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OBSERVATIONS OF GROUND RELEASED SULFUR HEXAFLUORIDE TRACER GAS PLUMES IN TWO UTAH WINTER STORMS

By

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Abstract. Research was conducted for a two month period over the Wasatch Plateau of Central Utah during the winter of 1990-91. A portion of this research was devoted to tracking sulfur hexafluoride (SF_6) released from various ground based locations during winter storms. A NOAA King Air research aircraft was the primary mode of tracking the SF_6. Seven flights were conducted under IFR conditions when SF_6 was released from a foothill or valley location. SF_6 was detected on six of these flights. *Information on SF_6 plume widths, concentrations, vertical extent, and* estimated numbers of ice crystals that would be possible if a silver iodide generator had been operated from the SF_6 release site are provided for two of these flights.

1. INTRODUCTION

North American Weather Consultants (NAWC) has conducted an operational winter cloud seeding program in portions of Utah since 1974. The goal of this operational program is to augment the naturally occurring snowfall in higher elevation areas of the State. The augmented snowfall results in augmented spring and summer streamflow and ground water recharge useful to irrigation and municipal water users. The design of this operational program includes the use of ground based, manually operated silver iodide generators. These generators have been located at local residences which are typically valley locations upwind of the higher elevation target areas.

Statistical target/control evaluations of the apparent effects of this operational program have been performed (Thompson and Griffith, 1981). The most recent evaluation (Griffith, **et al.**, 1991) indicates an average 11 percent increase from this operational program over 14 winter seasons. While these statistical results suggest a positive cloud seeding effect, it is desirable to establish physical documentation of the chain of events that can lead to this positive effect. Consequently, a research program has been conducted in Utah under the auspices of the National Oceanic and Atmospheric Administration (NOAA) since 1981 (Reinking, 1985), hereafter referred to as Utah/NOAA. The focus of this on-going research program in Utah has been four-fold (Utah Division of Water Resources, 1991):

- To describe the spatial and temporal distributions of supercooled liquid water (SLW) in winter clouds over Utah's mountains and the factors controlling the SLW,
- To understand how silver iodide (AgI) cloud seeding material may be delivered from ground generators to the winter cloud regions containing SLW,
- To gain a better understanding of the physical processes responsible for winter precipitation development, in natural and seeded orographic clouds, and
- To gain a better understanding of the *trajectories of natural and seeded precipitation* particles in winter orographic clouds.

The first goal, the documentation of the presence of supercooled liquid water, has been established in a variety of storm conditions in previous winter research periods (Long, 1986) (Huggins, 1990). Attention in recent years has shifted to the second goal, "to understand how silver iodide cloud seeding material may be delivered from ground generators to the winter cloud regions containing supercooled liquid water".

A field research program was conducted over the Wasatch Plateau of central Utah during the winter of 1990-91. This program included a variety of equipment and personnel (Utah Division of Water

Resources, 1991). One component of the research included the utilization of sulfur hexafluoride (SF_6) as a tracer gas to simulate the transport and dispersion of silver iodide nuclei. Earlier work conducted in North Dakota and Utah had successfully used this SF_6 tracer technique in this manner. This paper discusses results from this tracer work obtained on two different test days that occurred in March, 1991.

2. SUMMARY OF 1990-91 WINTER UTAH/NOAA RESEARCH PROGRAM DESIGN

A field research program was mounted in the Wasatch Plateau region of central Utah (Figures 1 and 2). Table 1 provides the locations, durations, and types of instruments provided on Figure 2. Operations were conducted from January 15 to March 15, 1991. A number of observation systems were utilized on this program. Of interest in this paper were the following.

- o A NOAA King Air C90 cloud physics aircraft which was operated from Provo, Utah. This aircraft carried an extensive array of cloud physics instrumentation which included:

  1. Total temperature (Rosemount Model 102),
  2. Dew point (General Eastern Model 101),
  3. Supercooled liquid water (King-CSIRO Model LWC-5), and
  4. Cloud particles (Particle Measurement Systems Model OAP-2DC-C).

  The aircraft did not carry any vertical motion sensing equipment besides the static pressure transducer. It also carried two instruments designed to observe either silver iodide nuclei directly or the tracer gas-sulfur hexafluoride (SF_6). The silver iodide detection instrument was an NCAR counter (Langer, 1973). The SF_6 detection instrument was a TGA-4000 analyzer manufactured by Scientech Inc.

- o A rawinsonde facility located at the Mt. Pleasant Airport. The location of the Mt. Pleasant Airport, as well as other locations mentioned in this paper, are provided in Figure 2. Soundings were taken from this location every one and one-half to three hours during the passage of winter storms through the research area.

- o Five weighing bucket precipitation sites and four automatic weather (PROBE) stations that reported 10 minute mean values of wind direction, wind speed, temperature, relative humidity, and standard deviation of wind direction.

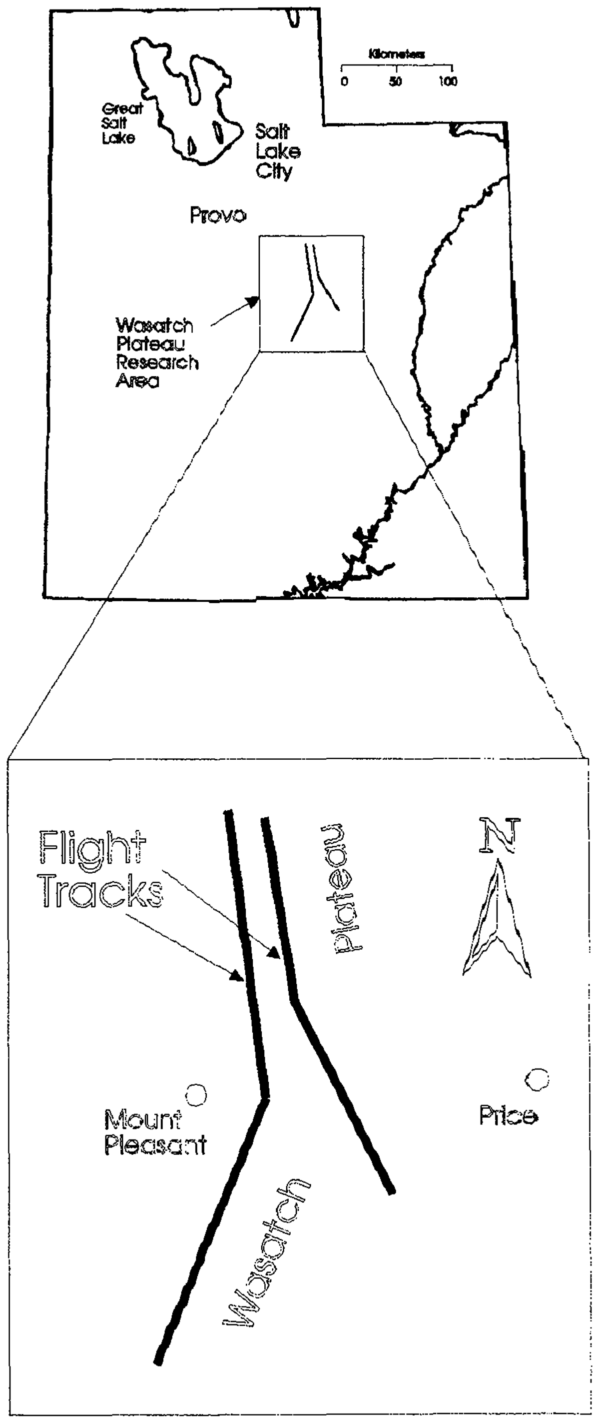

Figure 1 Location of the Wasatch Plateau Research Area.

- o Two microwave radiometers; one Bureau of Reclamation radiometer operated at a fixed location, near the summit of the Wasatch Plateau (Utah Department of Transportation - UDOT), while the other was operated by Desert Research Institute in a mobile configuration. Both instruments provided water vapor and liquid water measurements.

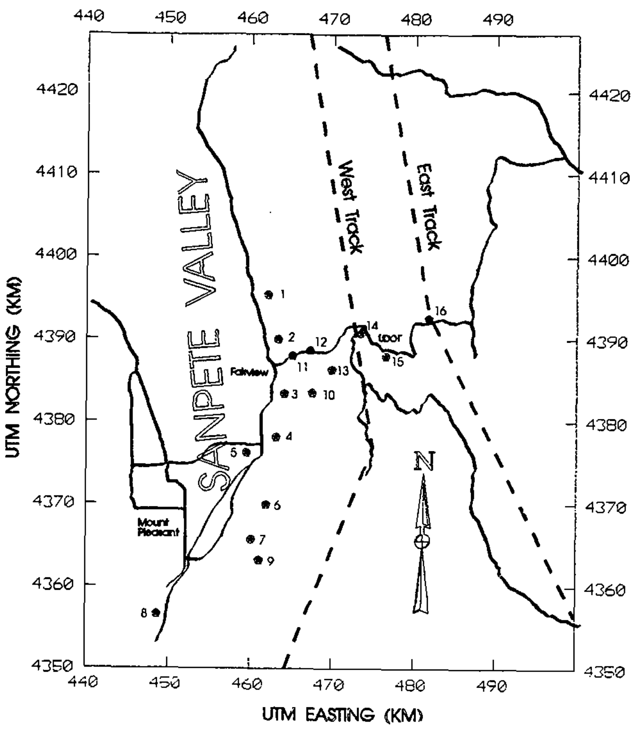

Figure 2 ***Locations of the Flight Tracks and Ground Based Sites***

Table 1
Types of Instrumentation, Elevations, and Locations of Sites in Figure 2

Site No.	Location	Type	Elevation m MSL
1	Milburn	AgI generator	2052
2	Fairview	AgI generator	1835
3	Fairview S.	AgI generator	1800
4	Mt. Pleasant	AgI generator	1787
5	Mt. Pleasant Airport	AgI generator, radiosonde, PROBE	1780
6	Spring City	AgI generator	1784
7	Spring City S.	AgI generator	1790
8	Ephraim	AgI generator	1800
9	Spring City	SF_6 release	1820
10	Birch Creek Canyon	SF_6 release	2150
11	Fairview Canyon	SF_6 release, PROBE, precip.	2024
12	Fairview Canyon, 4 mile	PROBE	2207
13	High elevation site	AgI generator, SF_6 release, PROBE, precip.	2500
14	UDOT	BUREC radiometer, SF_6 syringe, precip.	2665
15	Flat Canyon Campground	Precip.	2720
16	County line	Precip.	2848

- An SF_6 ground release capability that could be moved to different release points.

- A NAWC mobile van equipped with a TGA-4000 SF_6 tracer gas analyzer similar to that carried on board the NOAA King Air. It also was equipped with location (GPS), temperature and relative humidity sensors, and an on-board data acquisition system. This van was not a regular part of the operations, but was available for sampling on five days.

- A ground based sequential syringe sampler designed to take air samples for the detection of SF_6 which was utilized on a few of the experiments.

- A network of eight valley-based NAWC silver iodide generators.

3. SF_6 TRACER GAS AND DETECTION

Sulfur hexafluoride (SF_6) is a manmade material used primarily as an electrical insulating gas for high voltage power transmission equipment. The background concentration of SF_6 is quite low being on the order of one part per trillion (ppt). Detection of SF_6 relies primarily upon two methods: gas chromatography and electron capture. Gas chromatography requires collection of air samples, then subsequent analysis at a central location. Advances that began in the mid 1970's (Simmonds, et. al., 1976) continued into the 1980's in utilizing the electron capture technique to develop real time SF_6 analyzers. Such an analyzer is described in Benner and Lamb (1985). An operational version of this analyzer (LBF-3), manufactured by Scientech Inc. of Pullman, Washington, has been utilized in the North Dakota and Utah/NOAA research programs since 1985. Results of the release of SF_6 in summertime conditions from an airborne platform with detection by a second aircraft equipped with an LBF-3 real time analyzer have previously been reported (Griffith, 1985; Stith, et. al., 1986; Stith and Benner, 1987). Release of SF_6 from a ground location with detection either by ground or airborne sampling have also been reported (Wilkerson, et. al., 1987; Swart, et. al., 1987; Griffith, et. al., 1988; and Griffith, et. al., 1990). The LBF-3 analyzer provides significant detail on SF_6 plumes in the atmosphere. This detail results from a response time of .5 second and a threshold of detection of ten parts per trillion (ppt).

4. RELEVANT FACTORS

There are several factors relevant to analysis of the SF_6 tracer data. The air intake manifold on the King Air was subject to a build-up of icing in the lines leading to the NCAR counter and SF_6 analyzer. This intake was heated, but apparently the icing conditions encountered in Utah winter storms exceeded the capacity of the de-icing equipment. This factor rendered some of the NCAR counter and SF_6 data collected under moderate to heavy icing conditions suspect.

SF_6 was released from several locations during the 10 storm days. The release point on some days was in foothill locations on the east side of the Sanpete Valley in, or near, the mouths of canyons. On other days releases were made from a higher elevation site located approximately two-thirds of the distance up the windward side of the barrier. On some days releases were started at a valley or foothill location but were shifted to the higher elevation site.

On some cases the valley silver iodide generator network was turned on several hours to as much as a day before the conduct of the airborne research flights. The SF_6 releases, however, were often not initiated until the research aircraft departed Provo.

Measurements were made of the consumption of seeding solution in six of the manual generators by taking calibrated dip stick measurements before and after each experiment. These measurements were averaged for the research period. The resulting average consumption rate was .13 gallons of two percent silver iodide-acetone solution. This equates to an average eight grams of silver iodide per hour per generator. This rate is somewhat higher than the six grams per hour rate previously reported in Griffith, et al., 1991. The six grams per hour value was for a .10 gallon per hour consumption rate.

There were occasional problems with LORAN reception on the King Air research aircraft. These problems were more frequent during IFR flights under icing conditions (Heimbach, 1991).

Arlin Super (personal conversation) indicates that the King CSIRO liquid water contents recorded on the King Air flights were low by approximately a factor of six and that the Bureau microwave radiometer data is preliminary.

The final ice crystal data from the PMS 2DC probe were not available at the time this paper was written.

5. TWO TEST CASE DAYS IN MARCH, 1991

Sulfur hexafluoride tracer releases, either from a foothill or a higher elevation site, were made on 10 days under storm (IFR) conditions during the two month Utah/NOAA research program. Thirteen research flights were conducted on these 10 days. Heimbach (1991) and NAWC project information were used to summarize the 13 IFR research flights (Table 2). Of the 13 flights summarized in Table 2, eight had a valley or foothill SF_6 release point. The other five flights had either a high elevation or a combined foothill and high elevation release point. The eight flights (numbers 1, 5, 6, 7, 8, 9, 10, and 12 in Table 2) which were conducted when only a foothill SF_6 release was made most closely match the current seeding technique being used on the operational Utah winter program (i.e., predominantly valley released silver iodide). Of these eight flights, six flights encountered the SF_6 plume released from a foothill location. The first flight on March 2 (number eight in Table 2) was terminated early due to aircraft icing and air intake manifold icing problems which explains why SF_6 was not encountered on this flight. No SF_6 was detected on the first flight on March 1 (number six in Table 2). Consequently, if flight number eight on March 2 is discounted, six out of seven flights with a foothill release of SF_6 resulted in detecting the SF_6 plume over the Wasatch Plateau. Two of these flights, number nine on March 2 and number ten on March 6, were selected for more detailed analysis. The reasons for selecting these two cases included:

- o One case with convection present (March 2) and one with little convection (March 6)-as indicated from the aircraft flight scientist and instrument operator logs.
- o Both cases had good supporting information including ground SF_6 observations from NAWC's mobile van (March 2) and a ground based sequential syringe sampler (March 6).
- o A number of SF_6 plume encounters occurred on both flights which can give some information on average plume widths and concentrations.
- o Both the west and east flight tracks were flown on both flights with the SF_6 plume being encountered on both the east and west flight tracks.

5.1 Test Case Day, March 2

Figure 3 provides a portion of the National Weather Service 0500 MST surface analysis for this day. Utah was under post-frontal conditions. Clouds covered the research area during the day with snow observed at the Utah Department of Transportation (UDOT) project field site located on top of the Wasatch Plateau. Figures 4 and 5 provide two rawinsonde observations conducted from Mt. Pleasant (a valley site) at 1200 and 1500 MST.

One flight was conducted on this day from 0957 to 1125 MST. This flight was terminated early due to significant turbulence and icing problems. The second research flight on this day was conducted from 1238 to 1445 MST. All the valley silver iodide generators (locations provided in Figure 2) had been activated the previous day. Sulfur Hexafluoride was released at the mouth of Birch Creek Canyon at an elevation of 2,150 m MSL. Figure 2 provides the location. The release period was from 1230 to 1415 MST at a release rate of 34 kg of SF_6 per hour. Table 3 provides a summary of the meteorological conditions during the time of the second flight.

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Table 2

Summary of the 13 IFR Research Flights

No.Date	Flight Time (MST)	SF_6 Release Locations	Silver Iodide Rlse Locat.	Meteorological Setting	Problems	Comments
1. Jan. 28	1549-1750	Fairview Canyon	Valley Network	Pre-frontal	NCAR counter had trouble with false counts	Four fairly broad SF_6 plume encounters with maximum concentrations of 30-300 ppt.
2. Feb. 16	0912-1140	Spring City and high elevation site	Valley Network and high elev. site	Pre-frontal	Air sampling intake manifold deicing inadvertently left off	Only one SF_6 plume encounter, possibly due to icing in intake manifold
3. Feb. 16	1439-1723	Spring City and high elevation site	Valley Network and high elev. site	Pre-frontal	Heavy icing (up to 5 inches accumulation on aircraft); possible restriction of air sampling intake manifold	No SF_6 plume encounters
4. Feb. 17	1110-1415	High elev. site	Valley Network and high elev. site	Post-frontal	None	Ten SF_6 plume encounters, maximum concentrations 20-400 ppt
5. Feb. 28	1305-1640	Fairview Canyon	Valley Network and high elev. site	Post-frontal	LORAN problems	Fourteen SF_6 plume encounters with maximum concentrations from 30-300 ppt. NAWC mobile van also encountered SF_6 on Wasatch Plateau.
6. Mar. 1	1107-1445	Spring City	Valley Network	Pre-frontal	Possible air intake manifold icing	No SF_6 plume encounters; NAWC mobile van encountered SF_6 in valley
7. Mar. 1	1620-1850	Spring City	Valley Network	Pre-frontal	SF_6 release data logger malfunction, release rate logged manually, possible air intake manifold icing	Four SF_6 plume encounters; maximum concentrations less than 50 ppt. NAWC mobile van encountered SF_6 near UDOT
8. Mar. 2	0957-1125	Birch Creek Canyon	Valley Network	Post-frontal	Turbulence, aircraft icing, air intake manifold, loss of LORAN led to early termination of flight.	No SF_6 plume encounters
9. Mar. 2	1238-1445	Birch Creek Canyon	Valley Network	Post-frontal	Aircraft icing, LORAN problems air intake manifold icing	Six SF_6 plume encounters, maximum concentrations 30-300 ppt, NAWC mobile van encountered SF_6 on top Wasatch Plateau
10. Mar. 6	1600-1930	Birch Creek Canyon	Valley Network	Post-frontal	None	Fourteen SF_6 plume encounters, maximum concentrations 40-900 ppt.
11. Mar. 10	1258-1650	Spring City and high elev. site	Valley Network	Pre-frontal	NCAR counter compressor failed in turbulence - restarted in flight	VFR flight transitioned into IFR flight. Eight SF_6 plume encounters, maximum concentrations 30-500 ppt.
12. Mar. 11	1128-1415	Birch Creek Canyon	Valley Network	Pre-frontal	Air intake manifold icing	Six SF_6 plume encounters, maximum concentrations 20-1000 ppt.
13. Mar. 14	1136-1515	High elev. site and another high elev. site near Huntington Res.	High elev. site and Huntington Res.	Pre-frontal	LORAN problems, SF_6 release rate an order of magnitude low, possible air intake manifold icing	Fourteen SF_6 plume encounters, maximum concentrations 20-200 ppt.

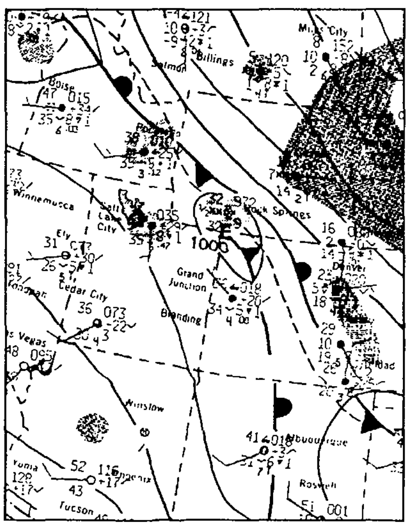

Figure 3 National Weather Service Surface Weather Map, 0500 MST, March 2.

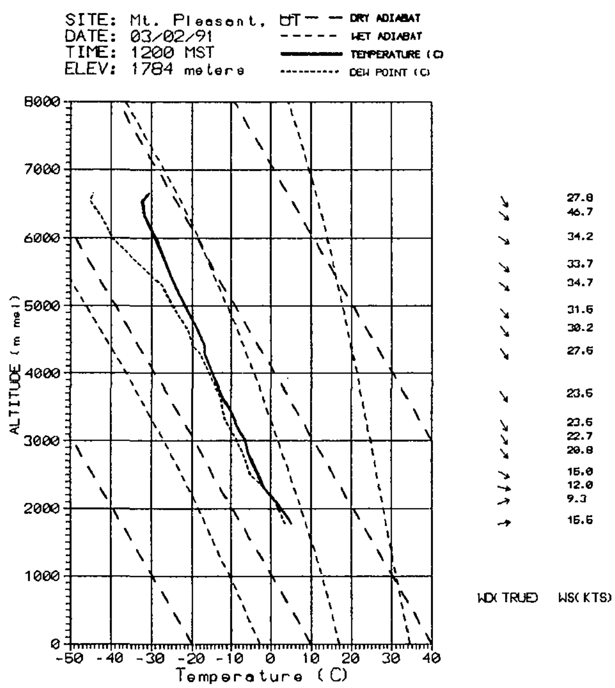

Figure 4 ***Mt. Pleasant, Utah Rawinsonde Observation, 1200 MST, March 2.***

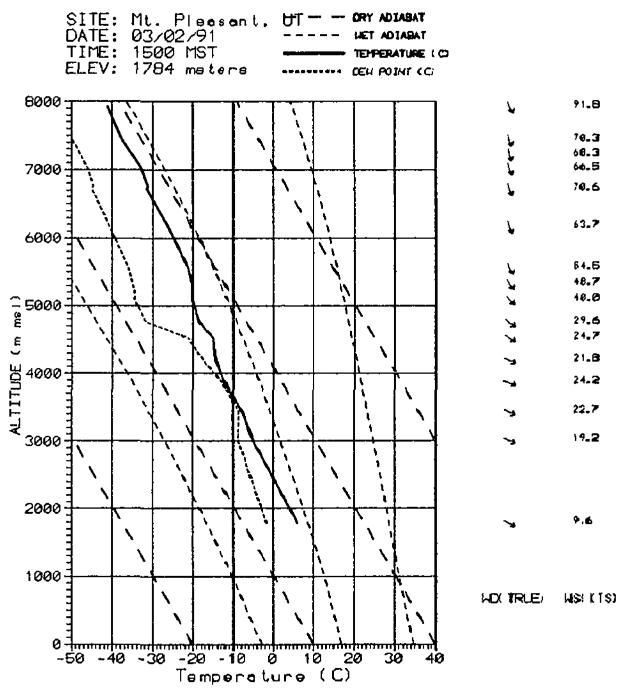

Figure 5 ***Mt. Pleasant, Utah Rawinsonde Observation, 1500 MST, March 2.***

Table 3

Summary of Meteorological Observations for the March 2 & 6 Test Cases

TIME (MST)	FAIRVIEW CANYON PRECIP (IN.)	HIGH ELEV. SITE PRECIP (IN.)	UDOT PRECIP (IN.)	FLAT CANYON PRECIP (IN.)	COUNTY LINE PRECIP (IN.)	UDOT RADIOMETER LIQUID WATER (MM) AVG.	UDOT RADIOMETER LIQUID WATER (MM) MAX	MT. PLEASANT AVG. WINDS (MPS)	MT. PLEASANT MAX SPEED (MPS)	MT. PLEASANT AVG. TEMP (°C)	FAIRVIEW CANYON AVG. WINDS (MPS)	FAIRVIEW CANYON MAX SPEED (MPS)	FAIRVIEW CANYON AVG. TEMP (°C)	FAIRVIEW CANYON 4 AVG. WINDS (MPS)	FAIRVIEW CANYON 4 MAX SPEED (MPS)	FAIRVIEW CANYON 4 AVG. TEMP (°C)	ESTIMATED CLOUD TOPS HEIGHT (KM)	ESTIMATED CLOUD TOPS TEMP (°C)
MARCH 2																		
1100-1200	.00	.00	.03	.01	.03	.18	.37	232/4.5	6	3.0	256/1.8	2	0.8	273/3.0	3	-1.3	-	-
1200-1300	.01	.00	.03	.01	.00	.15	.48	207/5.2	6	4.2	266/1.3	3	3.1	281/2.5	3	0.3	4	-14
1300-1400	.00	.00	.01	.00	.01	.07	.20	202/4.8	6	5.1	249/2.8	3	4.2	281/2.8	4	1.0	4	-14
1400-1500	.00	.00	.00	.00	.00	.13	.45	220/6.3	7	6.0	218/1.5	2	5.3	272/1.7	2	2.5	3.5	-10
MARCH 6																		
1500-1600	.00	.00	.00	.00	.00	.00	.00	234/3.8	4	-1.3	226/1.8	3	-0.9	276/1.8	2	-3.9	3.5	-17
1600-1700	.00	.00	.01	.00	.00	.00	.02	228/3.5	4	-1.2	242/1.3	2	-2.6	275/1.2	2	-5.0	3.8	-18
1700-1800	.00	.00	.01	.00	.00	.00	.00	259/2.7	3	-1.4	256/0.3	1	-3.7	273/1.0	1	-5.9	3.8	-18
1800-1900	.00	.00	.00	.00	.00	.00	.00	264/3.3	4	-1.8	253/0.7	1	-4.6	257/1.2	2	-6.7	3.5	-19

Aircraft sampling was conducted along two flight tracks (refer to Figure 2); one oriented approximately north-south over the western edge of the Wasatch Plateau and the other approximately 10 km east of the western track with a northwest-southeast orientation. The Wasatch Plateau rises to a maximum elevation of 3,440 m in this area. Flight legs on this flight were all flown at an altitude of approximately 3,750 m MSL. The aircraft encountered air frame icing and moderate turbulence.

The NAWC mobile van was driven in the research area during this day. The on-board SF_6 analyzer was operated to document any SF_6 existent at ground level.

5.2 Test Case Day, March 6, 1991

Figure 6 provides a portion of the National Weather Service 0500 MST surface analysis for this day. Utah was under post-frontal conditions. Broken clouds covered the research area. Figures 7 and 8 provide two rawinsonde observations taken at the Mt. Pleasant Airport site at 1500 and 1800 MST.

A research flight was conducted from 1600 to 1930 MST. All of the valley silver iodide generators had been turned on at 1330 MST. Sulfur hexafluoride was released at the mouth of Birch Creek Canyon from 1606 to 1900 MST at a release rate of 22.7 kg per hour. Table 3 provides a summary of the meteorological conditions during the time of the research flight.

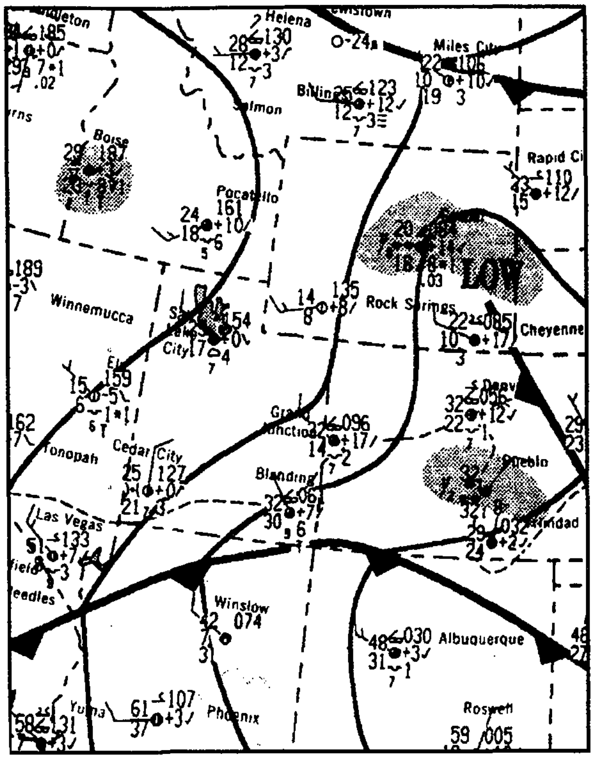

Figure 6 *National Weather Service Surface Weather Map, 0500 MST, March 6.*

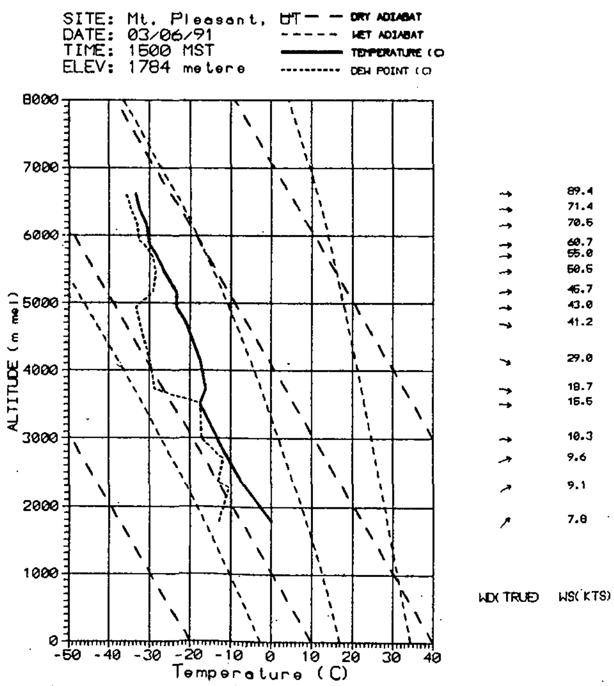

Figure 7 *Mt. Pleasant, Utah Rawinsonde Observation, 1500 MST, March 6.*

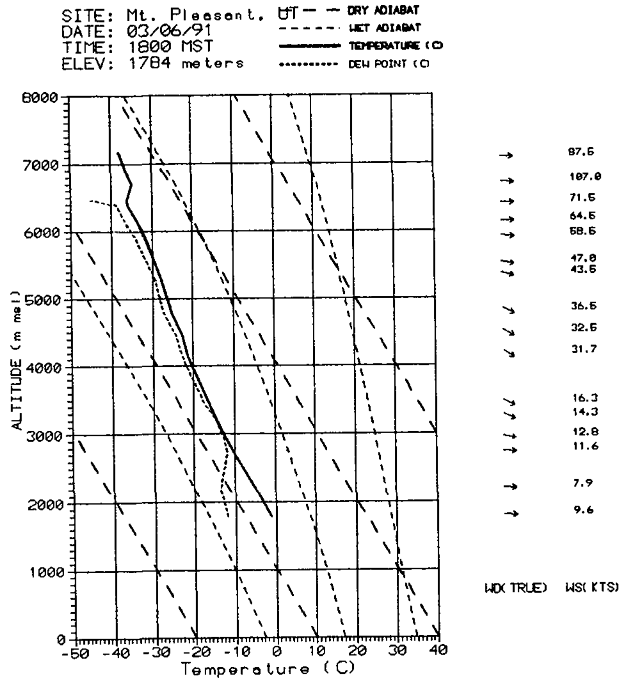

Figure 8 *Mt. Pleasant, Utah Rawinsonde Observation, 1800 MST, March 6.*

Aircraft sampling was conducted along the same two flight legs discussed in the March 2 case. Aircraft flight altitudes varied from 3,050 to 3,750 m MSL. The aircraft encountered minimal icing and turbulence.

The NAWC mobile van was not operated on this test day. Another surface sampling device was utilized on this case. This device consisted of a sequential syringe sampler. This device was sited near the UDOT operations center. Eight, one-half hour air samples were collected and later analyzed for SF_6 content.

6. RESULTS

The results obtained from these two test cases will be discussed separately.

6.1 March 2 Case

A total of seven aircraft flight legs were flown on this flight. Five legs were flown on the west track and two on the east track. SF_6 was detected on six of these legs. SF_6 was not detected on the last flight leg. This leg was aborted due to icing on the LORAN antenna.

Figure 9 provides a stacked plot of several variables for a representative SF_6 plume encounter for the first western flight leg as the aircraft was flying southbound at 3750 m MSL. Variables plotted (from top to bottom) include temperature (°C), liquid water content (gm^{-3}), pressure altitude (m), ice nuclei counts (NCAR counter operated at -20°C), and sulfur hexafluoride concentration (ppt). The SF_6 analyzer output voltages were converted into concentrations expressed in parts per trillion (ppt) on the basis of calibrations of the TGA-4000 analyzer conducted before and after each research flight. These calibrations utilized six different known concentration calibration gases and were performed while in flight.

Table 4 summarizes the information on all of the SF_6 plumes and related data. The aircraft speed was utilized to calculate the approximate width of the SF_6 plumes. Aircraft position was not utilized since LORAN data were occasionally missing. Table 4 indicates several relevant features. The SF_6 plumes detected on the western flight track were accompanied by maximum supercooled liquid water contents of .66 to .84 gm^{-3} at temperatures of approximately -12°C. There was no indication of any supercooled liquid water on the two eastern flight tracks in the SF_6 plumes, but there were pockets of supercooled liquid water on the eastern flight track outside the SF_6 plume. Maximum concentrations in these pockets were 0.30 gm^{-3}. The angle from the SF_6 release point to the end points of each SF_6 encounter was calculated. This information is provided in the last column of Table 4.

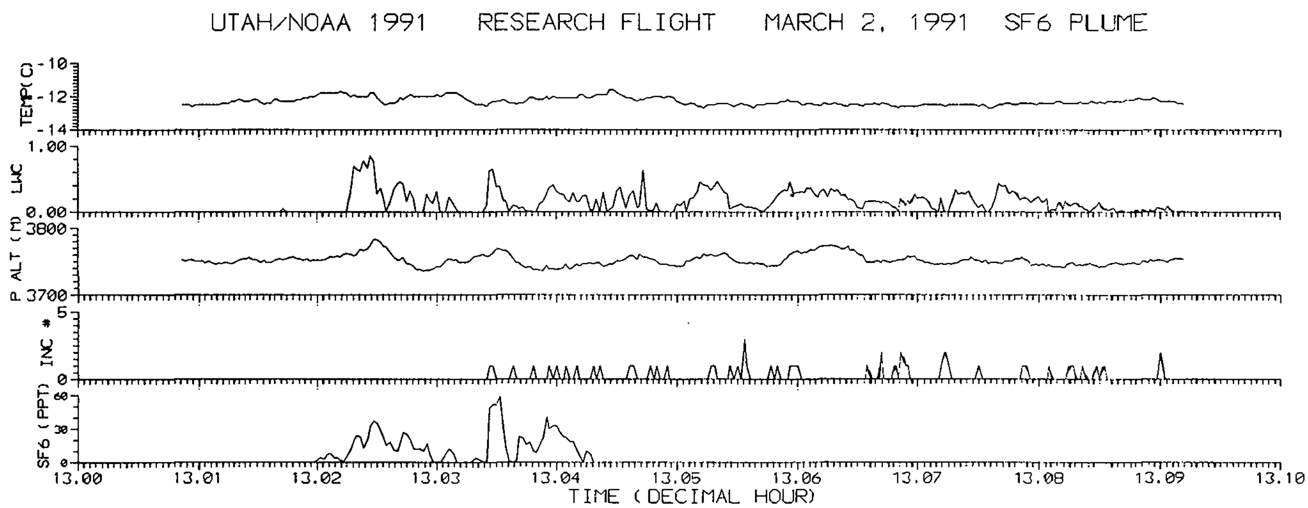

Figure 9 ***Stacked Plot of Relevant Variables Associated with an SF_6 Plume Encounter at 1302 MST March 2.***

Table 4

SF_6 Plume and Related Information from Second Flight on March 2

SF_6 Plme. No.	Time MST	Arcrft Track	Avg Arcrft Alt (M MSL)	Avg Arcrft True Air Spd (ms^{-1})	Avg Temp (°C)	Max* Liquid Wtr Cont (gm^{-3})	Time in SF6 Plume (Sec)	Avg SF_6 Conc (ppt)	Max SF_6 Conc (ppt)	Est SF_6 Plume Width (km)	Est Plume Angle (°)
1	1302	West	3753	83	-12.1	0.84	83	15	59	6.9	46
2	1315	West	3755	82	-12.3	0.66	71	48	185	5.8	40
3	1334	East	3750	84	-11.2	0.00	44	41	91	3.7	11
4	1342	East	3755	83	-11.2	0.00	113	17	55	9.4	25
5	1356	West	3754	81	-12.3	0.72	60	35	123	4.9	33
6	1411	West	3757	80	-12.3	0.66	39	7	46	3.1	21

**Note - These values are a factor of six times the raw values.*

One of the other variables plotted on Figure 9 is ice nuclei counts observed by the NCAR counter (operated at -20°C). Each of the stacked plots, for times near the SF_6 plume encounters, indicated the presence of some ice nuclei. These nuclei are interpreted to have resulted from the operation of the eight valley silver iodide ground generators. Recall that these valley generators were not co-located with the SF_6 release point. As a consequence it is not known if the ice nuclei resulted from one silver iodide generator or if they were the combination of several silver iodide plumes.

Figure 10 provides an X-Y summary plot of the locations of the six SF_6 plumes greater than 20 ppt. This figure indicates some veering in the flight level wind downwind of the barrier based upon the relative locations of the SF_6 plumes.

Figure 11 provides an X-Z summary plot of the six SF_6 plumes. A *vertical* transport of approximately 1,500 m is indicated. The SF_6 plume was no doubt transported to even higher altitudes based upon the observed SF_6 concentrations. Flight plans did not call for higher flight tracks to document the top of the SF_6 plumes.

The NAWC mobile van encountered the SF_6 plume on a number of traverses along the Skyline Road, south of UDOT. This road is approximately underneath a portion of the western flight track (refer to Figure 2). Maximum SF_6 concentrations reached 200 ppt; a value similar to that observed by the aircraft on the western flight track. Temperatures in the SF_6 plume at the surface varied between -5 to -7°C.

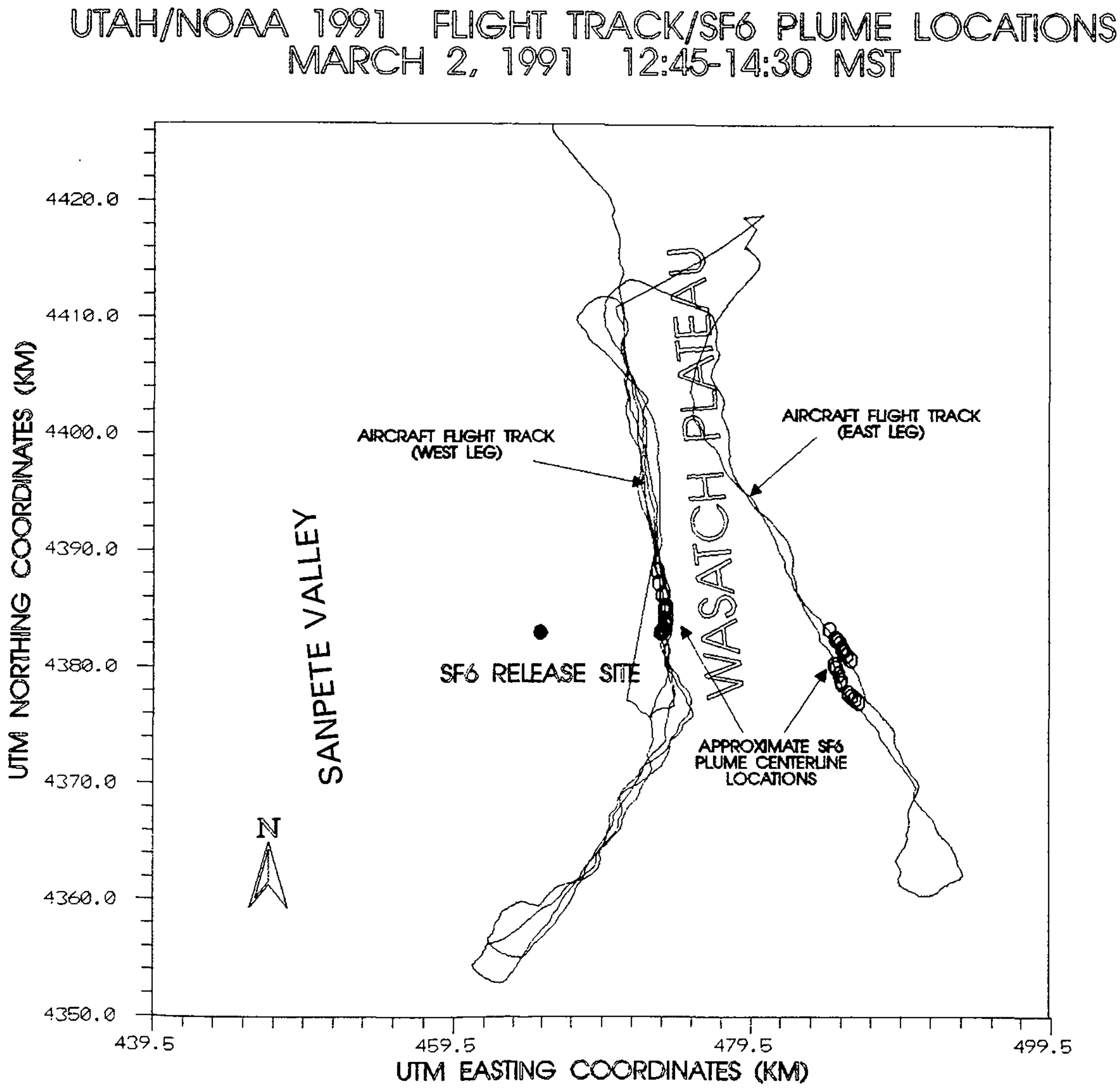

Figure 10 X-Y Summary Plot, SF_6 Plume Center Line Locations, 1245-1430 MST, March 2.

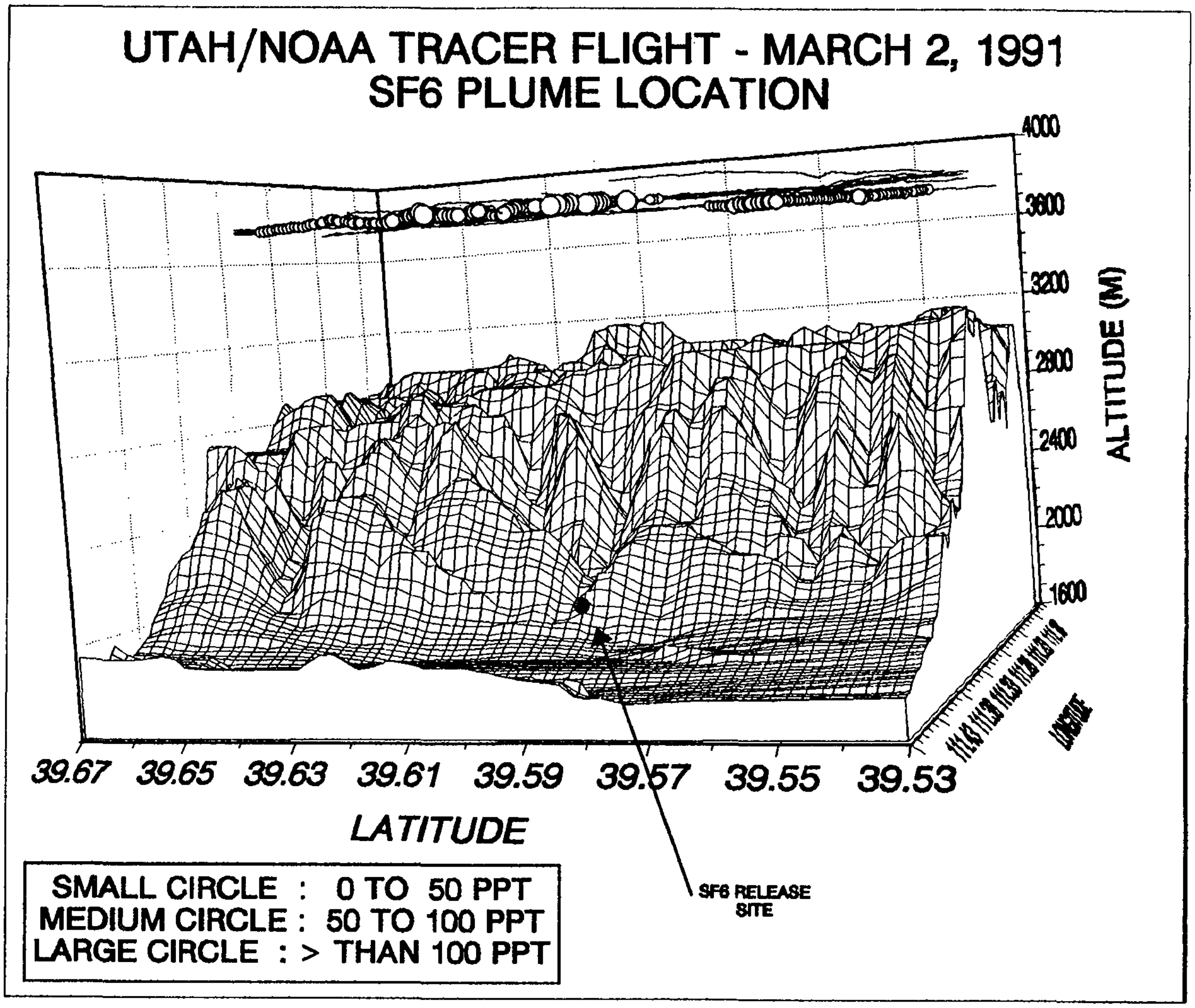

Figure 11 *X-Z Summary Plot, SF_6 Plume Locations and Concentrations, 1245-1430 MST, March 2.*

6.2 March 6 Case

A total of 14 aircraft flight legs were conducted on this research flight. SF_6 was detected on 10 of these legs. The surface and lower level winds were light during this case. If an average wind velocity of 2.6 ms^{-1} and a downwind transport distance of 7 km from the release site to the western flight track is used, then the SF_6 would not be expected to arrive at the western flight track until 45 minutes after the SF_6 release began. The SF_6 release began at 1606 MST and the first SF_6 plume encounter was at 1655, on the third flight leg. This time is in close agreement with the computed transport time.

Figure 12 provides a stacked plot of several variables similar to Figure 9 for the March 2 case.

Table 5 summarizes the information on all of the SF_6 plume encounters and related data. Some features of interest from Table 5 include the following. The air mass on this case was much colder than the March 2 case. There was a corresponding reduction in supercooled liquid water in this case. There was an indication of small amounts of supercooled liquid water in the SF_6 plume on the eastern flight track. There were two flight legs with a split SF_6 plume. At least one SF_6 plume seemed to be located in an isolated spike of supercooled liquid water content. This feature plus a close examination of the aircraft pressure altitude suggests this SF_6 plume may have been embedded in a small convective bubble. One of the more striking features was found on the last flight leg on which the SF_6 plume was detected. The SF_6 plume concentration encountered on this leg was the

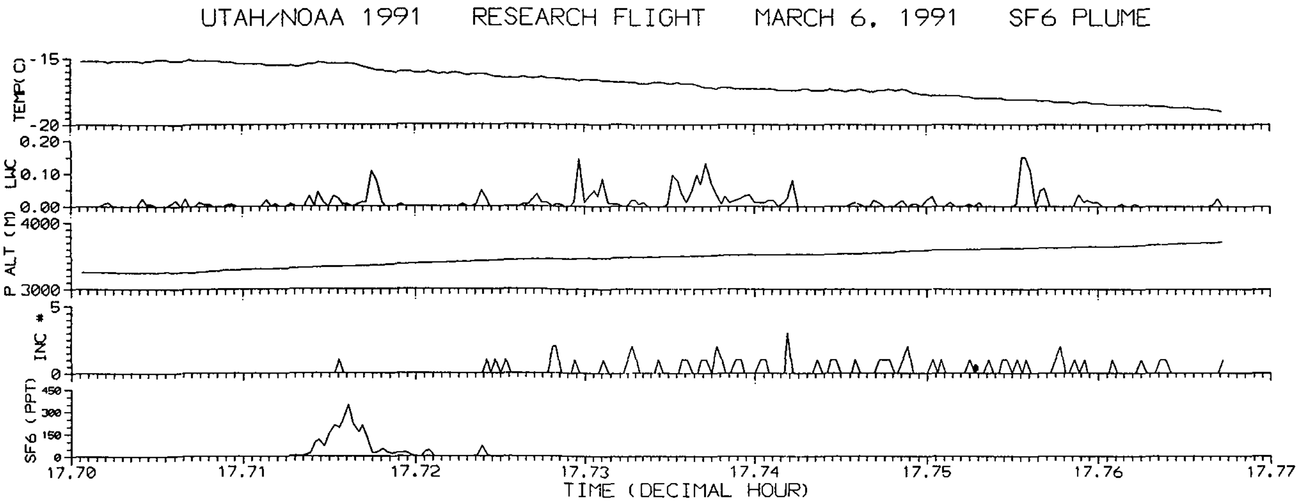

Figure 12 ***Stacked Plot of Relevant Variables Associated with an SF_6 Plume Encounter at 1743 MST, March 6.***

Table 5

SF_6 Plume and Related Information from March 6 Flight

SF_6 Plme. No.	Time MST	Arcrft Track	Avg Arcrft Alt (M MSL)	Avg Arcrft True Air Spd (ms^{-1})	Avg Temp (°C)	Max* Liquid Wtr Cont (gm^{-3})	Time in SF6 Plume (Sec)	Avg SF_6 Conc (ppt)	Max SF_6 Conc (ppt)	Est SF_6 Plume Width (km)	Est Plume Angle (°)
1	1655	West	3563	79	-17.4	0.06	14	25	62	1.1	8
2	1708	West	3264	80	-15.5	0.00	8	16	41	0.6	4
3	1720	East	3558	81	-17.6	0.18	71	30	109	5.8	19
4	1730	East	3545	82	-17.6	0.12	95	14	66	7.8	25
5	1743	West	3367	78	-15.8	0.12	43	61	345	3.4	20
6	1758	West	3304	80	-15.6	0.18	55	57	390	4.4	27
7	1808	West	3439	82	-16.8	0.06	50	20	189	4.1	29
8	1822	West	3726	79	-18.5	0.24	42	66	185	3.3	23
9	1834	West	3720	79	-18.5	0.00	24	51	194	1.9	13
10	1847	West	3717	80	-18.3	0.18	24	311	903	1.9	13

****Note - These values are a factor of six times the raw values.***

strongest concentration (903 ppt) observed on either of the two test case days. What makes this fact unique is that the flight altitude (3717 m) was the highest flown on the March 6 flight. The normal expectation would be for higher concentrations to be located at the lowest flight altitudes. The supercooled liquid water and pressure altitude tendencies within the SF_6 plume do suggest the possibility of an embedded "convective bubble" which could have been responsible for the vertical transport of this high concentration of SF_6.

A number of the ice nuclei counts from the NCAR counter operated at -20°C indicate the presence of the valley released silver iodide nuclei. Some of these NCAR counts may have been co-located with the SF_6 while others are widely dispersed.

Plume widths are wider and SF_6 concentrations generally lower on the eastern flight track compared to the western flight track.

Figure 13 provides an X-Y summary plot of the locations of SF_6 maximum concentrations greater than 20 ppt along the western and eastern flight tracks. Unlike the March 2 case, the plume locations on the eastern flight track appear to be directly east of the western flight track plumes. This figure suggests a bi-modal plume distribution on both the western and eastern flight tracks. A close examination of the underlying topography along with the prevailing westerly winds could suggest transport of the SF_6 up Birch Creek Canyon. Of interest in this scenario is the fact that Birch Creek Canyon splits into two canyons near the top of the Wasatch Plateau. It is possible that this feature produced the dual SF_6 plumes.

Figure 14 provides an X-Z summary plot of the maximum SF_6 concentrations greater than 20 ppt. This figure, similar to the March 2 case, indicates that the SF_6 plumes were transported 1,800 m vertically. Again, similar to the March 2 case, the SF_6 actually was no doubt transported to even higher altitudes based upon the observed SF_6 concentration at the highest flight track altitude (3,750 m MSL).

Table 6 provides the results obtained from the half-hour integrated syringe samples collected near the UDOT operations center. This table indicates that no SF_6 was observed from 1540 to 1610 MST; a reasonable result since the SF_6 release did not begin until 1606 MST. The following six, half-hour samples did, however, contain varying amounts of SF_6. These concentrations were typically 100 ppt or less except for the period from 1740 to 1810, when the concentration exceeded 600 ppt. The last sample, 1940 to 2010 MST, did not contain any SF_6, which is reasonable since the SF_6 release ended at 1900 MST.

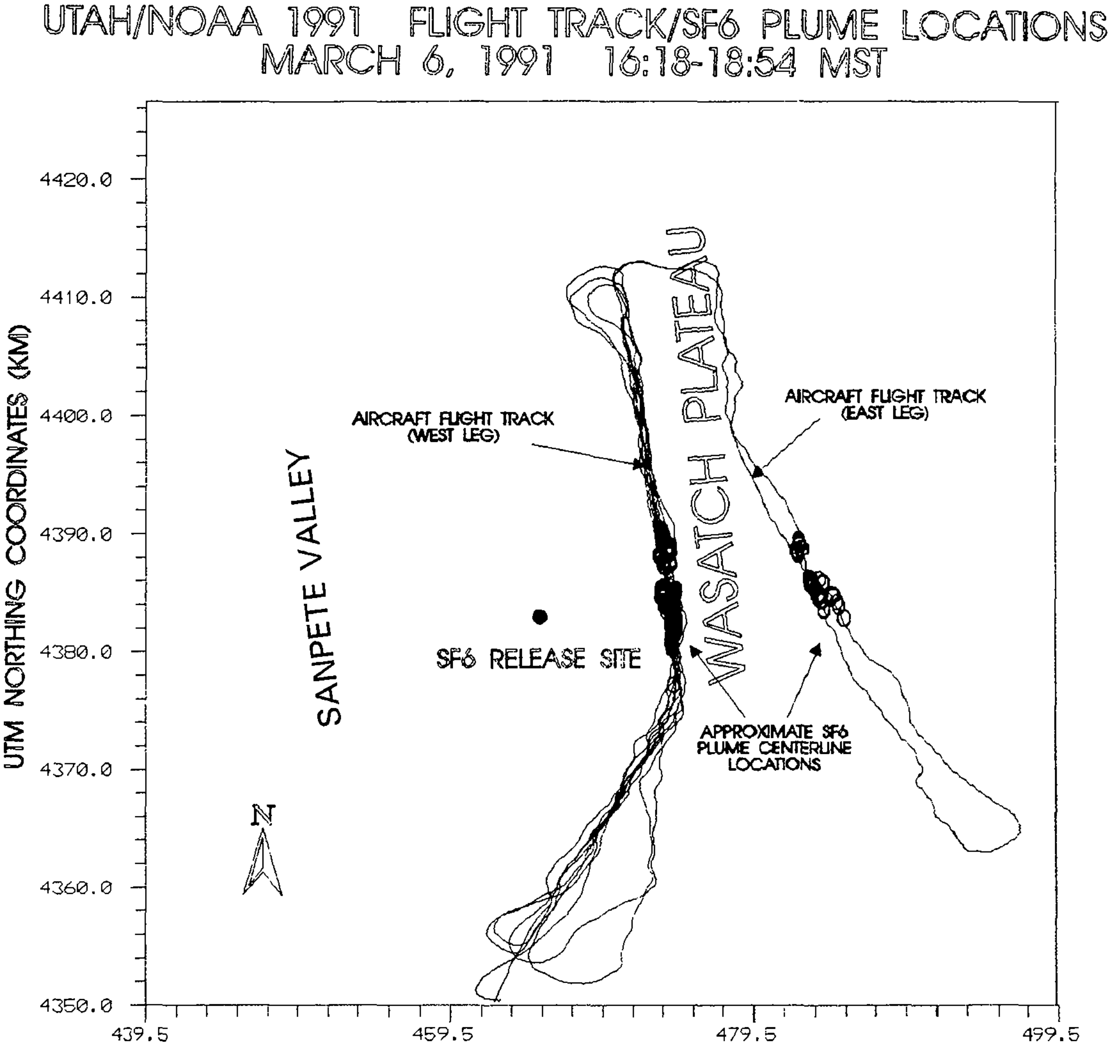

Figure 13 X-Y Summary Plot, SF_6 Plume Center Line Locations, 1618-1854 MST, March 6.

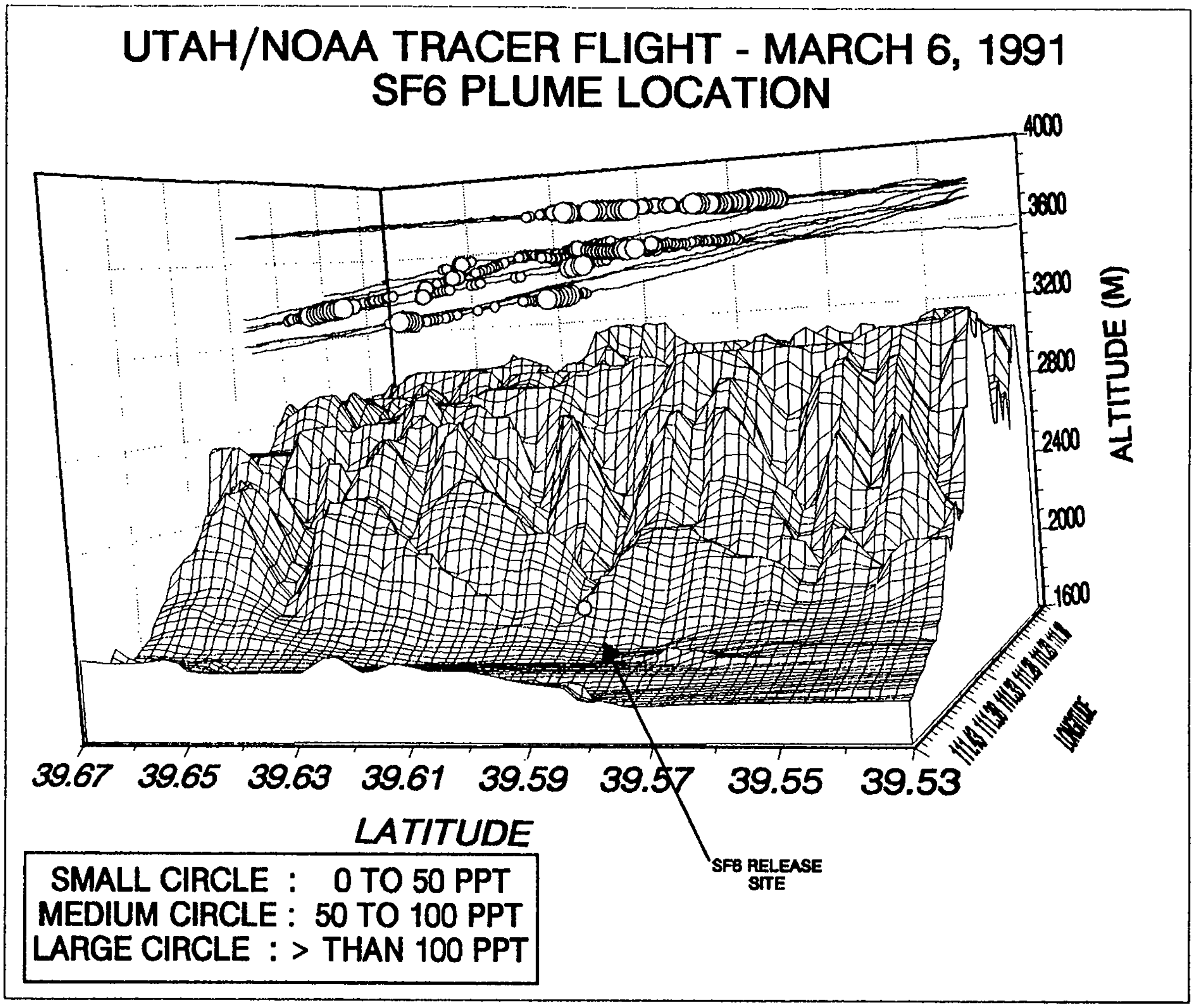

Figure 14 *X-Z Summary Plot, SF_6 Plume Locations and Concentrations, 1618-1854 MST, March 6.*

Table 6

Half-Hour Syringe Sampler
SF_6 Concentrations (ppt)
UDOT, March 6

Time (MST)	1540-1610	1610-1640	1640-1710	1710-1740	1740-1810	1810-1840	1840-1910	1910-1940
SF_6 Conc (ppt)	0	41	91	31	641	31	21	0

The overall impression from Table 6 is that of a meandering SF_6 plume that periodically passed by the UDOT site during each of the one-half hour periods. When comparing SF_6 concentrations in Table 6 with the aircraft observed SF_6 plumes, it is necessary to recall that the ground sampling was an integrated one-half hour sample, while those from the aircraft were essentially instantaneous values. Consequentially, to observe an average concentration of greater than 600 ppt for the 1740 to 1810 MST ground sample could have been the result of a much higher concentration passing by this site during this one-half hour interval, or the SF_6 plume remaining in the UDOT vicinity throughout the period.

7. DISCUSSION

The NCAR counter data from these two test cases indicate that silver iodide nuclei were transported from valley floor ground based silver iodide generators over the Wasatch Plateau. The background ice nuclei counts observed by the NCAR counter were <1 count per minute. A number of the flight legs on these two test cases experienced counts of 10-60 per minute. The SF_6 results provide detailed information concerning the transport of a tracer gas up and over the plateau. These SF_6 plumes rose to substantial heights above the release point; at least 1,500-1800 m and probably substantially higher. There is a suggestion that Birch Creek Canyon served as a transport medium for channeling of the SF_6 plumes. On some of the flight legs the SF_6 and silver iodide appeared to be co-located when an allowance is made for the difference in response times of the SF_6 and NCAR instruments, even though the two materials were released from different locations. This suggests that the silver iodide may have been channeled up through Birch Creek Canyon along with the SF_6.

Calculations can be made of the expected number of ice crystals that could have been produced had a NAWC ground based silver iodide generator been co-located with the SF_6 release point in Birch Creek Canyon. The formula is:

$$\frac{\chi AgI}{\chi SF_6} = \frac{Q\ AgI}{Q SF_6}$$

where: χAgI is the concentration of silver iodide,

χSF_6 is the sulfur hexafluoride concentration;

Q AgI is the release rate of silver iodide;

Q SF_6 is the release rate of sulfur hexafluoride.

The equation can be rearranged to:

$$\chi AgI = \frac{\chi\ SF_6\ Q\ AgI}{Q\ SF_6}$$

to solve for the concentration of silver iodide in the SF_6 plumes. Calibrations of the ground generator can be used to convert the mass of silver iodide (χAgI) into estimates of the number of ice crystals that could result. NAWC's generator has been tested in the Colorado State University Cloud Simulation Laboratory (Finnegan, 1982). The values from these calibrations for 0.50 gm^{-3} water content, maximum fan conditions, and for the pure silver iodide nuclei (produced through the combustion of silver iodide, ammonium iodide, and acetone) are:

at -12°C = 4×10^{14} crystals/g of AgI

at -16°C = 2.5×10^{15} crystals/g of AgI

Another factor is necessary to convert the observed SF_6 concentrations in ppt to units of mass. This factor is: 1 $\mu g/m_3$ = 167 ppt at standard temperatures and pressure. The King Air research aircraft was pressurized to 1525 m altitude (approximately 830 mb). The SF_6 analyzer was operated at cabin pressure. Consequently, the above relationship can be corrected to this pressure as follows:

$$\frac{830\text{ mb}}{1013\text{ mb}}(167\text{ ppt}) = 137\text{ ppt}$$

Utilizing this information plus the following for the March 2 case:

silver iodide release rate = 8g/hr.,

sulfur hexafluoride release rate = 34 kg/hr.,

average sulfur hexafluoride concentration = 40 ppt,

and the fact the SF_6 plume was at -12°C, results in an estimated 27 ice crystals per liter.

Similar calculations for the March 6 case where:

silver iodide release rate = 8 g/hr.,

sulfur hexafluoride release rate = 22.7 kg/hr.,

observed sulfur hexafluoride concentration = 50 ppt,

and the fact that the SF_6 plume was near -16°C (actually -17°C), results in an estimated 321 crystals per liter.

The large differences in the two cases are due to the following factors:

- An exponential increase in the number of crystals produced per gram of silver iodide with decreasing temperatures, and

- Higher SF_6 concentrations observed on the March 6 case with a lower SF_6 release rate than was utilized on the March 2 case.

The above calculations only consider the *potential impact of operating one ground based silver* iodide generator. In practice, plumes from adjacent generators operated in a given area may merge downwind of the release point. This factor could raise the calculations of ice crystals per liter. In an opposite sense, these may be losses of effective ice nuclei to cloud droplet and ice particle scavenging processes.

The SF_6 was transported over the Wasatch Plateau in these two cases with light surface winds observed in the upwind valley and at different locations on the windward slope. The SF_6 plumes reached temperature levels considered to be effective for silver iodide nucleation in both cases (-12 and -17°C). Some of the SF_6 plumes co-existed with low to moderate values of supercooled liquid water; another ingredient necessary for the production of a seeding effect.

Examination of the individual stacked plots for the March 2 test case indicated that the SF_6 was frequently present in regions of supercooled liquid water. These regions appeared to be associated with upward vertical motion. It is therefore concluded that these regions were associated with convection. The SF_6 plumes were observed at 1500-1800 m above the Wasatch Plateau. Based upon observed SF_6 concentrations, it is probable that these plumes reached higher altitudes. Table 4 indicates that the estimated cloud tops on March 2 were at 4 km. The plumes would have only needed to rise 250 m to reach the estimated cloud tops. Estimated cloud top temperatures were -14°C. Silver iodide, had it been co-released from the SF_6 site, could have produced more ice crystals than the calculated 27 crystals l^{-1} if it was transported to the estimated cloud top heights.

The March 6 test case was much colder than that of March 2. It was also a much weaker storm system producing only a few hundreths of precipitation on the plateau. Aircraft observations of supercooled liquid water were either 0 or occasionally .10 to .20 gm^{-3}. The Bureau radiometer at the UDOT site only observed a minimal amount of supercooled liquid water from 1600-1700 MST. The Desert Research Institute's mobile radiometer was operated along the Wasatch Plateau and also up and down Fairview Canyon. This mobile radiometer detected very little supercooled liquid water on this day except for a brief period from 1713 to 1728 MST. The mobile radiometer was driving down Fairview Canyon during this time. Liquid water values varied from .03 to .17 mm during this time. The Bureau radiometer at UDOT did not report any liquid water during this period. This period could have represented some seeding potential. This period was, in fact, being seeded from the valley based ground generator network as evidenced by NCAR counts considerably above background (several 10's of counts per minute). The cold *ambient temperatures at which the silver iodide* nuclei resided should have resulted in nucleation whenever the nuclei encountered any supercooled water droplets. The angles of dispersion (the last column in Tables 4 and 5) from the SF_6 ground based release point to the aircraft flight tracks ranged from 4 to 46°. An average of the angles from the four SF_6 plume encounters in March 2 on the west track was 35°. A similar average for the eight encounters on the west track for March 6 was 17°. Most of the difference between the two days averages occurred due to a very wide SF_6 plume being encountered on the first two western flight legs on March 2 (40 and 46°). It does appear there is still more lateral dispersion of the SF_6 on the March 2 versus March 6 case. The difference could be due to much stronger convection that was encountered on March 6. An average plume spread angle for the two days on the western flight track was 23°.

One important question that is not answered by this data set is whether multiple SF_6 releases from the valley generator network would merge over the Wasatch Plateau to form a relatively continuous "treated" volume. The NCAR counter data may provide some information on this question, but the lag time and flushing time of this instrument complicates such an analysis. A related question is, even if SF_6 and/or AgI is released at multiple valley sites, do the resultant plumes disperse in a relatively uniform fashion over the Wasatch Plateau, or are they channeled up some of the canyons as these test cases might suggest?

If it is assumed that there is uniform horizontal dispersion of AgI from the valley generators over the Wasatch Plateau, the mean SF_6 plume angle of 23° can be used to estimate a desired spacing between the valley generators. The mean distance from the ground based silver iodide generator sites to the western flight track is 10 km. In order for the plumes released from the valley to be continuous over the west track would require a generator spacing of 4.4 km based on an average dispersion angle of 23°. The spacing utilized in the conduct of the Utah operational seeding program is approximately 16 km. The spacing of the eight generators utilized in the conduct of this research program was approximately 5-10 km. Both the spacing on the operational and research program would appear to be too sparse on the basis of these calculations. Future research needs to address this question in more detail. The authors believe the best way to gain quantitative information on this question is through multiple valley releases of SF_6. Co-location of SF_6 releases with silver iodide releases would also be very beneficial. This would allow an analysis of ice crystals concentrations and sizes within and outside SF_6 plumes. These SF_6 plumes would be used to precisely "tag" the location of the silver iodide seeding material made possible by the very fast response time of the real-time SF_6 analyzer.

It is difficult to assess how representative the results from this two month research program may be of the climatology of Utah winter storms. Both of the test cases discussed in this paper were post-frontal. Post-frontal conditions in Utah in winter are frequently more convective than pre-frontal. The presence of convection may be important in the vertical dispersion of ground released seeding material.

It is concluded from this discussion that in these two test cases, silver iodide could have been transported from a release site at the mouth of Birch Creek Canyon into environmental conditions that would lead to nucleation. NCAR counter observations provide independent confirmation of the transport of silver iodide nuclei, released from the valley floor, over the Wasatch Plateau.

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