Kingdom of Saudi Arabia
Assessment of Rainfall Augmentation

2009 Spring Field Season

Final Report

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Through

Weather Modification Inc.

Fargo, North Dakota, USA

David Delene, Michael Poellot, Cedric Grainger, and Jeffrey Tilley

University of North Dakota

Grand Forks, North Dakota, USA

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Executive Summary

Instrument performance was very good during the spring 2009 IOP conducted in Riyadh, Saudi Arabia. Very good instrument performance combined with cloudy weather during the IOP resulted in excellent data being collected. Quality assurance of the spring 2009 IOP data has been finished. The results for the spring 2009 program are summarized below.

- Training during the spring IOP included 3 days of lectures by Dr. Jeffrey Tilley and 34 training activities by Dr. David Delene.
- The inlet test flight indicates that the side window location is a clean sampling location and free of engine exhaust contamination.
- Atmospheric sampling of the seeding plume indicates that 1 μm diameter concentration within a hygroscopic flare plume is similar to concentrations measured within the boundary layer in Saudi Arabia.
- The PCASP measurements in Saudi Arabia indicate that the accumulation mode aerosol size distribution is typically very broad. High CCN concentrations were often observed in below cloud base regions (e.g. 9 April 2009).
- The observations made on 9 April 2009 are very unique and should allow for an interesting modeling study to be conducted testing our understanding of the precipitation formation process in Saudi Arabia.
- While there exists super-cooled liquid water in clouds in the Riyadh region during spring time convection, observations like the 2 April 2009 case show a robust natural ice precipitation formation process and a warm rain process was only evident in the 9 and 12 April measurements.

Recommendations for future spring time field projects in Riyadh include the follow:

- A week of testing by scientists before the start of aircraft measurement flights.
- Restricting training during the IOP to aircraft flight debriefings and conduct lectures at a different time period.
- Continue to conduct weekly quality control measurements of all research instruments and conduct a cloud droplet sizing check before each cloud sampling flight.
- When possible, obtain aircraft vertical profiles in the morning before convection starts to enable improved convection modeling.
- Aircraft sampling should focus on below cloud CCN and updraft measurements, and vertical profiling of the cloud droplet size distribution.
- Focus on improving the AIMMS vertical wind measurements.

Introduction

The University of North Dakota worked with Weather Modification Inc. to conduct a research project to study precipitation formation in Saudi Arabia during 2009. An Intensive Operational Period (IOP), 15 March 2009 through 14 April 2009 was conducted in Saudi Arabia to obtain aircraft measurements of aerosol and cloud properties. The aircraft flight measurements conducted are summarized, quality control procedures conducted during the IOP are described, the methodology used for data quality assurance is described, and results of the scientific analysis presented. This report begins with a summary of the training of Saudi Arabia personnel that was conducted during the project.

Training Activities

Many training activities were conducted during the spring 2009 IOP. Dr. Jeffrey Tilley, from the University of North Dakota, conducted 3 days of lectures (11, 12, and 13 April). Lecture topics and dates were defined and scheduled a month ahead of time. In addition to lectures, Dr. Tilley worked closely with local scientists using their installation of the Weather and Research Forecasting (WRF) model. Topics coved by Dr. Tilley's lectures included the following:

- Microphysics Schemes Available in WRF and their Limitations
- Current Land Surface and Planetary Boundary Layer Schemes for Deserts
- Using Emerging Radar Technologies for Data Assimilation
- Simulation of Severe Convection at High Resolution (<1 km)
- Verification and Validation Techniques

Dr. David Delene conducted a total of 34 training activities during the spring 2009 IOP. These activities included local personnel taking part in research flights, tour of the research aircraft (Figure 1), discussions of scientific analysis of previous field project measurements, hands-on training on using software programs to process and analyze aircraft data, and eight debriefings of research flights conducted during the spring 2009 IOP. Preliminary data analysis was presented and discussed at these debriefings. Many debriefings included valuable information for weather modification pilots such as pictures and videos of clouds and corresponding measurements such as liquid water content. Robust software allowed data to be processed and analyzed after research flights and presented during a debriefing on the following day. The complete source code of the data processing software was set up on a local computer system and the University of North Dakota's 'cplot' analysis software was installed locally and demonstrated by Dr. Delene. Raw and processed data were downloaded to a local computer shortly after each flight, with a complete preliminary data set uploaded at the end of the IOP.

Figure 1: Dr. Yasser Hamed Khallaf Al-Ghifari taking a picture of the left pylon on the King Air 200 research aircraft during a tour conducted during the spring 2009 Intensive Operational Period (IOP) in Riyadh, Saudi Arabia.

As part of the National Center of Atmospheric Research (NCAR) program for training Saudi Arabia personnel from the Presidency of Meteorology and Environment, Ayman Al Bar visited UND on November 24, 2009. During the visit, Ayman toured the John D. Odegard School of Aerospace Sciences airport facility; saw the Department of Atmospheric Sciences Citation Research aircraft; toured the C-band polarimeteric radar, undergraduate student research lab, and instrumentation lab; visited with Atmospheric Science Department faculty and graduate students, observed Jeff Tilley's Introduction to Synoptic Meteorology class; and talked with UND Aerospace student, Misfer, who is part of the ARAMCO Saudi Arabia pilot training program. Also in collaboration with NCAR's training program, Jeff Tilley visited Boulder on December 12-14 to talk with Mohammed Al-Siami about how to further use the Weather Research and Forecasting (WRF) model in Saudi Arabia.

Spring 2009 Intensive Operating Period

Airborne Instruments

During the spring 2009 Saudi Arabia IOP, an instrumented King Air 200 aircraft (Figure 2), registration number N825ST, was used for cloud seeding and to conduct measurements of clouds and aerosols. The King Air 200 aircraft carried a set of cloud physics and aerosol instrumentation that included:

- Particle Measuring Systems [PMS] Forward Scattering Spectrometer Probe [FSSP – Serial Number (SN) 1947-028-160] (Measures cloud droplets between approximately 3 and 47 µm in diameter.)
- PMS 2-Dimensional Cloud Droplet Probe [2D-C – SN 11002] (Obtains 2-dimensional images of cloud droplets from 30 to 3000 µm in diameter.)
- Aventech Aircraft-Integrated Meteorological Measurement System [AIMMS – SN 20ADP080701] (Measures atmospheric state parameters including 3-dimensional winds.)
- PMS Passive Cavity Aerosol Spectrometer Probe [PCASP – SN 19610-0590-06] (Measures particles between approximately 0.1 and 3.0 µm in diameter.)
- Droplet Measurement Technologies [DMT] Hot Wire Liquid Water Probe [LWP – SN 0701-18] (Measures cloud liquid water content.)
- DMT Cloud Condensation Nuclei Counter [CCNC – SN 062] (Measures concentration of aerosols that activate at supersaturation between 0.1 and 1.2 %.)
- TSI Incorporated Condensation Particle Counter [CPC – SN 70907298] (Measures number concentration of particles larger than 10 nm).
- Edgetech Digital Aircraft Hygrometer [DAH – SN 1779 33344] (Measures dew point temperature.)
- Rosemount Aircraft Temperature Sensor (Measures total temperature.)
- King Air 200 Aircraft GPS System (Measures position and ground speed.)
- Pressure Transducers (Measures static and dynamic pressure.)
- Science Engineering Associates [SEA] M300 Data System (Acquires and records data from all aircraft instruments.)
- Cloud Seeding Racks (Carries up to 24 hygroscopic flares and 300 AgI flares.)

Figure 2: King Air 200 research aircraft and instruments used during the spring 2009 Intensive Operational Period (IOP) conducted in Riyadh, Saudi Arabia. The top-right panel shows the Droplet Measurement Technologies (DMT) Cloud Condensation Nuclei Counter (CCNC) inside the aircraft's cabin. The top-left panel shows the Rosemount Aircraft Temperature Sensor and DMT Hot Wire Liquid Water Probe. The bottom-left panel shows the 2-Dimensional Cloud Droplet Probe (2D-C) and Aircraft-Integrated Meteorological Measurement System (AIMMS). The bottom-middle panel shows the Passive Cavity Aerosol Spectrometer Probe (PCASP). The bottom-right panel shows the Forward Scattering Spectrometer Probe (FSSP).

Airborne Flights

A total of 16 research flights, 36.7 flight hours, were conducted during the spring 2009 IOP. Of these 16 flights, 14 flights (Figure 3) were conducted near Riyadh and two flights were conducted near Abha. Eleven of the flights obtained substantial in cloud measurements. Approximately half the days during the IOP had clouds to sample; however, low visibility due to dust and weather prevented conducting flights on some days. The 15 March through 14 April time period turned out to be an excellent time to have conducted the spring 2009 IOP in Riyadh, Saudi Arabia, and demonstrated that a rich dataset can be obtained during a 30 day IOP. Table 1 presents the summary of spring 2009 IOP flights.

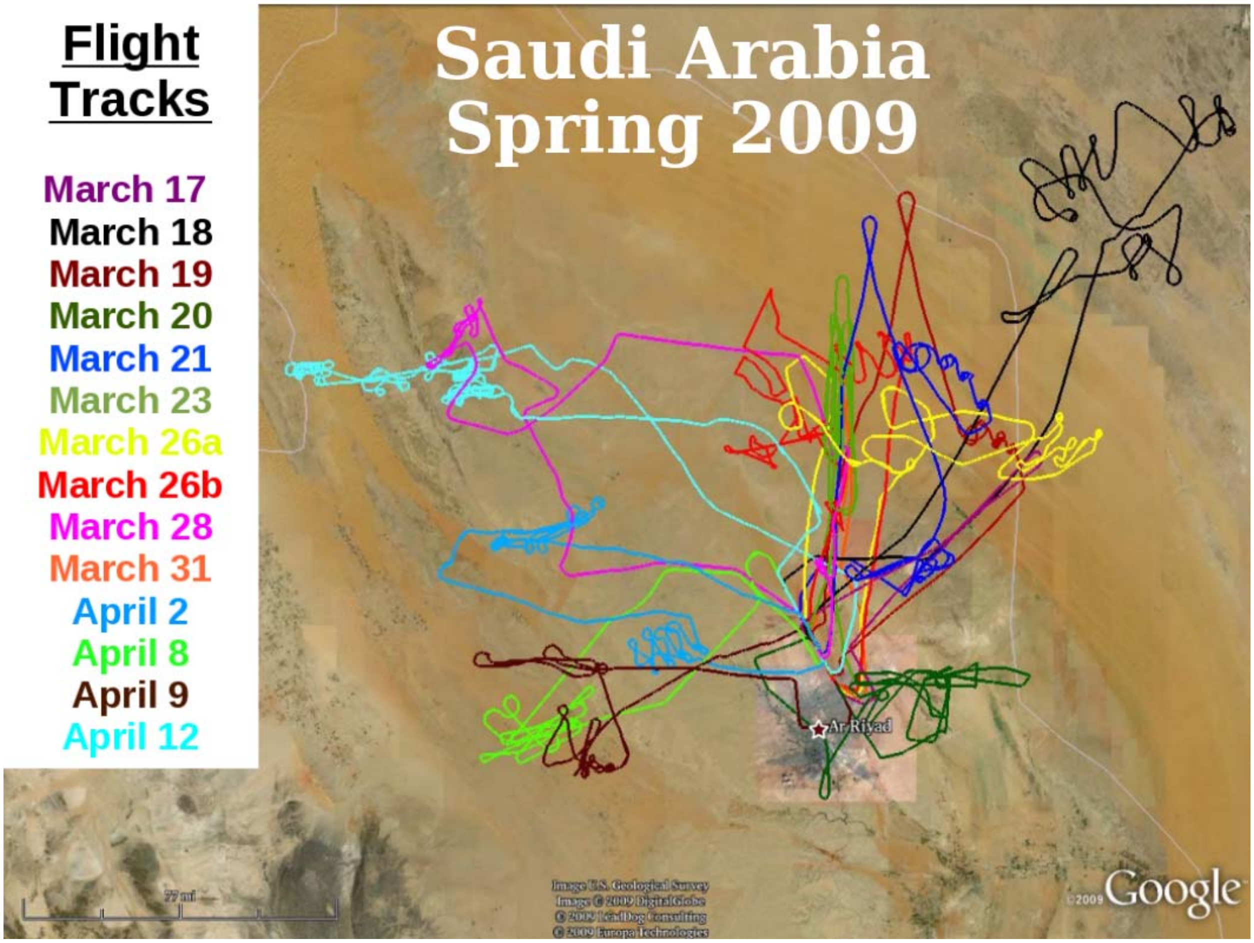

Figure 3: Flight tracks for research flights conducted near Riyadh, Saudi Arabia during the spring 2009 field project.

Table 1: Summary of research flights during the spring 2009 Intensive Operational Period (IOP) in Saudi Arabia. Time periods given indicate when aircraft measurements were recorded. The Flight Purpose column indicates the main flight objective. The Instruments column indicates instruments that were functioning correctly during at least part of the flight.

Date	**Start UTC**	**Stop**	**Total**	**Flight Purpose**	**Instruments**
yyyy/mm/dd	**hh:mm:ss**	**hh:mm:s**	**Hour**	**Type of Research**	**PCASP, FSSP, 2DC, AIMMS, CCNC, CPC**
2009/03/17	13:13:42	14:16:29	1.05	Instrument Check	PCASP, FSSP, 2DC, AIMMS
2009/03/18	07:55:33	11:10:38	3.25	Cloud Sampling	PCASP, FSSP, 2DC, AIMMS
2009/03/19	11:08:16	13:04:44	1.92	AIMMS Calibration	PCASP, FSSP, 2DC, AIMMS
2009/03/20	06:46:51	09:07:54	2.35	Cloud Sampling	PCASP, FSSP, 2DC, AIMMS, CCNC
2009/03/21	12:36:04	15:03:54	2.45	AIMMS Calibration	PCASP, FSSP, 2DC, AIMMS, CCNC
2009/03/23	11:44:54	14:13:25	2.48	AIMMS Validation	PCASP, FSSP, 2DC, AIMMS, CCNC
2009/03/26	06:39:42	08:50:20	2.18	Cloud Sampling	PCASP, FSSP, 2DC, AIMMS, CCNC
2009/03/26	11:36:15	13:52:41	2.27	Cloud Sampling	PCASP, FSSP, 2DC, AIMMS, CCNC
2009/03/28	11:48:21	14:02:47	2.24	Cloud Sampling	PCASP, FSSP, 2DC, AIMMS, CCNC
2009/03/31	12:26:17	13:36:00	1.16	Inlet Testing	PCASP, FSSP, 2DC, AIMMS, CCNC, CPC
2009/04/02	13:10:20	15:43:10	2.55	Cloud Sampling	PCASP, FSSP, 2DC, AIMMS, CCNC, CPC
2009/04/06	08:13:19	10:38:06	2.41	Khamis Clouds	PCASP, FSSP, 2DC, AIMMS, CCNC, CPC
2009/04/06	13:01:09	15:55:16	2.90	Khamis Clouds	PCASP, FSSP, 2DC, AIMMS, CCNC, CPC
2009/04/08	12:30:29	14:51:19	2.35	Cloud Sampling	PCASP, FSSP, 2DC, AIMMS, CCNC, CPC
2009/04/09	12:32:25	14:28:18	1.93	Cloud Sampling	PCASP, FSSP, 2DC, AIMMS, CCNC, CPC
2009/04/12	11:57:13	15:09:04	3.20	Cloud Sampling	PCASP, 2DC, AIMMS,CCNC, CPC

Instrument Quality Control

The model M300 data acquisition system (M300) manufactured by Science Engineering Associates, Inc. was used to acquire and record airborne measurements during the 2009 spring IOP. All measurement parameters were recorded at a frequency of at least 1 Hz during the project. The Aircraft Data Processing and Analysis (ADPAA) software package (Delene, 2009a) was used to process the binary data file recorded by the M300. The processing software is completely automated which enables generation of preliminary data within hours after completing a flight. This automation enabled a debriefing to be conducted where preliminary analysis was discussed the day following research flights. The following sections describe some of the quality control procedures that were conducted on instruments during the 2009 spring IOP.

Atmospheric Pressure

On 25 March 2009, the research aircraft's dynamic and static pressure transducers were calibrated using a National Institute of Standards and Technology (NIST) traceable pressure standard. The pressure transducer used to measure atmospheric pressure from the aircraft's copilot static port was found to have the following calibration equation:

STATIC_PR=275.6319*Volts – 0.8087

Where STATIC_PR is pressure in hPa, and Volts is the measured voltage on the Analog to Digital (A/D) board. The dynamic pressure transducer used to measure the aircraft's dynamic pressure used in the calculation of True Air Speed (TAS) was found to have the following calibration equation:

DYNAMIC_PR=14.6923*Volts + 0.4393

Where DYNAMIC_PR has units of hPa, and Volts is the measured voltage on the A/D board.

In addition to the aircraft measurements, the AIMMS also measures atmospheric pressure and TAS. While the difference between the AIMMS and aircraft atmospheric pressure measurement is approximately zero while the aircraft is not moving, it was differ during aircraft flights. The difference is found to be a function of TAS and increases to a difference of approximately 5 hPa at a TAS of 100 m/s and is a function of atmospheric pressure (Figure 4). Since the aircraft pressure measurement is greater than the AIMMS pressure measurement during flights, the difference is believed to be a dynamic effect on the aircraft's static port. Support for this conclusion is provided by the aircraft's manual which describes a static port dependence on TAS that is not accounted for in data processing. AIMMS atmospheric pressure and TAS are felt to be more accurate, and should be used when possible. Aircraft measurements are still important since they need to be used if problems occur with the AIMMS probe. Two cases that demonstrate the importance of measurement redundancy occurred during parts of 9 and 12 April flights where problems occurred in the AIMMS pressure measurements.

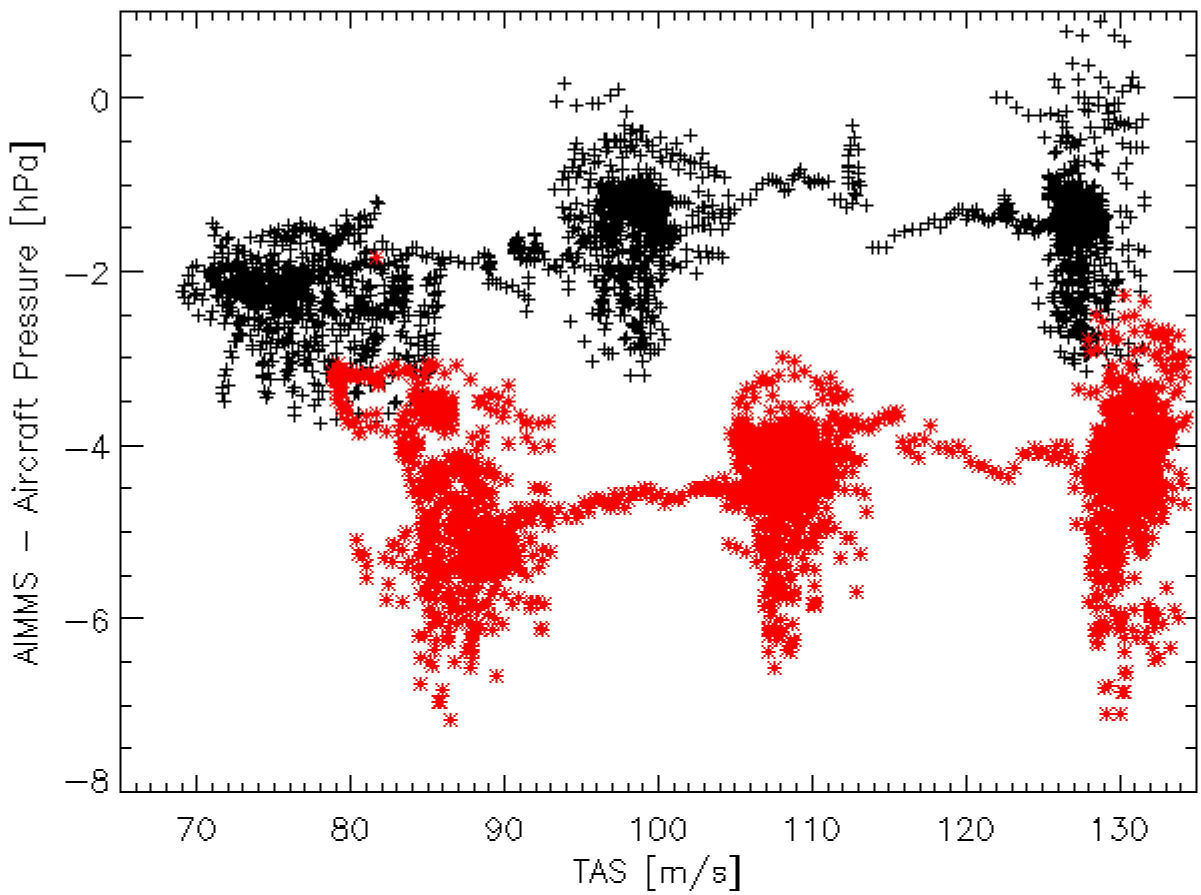

Figure 4: The difference between the AIMMS measured pressure and the pressure measured at the aircraft's static pressure port during the 23 March 2009 aircraft flight in Saudi Arabia. The black plus samples are during the 15,000 ft sampling, while the red starts are during the 21,000 ft sampling.

Air Temperature

On previous field projects in Saudi Arabia there has been noisy Rosemount temperature data and short time period (1-5 seconds) spikes in the Rosemount temperature data. During the spring 2009 IOP, noisy Rosemount temperature data only occurred during the end of the last flight (12 April 2009). This noisy data was not a result of a problem with the static or dynamic pressure measurement but a problem with the Rosemount's temperature probe itself, possibly in the instrument's signal conditioner. The AIMMS and Rosemount temperatures were typically similar; however, there were differences of several degrees in some cases. Typically, the AIMMS probe temperature was greater than the Rosemount temperature and greater than the temperature measured by rawinsonde (Figure 5). The Rosemount temperature probe is a more robust probe and should be used when available.

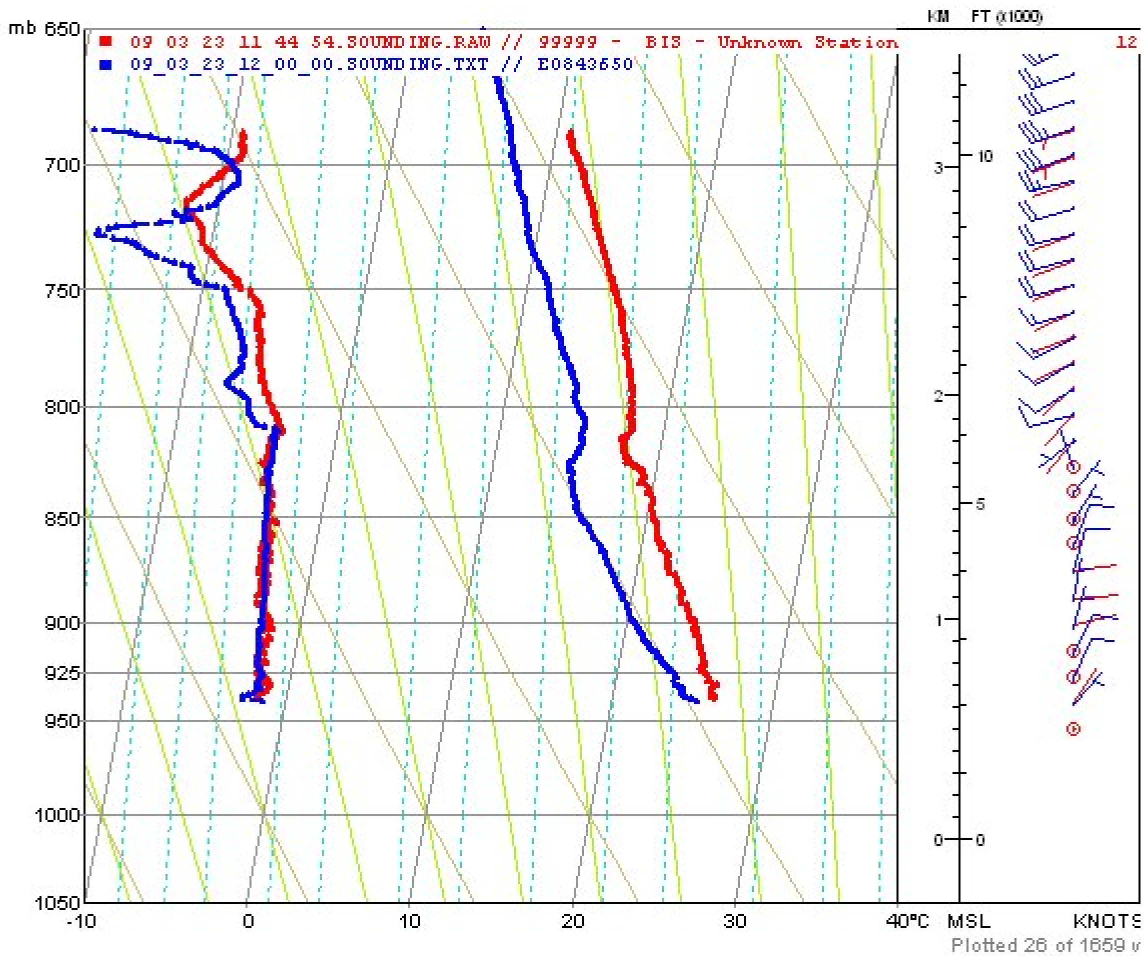

Figure 5: Comparison between the AIMMS measurements (red) and the Riyadh rawinsonde sounding on 23 March 2009.

Dew Point Temperature and Relative Humidity

During the spring 2009 Saudi Arabia IOP, two instruments measured atmospheric humidity, the Edgetech Digitial Aircraft Hygrometer and the AIMMS. The Aircraft Hygrometer uses a chilled mirror to measure dew point temperature, and the AIMMS measures relative humidity.

During the spring 2009 IOP, the dew point temperature (DewTemp) had the following relationship with voltage (Volts) measurements:

DewTemp=20.0*Volts - 40.0

The voltage range was from 0 to 5 volts which gives a dew point temperature range of -40.0 C to 60.0 C. This dew point temperature range is set in the Hygrometer itself and is easily changeable. During the Saudi Arabia IOP, dew point temperature measurements were between -40 C and 20 C. Future IOPs in Saudi Arabia should be conducted with the Hygrometer set to have a range of -60.0 C to 40.0 C.

Cloud free comparisons between the AIMMS and rawinsonde soundings indicate good agreement (Figure 5), measurements in and near clouds indicate that relative humidity data was very poor with the AIMMS typically measuring zero relative humidity in clouds. Figure 6 shows that when the first cloud penetration was conducted, the humidity values were near zero and very variable before and after the penetration. The hygrometer gives more reliable measurements and should be used in place of AIMMS relative humidity data; however, the hygrometer's dew point temperature measurement was consistently low during cloud penetrations throughout the spring 2009 IOP as is evident in Figure 7. Before the start of any future project, the hygrometer's mirror should be cleaned and a platinum resistance thermometer amplifier check performed.

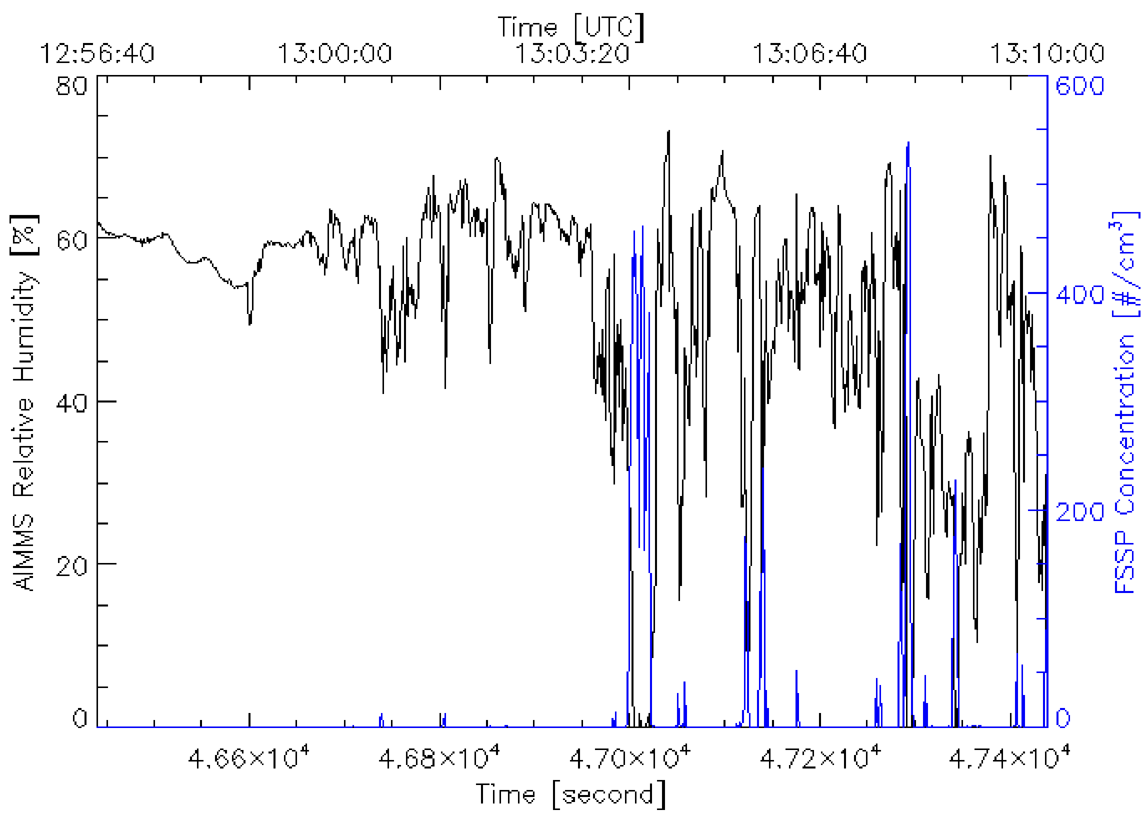

Figure 6: Time series showing the AIMMS relative humidity (black trace) and the FSSP cloud droplet concentration (blue trace) during the 8 April 2009 flight in Saudi Arabia. This time series is during the beginning of the flight just

after the aircraft reached a constant flight altitude of 4500 m (temperature of approximately -4 C). As indicated by the FSSP cloud droplet concentration, at approximately 47000 seconds the aircraft first penetrated a cloud.

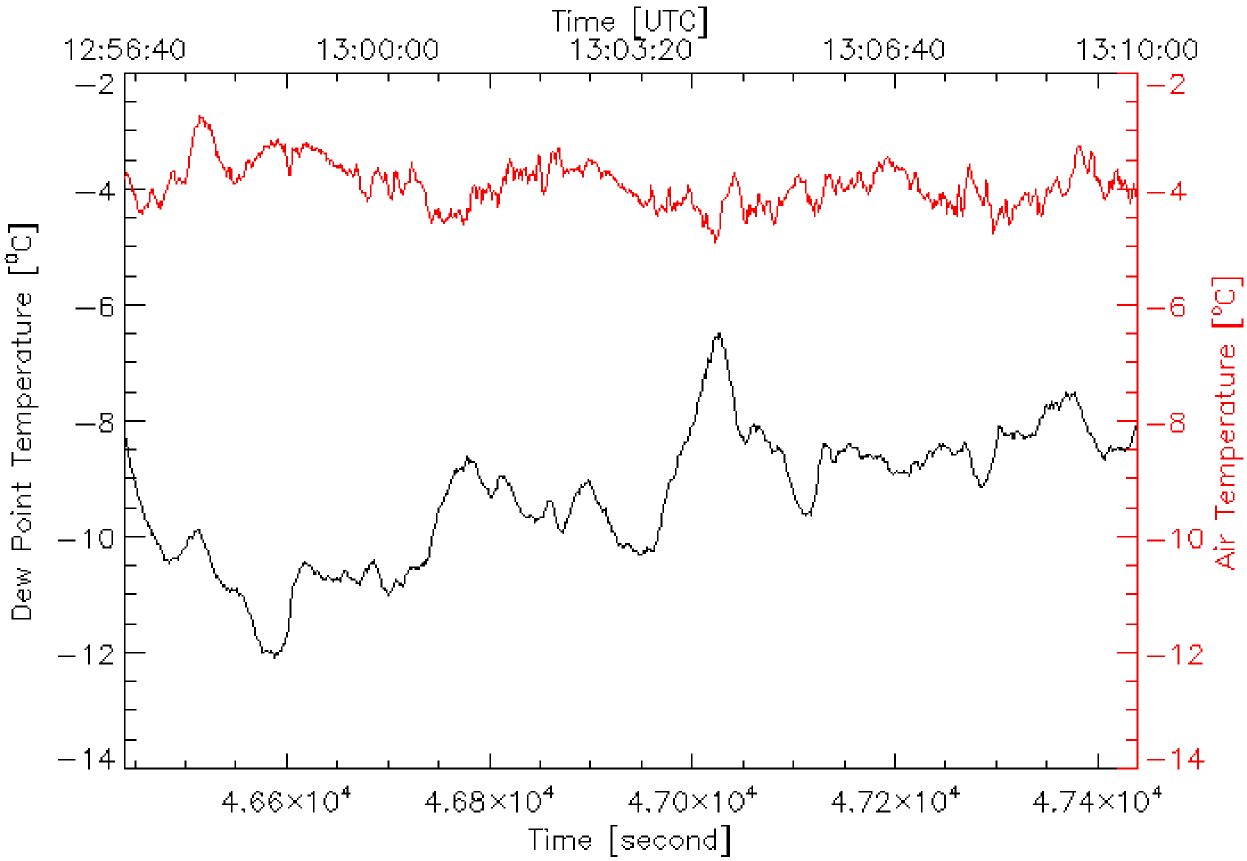

Figure 7: Time series showing the Edgetech dew point sensor measured dew point temperature (black trace) and Rosemount measured air temperature (red trace). This time series is during the beginning of the flight just after the aircraft reached a constant flight altitude of 4500 m. As indicated by the FSSP cloud droplet concentration given in Figure 6, at approximately 47000 seconds the aircraft first penetrated a cloud.

Atmospheric Winds

The AIMMS is the only instrument on the research aircraft that measures atmospheric winds. To better obtain higher frequency data and additional parameters, data from the AIMMS was recorded on a USB memory stick using a data Input/Output (I/O) module. Flights before 6 April 2009 had problems where the AIMMS would stop sending data out to the M300 data system. This problem was not fixed until another AIMMS was available where components could be swapped between the two instruments. The data lost problem was believed to be due to incorrect wiring of the data I/O module but could not be confirmed due to the intermittent nature of the problem.

Optical Aerosol Concentration

During the spring 2009 Saudi Arabia IOP, a PCASP probe was used to measure optical aerosol number concentration in the approximate size range of 0.1 to 3.0 μm in diameter.

Several times during the IOP, performance checks (Figure 8) were conducted on the PCASP by generating aerosols of known size and ensuring that the PCASP sized the particles accurately. These tests and a review of field measurements indicated that there were no problems with the PCASP measurement throughout the IOP.

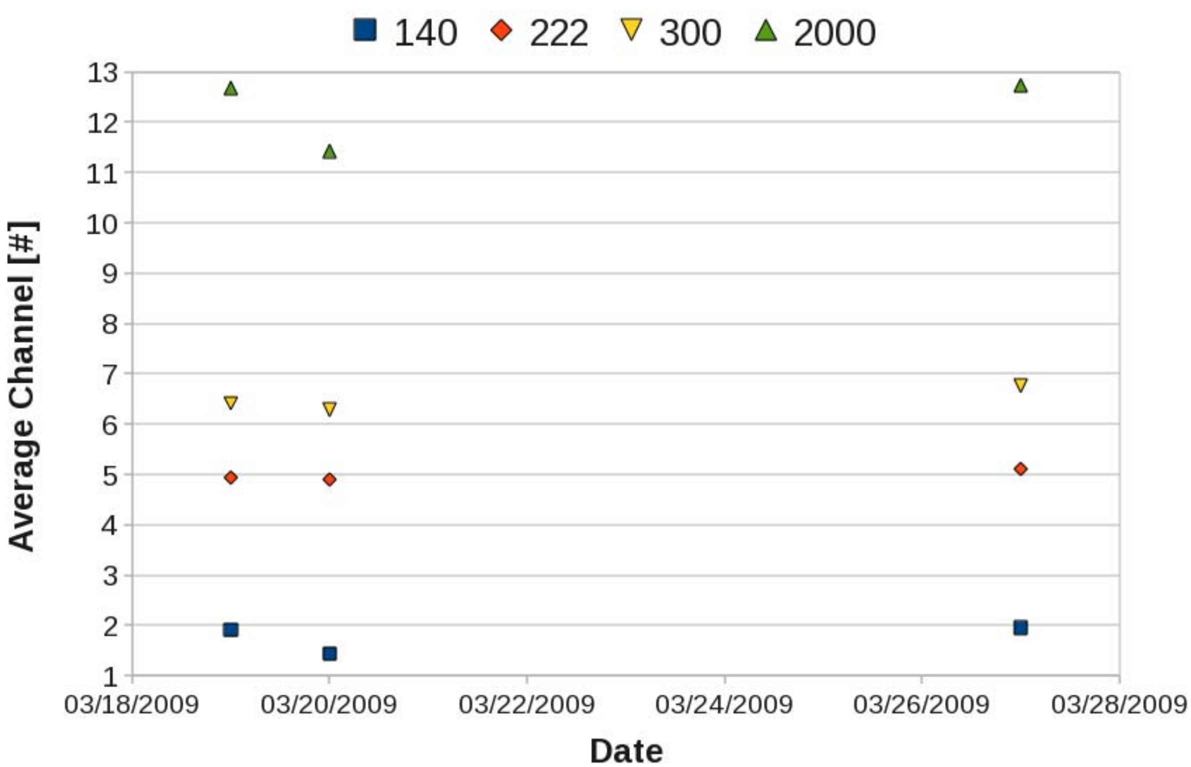

Figure 8: Average channel values from some valid performance checks conducted on the PCASP (Serial Number 19610-0590-06) during spring 2009 IOP. All checks were performed in Saudi Arabia while the PCASP was on the research King Air 200 aircraft (N825ST). Latex beads of 140, 222, 300 and 2000 nm were used during these performance checks.

Cloud Droplet Concentration

During the spring 2009 Saudi Arabia IOP many performance checks were conducted on the FSSP. Performance checks consisted of sampling beads (particles) of known size and refractive index using a procedure similar to a PCASP calibration. However, performance results are not used to apply a new calibration to FSSP measurements but instead the results are used to check that the FSSP is providing accurate size measurements. Some performance checks indicated that the FSSP was under sizing by more than two channels which prompted the FSSP being removed, cleaned, and the laser realigned. Sometimes this process had to be performed more than once before an acceptable performance was achieved. Dust infiltration is the most likely reason for the FSSP's sizing problems. Additional bags were placed over the FSSP while not in use; however, this did not eliminate the problem. It is suggested that on future projects in Saudi Arabia, optical instruments like the FSSP have a performance check conducted on the instrument before each flight. Conducting these tests does not only require personnel time, but the cleaning and aligning of the FSSP has the risk of damaging the instruments. This occurred before the last IOP flight on 12 April 2009. Other than this last flight, the effort devoted to the FSSP resulted in very good FSSP measurements (Figure 9). Future IOPs in Saudi Arabia should plan to conduct performance checks before each flight and use disposable easily sealable trash bags to cover instruments like the FSSP.

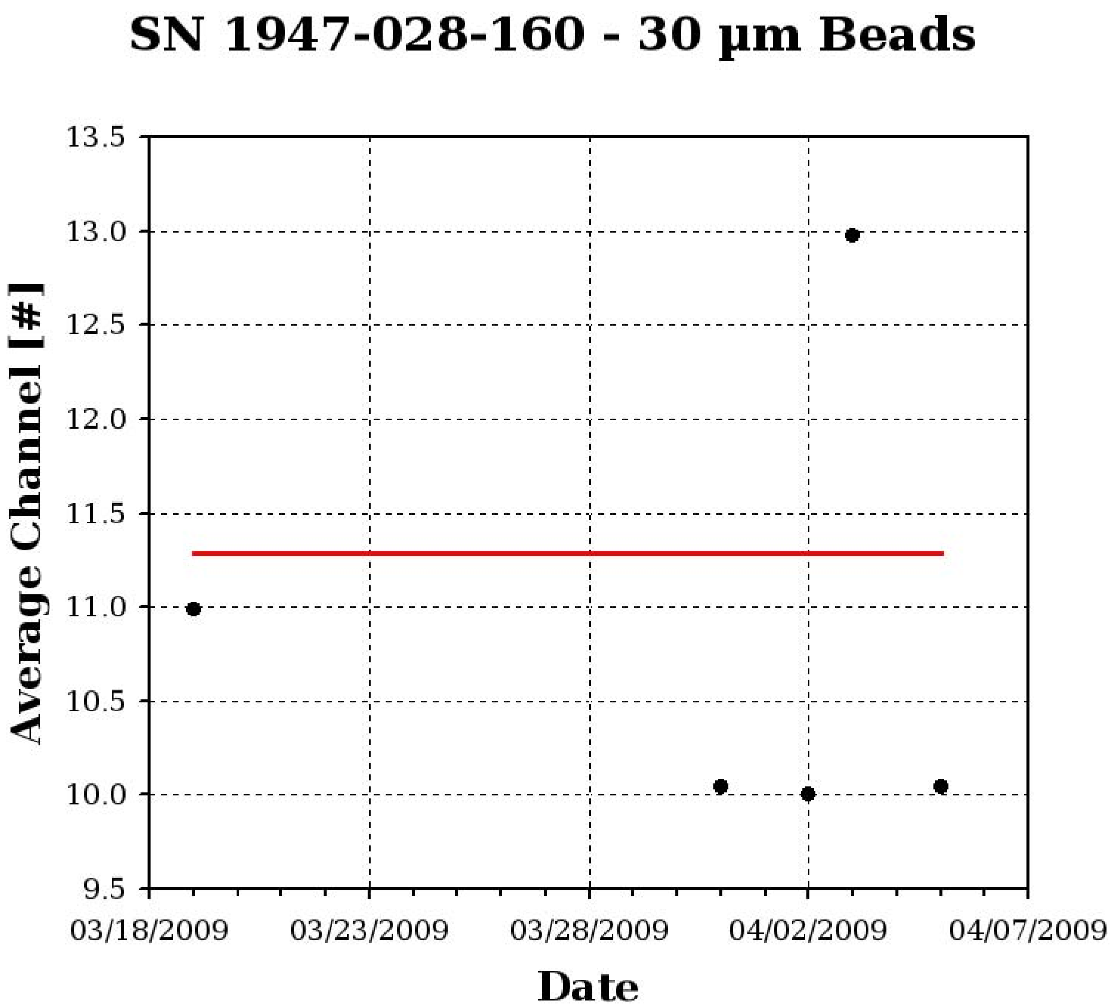

Figure 9: Average channel values from valid performance checks conducted on the FSSP (Serial Number 1947-028-160) during spring 2009 IOP using 30 µm beads. All checks were performed in Saudi Arabia while the FSSP was on the research King Air 200 aircraft (N825ST). The solid horizontal line indicates the "standard" average channel value.

Cloud Hydrometeor Images

The 2D-C rapidly samples a 32-element photodiode array to collect images of particles (hydrometeors) that pass through its sample volume. As particles shadow the array elements, images are stored as 32-bit slices of zeros and ones. Each bit represents a linear distance of approximately 25 µm. The stored images can be used to examine the sizes, shapes and numbers of particles sampled which in turn yields a particle size distribution, particle phase, and for ice, crystal particle habit.

The 2D-C data for the spring 2009 Saudi Arabia project have been examined for quality and completeness. Overall, image quality is good with one exception. Images are clear and true with no distortion in the along-track direction. This indicates that the probe was receiving a valid true air speed and sampling at the proper rate. There is no sign of electrical interference or static that is known to produce fuzzy or jagged edges on images. Thus, it is possible to distinguish particle phase and habit for particles larger than about 200 μm in diameter. The 2D-C data were processed using ADPAA algorithms for artifact rejection, sizing, and reconstruction of particle images not entirely contained within the instrument sample volume. The derived concentrations of particles also appear for the most part to be reasonable.

The primary data quality issue during the spring 2009 IOP related to 2D-C image data results from an issue known commonly as a "stuck bit". This occurs if one or more elements of the 32-bit array appear to be shadowed continuously or intermittently even though there are no particles passing through the sample volume. This may be due to either dirty optics or an electronic problem that causes a diode element to be low (shadowed) or appear to be low. This problem occurred on the following flights: 20 March, 26 March (both flights), 28 March, 9 April, and 12 April. Most of the time there was only one bit affected. The impact of this problem is to introduce uncertainty into particle concentration and sizing data. The bad bit data can be filtered out, but the filtering process removes some valid data for times when the bit truly was shadowed by a particle. It did appear that if particles larger than about 100-150 microns were present the occurrence of a "stuck bit" happened less frequently. This means that image data can be used to qualitatively assess particle phase (water or ice) and ice particle habit. However, use of the data for quantitative assessment of derived particle sizes and concentrations should be accompanied by examination of the raw image data. During future IOPs it is recommended that more spinning disk performance checks be conducted to check for "stuck bit" problems.

Cloud Condensation Nuclei Concentration

During the first week of the spring 2009 field project, valid Cloud Condensation Nuclei (CCN) measurements were not obtained since there were leaks in the counter (Droplet Measurement Technologies (DMT), SN 062). A hand operated vacuum pump was used to go through the tubing system on the CCN counter to find the location of leaks. All major leaks were fixed on 22 March 2009, with the last leak being related to a small filter (Figure 10). With major leaks fixed, the leak rate was 0.16 mb/s for a system vacuum test (450 to 500 mb). This is sufficiently less than the 2 mb/s recommended on page 45 of the CCN Operator Manual Rev. D. Leak issues were communicated to DMT during the December 2009 CCN counter workshop (Delene and Sever, 2009). Weekly CCN counter leak checks should be conducted during future IOPs in Saudi Arabia.

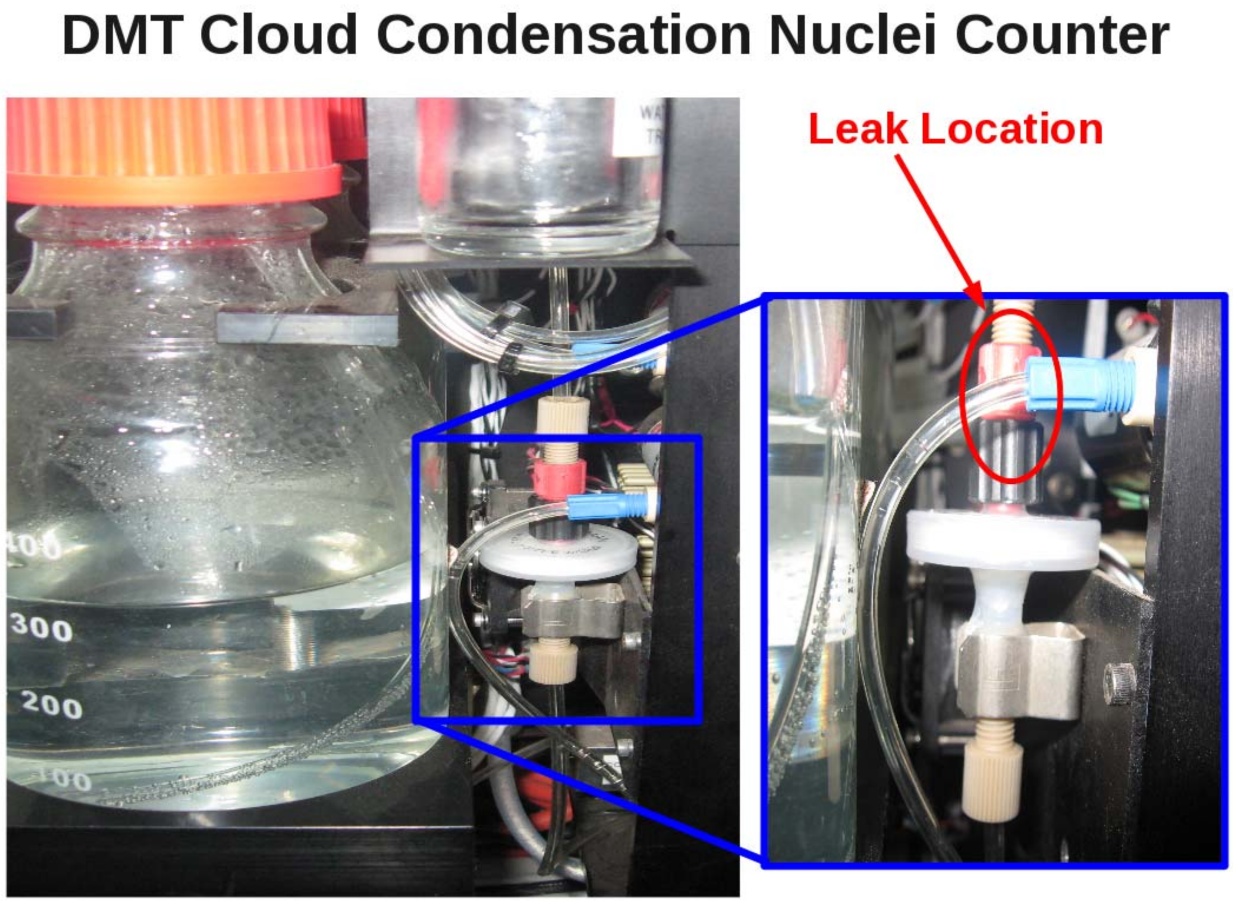

Figure 10: Location of the last major leak found in the DMT Cloud Condensation Nuclei counter after installation in the research aircraft for the spring 2009 field project.

During the last three weeks of the IOP, 25 hours of airborne and 10 hours of ground-based CCN data were collected. The counter was set to obtain CCN concentration spectra at 0.49, 0.59, and 0.9% effective supersaturation levels on the 8 April 2009 flight. In a similar fashion, ground CCN concentration spectra were run on four different days. All other measurements were done at 0.9% supersaturation level. Due to the pressure differences between the cabin and ambient environments, the CCN counter's pressure was stabilized using a Constant Pressure Inlet (DMT-CPI, SN# 0608-0018). On the 24th and 25th of March, sample and sheath flow rate calibrations were performed using a Sensidyne Gilibrator-2 air flow calibration kit. There were plans to make a supersaturation calibration check on the counter to ensure the correctness of the supersaturation readings; however, due to delays in shipment of the Aerosol Neutralizer (a part of Scanning Mobility Particle Sizer (SMPS) system) the calibration could not be completed during the spring 2009 IOP. However, the CCN counter was left installed in the aircraft until a supersaturation calibration was performed before the start of the summer 2009 IOP.

Condensation Particle Concentration

While not part of the original research plan, a TSI Condensation Particle Counter (CPC) was available and was installed and successfully collected measurements of the number concentration of particles larger than 10 nm on seven flights during the IOP. Initially, there were problems with the water removal configuration; however, this issue was solved after a few flights. Only concentration measurements from the CPC were recorded during the spring 2009 IOP; however, future IOPs should record auxiliary data from the CPC.

Measurement Quality Assurance

The ADPAA software package (Delene, 2009a) has been used extensively while conducting data quality assurance and for reprocessing the data files. Data quality assurance was started during the spring IOP and conducted throughout the summer and finished during the fall. A total of 680 edits were created in 69 edit files. Figure 11 illustrates an example to the type of edit made during the quality assurance process. Due to the AIMMS real-time software not using GPS position information when the roll angle magnitude exceeded 50 degrees, a time period of invalid AIMMS wind measurements occurred. Edits were made to remove (replace with the missing value code) the AIMMS wind parameters for this time period. Aventech has reviewed this data and is working on a firmware update to set the invalid wind flag if this situation occurs.

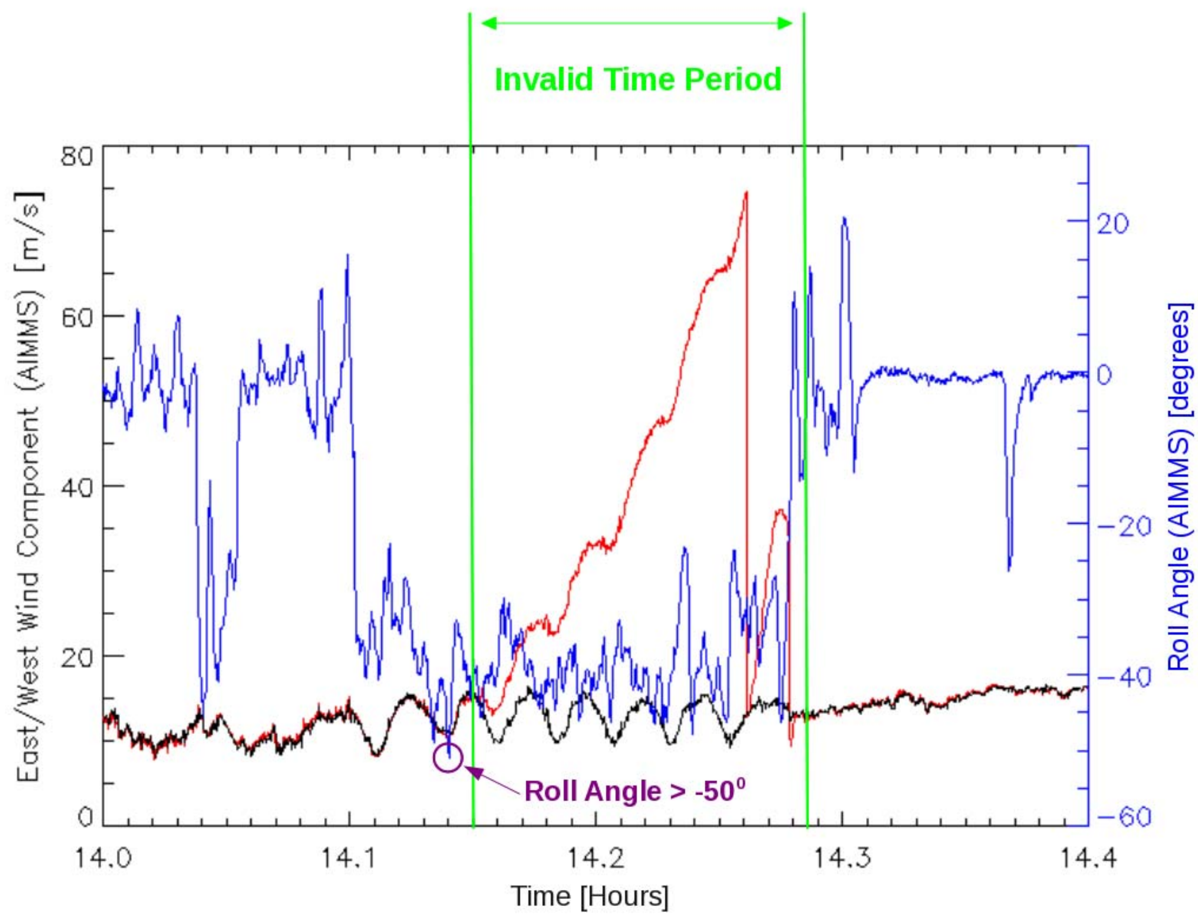

Figure 11: Time series showing post-processed (black) and real-time (red) solution of the AIMMS East/West wind component during the 8 April 2009 flight in Saudi Arabia. The aircraft roll angle (blue) is given along the left side axis.

Processed data files for the Spring 2009 Field Project are in ASCII format (Gaines and Hipskind, 2009) with a meta-data file header. Summary data files that contain parameters of interest have been created in ASCII and NetCDF formats. All project related files are contained within a directory structure (Delene, 2010) that has been used for previous projects in Saudi Arabia. A set of quick look plots for each flight have been created and are available online (UND Department of Atmospheric Sciences Gallery, 2010).

Research Results

With the excellent data set obtained during the Spring 2009 Field Project in Saudi Arabia, there is a great amount of analysis that can be conducted. In the sections below, the analysis to date is summarized.

Aerosol Inlet Location

The Condensation Particle Counter (CPC), along with the DMT Cloud Condensation Nuclei (CCN) counter was used on the 31 March 2009 inlet characterization flight to access the possibility of engine exhaust contamination of samples made at the front side window location by the aircraft's engine. The rear facing, unheated aerosol inlets allow sampling of aerosols by the CPC and CCN counter. Figure 12 shows that the statistical distributions are comparable between sampling from the side window location and the top front window location. Both locations show that the maneuvers (sideslip and turns) have distributions overlapping with the Standard distributions. Furthermore, the CPC and CCN counter do not show any spikes that would indicate engine exhaust contamination during any of the test maneuvers. Therefore, it is concluded that there is not an issue with pollution from the aircraft's engines when sampling from the front side window location on the King Air 200. Analysis of the atmospheric flare sampling analysis has been presented at the 2009 American Aerosol Association Research conference (Delene and Larson, 2009).

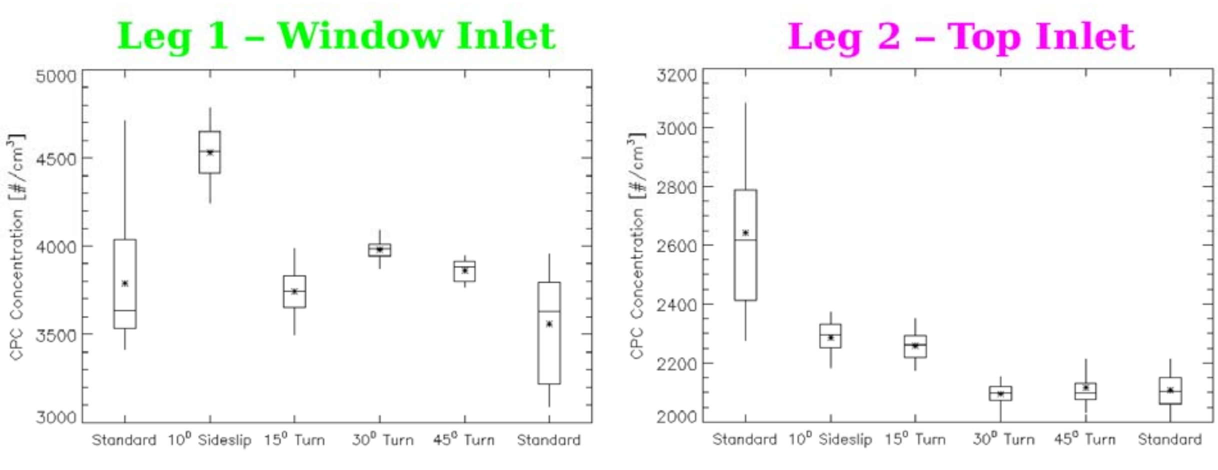

Figure 12: Statistical distribution of 1 Hz CPC measurements obtained during aircraft maneuvers designed to direct exhaust towards the window inlet. The 5, 25, 50, 75, and 95 percentiles are given by the box-and-whiskers, while the stars denote the mean values. Exact time intervals are given in the Table 2.

Table 2: Time period for inlet test maneuvers performed on the 31 March 2009 flight in Saudi Arabia.

Type	Start Time	End Time	Leg	Roll Angle
	[HH:MM:SS]	**[HH:MM:SS]**	**[#]**	**[degrees]**
Standard	12:41:25	12:45:49	1	1.3284
Sideslip	12:46:00	12:47:59	1	10.7845
15^0 Turn	12:50:30	12:52:09	1	16.0007
30^0 Turn	12:52:57	12:53:44	1	29.2789
45^0 Turn	12:54:28	12:54:49	1	45.4605
Standard	12:55:52	12:57:31	1	1.4209
Standard	12:57:32	12:59:09	2	1.1236
Sideslip	13:00:18	13:01:39	2	11.0590
15^0 Turn	13:03:25	13:05:04	2	15.8106
30^0 Turn	13:05:22	13:06:11	2	30.9984
45^0 Turn	13:07:07	13:08:00	2	45.4242
Standard	13:09:10	13:10:49	2	0.6172

Seeding Plume Sampling

To assess the aerosol size distribution produced in the atmosphere by the burning of hygroscopic flares several flights (19 March 2008, 4 August 2008, 2 April 2009 and 8 April 2009) have sampled the plume from burning seeding flares. On the 4 August 2008 flight, an instrumented research aircraft followed a flare burning aircraft to sample the aerosol size distribution produced by hygroscopic flares at different distances. Figure 13 shows the measured aerosol size spectrum produced by burning flares and how it compares to natural boundary layer aerosol size spectrum in Saudi Arabia. Only the very highest concentration measured within the plume produced by burning flares show aerosol concentrations around 1 µm that are above the boundary layer aerosol layer that would be typical below cloud. While the boundary layer aerosol may not be very hygroscopic like the aerosols produced from the flares, at these large sizes the aerosol should still act as cloud condensation nuclei; hence, the hygroscopic flares may not be very effective in increasing the number of large drops in spring time clouds in the Riyadh region. Analysis of the airborne flare sampling study has been presented at the 2009 American Aerosol Association Research conference (Oliver-Wedwick and Delene, 2009).

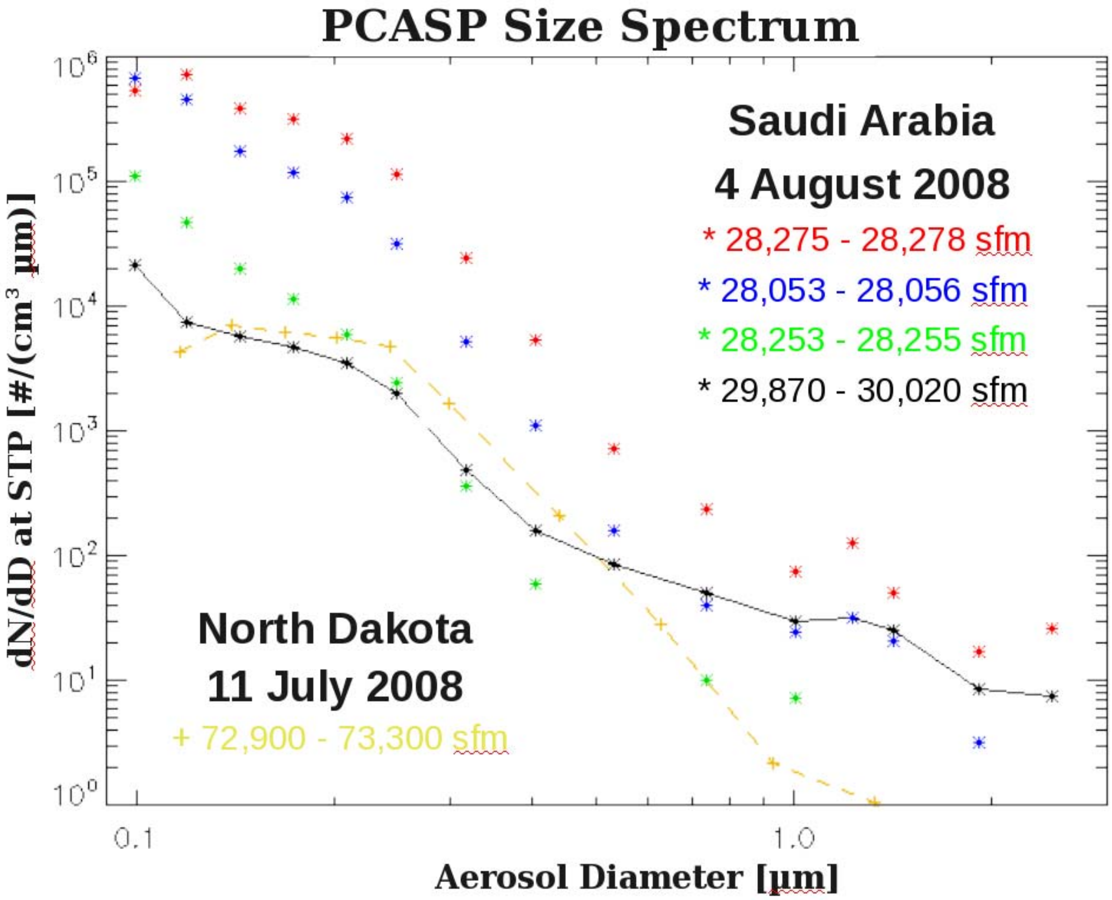

Figure 13: The aerosol size distribution at standard pressure and temperature measured by a Passive Cavity Aerosol Spectrometer Probe (PCASP) during the 4 August 2008 flight. The blue stars is for an in close (~1.5 km) flare sample obtained between 28,053 and 28,056 sfm. The green stars is for a middle (~2.3 km) flare sample obtained between 28,253 and 28,255 sfm. The red stars is for a farther away (~2.8 km) flare sample obtained between 28,275 and 28,278 sfm. All three flare samples were obtained at an altitude of approximately 6,500 m. The black solid line with black stars is a boundary layer natural aerosol obtained between 29,870 and 30,020 sfm at a constant altitude of approximately 3,500 m. The gold dashed line with gold plus is a boundary layer natural aerosol obtained between 72,900 and 73,300 sfm on the 11 July 2008 flight in North Dakota.

Cloud Condensation Nuclei

The DMT cloud condensation nuclei (CCN) counter was operated at a constant supersaturation of 0.56 %. Running the CCN counter at a constant supersaturation instead of scanning supersaturation values, allow areas where CCN concentrations change rapidly to be indentified (Figure 14). Figure 14 shows the PCASP spectrum below cloud base on the 9 April 2009 flight. The PCASP spectrum shows that the concentration of particles near 1 µm is similar to the concentration sampled in the hygroscopic seeding plume on 4 August 2008 (Figure 13).

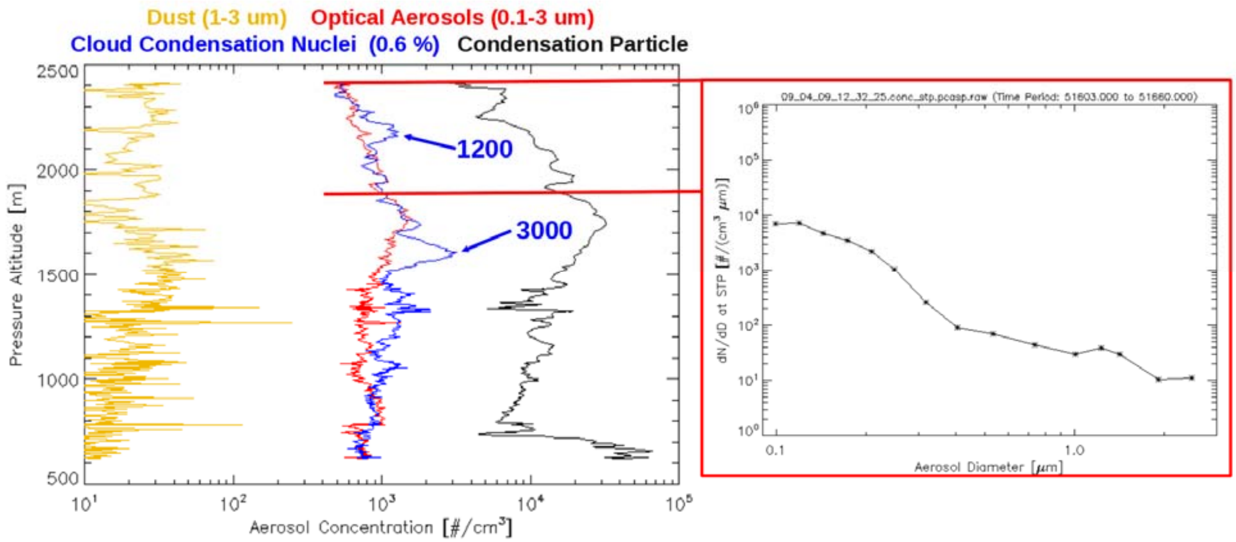

Figure 14: Descent aerosol profile (left panel) for 9 April 2009 flight in Saudi Arabia. The blue labels of 1200 and 3000 indicate cloud condensation nuclei (CCN) concentrations increase where the optical aerosol concentration does not increase. The PCASP spectrum (red box on right) is for the upper (1900 to 2400 m) of the profile.

AIMMS Winds

The vertical wind measurement from the AIMMS is a critical parameter for scientific analysis related to understanding aerosols and cloud interactions and the precipitation formation process. Three flights involved calibration and validation of the AIMMS during the spring 2009 IOP. Analysis of the 23 March 2008 wind validation flights indicates that horizontal winds (Figure 15) and vertical winds (Figure 16) were not greatly affected by aircraft motion which indicates an acceptable winds calibration. The vertical wind distributions agree (overlap); however, the vertical winds during the porpoise maneuvers generally have wider probability distributions (Figure 17:). The wider probability distribution during porpoise maneuvers indicates that not all of the aircraft movement is removed and improvements can be made to obtain more accurate vertical winds. Analysis of the AIMMS winds has been presented at the 2009 Fall Meeting of the American Geophysical Union (Kruse and Delene, 2009).

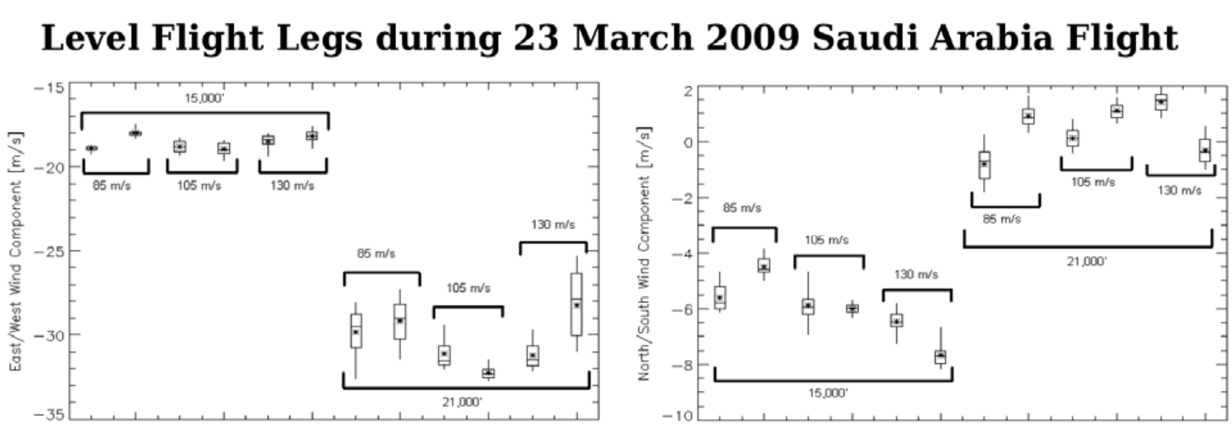

Figure 15: Summary statistics for the components of the horizontal wind from the AIMMS on 23 March 2009. All box-and-whiskers represent statistics from 1 Hz measurements made over an approximately three minute time period when the aircraft was flying straight and level. The aircraft altitude of the leg is given in the long interval notes and the true air speed (TAS) given by the short interval notes. The solid horizontal line in the center of the box is the median of the distribution, the top and bottom of the box is the 75 and 25 percentiles of the distribution, the top and bottom of the solid line extension is the 95 and 5 percentiles of the distribution, and the stars represent the mean of the distribution. Time periods for each analyze level is given in Table 3.

Table 3: The time periods used for the horizontal wind analysis of the 23 March 2009 Saudi Arabia flight.

Maneuver	Altitude	TAS	Start Time	End Time
	ft	m/s	HH:MM:SS	HH:MM:SS
Straight Level 1	15000	85	12:04:00	12:06:33
Straight Level 2	15000	85	12:16:18	12:29:04
Straight Level 3	15000	105	12:21:40	12:25:40
Straight Level 4	15000	105	12:36:00	12:36:48
Straight Level 5	15000	130	12:40:00	12:43:10
Straight Level 6	15000	130	12:51:30	12:54:26
Straight Level 7	21000	85	13:00:00	13:03:10
Straight Level 8	21000	85	13:10:20	13:13:40
Straight Level 9	21000	105	13:18:20	13:21:10
Straight Level 10	21000	105	13:28:40	13:31:10
Straight Level 11	21000	130	13:36:20	13:39:30
Straight Level 12	21000	130	13:48:00	13:51:20

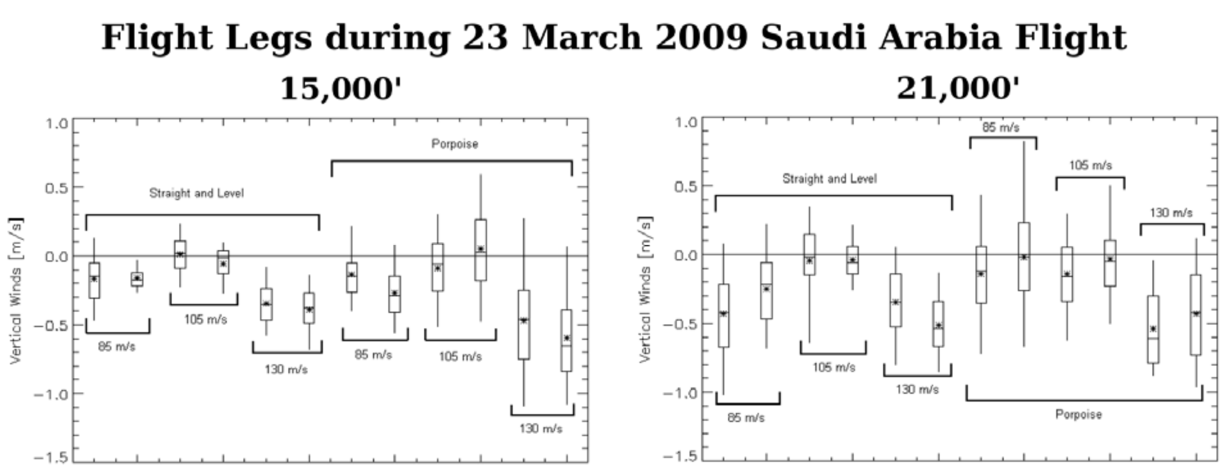

Figure 16: Summary statistics for the vertical wind from the AIMMS on 23 March 2009. All box-and-whiskers represent statistics from 1 Hz measurements. The first six box-and-whiskers are level legs and the last six box-and-whiskers are for porpoise legs. The solid horizontal line in the center of the box is the median of the distribution, the top and bottom of the box is the 75 and 25 percentiles of the distribution, the top and bottom of the dotted line extension is the 95 and 5 percentiles of the distribution and the stars represent the mean of the distribution. Time periods for each analyze level is given in Table 4.

Table 4: The time periods used for the vertical wind analysis of the 23 March 2009 Saudi Arabia flight.

Maneuver	15,000' MSL		21,000' MSL	
	Start Time HH:MM:SS	End Time HH:MM:SS	Start Time HH:MM:SS	End Time HH:MM:SS
Straight Level 1	12:04:00	12:06:30	13:00:00	13:03:10
Straight Level 2	12:16:18	12:19:04	13:10:20	13:13:40
Straight Level 3	12:21:40	12:25:40	13:18:20	13:21:10
Straight Level 4	12:35:00	12:37:48	13:28:40	13:31:10
Straight Level 5	12:40:00	12:43:10	13:36:20	13:39:30
Straight Level 6	12:51:30	12:54:26	13:48:00	13:51:20
Porpoise 1	12:06:30	12:08:20	13:03:10	13:04:44
Porpoise 2	12:14:30	12:16:18	13:08:45	13:10:20
Porpoise 3	12:25:40	12:29:09	13:21:10	13:22:55
Porpoise 4	12:33:50	12:35:00	13:26:50	13:28:35
Porpoise 5	12:43:10	12:45:25	13:39:30	13:40:55
Porpoise 6	12:50:10	12:51:30	13:46:45	13:48:05

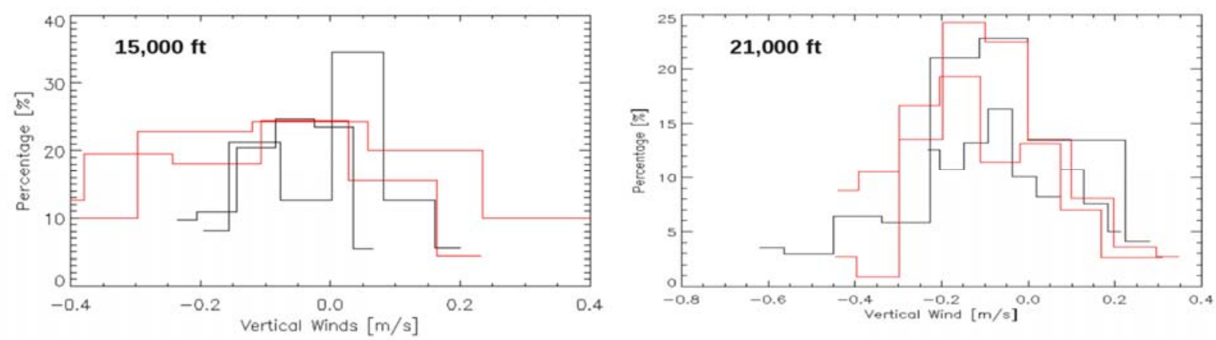

Figure 17: Histograms of the distribution of 1 Hz vertical winds at 15,000 ft (left) and 21,000 ft (right) during straight and level legs (black solid lines) and during porpoise maneuvers (red solid lines) during the AIMMS on 23 March 2009 flight in Saudi Arabia. The time intervals are given in Table 4. The true air speed for all maneuvers was approximately 105 m/s.

Working with the AIMMS probe manufacturer, Aventech, project personnel have been able to process and understand the USB recorded data and hence convert it to our standard ASCII file format. Work is ongoing to determine possible improvements to AIMMS wind measurements by using raw AIMMS data with wind processing software developed over many years of airborne research at the University of North Dakota.

9 April 2009 'Brown' Ice Flight Case Study

Photographs of ice accumulation on the unprotected leading edge of the aircraft's wing during the 9 April 2009 research in Saudi Arabia show a color change, from white during the time of low droplet number concentration, to brown during the time of high droplet number concentration. It is likely that the observation of brown ice build up on the aircraft wings were the result of the ingestion at cloud base of a high concentration of aerosols. This changing aerosol concentration had the result of changes in the cloud micro-physics properties near cloud top (Figure 18). The relation between the FSSP concentration and the droplet size spectrum was observed to change during the accumulation of brown ice (Figure 19). Results of the 9 April 2009 flight have been presented at a University of Wyoming Department Seminar (Delene, 2009b) and at the American Geophysics Union Fall Meeting (Delene, 2009c). Research is being expanded on the 9 April 2009 case study to include more cloud micro-physics, radar, sounding and modeling analysis.

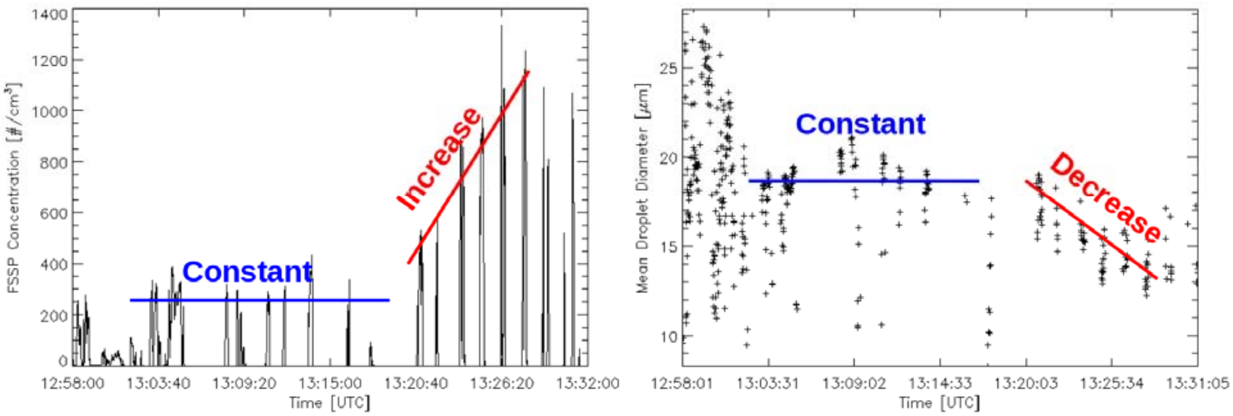

Figure 18: Time series (1 Hz) of cloud properties at 18,000 ft on the 9 April 2009 flight in Saudi Arabia. Droplet concentration and mean diameter are measured with an FSSP. The blue and red lines correspond to sampling different cloud cells. Within both cloud cells the liquid water concentration peaks were approximately the same at 1.5 g/m^3.

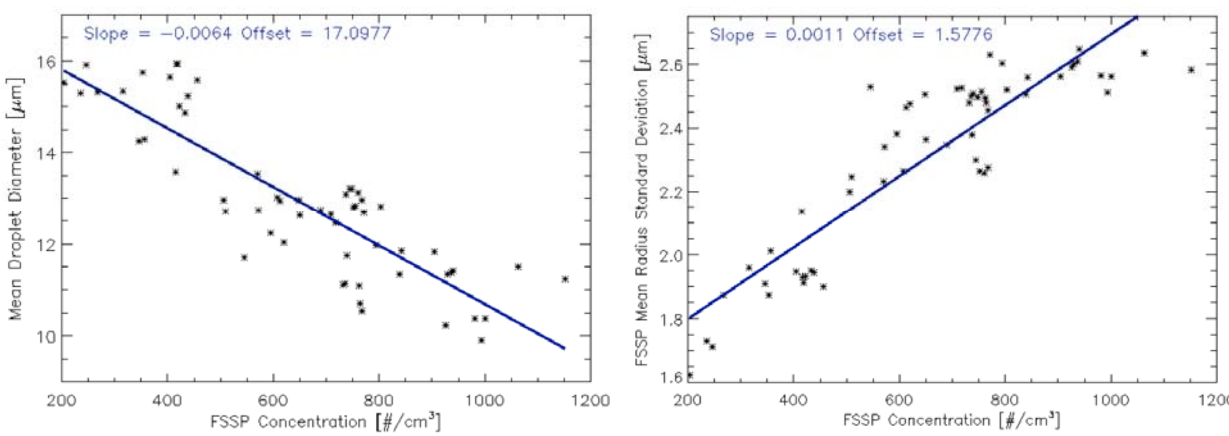

Figure 19: Relationships between cloud droplet concentration and cloud properties between 13:20 and 13:28 on 9 April 2009 flight. Only measurements with 1 Hz hot wire probe liquid water measurements above 1 g/m^3 are included in the analysis.

Cloud Droplet Effective Radius

Figure 20 shows cloud micro-physical observations of the natural precipitation formation process during the 2 April 2008 flight in Saudi Arabia. The greater effective droplet radius value for FSSP concentrations greater than 100 #/cm^3 is due to the formation of ice. The presence of ice and the fact that the cloud droplet effective radius never exceeded 12 um, indicate an ice phase precipitation formation process.

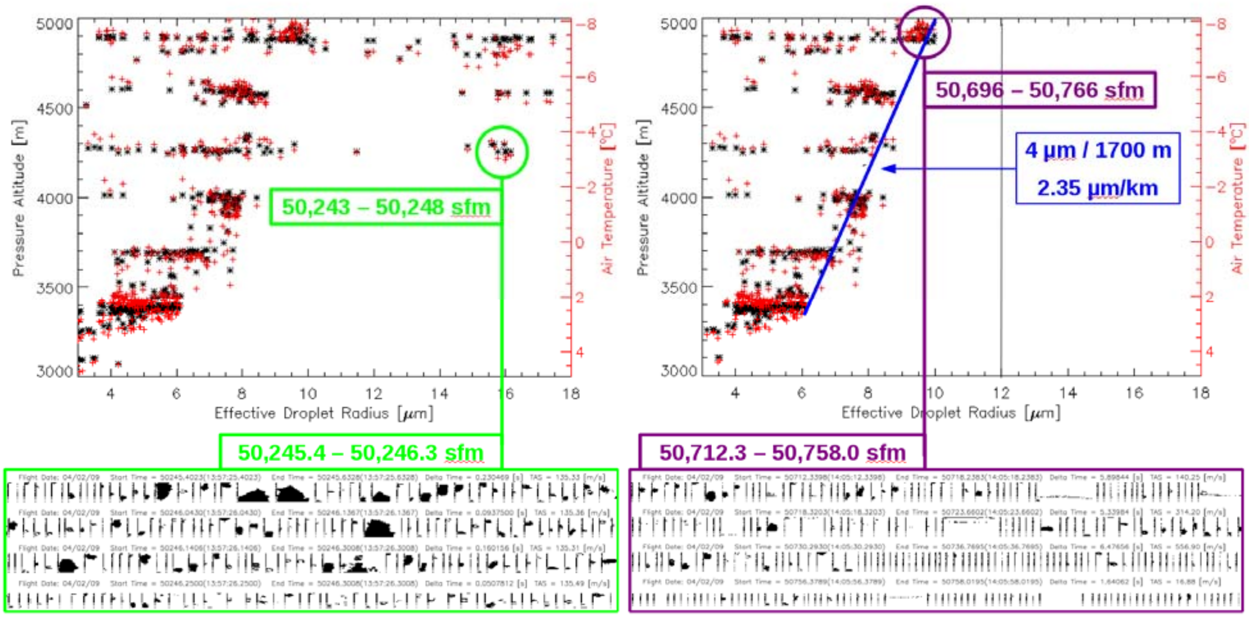

Figure 20: Sampling of cloud cell between cloud base and cloud top during time interval 49,100 to 50,800 sfm on 2 April 2008. Left panel shows all observations, while the right panel only includes FSSP concentrations at STP that are greater than 100 #/cm^3. The blue line gives the approximate rate of increase of effective droplet radius with height. Below each plot is a 2DC image for a selected time period given in the boxes.

Ice Phase Measurements

The PMS 2DC data for each of the cloud sampling flights were examined to ascertain what precipitation mechanism, Bergeron or collision-coalescence, was most likely predominant in the study clouds. The 2DC images were viewed to determine both size and phase of the sampled particles. Although the somewhat coarse resolution of this instrument (~25 µm) makes it impossible to determine the phase of particles smaller than about 150-200 µm, the images are well-suited for the study of precipitation size particles. Liquid precipitation particles are defined as having a diameter greater than 0.2 mm (200 µm); this definition will apply here to quasi-spherical ice particles as well. The liquid precipitation appear as circles with a smooth perimeter (Figure 21, top), while ice particles have varying degrees of asymmetry (Figure 21, bottom). There is some uncertainty in deciding whether a circular image represents a drop that is still liquid or has frozen, although a larger frozen drop will generally show some irregularity at the edge.

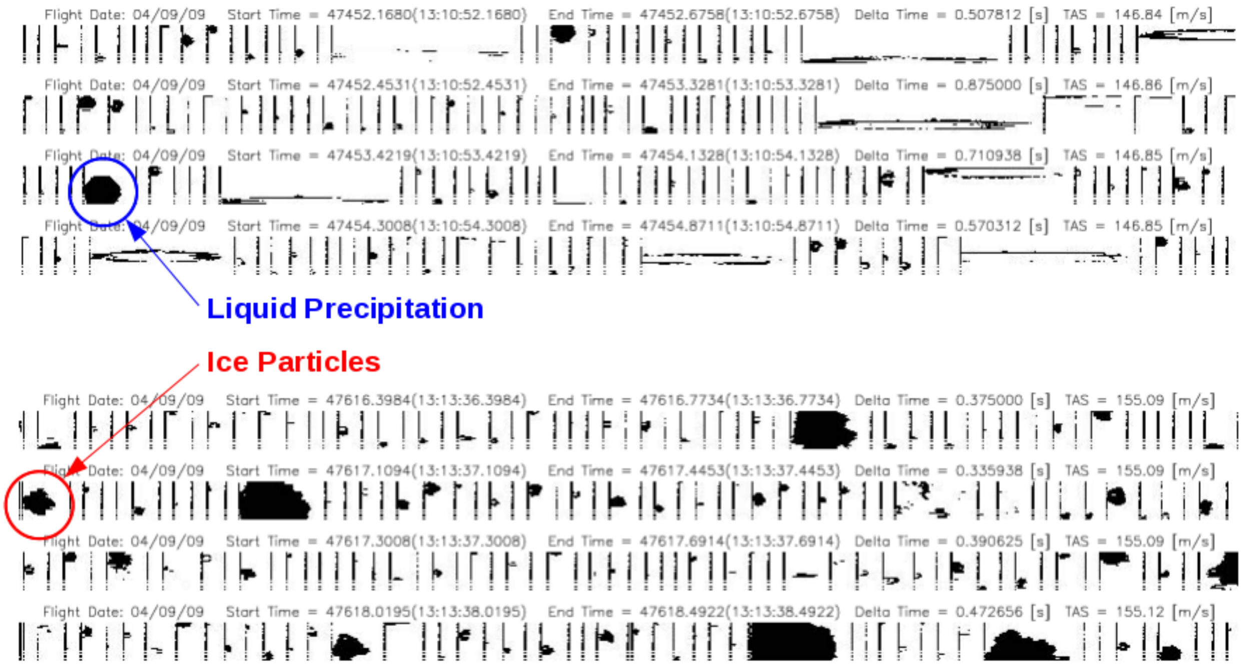

Figure 21: Examples of 2DC probe images obtain on the 9 April 2009 flight in Saudi Arabia.

A predominant precipitation mechanism was assigned to each flight based on the presence or absence of precipitation-sized particles and their phase. Only images from temperatures colder than freezing were considered. If the precipitation was liquid (circular images), it was assumed that a collision-coalescence ("warm rain") process was active. If the precipitation was frozen, a Bergeron ("cold rain") process was assumed to be active.

Of the 11 cloud sampling flights, a warm rain process was evident only on the last two – 9 and 12 April. The images from 9 April showed some large (>500 µm) drops on a number of the cloud penetrations. This was not the case for all penetrations, so both mechanisms may have been at work in clouds on that day. For 12 April, the evidence for warm rain is not as compelling since no circular images larger than ~200 µm are contained in the data. Many of these small images were thought to be liquid drops, though, because they were accompanied by high liquid water content as measured by the hot wire probe. Cloud liquid water content exceeded 0.9 g m^{-3} at temperatures as cold as -25 ºC. For the remainder of the flights the larger particle images exclusively indicated the presence of > 1 mm size graupel along with smaller rimed and unrimed ice crystals. (Note: little or no 2DC data were available for the 31 March mission.) Further analysis is suggested to investigate what conditions were present on 9 and 12 April that promoted collision-coalescence and/or inhibited the Bergeron process in the study clouds.

Conclusions

Instrument performance was very good during the spring 2009 IOP conducted in Riyadh, Saudi Arabia. Overall instrument performance was far better than any previous airborne IOP conducted in Saudi Arabia. Very good instrument performance combined with cloudy weather during the IOP resulted in excellent data being collected. Quality assurance of the spring 2009 IOP data has been finished. The inlet test flight indicates that the side window location is a clean sampling location free of engine exhaust contamination. Atmospheric sampling of the seeding plume indicates that the 1 µm diameter size particle concentration within a hygroscopic flare plume is approximately the same as the boundary layer aerosol in Saudi Arabia. Further analysis should look at how the flare plume compares to typical below cloud aerosol size spectrum and investigate how effective natural aerosols above 500 nm are as cloud condensation nuclei. The PCASP measurements in Saudi Arabia indicate that the accumulation mode aerosol size distribution is typically broad. High CCN concentrations were often observed in cloud base (e.g. 9 April 2009). The observations made on 9 April 2009 are very interesting and should allow for an interesting model study (to be conducted) that will test our understanding of the precipitation formation process in Saudi Arabia. While there exist super-cooled liquid water in clouds in the Riyadh region during spring time convection, observations like the 2 April 2009 case show a robust natural ice precipitation formation process and a warm rain process was evident only on 9 and 12 April. The rich data set collected during the Spring 2009 IOP enables many lines of analysis to be conducted. Additional analysis and field observations would help to clarify the natural precipitation formation process at work during the spring time convection in the Riyadh region.

Acknowledgments

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