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Cloud Particle Measurements in Thunderstorm Anvils and Possible Weather Threat to Aviation

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Since 1990, there have been at least 10 known incidents where jet aircraft have experienced loss of thrust in one or more turbofan engines while maneuvering in the anvil region near the central core of a thunderstorm. The exact cause of the uncommanded thrust reduction, commonly called engine rollback, is still under investigation. It appears that the rollback incidents may be associated with ingestion of high mass concentrations of ice particles, snow, and possibly small concentrations of supercooled liquid water in the anvil region. The characteristics of cloud particles in thunderstorm anvils have not been extensively studied. Results from analysis of aircraft observations in the anvils of midlatitude and tropical thunderstorms are discussed. Aircraft and limited radar observations show that most anvils associated with small, garden-variety thunderstorms contain low (<~0.4 g m^{-3}) mass concentrations of ice particles. In larger, more intense midlatitude storms, anvils may contain ice water contents from 1 to 3 g m^{-3}. The mean of the maximum particle dimension in the anvil region of the more intense storms showed a strong modal size of about 2 mm. The particles themselves appear to be ice crystals and aggregates of ice crystals, i.e., snowflakes. The mass concentration of ice particles usually decreases rapidly away from the center of thunderstorms, falling off to less than half its peak value within about 10 km of the central region of the storms. The data suggest that the ice water content is well below 1 g m^{-3} at a distance of ~50 km away from the central region of a thunderstorm, i.e., the region with high radar reflectivity.

I. Introduction

THUNDERSTORMS are ubiquitous on a global scale. It is estimated that nearly 2000 thunderstorms are in progress around the world at any point in time.[1] Commercial aircraft routes also cover much of the world. Standard airline routes blanket much of the northern hemisphere and portions of the southern hemisphere. Pilots of commercial aircraft typically deviate around thunderstorms that are along their course, but on occasion, flight through or in the vicinity of thunderstorms is unavoidable. Except for takeoff and landing and very short flight segments, commercial turbofan aircraft typically fly at altitudes above 30,000 ft mean sea level (msl). At these altitudes, the outflow (commonly called the anvil) region comprises the majority of the cloudy area associated with a typical thunderstorm.

Thunderstorms have been studied for nearly 50 years using meteorological radar and research aircraft. However, the large majority of the research projects have focused on the more dynamic aspects of thunderstorms, i.e., the production of heavy rain, hail, strong winds, and lightning. Very little research has been conducted on the portion of a thunderstorm commonly called the anvil. Named for its characteristic shape, the anvil is the outflow region of a thunderstorm above about 8 km where cold (−25 to −70°C) cloudy air spreads outward underneath the capping inversion of the tropopause.

Although commercial jet airliners routinely avoid all cloudy regions of thunderstorms, occasionally weather and/or traffic restrictions require jet aircraft to penetrate the anvil regions. The anvil typically does not contain heavy rain, hail, turbulence, lightning, or even airframe icing, conditions in thunderstorms usually considered hazardous to flight. However, since 1990, there have been at least 10 known incidents where a regional jet airliner suffered loss of engine power near a flight altitude of 30,000 ft msl while maneuvering near thunderstorms. In these cases, the engine(s) lost power slowly at first, culminating in a rapid (uncommanded) reduction of power to flight idle or even subidle, commonly called engine rollback. In most cases, engine power authority returned after descent through the freezing level. Reconstruction of events from flight recorder data, crew reports, and weather maps strongly suggests that the rollback incidents occurred in the outflow (anvil) region of thunderstorms.

Analysis of the meteorological conditions associated with these events suggests that the power loss to the engine(s) was associated with the engine ingestion of ice particles located in the anvils of thunderstorms. This is supported by measurements made by a specially instrumented airliner that was flown in the vicinity of thunderstorms. Although the airliner did not experience a rollback event, it was equipped to monitor engine parameters and had a particle measuring systems (PMS) forward-scattering spectrometer probe (FSSP).[2] The available data suggest that high mass concentrations of ice crystals and possibly small concentrations of supercooled liquid water may be cooling the exit guide vane (EGV) assembly in the low-pressure compressor section of the engine. Typically, in turbofan engines, this EGV assembly is not heated; instead, the dynamic heating resulting from compression of air by the fan and low-pressure section itself is adequate to keep ice from forming on an EGV. If ice does form on the EGV(s), it can disrupt the airflow, leading to a positive feedback scenario where the compressor loses pumping capacity, which results

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in an overall loss of power; thus fan speed slows, potentially resulting in engine rollback. In two of the rollback incidents, all four jet engines lost power and the aircraft made an emergency descent. Once below the freezing level, two or more of the engines were restarted and the aircraft landed safely at the nearest available airport.

In addition to the meteorology of thunderstorm anvils, we also discuss the instrumentational errors associated with measurements made in thunderstorm anvils by the FSSP and the standard aircraft total air temperature sensor. Cloud particle characteristics are presented based on more than 500,000 measurements made in anvils by research aircraft during two meteorological projects: The Cooperative Convective Precipitation Experiment (CCOPE) conducted near Miles City, Montana in 1981 and the Central Equatorial Pacific Experiment conducted in 1993 (CEPEX). Based on these data, some basic guidelines for avoiding anvil regions with high ice mass concentration and possibly supercooled liquid water are given as an aid to pilots.

II. Background

Early measurements of the ice water content (IWC) in tropical storms are reported by McNaughtan.[3] [The IWC is defined as the mass of ice (melted to its water equivalent) in a specific volume or mass of air and is given in units of g m^{-3} or g kg^{-1}.] This work was conducted because the turboprop engines sometimes malfunctioned on Bristol Britannia aircraft in ice crystal clouds in the equatorial zone. A special instrument, using a pitot tube to capture ice crystals, melt them, and measure the liquid water, was designed and built for this project. The results show that a mean melted water content of about 1.3 g m^{-3} was observed in clouds; however, peak values approaching 7 g m^{-3} were observed during some 1-min periods. The measurements apparently were not made in thunderstorm anvils, because the data were collected in the temperature range of −20 to 0°C, or 7000–18,000 ft msl for the International Civil Aviation Organization (ICAO) standard atmosphere. Also, the clouds contained mixtures of ice crystals and liquid water, and so the (melted) water contents reflected that mixture.

The IWC measurements reported by McNaughtan[3] are much higher than recent values of IWC in the −20 to 0°C range reported by Jeck,[4] who compiled PMS two-dimensional probe[2,5] measurements from several research aircraft. Some of the discrepancy between the results given by McNaughtan[3] and Jeck[4] may be because Jeck's data are for ice particles only and McNaughtan's measurements include supercooled liquid water. Also, the two measurement techniques differ substantially and both techniques are subject to measurement uncertainties.

Ice crystal sizes, concentrations, and IWC differ markedly in common cirrus clouds compared with thunderstorm anvils (which may take on the characteristics of cirrus after the storm dissipates and the anvil drifts away). Heymsfield and Knollenberg[6] reported the first two-dimensional probe measurements and replicator measurements in cirrus clouds over Minnesota and Colorado. They found that the mean crystal size was 0.6–1 mm, concentrations were 10–25 L^{-1}, and IWC ranged from 0.15 to 0.25 g m^{-3}. The particles were mostly individual crystals with habits characteristic of bullets, columns, and bullet rosettes. No supercooled liquid water was observed. Nearly 20 years later, Heymsfield et al.[7] reported more extensive measurements in cirrus clouds and found about the same crystal habits and IWC; however, the more recent measurements revealed an increase in small particles.

During the CCOPE project, a Sabreliner research aircraft owned by the National Center for Atmospheric Research (NCAR) made particle measurements using the PMS two-dimensional optical array precipitation (2D-P) probe[2] in anvils over eastern Montana during the summer of 1981. The in situ measurements were integrated with the NCAR ground-based

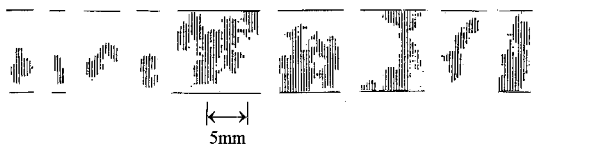

Fig. 1 Examples of 2D-P shadow images of particles observed in the anvil of the Aug. 1, 1981 CCOPE supercell storm.[9]

meteorological radar using the scheme proposed by Plank et al.[8] Some measurements collected in the anvils of six storms have been reported.[9–11] In general, the results show that the maximum IWC in the anvil region is on the order of 1–2 g m^{-3}, except in the area near the central part of the storm where measurements were made in updrafts, often containing small graupel particles.

The accuracy of IWC computed from two-dimensional images is difficult to quantify. Heymsfield[9] suggests that IWC accuracy is within a factor of 2. The incorporation of radar data using the Plank et al.[8] scheme may improve the IWC calculation under some conditions, but a rigorous uncertainty analysis has not been performed. The maximum crystal dimension ranged from 1 to 10 mm, and concentrations were on the order of 10 L^{-1}. Most particles were composed of aggregates of ice crystals, i.e., snow. Examples of shadow images of some of these particles are shown in Fig. 1. Heymsfield and Miller[11] showed that the flux of ice particles dropped off rapidly with distance from the storm center. Supercooled liquid water as measured by the Johnson–Williams (J–W) hot-wire device[12] was found only rarely, and then only in low concentrations in convective elements near the core of the storm.

Other field projects have provided less comprehensive data sets on thunderstorm anvils. The U.S. Air Force conducted in situ investigations of the particle spectra in cirrus near the Kwajalein Atoll in the 1970s. The purpose of this research was to document the particle spectra in cirrus clouds to better understand ablation of missile nose cones. Some of the missions were flown in thunderstorm anvils. Measurements were made with a U.S. Air Force RB-57F and a Learjet owned by Aeromet Incorporated. The public literature released as a result of this project does not contain information on particle statistics in anvils.

Knollenberg et al.[13] report particle distributions in thunderstorm anvils that penetrated the stratosphere over Panama. In general, their studies, conducted at about −80°C, supported previous work by Heymsfield[14] that showed low to moderate concentrations (order 10–100 L^{-1}) of ice particles with sizes smaller than 1 mm. The computed IWCs did not exceed a few hundredths g m^{-3}. Bennetts and Ouldridge[15] made measurements in a winter maritime cumulonimbus cloud near the United Kingdom. They reported ice particle concentrations on the order of 100 L^{-1}, mean particle size of a few tenths of a millimeter, and maximum IWCs of about 1 g m^{-3}. These values of IWC, however, were measured at an altitude of about 4 km.

Detwiler et al.[16] made measurements in a small multicell thunderstorm 150 km south of Bismarck, North Dakota on July 6, 1989. Using the University of North Dakota Citation II aircraft, measurements were made at 8.8 and 9.4 km, including passes through two convective cells near the central core region of the storm. No J–W cloud liquid water content was measured anywhere in the anvil. 2D-C images of particles in the core regions showed high (up to 1000 L^{-1}) concentrations of small (order 100 μm) ice particles. Downwind from the cores, the particles took on more of an appearance of aggregates.

New analyses of the CCOPE and CEPEX data are included in this paper and provide an enhanced database for interpreting the particle spectra in thunderstorm anvils.

III. General Characteristics of Rollback Events

There have been several known events since 1990 that have resulted in an uncommanded loss in engine performance (commonly called engine rollback) during flight in or near the anvil regions of thunderstorms. Some of the common features of these events are summarized here from flight recorder data and interviews with the flight crews: flight altitude from FL 280 to FL 310, ambient temperature from −33 to −27°C, in visible cloud, near thunderstorms, light or no airframe icing reported, "St. Elmo's" fire observed on some incidents, overshooting cloud tops often reported, and rapid total air temperature (TAT) increase prior to engine rollback.

In all cases, the available meteorological data showed that thunderstorms were in the vicinity, and often pilots were maneuvering around strong radar echoes. In no cases did the pilot or crew report more than trace or light airframe icing at flight altitude. Also, there were no reports of hydrometeors actually hitting the windscreen at the altitude the incidents occurred, as would be the case if rain, large graupel, or hail particles were present. These factors suggest that the aircraft were in the anvil regions of the thunderstorm where liquid supercooled water contents are typically zero or very low, and these can be regions with relatively high IWC.

Figure 2 shows an example of TAT and fan speed (N1) output from the aircraft flight recorder during one of the rollback incidents. It is important to note here that the apparent increase in TAT seen in Fig. 2 is not an actual increase in ambient air temperature. It is suspected that ice particles clogging the orifice inside the (heated) probe where the air makes a right-angle turn lead to the formation of an ice bridge. The purpose of the right-angle turn is to inertially separate cloud particles from the airflow. When the ice bridge forms, the probe heaters warm the sensor, which now is not ventilated with ambient air, to near the melting temperature of ice, i.e., 0°C. If heavy concentrations of ice particle ingestion persist, the probe continues to register an anomalous warm temperature. Once the aircraft exits the region of relatively high IWC or descends to a warmer temperature, the ice bridge apparently begins to sublimate and/or melt, and eventually airflow is reestablished and the probe resumes making normal measurements. Some wind-tunnel tests by the manufacturer of the TAT also suggest that high mass concentrations of ice crystals lead to this anomalous temperature rise. (The heated TAT probe meets all Federal Aviation Administration and MIL-SPEC regulations. The manufacturer tested the probe in a wind tunnel where ice particles with a mean size of about 1 mm and IWC up to 5 g m^{-3} were generated by shaving particles from a block of ice. The tests were conducted with and without small concentrations of liquid water. Basically, the results showed that the tendency for the TAT probe to clog with ice particles and register anomalously high temperatures occurred with and without supercooled liquid water, and it increased with small concentrations of supercooled liquid water.)

We want to emphasize that the TAT temperature output is not used in any way to control fuel flow or any other engine parameters. The anomalous rise in the TAT temperature is fortuitous only in that it forewarns that the aircraft may be in conditions that also appear to cause engine rollback. In other words, high mass concentrations of ice particles (and possibly small amounts of supercooled liquid water) appear to cause anomalous TAT warming and engine rollback, but these events occur in parallel, i.e., one event does not depend on the other event to occur.

Figure 3 is shown to demonstrate the strong correlation between anomalous warming of the TAT and the presence of ice crystals. The time series measurements in Fig. 3 show alternating warming to near 0°C and recovery of the TAT probe to the proper total air temperature (about −12°C) as an aircraft passes in and out of ice particles in the outflow region near a thunderstorm. The flight was conducted in the vicinity of Panama at FL 310, at a static air temperature of −32°C, and at a true airspeed of 200 m s^{-1} (which gives a dynamic heating of 20°C, assuming a recovery factor of 1). These data were collected by a regional jet that was specially equipped with an FSSP. The engines did not roll back; however, the FSSP cannot provide quantitative measurements of IWC. An analysis of the FSSP housekeeping data strongly suggests that the response of the FSSP in Fig. 3 is dominated by the breakup of large ice particles, i.e., snowflakes, hitting the sample tube. If this is the case, the relative IWC shown in Fig. 3 is roughly proportional to the concentration of large ice particles and snow in the anvil. Coincidentally, the breakup and slowed transit of particles through the sample volume results in measured par-

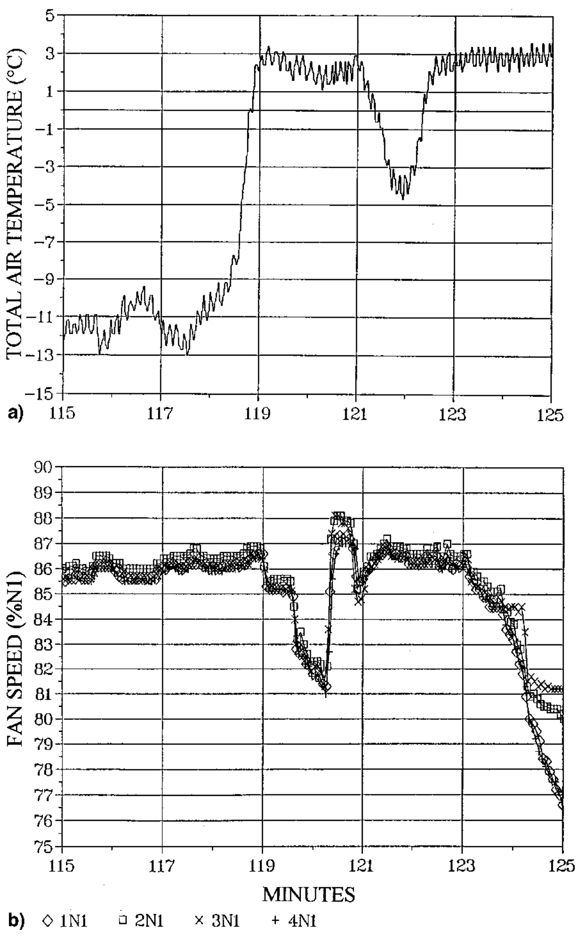

Fig. 2 Time series of a) TAT and b) jet engine fan speed (N1) plotted against aircraft time enroute in minutes. Data were collected by a flight recorder from an aircraft that was involved with a rollback incident.

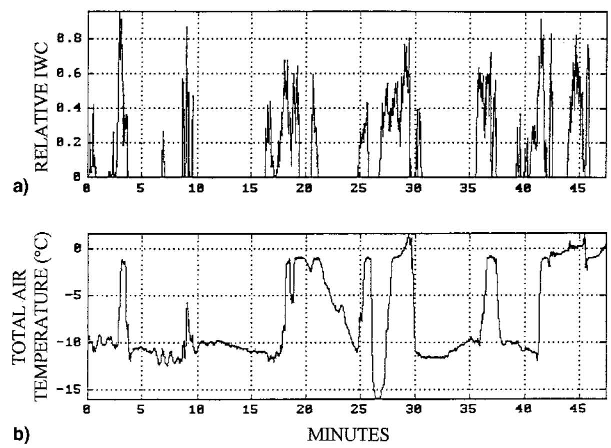

Fig. 3 Time series of a) relative IWC and b) total air temperature in regions of relatively high concentrations of ice crystals with ambient temperature = −32°C at FL 310.

ticle concentrations on the order of 20–200 cm^{-3}, similar to drop concentrations typically found in maritime clouds.

Holland et al.[17] explained an observation of rapid (18°C) warming of a similar TAT sensor and associated partial loss of engine performance as the result of a stratospheric intrusion of warm air. Interestingly, at the aircraft cruising speed of about 230 m s^{-1} at FL 370, the TAT would experience 26°C of dynamic warming (assuming a recovery factor of 1), so that the observed 18°C temperature rise from a static temperature of −45°C would bring the measured temperature to about −1°C, nearly the same value observed in Fig. 3 when the TAT probe was affected by ice particles. In the case reported by Holland et al.,[17] the aircraft experienced about 30–45 min of flight through a very large outflow region in the wake of 1979 Tropical Storm Kerry near Cairns, Australia. The Boeing 747 deviated near a line of convection, and so it was likely that it was exposed to high IWC regions for an extended period of time. The wind-tunnel tests and analysis of the rollback events suggest that the likelihood of both the anomalous TAT warming and engine rollback is increased by increasing both IWC and duration of the encounter. Thus, it is possible that the rapid TAT warming observed by Holland et al.[17] was not the result of a stratospheric intrusion but, instead, the result of instrument error (in their analysis, the authors accepted that the probe measurement was accurate to within 1.3°C).

It is worth considering whether the engines in any of the research aircraft used in these studies showed any indications of uncommanded power reduction. To the best of our knowledge, the Sabreliner and RB-57F, which have turbojet engines, did not experience any loss of power. The Citation, which has turbofan engines, did not report any indication of power reduction in the (relatively) small thunderstorm anvil it penetrated. The pilot of the Lear 36, when questioned, did recall some indications of slight power reduction in portions of the thunderstorm anvils. However, he reported that the computerized power controller was able to compensate, and no rollback occurred.

IV. Cloud Particle Characteristics in Anvils

In this section, we present results of new analyses of data from the CCOPE and CEPEX projects. All of the data presented here were processed from 2D-C (about 35-μm pixel resolution) and/or 2D-P measurements (200–300 μm pixel resolution depending on probe configuration). In the case of the CCOPE data, some ground-based radar measurements have been integrated with the results. Both the CCOPE and CEPEX data sets contain measurements from the J–W hot-wire liquid water content device.[12,18] We have not presented any of these measurements here because there was virtually no supercooled liquid water measured in the thunderstorm anvil regions. The rare exception occurred in convective cells with $T > -40$°C that were sampled in or very near the central portion of the thunderstorm. These cells always contained weak to moderate (5–15 m s^{-1}) updrafts and graupel particles. In contrast, supercooled liquid water and graupel particles were not observed in the anvil region, and vertical velocities were very weak, generally less than 1 m s^{-1}.

A. CCOPE Storms

Measurements in the anvils of six thunderstorms are presented (June 12, June 20, July 11, July 19, July 21, and Aug. 1, 1981). Some previous works[9,10,11,19,20] will be integrated into these analyses.

The CCOPE project was focused mainly on large multicellular thunderstorms, and in two cases (July 11 and Aug. 1) these storms evolved into unicellular supercells. The Aug. 1 supercell storm was very intense, with 47-m s^{-1} updrafts that produced softball-size hail and a maximum radar reflectivity of 72 dBz (Ref. 20). An analysis of the measured radar reflectivity factor indicates that an area of about 10 km^2 exceeded 60 dBz from 1600 to 1700 mountain daylight time (MDT), the period coinciding with in situ anvil measurements made by the NCAR Sabreliner research aircraft. Figure 4 shows a scatterplot of measurements of particle concentration, maximum particle dimension, and IWC plotted against altitude and temperature in the anvils of six storms studied in CCOPE. [Maximum particle dimension is used here because, due to the nature of two-dimensional images (Fig. 1), it is difficult to determine a particle diameter. However, techniques for computing the effective (spherical) particle diameter are available; an estimate for the effective diameter of anvil particles can be found by dividing the maximum particle dimension by about a factor of 3 or 4.] The data in Fig. 4 show that particle concentrations in the CCOPE anvils were low to moderate (compared to the higher concentrations discussed in Sec. II). This can be partially explained by the instrumentation on the Sabreliner research aircraft used in CCOPE. Because of the limited capability for mounting probes on the Sabreliner, it was equipped with one PMS two-dimensional probe that had a minimum size resolution of 300 μm. On the other hand, the observations reported by Detwiler et al.[16] are based on measurements with two PMS two-dimensional probes, one with a minimum size resolution of 33-μm and another with 200-μm resolution. Thus, the smaller particles, which typically occur in much higher concentrations than the larger particles, were not being measured in the CCOPE anvils. Figure 4 shows that particles in the CCOPE anvils were significantly larger than previously observed in other studies.[13,14,16] This is most likely attributable to the strong updrafts in the CCOPE storms.

The plot of IWC in Fig. 4 was computed by combining the in situ particle probe computations (using the method of Heymsfield et al.[7]) with ground-based radar measurements using the scheme proposed by Plank et al.[8] The measurements show a trend in the CCOPE anvils of decreasing IWC with height. This can be explained physically by particle sorting if the largest particles, which represent a significant portion of

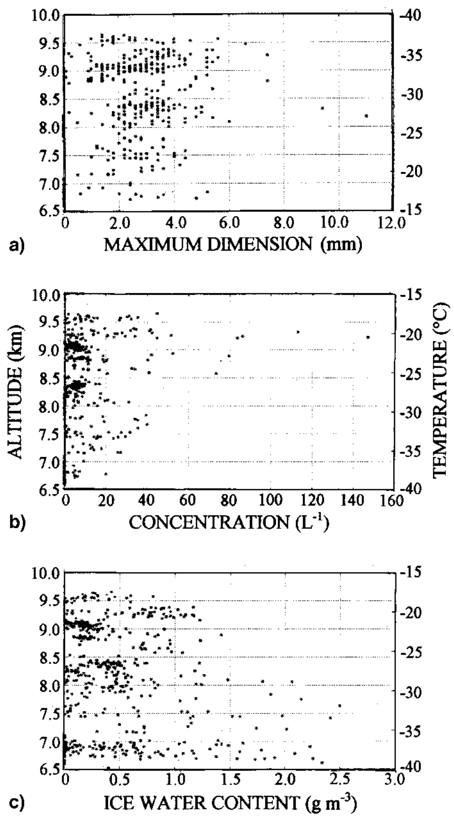

Fig. 4 Scatterplots of 1-km average measurements taken in the anvils of all CCOPE storms of a) maximum particle dimension, b) particle concentration, and c) ice water content plotted against altitude on the left scale and temperature on the right scale.

the mass, are not carried as high into the anvil as are the smaller particles.

Fankhauser[19] shows the position of the maximum radar echoes for the six CCOPE storms studied in this work. Using Fankhauser's measurements,[19] the concentrations of ice mass measured by the NCAR Sabreliner as a function of distance from the (radar) centers of the storms were determined. The results showed a strong correlation between the maximum IWC and maximum radar echo for those passes where IWC ≥ 1.5 g m^{-3}. The maximum IWC was found to systematically decrease from the radar center of the storm until a new maximum radar echo, i.e., a new cell, was detected. This suggests that individual cells in multicellular storms periodically deposit high concentrations of ice particles in the anvil, and that the concentration of ice particles diffuses with time as they drift with the mean wind. Because the updraft in a (unicellular) supercell storm is more continuous, one would expect a more continuous distribution of ice particles in the anvils of supercell storms.

Figure 5 shows IWC measured in five multicellular storms (excluding August 1 and including July 11 before it became a supercell). The IWC measurements are plotted as a function of distance from the maximum IWC value per aircraft pass through the anvil. Figure 5a shows measurements taken in the multicellular storms with a peak IWC max from 1.5 to 2.5 g m^{-3}, Figure 5b is a similar plot for $0.5 < IWC_{max} \leq 1.5$ g m^{-3}, and Fig. 5c shows measurements when $IWC_{max} \leq 0.5$ g m^{-3}. The composite data in Fig. 5 show a much stronger gradient when the peak IWC is high, suggesting that the roll-off in IWC near the core of the storm is more rapid. The measurements in Fig. 5a show that, on the average, IWC decreases to less than 50% of peak value within 5–10 km in multicellular storms. Figures 5b and 5c show that for the smaller peak values, the IWC decreases to 50% of peak in about 20–30 km. On the other hand, when IWC measurements from the Aug. 1 supercell storm are included, the decrease of IWC with distance from the peak is much more gradual, reaching 50% of peak in about 30–35 km. Because supercell storms exhibit a continuous strong updraft, the diffusion of ice particles in the anvil is offset by the continued production, possibly resulting in a relatively higher IWC as a function of distance away from the storm center.

B. CEPEX Storms

The CEPEX took place in March–April 1993. Measurements were made in the central Pacific near Fiji by a Learjet owned by Aeromet Incorporated. No radar measurements were made during this experiment. The cloud systems were typically banded and the combined anvils from individual storms often extended for a few thousand kilometers. The Learjet did not try to work individual cloud systems but, instead, flew prescribed legs through the extensive cirrus canopy that was visible on satellite images. There were considerably more data collected in CEPEX anvils than in CCOPE, and the measurements often continued from one cloud system to the next without actually exiting cirrus cloud. Objective data analysis techniques were used to separate the individual cloud systems. There were 24 missions flown on 20 days during CEPEX.

Figure 6 shows scatterplots of measurements of particle concentration, maximum particle dimension, and IWC in the same format previously shown for the CCOPE storms in Fig. 4. The

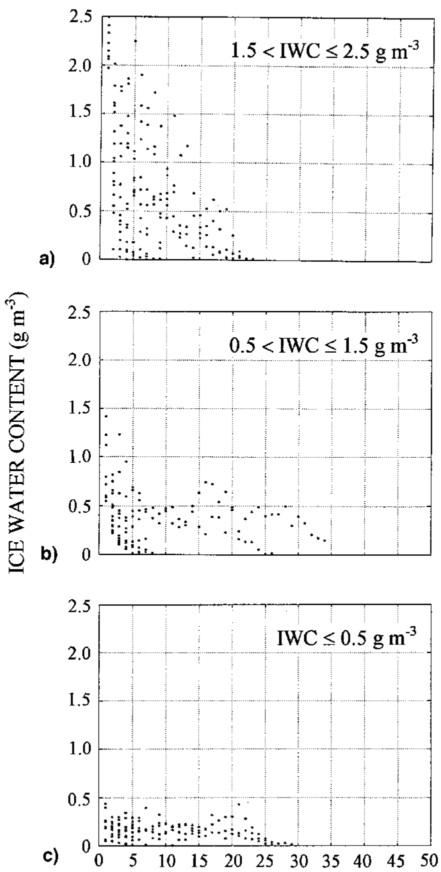

Fig. 5 Scatterplots of IWC in CCOPE multicellular storms vs relative horizontal position from the location of the maximum IWC for that pass. Comparison shows a) measurements for passes where maximum IWC is 1.5–2.5 g m^{-3}, b) IWC from 0.5–1.5 g m^{-3}, and c) IWC from 0–0.5 g m^{-3}.

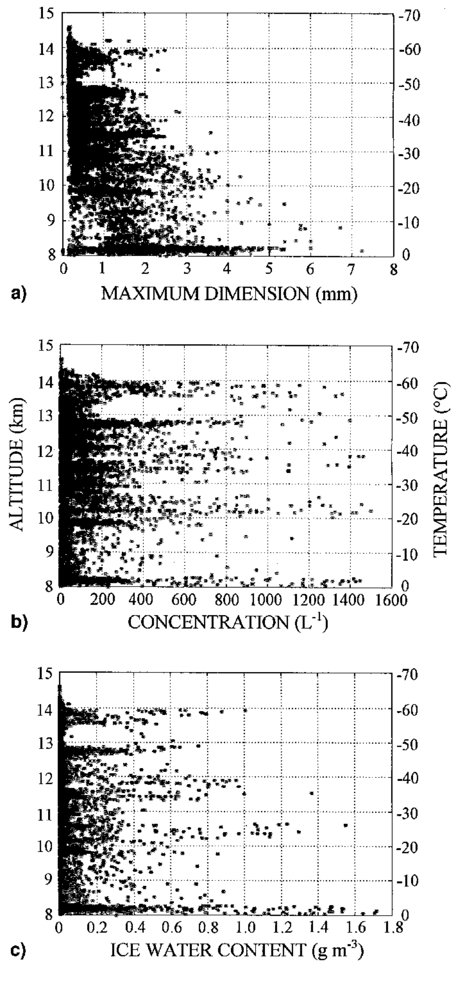

Fig. 6 Scatterplots of 2-km average measurements taken in the anvils of all CEPEX storms of a) maximum particle dimension, b) particle concentration, and c) ice water content plotted against altitude on the left scale and temperature on the right scale.

data points from both 2D-C and 2D-P probes shown in Fig. 4 are 2 km averages. The data show that particle concentrations in the CEPEX anvils were much higher than observations in CCOPE anvils. Some of the measurements even exceed the relatively high concentrations observed by Detwiler et al.[16] In general, the anvils extend to higher elevations in CEPEX, about 14.5 km, compared to about 12 km in CCOPE. This is expected in the tropics where the tropopause is usually 1–4 km higher than in the midlatitudes. The measurements show that particles in the CEPEX data set were not as large as those in CCOPE. There is a strong trend for decreasing particle size with increasing altitude (Fig. 6). The higher concentration of smaller particles observed in CEPEX may be explained by the three following factors.

1) Thunderstorm updraft velocities are typically lower in tropical storms compared with storms in the midlatitudes, thus, only the smaller particles would be transported to higher elevations.

2) The 2D-P probe used in CCOPE had a 300-μm size resolution, and smaller particles would be missed.

3) Data from CEPEX were collected over large distances and included measurements in thin cirrus clouds that occupied the spaces between thunderstorm anvils. The cirrus in these regions were thin and included particles that were typically much smaller than in the anvils. On the other hand, the CCOPE flights were focused exclusively on the anvil regions close to the thunderstorms.

The IWC measurements shown in Fig. 6 were computed based only on the two-dimensional image data using the method of Heymsfield et al.[7] Unlike CCOPE, there was no ground-based meteorological radar, and so the scheme developed by Plank et al.[8] could not be employed. The IWC data show a trend in the CEPEX anvils of decreasing IWC with height. This can be explained physically by particle sorting if the largest particles, which represent a significant portion of the mass, are not carried as high into the anvil. The vertical distribution of particles supports this premise, showing that larger particles are observed lower in the anvils of CEPEX storms.

Unlike CCOPE, CEPEX did not have ground-based radar coverage and it is very difficult to determine the centers of convection from satellite data. Thus, there is no independent source of information for determining the center of convection. However, analysis of CCOPE data suggest that in multicellular storms, high concentrations of ice particles are deposited in the anvil in bursts because of the cycle time of individual cells in these storms. The pockets with relatively high concentrations of ice particles then spread out as they drift downwind in the anvil.

Figure 7 shows IWC plotted as a function of distance from the maximum IWC value per aircraft pass in the same format shown previously for the CCOPE storms (Fig. 5). The data in Fig. 7 show a much stronger gradient when the peak IWC is high, suggesting that the roll-off in IWC near the core of new cells is more rapid. The variation with horizontal distance from peak IWC in CEPEX storms was very similar to that found in the CCOPE multicellular storms. On the average, IWC in CEPEX storms decreases to less than 50% of peak value within 5–10 km when the peak IWC > 1.5 g m^{-3}. For peak IWC values <1.5 g m^{-3}, the IWC decreases to 50% of peak in about 20–50 km. Lawson et al.[21] found that the concentration and distribution of IWC derived from the aircraft measurements shown here are in good general agreement with numerical simulations using the two-dimensional cloud model of Farley and Orville.[22]

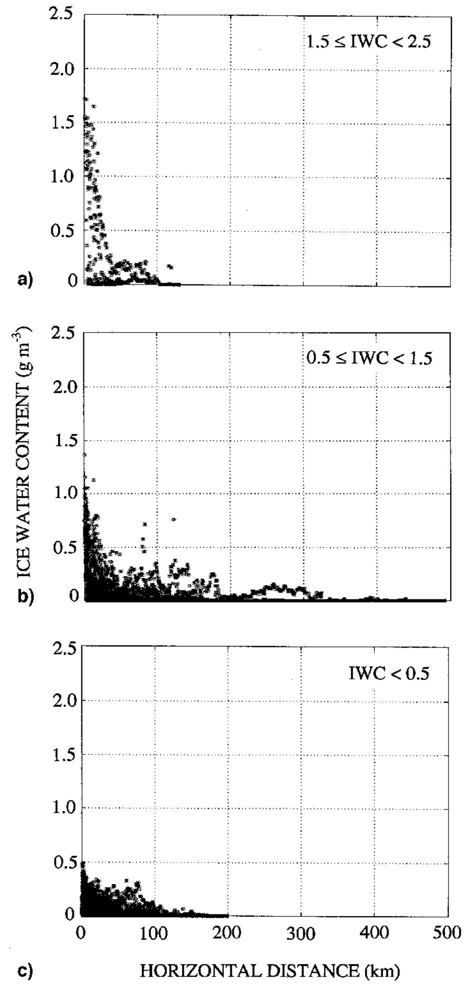

Fig. 7 Scatterplots of IWC in CEPEX storms vs relative horizontal position from the location of the maximum IWC for that pass. Comparison shows a) measurements for passes where maximum IWC is 1.5–2.5 g m^{-3}, b) IWC from 0.5–1.5 g m^{-3}, and c) IWC from 0–0.5 g m^{-3}.

C. Summary of Ice Particle Statistics

The average maximum dimension of ice particles in all midlatitude storms is 2.8 mm, which is substantially larger than the value of 0.8 mm determined from all of the measurements in cirrus and tropical storms combined. This is mostly attributable to the different size resolutions of the two-dimensional probes and sampling techniques used in the two data sets. The flight patterns in CCOPE thunderstorms were closely guided by ground-based meteorological radar that displayed aircraft position. This enabled the NCAR Sabreliner to investigate the anvil regions of intense midlatitude storms. The flight patterns in CEPEX were over the equatorial Pacific Ocean where there was no radar guidance. The Aeromet Learjet flew a more systematic course through large regions of combined cirrus and outflow from thunderstorm anvils. To filter out the primary influence of the cirrus clouds and give a better comparison of particle characteristics in the two regions, Table 1 shows statistics for all measurements and also the measurements for when IWC > 0.2 g m^{-3}.

Table 1 shows that the difference in mean and median IWC in CEPEX storms changes dramatically, from 0.05 to 0.45 and from 0.01 to 0.34 g m^{-3}, respectively, when the IWC > 0.2 g m^{-3} filter is applied. The data in Table 1 also show significant increases in mean particle concentration and particle size when the filter is used. As expected, the changes in the CCOPE measurements are small, because the majority of the measurements were made in anvils with relatively large particles. The large difference in particle concentration between the CCOPE and CEPEX data sets can be explained by the much larger minimum particle size resolution of the two-dimensional probe (300 μm) on the Sabreliner compared with 37 μm on the Learjet. This also suggests that the large majority of IWC in thun-

Table 1 Mean, median, and standard deviation of IWC, maximum particle dimension, and particle concentration measurements from all CCOPE and CEPEX storms including measurements with IWC > 0.2 g m^{-3}

	All CCOPE storms	All CEPEX storms	CCOPE storms IWC > 0.2 g m^{-3}	CEPEX storms IWC > 0.2 g m^{-3}
Mean IWC, g m^{-3}	0.46	0.05	0.65	0.45
Median IWC, g m^{-3}	0.33	0.01	0.51	0.34
Standard deviation 1σ	0.45	0.14	0.45	0.28
Standard deviation 3σ	1.34	0.41	1.34	0.84
Mean of maximum particle dimensions, cm	0.28	0.08	0.21	0.20
Median of maximum particle dimensions, cm	0.26	0.04	0.24	0.19
Standard deviation 1σ	0.13	0.08	0.18	0.07
Standard deviation 3σ	0.38	0.24	0.53	0.22
Mean particle concentration, L^{-1}	10.43	99.79	9.83	480.02
Median particle concentration, L^{-1}	6.09	40.22	5.66	401.90
Standard deviation 1σ	14.63	202.39	14.84	330.89
Standard deviation 3σ	43.88	607.16	44.53	992.68

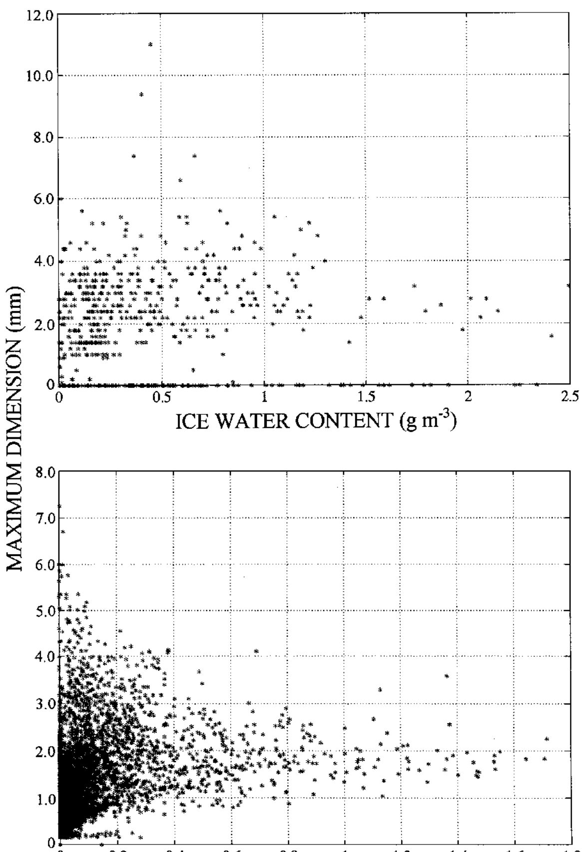

Fig. 8 Scatterplot of ice water content vs maximum particle dimension for a) all CCOPE storms and b) all CEPEX storms.

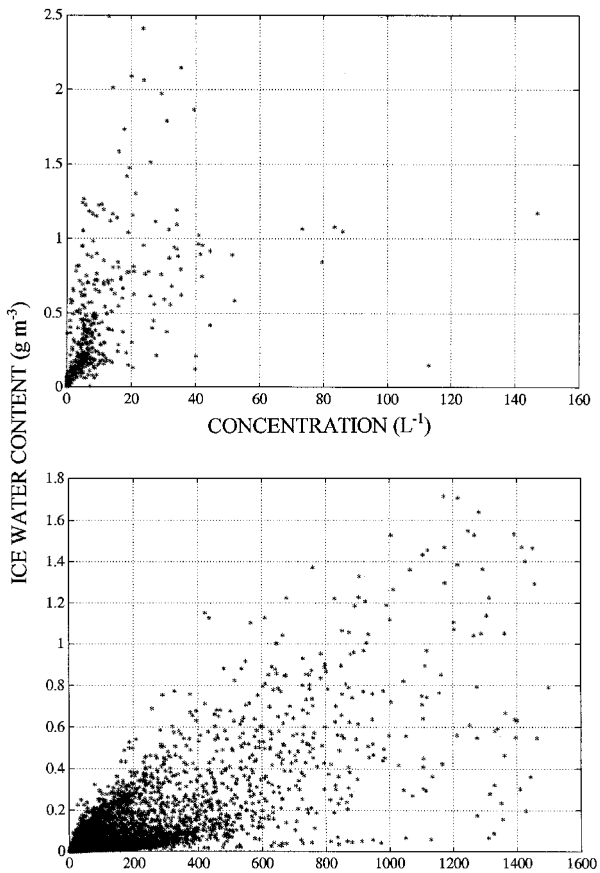

Fig. 9 Scatterplot of particle concentration versus ice water content for a) all CCOPE storms and b) all CEPEX storms.

derstorm anvils is found in particles with sizes greater than 300 µm.

In spite of the sampling differences, Table 1 shows there is still some indication that particle sizes in midlatitude thunderstorms may be slightly larger than in tropical storms (at least, in the storms investigated here). The mean-maximum and median-maximum particle dimensions in midlatitude anvils (2.1 and 2.4 mm, respectively) are still slightly larger than found in equatorial/tropical anvils (1.9 and 1.8 mm, respectively). This is supported by Fig. 8, which shows scatterplots of IWC vs maximum particle dimension for the CCOPE and CEPEX data sets. [The maximum particle dimension and particle concentration data were missing in the archived data files used here (not in the original measurements) for one anvil pass on Aug. 1 and July 11. The zero particle size data points along the abscissa in Fig. 8 represent the missing data. In Fig. 9, the small number of data points represent the missing CCOPE particle concentration measurements. If these measurements were included, there would likely be a stronger correlation in IWC vs concentration seen in the CCOPE measurements, more like the strong correlation in the CEPEX measurements seen in Fig. 9.] These data show that, except for the CEPEX regions with low IWC (<~0.2 g m^{-3}), most of the IWC is found in particles that display a striking modal (maximum) size about 2 mm. Figure 8 also shows that the region of IWC in the graph from about 0.4–2.5 g m^{-3} is strongly biased toward particles with a size of about 2 mm. This implies that the IWC does not increase mainly as a function of increasing particle size once ice particles of millimeter size are reached but, instead, from increasing particle concentration. This premise is supported by the measurements shown in Fig. 9, which shows plots of IWC vs particle concentration for CCOPE and CEPEX storms. The apparent finding that thunderstorm anvils with IWC > ~0.4 g m^{-3} exhibit a strong modal (maximum) particle dimension of about 2 mm is a surprising result.

V. Summary and Discussion

Since 1990, there have been about 10 known occurrences of uncommanded power reduction, commonly called rollback, in one or more of the turbofan engines of a regional jet flying in the anvil region of a thunderstorm at about 9 km. The available meteorological and flight data strongly suggest that the rollbacks were associated with high mass concentrations of ice crystals, snow, and possibly a small amount of supercooled liquid water within a temperature range of −40 → −30°C. About five min in advance of the rollback incidents, the (heated) total air temperature (TAT) sensor on the aircraft appeared to accumulate ice in a way that it warmed and indicated a TAT of about 0°C. This malfunction of the TAT sensor does not cause the engine rollback, but is indicative that it could occur. In all of the rollback incidents, after the aircraft descended below the freezing level, two or more engines regained power and the aircraft landed safely. Based on flight tests with an instrumented aircraft, it is suspected that the engine rollback may result from an accumulation of ice that disrupts the airflow in the vicinity of the exit guide vane assembly in the low-pressure compressor section. The regional jet experiencing the rollbacks is limited to FL 310, so that it does not fly nearly as high as most turbofan airliners. We know of no direct physical evidence that links this altitude to the rollback incidents, except possibly that the occurrence of supercooled liquid water is more likely at this altitude than at higher (colder) levels. While the pilots did not report much, if any, rime icing prior to the rollback encounters, it is not always possible to see a light accumulation of rime ice on the aircraft.

The meteorological and flight data build a picture suggesting that the engine rollback incidents are associated with the vertical transport of ice crystals, snow, and possibly supercooled liquid water that form in the updrafts of thunderstorms and are transported into the anvil region. If the ice particles encounter moderate to high (i.e., >~1 g m^{-3}) concentrations of liquid water lower in the updraft, they most often develop into graupel and/or hail particles that usually fall to the ground within about 10–20 km (horizontally) from the location of the updraft. Exceptions to this rule of thumb occur in storms with very high updrafts and moderate to strong vertical shear in the horizontal wind. If the ice particles encounter relatively low concentrations of liquid water and strong updrafts, they are likely to form into aggregates[23] that are transported up into the anvil region. The conditions most favorable for strong updrafts and low precipitation efficiency are often found over continental regions, particularly over elevated, inland plains at midlatitudes.

Tropical maritime storms are thought to have a higher likelihood than their midlatitude continental counterparts in producing precipitation that reaches the ground, e.g., Wallace and Hobbs.[24] Thus, maritime clouds are usually considered more efficient at producing precipitation. The ratio of condensate that is carried up into the anvil of a thunderstorm to that falling on the ground is likely to be lower in tropical maritime storms than in midlatitude continental storms. However, there is usually more total condensate available in maritime storms, and these storms often group together to form extremely large areas of cloud clusters with extensive combined anvils. The anvils from midlatitude mesoscale convective complexes also combine; however, the combined anvils from these systems are usually smaller in spatial extent than those from tropical cloud clusters. The tropopause is higher in the tropics (by about 1–4 km), so that ice particles in the anvils may be distributed over a greater vertical depth than in midlatitude continental storms. The conditions that favor high concentrations of ice mass in an anvil are 1) large moisture supply available at cloud base, 2) strong updraft velocity, 3) low to moderate liquid water content, i.e., low precipitation efficiency, and 4) low tropopause.

Some of these factors predominate in thunderstorms over the U.S. high plains, and other factors are favored in the tropics. It would require a quantitative assessment beyond the scope of this work to determine which location is most favorable climatologically for the production of large thunderstorm anvils with high ice water content. However, the measurements presented here suggest that the spatial extent of thunderstorm anvils may be greater in the tropics and that the IWC is higher over the Great Plains. A curious result of this research was the finding that there is a strong modal maximum size (~2 mm) of the ice particles in both tropical and midlatitude anvils with IWCs > ~0.4 g m^{-3}. In anvils with IWC > 0.4 g m^{-3}, the data suggest that increasing IWC correlates with increasing number concentration of ~2 mm particles. This result is apparently not explainable from instrumentation considerations and seemingly reflects the physics associated with vigorous thunderstorms.

Based on the available meteorological data from research aircraft, it appears that only the most vigorous thunderstorms, i.e., supercells, and complexes of thunderstorms, are associated with anvils that contain IWC > 1 g m^{-3} in regions outside of the main core of the storm. The highest IWC observed in thunderstorm anvils, based on measurements reported here using PMS two-dimensional probes, was about 2.5 g m^{-3}. There is currently insufficient data to determine the threshold concentration of IWC that will induce rollback. Based on the fact that literally billions of hours have been logged by commercial turbofan engines in common cirrus and anvils, with IWC typically <~0.2 g m^{-3}, it would appear that these clouds do not contain sufficient IWC to cause rollback problems. Also, it appears that rollback may be more likely to occur the longer the engines are exposed to relatively high mass concentrations of ice particles and snow at very cold temperatures. If, indeed, the TAT temperature rise and associated power loss reported in 1974 was an incipient rollback, it should be noted that this is the only reported incident of this kind associated with a Boeing 747, and this could possibly be a result of the large extent of high concentrations of IWC in the anvil remnants of Tropical Storm Kerry.

While we are not in a position to make recommendations to pilots, we can concur that the standard practice (see Federal Aviation Administration Advisory Circular 00-24B) of avoiding the regions of high radar reflectivity by at least 20 n mile is advisable. In terms of rollback avoidance, the main reason to remain as far as possible from the region of high radar reflectivity is that measurements show that the IWC typically drops off sharply as a function of distance from the storm center. Also, any regions containing convection, i.e., rising cloud parcels or overshooting tops, could contain supercooled liquid water, which may exacerbate the rollback problem. Lastly, the probability of rollback incidents appears to increase with duration in areas of relatively high IWC, so that minimizing the time of encounter in these thunderstorm anvil regions may be advisable.

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