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Treating clouds with a grain of salt

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[1] High concentrations of small atmospheric aerosols are known to reduce the size of cloud droplets, increase cloud albedo and suppress precipitation formation. In contrast, cloud simulations suggest that even low concentrations of large soluble aerosols should promote droplets' growth and rainfall. Until now, though, no observational evidence of such microphysical effects in natural circumstance over land has been presented. By using NOAA-AVHRR retrievals on cases where salt-dust from the Aral Sea interacts with clouds we show that large salt-containing dust particles increase cloud drops to sizes that promote precipitation. These findings are in line with the findings of the microphysical models and recent results from hygroscopic cloud seeding experiments for rain enhancement. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry. **Citation:** Rudich, Y., O. Khersonsky, and D. Rosenfeld, Treating clouds with a grain of salt, *Geophys. Res. Lett.*, *29*(22), 2060, doi:10.1029/2002GL016055, 2002.

1. Introduction

[2] Most small size aerosols types such as those of smoke from burning biomass, urban and industrial air pollution and desert dust reduce the size of cloud droplets [*Breon et al.*, 2002; *Rosenfeld*, 1999; *Rosenfeld*, 2000; *Rosenfeld et al.*, 2001], increase cloud albedo [*Albrecht*, 1989; *Twomey*, 1974] and suppress precipitation [*Ramanathan et al.*, 2001]. Cloud microphysical simulations, however, suggest that the presence of large soluble aerosols should induce opposite effects on clouds, namely increase droplets growth and promote precipitation formation [*Feingold et al.*, 1999; *Levin et al.*, 1996; *Reisin et al.*, 1996; *Yin et al.*, 2000]. These models conclude that while drizzle production *decreases* with increasing cloud condensation nuclei (CCN) concentration, the relative impact of giant CCN (GCCN) *increases* with increasing CCN concentration [*Feingold et al.*, 1999], implying that the strongest effects of introducing giant CCN occur when the background concentration of small nuclei is high, as that in continental clouds [*Yin et al.*, 2000].

[3] Due to the usually low ambient concentrations of large hygroscopic aerosols over land, observational evidence to this process of increasing coalescence and precipitation has not been observed until now in continental aerosols over land, with the exception of some very unique industrial emissions [*Hindman et al.*, 1977] and advertent hygroscopic cloud seeding [*Bruintjes*, 1999]. Most observations until now showed that continental aerosols largely suppress cloud droplets' growth. Salt-dust storms from the dry seabed of the desiccated Aral Sea provide the opportunity to show that natural salt-containing aerosols increase cloud drop sizes and enhance precipitation-forming processes on large continental scale. This has been recently observed also over land when sea salt aerosols interact with polluted air from continental origin [*Rosenfeld et al.*, 2002].

[4] The Aral Sea in central Asia can serve as a natural laboratory for studying the effects of the salt- dust storms on cloud microphysics and rain production mechanisms. The Aral Sea shrank by 40% since the 1960s (see Figure 1), exposing salty dried seabed and increasing the lake water salinity by a factor of 3 to 27 g/liter [*Micklin*, 1988]. As a result, the fragile and mobile surface at the central eastern shores of the dried sea became an active source for massive salt-containing dust storms reaching the height of 1200-m above ground [*Rafikov*, 1999]. The salt content of the dust is 30–40% in summer and close to 90% in winter. The dust also interacts with rain-producing systems, and the rainwater salinity in the region increased from 50 ± 20 mg/l measured in the 1960's up to 180 mg/l in the mid 1990's [*Razakov and Kosnazarov*, 1996].

[5] The size distribution and chemical composition of the salt-dust of the Aral Sea can be inferred from analysis of collected samples of desiccated sea bottom crust [*Singer et al.*, 2001; *Singer et al.*, 2002]. The soil of the desiccated sea bottom is dominated by silt (2–50 μm diameter) and fine sand (50–200 μm diameter), with a very low organic carbon content, less than 10% $CaCO_3$ and between 50 to 65% soluble salts [*Singer et al.*, 2002]. Chlorine and sulfate are the dominant anions of these soluble salts, with 5–10 μm crystallites [*Singer et al.*, 2001]. The size distribution of the dry salt-dust (by % volume of the dust sample) has a maximum at 3.8–6 μm, depending on the amount of salt in the soil and is shown in Figure 2 [*Singer et al.*, 2002]. The distribution extends down to 0.05 μm and up to 30 μm in particle diameter. The PM_{10} and $PM_{2.5}$ yield of the samples are ~70% and ~35%, respectively [*Singer et al.*, 2002].

2. Results and Discussion

[6] The interaction of salt-dust with clouds was studied using the methodology in which the effective radius of cloud droplets (r_e) near the top of deep convective clouds at various stages of their vertical development is retrieved

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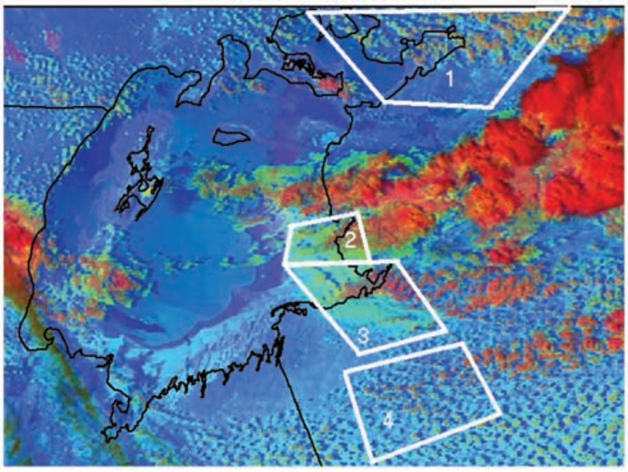

Figure 1. NOAA -AVHRR satellite image (11 May 1998 09:32 UT) showing clouds forming in salt-dust plumes off the eastern shores of the Aral Sea (frames 2 and 3). Clouds outside the dust storm are shown in frames 1 and 4. The visible channel modulates the red, the 3.7 μm reflectance component modulates the green, and the temperature modulates the blue. Therefore, clouds with large droplet sizes appear in red while yellow clouds have smaller droplet sizes. The dust is the intense yellow blur. The warm and dark surface background appears in blue. In addition to showing the microphysical effects of salt dust on clouds, the figure exemplifies the extent of the Aral Sea shrinking (The black outline of the coastline is from 1980, and the actual 1998 coastline).

from the NOAA-AVHRR satellite [*Rosenfeld and Lensky*, 1998]. The results are presented quantitatively in T-r_e graphs in which satellite-retrieved effective radii (r_e) of the cloud droplets are shown as a function of the cloud top temperature, which serves as a surrogate for cloud top height.

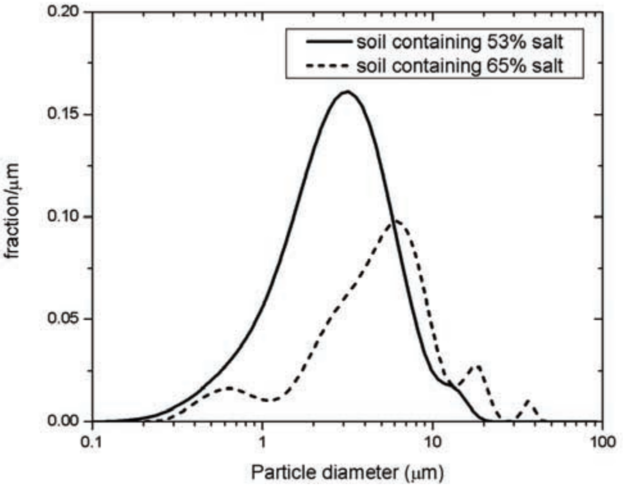

Figure 2. Size distributions of dust generated from two dry soil samples with different salt content collected from the dried seabed of the Aral Sea [*Singer et al.*, 2002]. The values on the ordinate are the percent of the original sample.

[7] Figure 1 shows a case of clouds directly developing in heavy salt-dust plumes originating from the source area in the eastern Aral shores (May 11, 1998). The salt-dust plumes are easily seen as yellow blur. The clouds that develop in the salt-dust plumes (areas 2 and 3, Figure 1) appear in dark red colors, indicating large r_e. Undisturbed background clouds are to the north and to the south of the dust storm areas (Regions 1 and 4). These clouds are more yellow, in comparison, indicating smaller r_e. Figure 3 presents satellite-retrieved T-r_e relationships (the four lines pertain to cloud properties in the four respectively marked areas in Figure 1). It is clearly observed that the undisturbed clouds in the adjacent regions have similar near-cloud base temperatures and the same vertical extent, suggesting that they also have comparable liquid water content. The lowest and warmest parts of the clouds that form in the heavy salt-dust have smaller r_e than the clouds in the dust-free air, suggesting that the initial number concentration of the cloud drops is larger in the dust-affected clouds. However, the r_e of the dust-affected clouds increases very quickly with cloud depth (i.e., with decreasing T) whereas the r_e of the dust-free clouds increases only slightly with cloud depth.

[8] The interaction between the clouds and the salt-dust in Figure 1 is clearly observed, and the effect is very conspicuous. The impact of 24 to 36 hours long-range transport of the salt-dust on developing clouds is still apparent, but to a lesser extent, in a different case shown in Figure 4. According to low-altitude (<1000 meters) back-trajectory calculations (using the NOAA-HYSPLIT4 model, (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model, 1997. Web address: http://www.arl.noaa.gov/ready/hysplit4.html, NOAA/ARL, Silver Spring, MD.), the sub-

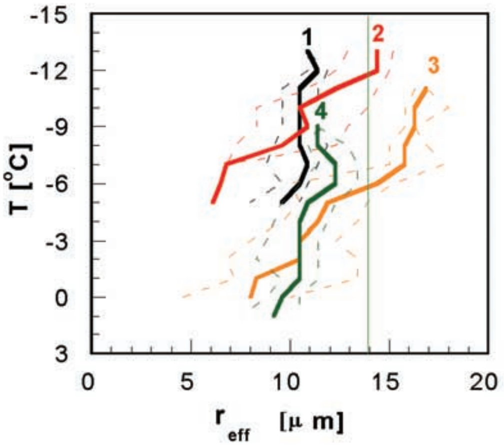

Figure 3. T-r_e relationship for the clouds in the 4 areas shown in Figure 1. T is the temperature and r_e is the cloud particle effective radius. The solid lines show the median r_e for a given T, and the broken lines show the 15th and 85th percentiles. The vertical green line marks the 14-μm precipitation threshold. Curves 2 and 3 for clouds forming in heavy salt-dust show smaller near-cloud-base r_e and much larger cloud-top r_e compared to background clouds of comparable depths (curves 1 and 4). Curves 5 and 6 belong to clouds outside the salt-dust plumes. This analysis shows the fast growth of cloud droplets with height above cloud base.

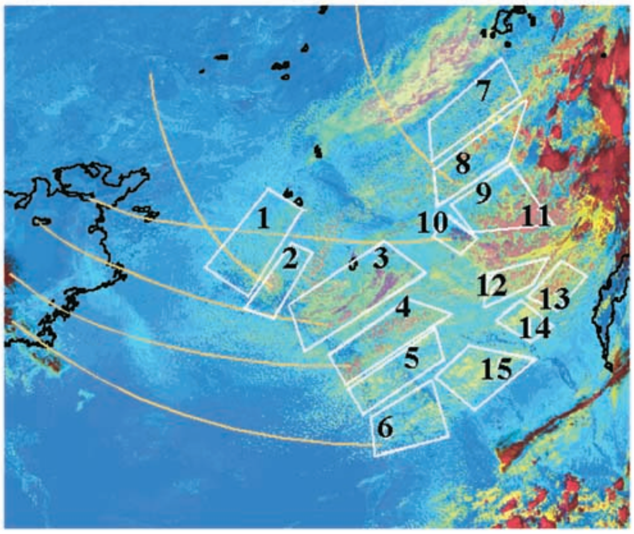

Figure 4. NOAA-AVHRR satellite image (July 5 1997 09:25 UT) showing the effect of long-range transport of salt-dust from the Aral Sea using the same color scheme as in Figure 1. The clouds in frames 3, 4, and 9–14 formed in the dust, as was verified by 24 to 36 hours back trajectory calculations (some of them shown in yellow lines). A dust plume coming off the central eastern shores of the Aral Sea is still observed.

cloud air flows from the central and northern shores of the Aral Sea to areas 3, 4, and 10–11 in Figure 4. The clouds in areas 1,2,5–8,14 and 15 formed in dust-free air according to the back trajectories. The clouds in areas 9, 12 and 13 are partially affected by the dust. The clouds in these areas have small r_e near their base, which increases steeply with cloud depth (the T-r_e plots are shown in Figure 5), but not as steeply as the clouds that feed directly from the heavily concentrated dust shown in Figure 1. The inferred dust is present at concentrations too low to be visibly observed. Back trajectory simulations for these clouds show that the air mass originated in the central eastern shores of the Aral Sea about 24 hours earlier (Figure 4, yellow lines), coinciding with a large dust storm that is clearly observed by satellite a day earlier. Ground observations from meteorological stations in Chimbay, Uzbekistan (42.57°N, 59.47°E), situated south of the Aral Sea, also reported several intense dust storms on both July 4 and 5, 1997, overlapping in time with the back trajectories [*Argaman*, private communication]. The clouds in the areas to the north and to the south of the inferred dust plume behave as normal continental clouds, with small near-cloud base r_e and little increase with cloud height (Figure 5, areas 1,2,5–8,14 and 15). The corresponding back trajectory calculations show that the air masses of these clouds did not cross the dust source areas at the eastern shores of the Aral Sea.

[9] These observations provide insight to the effect of the salt-dust on cloud microphysics. Here we encounter a case where visibly high concentrations of large and soluble particles (>0.3 μm diameter [*Singer et al.*, 2002]) with high salt content are present. Figure 3 shows that under conditions of heavy salt-dust loading (areas 2 and 3) r_e is small near cloud base (r_e < 8 μm, T = 0–2°C). However, r_e grows rapidly with height to more than 14-μm, the precipitation threshold [*Albrecht*, 1989; *Rosenfeld and Gutman*, 1994; *Rosenfeld et al.*, 2002], at the −10°C isotherm level. Clouds that develop far downwind of the salt source apparently ingest cleaner air containing less salt-dust, but still show the same increase of r_e with depth (lines 3, 4, and 9–13 in Figure 4) compared to the background clouds. The near-cloud-base r_e is larger than that of the background clouds, in contrast to the clouds in the concentrated salt dust.

[10] The satellite and granulometric dust observations are consistent with the following conceptual model: The dust close to the source supplies large concentrations of medium sized CCN in addition to the very large salt particles (∼ 0.5 μm and ∼5–10 μm, respectively) [*Singer et al.*, 2001; *Singer et al.*, 2002]. The numerous ∼0.5-μm salt particles

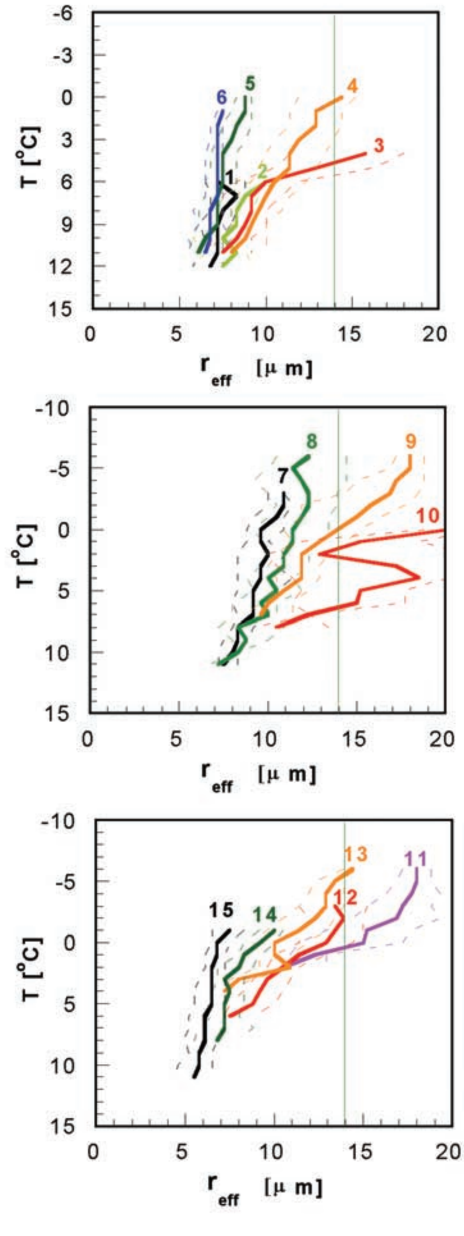

Figure 5. Analysis of the T-r_e relations for the clouds shown in Figure 4.

can nucleate cloud drops already at supersaturation <0.05%, yielding large concentrations of cloud drops at near-cloud base, in spite of the presence of the very large salt particles that reduce the supersaturation. Cloud microphysical modeling studies already noted that the presence of a few large and giant CCN [*Feingold et al.*, 1999; *Reisin et al.*, 1996; *Yin et al.*, 2000] can promote raindrops formation, and that the effect is larger for continental clouds. The giant and ultra giant CCN are activated at much lower supersaturation than the smaller particles and they grow more efficiently at the expense of the smaller droplets by diffusion and by efficient collision-coalescence well above cloud base [*Feingold et al.*, 1999; *Feingold et al.*, 2001; *Yin et al.*, 2000]. Subsequently r_e exceed the 14-μm precipitation threshold and rain drops can form (Figure 1, areas 2,3) [*Feingold et al.*, 1999; *Reisin et al.*, 1996; *Yin et al.*, 2000].

[11] In the case of more dilute dust, the lower dust concentrations lead to lower concentrations of cloud droplets that form on the dust particles, but the dust still reduces the maximum supersaturation at cloud base and prevents nucleation of the ambient small CCN [*Feingold et al.*, 1999; *Feingold et al.*, 2001]. This leads to lower concentrations and larger sizes of cloud base droplets, followed by enhanced coalescence at warm temperatures, as evident in areas 3,4 and 9–13 in Figure 4 and 5. Rain will develop through broadening of the droplet spectrum into drizzle, as opposed to the formation of rain drops on ultra-giant CCN without the general broadening of the droplet spectrum.

[12] It is clearly demonstrated here, for the first time, that in the case of the salt-dust storms in the Aral Sea, the aerosols do not lead to reduction in the cloud droplet radius as was previously shown for Saharan dust [*Rosenfeld et al.*, 2001] and other aerosols [*Breon et al.*, 2002; *Rosenfeld*, 1999; *Rosenfeld*, 2000] but rather promote their growth. In the Saharan dust case studies, the ambient aerosol contained only small amounts of soluble material and most of the aerosols were in the submicron size range [*Falkovich et al.*, 2001; *Rosenfeld et al.*, 2001]. In the case of the Aral dust storms, the opposite observed effect is attributed to the presence of large and highly soluble aerosols.

[13] The case studies presented here are unique as they directly link the presence of salt containing large dust particles with cloud properties. They serve as a natural laboratory showing how the addition of giant and ultra giant CCN to the continental atmosphere can enhance precipitation-formation processes. Furthermore, if the conceptual model is correct, it seems that rather low concentrations of salt dust can already be quite effective. These observations show that recent smaller scale hygroscopic seeding experiments [*Bruintjes*, 1999] apparently replicate what nature already does on its own on a large scale.

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