AIRCRAFT MEASUREMENTS OF THE IMPACTS OF POLLUTION AEROSOLS ON CLOUDS AND PRECIPITATION OVER THE SIERRA NEVADA

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ABSTRACT

Recent publications suggest that anthropogenic aerosols suppress orographic precipitation in California and elsewhere. A field campaign (SUPRECIP: Suppression of Precipitation) was conducted to investigate this hypothesized aerosol effect. The campaign consisted of in situ aircraft measurements of the polluting aerosols, the composition of the clouds ingesting them, and the way the precipitation-forming processes are affected. SUPRECIP was conducted during February and March of 2005 and February and March of 2006. The flights documented the aerosols and orographic clouds flowing into the central Sierra Nevada from the upwind densely populated industrialized/urbanized areas and contrasted them with the aerosols and clouds downwind of the sparsely-populated areas in the northern Sierra Nevada.

SUPRECIP found that the aerosols transported from the coastal regions are augmented greatly by local sources in the Central Valley resulting in high concentrations of aerosols in the eastern parts of the Central Valley and the Sierra foothills. This pattern is consistent with the detected patterns of suppressed orographic precipitation, occurring primarily in the southern and central Sierra Nevada, but not in the north. The precipitation suppression occurs mainly in the orographic clouds that are triggered from the boundary layer over the foothills and propagate over the mountains. The elevated orographic clouds that form at the crest are minimally affected. The clouds are affected mainly during the second half of the day and the subsequent evening, when solar heating mixes the boundary layer up to cloud bases. Local, yet unidentified non-urban sources are suspected to play a major role.

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1. INTRODUCTION

Anthropogenic aerosols from major coastal urban areas pollute the pristine maritime air masses that flow inland from the sea and bring much of the precipitation, especially over the mountain ranges. Satellite observations indicated that urban aerosols reduce cloud drop effective radii (r_e) and suppress both warm and mixed phase precipitation in the clouds downwind of the urban areas (Rosenfeld, 2000). This prompted studies that quantified the precipitation losses over topographical barriers downwind of major coastal urban areas in the western U.S (particularly in California) and in Israel. These results suggested losses of 15 – 25% of the annual precipitation over the western slopes of the hills (Givati and Rosenfeld, 2004, 2005; Rosenfeld and Givati, 2006, Givati and Rosenfeld, 2007, Rosenfeld et al., 2007). The suppression occurs mainly in the relatively shallow orographic clouds within the cold air mass of cyclones. The suppression that occurs over the upslope side is coupled with similar percentage enhancement on the much drier down slope side of the hills.

These results are consistent with other studies that have shown that higher cloud condensation nuclei (CCN) concentrations increase cloud droplet concentrations, decrease cloud droplet sizes, reduce droplet coalescence and thus precipitation (e.g., Hudson and Yum 2001; McFarquhar and Heymsfield 2001;Yum and Hudson 2002; Hudson and Mishra 2007). Therefore CCN from air pollution could be incorporated into orographic clouds, slowing down cloud-drop coalescence and riming on ice precipitation, hence delaying the conversion of cloud water into precipitation. The evidence includes significant decreasing trends of the ratio of hill / plains precipitation during the 20th century in polluted areas. Aerosol measurements from the IMPROVE aerosol monitoring network in the western U.S showed that the negative trends in the orographic precipitation are associated with elevated concentrations of fine aerosols (PM2.5). No trends are observed in similar nearby pristine areas (Givati and Rosenfeld, 2004).

In Central California the main precipitation suppression is postulated to occur during westerly flow that ingests anthropogenic CCN, which are incorporated into orographic clouds that form over the Sierra Nevada and are so shallow that their tops do not fully glaciate before crossing the mountain crest. This means that at least some of the water in these clouds remains in the form of cloud droplets that are not converted to precipitation (or at least ice hydrometeors) before crossing the divide, and hence re-evaporate after producing some precipitation on the downwind side of the crest. Recent model simulations support this hypothesis (Lynn et al., 2007; Woodley Weather Consultants, 2007).

Clouds with very cold base, near 0°C, already form as supercooled clouds with little room for rainout. In such clouds only quite pristine conditions would produce excess of precipitation embryos that would compete on the available cloud water and prevent the formation of hail. Already moderate concentrations of aerosols can suppress the formation of ice precipitation embryos to the extent that hail is substantially reduced.

2. THE SUPRECIP PROGRAM

Following the publication of many of the recent findings cited above a research effort called the Suppression of Precipitation (SUPRECIP) Program was conducted to make in situ aircraft measurements of the polluting aerosols, the composition of the clouds ingesting them, and the way the precipitation-forming processes are affected. The SUPRECIP field campaigns were aimed at making the measurements necessary for the validation of the above hypothesis that urban air pollution suppresses orographic precipitation.

SUPRECIP was conducted during February and March of 2005 (SUPRECIP 1) and February and March of 2006 (SUPRECIP 2). The Seeding Operations and Atmospheric Research (SOAR) Cheyenne II, turbo-prop, cloud physics research aircraft was used in SUPRECIP-1; the Cheyenne and an additional (SOAR) Cessna 340 aerosol aircraft were flown in SUPRECIP-2. These aircraft were used to measure atmospheric aerosols in pristine and polluted clouds and the impact of the aerosols on cloud-base microphysics, on the evolution with height of the cloud drop-size distribution and on the development of precipitation under warm and mixed-phase processes. They were used also to validate the multi-spectral satellite inferences of cloud structure and the effect of pollutants on cloud processes, especially the suppression of precipitation. This research effort is funded by the PIER (Public Interest Energy Research) Program of the California Energy Commission.

The Cheyenne II cloud physics aircraft that was used in SUPRECIP. The instruments and respective data sets taken by the aerosol and cloud physics airplanes included measurements of cloud microstructure, CN and CCN aerosols. The flights of these aircraft documented the aerosols and orographic clouds downwind of the densely populated areas in the north-central Sierra Nevada and contrasted them with the aerosols and clouds downwind of the sparsely-populated areas in the far northern Sierra Nevada.

3. A CASE STUDY

The linkage between ingested sub-cloud aerosols and cloud microphysics is best illustrated by a case study on the afternoon of February 28, 2006. A cold front had passed through the area the previous night and a post-frontal cold air mass moved from the west southwest over all of Central California by the following afternoon. Post-frontal instability caused convective clouds over the ocean, and triggered convective clouds over the coastal hills and over the Sierra Nevada. Although the instability decreased gradually during the day, rain showers from shallow clouds were still occurring over the ocean and the coastal ranges at 00Z on 1 March 2006. Figure 1 shows the Oakland radiosonde at that time.

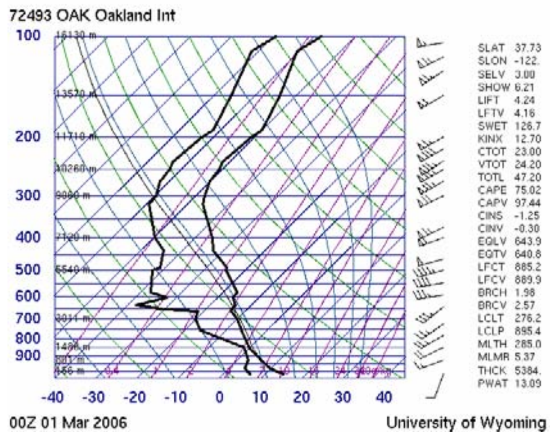


Figure 1: The Oakland radiosonde of 1 March 2006 at 00Z, which is near the time that the aircraft flew near Oakland.

A coordinated mission of the Cloud and Aerosol airplanes originated from the Sacramento Executive Airport to document the gradient in aerosols and cloud properties by doing cross sections from the Sierra Nevada to and from the Pacific Ocean. The aircraft departed Sacramento at 23:05Z and flew due east to the foothills and measured the convection generated there by the mountains. The next destination was the clouds that formed over the hills bounding the Central Valley to its west, about 60 km to the NE of Monterey. Next the aircraft sampled the clouds forming over the hills just at the Pacific coast at Big Sur. There the aircraft continued 35 km westward over the ocean and then turned north to measure convective clouds that were triggered by the ocean shoreline of San Francisco. Then the aircraft turned east over the north part of San Francisco Bay and measured a cloud just inland over Richmond, and then another cloud over Sacramento before finally landing. The tracks of the two aircraft and the locations of the measured clouds are provided in Figure 2.

The aerosol aircraft measurements are summarized in Figure 2. Because the supersaturation (or the temperature difference between the plates, dT) in the Cloud Condensation Nuclei Counter cycles every ~7 minutes, there was a need to correct the CCN data measured at low supersaturations to a common SS. Without correction or adjustment there would be too few data points measured at the same SS. In order to do this, it was necessary to find the relation between dT (instead of SS) and the CCN concentration for each flight separately, because this relation might be affected by the chemical composition of the aerosols, their sizes and their concentrations. After determining and applying the correction, the CCN concentrations were plotted for an entire flight to a common 0.85% SS for measurements in the boundary layer. On average, the ratio of CCN counts at super saturations of 0.85% and 0.5% was 1.89 with a standard deviation of 0.4.

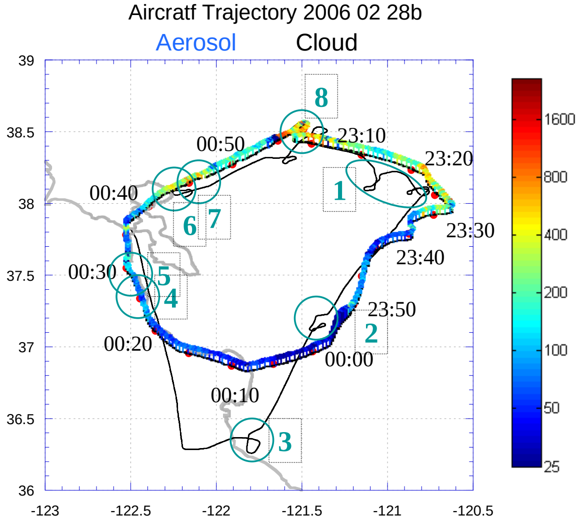


Figure 2: The tracks of the Cloud (black) and Aerosol (colored) airplanes. The time marks every 5 minutes are posted on the aerosol aircraft tracks, and labelled every 10 minutes. The CCN concentrations adjusted to supersaturation of 0.9% are shown in the color scale. The relative height of the aerosol aircraft above sea level is shown by the vertical displacement of the track. The measured clouds by the cloud physics aircraft are marked with green circles and numbered sequentially.

The aircraft aerosol measurements show CCN concentrations varying between 300 and 800 cm-3 over the first section to the SE at the western slopes of the Sierra Nevada. The CCN concentrations fell to about 100 cm^{-3} over the hills 60 km NE of Monterey, and continued falling to less than 40 cm^{-3} over Monterey Bay and likely also over Big Sur. The CCN increased again gradually to the north along the coastline and reached about 70 cm^{-3} there. They kept rising to about 100 cm^{-3} over the peninsula of San Francisco airport, and jumped locally to 800 cm^{-3} just to the north of the airport, but recovered back to less than 80 cm^{-3} to the north of the Golden Gate Bridge. The aircraft turned to the east and experienced a sharp increase of the CCN to more than 700 cm^{-3} over Richmond. The condensation nuclei (CN) then shot up > 10,000 cm^{-3}. This suggests an ample source of fresh small aerosols. The CCN remained generally above 500 cm-3 within the boundary layer all the way to landing in Sacramento.

The cloud- and precipitation particle size distributions are given in Figures 3-7. Cloud 1 was sampled stepping upward from base through its upshear towers, whereas its more mature portions glaciated and precipitated. Due to air traffic control limitations it was necessary to use different clouds in the same area for the lower and upper portions of the cross sections. The modal liquid water cloud drop diameter (D_L, defined as the drop diameter having the greatest

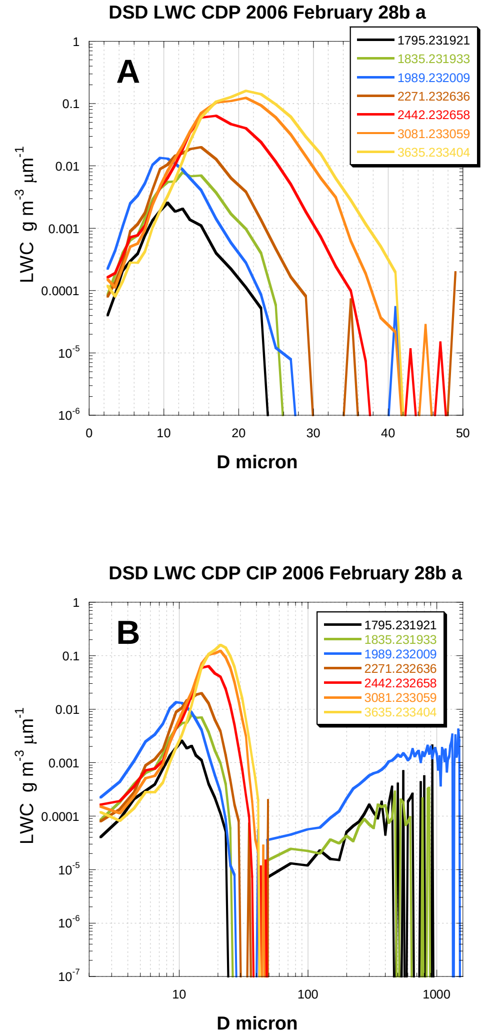


Figure 3: Plot of cloud droplet diameters as a function of liquid water content (LWC) for Cloud 1 over the western slopes of the Sierra Nevada (see location in Figure 2). The modal liquid water drop diameter occurs at the droplet size having the greatest water content. Cloud 1 developed in an air mass that had 300-800 CCN cm^{-3}. Panel A shows the Cloud Droplet Probe (CDP) measured LWC distribution. Each line represents the gross cloud drop size distribution of a whole cloud pass. The legend of the lines is composed of the pass height [m] to the left of the decimal point, and the pass starting GMT time [hhmmss] to the right of the point. The passes are ordered in altitude ascending order. Note the increase in cloud drop volume modal size with increasing cloud depth. Panel B shows the combined distributions of the CDP and the cloud imaging probe (CIP). According to the figure the large precipitation particles were well separated from the cloud drop size distribution, indicating lack of appreciable coalescence.

LWC) increased with height above cloud base. It reached 21 μm at the altitude of 3635 m, which is about 1900 m above cloud base. The temperature there was -8°C. This size is below the D_L threshold for the development of warm rain that was documented elsewhere as 24 μm (Andreae et al., 2004). In agreement with that, the D_L did not expand to drizzle size. Large precipitation particles occurred as graupel and formed a well separated distribution at the 1-mm size range (Figure 3).

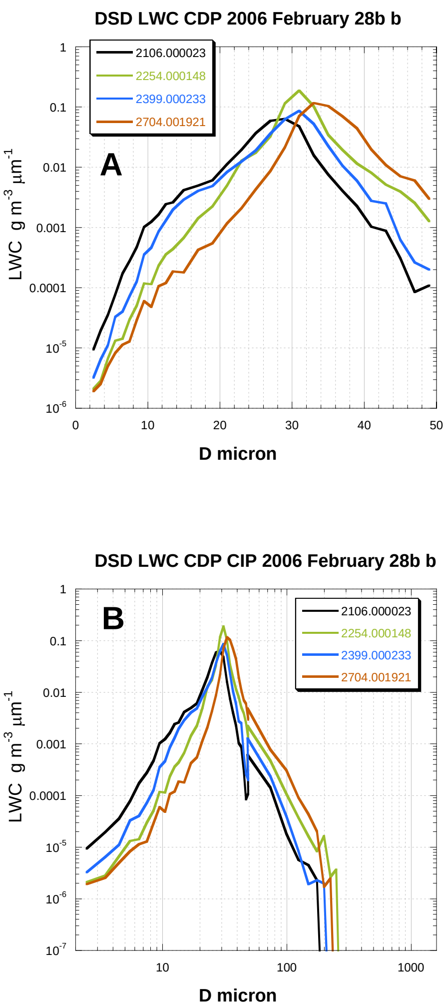


Figure 4: Same as Figure 3, but for Cloud 2 over the hills 60 km NE of Monterey (see location in Figure 2). It developed in an air mass that had 100 CCN cm^{-3}. The cloud drops are quite large and the distribution continues smoothly into the rain drop sizes. This indicates active warm rain processes.

From the location of Cloud 1 the aircraft was flown diagonally to the southwest and across the Central Valley. The valley was mostly cloud-free, except for some mid-level layer clouds. The next area of clouds was triggered by the ridge that bounds the Central Valley on its west. The cloud tops had a convective appearance and were sampled at the lowest allowed altitude - (2100 m, to provide safe-ground clearance over the highest terrain) up to the cloud tops at 2700 m. The temperature there was -3°C, but the maturing clouds were visibly turning into a diffused fibrillation texture, indicating the conversion of the cloud water to precipitation and/or ice crystals. Glaciation would be in such case produced probably by a mechanism of ice multiplication. The modal LWC drop size was 28 μm at 2100 m and reached 33 μm at the cloud top at 2700 m. This is clearly beyond the threshold (D_L = 24 μm) for warm rain (Gerber 1996; Yum and Hudson 2002). In agreement with that, the cloud droplet size distribution (DSD) was extended smoothly to the drizzle and small rain drop sizes, as measured by the CIP and presented in the panel B of Figure 4. The appearance of the warm rain is consistent with the decrease of the CCN concentrations to about 100 cm^{-3}.

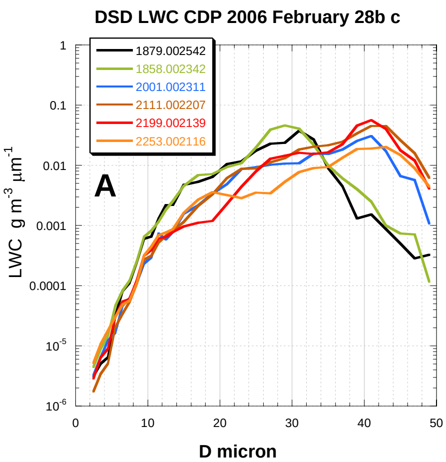
The aircraft continued flying to the SW to the next area of clouds (cloud 3). These were triggered by the coastal hills near Big Sur. The aircraft stepped vertically through the convective- looking cloud tops from the lowest safe height of 1880 m to their tops at a height of 2250 m at temperature of -3°C. The CCN concentrations as measured by the aerosol aircraft in Monterey Bay varied between 20 and 50 cm^{-3}. These low CCN concentrations produced large cloud drops ranging from a modal LWC drop diameter of 30 μm at 1880 m to 43 μm at the cloud tops. The DSD extended smoothly into drizzle and small rain drops (see Figure 5). Large hydrometeors were nearly absent. The cloud drops were so large so that the solar radiation reflected from the particles near the cloud top formed a cloud bow. These clouds had clearly created active warm rain.

From Big Sur the flight continued over the ocean and then turned north and flew at a constant altitude across Monterey Bay to the Golden Gate and then eastward back to Sacramento. This flight path took the aircraft along an aerosol gradient that increased from pristine over the ocean to polluted air just to the east of San Francisco Bay. Convective clouds grew along that flight path and reflected the impact of the changing CCN concentrations at that fixed altitude. Clouds 4 to 8 were penetrated along this gradient flight (Figure 6).

Cloud 4 was penetrated at the coastline of the peninsula to the west of San Francisco. The CCN concentration there was about 70 cm-3 and the cloud had a DL of 31 μm and created warm rain. A faint cloud bow was barely visible. Cloud 5 was penetrated a short distance to the north, where the CCN increased to 100 cm^{-3}. Cloud 5 still had warm rain, but to a lesser extent than Cloud 4. Shortly after passing directly over San Francisco International airport, over the Golden Gate Bridge, a short jump in the CCN occurred to about 600 cm^{-3} and recovered to the background of < 70 cm^{-3}.

The aircraft turned east and crossed the northern arm of San Francisco Bay. The CCN concentrations increased to about 300 cm^{-3} shortly after crossing the coast line. Cloud 6 formed over the eastern part of Richmond. Its modal LWC DSD decreased to 17 μm, well below the warm rain threshold of 24 μm. The CIP confirmed that this cloud had no precipitation particles. This occurred less than an hour after the time of the Oakland sounding at 00Z, which represented pretty well the local conditions and showed light southwesterly winds near the surface that veered to stronger west-southwest winds at the higher levels.

Cloud 7 occurred a few km farther east of cloud 6, where the CCN concentrations increased to 600 cm^{-3}. Its DL decreased further to 15 μm. Cloud 8 developed farther east over Sacramento, where the CCN concentration varied between 600 and 1000 cm^{-3}. The cloud had a similar microphysics to cloud 7. A vertical stepping through cloud 8 showed little widening of the DSD with height (Figure 7), which serves as an additional indication of the scarcity of coalescence in that cloud.



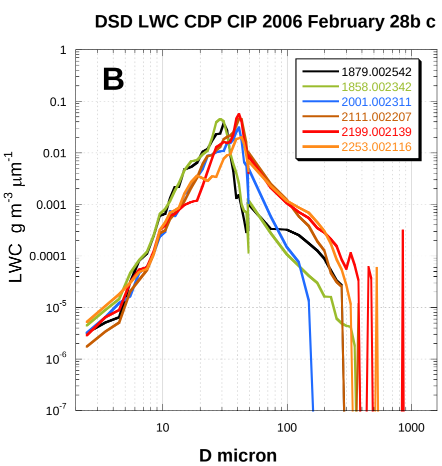
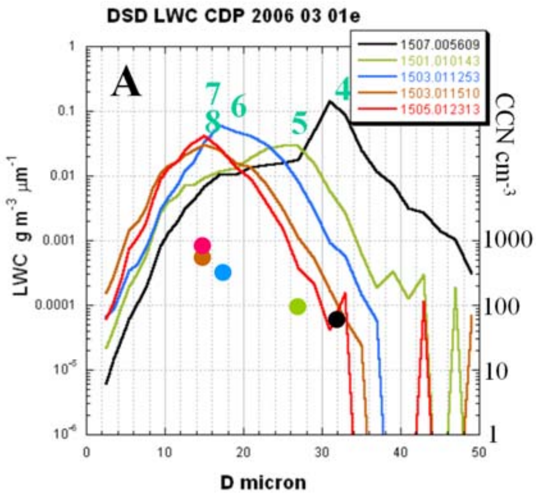


Figure 5: Same as Figure 3, but for Cloud 3 over the hills near Big Sur (see location in Figure 2). It developed in an air mass that had about 40 CCN cm^{-3}. The cloud drops are very large and the distribution continues smoothly into the rain drop sizes. This indicates very active warm rain processes.



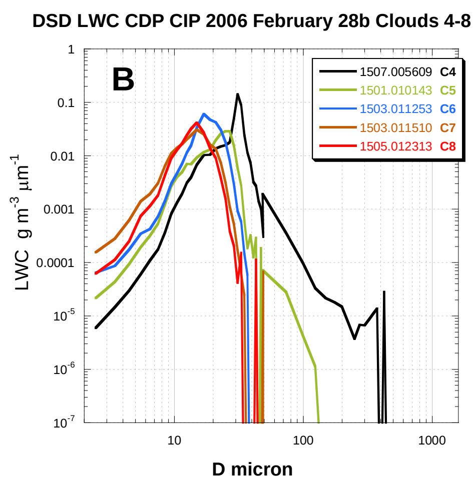
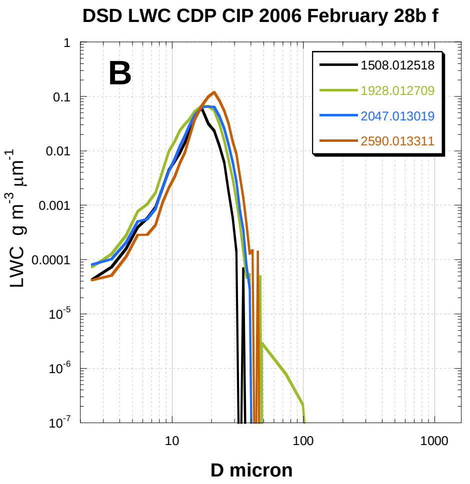


Figure 6: Same as Figure 3, but for single heights in clouds 4 – 8 in a cross-section from the Pacific Ocean to Sacramento, marked by C4, C5, C6, C7, and C8 respectively. The respective approximated CCN concentrations from the measurements made by the aerosol aircraft are denoted by the circles and are located under the peaks of the D_L plots having the same color. The CCN values are to be read from the right ordinate. The CCN concentrations are: C4: 70, C5: 100, C6: 300, C7: 600, C8: 800 cm^{-3}. The drops become markedly smaller with increasing CCN concentrations. Warm rain ceases at cloud 3 where 300 CCN cm^{-3} were present.

A satellite analysis shows that the satellite retrieved microphysics of the cloud field is in agreement with the in situ measurements. In summary, a detailed analysis of a single flight of SUPRECIP 2 showed a clear relationship between CCN concentrations, cloud microphysics and precipitation forming processes. The distribution of the CCN showed an unambiguous urban source, at least in the San Francisco Bay area. The role of the anthropogenic aerosols is demonstrated by the contrast between Cloud 2 some 50 km inland in a relatively sparsely populated area, compared with clouds 6 and 7 only several km inland over the heavily populated and industrialized Bay area. While Cloud 2 was quite pristine and produced ample coalescence and warm rain, coalescence in cloud 7 was highly suppressed and it produced no precipitation.



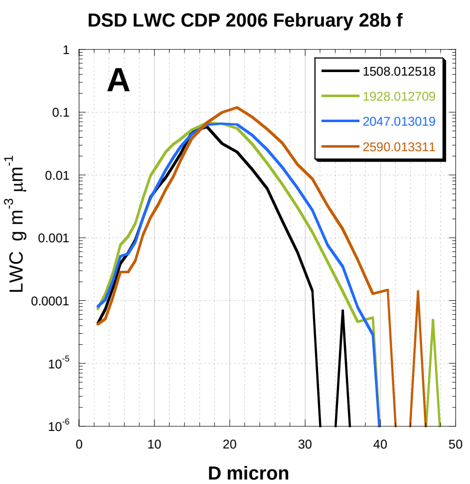


Figure 7: Same as Figure 3, but for the vertical cross section in Cloud 8 over Sacramento (see location in Figure 2). It developed in an air mass that had about 800 CCN cm^{-3}. The cloud drops are very small and do not expand much with height into raindrops, again as in Cloud 1.

The differences in the anthropogenic CCN likely explain the observed differences. Cloud base temperature over the coast (San Francisco) was warmer by about 2ºC than the cloud base inland (Sacramento). This cannot explain the observed differences in the clouds microstructure for the same height above cloud base, because it incurs a difference of less than 10% in the amount of adiabatic water for the same height above cloud base for the heights of interest. The fastest growth of D_L in near the cost line cannot be explained by the probable greater abundance of sea-spray generated giant CCN, because they would act to enlarge the tail of the cloud DSD and not its mode. Furthermore, both cloud base temperature and sea salt CCN should change at the same rate with distance from the coast over the urban and rural areas. Differences in land use would, if anything, contribute to the opposite effects with respect to the actually observed. The mountains at the coast line near Big Sur should enhance the updraft and cause smaller cloud drops and less coalescence, but in fact the largest drops and strongest warm rain were observed there. The urbanized area should have provided more sensible heat for greater updrafts, but this should play a minimal role with the weak winter solar heating. Therefore, there is no probable mechanisms that can explain the observed differences in the cloud microstructure and precipitation properties to which the authors are aware of, except for the differences in the anthropogenic CCN.

The satellite image, taken 3 to 4 hours before the flight, supports the aircraft observations and shows that an even greater source than the urban San Francisco Bay area for aerosols occurred in the central and southern Central Valley. A flight earlier in the day measured CN concentrations exceeding 20,000 cm^{-3} and CCN concentrations reaching 1000 cm^{-3} over the southern Central Valley.

The pristine clouds with large drops and warm rain processes produced a continuum of drop sizes from the cloud drops through the drizzle sizes to the small rain drops. In contrast, clouds with suppressed coalescence due to large CCN concentrations that grew to heights with cold temperatures still produced mixed phase precipitation mainly in the form of graupel. They produced distinctly different size distribution of the hydrometeors, which was separated from the cloud drop DSD. It is known from theoretical considerations and simulation studies that the decreased cloud drop sizes reduce also the mixed phase precipitation (Khain et al., 2001; Rosenfeld and Ulbrich, 2003, but the extent of this possible effect from the cloud physics measurements remains to be documented.

Similar response of clouds and precipitation forming processes to aerosols is apparent also in all the other research flights of SUPRECIP-2 as shown in the next subsection. The continued analyses and evaluation of the aircraft measurements provides compelling evidence for the detrimental role of anthropogenic aerosols on orographic precipitation in California, and explains how a climatological trend of increased CCN aerosols would cause the climatologically observed trends of the reduction in the orographic precipitation component in the southern and central Sierra Nevada.

4. ENSEMBLE RESULTS

The next step was the analysis of all of the cloud passes on all the flights of SUPRECIP 2 to determine the cloud depth necessary for each cloud to develop particles of precipitation size as a function of the measured sub-cloud CCN concentrations. This was done by determining the D_L for each measurement. The dependence of D_L on the CCN for all the measured clouds is provided in Fig. 8. This parameter has been used elsewhere (Andreae et al., 2004; Rosenfeld et al., 2006) as shown in Figure 9 that gives the drop size for the modal LWC as a function of height for several regions and weather regimes around the world. The precipitation threshold was found to be D(LWC) = 24 µm (Andreae et al., 2004) or D_{L24}. From this diagram one can determine the typical cloud depths necessary for clouds to reach this precipitation threshold.

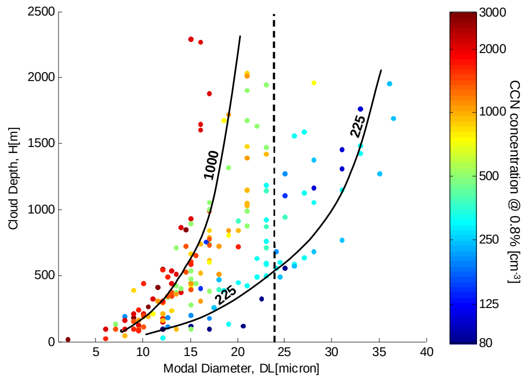


Figure 8. Scatter plot of the modal liquid water drop diameter (D_L) vs. the distance above cloud-base height. Each plotted point has been colorized according to the scale on the right where browns, reds and yellows indicate cloud passes with high sub-cloud CCN concentrations and blue points indicate cloud passes having low sub-cloud CCN concentrations. The vertical line marks the threshold for formation of precipitation-sized drops is when D_L = 24 µm. The two lines are the approximated contours of 225 and 1000 CCN cm^{-3}, as done by the contouring routine of MATLAB. The contouring was done after transferring the individual data points to a surface by linear interpolation and initial smoothing.

The results of the analysis of the SUPRECIP 2 cloud passes are presented in Figure 8. Each dot on the figure represents the D_L and its height above cloud base (H) for one cloud penetration. A cloud penetration was defined as a sequence of at least 3 seconds of CDP droplet concentration larger than 20 cm^{-3} and CDP LWC larger than 0.001 g/m^3. For each such penetration the average number of droplets in every size bin was calculated, and this gave the average size distribution for that penetration. Plotting the LWC density (for each bin normalized to the bin width) made it possible to derive the D_L for each penetration manually. Only convective or cloud elements (mostly embedded) entered this analysis. Embedded small convective elements constituted much of the orographic clouds that formed at the foothills of the Sierra Nevada. Layer cap clouds dominated near the crest, but even they were mostly composed of embedded convection with elevated bases. Due to the uncertainty of cloud base height of these clouds, the clouds that were included in Figure 8 were formed mostly at the foothills and lower to mid-level western slopes of the Sierra Nevada.

In order to be able to compare penetrations from different clouds and from different days, the cloud base height was subtracted from the penetration altitude to get the distance of the penetration from the cloud's base. The determination of the cloud's base is not always simple and straightforward because cloud base height can vary significantly even during a flight. Therefore, in some cases the cloud base height needed to be adjusted so that the D_L vs. Cloud Depth (on a logarithmic scale) would fall approximately on a straight line (because the droplets grow very fast near cloud base and then at a decreasing rate thereafter (only when coalescence is not playing an important role). This uncertainty in the exact cloud base height leads to some uncertainty in the lowest parts of Figure 8.

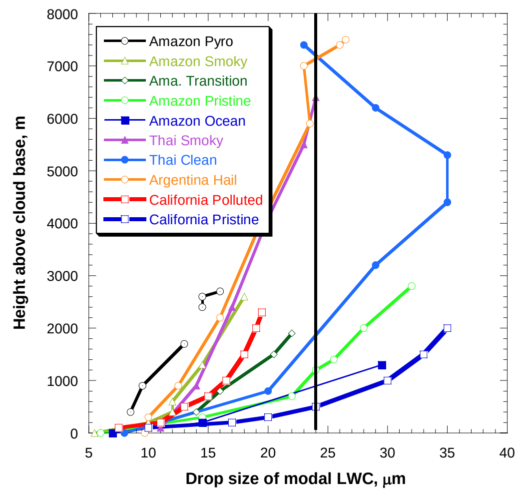


Figure 9. The global context of the dependence of the drop size modal LWC D_L on height above cloud base and temperature. The lines, according to their order in the legend, are: Amazon pyro-Cb, smoky, transition, pristine over land and pristine over ocean clouds (Andreae et al., 2004); Thailand pre-monsoon smoky and monsoon relatively clean clouds (Andreae et al., 2004); Argentina microphysically continental hail storms (Rosenfeld et al., 2006); California polluted and pristine clouds (Fig. 8 of this study). The vertical line at D_L=24 µm represents the warm rain threshold.

Lastly, the color of each small circle is determined by the measured (by the aerosol aircraft) CCN concentration in the vicinity and below the bases of the penetrated clouds at the maximum supersaturation of ~0.85%. The scale of the coloring is logarithmic in order to increase the definition/resolution at low CCN concentrations.

Figure 8 shows that the difference in D_L between clouds developing in polluted air (high CCN concentrations) and clouds developing in clean air becomes more and more pronounced with height. The D_L of polluted clouds having high CCN concentrations is significantly smaller higher in the clouds, because it increases more slowly with cloud depth than in clouds with low CCN concentrations. The clouds need to be deep enough and the D_L needs to reach ~24 µm before significant warm rain can occur. Therefore, the differences in the (warm) precipitation processes become larger higher in the clouds, at least up to 2-2.5 km above their bases, which was reached by the cloud physics aircraft. Because deeper clouds have a greater potential to precipitate large amounts of water, this figure indicates that the aerosols influence the precipitation amounts from these clouds. This serves as evidence of the direct connection between pollution aerosols and the suppression of precipitation at least in the winter shallow convective and orographic clouds in Central California.

Again, Figure 9 shows the global context of the height-D_L relations found for pristine and polluted clouds in the study area. According to Figure 9, the pristine clouds in California precipitated at heights starting at 0.5 km, shallower than in the pristine tropical clouds. The polluted clouds in California had larger drops than the respective smoky clouds in the Amazon and Thailand, reflecting the much greater concentration of smoke CCN there than exist currently in the California air pollution during rainy days. This means that the precipitation in these California clouds could be suppressed further if the air pollution concentrations become even greater.

5. DISCUSSION

The pieces of the research puzzle are slowly falling into place with respect to the trend of decreasing orographic precipitation over many areas of the globe and attendant losses in runoff (Woodley Weather Consultants, 2007) and spring flows (Rosenfeld et al., 2007. With respect to California it was determined also that the Pacific decadal oscillation (PDO) and the Southern Oscillation index (SOI) (Allan et al., 1991; Dettinger et al., 2004), cannot explain the observed declining trends in the orographic enhancement factor (Ro) (Rosenfeld and Givati, 2006).

These apparent losses in orographic precipitation are not limited to California. Rosenfeld and Givati (2006) expanded their study to the whole western USA, where they showed that Ro remained stable over hills in the more pristine areas in northern California and Oregon, but decreased again to the east of the densely populated and industrialized Seattle area. Similar effects were observed not only in the Pacific coastal areas, but also well inland. Precipitation was decreased by 18% over the mountains to the east of Salk Lake City, Utah, but remained unchanged at the southern extension of the same mountain range (Rosenfeld and Givati, 2006; Griffith et al., 2005). Similar effects were found during easterly winds over the eastern slope of the Rocky Mountains downwind (i.e., to the west) of Denver and Colorado Springs (Jirak and Cotton, 2006).

The common denominator for the regions suffering losses in orographic precipitation has been found in the multi-spectral satellite imagery that shows decreased cloud-particle (r_e) for the affected regions. In California this was addressed using multi-spectral satellite images from polar-orbiting satellites (Woodley Weather Consultants, 2007). On each day with a satellite overpass, the multi-spectral imagery was processed to infer the re of cloud particles for the clouds within selected areas within the field of view. This was done because previous studies had shown that areas with small re are slow to develop precipitation. After the satellite inferences had been made they were composited geographically. It was found that re increases more slowly with decreasing T in the central and southern Sierra compared to the northern Sierra. The slower increase of re with elevation is the most robust indicator for the slower development with height of precipitation in the clouds. This finding is consistent with the gauge and stream-flow analyses that show that the greatest losses of water occur in the central and southern Sierra (Woodley Weather Consultants, 2007). This suggested a major role of CCN pollutants that are ingested by the orographic clouds with consequent suppression of coalescence along the lines of the hypothesis put forth at the outset of this paper.

SUPRECIP was designed to address the potential linkages between pollution aerosols and the loss of orographic precipitation and subsequent runoff. SUPRECIP 1 showed a strong positive correlation between the satellite-inferred cloud microphysics and the aircraft-measured cloud microphysics. Thus, the areas in the central and southern Sierra that were shown by satellite to have smaller re than over the northern Sierra likely really do have suppressed precipitation forming processes.

It took SUPRECIP 2 to make this direct connection between the pollution aerosols and suppressed precipitation-forming processes. The scatter plot of the modal liquid water drop diameter (D_L) vs. the depth above cloud-base height (Figure 8) as a function of the ingested CCN shows that clouds growing in a polluted environment must reach greater depths to develop precipitation than clouds growing in a more pristine environment where the CCN concentrations are lower.

In looking at the temporal and spatial patterning of the pollution aerosols in California, it was determined that they typically exhibit a strong diurnal oscillation with the strongest upward transport during the late afternoon. Thus, the sampled clouds are more continental in character with smaller droplet sizes and diminished coalescence at this time of day. The aerosol concentrations were minimal over the sea and increased after traversing the shoreline, where urban and industrial development has taken place. The aerosols found over the Central Valley were not simply transported from the coastal areas, because on most days the CN and CCN concentrations in the Valley to the Sierra foothills exceeded what was found in the coastal urbanized areas. This is true especially in the central and southern Valley well to the east of sparsely populated coastal regions. This is consistent with slow gas to particle conversion and aging by coagulation of aerosol to form CCN. It appears, therefore, that the large aerosol concentrations that are likely suppressing the Sierra orographic precipitation are generated locally in the Valley itself having unknown specific origins and chemistry. This is consistent with the findings of Chow et al (2006) from an extensive aerosol measurement program in the San Joaquin Valley. Although transport of pollution aerosols from the sea and from coastal regions may play a role in the suppression of Sierra orographic precipitation, it would appear to be secondary to the role being played by the local generation of aerosols in regions of highest concentrations. Understanding this role would appear to be the next logical step in this research effort.

A component of this research effort was model simulation of the effects of aerosols (Lynn et al., 2007). The simulation with clean air produced more precipitation on the upwind mountain slope than the simulation with continental aerosols. After 3 hours of simulation time, the simulation with maritime aerosols produced about 30% more precipitation over the length of the mountain slope than the simulation with continental aerosols. Greater differences in precipitation amounts between simulations with clean and dirty air were obtained when ice microphysical processes were included in the model simulations.

Thus, the totality of the evidence from the research effort, involving precipitation and stream flow analyses, quantitative satellite measurements, numerical modeling and extensive aircraft measurements of cloud properties and aerosols, makes a strong case for the loss of precipitation and stream flows in the California Sierra Nevada due to the generation of anthropogenic pollutants and their ingestion into Sierra clouds.

6. CONCLUSIONS

SUPRECIP 2 met its primary objective of documenting the effects of pollution aerosols on clouds and their precipitation over the California Sierra Nevada. The aircraft measurements of cloud properties validated the satellite inferences of cloud microphysics. Those regions over which the processed multi-spectral imagery indicated the clouds had small droplet sizes and suppressed coalescence vs. those areas where the satellite inferences indicated the clouds had large droplet sizes and coalescence were verified by the aircraft measurements. This makes the satellite inferences of altered cloud properties in the central and southern Sierra all the more credible.

The key uncertainty at the outset of SUPRECIP was whether the altered cloud properties were due to the ingestion of pollution aerosols. Although SUPRECIP 1 gave the first indications of a link between the pollution aerosols and the suppression of precipitation-forming processes, it took SUPRECIP 2 utilizing two cloud physics aircraft to demonstrate the direct linkage between these aerosols and the regions in the central and southern Sierra Nevada that have suffered losses of orographic precipitation and stream flows. The analysis of several hundred cloud passes shows that in regions where high concentrations of CCN were measured by the base aerosol aircraft the clouds had to grow to greater depths to develop precipitation than clouds growing in regions of low CCN concentrations.

The spatial and temporal documentation of the CCN and CN aerosols was highly informative. Although the initial source of the pollution aerosols was clearly the urbanized coastal regions, the pollution aerosols in the Central Valley to the Sierra foothills cannot be explained readily by simple advection of the pollutants from the coastal urban areas. There is probably a major source of pollution aerosols in the Central Valley itself and these CCN and total (CN) aerosols are concentrated primarily over the Central Valley from just to the north of Sacramento southward along the foothills to south of Fresno. This is the same region that has been shown through statistical analysis of precipitation and stream-flow records to suffer the greatest loss of winter orographic precipitation and subsequent stream flows.

The pollution aerosols show a strong diurnal oscillation. In the morning these aerosols are concentrated at low levels, but by late afternoon they have been transported upward due to the afternoon heating. Thus, the regional clouds are most affected by the pollutants late in the day. The aircraft measurements indicate that the ratio of CCN to CN (total) aerosols is typically 0.10 to 0.20 whereas the measurements at the ground-based (Blodgett) site indicate that the ratios are higher.

Because the local generation of the pollution aerosols in the Central Valley appears to be a greater problem than the transport of pollution from the urbanized/industrialized coastal regions or inland from the Pacific, the next step in the research progression is to document the sources and chemical constituency of the aerosols in the Central Valley. The evidence amassed from SUPRECIP and the ancillary precursor research conducted by the authors indicates that the precipitation and stream flow losses are real and due primarily to the ingestion of pollutants by orographic clouds over the Sierra Nevada. Further, the results of model simulations demonstrating the detrimental effects of pollutants on Sierra orographic precipitation give additional weight to the hypothesis put forth at the outset of this paper.

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