Airborne In Situ and Ground-based Polarimetric Radar Measurements of Tropical Convection in Support of CRYSTAL-FACE

Final Report

NASA Grant NAG5-11509

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September 8, 2004

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1.0 Scope of Work

This report describes the work performed by the University of North Dakota (UND) under NASA Grant NAG5-11509, titled "Airborne In Situ and Ground-based Polarimetric Radar Measurements of Tropical Convection in Support of CRYSTAL-FACE." This work focused on the collection of data by two key platforms: the UND Citation II research aircraft and the NASA NPOL radar system. Prof. Michael Poellot led the deployment of the Citation and Dr. Paul Kucera led the operations of the NPOL radar in collaboration with John Gerlach (NPOL facility manager, NASA Wallops Flight Facility) and Rob Cifelli (Colorado State University).

As stated in the NRA, the CRYSTAL-FACE (C-F) mission addresses several key issues from the NASA Earth System Enterprise, including the variability of water in the atmosphere, the forcing provided by tropical cirrus and the response of the Earth system to this forcing. In situ measurements and radar observations of tropical convection, cirrus clouds and their environment are core elements of C-F. One of the primary issues that C-F is addressing is the relationship of tropical cirrus anvils to precipitating deep convection. Because convective clouds act as a source region for tropical cirrus anvils, it is important to obtain observations of the microphysical and spatial properties of the parent convective cells through the entire life cycle of the cloud system.

The in situ measurements from C-F are being used to validate remote sensing of Earth-Atmosphere properties, increase our knowledge of upper tropospheric water vapor and its distribution, and increase our knowledge of tropical cirrus cloud morphology and composition. Radar measurements, especially polarimetric diversity observations available from the NASA NPOL radar, are providing essential information about the initiation, modulation, and dissipation of convective cores and the generation of associated anvils in tropical convection. Specifically, NPOL radar measurements contain information about convective intensity and its vertical structure for comparison with thermodynamic and kinematic environmental measurements observed from soundings. Because of the polarimetric diversity of NPOL, statistics on bulk microphysical properties can be retrieved and compared to the other characteristics of convection and associated cirrus anvils.

In summary, the central objectives of this proposal were to deploy the UND Citation research aircraft as an in situ sensing platform for this mission and to provide collaborative analyses of the recorded data and to deploy the NPOL radar to observe the characteristics of cirrus and parent convection.

2.0 Objectives

Citation

The following are the proposed work objectives related to Citation operations:

1. Integrate guest instruments on the Citation as able and as selected by the CRYSTAL-FACE science team to help meet program objectives;

2. Operate the UND Citation research aircraft during the CRYSTAL-FACE observational period, including measurements of cloud microphysics, state parameters and winds;
3. Process data recorded on the Citation DAS and provide the data to the program archive;
4. Compile mission summaries for all flight missions; and
5. Perform collaborative analyses of the Citation data with other CRYSTAL-FACE investigators.

NPOL Radar

The following are the proposed work objectives related to NPOL operations and data analysis:

1. Field phase of CRYSTAL-FACE – data collection;
2. Quality control of NPOL radar data;
3. Development of precipitation fields and polarimetrically tuned Z-R relationships from NPOL radar data; and
4. Hydrometeor identification from polarimetric signatures examine the evolution of the convective systems observed by NPOL for priority cases

3.0 Work Accomplished

3.1. Citation

3.1.1 Integration of guest and new instrumentation – CFDC, CVI, CIN, CPI, HVPS, TDL

The suite of instrumentation to be flown on the Citation was determined through discussions with the CRYSTAL proposal review team. The final package (Table 1) was based on the measurement objectives and the capacity of the aircraft to carry and power the desired equipment. Some of these instruments were provided by guest scientists. The mission of the Citation to provide in situ cloud microphysical measurements was reflected in the choice of instruments.

Preparation for this field deployment actually began in January, after the grant award. Integration of this suite was a complex task in terms of number and nature of the instruments, and three of them had never been flown on the Citation before (CFDC, CIN, TDL). This suite also represented an unprecedented impact on the weight, space and electrical capabilities of the Citation, requiring several modifications. These included design and construction of a new instrument rack, the addition of electrical wiring and inverters for research power, and the design and construction of two new inlets for sampling. All aircraft modifications also required engineering and FAA approval. The design of the rack and one of the inlets, along with the engineering and FAA approvals, were all accomplished by UND. A contractor performed rack construction and the other inlet was built by NCAR, where a modification to the mount of the CVI was also done. The wiring and inverter installation was done during scheduled aircraft maintenance in April.

3.1.2 Deployment in Key West

The Citation was ferried to Key West Naval Air Station on June 30 and returned to Grand Forks on July 31. Research flight operations began on July 3 and a total of 13 research missions were flown during the experimental period. A list of these flights and primary objectives is given in Table 2. Overall, this was a highly successful measurement mission for this platform. Instrument reliability was high; excellent coordination and support was provided through pre-flight briefings and real-time coordination by the crew at NPOL. As seen in Table 2, a variety of conditions were sampled according to the science plan of the experiment.

3.1.3 Data Processing and Archival

All flight data were processed after each mission upon landing. These processed data were then uploaded to the experiment archive. These were considered preliminary at that point, with quality control and final instrument calibration activities still in progress. After the field program the processing proceeded along several fronts in parallel with analysis efforts, including quality control and archival.

The first step in quality control was to correct or flag known bad data associated with instrument problems noted during the flight missions. Instrument calibration issues were also addressed. Step two consisted of an extensive manual edit of the data. All recorded parameters were plotted and reviewed for reasonableness. Case study analyses also provided close scrutiny of select portions of the data. Measurements appearing abnormal or out of range have been flagged with missing data values.

Archive formats for C-F data were established in a data exchange plan for this project (http://espoarchive.nasa.gov/info/crystalf/dataex_plan.html). The Citation data were grouped into four categories to meet plan requirements: meteorological data (MET), cloud physics data (CLD), navigation data (NAV) and other observations (MIS). An additional file containing derived particle size distributions from the PMS FSSP probe was also created for each flight (FSS). A full description of data processing techniques, file formats and related information is presented at http://aerosol.atmos.und.edu/citation/index.html. During the archival process, quick-look plots were generated for select parameters and may be viewed at http://aerosol.atmos.und.edu/citation/gallery/Crystal-FACE. All data have been submitted to the ESPO archive.

3.1.4 Mission Summaries

Additional quick-look information has been compiled into Flight Summaries for each of the Citation missions during C-F. Each flight was broken down into segments and summary information compiled for each segment. These summaries have been added to the quick-look plot gallery described above. The summaries are attached to this report as Appendix A.

3.1.5 Collaborative Studies

Several collaborative studies have been completed using Citation data from C-F to address key science questions. Of particular interest were observations taken at cold

temperatures in a convective core on July 18 and those made in clear air on July 28 and July 29. The core penetration on July 18 was made at a temperature of approximately -35 °C at an altitude of 10 km. Updrafts exceeding 20 m s^{-1} were encountered along with regions of ice and supercooled liquid water droplets. These observations have led to the conclusion that in vigorous convection, heterogeneous ice nucleation processes are not sufficient to freeze all of the supercooled cloud droplets before homogenous freezing occurs (Heymsfield et al., 2004). In a separate analysis of the July 18 observations, environmental aerosol concentrations and model simulations point toward a significant role of mid-tropospheric aerosols in ice formation. Fridland et al. (2004) attribute the high concentration of small ice crystals in this cloud to the entrainment of aerosols which activate and later freeze homogeneously. This has implications for the possible effects of long-range transport of pollutants. Both studies considered the importance of homogeneous freezing to the radiative properties of anvil clouds.

The flights of July 28 and 29 encountered a layer of Saharan dust. Measurements with the CFDC by DeMott found the dust particles to act as ice nuclei, with high concentrations of >1 cm^{-3}. (DeMott et al., 2003). Observations with ground-based lidar confirmed the presence of the dust layer. Depolarization measurements of an altocumulus cloud layer indicated that the dust acted to generate ice crystals within (seed) the altocumulus at relatively warm temperatures (Sassen et al., 2004). Based on these observations it appears that the Saharan dust has similar properties and ice nucleating characteristics as Asian dust. This suggests possible large-scale climatic influences of dust with implications for changes due to anthropogenically-induced desertification.

Joint Aircraft/Radar Study

A study of the microphysical and radar properties of clouds occurring on July 16 is underway. Preliminary results were presented at the International Conference on Clouds and Precipitation in Bologna, Italy (Poellot et al. 2004).

3.2 NPOL Radar

3.2.1 Field Operations in South Florida

The NPOL radar was deployed in Southwest Florida about 10 km East of the Everglade City field site (Ochopee, Florida) near the of June. NPOL was operational on July 1 with the first day of 24 hr operations occurring on July 5. NPOL completed operations on July 29. Operational support was split between John Gerlach and PI's Kucera and Cifelli, with each PI in the field for approximately 3 weeks. Graduate and undergraduate students were invaluable in assisting in radar operations and preliminary analysis in the field. The radar operated almost continuously during this time supporting aircraft operations and collecting valuable information on the temporal evolution and three-dimensional structure of the convection observed during C-F. NPOL operated in a full-volume scan mode during the daytime hours and/or during aircraft missions and in a 3-tilt rain scan mode during all other periods. NPOL operated every day during the C-F field campaign, but had some minor antenna problems that mainly occurred during July 10-12. Intermittent air conditioning problems during the latter half of the campaign resulted in a reduced scanning mode (rain scan only) during non-critical operations.

NPOL data in general are considered high-quality. Any issues with data quality will be described in the next section.

3.2.2 Quality Control and Archival of NPOL data

A tremendous effort has gone (and is ongoing) into the quality control (QC) of the NPOL data. Several issues were identified with NPOL data during and after the field campaign. Data quality issues include: ground clutter, backlobe and sidelobe echo, wet antenna signal loss, and reflectivity calibration. Strong clutter returns occurred during strong refractive gradients periods which normally coincided with a minimum in convective activity. Strongly contaminated scans were identified by hand and flagged. The remaining dataset is being QC'ed for clutter using the standard QC algorithms developed by the NASA TRMM office.

Because of the design of the NPOL antenna, there are occurrences of false echo from sidelobe and backlobe returns. A sidelobe signature is seen as a high reflectivity circular ring center at the radar location. These scans are easily identified and were removed from the QC'ed dataset. Backlobe echo is the result of a small amount of signal being transmitted behind the reflector. A return is seen if the echo is 26 dB or higher above the minimum detectable signal. The signature of backlobe echo is a mirrored image of the strong echo (but 26 dB lower) that is located at the same range but 180° in azimuth from the original target. Backlobe echo has been difficult to remove because it 'looks' similar to weak, stratiform precipitation. Currently, we are deploying a combination of algorithms that examine the vertical structure and standard deviation of the specific differential phase to remove the backlobes.

Periods when NPOL has a wet antenna cause the signal to be reduced 10-12 dB from when the antenna is dry. We have not been able to identify a good QC correction algorithm for wet antenna. Therefore, we have removed all scans during wet antenna periods (identified by coincident rain gauge data). This removal of data is unfortunate, but results in only about 5% loss of the data.

The remaining data have been analyzed and compared with other datasets to determine the relative calibration. A comparison with the surrounding WSR-88D radars, the TRMM PR, and internal checks using the polarimetric fields indicated that NPOL had a reflectivity bias of -6.5 dB on average (Kucera and Frank 2003; Kucera et al. 2004). This reflectivity offset has been applied to the QC'ed NPOL dataset.

A version 1 QC'ed dataset is available from the UND ftp site: (ftp.aero.und.edu/public/atmos/crystal_face/npol/). This dataset only has the average reflectivity bias correction and a simple clutter rejection algorithm applied. Wet antenna and strong sidelobe scans have been removed from the QC dataset. A version 2 dataset is currently being processed that will account for the backlobe signatures, a daily reflectivity correction, ZDR bias correction, and more robust clutter algorithm correction. This dataset (considered final) will be delivered to the C-F archive by the end of December 2004.

Quicklook reflectivity products were created for every scan recorded during the C-F campaign. These scans have been archived at UND: ftp.aero.und.edu/public/atmos/crystal_face/images/ and at the C-F website in the following locations: http://espoarchive.nasa.gov/archive/arcs/crystalf/images/npol_1/, http://espoarchive.nasa.gov/archive/arcs/crystalf/images/npol_2/, http://espoarchive.nasa.gov/archive/arcs/crystalf/images/npol_3/, http://espoarchive.nasa.gov/archive/arcs/crystalf/images/npol_4/, http://espoarchive.nasa.gov/archive/arcs/crystalf/images/npol_5/.

3.2.3 Development of Polarimetrically-Tuned Rainfall Products

In close coordination with co-PI's Cifelli, Tom Rickenbach (NASA/GSFC), and Larry Carey (Texas A&M), we have created polarimetrically-tuned rainfall maps from NPOL data. Larry Carey tuned his polarimetric rainfall algorithm for the priority day of July 23. During this process, he also created pol-tuned reflectivity-rainfall (Z-R) relationships for the four surrounding WSR-88D radars (Key West, Miami, Melbourne, and Tampa Bay). Rainfall estimate were created for the five radars. In close coordination with Tom Rickenbach, rainfall maps from each radar were merged to create a composite rainfall map for South Florida. The rainfall products have a spatial resolution of 2 km and are mapped to a height of 2 km above ground. Rainfall maps were generated every 10 min. Rainfall maps were generated from each radar and merged for the remainder of the C-F campaign (July 3-29). These version 1 rainfall products are available from the UND ftp site: ftp.aero.und.edu/public/atmos/crystal_face/rainmaps/. Evaluation of the merged rainfall maps with rain gauge data for periods outside of July 23 shows a rainfall bias between radars. Most of the bias can be associated with the NPOL polarimetric rainfall algorithm. The amount of data used for the tuning was relatively small, which resulted in a large uncertainty in the rainfall algorithm, especially at the higher rainfall rates. Also, because of the remaining QC issues mentioned above, there is a larger the normal uncertainty in the rainfall maps. These issues are being addressed in the remaining QC work. It is anticipated that a version 2 (final) QC'ed rainfall product will be delivered to the C-F archive at the same time or shortly after the delivery of the QC'ed NPOL data in December 2004.

3.2.4 Hydrometeor Signature Studies

This task is the most complete of the proposed tasks. The main reason is the unanticipated extra effort involved in QC'ing NPOL data and the creation of the merged C-F radar rainfall products. However, microphysical comparisons have started with the initial radar/Citation comparison for the July 16 priority case, which was presented at the International Conference on Clouds and Precipitation in Bologna, Italy (Poellot et al. 2004). This work is currently being expanded to compare bulk microphysical properties to the in situ measurements from the Citation for July 16 and other priority cases on July 7, 9, 19, 21, and 23). This work will continue into Fall coincident with the final NPOL QC activities.

3.2.5 Collaborative Studies

There have been several ongoing studies outside the main tasks proposed in this work. There currently is a mesoscale modeling study underway in collaboration with Sue

van den Heever (CSU) that was initiated from detailed study of observed gust fronts during C-F (Frank and Kucera 2003). In an effort to study the evolution of convection and associated cirrus anvil, a study is underway to track cloud elements using both NPOL and available satellite data using a correlation tracking technique. A preliminary study for the July 16 priority day was presented at the Fall 2003 AGU meeting (Kucera et al. 2003). Another study was conducted to examine nitrogen generation from lightning discharge in thunderstorms observed by NPOL and EDOP during C-F (Ridley et al. 2004). Finally, there are ongoing research activities examining the characteristics of convection during C-F with NPOL and other independent datasets (Heymsfield and Belcher (NASA/GSFC), Tao and Lang (NASA/GSFC), and Zipser and Li (U of Utah)).

4.0 Publications

DeMott, P.J., K. Sassen, M. Poellot, D. Baumgardner, D.C. Rogers , S. Brooks, A.J. Prenni and S.M. Kreidenweis, 2003: African dust aerosols as atmospheric ice nuclei. *Geophysical Research Letters.* **30**, No. 14, 1732, doi:10.1029/2003GL017410

Frank, P. J. and P. A. Kucera, 2003: Radar characteristics of convection along colliding outflow boundaries observed during CRYSTAL-FACE. Preprints, *31st International Conference on Radar Meteorology, Seattle, Washington.*

Fridlind, A., A. Ackerman et al., 2004: Evidence for the predominance of mid-tropospheric aerosols as subtropical anvil cloud nuclei. *Science*, **34**, 718-722.

Heymsfield, A., L. Miloshevich, C. Schmitt, A. Bansemer, C. Twohy, M. Poellot and A. Fridlind, 2004: Homogeneous Ice Nucleation in Tropical Convection and its Influence on Cirrus Anvil Microphysics. accepted for publication, *J. Atmos. Sci.*

Heymsfield, A., A. Bansemer, C. Schmitt, C. Twohy and M. Poellot, 2004: Effective ice particle densities derived from aircraft data. *J. Atmos. Sci.*

Kucera, P. A., P. J. Frank, and A. J. Newman, 2004: Calibration comparisons between the TRMM PR and ground-based radars in South Florida. J. Appl. Meteor., (in preparation).

Kucera, P. A. and P. J. Frank, 2003: Comparison of echo characteristics observed during CAMEX4 and CRYSTAL-FACE. Preprints, Preprints, *31st International Conference on Radar Meteorology, Seattle, Washington.*

Kucera, P. A., P. J. Frank, and T. Williams, 2003: Tracking convective systems in south Florida: Source of cirrus anvils. *Fall 2003 AGU Meeting*, San Francisco, CA.

Phillips, V., S. Sherwood et al., 2004: Anvil glaciation in a deep cumulus updraft over Florida simulated with an explicit microphysics model. Part I – the impact of various nucleation processes. submitted to Quarterly Journal of the Royal Meteorological Society

Poellot, M., P. A. Kucera, A. Heymsfield, C. Twohy, H. Gerber, and C. Theisen, 2004: A case study of tropical cirrus anvil microphysics from CRYSTAL-FACE. Preprints, *14th International Conference on Clouds and Precipitation*, Bologna, Italy, July 2004.

Ridley, B., L. Ott, K. Pickering, L. Emmons, D. Montzka, A. Weinheimer, D. Knapp, F. Grahek, L. Li, G. Heymsfield, M. McGill, P. A. Kucera, M. J. Mahoney, D. Baumgardner, M. Schultz, and G. Brasseur, 2004: Florida Thunderstorms: A Faucet of Reactive Nitrogen to the Upper Troposphere. *J. Geophys. Res.* (*In Press*).

Sassen, K., P.J. DeMott, J. Prospero, and M. Poellot, 2003: Saharan dust storms and indirect aerosol effects on clouds: CRYSTAL-FACE results. *Geophys. Res. Lett.*, Vol 30, No. 12, 1633,

Table 1. Citation Instrumentation Suite

Instrument	Parameter	Investigator
CFDC	Ice nuclei concentrations, filter samples	DeMott (Colorado State) Rogers (NCAR)
CVI	Ice mass, residual particles	Twohy (Oregon State)
CIN	Mass extinction	Gerber (Gerber Scientific)
CPI	Cloud particle images	Heymsfield (NCAR)
HVPS	Precipitation particle images	Heymsfield (NCAR)
FSSP	Cloud droplet sizes	Poellot
PMS 2D-C	Cloud particle images	Poellot
CNC	Condensation nuclei concentrations	Poellot
TDL H2O	Water vapor concentration	Poellot
King, Rosemount	Supercooled liquid water	Poellot
State Parameters	Temperature, Pressure, Dew/Frost Point	Poellot
Winds	u, v, w, turbulence	Poellot
Aircraft Parameters	Position, Orientation, Motion	Poellot

Table 2. Citation Mission Summary

Date	Takeoff (UTC)	Land (UTC)	*Hours*	Comments
July 3	171444	211650	4.0	Steps and spirals
July 7	175842	214245	3.7	Steps and spirals; dense cirrus
July 9	175517	214935	3.9	Steps over east and west sites. Mixed phase over west site
July 11	142548	165155	2.5	Altostratus, Terra overpass
July 11	180651	221418	4.1	Anvil steps
July 16	183744	225329	4.2	Spirals, steps in anvils
July 18	165043	203043	3.7	Ice nucleation, anvil spiral
July 19	183648	224621	4.2	Anvil steps, spiral
July 21	183500	224852	4.2	Anvil steps, spiral
July 23	185225	232229	4.5	Anvil steps, spirals
July 25	150449	193147	4.5	Steps and spirals; samples over sites
July 26	202909	235643	3.5	Melting layer spiral descents
July 28	193833	220733	2.5	Growing tower samples; dust on descent
July 29	171101	212418	4.2	Anvil steps, spiral; dust on descent

Appendix A
Mission Summaries

Project Crystal-Face
July 3, 2002 – July 29, 2002
Citation Flight Summaries

Notes

Segment: A section of the flight where relevant samples where taken.

Three different types of segments:
1) Sample Line
2) Spiral (up or down)
3) Step Climbs (ascending or descending)

Leg: The level sections of a step climb where relevant samples where taken.

Cloud Region: The cloud or area of clouds where the sample was taken from.

Cloud regions are numbered and segments with same cloud region numbers indicate that those segments are in the same cloud region. If NC is shown in the cloud region column it indicates that there were no clouds present.

Parameters: Six different parameters included in the summaries:
1) **Temperature** given in degrees Celsius
2) **Frost Point** given in degrees Celsius
3) **Wind Direction** given in degrees
4) **Wind Speed** given in meters per second
5) **2-DC Concentration** given in number per liter
6) **Maximum 2-DC Concentration** given in number per liter
7) **2-DC Median Volume Diameter** given in microns

Values for each parameter are averaged over the segment or leg if the segment type is a step climb.

The temperature and frost point values are given as a range of the lowest to highest temperature for spiral types of segments.

The frost point parameter is measured by the laser hygrometer, unless other wise noted.

During a spiral type segment there is no valid wind

speed or direction.

Additional notes pertaining to specific flights are given on the spreadsheets.

Flight Summary

(Flights broken up into segments, step climbs broken down further into individual legs)
(All parameters are averaged over the segment time.)

Date: 7/3/02

Segment	Type	Leg	Begin Time (hr:min:sec)	End Time (hr:min:sec)	Begin Altitude (meters)	End Altitude (meters)	Cloud Region
1	Sample Line		17:39:35	17:56:39	9276	9276	1
2	Sample Line		18:00:34	18:08:52	9901	9901	1
3	Sample Line		18:12:14	18:17:00	9916	9916	2
4	Spiral Down		18:17:02	18:34:36	9910	7698	2
5	Spiral Up		18:34:37	18:49:47	7705	10548	2
6	Spiral Down		18:49:48	19:12:34	10547	7687	2
7	Sample Line		19:12:35	19:19:28	7691	7691	2
8	Step Climb (ascending)	1	19:25:00	19:54:01	9285	9285	2

Note: Values of zero were left out of the averages for the 2-DC parameters.

Segment	Type	Leg	Temperature (°C)	Frost Point (°C)	Wind Direction (Degrees)	Wind Speed (M/Sec)	Max. 2-DC Concentration (#/l)	2-DC Concentration (#/l)	2-DC MEVD (Microns)
1	Sample Line		-32	-33	282	5	290	17	352
2	Sample Line		-38	-40	324	7	722	69	223
3	Sample Line		-37	-37	268	8	796	175	310
4	Spiral Down		-37 to -21	-37 to -20	-	-	312	39	426
5	Spiral Up		-21 to -43	-21 to -43	-	-	318	49	318
6	Spiral Down		-43 to -14	-43 to -21	-	-	174	20	880
7	Sample Line		-15	-22	305	8	12	7	473
8	Step Climb (ascending)	1	-25	-35	298	6	12	2	383

Flight Summary

(Flights broken up into segments, step climbs broken down further into individual legs)
(All parameters are averaged over segment time.)

Date: 7/7/02

Segment	Type	Leg	Begin Time (hr:min:sec)	End Time (hr:min:sec)	Begin Altitude (meters)	End Altitude (meters)	Cloud Region
1	Step Climb (ascending)	1	18:34:44	18:57:41	8820	8820	1
		2	19:00:20	19:10:30	9421	9421	1
		3	19:14:08	19:22:30	10048	10048	1
		4	19:26:46	19:42:00	10662	10662	1
2	Sample Line		19:44:01	19:55:00	10656	10656	1
3	Sample Line		19:59:00	20:05:48	10652	10652	1
4	Spiral Down		20:06:49	20:24:30	10651	5781	1
5	Sample Line		20:24:31	20:29:04	5783	5783	1
6	Spiral Down		20:29:05	20:36:44	5778	3921	1
7	Spiral Up		20:36:45	20:57:58	3922	10055	1
8	Level Circle		20:57:59	21:19:02	10048	10048	1

Note: Used chilled mirror hygrometer for frost point temperature.

Note: * indicates a problem with the instrument and data is not averaged over entire time span.

Note: Values of zero were left out of the averages for the 2-DC parameters.

Segment	Type	Leg	Temperature (°C)	Frost Point (°C)	Wind Direction (Degrees)	Wind Speed (M/Sec)	Max. 2-DC Concentration (#/l)	2-DC Concentration (#/l)	2-DC MEVD (Microns)
1	Step Climb (ascending)	1	-28	-30	117*	5*	1598	221	417
		2	-34	-35	84*	15*	585	79	301
		3	-40	-41	188*	5*	516	40	267
		4	-45	-46	90*	7*	361	45	313
2	Sample Line		-45	-46	155	4	277	33	286
3	Sample Line		-45	-46	102	3	108	46	417
4	Spiral Down		-45 to -8	-47 to -10	-	-	150	55	445
5	Sample Line		-8	-9	114	5	181	53	535
6	Spiral Down		-8 to 2	-10 to -1	-	-	176	29	406
7	Spiral Up		2 to -40	-1 to -41	-	-	110	5	321
8	Level Circle		-40	-41	-	-	170	21	478

Flight Summary

(Flights broken up into segments, step climbs broken down further into individual legs)
(All parameters are averaged over segment time.)

Date: 7/11/02
Flight One

Segment	Type	Leg	Begin Time (hr:min:sec)	End Time (hr:min:sec)	Begin Altitude (meters)	End Altitude (meters)	Cloud Region
1	Step Climb (descending)	1	14:39:50	14:51:32	7310	7310	NC
		2	15:03:45	15:12:12	6090	6090	1
		3	15:15:59	15:27:56	5792	5792	1
2	Spiral Up		15:27:59	15:52:26	5791	9450	1
		1	15:31:33	15:35:03	7000	7000	1
		2	15:44:43	15:52:25	9445	9445	NC
3	Ascending Line		15:52:27	16:01:28	9452	10656	NC
4	Descending Line		16:01:29	16:11:56	10655	6390	NC
5	Sample Line		16:11:57	16:30:50	6395	6395	2

Note: Values of zero were left out of the averagaes for the 2-DC parameters.

Note: Used chilled mirror hygrometer for frost point temperature.

Note: Segment 2 is a spiral with two defined level spiraling legs

Segment	Type	Leg	Temperature (°C)	Frost Point (°C)	Wind Direction (Degrees)	Wind Speed (Knots)	Max. 2-DC Concentration (#/l)	2-DC Concentration (#/l)	2-DC MEVD (Microns)
1	Step Climb (desending)	1	-17	-18	228	4	0	0	0
		2	-9	-10	236	5	18	.5	348
		3	-8	-8	243	5	29	.8	289
2	Spiral Up		-7 to -34	-8 to -44	-	-	26	3	109
		1	-15	-16	-	-	26	3	109
		2	-34	-43	-	-	0	0	0
3	Ascending Line		-34 to -45	-44 to -50	136	3	0	0	0
4	Descending Line		-45 to -12	-50 to -12	102	4	0	0	0
5	Sample Line		-11	-12	237	3	7	3	178

Flight Summary

(Flights broken up into segments, step climbs broken down further into individual legs)
(All parameters are averaged over segment time.)

Date: 7/11/02
Flight Two

Segment	Type	Leg	Begin Time (hr:min:sec)	End Time (hr:min:sec)	Begin Altitude (meters)	End Altitude (meters)	Cloud Region
1	Step Climb	1	18:41:01	19:20:25	8825	8825	1
	(ascending)	2	19:23:42	19:52:55	9424	9424	1
		3	19:56:34	20:05:05	10034	10034	1
		4	20:08:31	20:15:52	10650	10650	1
		5	20:21:23	20:30:14	11256	11256	1
		6	20:31:46	20:41:14	11550	11550	1
		7	20:43:30	20:54:12	11847	11847	1
		8	20:56:14	21:06:51	12146	12146	1
		9	21:08:20	21:10:57	12444	12444	1
	?	*10*	*21:12:05*	*21:13:47*	*25940*	*25940*	*NC*
		11	21:13:48	21:21:08	12440	12440	1
		12	21:29:00	21:44:02	12750	12750	1
2	Spiral Down		21:44:03	22:05:25	12744	4013	1

Note: * indicates a problem with the instrument and data is not averaged over entire time span.

Note: Values of zero were left out of the averagaes for the 2-DC parameters.

Note: Used chilled mirror hygrometer for frost point temperature.

Note: Had problems with instruments during leg 10 of segment 1.

Segment	Type	Leg	Temperature (°C)	Frost Point (°C)	Wind Direction (Degrees)	Wind Speed (M/Sec)	Max. 2-DC Concentration (#/l)	2-DC Concentration (#/l)	2-DC MEVD (Microns)
1	Step Climb	1	-29	-32	185	4	97	3	321
	(ascending)	2	-34	-36	194	3	418	7	345
		3	-39	-40	181	2	127	35	412
		4	-44	-45	100	3	100	37	381
		5	-49	-51	80	4	155	44	274
		6	-52	-53	65	5	139	36	216
		7	-55	-56	53	4	148	30	166
		8	-57	-59	55	8	80	19	196
		9	-60	-60	64	6	27	4	123
	?	*10*	*-120*	*-61*	*58*	*6*	*0*	*0*	*0*
		11	-60	-61	67	7	21	1	102
		12	-62	-63	70	7*	78	2	103
2	Spiral Down		-62 to 3	-63 to -8	-	-	70	5	144

Flight Summary

(Flights broken up into segments, step climbs broken down further into individual legs)
(All parameters are averaged over segment time.)

Date: 7/16/02

Segment	Type	Leg	Begin Time (hr:min:sec)	End Time (hr:min:sec)	Begin Altitude (meters)	End Altitude (meters)	Cloud Region
1	Sample Line		19:01:47	19:07:02	8218	8218	NC
2	Spiral Up		19:07:03	19:20:33	8224	10002	NC
3	Spiral Down		19:20:34	19:33:09	9999	8235	1
4	Spiral Up		19:33:10	19:57:59	8236	10670	1
5	Step Climb (ascending)	1	19:58:00	20:16:23	10650	10650	2
		2	20:18:46	20:27:37	10950	10950	2
		3	20:29:02	21:16:45	11245	11245	2
6	Step Climb (descending)	1	21:19:17	21:27:08	10652	10652	2
		2	21:30:44	21:40:57	10040	10040	2
		3	21:43:53	21:52:35	9435	9435	2
		4	21:57:25	22:08:02	8830	8830	2
		5	22:12:01	22:19:59	8230	8230	2
		6	22:23:56	22:33:54	7616	7616	2

Note: * indicates a problem with the instrument and data is not averaged over entire time span.

Note: Values of zero were left out of the averagaes for the 2-DC parameters.

Segment	Type	Leg	Temperature (°C)	Frost Point (°C)	Wind Direction (Degrees)	Wind Speed (M/Sec)	Max. 2-DC Concentration (#/l)	2-DC Concentration (#/l)	2-DC MEVD (Microns)
1	Sample Line		-23	-50	73	12	0	0	0
2	Spiral Up		-23 to -38	-54 to -39	-	-	0	0	0
3	Spiral Down		-38 to -24	-38 to -52	-	-	102	3	334
4	Spiral Up		-24 to -44	-50 to -45	-	-	104	14	260
5	Step Climb (ascending)	1	-44	-49	80	16	433	11	194
		2	-46	-48	78	17	437	13	174
		3	-49	-51	83	15	1472	92	395
6	Step Climb (descending)	1	-44	-45	No Data	No Data	250	112	455
		2	-39	-40	No Data	No Data	173	83	450
		3	-34	-35	62*	12*	199	48	341
		4	-29	-30	89*	13*	147	63	449
		5	-24	-25	67	14	130	28	445
		6	-19	-25	55	10	62	5	448

Flight Summary

(Flights broken up into segments, step climbs broken down further into individual legs)
(All parameters are averaged over segment time.)

Date: 7/18/02

Segment	Type	Leg	Begin Time (hr:min:sec)	End Time (hr:min:sec)	Begin Altitude (meters)	End Altitude (meters)	Cloud Region
1	Step Climb (ascending)	1	17:08:19	17:36:49	7615	7615	1
		2	17:45:02	18:07:27	9458	9458	2
		3	18:11:17	18:36:52	10070	10070	2
2	Spiral Down		18:36:53	19:07:41	10065	4854	1
3	Spiral Up		19:07:42	19:11:00	4855	5907	1
4	Step Climb (ascending)	1	19:15:42	19:20:39	7625	7625	3
		2	19:28:06	19:34:35	9460	9460	3
		3	19:38:08	19:40:56	10080	10080	3
		4	19:45:27	19:49:29	10695	10695	3
5	Sample Line		19:51:34	20:04:31	10080	10080	3

Note: Values of zero were left out of the averagaes for the 2-DC parameters.

Segment	Type	Leg	Temperature (°C)	Frost Point (°C)	Wind Direction (Degrees)	Wind Speed (M/Sec)	Max. 2-DC Concentration (#/l)	2-DC Concentration (#/l)	2-DC MEVD (Microns)
1	Step Climb (ascending)	1	-20	-25	110	10	1238	19	303
		2	-34	-39	201	12	6440	83	274
		3	-39	-43	165	13	671	86	294
2	Spiral Down		-39 to -1	-40 to -8	-	-	348	8	327
3	Spiral Up		-1 to -8	-8 to -11	-	-	32	3	214
4	Step Climb (ascending)	1	-20	-25	227	8	746	38	270
		2	-33	-43	181	11	1443	680	363
		3	-39	-50	90	14	1417	185	305
		4	-44	-55	102	14	939	510	337
5	Sample Line		-39	-50	155	12	910	107	374

Flight Summary

(Flights broken up into segments, step climbs broken down further into individual legs)
(All parameters are averaged over segment time.)

Date: 7/19/02

Segment	Type	Leg	Begin Time (hr:min:sec)	End Time (hr:min:sec)	Begin Altitude (meters)	End Altitude (meters)	Cloud Region
1	Step Climb (ascending)	1	18:56:49	19:05:18	7612	7612	NC
		2	19:08:01	19:16:57	8223	8223	1
		3	19:19:27	19:25:14	8835	8835	1
		4	19:29:55	19:46:19	9440	9440	1
		5	19:48:20	19:58:19	10045	10045	1
		6	20:01:42	21:02:55	10668	10668	2
2	Step Climb (descending)	1	21:05:56	21:17:17	10060	10060	2
		2	21:20:38	21:29:06	9450	9450	2
		3	21:32:43	21:41:46	8843	8843	2
		4	21:44:09	21:54:21	8234	8234	2
		5	21:57:46	22:04:30	7626	7626	2
3	Spiral Up		22:04:31	22:22:00	7630	10670	2

Note: Values of zero were left out of the averagaes for the 2-DC parameters.

Segment	Type	Leg	Temperature (°C)	Frost Point (°C)	Wind Direction (Degrees)	Wind Speed (M/Sec)	Max. 2-DC Concentration (#/l)	2-DC Concentration (#/l)	2-DC MEVD (Microns)
1	Step Climb (ascending)	1	-22	-22	99	5	0	0	0
		2	-26	-26	89	6	28	10	237
		3	-30	-32	115	4	.03	.03	194
		4	-35	-37	101	6	71	14	297
		5	-41	-43	69	6	109	39	297
		6	-46	-49	63	10	663	75	308
2	Step Climb (descending)	1	-41	-42	85	6	351	84	382
		2	-35	-39	63	4	138	43	470
		3	-30	-32	112	3	264	46	441
		4	-26	-27	140	4	166	18	432
		5	-22	-23	184	4	56	12	378
3	Spiral Up		-22 to -45	-23 to -47	-	-	742	172	374

Flight Summary

(Flights broken up into segments, step climbs broken down further into individual legs)
(All parameters are averaged over segment time.)

Date: 7/21/02

Segment	Type	Leg	Begin Time (hr:min:sec)	End Time (hr:min:sec)	Begin Altitude (meters)	End Altitude (meters)	Cloud Region
1	Step Climb (ascending)	1	18:52:00	19:14:09	7615	7615	1
		2	19:17:02	19:23:38	8223	8223	1
2	Spiral Up		19:23:39	19:40:21	8223	10674	1
3	Step Climb (descending)	1	19:40:22	20:02:52	10680	10680	1
		2	20:05:55	20:19:03	10066	10066	1
		3	20:21:37	20:48:21	9448	9448	1
4	Step Climb (ascending)	1	20:49:00	20:57:05	9744	9744	1
		2	20:58:42	21:14:05	10048	10048	1
		3	21:17:39	21:41:48	10660	10660	1
5	Wide Circle		21:50:12	22:00:59	11867	11867	1
6	Sample Line		22:01:00	22:18:52	11867	11867	1

Note: Values of zero were left out of the averagaes for the 2-DC parameters.

Segment	Type	Leg	Temperature (°C)	Frost Point (°C)	Wind Direction (Degrees)	Wind Speed (M/Sec)	Max. 2-DC Concentration (#/l)	2-DC Concentration (#/l)	2-DC MEVD (Microns)
1	Step Climb (ascending)	1	-21	-21	282	4	15	3	285
		2	-24	-26	199	2	16	2	309
2	Sprial Up		-25 to -44	-26 to -46	-	-	177	48	406
3	Step Climb (descending)	1	-44	-46	34	7	122	33	380
		2	-39	-43	44	6	90	39	278
		3	-34	-37	138	5	71	10	330
4	Step Climb (ascending)	1	-36	-38	32	7	81	39	256
		2	-39	-45	33	6	95	18	240
		3	-44	-50	49	9	49	7	144
5	Wide Circle		-54	-60	40	13	3	1	110
6	Sample Line		-54	-59	39	10	70	28	352

Flight Summary

(Flights broken up into segments, step climbs broken down further into individual legs)
(All parameters are averaged over segment time.)

Date: 7/23/02

Segment	Type	Leg	Begin Time (hr:min:sec)	End Time (hr:min:sec)	Begin Altitude (meters)	End Altitude (meters)	Cloud Region
1	Step Climb (ascending)	1	19:27:28	19:31:11	9450	9450	NC
		2	19:34:40	19:45:51	10062	10062	1
		3	19:48:58	19:55:40	10684	10684	1
		4	19:58:24	20:06:16	10985	10985	1
		5	20:10:30	20:18:22	11276	11276	1
2	Step Climb (descending)	1	20:20:26	20:42:20	10996	10996	1
		2	20:44:01	21:01:46	10698	10698	1
		3	21:09:54	21:21:32	9769	9769	1
		4	21:24:24	21:30:30	9159	9159	1
		5	21:33:40	21:39:07	8850	8850	1
3	Spiral Up		21:39:08	21:53:35	8854	11293	1
4	Step Climb (ascending)	1	21:53:36	22:00:29	11290	11290	1
		2	22:05:02	22:23:40	11894	11894	1
5	Spiral Down		22:23:41	22:52:22	11890	7316	1

Note: Values of zero were left out of the averagaes for the 2-DC parameters.

Segment	Type	Leg	Temperature (°C)	Frost Point (°C)	Wind Direction (Degrees)	Wind Speed (M/Sec)	Max. 2-DC Concentration (#/l)	2-DC Concentration (#/l)	2-DC MEVD (Microns)
1	Step Climb (ascending)	1	-35	-37	13	7	0	0	0
		2	-40	-43	20	12	0.8	.2	496
		3	-45	-47	28	11	42	6	293
		4	-48	-51	38	14	141	34	211
		5	-50	-55	40	12	109	31	162
2	Step Climb (descending)	1	-48	-51	42	13	104	28	221
		2	-45	-47	34	12	1383	72	268
		3	-38	-39	48	9	412	49	313
		4	-33	-34	65	6	73	11	320
		5	-30	-33	31	6	20	3	267
3	Spiral Up		-30 to -50	-33 to -54	-	-	93	13	226
4	Step Climb (ascending)	1	-50	-56	31	11	2	1	81
		2	-55	-60	25	17	79	16	187
5	Sprial Down		-55 to -18	-60 to -19	-	-	193	15	261

Flight Summary

(Flights broken up into segments, step climbs broken down further into individual legs)
(All parameters are averged over segment time.)

Date: 7/25/02

Segment	Type	Leg	Begin Time (hr:min:sec)	End Time (hr:min:sec)	Begin Altitude (meters)	End Altitude (meters)	Cloud Region
1	Step Climb (ascending)	1	15:31:45	15:39:35	9384	9384	1
		2	15:45:05	15:48:08	9990	9990	1
		3	15:48:19	16:07:42	10045	10045	1
		4	16:11:01	16:20:40	10656	10656	1
2	Step Climb (ascending)	1	16:24:00	16:58:49	10045	10045	1
		2	17:02:03	17:09:09	10640	10640	2
		3	17:13:06	17:19:58	11234	11234	2
3	Step Climb (descending)	1	17:26:16	17:39:28	11835	11835	2
		2	17:46:36	17:53:28	9428	9428	2
4	Spiral Up		17:57:42	18:15:53	8207	11237	2
5	Sample Line		18:15:53	18:49:13	11230	11230	2
6	Spiral Down		18:49:14	19:13:20	11232	7095	3

Note: Values of zero were left out of the averagaes for the 2-DC parameters.

Segment	Type	Leg	Temperature (°C)	Frost Point (°C)	Wind Direction (Degrees)	Wind Speed (M/Sec)	Max. 2-DC Concentration (#/l)	2-DC Concentration (#/l)	2-DC MEVD (Microns)
1	Step Climb (ascending)	1	-34	-35	182	8	195	31	297
		2	-39	-41	180	8	205	45	315
		3	-40	-44	184	8	174	52	356
		4	-45	-48	192	5	481	67	250
2	Step Climb (ascending)	1	-40	-45	173	7	362	27	245
		2	-45	-51	201	5	51	9	272
		3	-51	-58	184	11	98	15	205
3	Step Climb (descending)	1	-56	-60	194	7	68	18	140
		2	-35	-36	180	5	199	39	311
4	Spiral Up		-25 to -50	-30 to -57	-	-	125	38	216
5	Sample Line		-51	-55	141	6	64	21	165
6	Spiral Down		-51 to -17	-54 to -18	-	-	90	31	391

Flight Summary

(Flights broken up into segments, step climbs broken down further into individual legs)
(All parameters are averaged over segment time.)

Date: 7/26/02

Segment	Type	Leg	Begin Time (hr:min:sec)	End Time (hr:min:sec)	Begin Altitude (meters)	End Altitude (meters)	Cloud Region
1	Sample Line		20:40:44	21:24:16	6383	6383	1
2	Spiral Down		21:24:17	21:52:53	6378	2991	1
3	Spiral Up .		21:52:54	22:09:28	2992	6385	1
4	Spiral Down		22:09:29	22:37:19	6384	3005	1
5	Spiral Up		22:37:20	22:51:33	3006	6335	1
6	Spiral Down		22:51:34	23:19:08	6334	3295	1
7	Sample Line		23:19:09	23:34:49	3297	3297	1

Note: Values of zero were left out of the averagaes for the 2-DC parameters.

Segment	Type	Leg	Temperature (°C)	Frost Point (°C)	Wind Direction (Degrees)	Wind Speed (M/Sec)	Max. 2-DC Concentration (#/l)	2-DC Concentration (#/l)	2-DC MEVD (Microns)
1	Sample Line		-10	-19	149	5	285	40	445
2	Spiral Down		-11 to 10	-13 to -1	-	-	1027	43	405
3	Spiral Up		10 to -11	-1 to -13	-	-	382	69	487
4	Spiral Down		-11 to 10	-13 to 0	-	-	594	55	457
5	Spiral Up		10 to -10	0 to -12	-	-	203	41	498
6	Spiral Down		-10 to 8	-12 to -2	-	-	177	30	459
7	Sample Line		8	-2	122	5	4	.3	716

Flight Summary

(Flights broken up into segments, step climbs broken down further into individual legs)
(All parameters are averaged over segment time.)

Date: 7/28/02

Segment	Type	Leg	Begin Time (hr:min:sec)	End Time (hr:min:sec)	Begin Altitude (meters)	End Altitude (meters)	Cloud Region
1	Step Climb (ascending)	1	20:01:45	20:10:48	8840	8840	1
		2	20:15:06	20:17:34	9450	9450	1
		3	20:21:43	20:32:12	10055	10055	2
2	Step Climb (ascending)	1	20:34:48	20:45:47	8854	8854	2
		2	20:48:48	21:39:57	9445	9445	2
3	Sample Line		21:42:01	21:47:31	8846	8846	NC
4	Spiral Down		21:47:32	21:54:20	8842	5997	3

Note: Values of zero were left out of the averagaes for the 2-DC parameters.

Segment	Type	Leg	Temperature (°C)	Frost Point (°C)	Wind Direction (Degrees)	Wind Speed (M/Sec)	Max. 2-DC Concentration (#/l)	2-DC Concentration (#/l)	2-DC MEVD (Microns)
1	Step Climb (ascending)	1	-30	-38	71	13	1869	364	420
		2	-34	-37	57	20	111	27	443
		3	-39	-49	51	17	245	68	449
2	Step Climb (ascending)	1	-30	-36	65	20	1506	292	478
		2	-34	-47	56	20	227	57	455
3	Sample Line		-31	-38	63	18	0	0	0
4	Spiral Down		-30 to -9	-37 to -29	-	-	17	4	473

Flight Summary

(Flights broken up into segments, step climbs broken down further into individual legs)

(All parameters are averaged over segment time.)

Date: 7/29/02

Segment	Type	Leg	Begin Time (hr:min:sec)	End Time (hr:min:sec)	Begin Altitude (meters)	End Altitude (meters)	Cloud Region
1	Step Climb (ascending)	1	17:27:07	17:59:36	7615	7615	1
		2	18:02:46	18:11:59	8226	8226	1
		3	18:15:20	18:30:37	8825	8825	1
		4	18:33:41	18:51:11	9428	9428	1
		5	18:54:52	19:31:58	10042	10042	1
		6	19:36:29	19:45:32	10648	10648	1
		7	19:49:30	20:01:00	11246	11246	1
2	Level Spiral		20:01:01	20:14:41	11242	11242	NC
3	Sample Line		20:14:42	20:20:22	11239	11239	1
4	Spiral Down		20:20:23	20:37:25	11239	7623	1

Note: Used dew point temperature in place of frost point temperature.

Note: * indicates a problem with the instrument and data is not averaged over entire time span.

Note: Values of zero were left out of the averagaes for the 2-DC parameters.

Segment	Type	Leg	Temperature (°C)	Frost Point (°C)	Wind Direction (Degrees)	Wind Speed (M/Sec)	Max. 2-DC Concentration (#/l)	2-DC Concentration (#/l)	2-DC MEVD (Microns)
1	Step Climb (ascending)	1	-21	-27	106	14	1501	319	440
		2	-26	-28	109	13	2332	468	434
		3	-30	-33	85	13	1283	269	451
		4	-36	-40	114	13	1934	394	432
		5	-41	-42	99*	18*	1849	328	418
		6	-45	-45	No Data	No Data	623	243	455
		7	-51	-51	No Data	No Data	991	317	461
2	Level Spiral		-50	-54	-	-	0	0	0
3	Sample Line		-50	-53	98	18	409	129	483
4	Spiral Down		-50 to -21	-51 to -22	-	-	2068	158	474