

Influence of the Kuwait oil fires plume (1991) on the microphysical development of clouds

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[1] Applications of new retrieval methods to old satellite data allowed us to study the effects of smoke from the Kuwait oil fires in 1991 on clouds and precipitation. The properties of smoke-affected and smoke-free clouds were compared on the background of the dust-laden desert atmosphere. Several effects were observed: (1) clouds typically developed at the top of the smoke plume, probably because of solar heating and induced convection by the strongly absorbing aerosols; (2) large salt particles from the burning mix of oil and brines formed giant cloud condensation nuclei (CCN) close to the source, which initiated coalescence in the highly polluted clouds; (3) farther away from the smoke source, the giant CCN were deposited, and the extremely high concentrations of medium and small CCN dominated cloud development by strongly suppressing drop coalescence and growth with altitude; and (4) the smaller cloud droplets in the smoke-affected clouds froze at colder temperatures and suppressed both the water and ice precipitation forming processes. These observations imply that over land the smoke particles are not washed out efficiently and can be transported to long distances, extending the observed effects to large areas. The absorption of solar radiation by the smoke induces convection above the smoke plumes and consequently leads to formation of clouds with roots at the top of the smoke layer. This process dominates over the semidirect effect of cloud evaporation due to the smoke-induced enhanced solar heating, at least in the case of the Kuwait fires. *INDEX TERMS*: 0305

Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; 0368 Atmospheric Composition and Structure: Troposphere—constituent transport and chemistry; *KEYWORDS*: aerosol, soot, smoke, cloud microphysics

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1. Introduction

[2] Aerosols ingested by clouds act as cloud condensation nuclei (CCN) and dictate the cloud droplet size distribution (DSD) and ability of clouds to precipitate [Baker, 1997]. Satellite observations showed that high concentrations of urban and industrial air pollution [Breon *et al.*, 2002; Rosenfeld, 2000; Schwartz *et al.*, 2002], desert dust [Rosenfeld *et al.*, 2001] and smoke from biomass burning [Feingold *et al.*, 2001; Rosenfeld, 1999] generally decrease cloud droplet sizes and therefore increase cloud reflectivity and suppress the precipitation efficiency of clouds [Ramanathan *et al.*, 2001]. These effects were predicted already by Twomey [1974] and Albrecht [1989]. In contrast, large salt dust particles over land [Rudich *et al.*, 2002] and sea spray over the ocean [Rosenfeld *et al.*, 2002] have recently been shown to promote cloud droplets

growth, in line with a unique observation over a paper mill plume [Hindman *et al.*, 1977], with modeling studies [Feingold *et al.*, 1999; Levin *et al.*, 1996; Yin *et al.*, 2000] and with hygroscopic cloud seeding experiments [Bruitjes, 1999].

[3] In addition to effecting clouds through cloud microphysics, pollution aerosols have substantial dynamic impacts on clouds and precipitation. Recently, model simulations have shown that black carbon aerosol over China have dramatic regional effects on precipitation because of absorption of incoming solar radiation by the black particles. The enhanced tropospheric absorption warmed the lower troposphere and reduced the surface heating and the convection. This led to changes in the regional and global circulation. [Menon *et al.*, 2002]. Regional effects on cloud formation due to black carbon have also been observed in the Mediterranean region [Lelieveld *et al.*, 2002] and down wind from the Indian subcontinent [Ackerman *et al.*, 2000; Ramanathan *et al.*, 2001]. However, the aerosol composi-

tion and magnitude of none of these cases can be compared to the catastrophic emissions from the Kuwait oil fires. The impacts of the intense fires on cloud properties and microphysics are not well known. In this study we focus on changes to cloud properties due to the effects of smoke on cloud microphysics.

[4] Some 700 oil wells were ignited in Kuwait at the end of the “Gulf War”, burning at a rate of 4–5 million barrels per day between February and November 1991 [Johnson *et al.*, 1991; Parungo *et al.*, 1992]. The Kuwait fires produced an unusually high concentration of aerosols with a broad size distribution and complex chemical composition which was measured in situ [Ferek *et al.*, 1992; Hobbs and Radke, 1992; Hudson and Clarke, 1992; Johnson *et al.*, 1991; Parungo *et al.*, 1992]. The fires resulted in a black plume that contained soot (15–20%), organics (30%), sulfate (8%), salt (30%), and mineral dust. The wealth of information from in situ measurements on the size distribution and chemical composition of the CCN in the smoke plume makes the Kuwait fire plume a unique environmental experiment in which the relative effect of the large CCN ($>1 \mu\text{m}$) present together with small CCN ($<0.1 \mu\text{m}$) can be probed. Here we apply new retrieval methods to old satellite data to study the effects of smoke from the Kuwait oil fires in 1991 on clouds and precipitation.

[5] The Kuwait plumes are unique owing to the presence of extremely high concentrations of particles, including black carbon, salt and dust. Hence, while our previous observations of aerosol-cloud interactions focused on the effect of a single aerosol type on cloud microphysics [Rosenfeld, 1999, 2000; Rosenfeld *et al.*, 2002, 2001; Rudich *et al.*, 2002], here we face the challenge of assessing the impact of a highly heterogeneous aerosol population from the mix of burning oil, brine and desert dust on cloud properties and precipitation forming processes.

2. CCN in the Plume From in Situ Particle Measurements

[6] Research flights in the Persian Gulf region were conducted during March, May, and June 1991 by several teams. In situ measurements were conducted in different plumes, at different altitudes, distances from the source, and also outside the plume to obtain detailed information about background aerosol. Altocumulus clouds were occasionally observed by aircraft inside or above the plume, but not elsewhere [Johnson *et al.*, 1991]. During the observation period, the plume top did not exceed 6 km in altitude [Hobbs and Radke, 1992].

[7] The smoke plume contained mostly soot aerosols with radius ranging between 0.015 and 35 μm and concentrations of up to 10^5 cm^{-3} [Hudson and Clarke, 1992; Parungo *et al.*, 1992]. Typically, the ultrafine particles ($0.003 \mu\text{m} < r < 0.015 \mu\text{m}$) concentration was 30% higher than that of the fine mode ($0.015 \mu\text{m} < r < 0.3 \mu\text{m}$) [Hudson and Clarke, 1992]. With increasing height and distance from the source, the concentration of the small and medium particles ($0.06 < r < 0.6 \mu\text{m}$) increased, while the coarse particles concentration ($r > 0.5 \mu\text{m}$) decreased, mainly because of sedimentation. The concentration of SO_2 in the plume reached 700 ppbv [Parungo *et al.*, 1992], decreasing with time because of photochemical conversion to H_2SO_4 and coating

soot, dust and sea salt particles by sulfate. As a result, the concentration of sulfate-coated particles and the thickness of the sulfate layers increased with altitude and distance from the source. Salt particles from burning brines and mineral dust particles were also measured in the plume, but at lower concentrations. Soot contained about 30% of the total aerosol sulfate mass, while salt and dust contained about 20% of the total aerosol sulfate mass. Less than 1% of the sulfate was present as H_2SO_4 particles. Outside of the plume, the background aerosol was composed mainly of mineral dust particles in low concentrations. Similar concentrations of dust particles were measured inside the plume [Hudson and Clarke, 1992].

[8] Coating of the soot particles by H_2SO_4 through heterogeneous nucleation [Parungo *et al.*, 1992] and the extensive photochemical production of nucleation and accumulation mode particles close to the edges of the plume, resulted in high concentration of very efficient CCN, ranging from 10^5 cm^{-3} a few km from the source to about 10^4 cm^{-3} some 300 km away [Hobbs and Radke, 1992]. The transformation of the primary particles to efficient CCN was very dramatic and most of the soot particles were coated by soluble sulfate [Hudson and Clarke, 1992] resulting in the large number of small CCN. It is calculated that the coarse particles ($r > 0.5 \mu\text{m}$), which were present closer to the source, could activate at supersaturation (Sc) smaller than 0.03%, and the smaller ones at Sc of 0.2% [Hudson and Clarke, 1992]. Activation of most particles at supersaturation of 0.2% was actually measured in the smoke plume [Ferek *et al.*, 1992; Hudson and Clarke, 1992]. About 70% of the aerosols in the plume were CCN at $\text{Sc} = 1\%$, reaching 16,000 CCN cm^{-3} , or 2000 CCN cm^{-3} for $\text{Sc} = 0.03\%$ [Hudson and Clarke, 1992]. Thus a large number of particles could be activated in low Sc . The competing effects of the large and small particles in this case make it an extremely interesting one.

3. Remote Sensing Analysis: Case Studies

[9] The effect of the Kuwait fires smoke plume on cloud development and microphysics was studied by analyzing satellite retrievals [Rosenfeld and Lensky, 1998] from the advanced very high resolution radiometer (AVHRR) sensor on board the National Oceanic and Atmospheric Administration Orbiting NOAA 11 satellite. This method includes a correction to atmospheric water vapor above the cloud tops, as described in section 2a by Rosenfeld and Lensky [1998]. This study provides additional insights about aerosols-cloud interactions in the Kuwait plume, complementing the information obtained formerly by the in situ measurements, as described in section 2. Several control cases in the years 1990 and 1992 were also analyzed for smoke free (clean) clouds, typical of this region. In retrievals from 1991, both smoke-contaminated and clean clouds were analyzed. Contaminated clouds were chosen within the visible smoke plume, while the clean clouds in 1991 were measured only where it was obvious that no smoke was present. Out of ~ 35 available cases of clouds visibly polluted by smoke, four case studies are presented here that demonstrate the most commonly observed effects of the smoke plume:

[10] 1. The first case (28 March 1991) was a thin, contaminated cloud formed (~ 130 km from the smoke

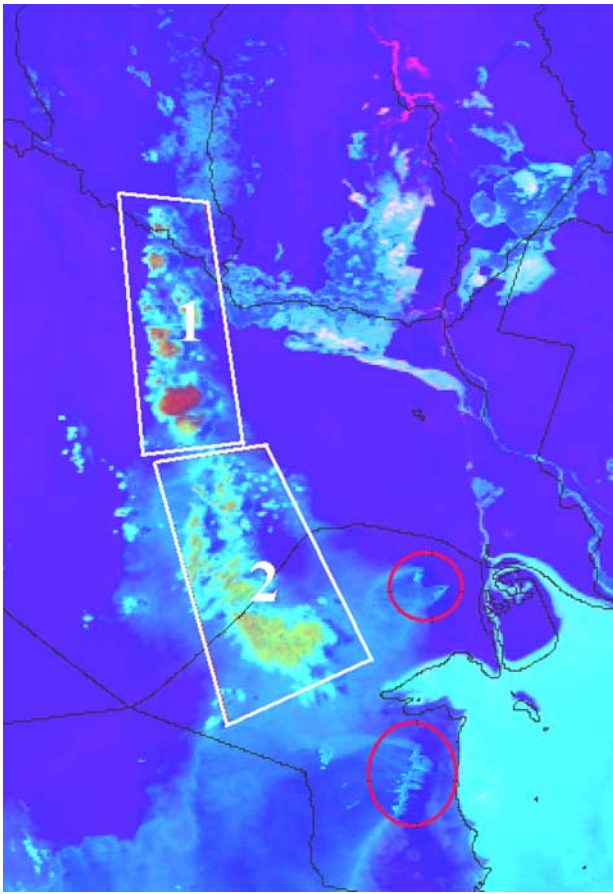


Figure 1. NOAA/AVHRR image over Kuwait and southern Iraq on 23 June 1991 showing the smoke plumes and clouds. The circles show the areas of the fires. The plume heads northwest. The blue background represents ground temperature of about 50°C. The light blue under the clouds shows where the plume is, and the temperature is about 40°C. The clouds develop only above the plume. The image is a color composite of visible channel of the AVHRR modulating the red, 3.7 μm reflectance modulating the green, and 11 μm temperature modulating the blue. The full color scheme and its physical interpretation are described by *Rosenfeld and Lensky [1998]*.

source) between two layers of smoke which was also observed by in situ aircraft measurements [*Johnson et al., 1991*]. Remote sensing analysis of temperature versus effective radius (r_e) at wavelength of 3.7 μm ($T-r_e$) indicates a near-cloud base temperature between 1 and 3°C, and r_e of 6.8 μm. The heavy smoke above the cloud absorbs some of the incident light at 3.7 μm and the cloud appears gray. The smoke layer also absorbed some of the light scattered by water droplets. In addition, multiple scattering by the cloud droplets multiplies more than tenfold the ray path within the clouds and hence the absorption by the smoke within the cloud. This reduction of the 3.7 μm reflectance lead to an overestimation of r_e , manifested by an apparent increase of the retrieved r_e , especially in the lower portions of the clouds and near cloud base. This behavior was observed only in clouds that developed in smoke plumes and not in clean clouds, and it contrasts the normal behavior of clouds

where smaller sizes drops are found closer to cloud base. Therefore the lowest part of the $T-r_e$ profile was deleted from the analysis when such increase of derived r_e was observed near the lowest portion of the cloud, usually 2°–3°C from cloud base.

[11] 2. The second observed effect of the smoke plume was to lower the surface temperature underneath because of the intense light absorption (Figure 1). For example, on 23 June 1991, the surrounding ground temperature is about 50°C, (using the thermal IR channel) while directly beneath the plume (~400 km away from the smoke source) it decreased to about 40°C. This is consistent with surface observations that reported a decrease of up to 10°C under the smoke [*Cahalan, 1992*]. As was often observed, the clouds in this day emerged from the top of the smoke plume and their $T-r_e$ properties could be determined reliably. Two clouds are shown in Figure 2. The first cloud (frame 2) formed closer to the fire source. The r_e at cloud base is about 8 μm, and the cloud does not develop much vertically. The clouds farther away from the fires (frame 1) had a slightly larger r_e at cloud base. With decreasing temperature, the droplets did not grow much until they abruptly froze at about -18°C.

[12] 3. Three cloud bands formed on 6 March 1991 (Figure 3). The southernmost band (frame 3, Figure 3) ingested clean air, the middle band (frame 2) ingested air contaminated by smoke, and the northernmost band (frame 1) ingested partly clean air. $T-r_e$ analysis for the three cloud bands is shown in Figure 4. The clouds that formed in the smoke (frame 2) have a near-cloud base temperature of $T = -1^\circ\text{C}$ and near cloud base droplet size of $r_e = 8 \mu\text{m}$. This size is probably overestimated in this case. The clean clouds (frame 3) had higher cloud base temperature and also larger r_e ($T = 6^\circ\text{C}$, $r_e = 12 \mu\text{m}$). The striking

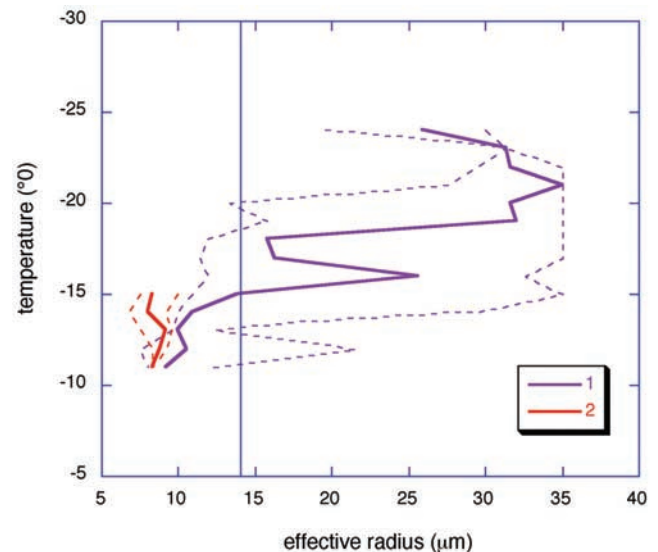


Figure 2. Temperature (°C) versus effective radius (μm) ($T-r_e$) plot of the clouds on 23 June 1991 shown in Figure 1. The vertical line at 14 μm represents the precipitation threshold. The plotted lines are 15% (dashed), 50% (solid), and 85% (dashed) percentage of the r_e . Purple and red lines are for frames 1 and 2 of Figure 1, respectively. The cloud base is very high, and the effective radius for frame 2 (closer to the smoke) does not grow with height.

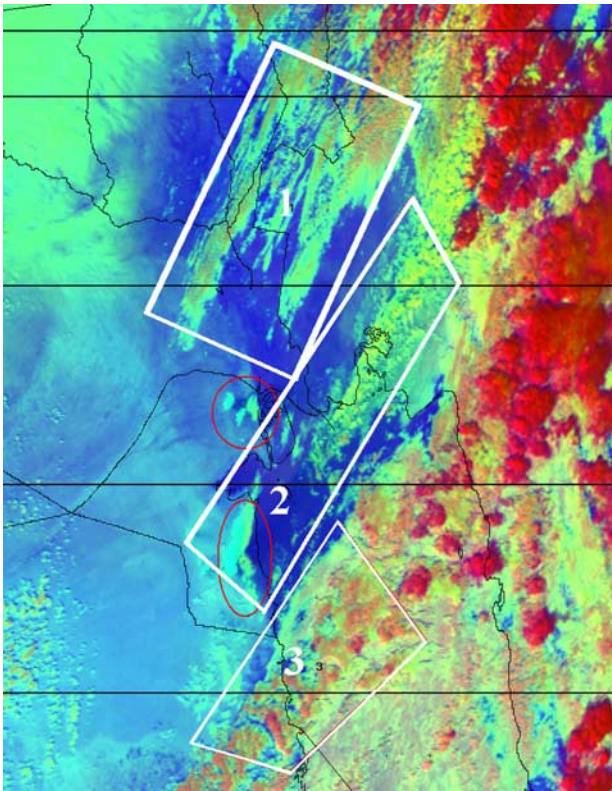


Figure 3. Same as Figure 1 but for the smoke in the area of Kuwait on 6 March 1991. The circles show the areas of the fires. The plume heads northeast. Frames 1 and 3 are smoke-free, while frame 2 is contaminated by the smoke. Analyses of the clouds in the frames are given in Figure 4.

difference between the clouds in frame 2 and in the other frames is that r_c does not increase with altitude, while clouds that formed in both bands outside the heavy smoke plume exhibit substantial growth with altitude. Although the

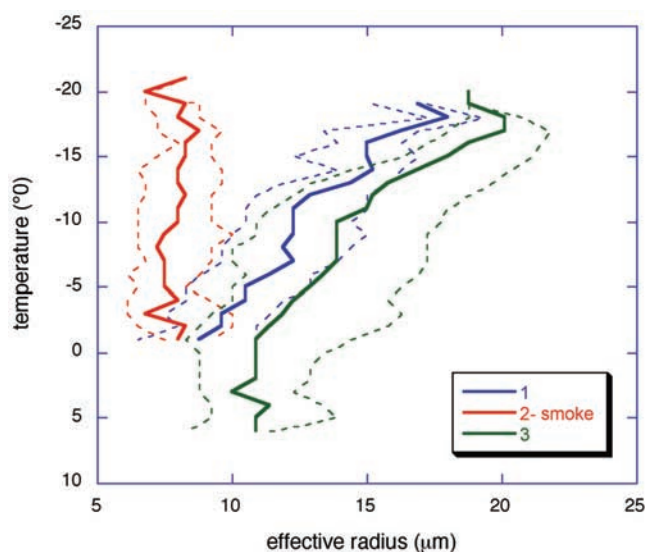


Figure 4. T - r_c plot of the clouds on 6 March 1991 shown in Figure 3. Blue, red, and green lines are for frames 1, 2, and 3, respectively. The red (contaminated clouds) line does not increase with altitude.

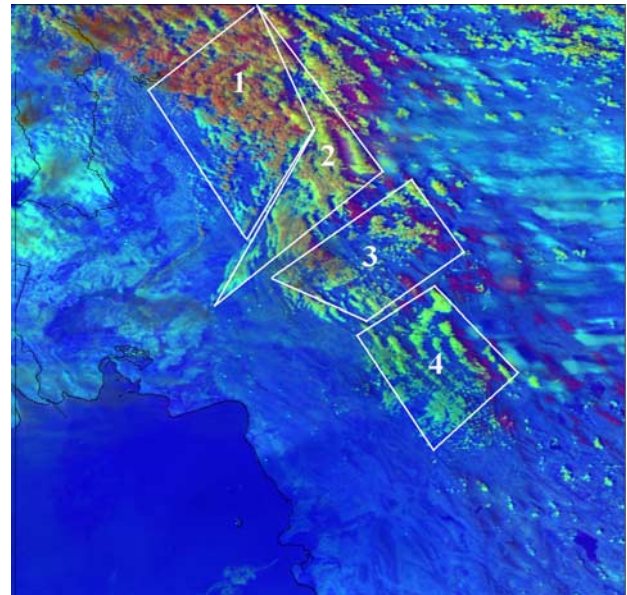


Figure 5. Same as Figure 1 but for the smoke plume on 10 March 1991. The purple spots are snow on the ground. Frames 1 and 2 are clouds that form in clean air, frame 3 is slightly contaminated, and frame 4 is contaminated by the smoke. Analyses of the clouds in the frames are given in Figure 6.

clouds in frames 1 and 2 have the same r_c near cloud base, they exhibit dramatically different growth pattern.

[13] 4. On 10 March 1991, the smoke plume extended about 420 km to the northeast, passing over the Zagros Mountains (Iran), creating orographic clouds (Figure 5). The clouds were exposed to the smoke in a gradient from north to south. The northernmost clouds (frames 1 and 2) were fed by clean air and they exhibit growth of r_c with altitude (Figure 6). The effective radius of clouds in frame 1 passed the 14 μm precipitation threshold at -19°C . The clouds in frame 2 did not have sufficient depth to reach the precipitation threshold, but their droplets size increase with altitude. The clouds in frame 4 form in the smoke plume and the droplets in these clouds do not increase with altitude. The effective radius above the cloud base is 5 μm at -9°C , and the cloud droplets do not grow even when they reach -20°C . The smoke plume, although not visible, may already affect the clouds in frame 3 as they behave similar to the cloud in frame 4.

[14] The analyzed T - r_c from all cases were divided into five categories according to their cloud base temperature: 10° to 5°C , 5° to 0°C , 0° to -5°C , -5° to -10°C , and -10° to -15°C . The T - r_c relationships are shown in Figure 7. Also shown in the figure (as dotted lines, similar colors) is the sample size for each trace. Since some of the clouds had their base inside the smoke plume, their r_c near cloud base may be slightly overestimated because of the strong absorption by the smoke. Nevertheless, we can still infer the growth of these cloud particles from the T - r_c curves.

[15] The analysis suggest that smoke-affected clouds with warm near-base cloud temperature (T_{base} between 10° and 5°C ; Figure 7a), exhibit the same r_c at cloud base and the same vertical profile as that as of clouds that form under clean conditions. The clouds presented in Figure 7a are all

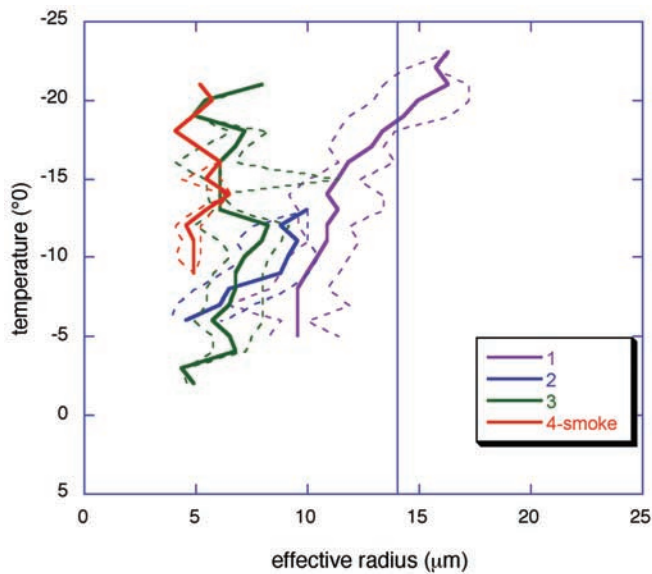


Figure 6. T - r_c plot of the clouds on 10 March 1991 shown in Figure 5. Purple, blue, green, and red lines are for frames 1, 2, 3, and 4 respectively. The green (slightly contaminated clouds) and the red (contaminated clouds) lines do not grow with height.

close to the source and at low altitude; therefore they are affected by the presence of giant CCN from the burning brines which cause the coalescence to develop in the clouds already at short distance above their base. In contrast, smoke-affected clouds that have $5 > T_{\text{base}} > -10^\circ\text{C}$ (Figures 7b–7d) have smaller r_c near cloud base and the growth of the droplets with altitude is strongly suppressed. While droplets in clouds that form in smoke-free regions grow gradually with altitude until freezing, the growth of cloud droplets in smoke-affected clouds is greatly suppressed. The r_c of the smoke-affected clouds remains small with height, and then at about -25° to -30°C abruptly increases to values typical of glaciated clouds. This suggests that coalescence is highly suppressed in these smoke-affected clouds, and that glaciation occurs without prior drop coalescence as in the clean clouds. Smoke-affected clouds with the lowest cloud base temperatures ($T_{\text{base}} < (-10^\circ\text{C})$) have slightly smaller r_c at cloud base than that of smoke-free clouds. With such cold bases, there is little room for coalescence before the occurrence of glaciation for both clean and smoky clouds, although some greater suppression of coalescence is noted for the smoke-affected clouds.

4. Discussion

[16] The dense smoke plume had several effects on cloud formation and properties. While the smoke led to cooling directly underneath and probably also to reduced convection originating from the boundary layer, clouds formed preferentially above the smoke and not in the vicinity. We suggest that these clouds form because of instability at the top of the smoke layer, driven by the strong absorption of solar radiation by the black smoke particles that warm the surrounding air. As a result, the heated smoke-laden air ascends and cools, leading to the formation of clouds

preferentially at the top and above the smoke-containing layer. Large instability at the upper part of the plume and immediately above it, as well as cooling of the air directly above the plume, were observed in situ by the research flights in 1991 [Herring and Hobbs, 1994]. Warming of the air because of dark pollution plumes from the Indian subcontinent was observed in the outflow from India [Ackerman et al., 2000], and was proposed to evaporate the clouds (i.e., the semidirect effect) instead of creating them as presented here. In fact, low-level cloud cover has slightly increased in that region between 1952 and 1996 [Norris, 2001]. It is possible that our proposed cloud formation mechanism may be dominating the semidirect effect in such scales as well. Large regional effects due to changes in the atmospheric vertical temperature profile caused by black carbon emissions from China were recently shown [Menon et al., 2002]. It is expected that dense biomass burning plumes from Africa and South America would also have such effects.

[17] The Kuwait smoke plume contained high concentration of particles with a broad size distribution and chemical composition. Close to the smoke source, large CCN were present in the plume because of the presence of large salt particles from the ejected brine. As the smoke ascended and drifted away from the source, two main processes were responsible for the evolution of the CCN spectrum: (i) Decrease in the number of large salt and dust particles, documented by in situ aircraft measurements [Parungo et al., 1992]; (ii) Formation of many small CCN, mainly by coating the small soot particles with sulfate and photochemical production of small sulfate aerosols [Hudson and Clarke, 1992; Parungo et al., 1992]. The changes in CCN spectra and their effects on the clouds properties was investigated by segregating the data, both in the smoke plume and in the smoke-free conditions, according to the cloud base temperatures. Lower cloud base temperature indicates clouds that form at higher altitudes, where it was shown that the aerosol size distributions truncated at smaller aerosol sizes [Parungo et al., 1992]. Unfortunately, the classification into five 5° intervals leaves us with only few cases in each T - r_c group. However, this data set represents all the available AVHRR data from the Kuwait smoke plume. Therefore the observations we discuss cannot be regarded as a statistical analysis but rather as an extended analysis of case studies. The observed trends, though, provide a consistent picture with a conceptual model that takes into account the opposite effects of the small and the giant CCN.

[18] Model studies [Feingold et al., 1999; Levin et al., 1996; Yin et al., 2000], recent remote sensing observations [Rosenfeld et al., 2002; Rudich et al., 2002] and cloud seeding experiments [Bruitjes, 1999] suggest that giant soluble CCN at cloud base could affect the cloud development. Giant CCN can produce larger droplets that grow rapidly at the expense of smaller droplets, initially by diffusion and then by efficient collision coalescence well above the cloud base. In addition, the presence of many large CCN reduces the critical supersaturation at the cloud base, preventing the activation of small CCN [Feingold et al., 1999]. Giant CCN, however, can still be activated to cloud droplets at even lower supersaturation. It is expected that large CCN should be most effective in initiating

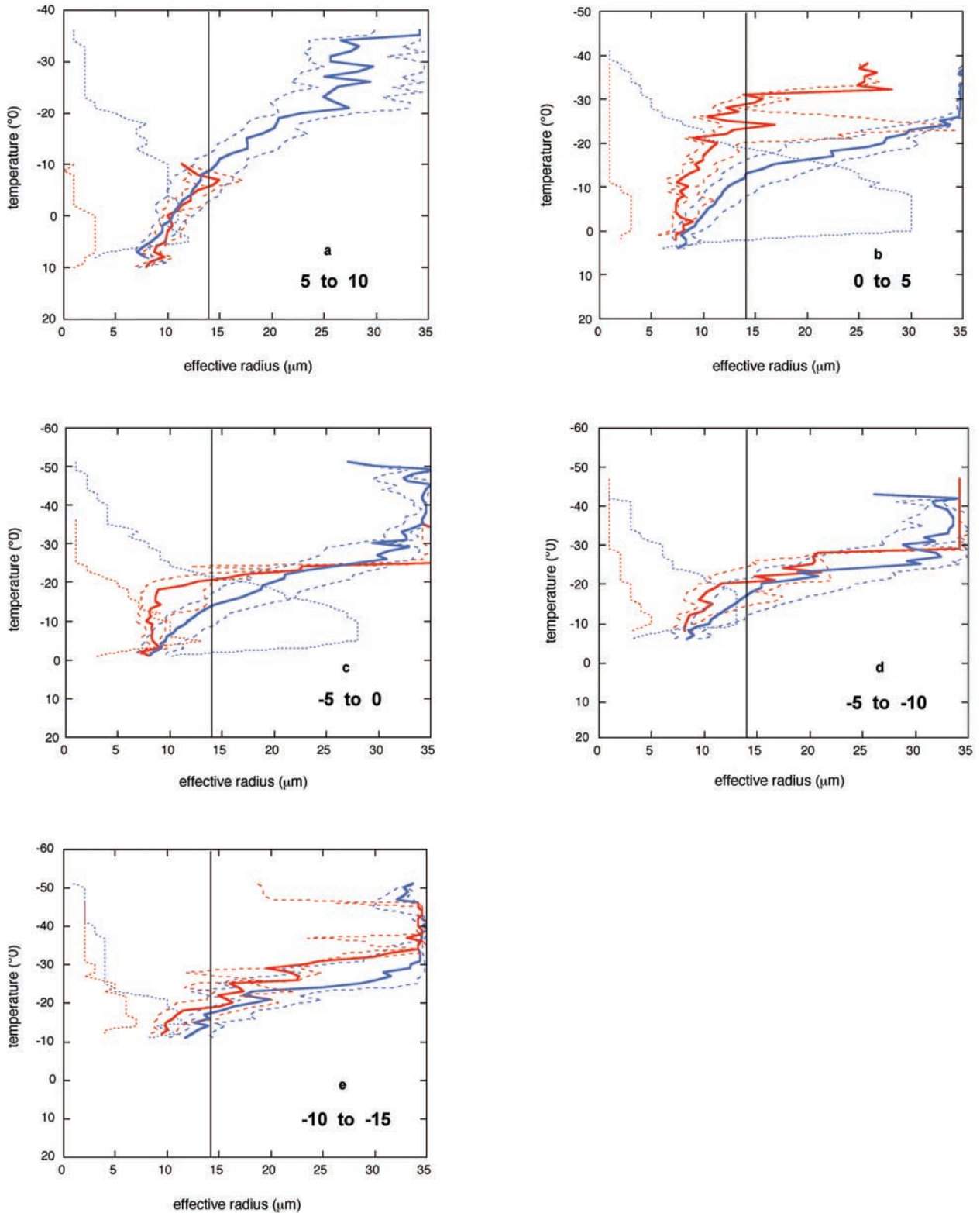


Figure 7. T - r_c plots segregated by near-cloud base temperature for clean and smoke-affected clouds. The average temperature (°C) versus effective radius (μm) of clean and contaminated clouds are shown in blue and red, respectively. The dashed lines are the 15% and 85% percentage of the r_c . The dotted lines represent the number of samples for each point (the same color coding, same X scale as r_c): (a) 10°–5°C, (b) 5°–0°C, (c) 0°–(–5)°C, (d) (–5°)–(–10)°C, and (e) (–10°)–(–15)°C.

precipitation on the background of many small droplets, such as in continental clouds [Feingold *et al.*, 1999; Yin *et al.*, 2000].

[19] The behavior of smoke-affected clouds with different cloud base temperatures can be understood in terms of the opposite effects of the GCCN and the high concentration of the small CCN. Close to the smoke source, the giant salt CCN nucleate large cloud drops at some distance above cloud base that initiate coalescence processes on the expense of the smaller CCN [Feingold *et al.*, 2001]. Therefore, at warmer cloud base temperatures and closer to the fires, r_c increases with decreasing T at the same rate as similar clouds forming outside the smoke (Figure 7a), despite the presence of the large numbers of small CCN in the smoke clouds. This is a similar situation to the clouds in the heavy salt dust storm rising from the dried lakebed of Aral Sea [Rudich *et al.*, 2002]. Further downwind or at higher altitude, the high concentration of small CCN dominate and the clouds behave as clouds that form in pollution plumes. Radiative effects which play a role in stratocumulus clouds [Nenes *et al.*, 2002] are not expected to be significant in these convective clouds.

[20] The background aerosols in the gulf region are composed primarily of desert dust, which make the background clouds already microphysically continental, with little coalescence [Rosenfeld *et al.*, 2001]. Desert dust was shown to act as ice nuclei (IN) at temperatures colder than -11°C . In situ and remote sensing measurements in convective clouds developing in heavy desert dust storm show that ice crystals develop below -12°C , and that clouds glaciate between -20° and -22°C [Rosenfeld *et al.*, 2001]. It was further shown (See the section “Aircraft Observations of Cloud-Dust Interactions” by Rosenfeld *et al.* [2001]) that the derived increase in the r_c at warmer temperatures was mainly due to the development of the ice phase and not due to coalescence. However, in the case of the Kuwait plume, the amount of dust in the background was below the threshold of detection as a “dust storm”. Therefore clouds that formed outside the plume showed some coalescence.

[21] The observed sharp increase in the effective radius with decreasing T observed for smoke-free clouds with $5 > T_{\text{base}} > -15^\circ\text{C}$ can be ascribed either to coalescence at $T > -5^\circ\text{C}$, or to the more likely development of ice phase at $T < -10^\circ\text{C}$ [Rosenfeld and Lensky, 1998]. The two effects are inseparable by the remote sensing techniques used here, because the ice phase develops faster in clouds with larger drops and more coalescence.

[22] In the smoke plume, many small aerosols are added to the background desert dust aerosols. It is observed that close to the source, the large CCN still dominate and compensate for the coalescence suppression effects of the small CCN, resulting in clouds that appear as if almost unperturbed. However, clouds that form in the smoke plume after the giant CCN sedimented contain very high concentrations of small drops than the background clouds. The coalescence and glaciation processes are therefore dominated by the high concentration of small CCN and are suppressed compared with the background clouds. This is manifested as smaller r_c near cloud base, as well as by the smaller increase of r_c with decreasing T . If the smoke particles are not a very efficient IN [Bertram *et al.*, 2002]

compared with the background desert aerosols, the higher concentration of CCN and small drops are expected to delay the glaciation of the polluted clouds to lower temperatures than in the background clouds, in agreement with the actual observations in many of the cases.

[23] To conclude, we can state the following.

[24] 1. Cloud microphysics is very susceptible to the presence of many small CCN, even on the background of highly continental air mass, and their effect extends from the warm phases (through suppression of coalescence) to delaying the freezing stage.

[25] 2. Giant CCN can restore the precipitation from highly polluted clouds, but their effect occurs on relatively small scale because of their fast deposition.

[26] 3. This implies that over land, smoke particles do not wash out efficiently and can be transported to long distances, extending the observed effects on a larger regional scale.

[27] 4. Large concentrations of small droplets delay clouds’ glaciation to as low as -30°C in spite of the ample ice nuclei in the form of the ambient mineral dust desert aerosols, suggesting the dominant role of CCN and cloud drop size distribution in the glaciation process of convective clouds.

[28] 5. Intense absorption of solar radiation by the smoke induces convection and formation of clouds with roots at the top of the smoke layer. This effect dominates the semidirect effect of clouds evaporation caused by the smoke-induced solar heating, at least in the case of the Kuwait fires.

[29] 6. This study demonstrates the important effects of aerosols transformations in the atmosphere and the role of multicomponent aerosols in modifying cloud properties.

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