Aircraft measurements of the impacts of pollution aerosols on clouds and precipitation over the Sierra Nevada

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Abstract

Satellite measurements in onshore-flowing clouds showed that they become more microphysically continental downwind of areas of major emissions of anthropogenic aerosols. Rain gauge analyses of orographic precipitation showed that the upslope precipitation in mountain ranges downwind was decreased with respect to the coastal precipitation during the 20th century along with the assumed increase in pollution aerosols. Following the publication of these findings a research effort called SUPRECIP (Suppression of Precipitation) 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. Preliminary results of SUPRECIP Phase 2 2006 are reported here. The program is funded by the PIER (Public Interest Energy Research) Program of the California Energy Commission.

The flights documented the aerosols and orographic clouds downwind of the densely populated areas in the central Sierra Nevada and contrasted them with the aerosols and clouds downwind of the sparsely-populated areas in the northern Sierra Nevada. The main results from the February 2005 campaign of SUPRECIP-1 are:

1. The in situ aircraft measurements of the cloud microstructure validated the satellite retrievals of cloud particle effective radius and microphysical phase.
2. Ample supercooled drizzle were found in the pristine orographic clouds with only few tens of drops cm^{-3}, and no drizzle with small concentrations of graupel were found in clouds with drop number concentrations of ~ 150 cm^{-3}.
3. The pristine clouds occurred in air masses that were apparently decoupled from the boundary layer in the early morning, whereas the more microphysically continental clouds occurred during the afternoon, when the surface inversion over the Central Valley disappeared.

Based on what was learned during the first season, a second field campaign was conducted in February and March 2006, called SUPRECIP-2. The cloud physics instruments were enhanced with another cloud drop spectrometer, and a second low level aerosol airplane was added. Two cloud physics aircraft were involved, making measurements of CCN, CN, cloud drop size distribution, hydrometeor images and size distribution, thermodynamic properties of the air and air 3-D winds. SUPRECIP-2 was augmented also by surface measurements of aerosols and chemical composition of the hydrometeors, made by collaborating research groups from the Desert Research Institute of the University of Nevada, The University of California Davis, and the SCRIPPS Oceanographic Institute of the University of California at San Diego. This provided coincident measurements of the low level aerosols and the properties of the clouds that ingest them. Preliminary results, reported here, confirm the link between anthropogenic aerosols and suppressing precipitation forming processes in the clouds in the context of California.

1. Introduction:

Anthropogenic aerosols from major coastal urban areas pollute the pristine maritime air masses that flow inland and bring much of the precipitation, especially over the mountain ranges. Satellite observations indicated that urban aerosols reduce cloud drop effective radii 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 western U.S (particularly in California) and in Israel. Thee results showed losses of 15 – 25% of the annual precipitation over the western slopes of the hills (Givati and Rosenfeld, 2004, 2005; Rosenfeld and Givati, 2006). 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 the hypothesis that air pollution aerosols that are incorporated in orographic clouds slow 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.

In Central California the main precipitation suppression is postulated to occur during westerly flow that captures anthropogenic CCN that are incorporated in certain orographic clouds that form over the Sierra Nevada—those that are sufficiently shallow so 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 and are lost to precipitation on the downwind side of the crest.

The SUPRECIP field campaigns were aimed at conducting the in situ aerosols and cloud measurements for validating the above hypothesis about the way urban air pollution suppresses orographic precipitation.

2. The field campaigns

A program, called the Suppression of Precipitation (SUPRECIP-1) Experiment, was conducted during February and the first week in March 2005 from Sacramento, California, to provide the needed documentation. The number, sizes, and concentrations of ingested aerosols, and the resulting internal cloud microphysical structure, were documented.

2.1 SUPRECIP-1 Objectives

SUPRECIP1 had two objectives:

1. Use a cloud physics aircraft to measure atmospheric aerosols in pristine and polluted clouds. Analyze these data to determine the impact of the aerosols on cloud-base microstructure, on the evolution with height of the cloud drop-size distribution, and on the development of precipitation under warm and mixed-phase processes.
2. Use the cloud microphysical measurements to validate the multi-spectral satellite inferences of cloud structure and the effect of pollutants on cloud processes especially the suppression of precipitation.

2.2 SUPRECIP-1 Outcomes

The weather during SUPRECIP was highly anomalous for the entire U.S. West Coast, consisting of dry conditions in the Pacific Northwest and flooding rains in Southern California. A high-pressure blocking pattern at the surface and aloft—and the resulting split in the jet-stream flow when it encountered the block—forced some of the weather disturbances to the north and northeast into Canada and Alaska, while some traveled southeastward under the blocking high to the Central and Southern California coast. This persistent region of low pressure under the block produced southerly and south-easterly winds and long periods of middle and high clouds over the Central and Northern Sierra for most of the project. The desired orographic clouds produced by the usual westerly winds into the Sierra were a rarity during SUPRECIP 1, and the program was extended through the first week in March 2005 in the hope of obtaining orographic storm events. Although the weather was a disappointment during SUPRECIP 1, much was learned in documenting the effect of pollutants on cloud microstructure and in validating the satellite inferences of cloud structure using the aircraft measurements and the concurrent radar depictions.

The Cheyenne cloud physics aircraft flew 21 flights in California, exclusive of the ferry flights to and from the state. Two flights were for the purposes of instrumentation calibration and the 19-flight balance were research flights. A total of 43 hours 26 minutes were expended during these flights out of a 70-hour flight allotment. Two flights were conducted on five of the 19 flight days, and two of the five were made during the one-week extension of the program into March 2005. Although the Cheyenne II cloud physics aircraft had its share of mechanical problems, no research flight opportunity was lost due to these problems. One research flight was terminated early, however, due to failure of the cloud droplet probe (CDP), which was repaired subsequently.

In addressing Objective 1, the project accomplished the following:

- Documentation of the regional aerosols, including pollutants from urban and industrial sources, and the effects of these aerosols on cloud structure and behavior.
- Demonstration that CCN aerosols, on which cloud droplets form, constitute about 10% of the overall regional atmospheric aerosols
- Documentation that the Sierra Nevada often receives precipitation from shallow clouds that remain pristine as long as they do not ingest pollutants from the atmospheric boundary layer.
- Demonstration that high concentrations of small CCN aerosols inhibit precipitation when they are ingested from the boundary layer because of either convective transport or orographic lift.

Despite the many accomplishments, Objective 1 was not reached fully due to two problems:

- Incomplete documentation of the aerosols in the atmospheric boundary layer, due to the near impossibility of obtaining clearance to conduct flight under instrument flight rules (IFR) in the boundary layer in the San Francisco/Oakland/Sacramento heavily populated urban and industrial areas. A second aircraft flying under visual flight rules (VFR) would have been necessary to obtain the needed documentation.
- The great lack of orographic cloud conditions over the California Sierra due to weak wind flow into the Sierra during virtually all of the period of flight operations. A longer period of operations would have been required to obtain the desired orographic clouds for study.

With respect to Objective 2, the satellite and aircraft inferences of cloud microstructure were made, in terms of the effective radius. The satellite inferences were made for all of the cloud pixels within a series of boxes along the flight track. Each box was defined such that it encompassed some of the individual aircraft cloud passes. This strategy made it possible to compare the effective radius for the cloud passes at the height and temperature of the pass with the satellite inferences of the effective diameters at the 50th percentile for the composite cloud for all clouds in the box. Considering the differences in scale (i.e., individual cloud passes vs. the composite cloud within a box that contains the cloud passes) and time, the agreement is remarkably good (linear correlation=0.73), giving increased credibility to the satellite inferences of suppressed precipitation-forming processes associated with pollution. For the purposes of this research effort, this is an extremely important finding.

In addressing objective 2, this project accomplished the following:

- Validation of the satellite inferences of cloud microstructure using the in-cloud measurements from the cloud physics aircraft on two days of measurement (February 7 and March 4, 2005).
- Verification that pollution aerosols are instrumental in altering the internal structure of the clouds and their resultant precipitation.

Despite these accomplishments, Objective 2 was not reached fully, because the sample was too small to justify a claim that the validity of the satellite inferences had been proved.

3. SUPRECIP-2

SUPRECIP-2 was conducted in February and March 2006. The cloud physics instruments were enhanced with another cloud drop spectrometer, and a second low level aerosol airplane was added. Two cloud physics aircraft were involved, making measurements of CCN, CN, cloud drop size distribution, hydrometeor images and size distribution, thermodynamic properties of the air and air 3-D winds. SUPRECIP-2 was augmented also by surface measurements of aerosols and chemical composition of the hydrometeors, made by collaborating research groups from the Desert Research Institute of the University of Nevada, The University of California Davis, and the SCRIPPS Oceanographic Institute of the University of California at San Diego. This provided coincident measurements of the low level aerosols and the properties of the clouds that ingest them. Preliminary results, reported here, confirm the link between anthropogenic aerosols and suppressing precipitation forming processes in the clouds in the context of California.

During SUPRECIP-2 53 research missions were flown, 25 by the Cheyenne 2 cloud physics aircraft and 28 by the Cessna 340 aerosol aircraft. A little over half (27 of 53) of the research missions were flown in March 2006. After a slow beginning with mostly unsuitable weather during February 2006, the weather improved greatly for our purposes, resulting in 10 flight days in March 2006. Only 47 minutes of flight time remain out of a total allotment of 110 hours.

The cloud physics airplane is illustrated in Figure 1. The instruments and respective data sets taken by the aerosol and cloud physics airplanes are given in Tables 1 and 2, respectively. The sortie briefs of all the missions flown in SUPRECIP-2 are provided in Table 3.

The deadline for submission of this extended abstract is only two months after the conclusion of the field campaign. Therefore, no overview of the results is yet available. Instead, all that we can provide at this stage is a few examples of the observed links between aerosols, clouds and precipitation.

4. Preliminary results of SUPRECIP-2: Afternoon of 28 February 2006

A WSW post frontal cold air prevailed over the area of Central California, after a cold front passed late last night. Instability caused convective clouds over the ocean, and triggered convective clouds over the coastal hills and over the Sierra Nevada. The instability decreased gradually during the day, but still rain showers from shallow clouds occurred over the ocean and the coastal ranges at 00Z 1 March 2006. The Oakland radiosonde of that time is given in Figure 2.

A coordinated mission of the Cloud and Aerosol airplanes originated from Sacramento Executive Airport in a mission to document the gradient in aerosols and respective cloud properties in cross sections from the Sierra Nevada to the Pacific Ocean and back.

The airplanes departed Sacramento at 23:05Z and flew due east to the foothills and measured there the convection generated by the mountains. The next destination was the clouds that formed over the hills bounding the Central Valley from its west, about 60 km to the NE of Monterrey. Next we measured the clouds forming over the hills just at the Pacific coast at Big Sur. There we continued 35 km westward over the ocean and then turned north and measured convective clouds that were triggered by the ocean shoreline of San Francisco. We 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 track of the two airplanes is marked in Figure 3. The locations of the measured clouds are also marked in that figure.

Figure 1: The SOAR Cheyenne II cloud physics aircraft.

Table 1: Data sets from the Aerosol aircraft

VARIABLE	INSTRUMENT	RANGE	ACCURACY	RESOLUTION	FREQUENCY
Air temperature	Rosemount 102DB1CB	-50°C to +50°C	0.1°C	0.01°C	1 Hz
Liquid water content	DMT LWC-100	0 to 3 g/m^3	0.05 g/m^3	0.01 g/m^3	1 Hz
Logging, telemetry & event markers	ESD DTS (GPS)				1 Hz
Isokinetic aerosol inlet	Brechtel double diffuser inlet	28 lpm			100 m/s
CN concentration	TSI 3022A	>2 nm		0-10^5 /cm^3	1 Hz
CCN	DMT CCN counter	0.5 to 10 µm 0.1 to 1.2 % SS		0.5 µm, 20 bins	1 Hz

Table 2: Data sets from the Cloud physics aircraft:

VARIABLE	INSTRUMENT	RANGE	ACCURACY	RESOLUTION	FREQUENCY
Air temperature	Rosemount 102DB1CB	-50°C to +50°C	0.1°C	0.01°C	1 Hz
Air temperature (reverse flow)	0.038" DIA. Bead Thermistor	-30°C to +50°C	0.05°C/0.3°C incl DHC	0.01°C	< 1 s TC
Relative humidity (reverse flow)	Thermoset Polymer RH Sensor	0 to 100% RH	2% RH	0.1% RH	5 s TC @ 20°C
Barometric pressure	MEMS Pressure Sensor	0 to 110000 Pa	100 Pa	10 Pa	20 Hz
u wind component (+ North)	Extended Kalman Filter (EKF)		0.50 m/s @ 75 m/s TAS	0.01 m/s	5 Hz
v wind component (+ East)	Extended Kalman Filter (EKF)		0.50 m/s @ 75 m/s TAS	0.01 m/s	5 Hz
w wind component (+ Down)	Extended Kalman Filter (EKF)		0.50 m/s @ 75 m/s TAS	0.01 m/s	5 Hz
Position (Latitude/Longitude)	WAAS DGPS		2 m (2 σ)	< 1 m	5 Hz
Altitude	WAAS DGPS	-300 to 18000 m	5 m (2 σ)	< 1 m	5 Hz
Geometric Altitude	King KRA 405 Radar Altimeter	0 to 2000 ft	3% < 500 ft 5% > 500 ft	0.48 ft (0.15 m)	
Roll Attitude (ϕ)	MEMS IMU/GPS/EKF	-60 to +60°	0.1°	0.01°	5 Hz
Pitch Attitude (θ)	MEMS IMU/GPS/EKF	-60 to +60°	0.2°	0.01°	5 Hz
Yaw Attitude (ψ)/ Heading	MEMS IMU/GPS/EKF	0 to 360°	0.1°	0.01°	5 Hz
Angle of attack (α)	MEMS Pressure Sensor	-15 to +15°	0.03° @ 150 m/s	0.001° @ 150 m/s	20 Hz
Side-slip (β)	MEMS Pressure Sensor	-15 to +15°	0.03° @ 150 m/s	0.001° @ 150 m/s	20 Hz
True Air Speed	MEMS Pressure Sensor	0 to 150 m/s	0.1 m/s	0.01 m/s	20 Hz
Logging, telemetry & event markers	ESD DTS (GPS)				1 Hz
Cloud droplet spectra	DMT CDP	2 to 50 µm		1 to 2 µm, 30 bins	1 Hz
	PMS FSSP SPP-100	2 to 47 µm		1 to 2 µm, 30 bins	1 Hz
Cloud particle spectra	DMT CIP 1D	25 to 1550 µm		25 µm, 62 bins	1 Hz
Cloud particle image	DMT CIP 2D	25 to 1550 µm		25 µm	
Liquid water content	DMT LWC-100	0 to 3 g/m^3	0.05 g/m^3	0.01 g/m^3	1 Hz
	CDP calculated	> 3 g/m^3			1 Hz
	FSSP calculated	> 3 g/m^3			1 Hz
CN concentration	TSI 3010	>7 nm		0-10^5 /cm^3	1 Hz

Table 3: SUPRECIP-2 sorties inventory

Date	Takeof Cloud	Landin g Cloud	Takeof f Aero	Landin g Aero	Summary of data collected on this flight
02-03-2006	22:20	23:30	22:27	23:39	Cloud physics aircraft flies in shallow Sc cloud in the central valley. Aerosol aircraft flies below the cloud bases of the Sc cloud measured by the cloud physics aircraft.
02-04-2006	21:10	23:40	21:10	23:55	Cloud physics flight in weak orographic clouds to a location south of Tahoe and north of Squaw Valley, continuing along the foothills towards Chico. Aerosol aircraft flies a coordinated flight track along the foothills.
02-08-2006	no flight		22:55	00:49	Aerosol measurements over the Blodgett Forest Research Station.
02-10-2006	23:33	00:30	23:33	02:33	Inter-comparison aerosol measurements between the two aircraft. Aerosol aircraft continues to measure aerosol concentrations around the San Francisco area.
02-15-2006	18:07	20:05	18:10	21:25	Cloud physics flight in convective clouds over the foothills and aerosol flight over the northern and central Sierra foothills. The flight started with a formation flight to Blodget. Cloud physics data is good until 19:30 when the aircraft lost power.
02-16-2006	22:04	00:24	22:10	00:30	Cloud physics flight and aerosol flight over the northern Sierra foothills orographic clouds and coastal orographic clouds, starting with a formation flight to Blodget. Cloud physics data is good until 23:52 when the aircraft lost power.
02-17-2006	no flight		22:57	00:10	Aerosol flight starting towards Blodget. IFR conditions prevailed and aircraft had to return to base before reaching Blodget. Flight in rain below cloud base.
02-18-2006	no flight		18:12	21:33	Aerosol flight starting towards Blodget and continuing towards Monterey and San Francisco bay.
02-26-2006	18:40	20:14	20:20	22:15	Cloud physics measurements of synoptically driven Altocumulus with embedded weak convection west of the Sierra crest. Aerosol flight to Blodget. Aerosol aircraft flew in virga and some rain.
02-27-2006	17:08	19:16	17:10	19:29	Cloud physics flight in ice precipitation over the Sierra and in convective clouds northeast of Oakland. Aerosol flight towards Blodget continuing towards Oakland. The aerosol aircraft was in and out of precipitation until 1745Z. The cloud physics aircraft had false airspeed readings.
	22:14	23:20	22:15	23:54	Both aircraft started in formation and broke off at Hangtown. The cloud physics aircraft flew through pre-frontal precipitation layers. Intermittent airspeed readings occurred again and it was decided to cancel the flight. Aerosol aircraft continued towards Stockton.
02-28-2006	17:29	20:12	17:34	20:30	Cloud physics flight in the convective and orographic clouds over the Sierra foothills, coastal range and over the ocean. Aerosol aircraft flies in coordination with the cloud physics aircraft but remains over the central valley and the coastal range.
	22:55	01:45	22:54	01:06	Cloud physics flight measuring convective clouds and aerosols in a mixed boundary layer in the central valley and off the coast. Aerosol aircraft flies in coordination along the approximate same flight track.
03-01-2006	21:25	00:37	21:24	00:23	Both aircraft started in formation and broke off at Hangtown. Aircraft flew coordinated tracks taking aerosol and cloud measurements over the foothills, west towards Mendocino and over the ocean.
03-02-	17:01	18:09	17:01	18:55	Cloud physics flight measuring orographic clouds and aerosols over

2006					the foothills and the windward side of the Sierra above Squaw Valley. Aerosol aircraft measures aerosols vertically.
	19:37	20:57	19:47	21:00	Same as above to study the evolution of the front.
	22:58	00:21	22:50	23:55	Same as above to study the evolution and the affects of mixing in the boundary layer.
03-03-2006	17:32	19:43	17:31	18:43	Cloud physics flight in receding frontal cloud band over the Sierra. Aerosol aircraft flew in the Sacramento local area to document the aerosols with height.
	21:35	23:45	21:48	23:55	The frontal cloud band moved to the east and new vigorous convective clouds developed on the mountains and around Sacramento. Data system crashed from 23:27 to 23:35.
03-06-2006	17:46	19:28	17:40	18:44	Cloud physics aircraft flew on the west side of a receding frontal cloud band over the Sierra, conducting penetrations of orographic cloud tops . Aerosol aircraft flew in the Sacramento area below cloud base and near the foothills.
03-07-2006	17:03	19:34	17:00	18:30	Cloud physics flight in very messy layered cloud with embedded deep convection. The aircraft tracked as far south as Fresno and climbed into the high Sierra.
	22:03	23:29	22:03	23:56	Planned aerosol and cloud physics flight measuring clouds and aerosols north of Sacramento. Data system failure.
03-09-2006	19:28	22:07	19:22	23:00	Cloud physics flight into the orographic clouds first towards Hangtown in the foothills and then south along Sierra towards Fresno. The aerosol aircraft flew below the cloud bases and up to 10,000 ft near the Blodget site, then followed the cloud physics aircraft track south.
03-10-2006	18:36	20:47	17:03	20:39	Cloud physics measurements climbing to the Sierra crest, along the Sierra crest, and descending with further measurements along the central valley. Good CN data on the aerosol aircraft but the CCN counter power fails.
03-11-2006	17:26	19:43	17:21	19:15	With a cold trough centered over the central valley, precipitation echoes were abundant. Cloud physics flight was conducted from Sacramento to Hangtown and then to the SSE along the foothills. Aerosol aircraft flew in the Sacramento area up to 10,000ft.
03-13-2006	18:14	19:55	18:06	19:34	Cloud physics aircraft followed aerosol aircraft to Linden. Aerosol aircraft returned to Sacramento while the cloud physics aircraft climbed to the Sierra crest, flew along the crest and descended back towards the valley. Temperature unreliable.
03-14-2006	17:49	21:50	17:45	20:39	Cloud physics flight in layered glaciated cloud over the Sierra foothills and crest above Squaw Valley. Convective cloud profiles over the foothills, over the coastal hills and the ocean. Temperature unreliable.

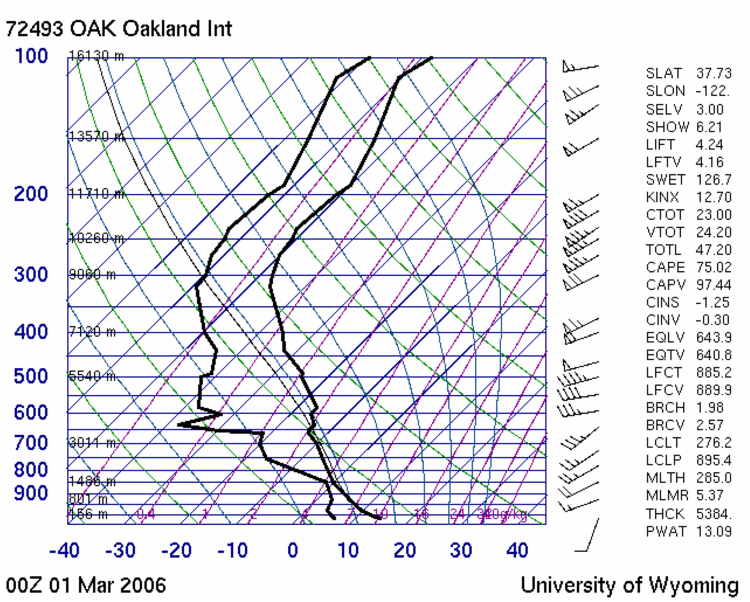


Figure 2: The Oakland radiosonde of 1 March 2006 at 00Z, which is near the time that the airplanes flew near Oakland.

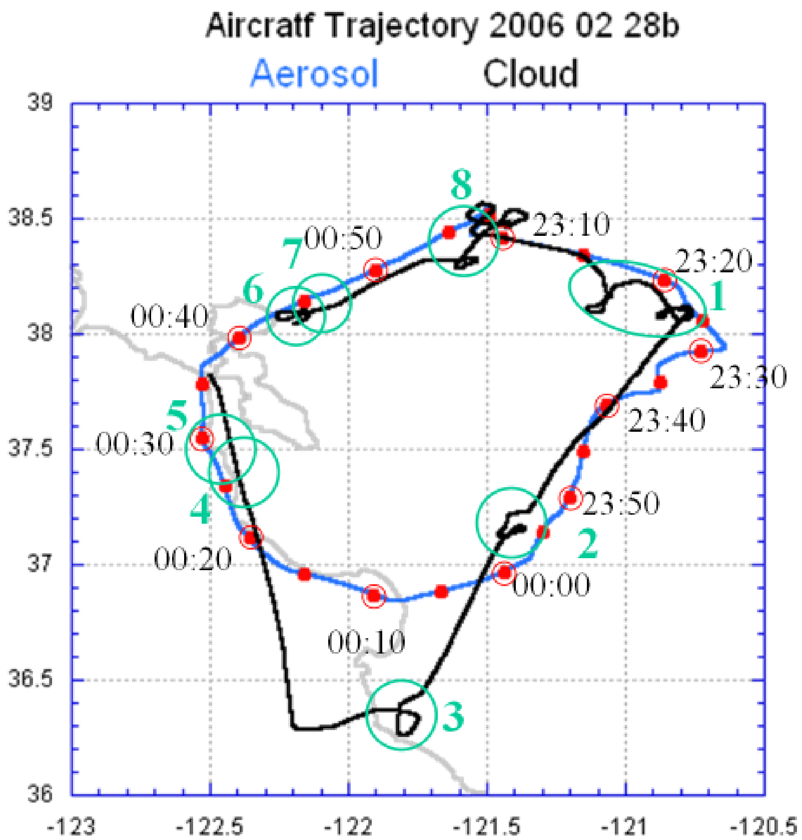


Figure 3: The trajectories of the Cloud (black) and Aerosol (blue) airplanes. The time marks every 5 minutes are posted on the aerosol aircraft trajectories, and labelled every 10 minutes. The measured clouds by the cloud physics aircraft are marked with green circles and numbered sequentially.

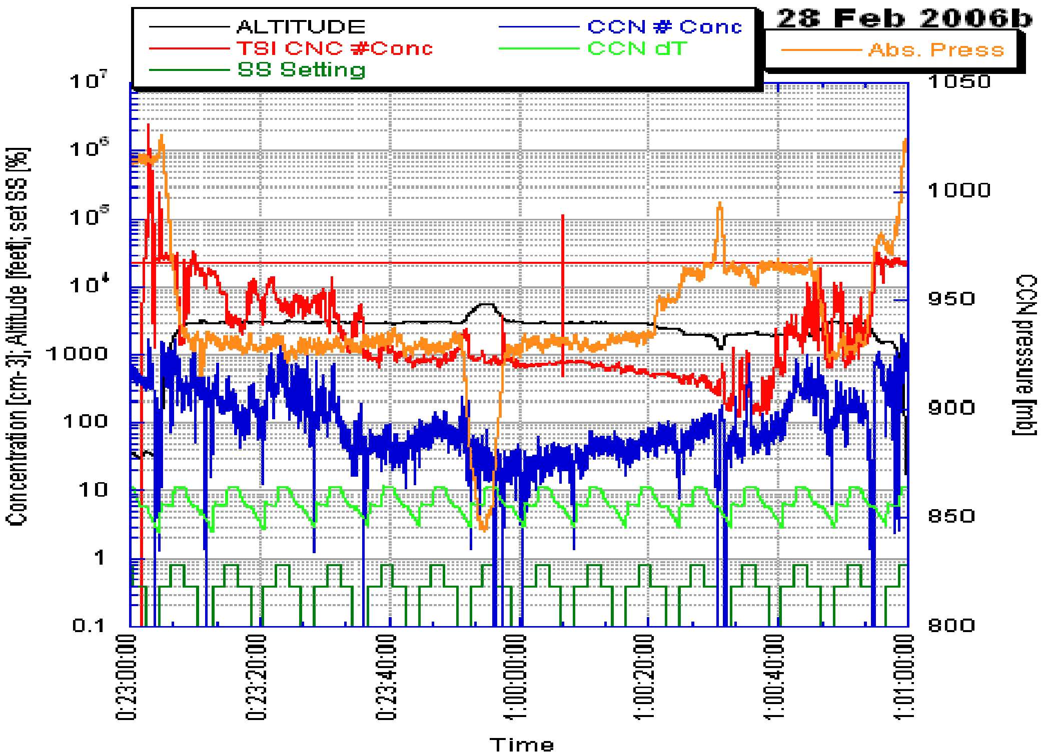
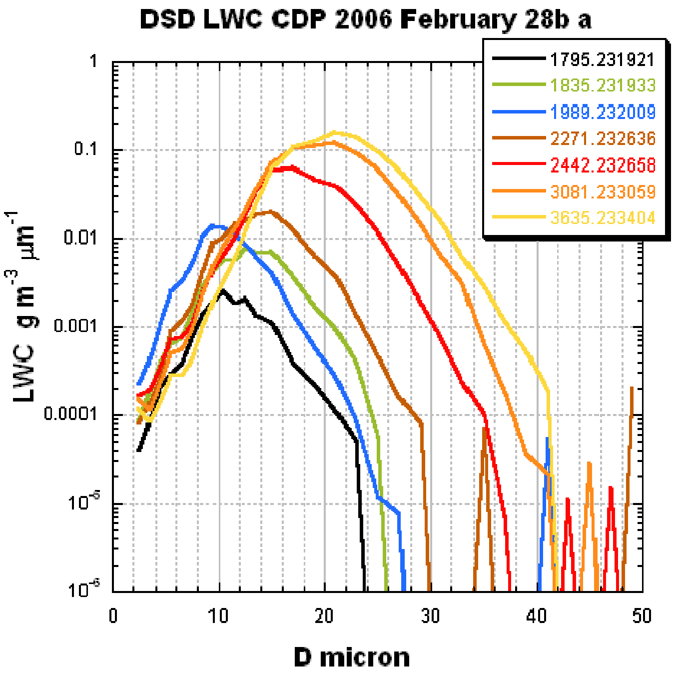


Figure 4: The full flight summary of the aerosol aircraft. The measured values can be related to the geographic points by the time reference in the flight trajectory in Figure 3. On the left ordinate shown: Black line: Altitude [feet]; Red line: TSI CNC, condensation nuclei [cm-3]; Dark green line: Super saturation setting for the CCN counter [degrees K]; Blue: CCN concentrations [cm-3]; Light green: Temperature differences between the upper and lower portions of the CCN counter. On the right ordinate shown in orange is the pressure at the CCN chamber [mb]. Sharp pressure excursions incur dynamic effects of compression or decompression with respective heating or cooling and instrumental non-meteorological increase or decrease of the CCN counts.

The Aerosol aircraft measurements are summarized in Figure 4. They show CCN concentrations at super saturation of 1% 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 fall to about 100 cm^{-3} over the hills 60 km NE of Monterrey, and continue falling to less than 40 cm^{-3} over the Monterrey Bay and likely also over Big Sur. The CCN increase again gradually northward along the coastline and reaching about 70 cm^{-3} there. They keep rising to about 100 cm^{-3} over the peninsula of San Francisco airport, and locally jump to 800 cm^{-3} just to the north of the airport, but recover back to less than 80 cm^{-3} to the north of the Golden Gate. We turned to the east and experienced a sharp increase of the CCN to more than 700 cm^{-3} over Richmond. The CN shot up to more than 10,000 cm^{-3}. This suggests ample source of fresh small aerosols. The CCN remained at that level within the boundary layer all the way to landing in Sacramento.

The clouds and precipitation particle size distributions are given in Figures 5-9. Cloud 1 was sampled stepping upward from its base at its up shear towers, whereas its more mature portions glaciated and precipitated. Due to air traffic control limitations we had to use different clouds in the same area for the lower and upper portions of the cross sections. The modal LWC size of the drop size distribution (DSD) increased with height above cloud base. It reached 21 μm at the height of 3635 m, which is about 1900 m above cloud base. The temperature there was -8°C. This size is below the threshold for modal LWC DSD for warm rain that was documented elsewhere as 24 μm (Andreae et al., 2003). In agreement with that, the DSD did not expand to the drizzle size. Large precipitation particles occurred as graupel and formed a well separated distribution at the 1-mm size range.



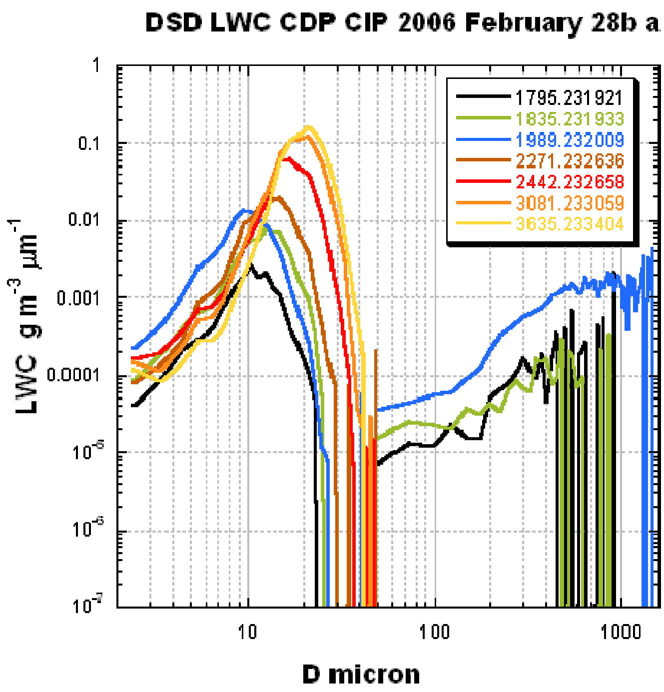
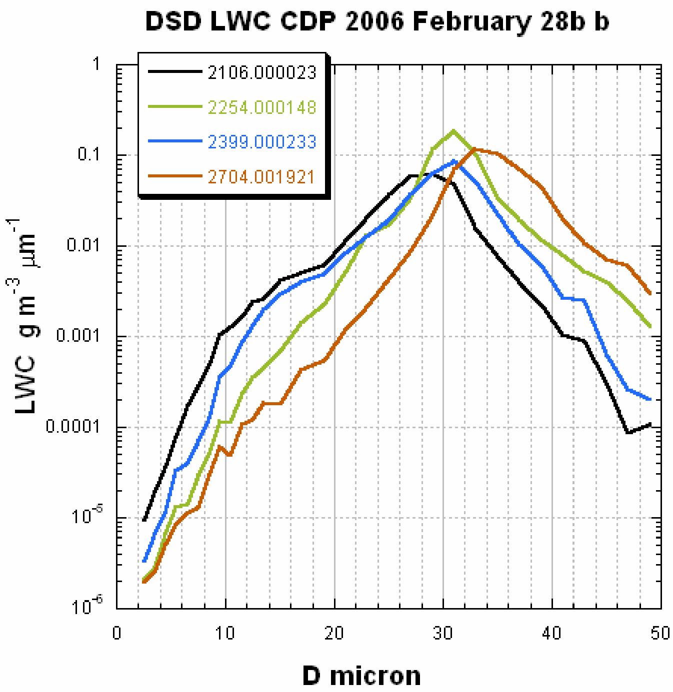


Figure 5: Cloud 1 over the western slopes of the Sierra Nevada (see location in Figure 3). It developed in air mass that had 300-800 CCN cm^{-3}. The upper panel shows the CDP measured liquid water content distribution. Each line represents the gross cloud drop size distribution of a whole cloud pass. 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. The lower panel shows the combined distributions of the CDP and CIP. According to the figure the large precipitation particles were well separated from the cloud drop size distribution, indicating lack of appreciable coalescence.



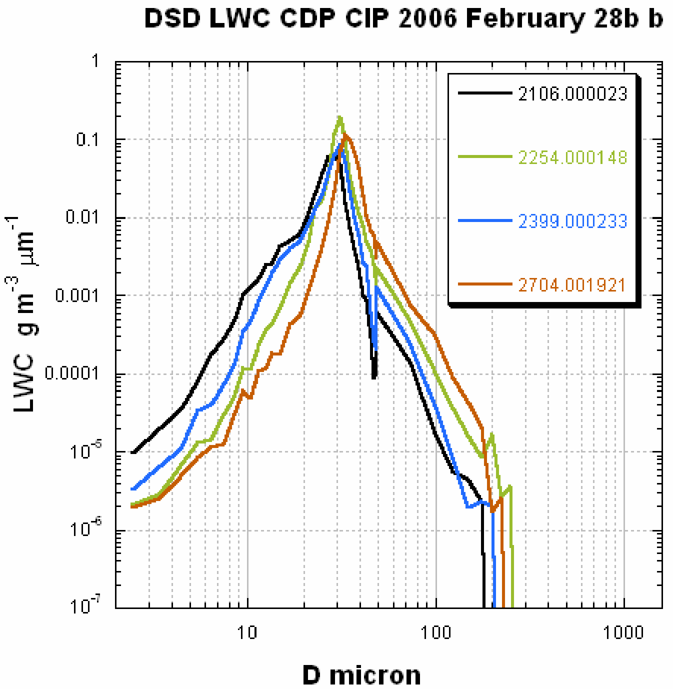
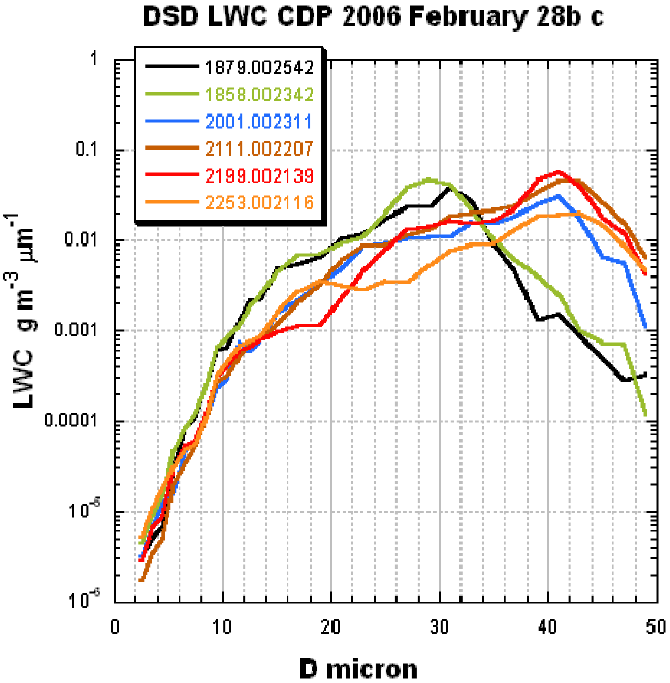


Figure 6: Same as Figure 5, but for Cloud 2 over the hills 60 km NE of Monterrey (see location in Figure 3). It developed in air mass that had 100 CCN cm^{-3}. The cloud drops are quite large and the distribution continues smoothly into the rain drop sizes. This indicates active warm rain processes.



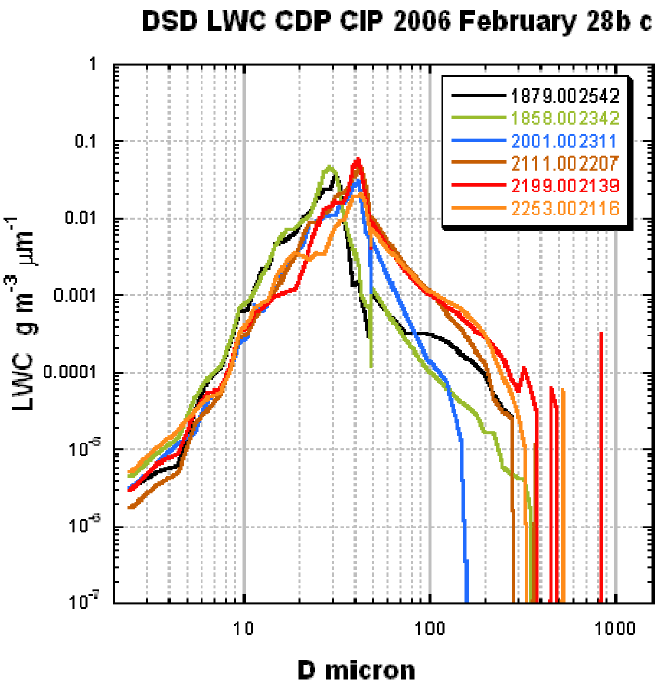
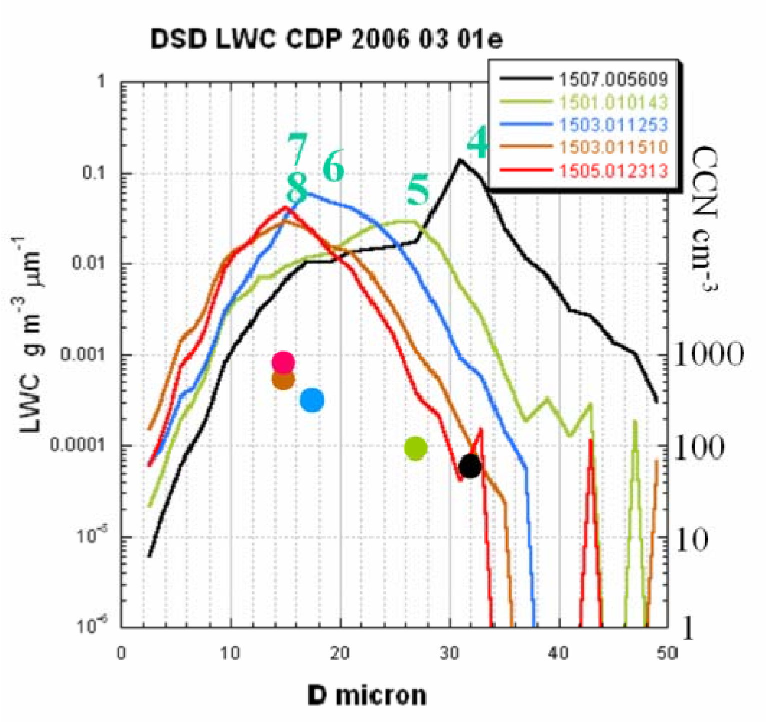


Figure 7: Same as Figure 5, but for Cloud 3 over the hills near Big Sur (see location in Figure 3). It developed in an air mass that had about 40 CCN cm^{-3}. The cloud drops are very large and the distribution continues smoothly into the rain drop sizes. This indicates very active warm rain processes.



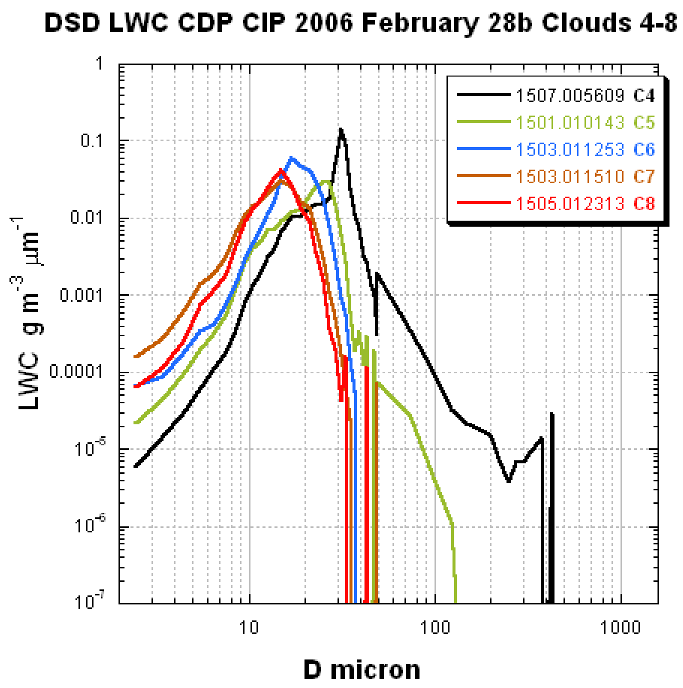
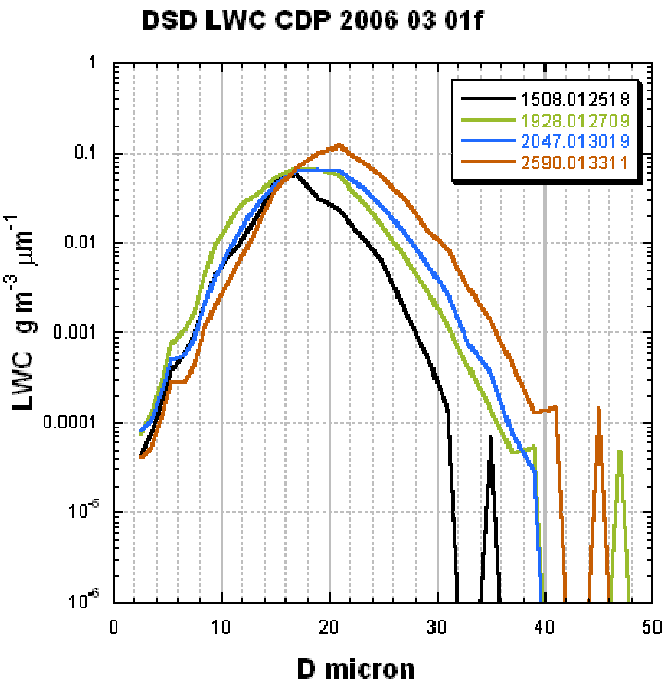


Figure 8: Same as Figure 5, but for single heights in clouds 4 – 8 in a cross-section from the Pacific Ocean to Sacramento, marked by C4, C5, C6, C7, and C8 respectively. The respective approximated CCN concentrations are denoted by the circles with the respective colors of the lines and located under the modal LWC and at the CCN values on 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, with 300 CCN cm^{-3}.



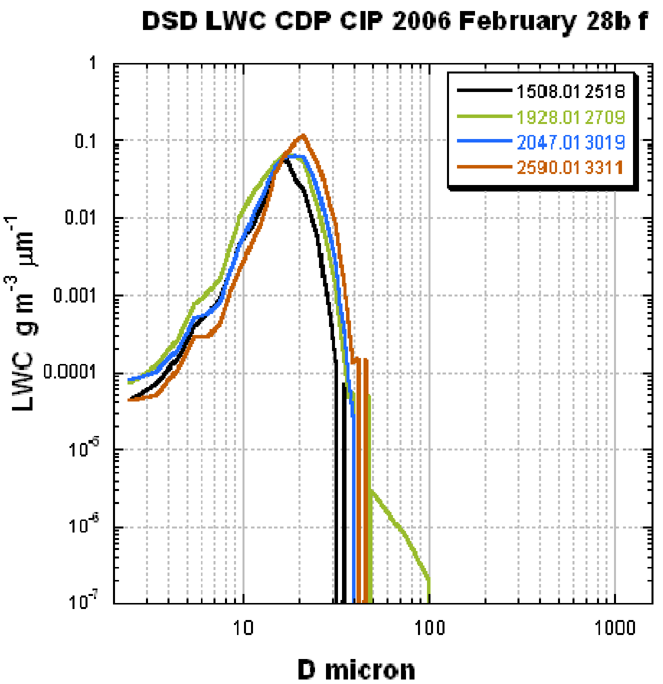


Figure 9: Same as Figure 5, but for vertical cross section in Cloud 8 over Sacramento (see location in Figure 3). It developed in an air mass that had about 800 CCN cm^{-3}. The cloud drops are very small and do not expand much with height into raindrops, again as in Cloud 1.

From the location of Cloud 1 we flew SW diagonally 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 to its west. The cloud tops had a convective appearance, and we sampled them from the lowest altitude that we were allowed (2100 m, due to safety ground clearance over the highest terrain) up to the cloud tops at 2700 m. The temperature there was -3^{o}C, but maturing clouds were visibly glaciating, probably by a mechanism of ice multiplication. The modal LWC DSD was 28 μm at 2100 m and reached 33 μm at the cloud top at 2700 m. This is clearly beyond the value of the warm rain threshold. In agreement with that, the DSD was extended smoothly to the drizzle and small rain drop sizes, as measured by the CIP and presented at the lower panel of Figure 6. The appearance of the warm rain is consistent with the decrease of the CCN concentrations to about 100 cm^{-3}.

We continued flying to the SW to the next area of clouds (cloud 3) that were triggered by the coastal hills at the area of Big Sur. We stepped vertically through the convective looking cloud tops from lowest safety height of 1880 m to their tops at height of 2250 m and temperature of -3^{o}C. The CCN concentrations as measured by the aerosol aircraft in Monterrey Bay varied between 20 and 50 cm^{-3}, which are extremely low. Consistently, the clouds had very large drops ranging from modal LWC DSD 30 μm at the 1880 m to 43 μm at the cloud tops. The DSD was extended smoothly into the drizzle and small rain drops (see Figure 7). 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 warm rain very actively.

From Big Sur we continued into the ocean and then turned north and flew at a constant altitude across the Monterrey Bay to the Golden Gate and then eastward back to Sacramento. This flight path took us along an aerosol gradient that increased from pristine over ocean to polluted air just to the east of the 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. Their properties are summarized in Figure 8.

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 modal LWC DSD of 31 μm and created warm rain. A faint cloud bow was barely visible. Shortly after passing directly overhead San Francisco International airport a short jump in the CCN occurred to about 600 cm^{-3} and recovered to the background of < 70 cm^{-3}. Cloud 5 was penetrated just to the north of Golden Gate, where the CCN increased to 100 cm^{-3}. Cloud 5 still had warm rain, but to a lesser extant than Cloud 4.

We turned east and crossed the northern arm of the San Francisco Bay. The CCN concentrations increased to about 300 cm^{-3} shortly after crossing the coast line. Cloud 6 that 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 south-westerly winds near the surface that veered to stronger WSW wind at the higher levels. This wind brought the urban air pollution to the flight track.

Cloud 7 occurred a few km farther east of cloud 6, where the CCN concentrations increased to 600 cm^{-3}. Its modal LWC DSD decreased further to 15 μm. Cloud 9 developed farther east over Sacramento, where the CCN concentration varied between 600 and 1000 cm^{-3}. The cloud had a similar microstructure to cloud 8. A vertical stepping through cloud 9 showed little widening of the DSD with height (Figure 9), which serve as additional indication of the scarcity of coalescence in that cloud.

A satellite analysis (Figure 10) shows that the satellite retrieved microstructure of the cloud field is in agreement with the in situ measurements that suggest suppression of precipitation in Area 1, which includes Cloud 1, while showing ample warm rain at Area 3, which is includes Cloud 3.

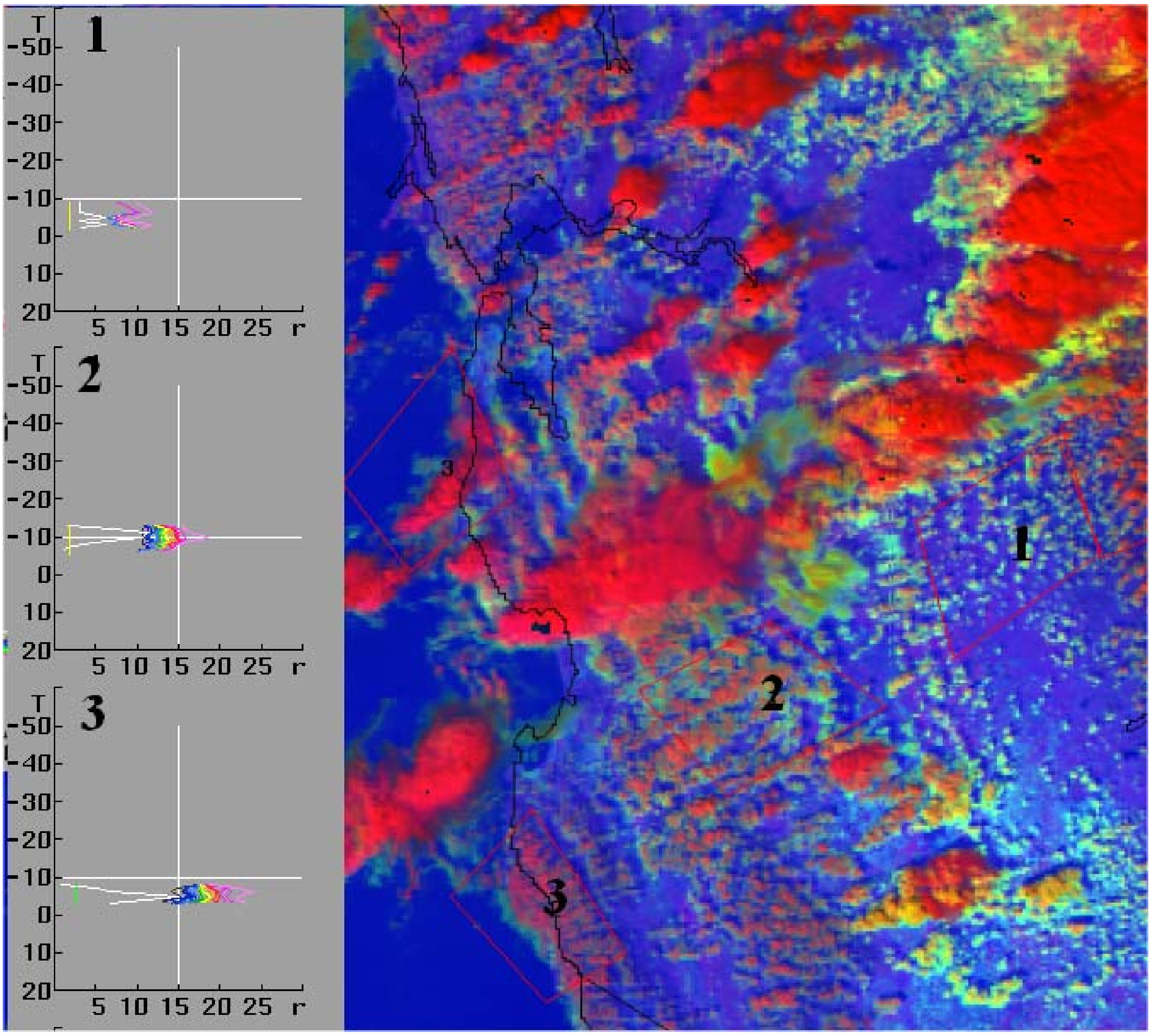


Figure 10: Aqua MODIS image of the clouds in the San Francisco-Sacramento area on 2006 02 28 21:00Z. The color scale is a composite following Rosenfeld and Lensky (1998) where the red is modulated by the visible solar reflectance, blue modulated by the thermal temperature, and green modulated by the 3.7 μm solar reflectance component. The green is brighter for smaller cloud particles. Therefore, the polluted clouds with small drops appear yellow (see Area 1), whereas the ice clouds appear red. Pristine water clouds appear magenta (see Area 3), because they have low green (large water drops) and high blue (warm temperature). The line graphs provide the relations between the satellite indicated cloud top temperatures and the cloud top particle effective radii. The effective radius of cloud top effective radius is much smaller than the precipitation threshold of 14 μm (Rosenfeld and Gutman, 1994) at the foothills in Area 1, but is much larger than that over the coastline in Area 3.

5. Summary

A preliminary analysis of single flight of SUPRECIP 2 showed a clear relation between CCN concentrations, cloud microstructure 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 at a relatively scarcely 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.

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 DSD. It is known from theoretical considerations and simulation studies that the decreased cloud drop sizes reduce also the mixed phase precipitation, 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. The continued analyses and evaluation of the results is likely to provide compelling evidence for the detrimental role of anthropogenic aerosols on orographic precipitation in California, and explain the climatologically observed trends of the reduction in the orographic precipitation component at the southern and central Sierra Nevada.

6. Acknowledgements

Because nothing meaningful in life happens without the assistance of others, we want to acknowledge the assistance that the flight program under Woodley Weather Consultants received for our efforts. First and foremost we very much appreciate the funding for our efforts from the California Energy Commission and the enthusiastic support of Guido Franco of the PIER Program. We also thank personnel at the CIEE of the University of California for handling the contracting for SUPRECIP-2. Without them there would have been no program.

We acknowledge also our field colleagues including Dr. Jim Hudson of the Desert Research Institute, Dr. Steven Cliff of UC Davis and Ms. Odelle Hartley of UC San Diego. We have already exchanged aerosol data with Dr. Hudson and we look forward to our interactions with the UC Davis and UC San Diego research groups that have only just begun.

Gary Walker piloted the Cheyenne 2 cloud physics aircraft under very challenging circumstances. Flying winter clouds over mountains under icing conditions is very difficult. Some would choose not to do it at all. We not only appreciate Gary's flight expertise; We appreciate his friendly relaxed manner in getting the job done. We also thank Mr. Kevin McLaughlin from West Sacramento who piloted the Cessna 340 aerosol aircraft. His familiarity with the Sacramento was especially helpful. Finally, we thank Dr. Jim Hudson of the Desert Research Institute for his loan of some aerosol instrumentation that was used on the research aircraft. These proved to be very valuable to us.

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