"REVIEWED"

MODELING AND OBSERVATIONS OF VALLEY-RELEASED SILVER IODIDE DURING A STABLE WINTER STORM OVER THE WASATCH PLATEAU OF UTAH

James A. Heimbach, Jr.
University of North Carolina
Asheville, NC

William D. Hall
National Center for Atmospheric Research
Boulder, CO

Arlin B. Super
Water Resources
Bureau of Reclamation
Denver, CO

Abstract. An experiment was conducted over Utah's Wasatch Plateau which, due to stable conditions, resulted in unexpected transport of silver iodide (AgI) and sulfur hexafluoride (SF6) tracer gas from valley floor and canyon mouth locations. The AgI ice nuclei (IN) and gas were transported vertically more than 1 km above the valley release sites in spite of the existence of a valley-based inversion beneath a saturated pseudoadiabatic layer. The Plateau top was well-targeted by IN at the surface; however, few IN were found at aircraft sampling levels. The SF6 was poorly targeted, with most of the surface penetrations by a mobile sampler being in the valley or in a canyon accessible by highway north of the release point. There were only three small airborne penetrations of the SF6.

The four-dimensional mesoscale model of Clark and associates was applied to this case. The model showed generally good agreement with the field observations and offered some insight into the manner in which the tracer material was transported over the Plateau. The model suggests that the AgI was initially transported from the surface through the inversion by the gravity wave mechanism, whereas the SF6 likely had a limited initial vertical impetus through anabatic motion.

1. INTRODUCTION

This paper examines the transport of valley-released silver iodide (AgI) over the Wasatch Plateau of central Utah (hereafter Plateau) during an experiment with a surface-based inversion. The case discussed herein occurred on 7 February during the early 1994 winter field program. In the sections which follow, the experiment and observations are briefly described, as is the application of the four-dimensional Clark mesoscale model to estimate the character of transport in unsampled regions.

Other case studies of transport have been reported for the Plateau. For example, Super and Huggins describe targeting of valley- and canyon-released AgI in an analysis of surface observations (1992a) and aircraft observations (1992b) from the 1989-90 field season. Surface silver-in-snow and real-time IN measurements indicated that AgI was transported up a major canyon over the Plateau but in limited amounts. Co-released sulfur hexafluoride (SF_6) was detected by the program's aircraft for only one of five flights. These two papers highlighted the difficulty in targeting seeding material. Heimbach and Hall (1994) applied the Clark mesoscale model (Clark 1977; Clark and Hall 1995) using various release configurations in a case which had neutral stability and no embedded convection. They found that transport of seeding material over the Plateau was dependent on the placement of the sources. They also demonstrated that downwind depletion of supercooled liquid water (SLW) was at least in part due to subsidence warming within a gravity wave pattern. Holroyd *et al.* (1995) reported on the analysis of the 21 February 1994 experiment which had weak surface winds, light snowfall and weak convection in thin orographic clouds over the Plateau. In that experiment, AgI and SF_6 were co-released from a site well up the windward side of the Plateau. A microphysical seeding signal was associated with the IN plume both at the surface and aloft. Modeling results of transport were reasonably close to observations for this case. Bruintjes *et al.* (1995) applied the Clark model to three cases from the 1987 Arizona/NOAA Cooperative program, another winter orographic experiment. Each case had a single point-source of SF_6. Results from field observations and the model led them to conclude that the transport and diffusion of seeding material are dependent upon the flow and stability conditions around the valley release site, and gravity waves stimulated by upwind terrain.

2. EXPERIMENTAL DESIGN AND INSTRUMENTATION

The early 1994 Utah field program was conducted under the auspices of the Utah/NOAA Cooperative Atmospheric Modification Program (AMP) which investigated the long-standing Utah operational winter weather modification program.

One of the goals of the Utah/NOAA AMP is to examine the transport and diffusion of seeding material over target areas. Targeting has been cited as a significant problem in winter orographic weather modification projects (Reynolds *et al.* 1989; Super 1990; Super and Huggins 1992a and 1992b). Beginning in the winter of 1989-90, field work has been conducted over the Plateau of central Utah to take advantage of the year-around highway access over the Plateau and less complex summits allowing lower-level aircraft sampling. The smoothed terrain applied in the Clark model is displayed in Fig. 1, and locations of instrumentation are included in Fig. 2.

Only the instrumentation relevant to this paper is described below. Stationary surface sampling sites include three automatic weather stations, the Radar-Radiometer Site (RRS) located on the west edge of the Plateau, and the Target (TAR) Site located toward its eastern edge. One automatic weather station was located midway up of Fairview Canyon through which Highway 31 runs, one was well up Birch Creek Canyon, and the third was at the Mount Pleasant Airport (MPA) located south of Fairview. MPA was also the radiosonde release site. The RRS was the principal surface sampling location where variables of state, wind from a heated anemometer, SLW presence from a Rosemount icing indicator, vertically-integrated SLW measured by a microwave radiometer, and continuous IN measurements (discussed later) were recorded. The TAR Site was intended to sample the downwind portions of a surface plume and recorded the same parameters as described for the RRS above, excepting the radiometer.

An instrumented van, fitted and operated by North American Weather Consultants (NAWC), was equipped to record variables of state, wind, and IN and SF_6 encounters. A global positioning system (GPS) receiver provided positioning for the van.

An instrumented aircraft was provided by USDC/NOAA/ARC and its configuration and scientific direction were by NOAA/ERL/ARL, Boulder, CO. This was a Beechcraft King Air C-90

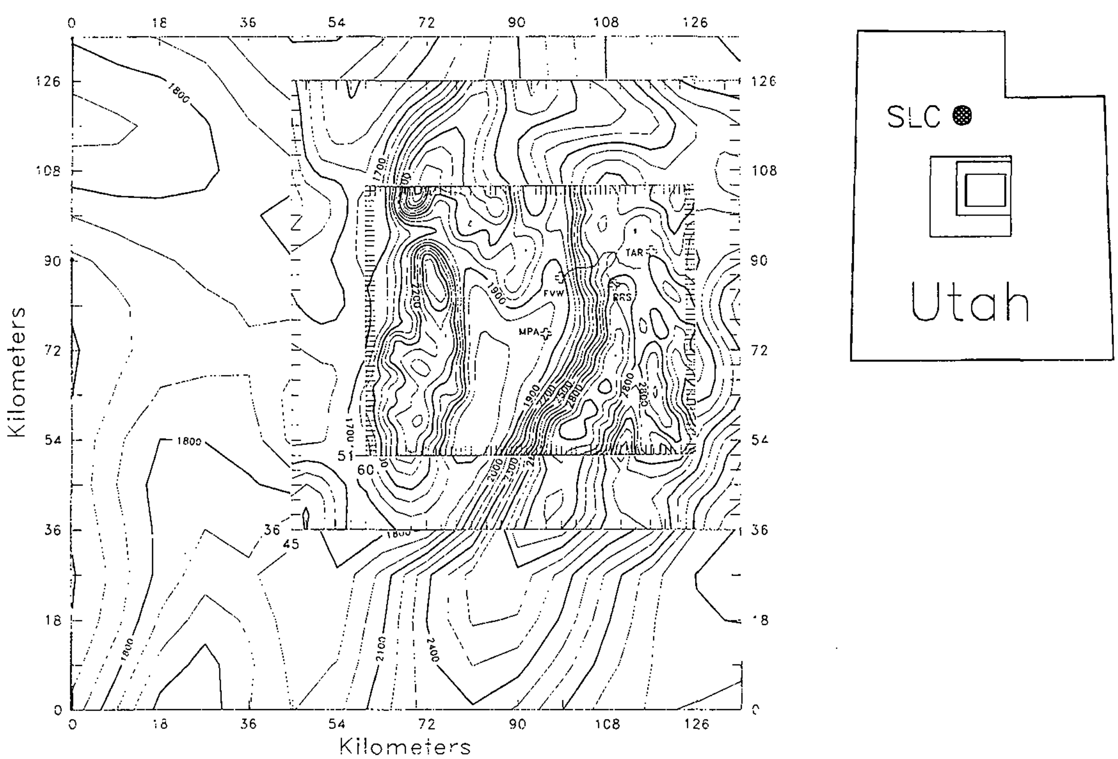

Fig. 1. The three domains and their relative positions applied in the Clark model. The respective tic marks indicate horizontal grid spacing and distances are relative to the southwest corner of the outermost domain. Highways 31 and 264 are entered.

"REVIEWED"

(N46RF). The aircraft recorded variables of state, SLW content, horizontal winds, IN and SF_6. Positioning was by LORAN and GPS. Three designated flight tracks were used; two roughly north-south on the upwind and downwind edge of the Plateau (indicated in Fig. 5), and one from the southwest-to-northeast over the RRS. Due to the relatively uncomplicated topography of the Plateau in the vicinity of the target area, a waiver was granted by the FAA to allow a minimum IFR flight of 300 m above ground level (AGL).

AgI was released from three valley sites established by NAWC in the Sanpete Valley. The generators burned 2% by weight AgI in composition with NH_4I-acetone-water in a propane flame. The generators each burned 8 gm AgI hr^{-1}. Ice nuclei were measured continuously by National Center for Atmospheric Research (NCAR) acoustical IN detectors (Langer 1973). Because of delays caused by intake plumbing, time to grow a detectable ice crystal (≥20 μm) and sample mixing within a cloud chamber, the recorded IN plume has a lag time to plume detection and an indicated width which is wider than the actual plume. For the aircraft IN counter, the lag was found to be 92 s whereas for the surface IN detectors, 60 s was applied. Approximately one in ten IN within a given sample are detected due to chamber wall losses and other factors (Langer 1973). Because the sample rate of these IN counters is approximately 10 L min^{-1}, one count per minute yields approximately one IN L^{-1}.

Sulfur hexafluoride was released from the mouth of Birch Creek Canyon which is located about 6 km south of Fairview Canyon. The SF_6 release point was about 1.5 km east of the northern-most AgI generator. Sampling of SF_6 was with Scientech Inc. fast-response detectors described by Benner and Lamb (1985). This device was designed for continuous, real-time measurements of SF_6 with mixing ratios as low as five parts per trillion by volume (pptv). The lag time for the van's SF_6 system was 3 s, whereas that for the aircraft was 23 s for this date. The latter was longer due to the greater intake plumbing and an in-line hydrocarbon scrubber.

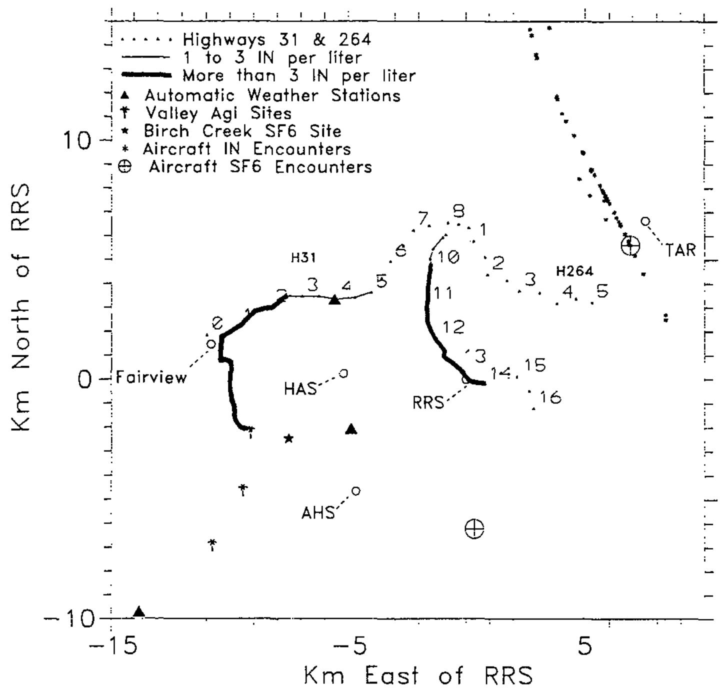

Fig. 2. Ice nucleus plume encounters (effective at -20°C) by the van for the period 0710 - 0921 on 7 February 1994. The numbers to upper right of the points represent mile markers on Highways 31 and 264. Aircraft IN and SF_6 plume encounters are also indicated.

3. WEATHER FOR 7 FEBRUARY 1994 CASE

Flow aloft over the southwestern U.S. was zonal and the subtropical jet was established over that region. An upper-level trough extended from British Columbia southwest into the eastern Pacific. At the surface, there was a high over the Four Corners area and a quasi-stationary front extended from Idaho southeast through Colorado, then toward New England. A frontal system anchored in a low over California brought moisture to the experimental area. Wave clouds were observed over the mountains by the air crew and no embedded convection was observed.

The principal reason for selecting this case was the surface inversion present in the 0800 (all times MST) MPA sounding. By the 1200 sounding, this inversion was replaced by nearly adiabatic conditions near the surface, but with stable conditions above. Figure 3 is a sounding composited from the 0800 and 1200 MPA soundings plus aircraft data, used to initialize the model.

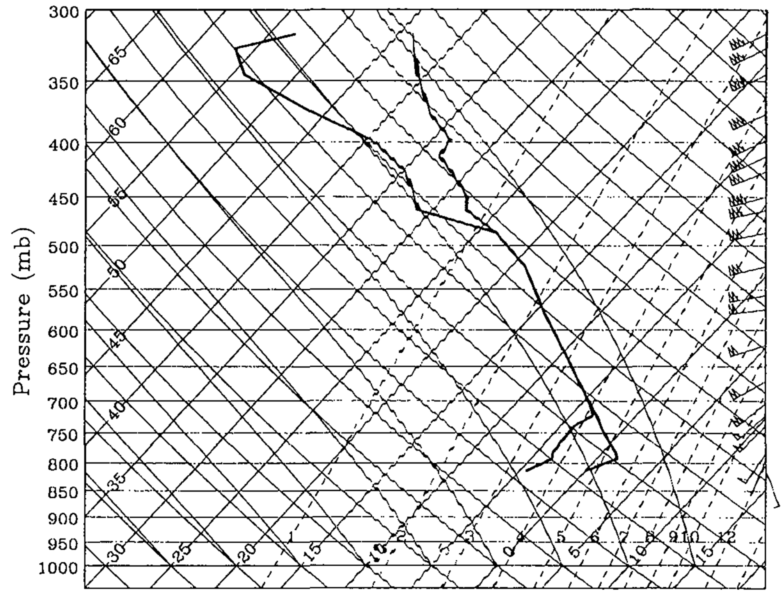

Fig. 3. Sounding used for model initialization, 7 February 1994.

Cool temperatures and high SLW content provided seeding potential. The temperatures at the RRS were approx. -7°C at 0700, rising to about -5°C by 1300. Those at the TAR Site were slightly warmer. At flight level, the temperatures ranged from -13°C at 4.0 km to -8°C at 3.4 km. The Rosemount probe at the RRS indicated surface-level SLW with 1 or 2 "trips" (cycles of rime ice accumulation and deicing by heating) per hour between 0730 to 1600 and again after 1830. No Rosemount SLW "trips" were recorded at the TAR Site during this period. The RRS radiometer indicated up to 0.8 mm vertically integrated SLW.

4. EXPERIMENTAL OPERATIONS FOR 7 FEBRUARY 1994 CASE.

Silver iodide was released from the three NAWC valley sites from 0600 to 0848 and again from 0905 to 1357. Sulfur hexafluoride was released at the Birch Creek Canyon mouth from 0755 to 0834 and again from 1101 to 1330. The breaks in releases were due to uncertainty about future aircraft operations discussed below.

There were two sampling routes driven by the van on this date. Both started at the base site near the northernmost AgI generator. From there, the van traveled northward to Fairview, eastward up the Fairview Canyon on Highway 31, then south on the Plateau top until past the RRS. The return was along the same route. The first route was from 0712 to 0915, excluding start up and calibration, and the second was from 1222 to 1418. During the first part of the earlier trip, the data acquisition system malfunctioned east of Fairview. Therefore, most of the data for the van is from hand-written notes. The TAR Site operated during periods of van and aircraft sampling, and the RRS operated throughout that day.

There were two flights on this day; however, the first has little scientific interest beyond some cloud physics data collected in the Provo area. Prior to takeoff for the first flight, a deice boot failure occurred, forcing an early termination of the flight. The second flight took off at 1043 and lasted 3.4 hrs. During the second flight the aircraft sampled along each of the three prespecified flight tracks beginning with three passes on the west track, followed by three passes on the southwest-to-northeast track, then four passes on the east track, and finally four passes on the west track.

5. PLUME TRACING

Figure 2 shows IN plume penetrations by the van during the first of the two trips. The thin lines indicate IN detection at ≤3 IN min^{-1} and the thick lines are for > 3 IN min^{-1}. This is equivalent to the units L^{-1}, assuming one in ten IN are detected due to cloud chamber loss and a sample flow rate of 10 L min^{-1}. Both the up-mountain and return legs indicated high IN concentrations from the base to Fairview. This would be expected because of the southerly component of the surface winds, the vicinity of the AgI generators and valley inversion conditions. The highest IN concentrations found by the van outside the valley were during the southward then northward traverses on the Plateau during the first trip. For the second van trip, only weak count rates (≤3 IN min^{-1}) were detected E of Fairview, and these were limited to portions of the Fairview Canyon and the northernmost three miles of Highway 31 on top of the Plateau (Fig. not included).

The high IN counts found on the Plateau top during the first van traverse were verified by IN measurements at the RRS where high concentrations were detected as soon as the IN counter was turned on at 0730. The maximum IN concentrations, effective at -20°C, reached almost 600 L^{-1} by 0830. Thereafter, values diminished with time but stayed above 5 L^{-1} until about 1230 after which concentrations slowly approached background levels.

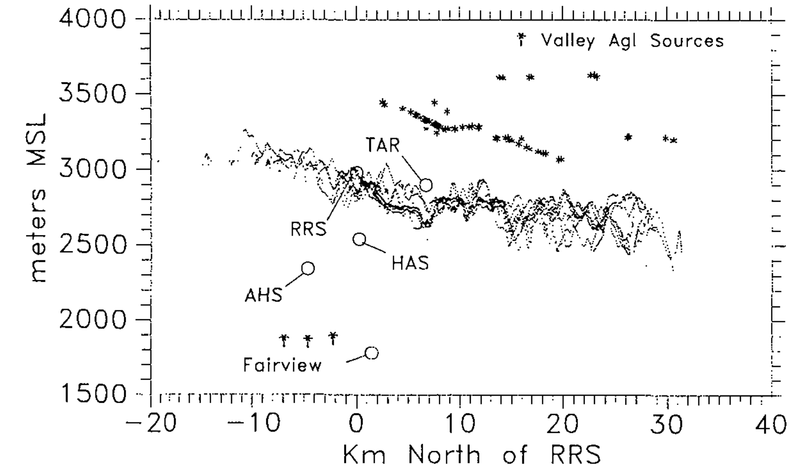

Fig. 4. South-to-north vertical cross section showing positions of aircraft-measured IN lagged by 92 s. The terrain was derived from aircraft radar altimeter measurements.

Of the fourteen passes made by the aircraft on this date, only one had a significant IN plume encounter. This was at approximately 1230 over the E track. Figure 2 shows aircraft-detected IN whose positions are lagged by 92 seconds. Two areas of sparse IN were also detected using the assumption that one IN registered within a minute of another presumes the two were above background. During both the 1991 and 1994 field seasons, the aircraft-sampled background IN concentrations were consistently far less than 1 min^{-1} (<1 L^{-1}) and for the most part zero. The areas of sparse IN are on the downwind portions of the southwest-to-northeast track and 15 km north-northwest of the TAR Site (beyond the borders of Fig. 2).

Figure 4 is a S-N vertical cross section depicting lagged aircraft IN encounters meeting the two IN within 1 min criteria. Surface terrain derived from the aircraft's radar altimeter is included. The only significant airborne IN encounter is the line of asterisks at the lowest altitude. The IN plotted above this were found on the far northeast portion of the southwest-to-northeast path. The IN group to the north are associated with a weak SF_6 encounter.

At the TAR Site, high IN concentrations were detected between 0753 and 1019, and again between 1134 and 1306. The peak concentrations (effective at -20°C for the earlier period was 3000 L^{-1}, and for the latter, 1600 L^{-1}. Between these periods, lesser IN concentrations were found and values dropped to background levels by 1346.

The van detected SF_6 only on its down-canyon portion of the Fairview Canyon route for the first trip, from the top of Fairview Canyon to the outskirts of Fairview. During the second trip, SF_6 was found in both directions over the same route, but from the outskirts of Fairview to mile marker 4 (each mile along the highways is shown in Fig. 2) traveling east, and from mile markers 8 to 2 traveling west.

The aircraft detected three marginal SF_6 plumes. Two of these encounters are shown as crossed circles in Fig. 2. More plumes may have existed; however, the signals, if they existed, were not sufficiently above the noise level (10 to 20 pptv) to use with certainty. Moreover, rapid drifting of the baseline was noted during periods of this flight. The times of SF_6 plume encounters are 1125, 1230, and 1259. The first was approximately 7 km south of the RRS and the last was in the same area as the sparse IN plume found north-northwest of the TAR Site.

Surface and airborne sampling indicate there was successful transport of seeding material from the valley sites over the Plateau, but in a shallow layer. The RRS sampling suggests that this transport continued until near 1230. The reduction of IN concentration could not have been due to generator shutdown since the last generator was turned off at 1357. At 1240 the (MPA) winds shifted from a generally easterly direction to one which had a northerly component for a half hour. The TAR Site was successfully targeted by the valley releases as well, though not continuously. There was some vertical mixing apparent along the E track, allowing some IN to be detected at flight levels from 300 to 500 m AGL.

The surface SF_6 tracing indicated a north- and northwestward transport in the valley, reinforcing the notion of pooling. There were several periods of down-canyon flow in Fairview Canyon after 0900. The Birch Creek Canyon weather station indicated an easterly component only at 0730 and 0930, but this site was further up the canyon than the release site. The MPA weather station indicated an easterly component until 1335. The easterly component of the SF_6, and the westerly transport of the IN plume over the top of the Plateau suggest a complex flow pattern for this case.

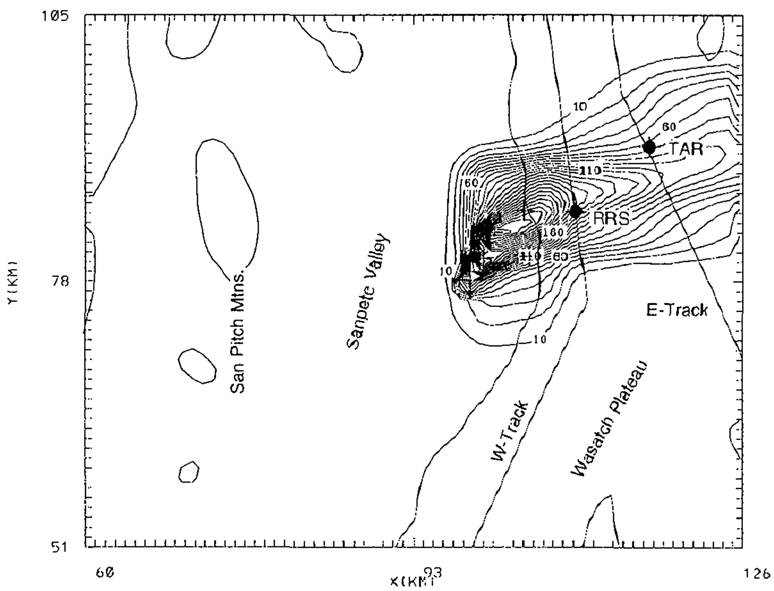

Fig. 5. Model estimates of AgI concentration at the surface after a 2 h simulated release from the three valley sites. The minimum contour and contour interval are 10 pgm⁻³.

6. MODELING AGI TRANSPORT

Although diverse and high quality data were obtained in the measurement program, key areas were not sampled. To estimate conditions in these areas, the four-dimensional mesoscale model of Clark and associates was applied (Clark 1977; Clark and Hall 1995). The model is nonhydrostatic and anelastic implying vertical accelerations are permitted, but the anelastic continuity equation is used to eliminate acoustic-scale waves. The model uses geo-spherical nonorthogonal coordinates. The vertical coordinates are aligned with the terrain at the lowest level and the top of the outermost domain is at a constant height (17.5 km MSL). The vertical grid increments are stretched starting with 50 m at the surface, expanding to 0.5 km at the top. The model's configuration for application to the Plateau has three interactively-nested domains to insure that large-scale meteorological features contribute to the fine-scale innermost domain while conserving computer resources. Figure 1 illustrates the three nested domains. The horizontal resolutions of the three are 9, 3, and 1 km, and the mesh sizes are 16 by 16 for the outermost domain, 30 by 30 for the middle, and 66 by 54 for the innermost domain.

The model applied the Kessler (1969) bulk parameterization which assumes two types of condensate; cloud water and rain water. The ice phase mechanism was not invoked for this case study. Eulerian transport is used in the model which produces an instantaneous spread of seeding material through one grid element, 1 km by 1 km by 50 m for the innermost domain. This initial spread is large in comparison to the true plume dimension. However, with time this contribution is small compared to the contributions by meteorological factors.

The model was run on the National Center for Atmospheric Research (NCAR) CRAY Y-MP8/864. Job submission and graphics processing were done on local workstations accessing the CRAY via the internet. Initialization was from the single composited sounding discussed previously (Fig. 3). The model was run for one simulated hour, then simulated releases of AgI from the three valley sites were started simultaneously and the model was run an additional 2 h simulated time.

7. MODELING RESULTS

Figure 5, a plot of surface AgI concentrations, shows the three AgI plumes rapidly merging, then moving to the east-northeast over the Plateau. The plume tends to follow the lower terrain over the western portions of the Plateau, and the core of the plume passes four km south of the TAR site. The easterly surface component of wind observed in the valley was not predicted by the model; however, there was a zone of near zero speed in the center of the valley.

The question is, how can the seeding material be transported over the Plateau during inversion conditions with weak or easterly winds in the valley, and no buoyancy aloft. The stable atmospheric conditions permit the formation of gravity waves. The Brunt-Väisälä frequency of vertical oscillations in a stable conditions is,

$$\nu = \left[\frac{g}{\theta}\frac{\partial \theta}{\partial z}\right]^{0.5}. \qquad (1)$$

A representative mean potential temperature from the initialization sounding is 299 °K, and the $\partial\theta/\partial z$ term is 3.5 °K km^{-1}. Dividing $2\pi U$ by the resulting frequency, where U is a representative cross-barrier speed set to 18 m s^{-1}, gives a gravity wavelength of 11 km for this case. Figure 6 shows a W-E cross section of vertical velocities after 180 simulated min. The modeled wavelength is somewhat larger than that estimated by Eq. (1). The stimulus for the gravity waves appears to be principally from the San Pitch Mountains. There is an upward motion over the E edge of the Sanpete valley which may be reinforced by an orographic component. A zone of negative vertical velocity begins east of the windward edge of the Plateau, and another positive zone exists over the TAR area. Although there are high concentrations of AgI at the surface over the Plateau, the only significant IN plume sampled by the aircraft occurred where the model indicated a gravity wave produced positive vertical motion. The initial vertical transport of the seeding material in the valley may have been by the gravity wave mechanism. After the initial vertical impetus, orographic lifting likely contributed to the transport over the Plateau as evidenced by the generally southwesterly to west-southwesterly flow at the RRS. The AgI was apparently transported over in a shallow layer except where influenced by the next downwind zone of positive vertical motion.

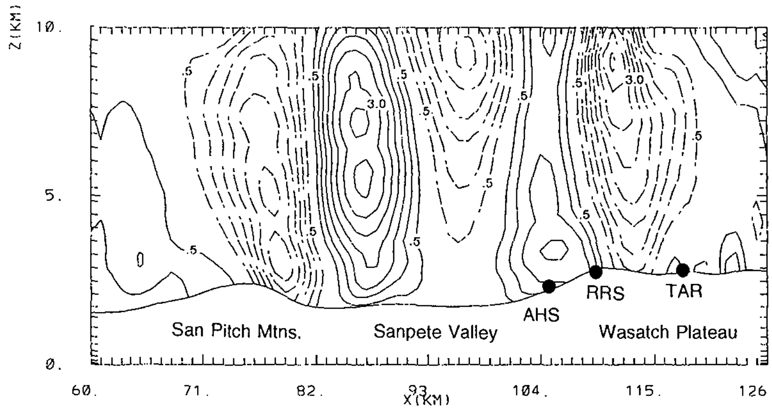

Fig. 6. West-to-east vertical cross section of vertical velocity after 3 h simulated time (Same time as Fig. 5). The N-S position of cross section is approximately through the RRS. The contour interval is 0.5 m s^{-1} and negative contours are dashed.

8. DISCUSSION

The transport of AgI released from three valley sites was examined for an experiment conducted on 7 February 1994. Sulfur hexafluoride was also released from the mouth of a canyon located about 1.5 km east of the northern-most AgI generator. The observations indicate transport of the AgI over the Plateau despite its being released in a stable surface layer with weak and sometimes easterly winds.

At both the RRS and the TAR Site, concentrations of 100 IN L^{-1} were commonly sampled with the acoustical IN counter, effective at -20°C. The temperatures at these sites were approximately -6°C. The IN effectiveness of the generators and solution used is 2.5 orders of magnitude less at -6°C then at -20°C (DeMott *et al.* 1995), giving an effective concentration of only 0.24 IN L^{-1} at the Plateau-top sites. There were, however, periods having concentrations of several thousand per liter effective at -20°C suggesting effective concentrations on the order of 5 L^{-1}.

No IN or SF_6 plumes were detected by the aircraft on the west track which could sample no lower than 300 m above ground level. The only significant IN plume detected aloft was over the east track in the vicinity of the TAR Site up to 3.5 km MSL (minimum IFR elevation). For the acoustic IN counter, the indicated spread of an IN encounter is due to actual spread plus a temporal component from mixing within the cloud chamber (Heimbach *et al.* 1977). For this reason, estimating the peak concentration of IN at a point is difficult for aircraft sampling. Adjusting for cloud chamber mixing, the maximum aircraft-measured concentration of IN was less than 20 IN L^{-1} effective at -20°C. The temperature at this level was -8°C, implying the maximum concentration of effective IN was less than 1.5 L^{-1}. Zones of SLW over the Plateau were targeted by IN, though indications are that this was in a shallow layer. Later in the experiment, IN concentrations on the Plateau were reduced to near-background levels.

For the present case study, modeling suggests that the valley-released AgI had an initial vertical impetus by the gravity wave mechanism which provided transport above the surface inversion. This was followed by orographic forcing in a more organized westerly flow. The model confirmed the confinement of the plume to a shallow layer and subsequent lifting again due to a gravity wave further eastward in the vicinity of the TAR Site.

It may be possible to exploit the influence of gravity waves in surface-based seeding strategies. This was explored by Heimbach and Hall (1994) who applied the model to several source configurations. Super (1994) suggested that targeting might be enhanced if releases were from a barrier upwind of the Plateau, in this case the San Pitch Mountains. Targeting from high altitude releases is generally successful provided there is an organized cross-barrier wind component. On the other hand, valley releases have uncertainties in terms of reaching the target and doing so in sufficient concentrations (*ibid*). Therefore, the gravity wave mechanism would be best exploited with valley releases which can "load" an entire valley floor with high IN concentrations. The wave structures can be wide-ranging depending on speed and stability, making a broad source area or pool of aerosol advantageous. Seeding from the valley sites could not take advantage of fast-acting forced-condensation nuclei (Finnegan and Pitter 1988) because the temperatures are frequently above -6 °C (Li and Pitter 1997). Therefore, a contact nucleant would be appropriate provided the gravity wave mechanism contributed to a deep enough lifting to reach sufficiently colder temperatures.

The criteria for judging the possibility of gravity wave excitation are uncomplicated: 1/ a cross-barrier wind component exists, and 2/ the atmosphere is stable. For the latter, this implies θ increases with height which includes moist adiabatic profiles commonly observed in project soundings. A more objective criteria can be devised using the Froude number, Fr. This is a nondimensional ratio of vertical perturbation to horizontal wind speed,

$$Fr = \frac{\nu h}{U}, \tag{2}$$

where U = cross-barrier wind speed, ν = the Brunt-Väisällä frequency (Eq. 1), and h = the height of the barrier. Gravity waves are stimulated when Fr<1 (Bruintjes *et al.* 1995), a criteria easily tested with a sounding. For Froude numbers between 1 and 2, high amplitude waves can be formed over the lee slope of a barrier (Smolarkeiwicz and Rotunno 1989). This suggests that for low wind speed and high stability conditions, the lee of the San Pitch Mountains could be a reasonable release zone. However; dilution, the subsequent downward portion of the wave and horizontal targeting issues complicate this application. For the current case, Fig. 6 suggests that the upwind side of this barrier would be appropriate.

Super (1995) suggests the Utah operational network in the Sanpete Valley, though sometimes successful at targeting the Plateau, often provided low concentrations effective at the ambient temperatures. Effective targeting would require a strong source configuration with many more generators and/or higher output generators. Figure 6 also indicates that the west side of the Sanpete Valley could provide some initial upward impetus; however, the subsidence portion of the gravity wave could have a detrimental influence on targeting. Releases further upwind of the current valley sites have the disadvantage of greater dispersion which would reduce the concentrations over the target, and greater difficulty in horizontal targeting.

Acknowledgements. Many people contributed to the 1994 Utah/NOAA Cooperative Program and in later analysis which provided data used in this paper. C. Ogden was operations director of the program. The van data were provided by W. Hauze of NAWC. The aircraft was provided by NOAA/ERL/ARC and D. Wellman was responsible for the aircraft instrumentation and its quality control. T. Clark and R. Bruintjes are acknowledged for their many helpful discussions related to the application of the model to winter orographic storm situations. The two anonymous reviewers of this paper are thanked for their clarifying suggestions. This research was funded by the NOAA Atmospheric Modification Program under the direction of J. Golden in cooperation with the Utah Division of Water Resources. CRAY time was through NCAR which is partially funded by the National Science Foundation.

10. REFERENCES

Benner, R.L. and R. Lamb, 1985: A fast response continuous analyzer for halogenated atmospheric tracers. *J. Atmos. Oceanic Tech.*, **6**, 582-589.

Bruintjes, R.T., T.L. Clark and W.D. Hall, 1995: The dispersion of tracer plumes in mountainous regions in central Arizona: Comparisons between observations and modeling results. *J. Appl. Meteor.*, **34**, 971-988.

Clark, T.L., 1977: A small scale dynamic model using terrain following coordinate transformation. *J. Comp. Physics*, **24**, 186-215.

________and W.D. Hall, 1995: *Documentation of the Clark Anelastic Model, Version G2TC36.* National Center for Atmospheric Research, Boulder, CO, 168 pp.

DeMott, P.J., A.B. Super, G. Langer, D.C. Rogers and J.T. McPartland, 1995: Comparative characterizations of the ice nucleaus ability of AgI aerosols by three methods. *J. Wea. Mod.*, **27**, 1-16.

Finnegan, W.G., and R.L. Pitter, 1988: Rapid ice nucleation by acetone-silver iodide generator aerosols. *J. Wea. Mod.*, **20**, 51-53.

Heimbach, J.A., Jr. and W.D. Hall, 1994: Applications of the Clark Model to winter storms over the Wasatch Plateau. *J. Wea. Mod.*, **26**, 1-11.

________, A.B. Super and J.T. McPartland, 1977: A suggested technique for the analysis of airborne continous ice nucleus data. *J. Appl. Meteor.*, **16**, 255-261.

Holroyd, E.W., J.A. Heimbach, Jr. and A.B. Super, 1995: Observations and model simulations of AgI seeding within a winter storm over Utah's Wasatch Plateau. *J. Wea. Mod.*, **27**, 36-56.

Kessler, E., 1969: On the distribution and continuity of water substance in atmospheric circulations. *Meteor. Monogr.*, **No. 32**, Amer. Meteor. Soc., 94 pp.

Langer, G., 1973: Evaluation of NCAR ice nuclei counter. Part I: Basic operations. *J. Appl. Meteor.*, **10**, 1000-1011.

Li, Z., and R.L. Pitter, 1997: Numerical comparison of two ice crystal formation mechanisms on snowfall enhancement from ground-based aerosol generators. *J. Appl. Meteor.*, **36**, 70-85.

Reynolds, D.A., J.A. Humphries and R.H. Stone, 1989: Evaluation of a 2-month cooperative ground-based silver iodide seeding program. *J. Wea. Mod.*, **21**, 14-28.

Smolarkiewicz, P.K., and R. Rotunno, 1989: Low Froude number flow past three-dimensional obstacles. Part I: Baroclinically generated lee vorticies. *J. Atmos. Sci.*, **46**, 1154-1164.

Super, A.B., 1990: Winter orographic cloud seeding in the intermountain west. *J. Wea. Mod.*, **22**, 106-116.

________, 1994: Implications of early 1991 observations of supercooled liquid water, precipitation and silver iodide on Utah's Wasatch Plateau. *J. Wea. Mod.*, **26**, 19-32.

________, 1995: Case studies of microphysical response to valley-released operational AgI seeding of the Wasatch Plateau, Utah. *J. Wea. Mod.*, **27**, 57-83.

________ and A.W. Huggins, 1992a: Investigations of the targeting of ground-released silver iodide in Utah. Part I: Ground observations of silver-in-snow and ice nuclei. *J. Wea. Mod.*, **24**, 19-34.

________ and ________, 1992b: Investigations of the targeting of ground-released silver iodide in Utah. Part II: Aircraft observations. *J. Wea. Mod.*, **24**, 35-58.