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EFFECTS OF NATURAL AND ANTHROPOGENIC POLLUTION ON THE INITIATION OF WARM RAIN IN TROPICAL REGIONS

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1. INTRODUCTION

The development of clouds and precipitation is determined by preexisting atmospheric conditions that are related to both microphysical and dynamical processes. In particular, the presence of particles which act as centers for condensation of water vapor, typically at supersaturations of a few tenths of a percent, is fundamental to the formation of water droplets in clouds. The concentration of potential cloud condensation nuclei (CCN), a subset of the atmospheric aerosol, determines that of cloud droplets and this, in turn, controls the size of the droplets and the efficiency with which precipitable particles can be produced in a cloud.

Convective precipitation development through warm rain mechanisms can be thought as a multi-stage process involving the nucleation of cloud droplets, followed by condensation, and their subsequent growth via collision-coalescence to precipitable sizes. Within the large variety of CCN that exists, some of them are more efficient than others because they are more hygroscopic and can deliquesce water at relative humidities even below 100%. In some cases, a large production of cloud droplets through nucleation may give way to an exaggerated competition for the available liquid water, thus suppressing rain-sized drop formation. Also, some clouds have lifetimes that are too short to permit precipitation development, while others entrain so much dry air that they do not have enough liquid water to fuel raindrop production.

Nowadays it is known that the production of aerosol particles from anthropogenic sources modify cloud droplet distributions, thus affecting cloud radiative and precipitation properties. For example, Warner and Twomey (1967) and Warner (1968) investigated the effects on cloud droplet concentration and the subsequent production of rain due to the emission of smoke from sugar-cane fires. The influence of urban and industrial air pollution on precipitation has been postulated to both inhibit (Gunn and Phillips 1957) and enhance (Eagen *et al*. 1974) rainfall at local and regional scales, but the issue remains in controversy. More recently, tracks of enhanced cloud reflectivity over the ocean became widely recognized as the impact of ship-stack effluents on the cloud drop size distribution and water content (Coakley *et al*. 1987; Radke *et al*. 1989). Furthermore, Rosenfeld and Lenski (1998) and Rosenfeld (1999) have shown that smoke from biomass burning act to suppress coalescence processes in clouds ingesting it. However, the detailed understanding of the chain of events leading to those particular conditions is still limited.

The purpose of the present work is to investigate the effects of aerosol particles produced by forest fires and urban pollution on the initiation and development of warm rain processes. In particular, the question on how aerosol particles below cloud base may affect the initiation of coalescence and the production of rain

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is addressed making use of a one-dimensional numerical model that simultaneously calculates growth by condensation and coalescence, including the activation of CCN (Cooper et al. 1997). Data were gathered from a field project carried out in Indonesia during an episode of gigantic forest fires that took place in that region in 1997. The results presented in what follows correspond to two cases: one related to measurements of smoke from forest fires over Kalimantan (December 15) and one including effects of megacity pollution sources on clouds growing in the vicinity of Jakarta (December 13).

2. METHODOLOGY

The effects of aerosol particles on warm rain processes were studied using a one-dimensional, numerical model with detailed microphysics, representing the growth of a cloud droplet population during adiabatic ascent of a closed parcel in a cloud. A brief description of the model is presented here, while details on the numerical procedures can be found in Cooper *et al*. (1997).

The warm microphysical processes include the activation of a CCN population, and the simultaneous growth via condensation and collision-coalescence. The model uses a variable bin location scheme, which concentrates size categories where resolution is needed. Droplets are assigned to one of up to 256 logarithmically spaced bins, ranging from 0.02 μm to 2 cm particle diameter, D.

Several parameterizations for CCN spectra can be used in the model. Generally, Aitken nuclei ($D \lesssim 0.2$ μm) are represented by a power law for the cumulative number concentration, $N(S)$, of cloud condensation nuclei active at or below the supersaturation S; whereas a Junge power law for the cumulative number concentration, $N(D)$, of CCN with diameters larger than D is used for large nuclei ($0.2 \lesssim D \lesssim 2$ μm). Their functional forms are the following:

$$N(S) = C\,(S/S_o)^{k} \quad , \qquad (1)$$

and

$$d\,N(D) / d\,(\log D) = A_\beta / (D/D_o)^{\beta} \quad , \qquad (2)$$

where k and β are the slope parameters of the fits, S_o is the reference supersaturation (typically 1%) at which $N(S)$ equals C; and D_o is the reference diameter (typically 1 cm) at which the particle concentration per logarithmic size interval equals A_β. Alternatively, lognormal distributions of the following form can be used to parameterize different size ranges, including giant (D > 2 μm) nuclei:

$$\frac{d\,N(D)}{d\,(\log D)} = \frac{N_D}{(2\pi)^{1/2}\log\sigma}\ exp\left[-\frac{(\log D - \log Dm)^2}{2\log^2\sigma}\right] \qquad (3)$$

where N_D is the total CCN concentration (full size range) and D_m and σ are the geometric mean particle diameter and standard deviation of the distribution, respectively. Given the multimodal nature of atmospheric aerosol, for modeling purposes it has been found to be convenient to describe size spectra through the superposition of several analytical forms as those described by Equations 1 to 3 (see Section 3).

For the simulations presented here, a local temperature sounding was used for levels below 550 mb. Above this level, any further ascent was inhibited by the introduction of an artificial, stable layer of 20ºC. The cloud base pressure and temperature were 850 mb and 18.5°C, respectively. The parcel was allowed to rise as driven by buoyancy, with an initial updraft of 3 m/s, from cloud base until reaching zero vertical velocity at about 4 km above (about 6 min after passage through) cloud base. The parcel was then arbitrarily held at this level, corresponding to a temperature close to 0ºC, thus providing a total growth time of up to 30 min until full conversion of cloud water into precipitation was accomplished.

It is worth mentioning that drop breakup and sedimentation are not included in the calculations. The latter is a significant deficiency in the model, since it may lead to quite unrealistic results for long simulation times, when millimeter-sized drops with fall speeds comparable to the assumed updrafts may have formed. This weakness applies to many other standard coalescence calculations. Because the objective here is to determine if the warm-rain process can be accelerated, delayed or even suppressed by modified aerosol spectra, conclusions drawn from these calculations must be interpreted in a comparative and qualitative manner. In other words, the modeling results require careful interpretation to compensate for this and other weaknesses of the closed parcel model. Thus, the approach taken here consisted in realizing calculations for a “non-polluted” case and then repeating them using the modified particle spectra for the polluted scenario. No changes in the environmental conditions were made between scenarios except for the input spectra of particles emitted by the sources here investigated: biomass burning or urban pollution.

3. DATA AND PARAMETERIZATIONS

In the aftermath of two gigantic forest fires that occurred in Southeast Asia between September and November 1997, an intensive, short-term program of cloud physics measurements was conducted in potential rain clouds over that region. BASIC (Brief Assessment of the Affects of Smoke on Indonesian Clouds) was a cooperative effort between several institutions from Indonesia, Thailand and other ASEAN countries along with NCAR, during December 1997. One of the main objectives of BASIC consisted in investigating the effects of smoke produced by forest fires and other man-made sources of aerosols, such as city pollution, on the precipitation efficiency of clouds. The program integrated *in-situ* data collected using a research aircraft with data obtained from remote sensors (satellites and radar) and surface observations. The operations center for the project was located at Halim airport, in Jakarta, and data gathering flights were conducted over Java, Kalimantan and Sumatra. In these two latter areas, cloud penetrations included both zones affected by smoke from fires that were still burning and unaffected zones.

Measurements of particle concentration affecting initial cloud development, such as aerosols, CCN and droplets near cloud base, were emphasized during the field campaign. Unfortunately, a CCN counter operated near cloud base suffered a malfunction, probably due to an overload condition, and no data were available. Thus, in order to simulate unpolluted scenarios it was decided to use proxy, available CCN data from similar regions in Thailand: Khon Khan for Kalimantan, and Bangkok for Jakarta (Bruintjes *et al*. 1999a). The first area, located in the central-eastern part of the country, is an important rice production center where rice fields are burned twice a year to prepare the land for the next crop. Bangkok is the capital of the country and shows similar urban pollution characteristics as most cities in the region. Measurements of aerosol spectra were made with a Passive Cavity Aerosol Spectrometer Probe (PCASP) for the two BASIC cases discussed here, and fit to a linear combination of the analytical forms given by Equations 1 to 3.

For each of the two cases studied (CCN spectra modified by biomass burning and urban pollution over Kalimantan and Jakarta, respectively) different scenarios were used, as follows:

- For the "non-polluted" cases, the CCN activation spectra from Thailand were used as input for the model (hereafter *Background Scenarios*).
- For the pollution cases, it was assumed that all aerosol particles as measured by the PCASP were potential CCN. With the aim of investigating the particular effects of the larger nuclei ($D \gtrsim 0.7$ μm), the pollution cases were in turn approached in two ways:

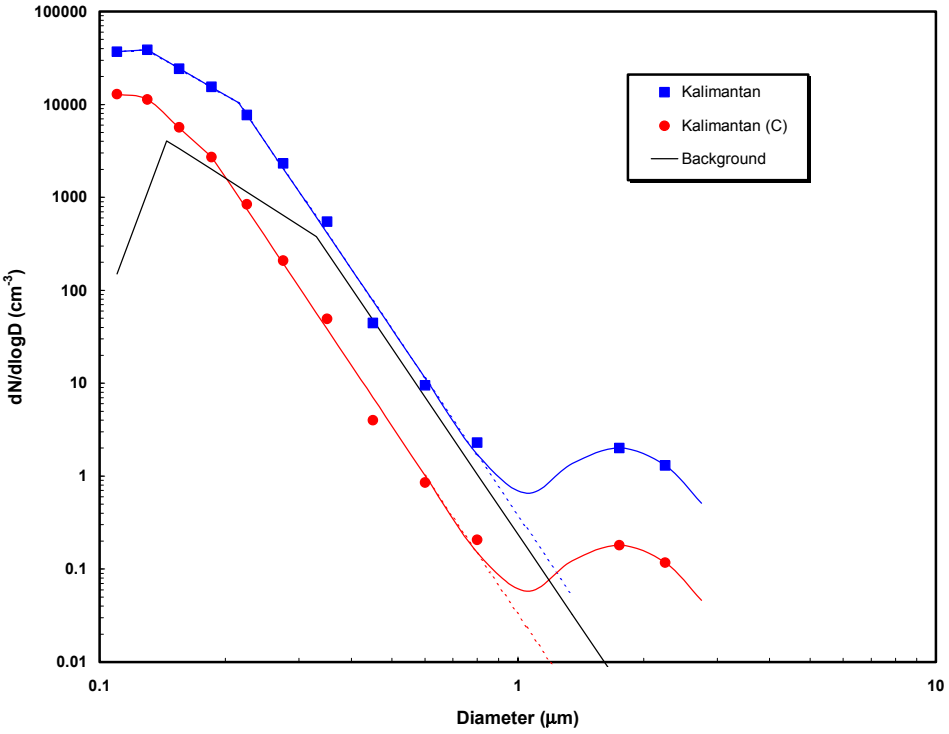
  Scenario 1: Larger particles were suppressed by assuming that they followed the same Junge power law as large nuclei.

  Scenario 2: Larger particles were included using a lognormal distribution (Equation 3) parameterization.
- Observations of smoke generated by forest fires over the Amazon region indicate that sulfate is a significant component of the aerosol produced by both young and aged smoke (Reid *et al*. 1998). Accordingly, for smoke from biomass burning in Kalimantan, further numerical experiments were carried out assuming that all aerosol particles consisted entirely of ammonium sulfate and then modifying the PCASP particle spectrum using the scheme proposed by Bigg (1986). This corrected scenario was also subdivided into two cases (*Scenarios C1* and *C2*) to consider the effects of the larger aerosol particles as described before for Scenarios 1 and 2.

The data and parameterizations used in the different scenarios described above are shown in *Figure 1*. The results of the numerical experiments are presented in the following section.

4. DISCUSSION AND CONCLUSIONS

For the sake of briefness, only the results of the calculations for the *Background* and *C2* scenarios of the Kalimantan case study are discussed here in detail. For these particular cases, *Figure 2* shows the calculated mass drop-size distributions corresponding to growth times of up to 20 minutes after passage through cloud base. Other study cases are discussed on the basis of the droplet concentration time-series predicted by the model, shown in *Figure 3*.



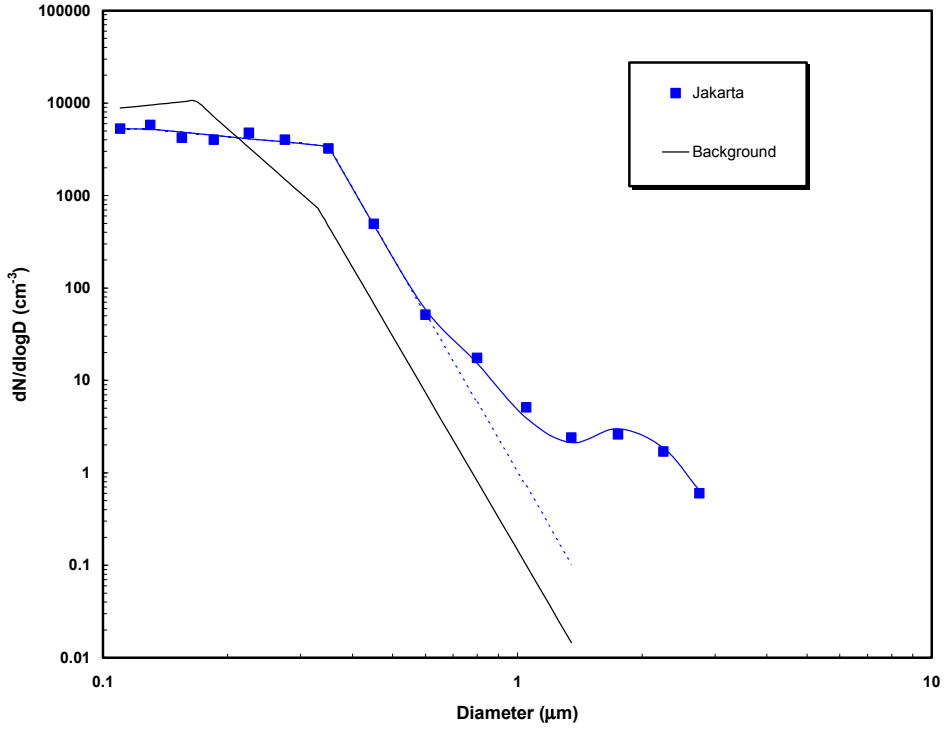


Figure 1. Particle-size distributions of aerosols near cloud base and corresponding parameterizations obtained during BASIC over Kalimantan (December 15) and Jakarta (December 13) in 1997. Broken and continuous lines represent *Scenarios 1* and *2*, respectively. *Background scenarios* correspond to CCN spectra from Khon Khan and Bangkok, respectively. Kalimantan data for *Scenarios C1* and *C2* are also shown.

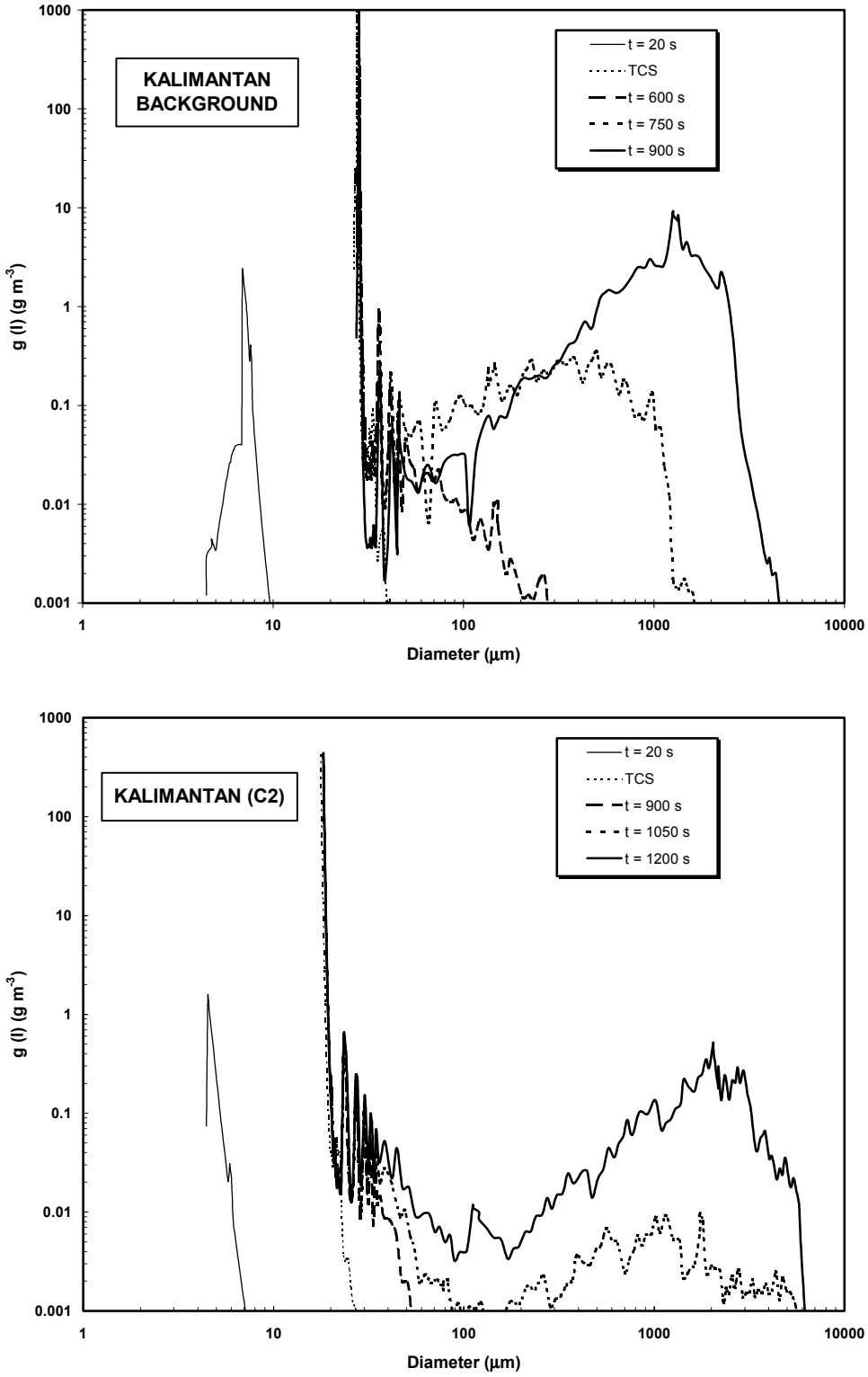


Figure 2. Mass distribution functions for different times after passage through cloud base calculated with the model for the Kalimantan case study,. Top and lower panels correspond to *Background* and *C2 Scenarios*, respectively. TCS refers to the time at which the parcel reaches zero vertical velocity (about 6 min).

For the *Background Scenario*, it can be appreciated from *Figure 2* that drizzle (drop diameters larger than 200 μm) starts forming 10 minutes after passage through cloud base, and significant precipitation (larger than 1 to 2 mm hr^{-1}) is noticed after about 11 minutes. This behavior lasts for several minutes until full cloud water conversion to precipitation occurs (after about 12 minutes in this case). In comparison, for the *C2-Scenario*, both drizzle and significant precipitation occur well after 15 minutes after passage through cloud base. In other words, the model predicts a delay of about 5 minutes between the non-polluted and smoke-polluted cases for warm rain to develop. This general pattern is better illustrated in *Figure 3*, which shows the time-dependent droplet concentrations (diameters less than 200 μm) predicted by the model for all the different scenarios here considered. As expected, all smoked-polluted scenarios show larger droplet concentrations with respect to the non-polluted case. Some measurements of cloud droplet concentration made during BASIC (Bruintjes *et al*. 1999b) indicate that typical values near cloud base are of the order of 1100 cm^{-3}, which compare well with values predicted here for *Scenarios C1* and *C2*. It is not clear if the inclusion of larger nuclei in the initial CCN spectra (*Scenarios 2* and *C2*) further delays the initiation of rain, but the depletion of cloud water by precipitation seems to occur faster. The urban-polluted cases from Jakarta shown here display a similar behavior. However, it has to be noticed that in this case the CCN input spectra was not modified, that is, similar results as in the previous cases are obtained by assuming that all aerosol particles are potential cloud condensation nuclei.

The increase of the droplet concentration with respect to the *Background Scenario*s shown here are also indicative of the suppression of the coalescence process by modified aerosol spectra. It could be concluded that aerosol particles from smoke produced by fires and urban pollution reduce precipitation efficiency in clouds because the added particles simply modify the natural CCN population to one with similar sizes but higher concentrations; thus, smaller and more numerous droplets would be expected to appear and coalescence would be slower. However, this has not necessarily to be the case, since the modification of the CCN spectra may occur differentiated according to particle size.

Nevertheless, the current results provide evidence that biomass burning and urban pollution reduce the precipitation efficiency of warm clouds. Further studies are required, however, to verify these initial results on a larger set of data.

5. REFERENCES

Bigg, E.K., 1986: Discrepancy between observation and prediction of concentrations of cloud condensation nuclei. *Atmos*. *Res.*, **20**, 82-86.

Bruintjes, R.T., R.M. Rasmussen, W. Sukarnjanaset, P. Sudhikoses and N. Tantipubthong, 1999a: Variations of cloud condensation nuclei (CCN) and aerosol particles over Thailand and the possible impacts on precipitation formation in clouds. *Seventh W.M.O. Scientific Conference on Weather Modification*. Chaing Mai, Thailand. WMO TD No. 936, 33-36.

Bruintjes, R.T., R.M. Rasmussen, W. Sukarnjanaset, P. Sudhikoses, N. Tantipubthong and M. Karmini 1999b: The effects of the smoke and haze from the Indonesian fires on cloud microstructure and precipitation development. *Seventh W.M.O. Scientific Conference on Weather Modification*. Chaing Mai, Thailand. WMO TD No. 936, 533-536.

Coakley, J.A., R.L. Bernstein and P.R. Durkee, 1987: Effects of ship-stack effluents on cloud reflectivity. *Science*, **237**, 1020-1022.

Cooper, W.A., R.T. Bruintjes and G.K. Mather, 1997: Calculations pertaining to hygroscopic seeding with flares. *J. Appl. Meteor.*, **36**, 1449-1469.

Eagen, R.C., P.V. Hobbs and L.F. Radke, 1974: Particle emissions from a large Kraft paper mill and its effects on the microstructure of warm clouds. *J. Appl. Meteor.*, **13**, 535-552.

Gunn, R., and B.B. Phillips, 1957: An experimental investigation of the effect of air pollution on the initiation of rain. *J. Meteor.*, **14**, 272-280.

Radke, L.F., J.A. Coakley and M.D. King, 1989: Direct and remote sensing observations of the effects of ships on clouds. *Science*, **246**, 1146-1149.

Reid, J.S., P.V. Hobbs, R.J. Ferek, D.R. Blake, J.V. Martins, M.R. Dunlap and C. Liousse, 1998: Physical, chemical, and optical properties of regional hazes dominated by smoke in Brazil. *J. Geophys. Res.*, **103D**, 32059-32080.

Rosenfeld, D., 1999: TRMM observed first direct evidence of smoke from forest fires inhibiting rainfall. *Geophys. Res. Lett.*, **26**, 3105-3108.

Rosenfeld, D., and I.M. Lenski, 1998: Satellite-based insights into precipitation formation processes in continental and maritime convective clouds. *Bull. Amer. Meteor. Soc.*, **79**, 2457-2476.

Warner, J., 1968: A reduction in rainfall associated with smoke from sugar-cane fires. An inadvertent weather modification? *J. Appl. Meteor.*, **7**, 247-251.

Warner, J., and S. Twomey, 1967: The production of cloud nuclei by cane fires and the effect on cloud droplet concentration. *J. Atmos. Sci.*, **24**, 704-706.

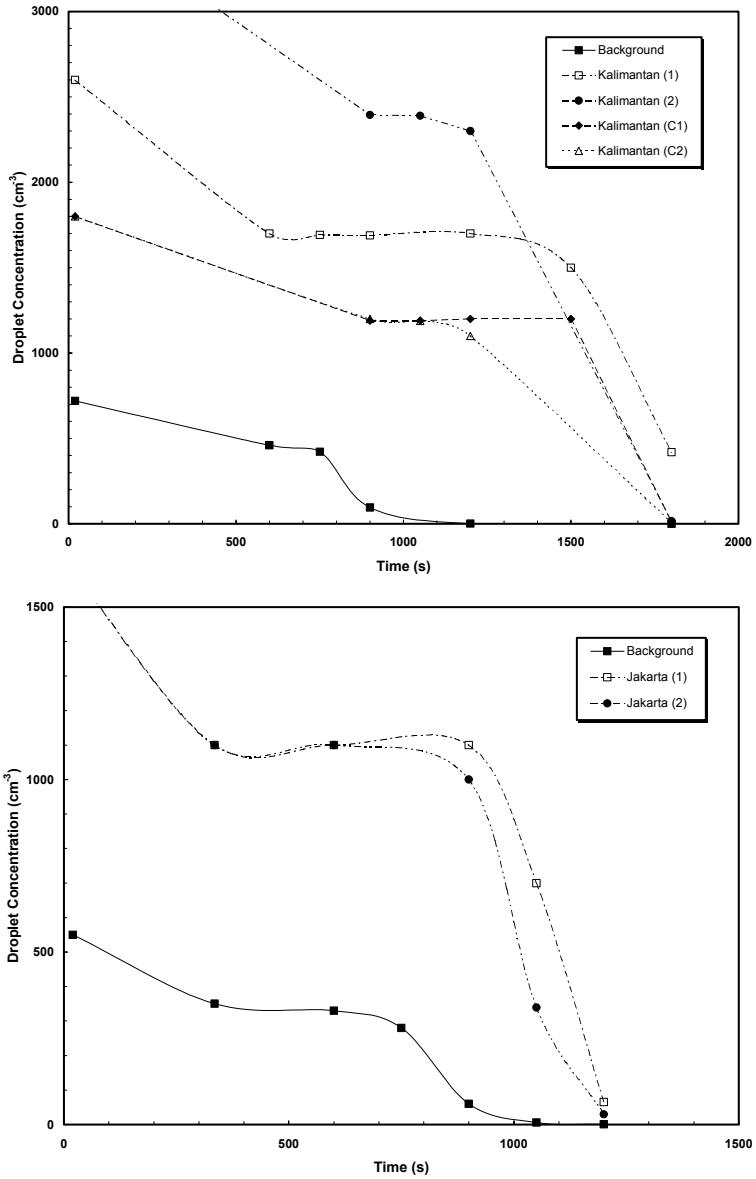


Figure 3. Time-dependent droplet concentrations predicted by the model for the different scenarios.