Observed Microphysical Structure of Midlevel, Mixed-Phase Clouds

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ABSTRACT

This paper analyzes airborne measurements of six midlevel clouds observed over the Great Plains of the United States in late 1999 and early 2000 during the fifth of the Complex Layered-Cloud Experiments (CLEX-5). Data show that these innocuous-looking clouds display complicated microphysical and thermodynamic structures. Five of the six cases exhibit mixed-phase conditions in temperatures ranging from near 0°C to −31°C, at altitudes of 2400 to 7200 m MSL. Four of the cases consist of a single cloud layer, while the other two are multilayered systems. In the thin, mixed-phase, single-layered clouds that the authors observed, there is an increase of liquid water content with altitude, whereas the ice water content maximizes in the mid- to lower part of the clouds. This contrasts the two multilayered systems the authors observed, in which significant amounts of ice occur in the top as well as the bottom of the individual layers of each system.

A lack of significant temperature inversions or wind shears in the observed clouds is a major difference from the thermodynamic structure of most stratocumulus systems. Virtual potential temperature jumps were less than or equal to 1°C ± 2°C at the top and bottom of cloud layers. In the thin, single-layer clouds, particle size distributions show an increase in drop size with increasing altitude. A noteworthy contribution to this observational study was the use of the Cloud Particle Imager (CPI) instrument for the qualitative analysis of particle shapes and altitudes of occurrence through the cloud. Finally, the liquid water contents observed in this research are compared with those of previous observational studies of altocumulus and altostratus clouds.

1. Introduction

Midlevel, nonprecipitating clouds are the “forgotten clouds” (Vonder Haar et al. 1997) in atmospheric science, often overlooked in favor of boundary layer clouds or upper-level cirrus clouds. The study of altocumulus clouds suffers neglect because they are not associated with severe weather and rarely produce precipitation that reaches the ground (Gedzelman 1988). Yet these clouds need to be further scrutinized and understood. Warren et al. (1988a,b) point out that altocumulus and altostratus are ubiquitous: together they cover 22% of the earth’s surface.

These clouds often extend through or are completely above the freezing level and often contain a mixture of liquid and ice. Matveev (1984) reported that more than 30% of clouds between −8° and −26°C were mixed phase. Cober et al. (2001b) encountered mixed-phase conditions in 26% and 46% of the clouds observed, respectively, in the First and Third Canadian Freezing Drizzle Experiments. These experiments targeted cloud regions containing large, supercooled droplets.

The precise mixture of liquid and ice may have important implications for cloud processes. Ice crystal habit affects particle growth rate (Korolev et al. 1999), remote sensing of optical depth (Mishchenko et al. 1996), and radiative fluxes (Sun and Shine 1994). These latter authors also state that “assuming the ice to be in liquid form in simulations commits a greater error than if ice is totally ignored” and called for refined observations of morphology and microphysics of mixed-phase clouds.

A further motivation for refined measurements of midlevel, mixed-phase clouds is to provide improved data for the initialization of numerical weather prediction models and for the development of cloud parameterizations. One significant lesson learned from Op-
erations Desert Shield and Desert Storm was the difficulty of forecasting midlevel clouds, which routinely covered target areas and hampered missions (Vonder Haar et al. 1997). There were also midlevel cloud impacts on military operations in the recent Balkans conflict. Uninhabited Aerial Vehicles used the midaltitude ranges for targeting, forward air control, and battle damage assessments, all of which are hampered by midlevel cloudiness. For strike aircraft, general rules of engagement were to stay at or above 4500 m and to visually identify all targets. Due to midlevel cloudiness, aircraft often returned home without expending any ordnance. Furthermore, aircraft refuelings took place between 3000 and 5500 m, and were often canceled due to clouds at this level. Models were generally poor at capturing the areal coverage or longevity of midlevel clouds, impacting planning forecasts. Regarding civilian aviation, midlevel clouds restrict flight visibility and pose a possible icing hazard. Twenty-two percent of the icing environments measured during the First and Third Canadian Freezing Drizzle Experiments consisted of mixed-phase conditions (Cober et al. 2001a).

Several agencies have realized the importance of using mixed-phase cloud microphysics in their forecast models, including the European Centre for Medium-Range Weather Forecasts (ECMWF). For example, results of two separate 10-day runs of the ECMWF model, one using all liquid and the other partitioned into ice and liquid, showed significant differences in various global mean quantities (Roeckel et al. 1991). Furthermore, some prior studies have indicated potential problems with current schemes for mixed-phase clouds. For instance, Tiedtke (1993) tested a prognostic cloud scheme in the global forecast model of the ECMWF, distinguishing cloud water from cloud ice solely on the basis of temperature. However, Hobbs and Rangno (1998) found ice particle concentrations were poorly correlated with temperature and, if anything, showed a decrease in concentration with decreasing temperature. Their analysis showed cloud phase to be more related to age than temperature, stating that, “On some occasions, clouds with temperatures as low as −24.5°C were found to be virtually unglaciated.”

Literature on the structure of midlevel or mixed-phase clouds is relatively sparse. The findings that have been published can be divided into observational studies and modeling studies. Observational studies have been completed by Field (1999), Heymsfield et al. (1991), Hobbs and Rangno (1985), Paltridge et al. (1986), Rauber and Tokay (1991), Tulich and Vonder Haar (1998), Young et al. (2000), Hobbs and Rangno (1998), Lawson et al. (2001), Hobbs et al. (2001), and Pinto et al. (2001). The latter four papers investigate arctic low-level and midlevel clouds, which turn out to have similar microphysical structures as the midlatitude midlevel clouds we study. However, one cannot assume there is similarity in all aspects, since the forcing in the arctic and midlatitudes differs. For instance, the diurnal cycle of solar radiation is weaker in the arctic than in midlatitudes. Also, boundary layer clouds may differ from midlevel clouds because near the ground one would expect the large-scale vertical velocity to have a smaller magnitude than at midaltitudes. As for numerical simulations, although there have been several simulations of liquid-only clouds that exist at midlevels (e.g., Liu and Krueger 1998; Starr and Cox 1985) and several simulations of arctic stratus that are mixed phase (e.g., Harrington et al. 1999; Jiang et al. 2000), few researchers have modeled both midlevel and mixed-phase clouds in detail.

In this paper, we describe an observational study of five mixed-phase altostratus and altocumulus clouds that was recently completed during the fifth of the Complex Layered-Cloud Experiments (CLEX-5) field campaign. During the experiment, the University of North Dakota (UND) Citation II research aircraft took in situ microphysical measurements of midlevel clouds over the central and northern Great Plains of the United States from 5 November through 5 December 1999. The flights yielded four cloud cases, designated as 11 Nov and 2, 4, and 5 Dec 99. The 11 Nov 99 case was a Lagrangian measurement (e.g., Passarelli 1978; Bretherton and Pincus 1995; Field 1999) over east-central Montana, while the December cases were sampled over the Atmospheric Radiation Measurement (ARM) site in north-central Oklahoma. Additional measurements were obtained over the ARM site on 10 March 2000 (10 Mar 00), during a Cloud Intensive Observing Period, and an opportunistic flight on 12 April 2000 (12 Apr 00) by the Stratton Park Engineering Company (SPEC) Learjet.

The aim of this study is to characterize the morphology of mixed-phase clouds in order to mold a conceptual picture of the microphysical and thermodynamic mechanisms that drive them. To that end, we will review the instrumentation and aircraft sampling strategy, discuss the synoptic situations, present the measurements, compare our case studies with prior observations by other authors, and speculate on microphysical differences between single- and multilayered clouds.

2. Instrumentation

Most of the measurements reported in this paper were obtained aboard the University of North Dakota’s Citation II research aircraft. The basic instrument package is described in Poellot et al. (1999) and includes measurements of temperature, dewpoint temperature, pressure, and cloud microphysics, along with aircraft position, attitude, and performance characteristics at a 25-Hz data rate. Winds are computed from measurements of airspeed; angles of attack and sideslip from a ported radome; and static pressure, aircraft velocity, and attitude from an Inertial Navigation System, using the method of Lenschow (1986). The aircraft also carried Eppley pyrgeometers and pyranometers to measure the upward and downward shortwave and longwave broad-
band fluxes, and a forward-looking video camera to monitor visual conditions.

For this study, the focus is on the cloud microphysical measurements, which were made with an array of Particle Measuring System (PMS) probes at a 4-Hz data rate, and a Cloud Particle Imager (CPI) by SPEC, Inc. The PMS probes include the Forward Scattering Spectrometer Probe (FSSP), the Two-Dimensional (2D-C) Optical Array Imaging Probe, and the King Liquid Water Probe. Each PMS instrument is described in detail in the National Center for Atmospheric Research (NCAR) Research Aviation Facility Bulletin 24 (Baumgardner 1989). The 12 Apr 00 flight took place aboard a Learjet leased by SPEC, Inc. This aircraft had the same basic instrument package as described for the Citation II, including PMS and King probes, CPI, temperature, and altitude sensors; however, the analog data were recorded at the slower rate of 1 Hz. Since the microphysical measurements are critical to this study, we now present a detailed review of the individual instrument characteristics and corrections.

a. Forward Scattering Spectral Probe (FSSP)

The FSSP measures particles in the 2–47-μm diameter ranges by relating particle size to the amount of light a spherical particle scatters in the forward direction. FSSP concentrations are corrected for electronic delays and dead time following Baumgardner et al. (1985), while sizes are corrected for electronic response times using Baumgardner and Spowart (1990). These corrections minimize two limitations of FSSP measurements. The first limitation is that cloud particle concentrations are underestimated when particles are either coincident in the beam or pass through the sensing area of the probe during the electronic processing period of a previous particle. This factor produces a 10% error for concentrations greater than about 300 cm$^{-3}$, which were very rarely observed in our measurements. The second limitation involves the sizing accuracy of the probe, which is affected by nonuniformities of the laser beam. This can cause errors in the amount of light that a particle scatters.

The response time of the electronics also causes several problems, including undersizing of particles, detection of particles coincident in the beam as a larger single particle, and failure to discriminate between ice particles and liquid droplets. In fact, Gardiner and Hallett (1985) describe FSSP particle size distributions in mixed-phase clouds as spurious, while McFarquhar and Heymsfield (1996) note that distributions are of poor quality when large nonspherical ice is present. Recent laboratory investigations (e.g., Arnott et al. 2000) and comparisons with other particle counters (e.g., Poellot et al. 1999; Lawson et al. 2001) strongly suggest that the FSSP counts both small (<50 μm) ice particles and cloud drops with equal efficiency. Therefore, quantitative measurements of liquid water content (LWC) are suspect in mixed-phase conditions as errors in FSSP sizing are raised to the third power. There may be some contamination of the FSSP measurements by small ice particles, but due to high supersaturation with respect to ice, most ice particles grow rapidly to recognizable, nonspherical shapes of larger than 25 μm in less than a minute in mixed-phase clouds (Lawson et al. 2001). A visual inspection of the CPI images showed that only 1.3% of the liquid droplets had radii greater than 24 μm (although we note that distinguishing the phase of the smallest particles is limited by the CPI’s pixel size, 2.3 μm). This gives us some confidence that we captured nearly all of the cloud liquid water droplets with the FSSP instrument.

b. Two-dimensional cloud (2D-C) probe

The 2D-C probe measures particles from 33 to 1056 μm in diameter by illuminating a two-dimensional array of photodiodes with a helium–neon laser. As a particle passes through the beam, a shadow image is cast on the diodes. The total number of occulted diodes then represents particle size. UND processed the 2D-C data using artifact rejection criteria described in Cooper (1978). Comparisons of artifact rejection techniques between the UND and a more recent NCAR software package showed a 20% decrease in concentration for ice concentrations less than about 30 L$^{-1}$, linearly increasing to a 40% increase for concentrations greater than 150 L$^{-1}$. Particle sizes and concentrations are corrected for airspeed according to an algorithm provided by Baumgardner (1987).

2D-C particle sizing errors have been analyzed in prior work. Significant errors include oversizing of particles because they are out of focus (Korolev et al. 1991; Strapp et al. 2001), undersizing and undercounting of smaller particles because of the nonzero response time of the instrument (Baumgardner and Korolev 1997; Strapp et al. 2001), and mis-sizing of particles because of the discrete nature of the pixel array (Korolev et al. 1998; Strapp et al. 2001). Furthermore, since the 2D-C sample volume is limited, poor sampling statistics may result if ice number concentration is low, especially for larger particles. To mitigate the poor sampling, we averaged ice water content (IWC) in Figs. 4–6 and 8–9 over 10 s. Finally, there is an inherent uncertainty in using two-dimensional images, such as those recorded by the 2D-C, to derive IWC. This is discussed further below. Two less crucial limitations of the probe for our purposes are the distortion of images at airspeeds greater than 132 m s$^{-1}$, and a problem in high ice concentrations. The first limitation is not a factor for the Citation flights, as it flew at mean airspeeds of 112 m s$^{-1}$, but may have been a factor for the single Learjet flight, with mean airspeeds of 150 m s$^{-1}$. The other limitation involves a second buffer in the system becoming filled before the first buffer empties to the data system, causing an overload period in which the probe cannot take
measurements. Ice concentrations were relatively low for our measurements, making this second effect negligible.

c. King liquid water probe

The King Liquid Water Probe is based on the design discussed in King et al. (1978). It is a hot wire instrument that measures the amount of power necessary to maintain a heated element at a constant temperature while it is being cooled by convection and evaporation of cloud droplets. The liquid water content can be directly related to power consumption using a total energy equation.

The first limitation of this device occurs when droplet diameters become greater than 50 μm, as droplets begin to break up on the sensing element and are removed by the airflow before they totally evaporate, causing an underestimation of liquid water (Biter et al. 1987). This problem was minimized in our measurements by the lack of large cloud droplets in our midlevel, mixed-phase clouds. A second limiting factor is the presence of large quantities of ice particles. Cober et al. (2000) found a “false LWC signal” of 15%–20% of the total ice mass when the hot-wire probe was operated at airspeeds of 100 m s$^{-1}$. This false signal increases to about 40% when the instrument is operated at airspeeds of 200 m s$^{-1}$ (Strapp et al. 1999). This would suggest a maximum false LWC signal on the order of 25%–30% for the Learjet on 12 Apr 00, and approximately 20% for the Citation cases, given the aircraft airspeeds mentioned earlier.

To correct for the cooling effects of dry air on the King hot-wire probe, offsets were determined for each leg by noting measurements in the ambient air outside of cloud at the same airspeed and air density. The offsets were checked for consistency at every flight level and then subtracted from the measured values. Since the correction amount varies slightly with air density, the vertical profile of King LWC from the spiral soundings had to be corrected by subtracting a simple linear formula that effectively zeroed the profile in noncloud regions.

The liquid water content measurements between the King and FSSP probes showed generally good agreement, with differences less than 35% most of the time. Different response times of the instruments and the FSSP sizing errors discussed earlier probably caused us some of the same large momentary differences in LWC as reported in Hobbs and Rangno (1998).

d. Cloud particle imager (CPI)

The CPI is a relatively new instrument that records high-resolution (2.3 μm) digital images of cloud particles and processes them “on the fly” (Lawson and Jensen 1998). This instrument casts images of particles on a solid-state, one-million-pixel CCD camera, freezing the motion of particles with a 20-ns pulsed, high-power laser diode. Because of the high resolution of the images, the CPI helps resolve qualitative questions regarding cloud phase. Since the CPI is a relatively new instrument, a thorough analysis of its response characteristics is a work in progress (Lawson et al. 2001).

3. Data processing and flight patterns

a. Data processing

Aircraft motion data were processed to eliminate pitch, roll, and yaw effects, so that only straight and level flight sublegs remained. To aid in the comparisons between the six cases, we elected to report LWC from the King probe, except for the 10 Mar 00 case where FSSP measurements are used due to a system failure of the King probe during that particular flight. Use of the King probe for most flights negated the need to correct FSSP LWC errors due to ice contamination. Following Hobbs and Rangno (1998), the in-cloud portions of a given flight leg were demarcated by requiring that FSSP concentrations be at least 1 cm$^{-3}$ and that the King probe indicate a sustained deviation from zero. We then computed mean time-weighted in-cloud LWC and other microphysical quantities from the in-cloud portions for each flight leg. The flight legs that were made above and below cloud were vertically displaced 100–200 m from the nearest cloud boundary.

Ice water content was calculated using the method of Mitchell et al. (1990) (hereafter referred to as M90), which is one of several papers that gives dimension-to-mass relationships. Because our spiral descents contained a mixture of aggregates, dendrites, hexagonal plates, columns, bullets, etc., we chose the “all snow types” formulation from M90. Several papers (e.g., M90; Heymsfield and Platt 1984; Heymsfield and Parrish 1986) discuss the large uncertainties in IWC calculations, including assumptions about the physical characteristics of the ice particles.

Two important caveats must be made concerning the IWC calculations. First, the sampling statistics for the larger particles are poor but are influential in the computation of IWC. Second, a large error is incurred by estimating ice mass from particle dimension; M90 compare their mass–dimension relationship with other relationships and observed data, and they find typical discrepancies of about a factor of 2. Therefore the IWC in all our plots and calculations must be regarded as having an uncertainty of at least a factor of 2. Since the M90 computations are presented exclusively in this study, the values within and among layers at the same pressure are directly comparable; this may not be true if comparing layers at significantly different pressures or if comparing our results with studies that use a different method to compute IWC.
b. Flight patterns

Three basic flight patterns were used in CLEX-5 and the auxiliary data collections: a Lagrangian racetrack, an Eulerian racetrack pattern over a fixed point, and a slow, spiral sounding. The basic sampling pattern consisted of a series of racetrack-shaped patterns: typically, one was obtained above cloud, several at various altitudes within cloud, and one below cloud. Lagrangian racetracks were displaced horizontally from one another so that the aircraft drifted with the horizontal wind, as shown in Fig. 1 for the 11 Nov 99 flight. Airspace restrictions prevented us from making Lagrangian measurements for the cases over the Southern Great Plains (atmospheric radiation measurement) ARM site, namely, the cloud cases on and after 2 Dec 1999. For this reason, clouds over the ARM site were sampled while centered at a fixed latitude and longitude (i.e., in an Eulerian fashion), with the longer dimension of the racetrack approximately 20 km in length. To obtain vertical samples of the clouds, the aircraft performed spiral descents at the fixed rate of 300 m min$^{-1}$. These aircraft thermodynamic soundings typically extended from a few hundred meters above cloud top to the same distance below cloud base and had a diameter of 5 km.

4. Synoptic and mesoscale situations

Satellite images of each of the clouds that were sampled are shown in Fig. 2, along with the corresponding 500-mb geopotential height maps. All of the clouds formed in regions of large-scale lifting associated with an upper-level disturbance. A description of the synoptic and mesoscale situation for each cloud system follows.

11 Nov 99: A large area of mid- and upper-level cloudiness advected eastward along the Wyoming–Montana border, about halfway between Casper, Wyoming, and Great Falls, Montana. The cloud system marked the northern end of a very strong ridge axis, with the high-pressure center located in Mexico. The surface high was near the four-corners region of the United States. A potential vorticity (PV) patch, associated with an upper-level shortwave on the U.S.–Canadian border, moved across northern Montana and enhanced the early morning clouds beginning around local noon. The Lagrangian aircraft sample took place between 1923 and 2040 UTC, as the cloud field was dissipating after cresting the ridge axis and losing the support of the PV maximum, which had moved east of the area (Larson et al. 2001).

2 Dec 99: Bands of mid- and upper-level cloud, associated with a deep upper-level trough that extended from the Dakotas to the southern tip of the Baja Peninsula, moved across the Texas panhandle and into northern Oklahoma. These clouds were east of a dry air slot over New Mexico and southern Colorado. The dry slot eventually moved into the area and helped trigger prefrontal convection ahead of a slow-moving cold front that was situated from south-central Minnesota to southern New Mexico. The 300-mb winds were SSW at 70 kt (36.0 m s$^{-1}$) at the ARM site, as the central core of a 100-kt (51.4 m s$^{-1}$) jet stream developed over northeast Texas. A prefrontal midlevel cloud band was sampled as it moved over north central Oklahoma from 1453 to 1605 UTC.

4 Dec 99: Frontal passage the evening of 3 December 1999 generated a great deal of convection, with thunderstorms over northern and eastern Oklahoma lasting throughout the night. The storms included some severe cells, with five tornadoes reported in a triangular area between Ponca City, Tulsa, and Oklahoma City, Oklahoma. Light to moderate rain continued through the morning and early afternoon hours, but stopped by midafternoon. Midlevel, pseudoconvective clouds (we use the term pseudoconvective here to indicate that the midlevel cloud formed as a result of convection upstream of our aircraft measurements. The cloud was
Fig. 2. Visible GOES satellite pictures and 500-mb geopotential heights (decameters) showing the synoptic and mesoscale situations for (from top to bottom) 11 Nov, 2 Dec, 4 Dec, 5 Dec 99, and 10 Mar and 12 Apr 00. Aircraft observation point is located roughly at the tip of the arrow.
much thicker than the other cloud layers in this study, but was stratiform in appearance during the sample time) moved into the area from the west-southwest at that time, prompting a flight over the ARM site from 2030 until 2207 UTC. A stratus cloud deck with a base of about 650 m was evident beneath the midlevel cloud layers. The jet core was directly over the ARM site during this time, with winds in excess of 100 kt (51.4 m s\(^{-1}\)).

5 Dec 99: An upper-level low pressure center moved just north of the Oklahoma border behind the strong surface system that preceded it the evening of 4 December 1999. Snow fell overnight, with light flurries lingering into the early morning hours. Ponca City, Oklahoma, was on the western edge of a “wrap-around” cloud field, with nonprecipitating low- and midlevel clouds advecting over the ARM site around the north and west sides of the upper-level low. This system was sampled for approximately 45 min, from 1430 to 1515 UTC, until it moved east of the flight area. The 300-mb winds were northerly at approximately 30 kt (15.4 m s\(^{-1}\)). The middle cloud deck extended from 2390 to 3002 m, with stratus beneath it from 1400 to 2200 m.

10 Mar 00: Midlevel cloudiness on 10 March 2000 was associated with lifting due to an upper-level trough that moved from the Front Range of the Rocky Mountains into the western Great Plains during the day. A 90-kt (46.3 m s\(^{-1}\)) jet stream flowed from the Texas panhandle across Oklahoma and into the Ohio River Valley, helping to support the system. It also brought southwesterly flow over an 850-mb low pressure center in southern Oklahoma, and a quasi-stationary surface low that was located just south of the Texas–Oklahoma border. This setting generated a thick layer of cirrus cloud over the ARM site, which eventually evolved into the multilayered midlevel cloud that was sampled between 1713 and 1939 UTC.

12 Apr 00: This case had a very similar synoptic situation to that of 10 Mar 00. An upper-level low was again resident over the Texas panhandle, but it was somewhat weaker. The main jet stream rode up across the northern tier of the United States, but a weaker 55-kt (28.3 m s\(^{-1}\)) jet streak wrapped around the southern end of the upper-level low, across the panhandle region into northeastern Oklahoma. A strong surface ridge of high pressure extended from the Great Lakes southward into east-central Oklahoma, where it clashed with a quasi-stationary frontal boundary extending from the surface low-pressure center near Houston, Texas. In addition to being a similar synoptic situation to the 10 Mar 00 case, it also generated a similar three-layer cloud system. The Learjet sampled this cloud from 1700 to 1810 UTC.

5. Measurements

Figure 3 shows the basic CLEX-5 cloud measurements [temperature, liquid water content, pressure, winds, and cloud fraction (CF)] at the relative time and location they were observed with respect to the cloud. The measurements for the spirals are point values, while those given for the flight legs are horizontally averaged values.

In this section, we first document the cloud structure as represented by averages of horizontal aircraft legs, and then address several questions concerning cloud structure. First, how is the liquid and ice vertically structured through our mixed-phase clouds? What are the particle size distributions? Do strong wind shears or temperature inversions occur in our clouds? Finally, is IWC correlated with temperature?

a. Summary of mean observed microphysical parameters

The means from the horizontal flight legs we sampled are summarized in Table 1. Mixed-phase conditions were evident in five of the six cloud systems, ranging in altitude from 2390 m to 7220 m. The 5 Dec 99 cloud was entirely above the freezing level, with a mean temperature of \(-7^\circ\)C, but consisted almost entirely of liquid water. The synoptic conditions were somewhat similar for the cloud cases after 11 Nov 1999, which were all measured over the ARM site in Oklahoma. The first four cases chronologically were all single-layer clouds, while the 10 Mar and 12 Apr 00 clouds consisted of multiple layers. Three of the single-layer clouds were approximately 600 m thick, while the 4 Dec 99 pseudoconvective cloud was greater than 1500 m thick. The multilayered systems each covered about 3000 m in vertical extent, with internal layers 400–900 m in depth. Temperatures varied from a near-freezing value \(-0.9^\circ\)C to a low of \(-30.3^\circ\)C. Mean LWC values were on the order of 0.01–0.15 g m\(^{-3}\), with a maximum measured point value for all CLEX-5 clouds of 0.35 g m\(^{-3}\), occurring near the top of the 5 Dec 99 cloud. Mean in-cloud FSSP concentrations for the aircraft legs varied from about 1.0 to 127.5 cm\(^{-3}\), with an overall mean for all clouds of 38.3 cm\(^{-3}\). The mean in-cloud 2D-C concentrations ranged from about 0.1 to 73.9 L\(^{-1}\), with an overall mean of 9.8 L\(^{-1}\) (0.7 L\(^{-1}\) if the 4 Dec 99 values are omitted). Horizontal winds were from the south through west at approximately 20–30 m s\(^{-1}\) for all clouds except 5 Dec 99, which was located in northerly flow. The standard deviation of the vertical wind was highest throughout the 11 Nov and 4 Dec 99 clouds (\(-0.60 to 0.84 \text{ m s}^{-1}\)), as well as the top of the 2 Dec 99 cloud (0.70 m s\(^{-1}\)), indicating greater turbulent mixing in these cases.

As mentioned previously, the 11 Nov 99 case was a Lagrangian sample, so the aircraft remained in the same cloud column with time and measured the evolution of the various microphysical parameters as it drifted in a westerly flow at approximately 25 kt (12.9 m s\(^{-1}\)). The flight legs on 11 Nov 99 are in chronological order, so the overall decrease in LWC represents a temporal change,
FIG. 3a. Cloud evolution diagram for the 11 Nov 99 case showing the time and height of the spiral soundings and subsequent racetracks. Measurements for the spirals are point values, while those for the flight legs are horizontally averaged values. Measurements listed are temperature ($T$), liquid water content (LWC), pressure ($P$), horizontal wind direction and speed, and cloud fraction (CF). Light shading represents lower CF.

FIG. 3b. Same as the previous figure except for 2 Dec 99 Eulerian aircraft data.
FIG. 3c. Same as the previous figure except for 4 Dec 99.

FIG. 3d. Same as the previous figure except for 5 Dec 99.
FIG. 3e. Same as the previous figure except for the multilayered cloud system on 10 Mar 00. Note that the original three layers devolved into two layers after about 1831 UTC, and the bottom layer ascended to a slightly higher height with time.

FIG. 3f. Same as the previous figure except for 12 Apr 00. Pressure and wind data were not analyzed from this flight.
midlevel stratus cloud, whereas significant ice existed
thermore, Lawson et al. (2001) observed a region of
boundary layer stratus (Harrington et al. 1999). Fur-
arctic boundary layer (Pinto 1998). The same structure
levels (Hobbs et al. 2001; Pinto et al. 2001) and in the
phase cloud layers in which LWC increases with height
from the horizontal aircraft legs in Table 1.
imagery and corroborated quantitatively by 2D-C data
qualitatively by the altitudes of ice crystals in the CPI
measurements during the 2 Dec sounding are corroborated
located in the bottom two-thirds of the cloud. The 2D-C
was measured by the 2D-C probe during the sounding was
systems. The 2 Dec case contains little ice, but all ice that
vertical on 4 Dec 99 and for the multilayered cloud sys-
tems. The 2 Dec 99 cloud contains little ice, but all ice that
were found in the cloud field.
We now discuss the profiles of the various cases. The
profiles for single-layer cases of 11 Nov and 2 Dec 99
clouds look similar in shape but have some significant
differences. The LWC in the 11 Nov 99 cloud is nearly
twice that of the 2 Dec 99 case, which is related to the
test that the cooler 2 Dec 99 case has a smaller adiabatic
liquid water content. Despite having a lower LWC than
11 Nov 99, the 2 Dec 99 cloud contains bigger and more heavily rimed ice crystals. Despite being 14°C
cooler than the 11 Nov 99 case, the 2 Dec 99 cloud has
lower ice number concentrations.
The plots show a tendency for LWC to increase with
height in the thin single-layer cases (11 Nov, 2 Dec, and
5 Dec 99) and, to a lesser degree, in the individual layers
of multilayered clouds. In most cases, the LWC is a maximum
at cloud top. An exception occurs for 5 Dec 99,
when LWC peaks about 190 m below cloud top, near a
small temperature inversion. This will be discussed in
more detail later. Ice water content maximizes in the mid
to lower parts of the single-layer clouds on 11 Nov and
2 Dec 99, whereas it is more evenly distributed in the vertical on 4 Dec 99 and for the multilayered cloud sys-
tems. The 2 Dec case contains little ice, but all ice that
was measured by the 2D-C probe during the sounding was
located in the bottom two-thirds of the cloud. The 2D-C
measurements during the 2 Dec sounding are corroborated
qualitatively by the altitudes of ice crystals in the CPI
imagery and corroborated quantitatively by 2D-C data from the horizontal aircraft legs in Table 1.
Several prior works have observed single, mixed-
phase cloud layers in which LWC increases with height and IWC decreases with height, both in the arctic mid-
levels (Hobbs et al. 2001; Pinto et al. 2001) and in the
arctic boundary layer (Pinto 1998). The same structure
has also been obtained in numerical simulations of arctic
boundary layer stratus (Harrington et al. 1999). Fur-
thermore, Lawson et al. (2001) observed a region of
nearly ice-free liquid in the top of a 4-km deep, arctic,
midlevel stratus cloud, whereas significant ice existed
in lower parts of the cloud. Also, Cober et al. (1995)
observed thin cloud-top layers (~100 m) of supercooled
water at temperatures cooler than ~10°C, with the cloud
down fully glaciated. Finally, Rauber and Tokay (1991)
cited numerous observations of a narrow layer of su-
percooled water at cloud top. They suggested that the
liquid at cloud top is able to persist despite depositional
growth by ice crystals because ice crystals near cloud
top are small.
The aforementioned body of evidence hints that the
tendency for LWC to maximize in the upper part of a
thin, single-layer, mixed-phase cloud and for IWC to
maximize in the lower part of the cloud is more wide-
spread than the two cases (11 Nov and 2 Dec 99) that
we observed. We speculate that IWC is larger in the
bottom part of thin, single-layer, mixed-phase clouds
because as ice crystals grow, they sediment to lower
altitudes. The LWC tends to increase with altitude in
such clouds, we speculate, if the total water content
(liquid plus vapor) and liquid water potential temper-
are reasonably well mixed in the vertical, and if the
ice number concentration and size are small enough
so that ice growth cannot significantly deplete the liquid
(Rauber and Tokay 1991). We note that even if LWC
were to increase with height in most individual layers,
this would not imply that climatological profiles aver-
aged over populations of clouds at different altitudes
would show the same trend (Gultepe and Isaac 1997).
Included in Figs. 4–8 are adiabatic profiles of LWC.
These show that the observed LWC profiles are fairly
close to adiabatic for the 11 Nov 99 and 2 Dec 99 clouds,
less adiabatic for the 5 Dec 99 cloud, and far from
adiabatic for the 4 Dec 99 and 10 Mar 00 clouds. The
more adiabatic layers tend to be those that are better
mixed in the conserved variables.
The 5 Dec 99 cloud was 6°–8°C below freezing and
was composed almost entirely of small supercooled liq-
uid droplets. The maximum LWC was 0.35 g m⁻³ but,
unlike the clouds measured on 11 Nov and 2 Dec 99,
cloud-top entrainment appears to have had a disprop-
orportionately strong drying effect on the top two hundred
meters of the 5 Dec 99 cloud. This seems to be related
to a weak temperature inversion of 0.5°–1.0°C at 2810
m, which corresponds to the location of the LWC max-
imum. We speculate that the inversion decoupled the
top of the cloud from the main body and hindered dry
air from being transported below the inversion, resulting
in the observed LWC shape.
The 4 Dec 99 cloud is somewhat of a novelty in this
study, as it was moderately deep, but not separated into
distinct layers. The obvious vertical discontinuities in
LWC and IWC in Fig. 6 are due to air traffic control
time delays of up to 15 min between each of the three
distinct segments. The mean values listed in Table 1 are
more meaningful quantitatively, but this profile high-
lights one of the major problems with Eulerian mea-
surements over the ARM site: the cloud profile may
change as the aircraft measures it.
TABLE 1. Mean time-weighted in-cloud values of measurement location, height, begin and end times of sublegs, corresponding lengths of sublegs, cloud fraction (CF), liquid water content (LWC), std dev of LWC ($\sigma_{LWC}$), temperature ($T$), pressure ($P$), horizontal wind direction and speed, std dev of the vertical wind ($\sigma_w$), FSSP concentration, 2D-C concentration, std dev of 2D-C concentration ($\sigma_{2D-C}$), and ice water content (IWC) as computed by Mitchell et al. (1990) for the 11 Nov, 2 Dec, 4 Dec, and 5 Dec 99 cases, as well as 10 Mar 00, respectively. Each leg was broken into straight and level sublegs, all flown at the same altitude, so that a leg simply denotes here a constant-altitude, noncontiguous set of sublegs. Temperature ($T$), $P$, direction, speed, $\sigma_w$ were computed as weighted averages over the entirety of the sublegs. Cloud fraction is the percentage of all measurements in a given flight leg (i.e., within a set of sublegs) that met the in-cloud criteria. The remaining variables are computed as weighted averages over the in-cloud portions of the leg (set of sublegs): LWC, $\sigma_{LWC}$, FSSP concentration, 2D-C concentration, std dev of 2D-C concentration, and LWC. T, M, and B signify cloud top, middle, and bottom, respectively. I/O denotes that the aircraft flew in and out of cloud. 12 Apr 00 mean horizontal leg data were not analyzed.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Leg Location</th>
<th>Height</th>
<th>Begin and end times of sublegs (UTC)</th>
<th>Lengths of sublegs (km, km, km)</th>
<th>CF (%)</th>
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<tbody>
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<td>2</td>
<td>In (B)</td>
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<td>1941:19–42:39, 45:09–47:09</td>
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<tr>
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<td>2006:58–09:15, 12:17–14:08</td>
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<td>2015:38–17:18, 20:54–22:42</td>
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<tr>
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<td>22</td>
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<td>4877</td>
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<td>12.59</td>
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<td>Leg (g m⁻²)</td>
<td>LWC (g m⁻²)</td>
<td>(\sigma_{\text{LWC}}) (µm)</td>
<td>(T) (°C)</td>
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<td>0.016</td>
<td>-21.2</td>
<td>503.9</td>
<td>239</td>
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</tbody>
</table>
As mentioned previously, the 4 Dec 99 cloud was pseudoconvective in nature; although it was relatively quiescent for about a two-hour period during the aircraft measurements, there was considerable convective activity before and immediately afterward. The observations followed a period of thunderstorms, with intense rainfall and gusty conditions at the surface, and preceded a squall line that was moving in from the southwest during our flight. The very large and heavily rimed particles shown in the CPI images offer support to the argument that this cloud was convective in nature. These conditions may explain why the cloud is deeper, and the ice distributed more uniformly with height, than in the other cases. Also, note the mean LWC was an order of magnitude less than the other single-layer clouds. This may be due to the presence of large amounts of ice, which grew at the expense of the liquid.

The 10 Mar and 12 Apr 00 cases illustrate an important feature of the multilayered systems observed in this study: significant amounts of ice appear at the top of the cloud layers, in contrast to the mid- to lower-cloud maximum observed in the single-layer cases. This suggests that different mechanisms or processes may be at work for the single-layer clouds and multilayered systems. Despite the difference in the vertical distribution of ice, the individual layers of the 10 Mar 00 case retain the same characteristic increase of LWC with height as the single-layer cases. However, the maximum
LWC is only about 0.04 g m\(^{-3}\), an order of magnitude less than that of the single-layer clouds, and close to the noise threshold of the FSSP. The LWC signal could possibly be ice that is falsely attributed as liquid. The 12 Apr 00 sounding, on the other hand, has a maximum sustained LWC of 0.14 g m\(^{-3}\), which is closer to the single-layer values.

c. Liquid droplet and ice particle spectra

Now that the liquid and ice structure has been presented in a bulk sense, it is interesting to look at how the size and concentration of the liquid droplets and ice particles vary through the depth of the cloud layer. To do so, we examine horizontal legs at various altitudes. Because of the dichotomy between ice particle and liquid droplet sizes, as discussed in the final paragraph of section 2a, we use the FSSP measurements for the liquid water droplet spectra and 2D-C measurements in the larger-sized bins for the ice particle spectra.

First, the liquid droplet spectra are shown in Fig. 10 using the FSSP measurements. The liquid water spectra consist of droplet radius (microns) plotted against mean concentration (number per cubic centimeter per micron). The thin, single-layer clouds all exhibit a common trait: droplet sizes increase with increasing height through the layer. For the 11 Nov and 2 Dec 99 cases, the mean concentration also increases with height. The increase with height of both droplet size and concentration is consistent with the increase in LWC with height seen in the previous section.

The 5 Dec 99 droplet spectra show the same increase in size with height as the 11 Nov and 2 Dec 99 cases, but the droplets do not show the same increase in concentration with height. Recall that the 5 Dec 99 case had a small temperature inversion that appeared to de-
Fig. 6. Same as Fig. 4 except for 4 Dec 99. This cloud was “pseudo-convective,” as it originated from convection upstream that advected over the ARM site. The two discontinuities in LWC and IWC are a result of air traffic control delays of up to 15 min.

couple the uppermost part of the cloud, increasing its exposure to entrainment, which in turn may have led to the reduced number concentration near cloud top. The liquid droplet spectra for the 12 Apr 00 case are not shown because the FSSP instrument was inoperative, and they are not shown for the 10 Mar 00 case because the LWC is so low that when distributed across the individual size bins, sampling statistics are poor.

Figure 11 shows how ice particle sizes and concentrations are distributed vertically through the cloud systems. In this figure, we show the single-layer cloud from 11 Nov 99 and the two multilayered systems from 10 Mar and 12 Apr 00. In the single-layer cloud, the 2D-C ice particle concentration peaks in the bottom half of the cloud, with a mean of approximately 20 $\text{L}^{-1}$, and a maximum of 55 $\text{L}^{-1}$. The mean size appears to be about 60–80 $\mu$m in radius, with a couple of particles near the base of the cloud approaching 200 $\mu$m.

Unlike the single-layer cloud, the concentrations of both the multilayered systems exhibit rather consistent particle concentrations through the vertical, although the 12 Apr 00 case does vary somewhat from about 50 to 150 $\text{L}^{-1}$. The main difference between the multilayered systems is that the particle sizes remain relatively constant through all layers of the 10 Mar 00 system, but increase steadily in size with decreasing altitude in the 12 Apr 00 case.

d. Wind and temperature structure

Studies of stratuscumulus clouds often reveal substantial temperature inversions at cloud top. For example, Albrecht et al. (1988) showed temperature inversions as strong as 7°–8°C in their analysis of marine stratuscumulus off the coast of California taken during the First International Satellite Cloud Climatology Project Regional Experiment (FIRE). Likewise, Nicholls (1984) reported inversions of 5°C from a study of daytime stra-
FIG. 7. Same as Fig. 4 except for 5 Dec 99. This cloud was composed almost entirely of supercooled liquid droplets in temperatures ranging from $-6^\circ$ to $-8^\circ$C. We speculate that a small temperature inversion may have decoupled the uppermost portion of the system, subjecting that part of the cloud to more dry air entrainment from aloft, resulting in the decrease in LWC with height.

tocumulus over the North Sea, and Bretherton and Pincus (1995) observed $2^\circ$–$4^\circ$C inversions in temperature soundings from the Atlantic Stratocumulus Transition Experiment. In contrast, the CLEX-5 measurements of midlevel clouds showed an almost linear decrease of temperature with height through the cloud, including the cloud boundaries (Fig. 12). In all six cases, there was less than a $1^\circ$C inversion at cloud top. We speculate that the midlevel clouds we observed did not have strong inversions because 1) no strong inversions were present when the cloud formed, and 2) unlike many marine stratocumulus clouds, the midlevel clouds did not persist long enough to allow internal dynamic and thermodynamic processes to generate such inversions. For instance, the inversion above marine stratocumulus is often maintained in part by subsidence warming above cloud top, whereas altocumulus clouds, which are not usually sustained by surface fluxes, cannot persist for long when subjected to subsidence warming (Larson et al. 2001).

Figure 13 shows that in most cases, the vertical profile of virtual potential temperature ($\theta_v$) increased monotonically with height until it reached cloud base, and then remained constant or increased by only $1^\circ$C through an entire cloud layer. Just below or right at the cloud top, it typically increased sharply by $1^\circ$–$2^\circ$C through a depth of about 100 m. The observed $\theta_v$ profiles have been overplotted with $\theta_v$ profiles corresponding to adiabatic ascent from cloud base of a parcel that condenses liquid but no ice (thin lines in Fig. 13). The observed profile on 11 Nov 99 closely follows the adiabatic profile, indicating that a parcel lifted from cloud base experiences neutral buoyancy. The observed profiles also follow moist adiabats for the layer on 2 Dec 99 and the top layer on 10 Mar 00; these clouds are so cold that moist and dry adiabats are similar. A parcel lifted from
cloud base in the 5 Dec 99 layer would experience stable stratification because of several small inversions within the cloud layer. The bottom and middle layers on 10 Mar 00 have nearly constant $\theta_e$ profiles, which corresponds to near neutrality for a dry parcel. This is probably associated with the very low liquid amounts in these layers.

Inspection of the in-cloud horizontal winds with those found above or below cloud in Table 1 show that wind shears were also virtually nonexistent at the cloud interfaces for most cases. We did not compute winds for the 12 Apr 00 case, but the horizontal wind field was examined for both directional and speed shears at the cloud boundaries in the other five cases. One sharp directional wind shear of 35° was obvious at the top of the bottom layer on 10 Mar 00 and there was a sizable cloud-top speed shear for the 4 Dec 99 pseudoconvective case, but otherwise the vertical profiles of the horizontal wind field did not deviate by more than 10° in direction or 5 m s$^{-1}$ in speed at the ambient air interfaces.

The lack of shears is also a difference from many stratocumulus clouds, which are coupled by drag forces to the surface and are fairly well mixed in the vertical by turbulence (Geisler and Kraus 1969). Therefore, there tends to be little shear within the boundary layer, but a wind speed or directional discontinuity across the inversion (e.g., Brost et al. 1982). Conversely, midlevel clouds are decoupled from surface processes, so normally the whole layer simply drifts with the mean ambient wind. There are exceptions to this simplified conceptual picture. Rauber and Tokay (1991) mention that shears can result in part from the downward transfer of jet stream level momentum in the subsiding air above cloud top. However, due to the lack of mechanical wind shear in the clouds observed in this study, it seems unlikely that any wave motions or local circulations were induced by this mechanism. This suggests that
cloud-top radiative cooling and/or cloud base radiative warming is the primary mechanism for generating turbulence in these altocumulus clouds, although the entrainment induced by such turbulence may lead to evaporative cooling of cloud droplets and hence further generation of turbulence.

Finally, Hobbs and Rangno (1998) and Korolev et al. (2000) previously showed that ice particle concentrations were poorly correlated with temperature. They noted that ice particle concentrations were correlated better with the size of the largest droplets, and agreed with Pinto (1998) that ice particle concentration may be linked to the age of the cloud, with higher concentrations at later stages of the lifecycle. Gultepe et al. (2001) also found that ice particle concentration for ice particles less than 1000 µm is poorly correlated with temperature in glaciated stratiform clouds. We found a similar relationship between 2D-C concentrations and temperature (not shown), and then utilized the method of M90 to examine the relationship between IWC and temperature. Ice water content is a function of both particle concentration and size, and is plotted versus temperature for the combination of all mixed-phase cases (Fig. 14). The IWC peaks in the temperature region between −8° and −20°C. This includes the temperature at which the difference between saturation vapor pressure with respect to ice and water maximizes (−12°C), and also the maximum growth habit regime of plates, stellars, and dendritic ice crystals, which is centered at approximately −15°C (Rogers and Yau 1989).

6. Comparison of findings with other observational studies

As noted in the introduction, several authors have previously completed observational studies of mixed-phase clouds. The general findings are compared to CLEX-5 measurements in Table 2 and are summarized in this section.

Heymsfield et al. (1991) took aircraft measurements
of two clouds near Green Bay, Wisconsin, in October 1986. The first was a thin cloud, about 200 m thick, with a base at 7300 m, and the second was on the order of 500 m thick with a base at 7500 m. Liquid water contents in the first case were only 0.01 to 0.02 g m$^{-3}$, while the second case ranged from 0.04 to 0.12 g m$^{-3}$. These values fall within the CLEX-5 range, but are on the low end of the measurements. The temperatures were $-29^\circ$ to $-31^\circ$C, which is similar to the coldest cloud encountered on 2 Dec 99.

The several dozen altocumulus and altostratus clouds observed by Hobbs and Rangno (1985) and the altostratus cloud observed by Paltridge et al. (1986) have similar or somewhat greater LWC than those observed in CLEX-5. Hobbs and Rangno (1998) observed mid-level clouds over the Beaufort Sea near Alaska and made the counterintuitive observation that ice particle concentrations were poorly correlated with temperature. Relatedly, our clouds also exhibit poor correlation between temperature and IWC.
Pinto (1998) analyzed two arctic mixed-phase boundary layer clouds in the temperature range $-13^\circ$ to $-20^\circ$C. He found that LWC generally increased with height through the cloud layer with a maximum just below cloud top. This is in good agreement with CLEX-5 measurements and previously described studies. Total cloud ice generally decreased with height through the layer with a maximum near cloud base. That trend is also suggested in the single-layer clouds we observed on 11 Nov 99 and 2 Dec 99.

Tulich and Vonder Haar (1998) examined measured structures of a multilayer cloud in great detail. The system started out as an altostratus layer from 5800 to 6000 m, with an altocumulus layer rising into it from a base
of approximately 5125 m. Mean LWC varied from a minimum of 0.03 g m\(^{-3}\) to a maximum of 0.31 g m\(^{-3}\) through the center of the cloud system. The mean value for most flight legs was 0.08–0.16 g m\(^{-3}\). All values compare well to those in CLEX-5.

Three recent studies of arctic midlevel clouds (Lawson et al. 2001; Hobbs et al. 2001; Pinto et al. 2001) show similar cloud depths, LWC, and temperatures as the CLEX-5 clouds. In addition, based on 2D-C measurements, the arctic midlevel clouds had ice number

![Normalized Height vs. Temperature](image1)

**Fig. 12.** Vertical profile of temperatures for four of the cloud cases, including the individual layers of the 10 Mar 00 case. Normalized height is defined such that zero corresponds to cloud base and unity corresponds to cloud top. Note the lack of temperature inversions.

![Normalized Height vs. Virtual Potential Temperature](image2)

**Fig. 13.** Vertical profile of virtual potential temperature for the same cases as Fig. 12. This variable allows for slightly easier determination of midlevel cloud boundaries than temperature inversions, as there is usually a 1–2-K increase of \(\theta_v\) at cloud top (not seen at the top of the bottom and midlayers of 10 Mar 00 case). Overplotted (thin lines) on the observed \(\theta_v\) profiles are \(\theta_v\) profiles corresponding to adiabatic ascent from cloud base of a parcel that condenses liquid but no ice.
concentrations ranging from <1 to 20 L⁻¹, similar to the range of values in CLEX (0–8 L⁻¹) except for the 4 Dec 99 pseudoconvective CLEX case, which had ice number concentrations of up to 74 L⁻¹.

7. Differences between single and multilayered clouds: Seeder-feeder?

For the thin, single-layer, mixed-phase clouds, namely those on 11 Nov 99 and 2 Dec 99, the aircraft measurements show that IWC maximizes in the mid to lower part of the cloud. We speculate that this is because of sedimentation (e.g., Figs. 4–5). However, a more even vertical distribution of IWC is apparent in both multilayered cloud systems we observed (e.g., Figs. 8–9). In this section we explore the hypothesis that for these multilayer cases, the ice in the top of the middle and lower layers may have been introduced, in part at least, by a seeder-feeder process. By this we mean a process in which ice particles form in clouds above and sediment into clouds below (e.g., Cotton and Anthes 1989). Pinto et al. (2001), Hobbs et al. (2001), and Lawson et al. (2001) all noted seeding in multilayered arctic clouds.

The main evidence for a seeder-feeder mechanism in the multilayer cases in this study is the detection of some ice particles between the layers by the CPI and the 2D-C probes (Figs. 8–9). Ice particles were observed between all layers on 12 Apr 00 and between the top two layers of the 10 Mar 00 case. However, there were no direct observations of ice particles falling from the middle cloud layer into the lowest layer on 10 Mar 00, despite a uniform IWC profile throughout the 400-m depth of the lowest cloud. It is possible that ice particles fell into the lowest layer earlier and remained in the cloud during the aircraft measurements. The fact that a 70-m-thick band of liquid water was observed approximately 140 m above the lowest layer hints that a fourth layer may have existed between the middle and low cloud shortly before we executed the spiral. This fourth layer may have seeded the lowest cloud and then dissipated or advected out of the ARM site area ahead of the other layers.

Another piece of evidence for the seeder-feeder mechanism is that the temperature of the bottom layer for 10 Mar 00 ranged from −0.9° to −4.1°C, yet many particles were not the plates or hollow columns one would expect to find at these temperatures. [Relationships between temperature and ice crystal growth habits have been established by, e.g., Nakaya (1954), Kobayashi (1957), and Hallett and Mason (1958).] Instead, we observed more stellar-shaped crystals, which grow at temperatures colder than −10°C. Since the middle layer cloud was situated between −7.7° and −14.7°C, the particles may have formed and grew there before seeding the lowest layer (see Hobbs and Rangno 1998).

The irregular shapes (Figs. 4–9) found in all of these clouds also suggest that the ice particles may have experienced alternating periods of growth and sublimation, as proposed by Korolev et al. (1999) for arctic stratus clouds. For example, several of the larger particles in the lowest layer had thin necks connecting bigger pieces of the crystal together, and others had a smooth, rounded

![Ice Water Content vs. Temperature](image)

**Fig. 14.** Variation of ice water content with temperature for the five mixed-phase cloud cases. Highest values of IWC are between −8° and −20°C, a range that includes both the maximum in saturation vapor pressure difference between ice and liquid (−12°C), and the maximum growth rate of platelike and dendritic crystals (−15°C).

<table>
<thead>
<tr>
<th>Author</th>
<th>Cloud depth (m)</th>
<th>LWC (g m⁻³)</th>
<th>T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heymsfield et al. (1991)</td>
<td>200–500</td>
<td>0.01–0.12</td>
<td>−29 to −31</td>
</tr>
<tr>
<td>Hobbs and Rangno (1985)</td>
<td>100–1000</td>
<td>&lt;0.1–1.3</td>
<td>−4.5 to −26</td>
</tr>
<tr>
<td>Hobbs and Rangno (1998)</td>
<td>30–800</td>
<td>0.02–0.14</td>
<td>−1 to −31</td>
</tr>
<tr>
<td>Paltridge et al. (1986)</td>
<td>300–700</td>
<td>0.01–1.2</td>
<td>−6 to −11</td>
</tr>
<tr>
<td>Pinto (1998)</td>
<td>130–290</td>
<td>0.005–0.1</td>
<td>−13 to −20</td>
</tr>
<tr>
<td>Tulich and Vonder Haar (1998)</td>
<td>200–800</td>
<td>0.03–0.31</td>
<td>−10 to −23</td>
</tr>
<tr>
<td>Lawson et al. (2001)</td>
<td>4000</td>
<td>0.0–0.2</td>
<td>0 to −23</td>
</tr>
<tr>
<td>Pinto et al. (2001)</td>
<td>50–430</td>
<td>0.01–0.08</td>
<td>−12 to −31</td>
</tr>
<tr>
<td>Hobbs et al. (2001)</td>
<td>90–350</td>
<td>0.02–0.23</td>
<td>−5 to −21</td>
</tr>
<tr>
<td>CLEX</td>
<td>400–1500</td>
<td>0.005–0.35</td>
<td>−0.9 to −31</td>
</tr>
</tbody>
</table>
appearance. Both of these features indicate sublimation. Some of the particles also appeared to have faceted polycrystalline structures, consisting of combinations of different ice crystal habits growing in different directions. This suggests that the ice particles experienced several different temperatures, and thus growth habit regimes, as they fell through and between cloud layers.

The evidence in favor of the seeder-feeder effect is counterbalanced by evidence that the effect is weak. Namely, although we did directly observe ice particles between the cloud layers, the number of ice particles was small (see Figs. 8 and 9), probably too small to account for all the ice in the tops of the middle and lower layers. Furthermore, our sample of cloud systems—two single-layer cases and two multilayer cases—is limited. Given so few cases, we cannot make general statements about the vertical structure of ice or the efficacy of the seeder-feeder mechanism in multilayer cloud systems.

8. Summary and conclusions

In this paper, airborne measurements of the microphysical structure of six midlevel clouds were described. The cases comprised a single-layer cloud consisting primarily of liquid water; three mixed-phase, single layers; and two multilayer, mixed-phase clouds. The 11 Nov 99 cloud formed as a PV maximum swept into northern Montana and provided some lift for moisture being advected around the apex of a large ridge axis. The five cloud cases in Oklahoma all developed in association with a midtropospheric low-pressure center. With the exception of the “wrap-around” cloud embedded in northerly flow on 5 Dec 99, the other clouds usually formed in southwesterly to westerly flow ahead of a midtropospheric low.

Mean values of the microphysical parameters obtained from horizontal aircraft legs were highlighted and contrasted. Clouds were sampled from 2390 to just over 7000-m altitude, and were typically 500–600 m in depth. In-cloud temperatures ranged from just below 0°C to a low of −31°C. Peak liquid water content was 0.35 g m⁻³, with mean in-cloud values over entire racetracks generally ranging between 0.01 and 0.15 g m⁻³. Drop sizes increased with altitude in the thin, single-layer clouds. Horizontal wind speeds increased gradually with height and were normally 25–30 m s⁻¹. The standard deviation of the vertical wind was normally 0.15–0.75 m s⁻¹, providing a relative measure of mixing and turbulence between the various cases.

We found that LWC tended to increase with altitude in the single layers on 11 Nov 99 and 2 Dec 99. IWC was larger in the lower part relative to the upper part of the single layers on 11 Nov 99 and 2 Dec 99, but IWC was more evenly distributed in the vertical through the multilayered systems we observed. We explored the idea that the seeder-feeder mechanism caused the disparity, as ice sedimentation may have fed the lower layers in multilayered systems. This idea was supported by the presence of ice crystals having growth habits from colder temperatures than where they were observed, and the detection of ice crystals in clear air between cloud layers by the 2D-C and CPI imagery. However, the number of particles between layers was small.

In contrast to numerous observations of marine stratocumulus, the midlevel clouds we observed lacked strong temperature inversions or wind shears at the cloud interfaces. We did not observe strong temperature inversions, we speculate, because the clouds we observed did not survive long enough to form them and because there were no preexisting inversions. Wind shears may have been weak because altocumulus clouds tend to drift with the horizontal wind, rather than being tied to the ground by turbulence. The temperature inversion and shear-generated turbulence are important because both factors help determine the rate at which dry air is entrained into the cloud.

Our midlevel clouds showed poor correlation between IWC and temperature. A maximum in IWC was found in the −8° to −20°C temperature range, which includes the temperature where the difference between saturation vapor pressure with respect to ice and water maximizes, and also the temperature of maximum growth of ice crystals having platelike and dendritic structures.

One goal of this work is to understand the relative importance of cloud microphysical, radiative, and dynamic processes. This is useful because it is difficult for theorists, experimentalists, or modelers to proceed unless they know which process to focus on. The data collected in this study augment the observational base needed to aid development of better parameterizations in large-scale numerical models and improved satellite retrievals of cloud properties.

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