COMPLEX LAYERED CLOUD EXPERIMENT (CLEX-5): PRELIMINARY PHENOMENOLOGY OF FOUR CASE STUDIES

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OBJECTIVE:

One significant lesson learned from Operations DESERT SHIELD and DESERT STORM was the importance of forecasting mid-level clouds, as they routinely covered target areas and hampered missions. To better forecast mid-level clouds, we need first to better understand their structure and evolution. An observational study of several mixed phase non-precipitating altostratus and altocumulus clouds was recently completed in the CLEX-5 (Complex Layered Cloud Experiment 5 Nov - 5 Dec 1999) field campaign. During this experiment, the University of North Dakota Citation II research aircraft took in-situ microphysical measurements of mid-level clouds over the central and northern Great Plains of the United States. In this paper, we characterize the morphology of four of these mixed-phase clouds in order to begin molding a conceptual picture of their formation, evolution and dissipation mechanisms. An overview of the instrumentation and aircraft sampling strategy will precede a short synoptic discussion and a table summarizing the mean microphysical values sampled for each of the four cases. Finally, we will compare our measurements to those obtained in previous studies of this cloud type by several authors (Heymsfield, et. al., 1991; Hobbs and Rangno, 1985, 1998; Paltridge, et.al., 1986; Pinto, 1998; and Tulich and Vonder Haar, 1998).

RESEARCH ACCOMPLISHED:

All research accomplished thus far has centered on processing and analysis of the aircraft data from the CLEX-5 Experiment. The experiment yielded four mixed-phase cloud cases from 11 Nov and 2, 4, and 5 Dec 99. The 11 Nov 99 case was a Lagrangian measurement over east-central Montana, while the December cases were sampled over the Atmospheric Radiation Measurement (ARM) site in north-central Oklahoma. We now describe the instrumentation, aircraft sampling strategy, preliminary research results, and a cursory comparison with previous measurements of mid-level, mixed-phase clouds.

A. Instrumentation

All of the measurements reported in this paper were obtained aboard the University of North Dakota's Citation II research aircraft. An aircraft description, summary of measurement capabilities and aircraft performance characteristics are available via the Internet at: http://www.aero.und.nodak.edu/ATS/citation.html . The basic instrumentation package measures temperature, dewpoint temperature, pressure, wind and cloud microphysics, along with aircraft position, attitude and performance characteristics. For our study, we focus on the cloud microphysical measurements, which were made with an array of Particle Measuring System (PMS) probes. These probes include the Forward Scattering Spectrometer Probe (FSSP), one-dimensional (1D-C) and two-dimensional (2D-C) optical array imaging probes, and the King Liquid Water Probe. All of these instruments are described in detail in NCAR's Research Aviation Facility Bulletin 24 (Baumgardner, 1981). We also employed the Cloud Particle Imager, a relatively new instrument, which records high- resolution (2.3 micron) digital images of cloud particles and processes them "on the fly" (Lawson and Jensen, 1998).

B. Aircraft Sampling Strategy

We used three basic flight patterns in CLEX-5: a racetrack pattern over a fixed point, Lagrangian racetracks, and a slow, spiral sounding. The racetrack is the basic sampling pattern. It involves a series of racetrack-shaped patterns at different altitudes. For a typical cloud of one kilometer thickness, we made five racetracks at different altitudes: one above cloud, three in-cloud, and another below cloud. Relative rapid descents were made between racetracks. Lagrangian racetracks were horizontally displaced from one another so the aircraft drifted with the horizontal wind at mid-cloud level. We sampled the wind speed and direction during the first mid-cloud racetrack and used this information to determine the horizontal position of subsequent racetracks, so that we stayed in the same relative cloud parcel for the duration of the measurement time.

Airspace restrictions prevented us from making Lagrangian measurements over the Southern Great Plains ARM site on 2, 4 and 5 Dec 99. Hence, we sampled clouds over the ARM site while centered at a fixed latitude and longitude. The racetracks were contained entirely within a reasonably homogeneous cloud region, with the longer dimension of the racetrack approximately 20 km in length. Above and below cloud racetracks were made far enough away from the cloud so they occurred entirely within clear air. The highest racetrack within cloud was made just enough below cloud top so the racetrack was entirely within cloud. Similarly, the lowest racetrack within cloud was just above cloud base. The racetracks within cloud were vertically separated by 200-500 m, depending on cloud depth. Due to limited upper air data, and the desire to get a vertical sample of the clouds, the aircraft performed slow spiral descents for a thermodynamic sounding. The aircraft sounding extended from about one kilometer above cloud top to a kilometer below cloud base, at a constant 1,000 feet per minute rate.

C. Synoptic Situations

a) 11 Nov 1999: A large area of mid and upper level cloudiness was advecting eastward along the Wyoming-Montana border, over the north end of a ridge axis about halfway between Casper, WY and Mile City, MT. An upper level shortwave moving across the area from the Nevada-Utah border enhanced early morning clouds beginning around local noon. Our Lagrangian aircraft sample took place between 1923 and 2040 UTC, as the cloud field crested the ridge axis and eventually dissipated.

b) 2 Dec 99 Case: Bands of mid and upper level cloud moved across the Texas Panhandle and into northern Oklahoma. This area of cloudiness was east of a dry air slot over New Mexico and southern Colorado, which eventually moved into the area and helped to fire pre-frontal convection. We sampled this cloud band as it moved over the ARM site between 1453 and 1605 UTC.

c) 4 Dec 99 Case: Frontal passage the evening of 3 Dec 99 generated a great deal of convection, with thunderstorms all night and five tornadoes reported in a triangular area between Ponca City, Tulsa and Oklahoma City. Light to moderate rain continued through the morning and early afternoon hours, but stopped by mid-afternoon. Mid-level non-convective clouds moved into the area from the west-southwest at that time, allowing a flight over the ARM site from 2030 until 2207 UTC. A stratus cloud deck with bases of about 2,000 feet was beneath the mid-level cloud layers.

d) 5 Dec 99 Case: An upper level low moved through the area behind the strong surface system on the evening of 4 Dec 99. Some snow fell overnight and some light flurries lingered into the early morning hours. Ponca City was on the back (western) edge of a "wrap-around" cloud field, with non-precipitating low and mid-level clouds over the ARM site. A layer of stratus clouds was beneath the mid-level deck, with bases at 4,300 feet and tops at about 7,000 feet. We sampled this system for approximately 45 minutes, from 1430 to 1515 UTC.

D. Measurements

Aircraft data were processed to eliminate pitch, roll and yaw effects, so that only straight and level flight legs remained. We defined the in-cloud legs as those having non-zero FSSP measurements and King Liquid Water Probe readings above a given offset value. These King instrument offsets were determined for each flight leg by noting the measurements in the ambient air outside of cloud and were checked for consistency at a given flight level. The resultant flight legs for each of the four cases, with respective times and altitudes (MSL), are shown in Tables 1-4.

Flight Legs for 11 Nov 99

19:23:50	19:24:34	19:26:38	19:27:11		
Spiral	Top: 5730 m	Base: 5180 m	550 m Thick	Turns	
1a	19:29:48	19:30:50	Under	Level	~4525m
1b	19:33:01	19:34:35	Cloud		~4525m
1c	19:37:30	19:39:33			~4525m
2a	19:41:19	19:42:39	In Bottom	Level	~5280m
2b	19:45:09	19:47:09			~5280m
3a	19:49:25	19:51:35	In Top	Level	~5610m
3b	19:54:15	19:56:34			~5610m
4a	19:58:05	20:00:03	Above	Level	~5795m
4b	20:03:28	20:05:17	Cloud		~5795m
5a	20:06:58	20:09:15	In Middle	Level	~5545m
5b	20:12:17	20:14:08	Top		~5545m
6a	20:15:38	20:17:18	In Middle	Level	~5435m
6b	20:20:54	20:22:42	Bottom		~5435m
7a	20:24:20	20:25:34	At Base	Level	~5180m
7b	20:29:17	20:31:15			~5180m
8a	20:33:29	20:35:28	Below	Level	~4875m
8b	20:38:17	20:39:06	Dissipated		~4875m

Table 1. Level flight legs for 11 Nov 99 Lagrangian flight over Eastern Montana.

Flight Legs for 2 Dec 99

14:53:22	15:01:58	15:09:52	15:10:20		
Spiral	Top: 7180 m	Base: 6560 m	620 m Thick	Turns	
1a	14:48:00	14:48:56	Above	Level	~8240m
1b	14:49:31	14:49:56	Cloud		~8240m
2a	15:13:41	15:15:25	In Bottom	Level	~6710m
2b	15:17:03	15:17:30	Cloud		~6710m
2c	15:17:37	15:18:14			~6710m
2d	15:20:03	15:21:17			~6710m
3a	15:22:12	15:22:43	In Middle	Level	~7010m
3b	15:24:15	15:25:25	Cloud		~7010m
4a	15:31:13	15:32:16			~7010m
4b	15:34:24	15:35:16			~7010m
5a	15:38:16	15:38:49	Above Cloud	Level	~7315m
5b	15:40:41	15:41:32			~7315m
6	15:46:19	15:47:45	Out of Cloud	Level	~6970m
7a	15:49:37	15:50:13	In Middle	Dissip	~6890m
7b	15:52:05	15:54:20	Out	Level	~6890m
7c	15:56:04	15:57:01	Out		~6890m
8	16:04:35	16:05:55	Low ST	Descend	~1200m

Table 2. Same as Table 1 except for 2 Dec 99 Flight over ARM site in Oklahoma.

Flight Legs for 4 Dec 99

No Spiral	Top: 5500 m	Base: 4000 m	1500 m Thick		
1a	20:31:30	20:32:32	Above Cloud	Level	~6712m
1b	20:36:53	20:37:42	Above Cloud	Level	~6712m
1c	20:38:04	20:39:43	Above Cloud	Level	~6712m
1d	20:40:06	20:40:46	Above Cloud	Level	~6712m
1e	20:48:08	20:54:13	Descend	Top	~6700m
2	20:54:49	20:56:18	In Cloud	Level	~5200m
3a	20:58:29	20:59:22	In (Low lwc)	Level	~4900m
3b	21:01:48	21:04:21	Out	Level	~4900m
3c	21:05:35	21:07:11	Out	Level	~4900m
3d	21:09:43	21:13:18	Between	Level	~4900m
4	21:14:54	21:28:20	Beside	Inc Turns	~4900m
5a	21:29:35	21:30:52	Out	Level	~4900m
5b	21:34:15	21:35:35	In Cloud	Level	~4900m
5c	21:36:51	21:37:41	In (Low lwc)	Level	~4900m
5d	21:39:35	21:41:58	In Cloud	Level	~4900m
5e	21:43:18	21:44:14	Out	Level	~4900m
6a	21:46:38	21:48:20	In Cloud	Level	~4285m
6b	21:49:42	21:50:32	Out	Level	~4285m
6c	21:52:00	21:52:25	Out	Level	~4285m
6d	21:53:00	21:54:31	In Cloud	Level	~4285m
7a	21:58:09	21:58:45	Out	Level	~4290m
7b	21:59:31	22:00:26	In	Level	~4290m

Table 3. Same as Table 2 except for 4 Dec 99 flight over ARM site.

Flight Legs for 5 Dec 99

14:23:24	14:23:47	14:26:56	14:27:26		
Spiral	Top: 2988 m	Base: 2390 m	598 m Thick	Turns	
1a	14:29:25	14:30:04	In	Level	~2590m
1b	14:31:29	14:33:31	In	Level	~2590m
1c	14:35:52	14:36:27	In	Level	~2590m
1d	14:36:45	14:37:39	In	Level	~2590m
2a	14:39:36	14:40:14	Out	Level	~2590m
2b	14:40:18	14:42:42	In	Level	~2590m
2c	14:43:54	14:44:43	In	Level	~2590m
3	14:47:11	14:49:03	In	Level	~2390m
4a	14:54:48	14:55:21	In	Level	~2625m
4b	14:56:38	14:58:01	In	Level	~2625m
5a	15:03:48	15:05:14	In	Level	~2805m
5b	15:06:21	15:07:10	Out	Level	~2805m
6a	15:09:43	15:12:55	Out	Level	~2385m
6b	15:14:05	15:15:02	Out	Level	~2385m

Table 4. Same as Table 3 except for 5 Dec 99 flight over ARM site in Oklahoma.

Mean values of temperature, dewpoint temperature, pressure, liquid water content, vertical and horizontal wind speed, and wind direction for each flight leg of each of the four cases are shown in Tables 5-8. With the exception of the liquid water content, all of these values represent raw, uncorrected output from the aircraft instruments, so care should be used in any quantitative interpretations. However, the values compare well with a cursory examination of upper level sounding data. Mixed phase conditions were evident in both the CPI images and the size distributions from the 2D-C probe throughout all four of the cases.

As mentioned previously, the 11 Nov 99 case (Table 5) was a Lagrangian sample, so we remained in the same cloud parcel with time and saw the evolution of the various microphysical parameters as we drifted eastward. The ground track is shown in Figure 1. In-cloud temperatures ranged from about -12.5 to –16.5 C through a cloud depth of just over 500 m. Liquid water contents were highest in the mid and upper portions of the cloud (0.114 to 0.150 g/m^3), and dropped to less than 0.02 g/m^3 at cloud base, which were just below 5,200 m.

Table 6 lists the mean microphysical values for the 2 Dec case. Temperatures ranged from –26.5 to –30.3° C through a cloud depth of just over 600 meters, so this system was about 15° C cooler than the previous case. Liquid water contents were about half of those measured in the 11 Nov case, with mean values of 0.011 g/m^3 in leg 2 and 0.063 g/m^3 in legs 3 and 4. Ice contents are still being derived, but we hypothesize that the ratio of ice to water may be higher in this case. Also, the vertical wind field shows very little upward motion throughout the sample time, in contrast to the 0.5 to 2.8 m/s upward vertical motions seen on 11 Nov 99. Again, the vertical wind measurements have not had any corrections applied yet, other than for aircraft maneuvers. However, the relative differences may point towards qualitative arguments for specific formation, evolution and dissipation mechanisms.

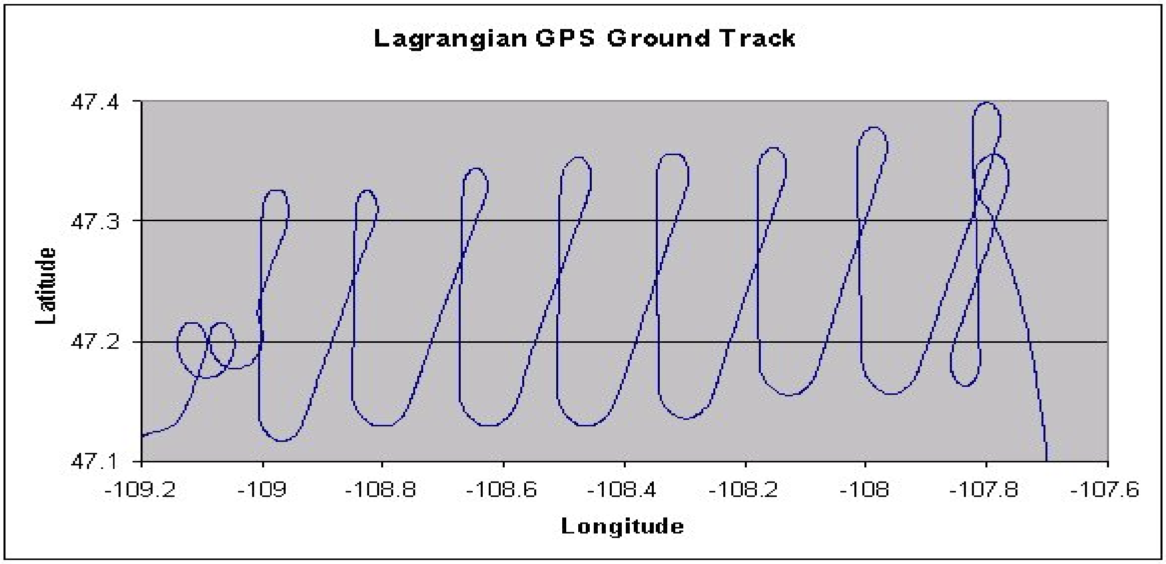

Figure 1. Citation aircraft ground track during the 11 Nov 99 Lagrangian Measurement.

Mean Values for 11 Nov 99 Legs

	height	T	p	lwc	stdev	vert wind	stdev	u / v	dir	Location
	[m]	[C]	[mb]	[g/m3]	g/m3s]	[m/s]	[m/s]	[m/s]	[deg]	
1a	4540	-8.43	574.2	0.000	0.0023	-0.254	0.2727	23.5	267	
1b	4515	-8.24	576.1	0.000	0.0014	0.430	0.1917	23.9	268	
1c	4521	-8.25	575.7	0.000	0.0014	1.580	0.2178	23.9	269	
mean	**4525**	**-8.31**	**575.3**	0.000	**0.0017**	**0.585**	**0.2274**	**23.8**	**268**	**Under**
2a	5278	-13.89	520.4	0.017	0.0312	1.280	0.7902	26.6	265	
2b	5280	-13.87	520.3	0.018	0.0163	1.067	0.6792	25.9	267	
mean	**5279**	**-13.88**	**520.4**	**0.018**	**0.0238**	**1.174**	**0.7347**	**26.3**	**266**	**In Bottom**
3a	5609	-16.49	497.7	0.164	0.0710	0.518	0.6346	27.3	268	
3b	5607	-16.31	497.8	0.136	0.0560	0.667	0.6445	25.7	269	
mean	**5608**	**-16.40**	**497.8**	**0.150**	**0.0635**	**0.593**	**0.6396**	**26.5**	**269**	**In Top**
4a	5793	-16.32	485.3	0.000	0.0011	0.660	0.2901	26.2	269	
4b	5795	-16.25	485.2	0.000	0.0012	1.380	0.2813	22.7	271	
mean	**5794**	**-16.29**	**485.3**	0.000	**0.0012**	**1.020**	**0.2857**	**24.5**	**270**	**Above**
5a	5545	-15.77	502.0	0.111	0.0670	0.294	0.7213	27.7	269	
5b	5547	-15.75	501.8	0.116	0.0487	0.910	0.6384	24.4	271	
mean	**5546**	**-15.76**	**501.9**	**0.114**	**0.0579**	**0.602**	**0.6799**	**26.1**	**270**	**In Middle**
6a	5440	-14.9	509.2	0.072	0.0373	1.210	0.9204	26.8	270	
6b	5428	-14.89	510.0	0.054	0.0238	3.130	0.7638	24.3	272	
mean	**5434**	**-14.90**	**509.6**	**0.063**	**0.0306**	**2.170**	**0.8421**	**25.6**	**271**	**In Middle**
7a	5181	-12.72	527.2	0.004	0.0051	3.505	0.3945	28.0	270	
7b	5183	-12.7	527.2	0.002	0.0025	2.230	0.6095	22.9	272	
mean	**5182**	**-12.71**	**527.2**	0.003	**0.0038**	**2.868**	**0.5020**	**25.5**	**271**	**In Bottom**
8a	4875	-9.99	549.3	0.004	0.0028	1.350	0.2964	29.3	272	
8b	4878	-10.05	549.1	0.003	0.0024	1.080	0.9573	22.3	273	
mean	**4877**	**-10.02**	**549.2**	0.004	**0.0026**	**1.215**	**0.6269**	**25.8**	**273**	**Below**

Table 5. Mean microphysical values for each leg of the 11 Nov 99 cloud sample.

Mean Values for 2 Dec 99 Legs

	height	T	p	lwc	stdev	w	stdev	u / v	dir	Location
	[m]	[C]	[mb]	[g/m3]	[g/m3]	[m/s]	[m/s]	[m/s]	[deg]	
1a	8235	-37.56	344.0	0.0000	0.0016	-0.46	0.2469	33.0	253	
1b	8241	-37.49	343.7	0.0000	0.0006	-0.17	0.0735	22.5	231	
mean	**8238**	**-37.53**	**343.9**	**0.0000**	**0.0011**	**-0.32**	**0.1602**	**27.8**	**242**	Above
2a	6713	-27.20	427.4	0.0118	0.0114	0.02	0.2904	20.9	201	
2b	6708	-27.08	427.7	0.0108	0.0109	-0.55	0.8135	27.5	206	
2c	*6711*	*-27.09*	*427.5*	0.0028	*0.0016*	*-0.29*	*0.4633*	*26.8*	*208*	*Low*
2d	6711	-27.04	427.6	0.0115	0.0125	-0.18	0.8006	23.7	204	
mean	**6711**	**-27.11**	**427.6**	**0.0114**	**0.0116**	**-0.24**	**0.6348**	**24.0**	**204**	In Cloud
3a	7007	-29.75	410.2	0.0690	0.0195	0.35	1.0178	23.7	202	
3b	7007	-29.67	410.2	0.0696	0.0226	0.04	0.8244	26.3	206	
4a	7010	-29.62	410.0	0.0638	0.0181	0.11	0.5266	26.0	206	
4b	7007	-29.59	410.2	0.0485	0.0130	0.04	0.5879	24.7	204	
mean	**7008**	**-29.66**	**410.2**	**0.0627**	**0.0183**	**0.14**	**0.7392**	**25.2**	**205**	In Cloud
5a	7312	-29.99	392.9	0.0000	0.0005	-0.09	0.0919	27.9	212	
5b	7316	-30.47	392.6	0.0000	0.0006	-0.09	0.1973	25.9	212	
mean	**7314**	**-30.23**	**392.8**	**0.0000**	**0.0006**	**-0.09**	**0.1446**	**26.9**	**212**	Above
6	6969	-27.83	412.4	0.0000	0.0009	0.00	0.2122	24.6	209	Out
7a	**6886**	**-28.51**	**417.2**	**0.0084**	**0.0079**	**-0.37**	**0.2542**	**25.3**	**206**	**In Dissip**
7b	6892	-27.67	416.9	0.0000	0.0018	0.08	0.3483	23.2	205	Out
7c	6891	-27.96	416.9	0.0000	0.0013	-0.49	0.0812	31.6	207	Out
mean	**6892**	**-27.82**	**416.9**	**0.0000**	**0.0016**	**-0.21**	**0.2148**	**27.4**	**206**	Aft Dissip

Table 6. Same as Table 5 except for 2 Dec 99 sample over ARM site in Oklahoma.

Mean Values for 5 Dec 99 Legs

	height	T	p	lwc	stdev	w	stdev	u / v	dir	Loc	
	[m]	[C]	[mb]	[g/m3]	[g/m3]	[m/s]	[m/s]	[m/s]	[deg]		
1a	2590	-7.30	738.4	0.0623	0.0296	0.58	0.2332	17.1	338	In	Level
1b	2591	-7.15	738.4	0.1025	0.0222	0.42	0.3069	19.7	346	In	Level
1c	2593	-7.05	738.1	0.1393	0.0279	0.95	0.1633	20.6	352	In	Level
1d	2594	-6.90	738.0	0.0460	0.0150	0.56	0.2863	20.8	350	In	Level
mean	**2592**	**-7.10**	**738.2**	**0.0875**	**0.0237**	**0.6275**	**0.2474**	**19.55**	**346.5**		
2a	2593	-6.69	738.1	0.0000	0.0044	1.12	0.2203	19.5	351	Out	Level
2b	2592	-6.93	738.2	0.0955	0.0197	0.57	0.1900	21.1	354	In	Level
2c	2592	-6.85	738.3	0.0543	0.0413	0.69	0.2903	21.0	352	In	Level
mean	**2592**	**-6.89**	**738.3**	**0.0749**	**0.0305**	**0.63**	**0.2402**	**21.05**	**353**		
3	**2390**	**-6.52**	**757.2**	**0.1293**	**0.0549**	**0.11**	**0.3405**	**18.0**	**344**	**In**	**Level**
4a	2626	-7.27	735.1	0.0236	0.0169	0.87	0.1958	20.1	349	In	Level
4b	2624	-7.07	735.3	0.1144	0.0453	0.71	0.1139	28.0	358	In	Level
mean	**2625**	**-7.17**	**735.2**	**0.0690**	**0.0311**	**0.79**	**0.1549**	**24.05**	**353.5**		
5a	**2809**	**-7.98**	**718.3**	**0.0505**	**0.0312**	**0.75**	**0.2037**	**20.3**	**353**	**In**	**Level**
5b	2810	-7.53	718.2	0.0000	0.0032	0.91	0.1623	18.2	336	Out	Level
6a	2386	-5.97	757.5	0.0000	0.0048	0.94	0.3182	19.1	350	Out	Level
6b	2386	-5.81	757.6	0.0000	0.0017	0.95	0.1999	20.8	351	Out	Level
mean	**2386**	**-5.89**	**757.6**	**0.0000**	**0.0033**	**0.945**	**0.2591**	**19.95**	**350.5**		

Table 7. Same as Table 6 except for 5 Dec 99 flight.

	Mean Values for 4 Dec 99 Legs					***mean computed for In-Cloud legs only**					
	height [m]	T [C]	p [mb]	lwc [g/m3]	stdev [g/m3]	w [m/s]	stdev [m/s]	u / v [m/s]	dir [deg]	Location	
1a	6713	-27.53	427.4	0.0000	0.0020	-0.35	0.7644	50.9	185	Above	Level
1b	6711	-27.43	427.6	0.0000	0.0010	-0.15	0.3221	50.1	185	Above	Level
1c	6710	-27.87	427.6	0.0000	0.0034	-0.25	0.7107	52.2	185	Above	Level
1d	6713	-28.15	427.5	0.0000	0.0011	-0.03	0.2025	51.5	184	Above	Level
mean	**6712**	**-27.75**	**427.5**	**0.0000**	**0.0019**	**-0.20**	**0.4999**	**51.2**	**185**	Above	
1e										Descend	Top
2	**5199**	**-18.93**	**526.0**	**0.0147**	**0.0139**	**-0.14**	**0.3163**	**32.0**	**189**	**In Cloud**	**Level**
3a	**4894**	**-16.4**	**547.9**	**0.0044**	**0.0034**	**0.35**	**0.2410**	**34.1**	**189**	**In (Low lwc)**	**Level**
3b	4898	-16.32	547.6	0.0000	0.0051	-0.10	0.3118	33.7	194	Out	Level
3c	4901	-16.53	547.4	0.0000	0.0068	0.25	0.3889	33.6	191	Out	Level
3d	4898	-16.41	547.6	0.0000	0.0041	-0.11	0.4133	33.0	193	Between	Level
mean	**4899**	**-16.42**	**547.5**	**0.0000**	**0.0053**	**0.01**	**0.3713**	**33.4**	**193**		
4										Beside	Inc Turns
5a	4899	-16.77	547.5	0.0000	0.0018	-0.18	0.2371	32.7	189	Out	Level
5b	**4902**	**-16.96**	**547.3**	**0.0052**	**0.0058**	**-0.57**	**0.4274**	**32.1**	**191**	**In Cloud**	**Level**
5c	**4902**	**-16.95**	**547.3**	**0.0061**	**0.0037**	**-0.44**	**0.6963**	**32.6**	**191**	**In (Low lwc)**	**Level**
5d	**4905**	**-17.01**	**547.1**	**0.0085**	**0.0086**	**-0.43**	**0.9128**	**30.3**	**190**	**In Cloud**	**Level**
5e	4909	-16.91	546.8	0.0000	0.0042	-0.09	0.5024	33.5	191	Out	Level
***mean**	**4903**	**-16.97**	**547.2**	**0.0066**	**0.0060**	**-0.48**	**0.6788**	**31.7**	**191**		
6a	**4287**	**-13.03**	**593.7**	**0.0172**	**0.0148**	**-0.49**	**0.6842**	**21.0**	**188**	**In Cloud**	**Level**
6b	4284	-12.77	593.9	0.0000	0.0072	-0.50	0.8365	25.1	191	Out	Level
6c	4288	-12.73	593.6	0.0000	0.0074	0.16	0.4393	24.6	189	Out	Level
6d	**4289**	**-13.22**	**593.5**	**0.0398**	**0.0345**	**-0.40**	**0.5766**	**19.2**	**185**	**In Cloud**	**Level**
***mean**	**4288**	**-13.13**	**593.6**	**0.0285**	**0.0247**	**-0.45**	**0.6304**	**20.1**	**187**		
7a	4292	-13.18	593.3	0.0000	0.0075	1.58	0.6121	25.5	188	Out	Level
7b	**4291**	**-13.31**	**593.4**	**0.0417**	**0.0184**	**1.34**	**0.7996**	**16.9**	**185**	**In**	**Level**

Table 8. Same as Table 7 except for 4 Dec 99 flight over ARM site in Oklahoma.

Mean microphysical values for the 4 Dec 99 case are shown above in Table 8. Temperatures in this case were similar to those found on 11 Nov 99 over Montana in the range from –12 to –16° C. In contrast, though, this cloud was approximately 1500 m deep, which is nearly threefold that of the Montana cloud. Liquid water contents were more similar to the 2 Dec case, with mean values ranging from a low of 0.0044 g/m^3 in leg 3a to a maximum around 0.040 g/m^3 in legs 6d and 7b. Interestingly, the vertical wind field shows mostly downward motion throughout the sample time, except for legs 3a, 7 and 7b. These and other inhomogeneities in the measured fields over the ARM site may be related to the Eulerian nature of the sample; we were flying racetrack patterns through cloud fields that were advecting into the area and changing with time. Also, our north-south distance between successive legs was on the order of 10-12 km, which may also have contributed to the differences we see in the data.

Finally, Table 7 shows the mean values measured on 5 Dec 99. These temperatures are the warmest of the four cases, with a mean of about –7° C and a range of $\pm$ 1° C. Cloud depth was on the order of 600 m, which is very similar to the 11 Nov and 2 Dec 99 cases. Liquid water contents were fairly high and similar to the Montana case, with values of 00505 to 0.1393 g/m^3. One reason they may be high is that there was not much ice in this cloud; some particles were evident on the CPI and 2D-C, but not many. The ice that was present also tended to be smaller than those seen in other cases. Although this was a post-frontal cloud, the vertical motion was upward and on the order of 0.5 to 1 m/s while the cloud persisted.

E. Comparison of CLEX-5 with Other Studies

Heymsfield, et. al. (1991) took aircraft measurements of two clouds near Green Bay, WI in October of 1986. The first was a thin cloud about 200 m thick with a base at 7.3 km altitude, while the second was on the order of 500 m thick with a base at 7.5 km. Liquid water contents in the first case were only .01 to .02 g/m^3, while the second was in the range from 0.04 to 0.12 g/m^3. These values fall within the range of those measured in CLEX-5, but are closer to the low end of our measurements. The temperatures were –29 to –31° C, which is similar to our coldest day on 2 Dec 99. Vertical velocities in this study varied from .25 to .75 m/s, which also compares quite favorably to those we measured during CLEX-5.

Hobbs and Rangno (1985) reported the findings on measurements and observations of 90 cumuliform and 72 stratiform clouds. One of their illustrative examples is an altocumulus (AC) cloud over Washington State with bases at 5 km (AGL), temperatures ranging from –8 to –13° C, and approximately 800 m deep. The measured maximum liquid water content was 1.3 g/m^3 near cloud top, which more than twice that found in CLEX-5 and over an order of magnitude higher than the October 1986 clouds previously discussed. However, this may be attributed to the difference in maritime and continental climates. Their study also cites ice particle concentrations of 0.1 to 2 /liter.

Airborne measurements of mid-level clouds over the Beaufort Sea in Alaska were also reported by Hobbs and Rangno (1998). In this study, they found AC 30 to 800 m thick, with temperatures in the 1 to –31° C range. Mean liquid water contents varied from 0.02 to 0.14 g/m^3, which is in good agreement with our measurements. Droplet concentrations were 105-450/cm^3, with average effective cloud droplet radius of 10 μm. As an interesting side note, one of the conclusions of this particular study was that ice particle concentrations were poorly correlated with temperature…if anything, they showed a decrease in concentration with decreases in temperature, which is rather counterintuitive.

Paltridge, et. al., (1986) completed a case study of ice particle growth in a mixed-phase altostratus (AS) cloud. The system was divided into two layers, with the first from 2600 to 3300 m and the second from 3300 to 3600 m. Liquid water contents varied from 0.0 to 1.2 g/m^3, depending on location within the cloud, which compares favorably with our four cases. Temperatures in cloud ranged from –6 to -11° C, which is comparable to our 5 Dec 99 case. Upward vertical motion was calculated in this study to be approximately .09 m/s, which is an about an order of magnitude lower than those we measured or those reported by Heymsfield, et. al. (1991).

Pinto (1998) analyzed two Arctic mixed-phase cloudy boundary layers in the temperature range –13 to –20° C. He found that liquid water content generally increased with height through the cloud layer with a maximum just below cloud top. Values were on the order of 0.005 to just over 0.1 g/m^3, which is in good agreement with our measurements and previously described studies. Total cloud ice generally decreased with height through the layer with a maximum near cloud base. Although we don't show any of these values here, that trend is apparent in our data. Typical vertical velocities in this study were +0.002 m/s in one cloud and -0.005 m/s in the other. Due to these low values, Pinto concluded that the sign of vertical velocity is relatively unimportant for cloud existence. These values are much lower than those seen in other cases examined thus far, and are well below the noise level of the Citation instruments.

Finally, Tulich and Vonder Haar (1998) examined measured structures of a multi-layer cloud in great detail. The system started out as an AS layer from 5800 to 6000 m, with an AC layer rising into it from a base of approximately 5125 m. Mean liquid water contents 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 to 0.16 g/m^3. The reason for the higher mid layer value may be due to the fact that this was a summer time system, and appeared to have formed from detrained convective moisture. Mean in-cloud vertical motion ranged from +0.6 to –0.5 m/s, with maximum values of +2.2 and –1.8 m/s. All values compare reasonably well to the CLEX-5 measurements.

CONCLUSIONS:

To summarize the overall CLEX-5 aircraft measurements, we found ice and liquid water mixed phase conditions in all four cloud systems, ranging in altitude from 2400 m up to 7200 m. It is noteworthy that synoptic conditions were different in each case. Three of the clouds were on the order of 600 m thick, while one case was 1500 m thick. Temperatures varied from a mean of about –7° C to –28.5° C. In two of the cases, liquid water content values were approximately 0.005 to 0.05 g/m^3, while the remaining two cases had higher values in the 0.05 to 1.50 g/m^3 range. Upward vertical motion was positive for the higher liquid water cases, and tended towards negative values on the days when we measured lower amounts. The 11 Nov 99 case was a Lagrangian measurement following a cloud parcel in eastern Montana, while the other three days were more Eulerian in nature over the ARM site in north-central Oklahoma.

Observations of cloud temperature, height, liquid water content and vertical wind field from previous studies generally showed very good agreement with the CLEX-5 measurements. One exception was the very low vertical velocities found in autumnal Arctic clouds. Mixed phase conditions have been documented in clouds with temperatures of –5 to -31° C, liquid water contents of 0.001 to approximately 1.3 g/m^3, and vertical winds of $\pm$ .002 to around $\pm$ 2.5 m/s.

RECOMMENDATIONS:

Future work will center on refinement of the measurements taken thus far, along with processing more of the data set, such as liquid and ice particle sizes and concentrations. We will also be deriving products from the measurements, such as turbulent kinetic energy, potential temperature, lapse rates, radiative heating and cooling rates, etc. Some radiative transfer modeling with the Spherical Harmonic Discrete Ordinate Method, as well as 2-dimensional RAMS cloud simulations, is also planned. In addition to working with the current data, we have recently gained two more case studies and will be trying for a third within the next month. Once we get the aircraft data processed, the next step is to begin tying the measurements to satellite imagery, in the hopes of developing improved forecasting techniques and remote sensing algorithms for mixed phase systems.

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