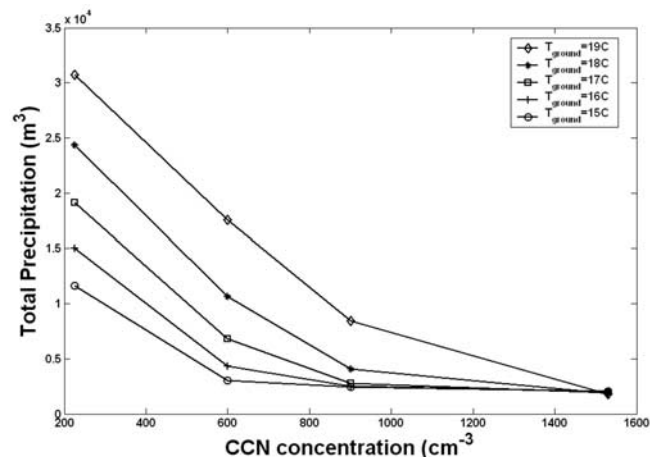


Figure 5. Total ground precipitation as a function of initial CCN concentration for simulations with Meyers *et al.* [1992] and Bigg [1953] ice forming formulations. These results correspond to the cases in rows 1–4 in Table 2.

Table 3. Relative Contributions of Different Factors and the Contribution of Their Interactions to Variation in Precipitation for Changes of Atmospheric Soundings, Initial CCN Concentrations, and Ice Forming Processes^a

	Tg:19°C → 18°C			Tg:19°C → 17°C		
	CCN: 225 cm ⁻³ → 600 cm ⁻³	CCN: 225 cm ⁻³ → 900 cm ⁻³	CCN: 225 cm ⁻³ → 1530 cm ⁻³	CCN: 225 cm ⁻³ → 600 cm ⁻³	CCN: 225 cm ⁻³ → 900 cm ⁻³	CCN: 225 cm ⁻³ → 1530 cm ⁻³
A (CCN)	13.0	30.4	53.3	12.1	28.3	50.2
B (Dep/Cond.-Frz.)	14.9	12.7	9.5	13.7	12.0	9.0
AB	0.2	0.2	0.0	0.2	0.2	0.0
C (Imm.-Frz.)	55.6	42.6	25.8	51.2	40.5	25.6
AC	0.1	0.0	0.9	0.0	0.0	1.4
BC	12.3	11.2	8.9	11.6	11.0	8.6
ABC	0.3	0.4	0.2	0.2	0.4	0.1
D (sounding)	3.5	2.3	1.0	10.9	7.1	3.5
AD	0.0	0.0	0.2	0.0	0.1	0.9
BD	0.0	0.0	0.0	0.0	0.0	0.1
ABD	0.0	0.0	0.0	0.0	0.0	0.1
CD	0.0	0.1	0.1	0.1	0.2	0.2
ACD	0.0	0.1	0.1	0.1	0.2	0.2
BCD	0.0	0.0	0.0	0.0	0.0	0.1
ABCD	0.0	0.0	0.0	0.0	0.0	0.1
Interaction	0.7	0.8	1.5	0.6	1.1	3.1
Ice	82.8	66.5	44.1	76.5	63.5	43.2

	Tg:19°C → 16°C			Tg:19°C → 15°C		
	CCN: 225 cm ⁻³ → 600 cm ⁻³	CCN: 225 cm ⁻³ → 900 cm ⁻³	CCN: 225 cm ⁻³ → 1530 cm ⁻³	CCN: 225 cm ⁻³ → 600 cm ⁻³	CCN: 225 cm ⁻³ → 900 cm ⁻³	CCN: 225 cm ⁻³ → 1530 cm ⁻³
A (CCN)	10.9	25.7	46.5	9.5	22.7	42.2
B (Dep/Cond.-Frz.)	12.2	11.1	8.4	10.9	10.1	7.7
AB	0.1	0.1	0.0	0.1	0.0	0.0
C (Imm.-Frz.)	45.8	37.5	24.7	40.2	34.2	23.3
AC	0.0	0.1	1.6	0.0	0.2	1.8
BC	10.7	10.5	7.9	9.9	9.8	7.4
ABC	0.2	0.3	0.0	0.2	0.2	0.0
D (sounding)	19.6	13.2	7.2	28.3	19.8	11.5
AD	0.0	0.4	2.1	0.0	0.9	3.5
BD	0.0	0.0	0.2	0.0	0.1	0.4
ABD	0.0	0.0	0.2	0.0	0.1	0.3
CD	0.3	0.7	0.5	0.7	1.3	0.9
ACD	0.1	0.4	0.3	0.2	0.5	0.3
BCD	0.0	0.0	0.2	0.0	0.1	0.3
ABCD	0.0	0.0	0.2	0.0	0.1	0.3
Interaction	0.8	2.0	5.3	1.2	3.4	7.9
Ice	68.7	59.1	41.1	60.9	54.1	38.3

^aThe parameters are labeled as follows: A, CCN; B, deposition and condensation freezing; C, immersion freezing; and D, atmospheric sounding.

Table 3 show the integrated effect of the ice forming processes including the interactions among them and the integrated effect of the interaction between the atmospheric sounding, the initial CCN concentration and the ice forming processes. Table 3 shows the relative contribution in percent of each parameter when different values of the factors is applied (e.g., CCN is changed between 225 cm⁻³ and 1530 cm⁻³). Table 3 illustrates the important role of the ice forming processes on precipitation. For example, it shows that reducing Tg from 19 to 17°C, and increasing the CCN from 225 to 600 cm⁻³, ice processes contribute over 76% to the change in precipitation. This relative role decreases as one pollutes the cloud even further (e.g., see the case of Tg from 19 to 17°C and CCN from 225 to 1530 cm⁻³).

[59] Table 2 shows that changing from Tg19_225_DP0_IM0, to Tg19_225_DP1_IM1 (i.e., adding immersion freezing and ice nucleation by deposition and condensation freezing) reduces the total rainfall by more than half from 67,000 m³ to about 30,000 m³. If Tg is reduced by 2°C

and the initial CCN is changed to 600 cm⁻³ (Tg17_600_DP1_IM1) the total precipitation is reduced to 6800 m³. The role of ice is therefore crucial and should not be ignored.

[60] From Table 3 it is concluded that immersion freezing processes (labeled C) have a larger effect on precipitation than the production of ice crystals from deposition/condensation freezing. Even when CCN concentration and atmospheric sounding change from 225 to 1530 cm⁻³ and from 19°C to 15°C, respectively, the contribution of the immersion freezing is 23%.

[61] Table 4 shows the relative contribution of the atmospheric sounding, the initial CCN concentration and their interactions when only the effect of these two factors is analyzed. Figure 7 shows a graphical illustration of how to interpret the results shown on Table 4. The gray rectangles mark the experimental design while each corner in a rectangle marks a single experiment. Figures 7a and 7b show the relative contribution of CCN and sounding to the suppression of precipitation in each experimental design.

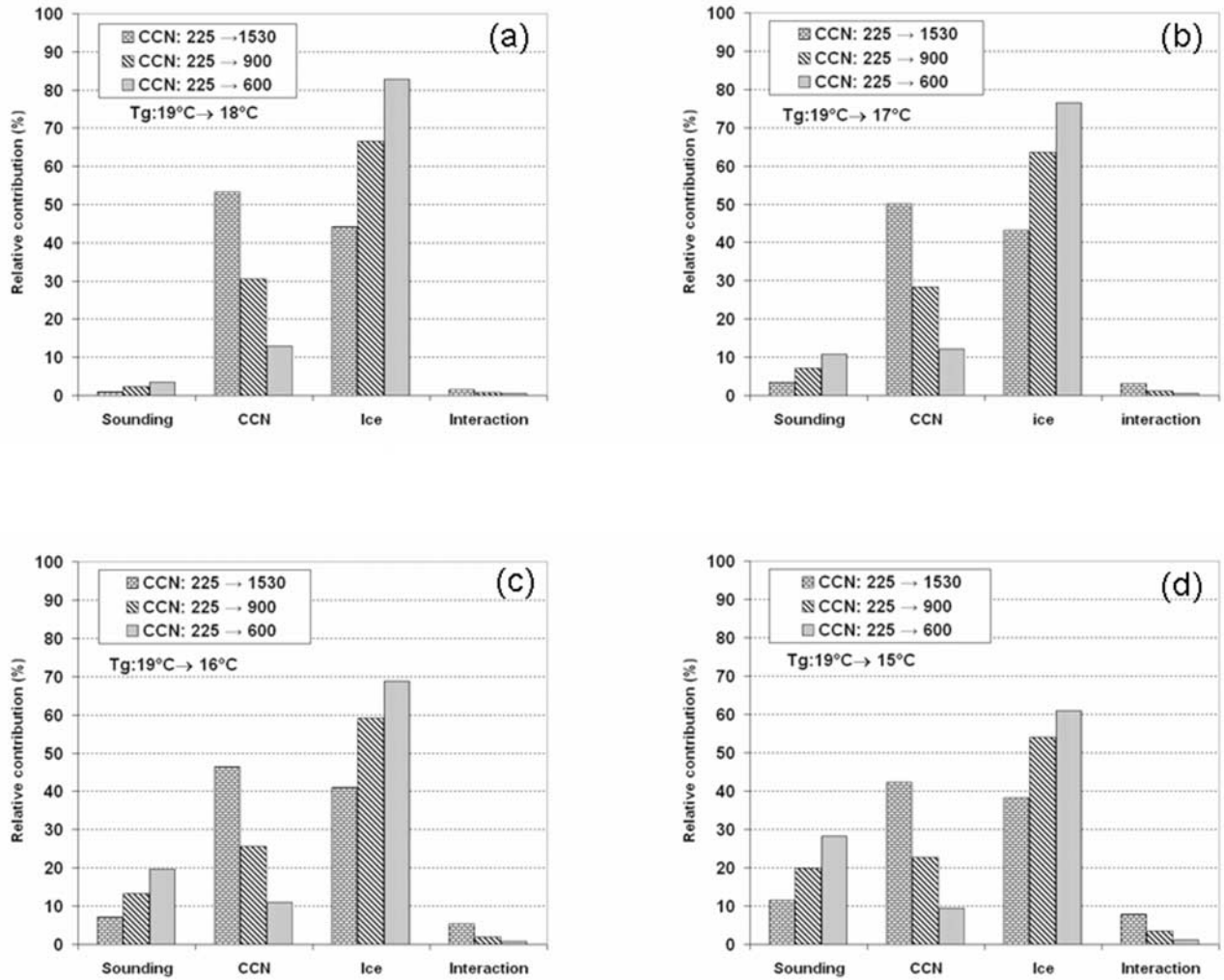


Figure 6. Relative contribution to precipitation suppression due to changing of CCN concentrations, ice forming processes and atmospheric soundings. The chart is based on the data provided in Table 3.

Table 4. Relative Contributions of CCN and the Effects of Changing the Atmospheric Sounding

	CCN: 225 cm ⁻³ → 600 cm ⁻³	CCN: 225 cm ⁻³ → 900 cm ⁻³	CCN: 225 cm ⁻³ → 1530 cm ⁻³
	<i>T_g: 19°C → 18°C</i>		
CCN	80.2	93.8	97.0
Sounding	19.7	6.0	1.5
Interaction	0.0	0.2	1.5
	<i>T_g: 19°C → 17°C</i>		
CCN	56.5	81.7	88.7
Sounding	43.5	16.3	5.5
Interaction	0.1	1.9	5.8
	<i>T_g: 19°C → 16°C</i>		
CCN	40.3	68.2	78.0
Sounding	59.3	26.4	10.7
Interaction	0.4	5.4	11.3
	<i>T_g: 19°C → 15°C</i>		
CCN	29.2	55.3	67.0
Sounding	69.5	35.1	16.0
Interaction	1.3	9.6	17.0

The results from Table 4 are also shown graphically in Figure 8.

[62] The relative quantitative effects of increased CCN and decreased T_g to the suppression of precipitation can be seen by the relative contribution of each when the T_g is first changed from 19°C to 17°C, the CCN from 225 cm⁻³ to 600 cm⁻³ and then T_g is changed from 19°C to 15°C and CCN from 225 cm⁻³ to 900 cm⁻³. From Table 4 it becomes clear that the increase in CCN by 375 cm⁻³ when the temperature is lowered from 19°C to 17°C contributes 56% to the suppression of precipitation, while the change in T_g only contributes 43%. However, further lowering T_g to 15°C and increasing CCN in the same amount as in the previous experiment, namely to 600 cm⁻³, reduces the effects of CCN to 29%, while increasing the effects of the lower temperature to 69%. Further increase of the CCN to 900 cm⁻³ with T_g lowered from 19°C to 15°C, again increases the relative contribution of the CCN to 55%. This illustrates that similar contribution to suppression of precipitation is obtained by either changing T_g by 2°C or increasing CCN by about 400 cm⁻³.

[63] Table 5 shows the relative contributions of the initial CCN concentrations, the ice forming processes and their interactions to the suppression of precipitation, separately for each of the atmospheric soundings. The last two rows in Table 5 show the integrated effect of the ice forming processes including the interactions among them, and the integrated effect of the interactions between the initial CCN concentration and the ice forming processes. The initial CCN concentrations used for this analysis were 225 and 1530 cm⁻³, representing the cleanest and the most polluted environments. The data used for calculating the relative effects of each factor and their interactions correspond to simulations that are marked in bold in Table 2 (for each atmospheric profile separately). The results from Table 5 are also shown graphically in Figure 9. In Figure 9 the relative contributions of CCN, ice forming processes and their interactions to the variability in the total precipitation is presented.

[64] It is apparent from Figure 9 that the ice processes in the model have greater impact on precipitation suppression when the clouds are developed in a colder environments, in which LWC is lower and the effect of the cloud droplet size distribution plays a less dominant role as compared to the role of ice. In contrast, a change of the CCN concentration from clean to polluted environment has greater influence on precipitation in a warmer environment where the LWC is large and the CCN concentrations affect the distribution of cloud droplets and the efficiency of rain-drop production.

[65] From Table 5 and Figure 9 it is concluded that the contribution of immersion freezing (labeled C) on precipitation increases as the environment becomes colder. On the basis of the parameterization of *Bigg* [1953], the rate of drop freezing depends on temperature and the drop mass. Therefore, in the coldest cloud ($T_g = 15^\circ\text{C}$), immersion freezing produces large concentrations of small ice crystals (produced from the freezing of small drops). Since many more small drops freeze, the subsequent growth by deposition is reduced, thus significantly suppressing precipitation. Furthermore, in the colder clouds the interaction of immersion freezing and CCN is also significant (7.5%) compared to 3.5% and 0.5% in the warmer atmosphere. In the warmer cases the influence of immersion freezing by itself is less significant because a large fraction of the precipitation is produced in the warmer regions of the cloud.

[66] Figure 10 presents the time variation (from the time when precipitation began to reach the ground) of the relative contributions of initial CCN, ice forming processes and their

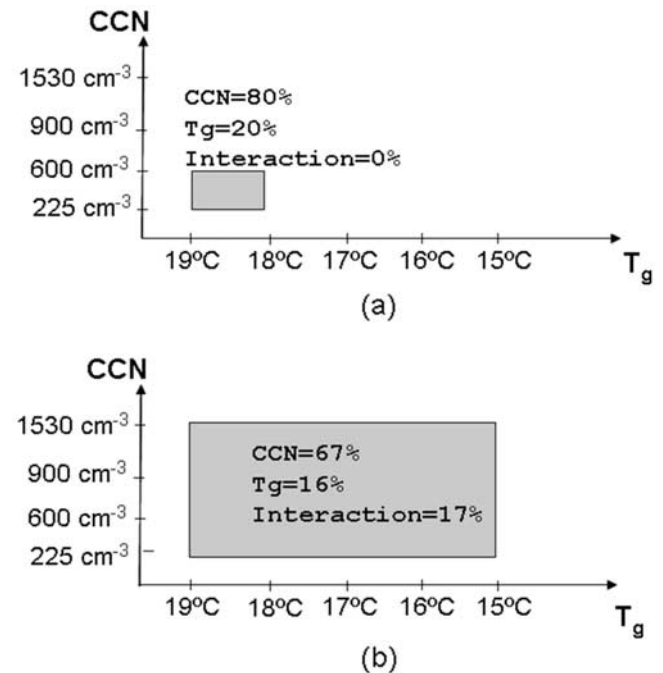


Figure 7. Graphical illustration of the experimental design for calculation of the relative contributions to precipitation suppression due to changing of CCN concentrations and atmospheric soundings.

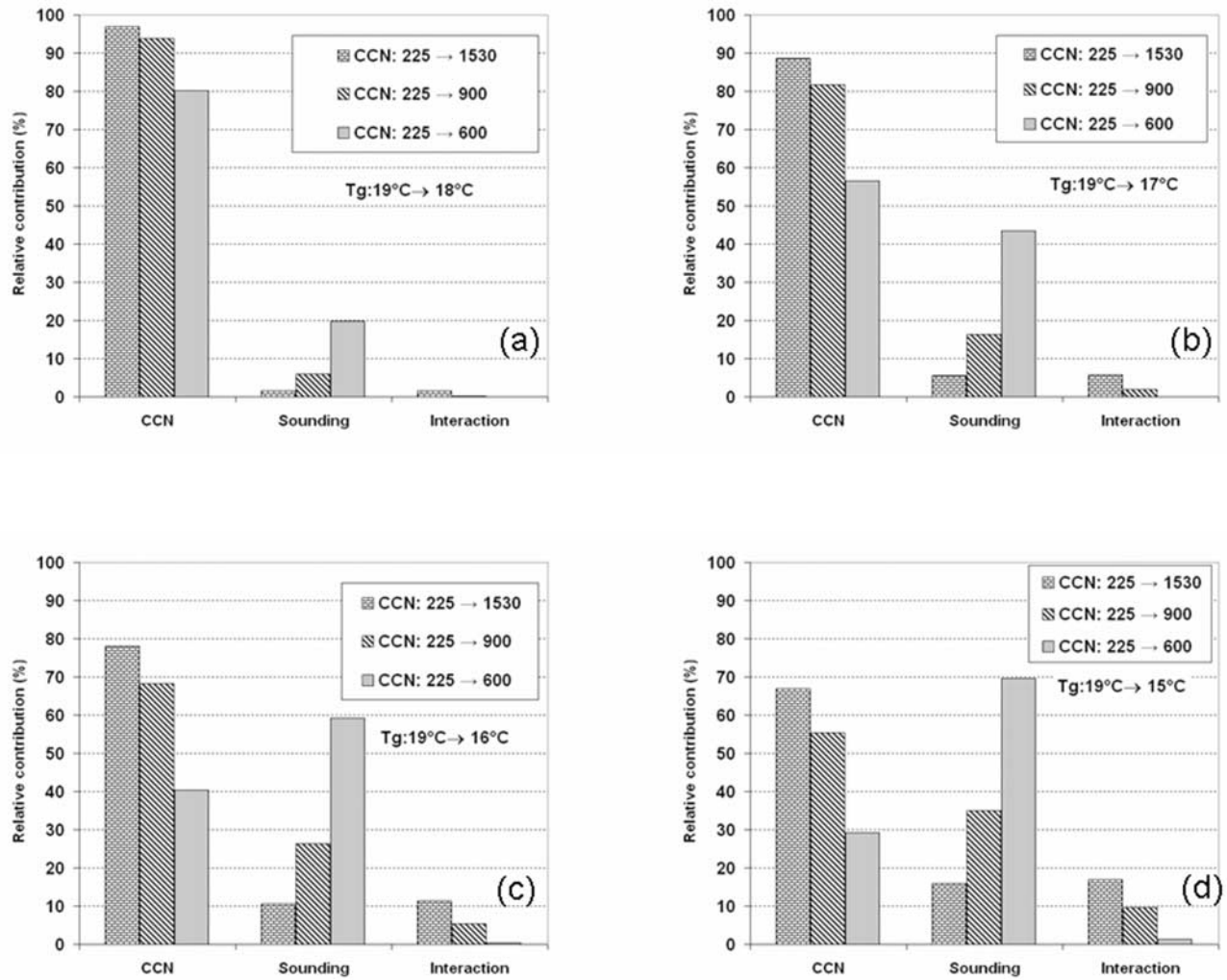


Figure 8. Relative contributions to precipitation suppression due to changing of CCN concentrations and atmospheric soundings. The chart is based on the data provided in Table 4.

interactions for three of the atmospheric soundings (19°C, 17°C and 15°C).

[67] Figure 10 demonstrates that at the beginning of the precipitation period the interactions between the factors are responsible for most of the variation in the precipitation.

The role of CCN in the suppression of precipitation becomes dominant during the mature stage. The effect of immersion freezing on suppression of precipitation increases during the cloud lifetime. This is because as precipitation continues, the fraction of the remaining cloud

Table 5. Relative Contribution to Precipitation Suppression Due to Changing of CCN Concentrations and Ice Forming Processes Shown Separately for Five Atmospheric Soundings^a

	Tg = 19°C	Tg = 18°C	Tg = 17°C	Tg = 16°C	Tg = 15°C
A (CCN)	55.2	52.7	49.5	46.5	42.8
B (Dep./Cond. Frz)	8.9	10.3	10.2	9.8	9.4
AB	0.1	0.0	0.1	0.4	1.0
C (Imm. Frz.)	26.4	25.8	27.5	28.9	29.8
AC	0.4	1.6	3.4	5.3	7.4
BC	8.6	9.4	9.4	9.1	9.1
ABC	0.3	0.2	0.0	0.1	0.4
Total Ice	44.2	45.5	47.2	48.5	50.3
Total Interaction	0.9	1.8	3.5	5.8	8.8

^aThe parameters are labeled as follows: A, initial CCN concentrations; B, deposition and condensation freezing; and C, immersion freezing. The cases that were used to construct this table are labeled in bold in Table 2.

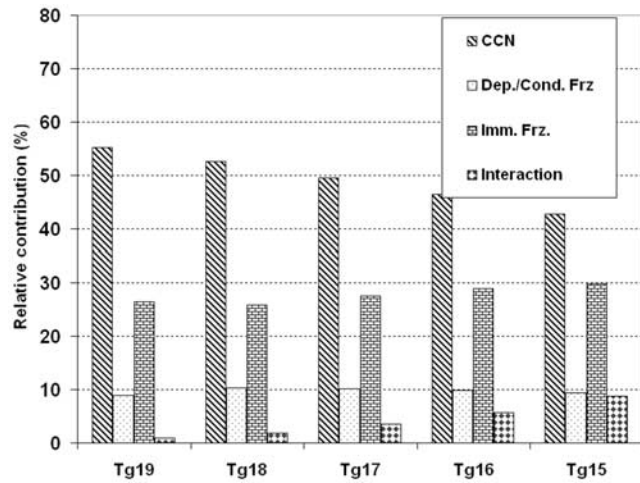


Figure 9. Relative contribution to precipitation suppression due to changing of CCN concentrations and ice forming processes shown separately for five atmospheric soundings.

that will not precipitate resides in the form of ice in the upper reaches of the cloud.

4. Conclusions

[68] The factorial method for analysis of experiments is presented and it is used to evaluate the relative contributions of atmospheric thermodynamic conditions as compared to the contributions of cloud microphysical processes (e.g., CCN concentrations and ice forming processes) to precipitation in mixed phase convective clouds. In addition, the method is used to evaluate the relative contributions to precipitation of the interactions among the different factors (parameters). One of the important features of using this method is the ability to evaluate the relative importance of each parameter to variation in precipitation amounts as a function of time.

[69] The TAU-2D cloud model was used to simulate 80 scenarios in order to determine the relative contributions of CCN, ice and the atmospheric thermodynamic conditions to precipitation suppression. Our main conclusions from the analysis are as follows:

[70] 1. If increased CCN and decreased temperature (keeping the relative humidity unchanged) act simultaneously to suppress precipitation, a decrease of about 2°C in ground temperature, which corresponds in our case to a decrease of 0.4 g kg⁻¹ in the maximum liquid water content in the cloud, has a similar suppression effect on precipitation as an increase of about 400 cm⁻³ in CCN concentration. These results are valid for a winter Mediterranean mixed phase convective cloud.

[71] 2. The effect of ice forming processes on precipitation amounts becomes as significant as increases in CCN as the cloud develops in colder environment. For example, the relative contribution of CCN to precipitation suppression falls from 55% to 42% when the atmospheric profile was cooled by 4°C while the relative contribution of ice increased from 44% to 50%.

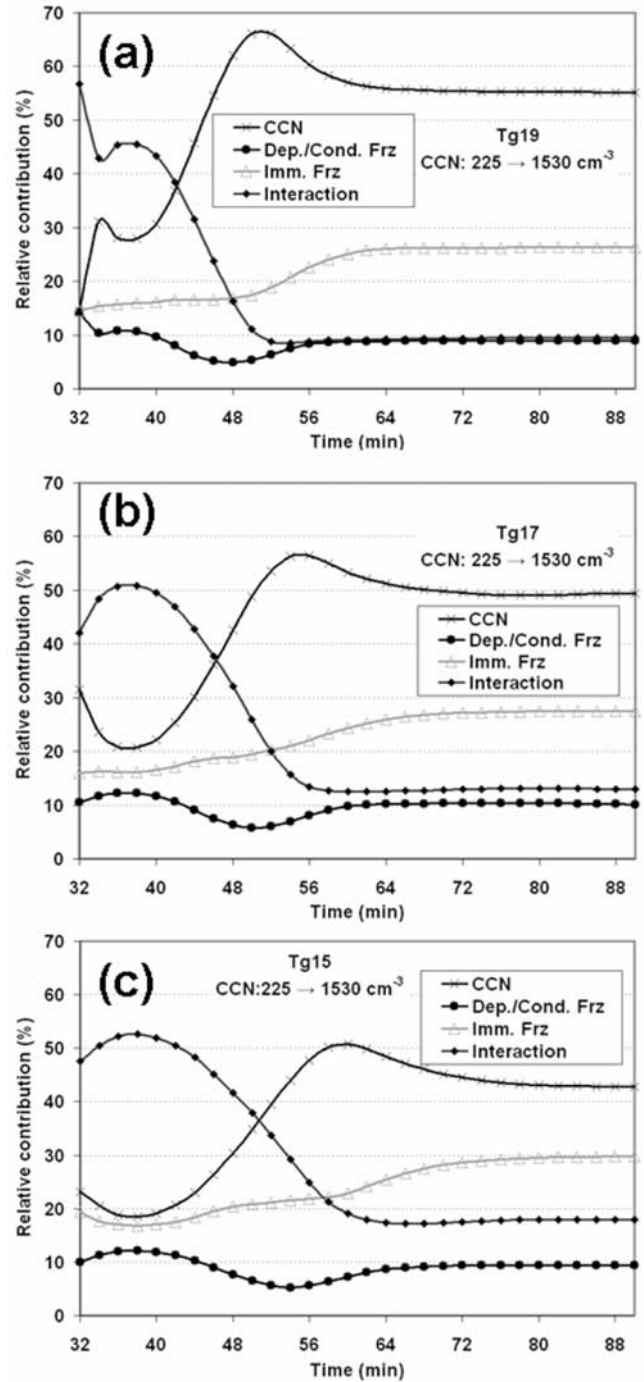


Figure 10. Time variation of relative contribution to precipitation suppression due to changing of CCN concentrations and ice forming processes shown separately for three atmospheric soundings. The graphs correspond to the cases that are analyzed in Table 5 (bold marked cases in Table 2).

[72] 3. Changes in CCN or in ice formation processes affect the precipitation differently during the various stages of the cloud development. At the initial stages of the rain period CCN play a dominant role, while during the mature stage of the clouds the relative contributions of the ice forming processes increase.

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