MODELING AgI TARGETING EFFECTIVENESS FOR FIVE GENERALIZED WEATHER CLASSES IN UTAH

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ABSTRACT Rawinsonde observations from the 1991 and 1994 Utah/NOAA field programs were stratified into five classes based on temperature profiles. The classed soundings were used to initialize the Clark mesoscale model to simulate AgI transport from three operational generator sites in the valley upwind of the Wasatch Plateau in central Utah. The goal was to generalize ranges of conditions which would allow successful targeting of valley-released AgI. Not unexpectedly, the most unstable sounding class produced the best targeting. This class was the coldest of the five, producing more effective ice nuclei from the available AgI because of the temperature dependence of this ice nucleating agent. In general, the modeled results were in agreement with selected case studies of field observations. Wind characteristics were also shown to be important for successful targeting.

1. INTRODUCTION

In this paper, a numerical model is used to investigate the transport and diffusion characteristics of several atmospheric stability classes observed just upwind of Utah's Wasatch Plateau (hereafter Plateau). Operational winter orographic cloud seeding has been done in Utah continuously since January 1974 with the exception of a single winter (Griffith *et al.* 1991). From 1981 through 1994, field research programs were conducted approximately biennially as part of the Atmospheric Modification Program (AMP) under the auspices of the National Oceanic and Atmospheric Administration (NOAA)-State of Utah Cooperative Program. The Utah/NOAA AMP is one of six programs which piggy-backed research on ongoing State programs (Golden 1995). The overall goals of the Utah/NOAA Cooperative Program were to evaluate the effectiveness of the Utah operational program and to recommend means of improving it. The initial Utah research area was the Tushar Mountains, but field work during and after the 1989-90 winter shifted northward to the Plateau. The Plateau offers superior logistic opportunities including high altitude all-weather roads and the opportunity for aircraft sampling near the surface with the lack of isolated mountain peaks.

One of the main scientific objectives of the Utah/NOAA AMP has been "To understand the atmospheric processes permitting, or preventing, the transport and diffusion of significant concentrations of ground-released silver iodide (AgI) to supercooled liquid water (SLW) regions in orographic clouds," (Utah Dept. of Natural Resources 1994). 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). Plateau field programs during the 1989-90 winter and again during early 1991 and early 1994 emphasized the study of transport and diffusion. In these programs AgI and sulfur hexafluoride (SF_6) were traced on the surface and aloft. Several transport and diffusion case studies have been reported as a result of these field programs. For example, Super and Huggins described 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 ice nuclei (IN) measurements indicated that AgI was sometimes transported up a major canyon over the Plateau, but in limited amounts. Co-released SF6 was detected by the aircraft for one of five reported flights. These two papers highlighted the difficulty in targeting seeding material released from low altitudes.

Super (1995) summarized the targeting effectiveness of six case studies from the early 1991 season in which valley-released AgI was tracked over the Plateau to flight levels. Five of these cases had embedded convection. He documented that the vertical AgI transport was generally less than 1 km above surface level (ASL). There was some evidence of enhanced aircraft-measured ice particle concentrations for half of the cases which had temperatures less than -9 °C.

Huggins (1995) used three cases from the early 1991 field season to examine the depletion of

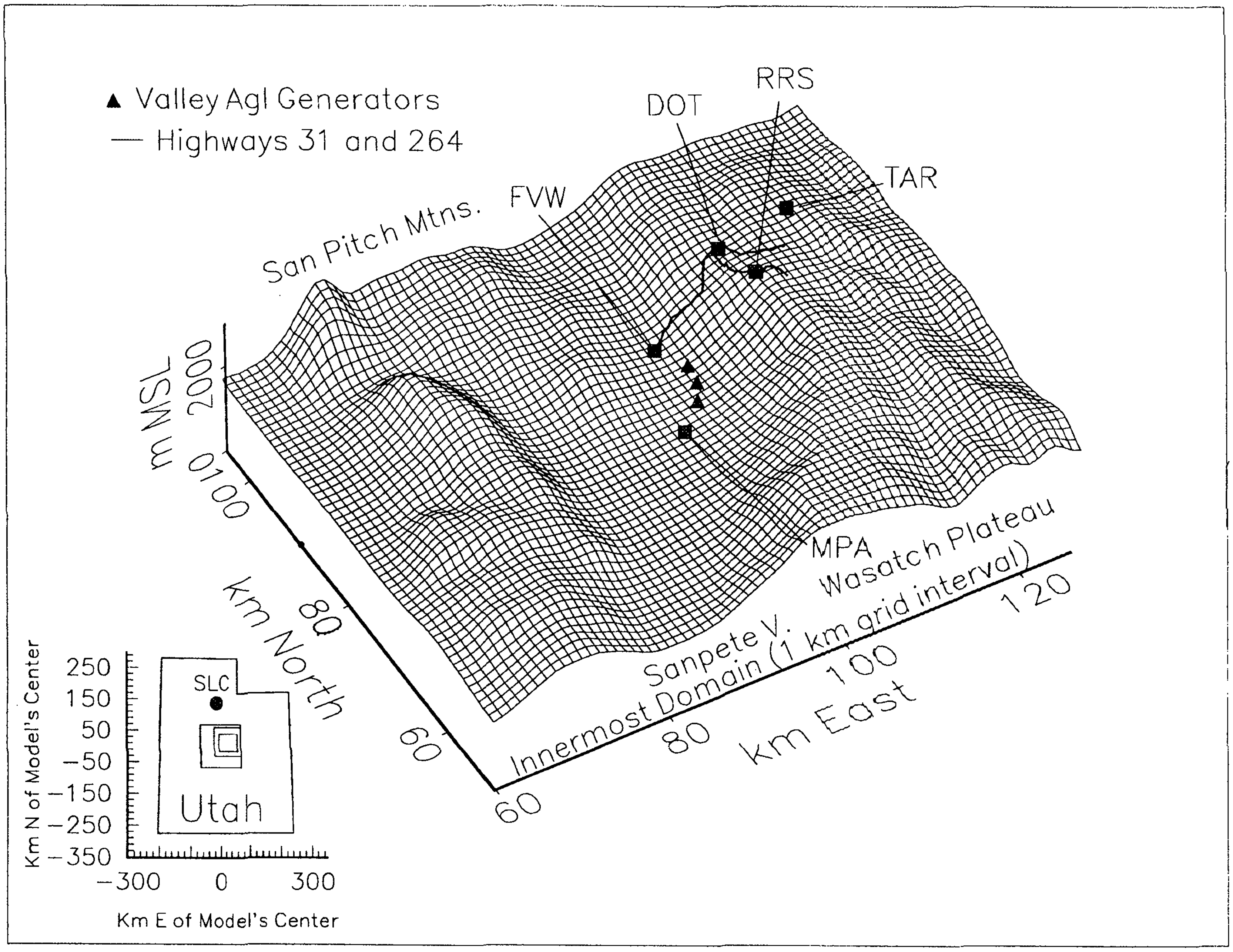


Fig. 1. The innermost model domain and its relative position to the other domains applied in the Clark model. Distances are relative to the southwest corner of the outermost domain and acronyms are defined in the text.

SLW across the Plateau. The depletion was significant, presumably because of conversion to precipitation. However, modeling by Heimbach and Hall (1994) suggests that some of the depletion may be due to subsidence warming within a gravity wave pattern. One of Huggins' cases had a valley release which was not detected, and the other two had releases from one or both of the high altitude release sites. Plumes from the high altitude sites were transported over the Plateau and, in one case, there was evidence that crystals nucleated by the AgI plume were detected by radar.

Although the data collected during the field programs were of high quality, their spatial scope was limited to surface measurements around Highways 31 and 264 over the Plateau (See Fig. 1), and flight levels above 300 m ASL. To estimate weather conditions and transport and diffusion characteristics below flight levels, and over a wider area, the mesoscale model of Clark and associates (Clark *et al.* 1996) was applied. Several applications of this model to the Utah program have been previously reported. For example, Heimbach and Hall (1994) modeled 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. 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. Modeling results of transport were reasonably close to observations for this case. On this date, AgI and SF_6 were co-released from a high-altitude site located well up the Plateau's windward side. A microphysical seeding signal was associated with the IN plume both at the Plateau top and aloft.

Heimbach, Hall and Super (1997) (hereafter HHS) modeled the transport of AgI released from three valley sites during the 7 February 1994 experiment which had a surface-based inversion. Sulfur hexafluoride was also released on this date from the mouth of a major canyon located on the windward side of the Plateau. Field observations indicated AgI transport over the Plateau mostly within a shallow layer in spite of being released within a stable surface layer with weak and sometimes easterly winds. Aircraft measurements of ice nuclei were sparse and limited to the lowest flight track, to within 0.3 km ASL. Modeling of this case suggested that the valley-released AgI had an initial vertical impetus by a gravity wave mechanism stimulated by the San Pitch Mountains to the west. This impetus was followed by orographic forcing in a more organized westerly flow. The potential benefit of gravity waves to transport and diffusion was suggested by Bruintjes *et al.* (1995) who applied the Clark model to three cases from the 1987 Arizona/NOAA AMP. Each Arizona case had a single point-source of SF_6. Results from field observations and the model led Bruintjes *et al.* to conclude that the transport and diffusion of seeding material was dependent upon the flow and stability conditions around the valley release site, and gravity waves stimulated by upwind terrain.

The Clark model was applied to a four-day winter storm over the Black Hills by Farley *et al.* (1997). Their goal was to test ground-based seeding. Targeting effectiveness was inherent in their analysis. The strong vertical shear and warm temperatures of the first two days made targeting and effective nucleation questionable. The third day, which had ample SLW, was successfully targeted by four out of five generators. The fourth day was cold enough for the glaciogenic process to be initiated naturally. The simulation indicated that seeding on the third day would increase the precipitation by approximately 100% in the northern (upwind) portions of the Black Hills, while decreasing the accumulation over the southern portions by 50%. The overall simulated net increase was 28%

Field measurements and modeling suggest that there is a wide range of targeting effectiveness in the Utah operational seeding program. Orography, gravity waves, and wet and dry stabilities have strong influences on how releases from various surface sites succeed in targeting SLW zones. With the usefulness of modeling having been established in earlier work, it seemed prudent to apply the model in the operational sense to several generalized weather types. This paper reports on modeling of five stability types ranging from dry adiabatic from the surface to well above the Plateau, to a profile which had a surface inversion. Silver iodide releases were simulated from the three 1994 operational valley sites in the Sanpete Valley.

2. INSTRUMENTATION

The data utilized for this paper came from the early 1991 and 1994 field programs conducted over the Plateau of central Utah. The Plateau has the advantage of year-around highway access and its less complex terrain allows lower aerial sampling. Only the instrumentation relevant to this paper is described below.

Fig. 1 depicts the smoothed terrain of the innermost of three domains used in the model and points relevant to this paper. The principal surface sampling site was the RRS (Radar-Radiometer Site) located near the west edge of the Plateau at an elevation of 2981 m above mean sea level (MSL) or 703 hPa standard pressure. The TAR (Target) site, located on the eastern side of the Plateau, was established to sample in the area expected to be impacted by the seeding. The portions of Highways 31 and 264 sampled by mobile instrumentation are shown on Fig. 1. Highway 264 branches to the north of Highway 31 on top of the Plateau.

The Mount Pleasant airport and the town of Fairview are indicated as MPA and FVW in Fig. 1. The former had a rawinsonde release site and the latter is included as a geographical reference. To the west, the San Pitch Mountains rise approximately 800 m above MPA, and to the east, the Plateau rises approximately 1200 m. Three automatic surface weather stations were operated for both field programs. One station was about 3 km above the mouth of Fairview Canyon through which Highway 31 runs, one was in Birch Creek Canyon, and the third was at the Mount Pleasant Airport located south of Fairview. In 1991 a fourth automatic surface weather station was operated at the entrance to Fairview Canyon. In 1994, the RRS was the principal surface sampling location where variables of state, wind from a heated anemometer, Rosemount icing meter "trips", vertically-integrated SLW measured by a microwave radiometer, and continuous IN measurements were recorded. During the 1991 program, several of the RRS parameters were measured at the DOT (Department of Transportation) site, 10 km north of RRS. These instruments were moved to the RRS in early 1994 because it became apparent that the RRS was in a more favorable position. In both field programs, one or two instrumented vans were equipped to record variables of state, wind, and IN and SF_6 encounters. The Bureau of Reclamation's and Desert Research Institute's mobile radiometers were present for both field seasons.

An instrumented Beechcraft King Air C-90 (N46RF) was provided by NOAA. The aircraft recorded variables of state, liquid water content, horizontal winds, IN and SF_6. Aircraft position was recorded from both LORAN and GPS. There were three designated flight tracks; two roughly N-S on the upwind and downwind edge of the Plateau (shown in modeling results figures), and one crossing the Plateau from southwest to northeast, directly over the RRS. Due to the relatively uncomplicated topography of the Plateau top in the vicinity of the target area, a waver was granted by the FAA to allow minimum IFR flight as low as 300 m ASL.

For both field programs, mobile IN detection was done at the surface by a specially-equipped four-wheel drive vehicle (hereafter Suburban). This vehicle also recorded parameters of state, and had a vane-mounted PMS 2D-C probe for ice particle monitoring on a mast well above the vehicle. During the 1991 field season, from which the verification data came, the Suburban had no automatic positioning in 1991, but time was noted each 0.5 mile for position reference of the recorded variables. A forward-looking video camera provided a view of the general weather conditions.

Eight valley seeding sites in 1991 and three in 1994 were operated by North American Weather Consultants (NAWC) as part of the Utah operational network. The 1994 AgI generator sites were used in the model simulations (See Fig. 1). These generators used 2% by weight AgI in composition with NH_4I-acetone-water in a propane flame at a rate of 8 gm AgI h^{-1}. Ice nuclei were measured by continuous acoustical IN detectors (Langer 1973). The lag time for this device is about one minute because of plumbing delays and time needed to grow detectable ice crystals (≥ 20 μm). Sample mixing within the cloud chamber produces an indicated width which is wider than the actual plume. Approximately one in ten IN in the sample are detected due to chamber wall losses. Because the sample rate of these detectors is approximately 10 L min^{-1}, one count per minute corresponds to one IN L^{-1} effective at the cloud chamber temperature of -20°C.

Further instrumentation details are given by Huggins (1994) for the radar and radiometer sampling, Super (1995) for the other surface instrumentation, and Heimbach and Wellman (1994) for the aircraft systems.

3. SPECIFYING COMPOSITE SOUNDING DATA FOR MODEL INITIALIZATION

Four-hour periods, centered at the MPA sounding launch times during the 1991 and 1994 field programs, were examined to determine a subpopulation which was potentially seedable. To be seedable, a period was required to have a westerly wind component at 700 hPa and detectable SLW. The SLW could be detected by radiometer or Rosemount icing meter "trips" on the Plateau top. Other data sources were examined to further test the candidates which included RRS log books, DOT winds, precipitation gauge records, aircraft notes and notes from the instrumented surface vehicles. Four periods were eliminated due to lack of clouds needed to confirm radiometer measurements and/or winds shifting too much to provide consistently seedable conditions. Of the 92 soundings taken for the two field programs, 72 met the seedability criteria defined above.

The 72 soundings of the final pool were plotted and examined without consideration of date. Five classes were derived using the dry bulb temperature profile. These are defined in the top part of Table 1. The soundings for each class had the parameters derived as described in the bottom of Table 1 to define a composite sounding for each class. Since there was a range of temperatures for a given level, the composite sounding was drawn to pass through the point defined as the mean temperature of each class at the standard pressure of the RRS, 703 hPa.

For example, the construction of the composite class A sounding began with drawing a dry adiabatic lapse rate through 703 hPa and the average temperature for that class at RRS which is -8.1 °C. The dry adiabatic lapse rate represents the sounding from the surface to the average pressure level (654 hPa) where the ambient lapse rate changed to approximately the standard tropospheric lapse rate (6.5 °C km^{-1}). The composite sounding's tropopause was the average for the class (390 hPa) and above this the temperature was a constant -53.3 °C. The moisture profile was defined by the average base and top of the saturated layer which for class A are 661 and 650 hPa. Beneath 661 hPa the dew point is connected to the

Table 1. Definition of five classes of composite soundings used to initialize the model.

Class	Description
A	Dry adiabatic lapse rate from the surface to at least the Plateau top (RRS).
B	Dry adiabatic lapse rate from the surface changing to moist adiabatic lapse rate below the Plateau top.
C	Moist adiabatic lapse rate from the surface to above 600 hPa.
D	Elevated stable layer between 750 hPa and Plateau top.
E	Surface-based stable layer ($\gamma < \Gamma_s$).

Higher level temperature profile characteristics:

- A, B and D sounding types have a standard lapse rate (6.5 °C km^{-1}) above the mean level where this rate begins.
- C and E types have a moist adiabatic lapse rate above a stable layer to the tropopause.
- All sounding types assume isothermal conditions above the mean tropopause height for each class.
- For types D and E, the stable layers are defined by the mean base (or surface) and top, and mean ΔT through the stable layer for each class.

Moisture profiles are defined as follows:

- The surface dew point is the mean surface temperature minus the average dew point depression for a given class.
- The base of the saturated level is the average base of saturation for all but class B. For class B, the base of the saturated level is at the mean level where the dry adiabatic lapse rate changes to moist adiabatic.
- The top of the saturated layer is the mean top of the saturated layer for each class.
- The dew point depression above the saturated layer increases to 15 °C at the tropopause and remains at 15 °C above this level.

surface dew point defined by the surface temperature minus the average surface dew point depression. Above 650 hPa, the dew point spread increases to 15 °C at the tropopause, and is constant at higher levels.

The winds are representative profiles from each of the sounding classes with some smoothing done to insure computational stability. Table 2 inventories the classes. Figure 2 shows each of the composite soundings.

4. MODEL DESCRIPTION AND APPLICATION

Applications of numerical modeling to weather modification began in the 1950's (Orville 1996). They have served as a test bed for new concepts and many new theoretical developments have been discovered through their use. Though the use of modeling has been encouraging, Orville (*ibid.*) stresses the continued need for field tests because of the difficulty of describing the complex dynamic, kinematic and microphysical processes and interactions.

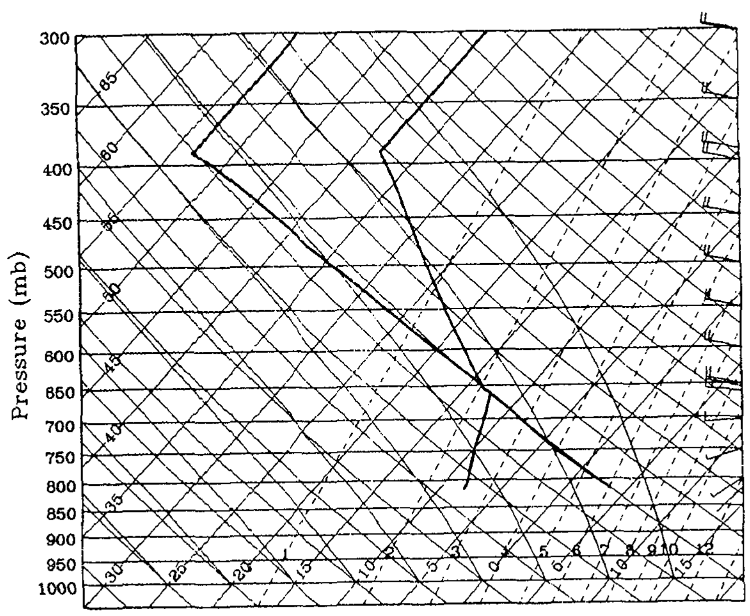
Table 2. Inventory of soundings for five classes.

Class	No. of Sndngs	1991	1994	Exp. Days represented
A	12	7	5	8
B	9	6	3	8
C	8	6	2	6
D	5	3	2	5
E	12	4	8	10
Other	26	18	8	17
Total	72	44	28	24

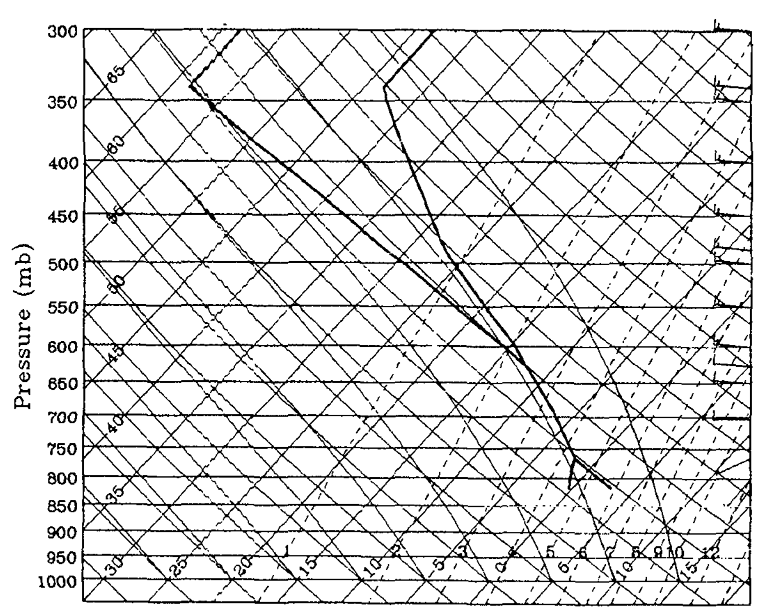
Reasons for Other category:

Early termination	4
Not class A through E	19
Questionable data	3

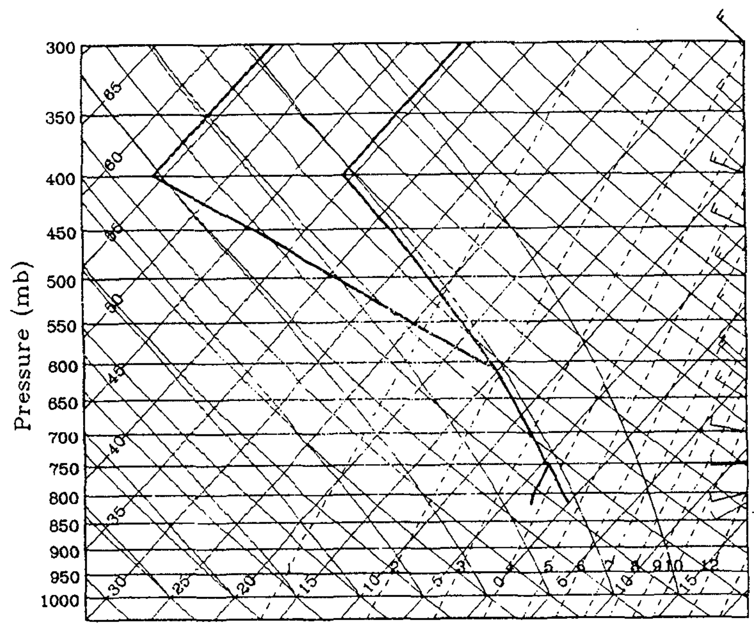
Version 38 of the four-dimensional mesoscale model of Clark and associates was applied for this



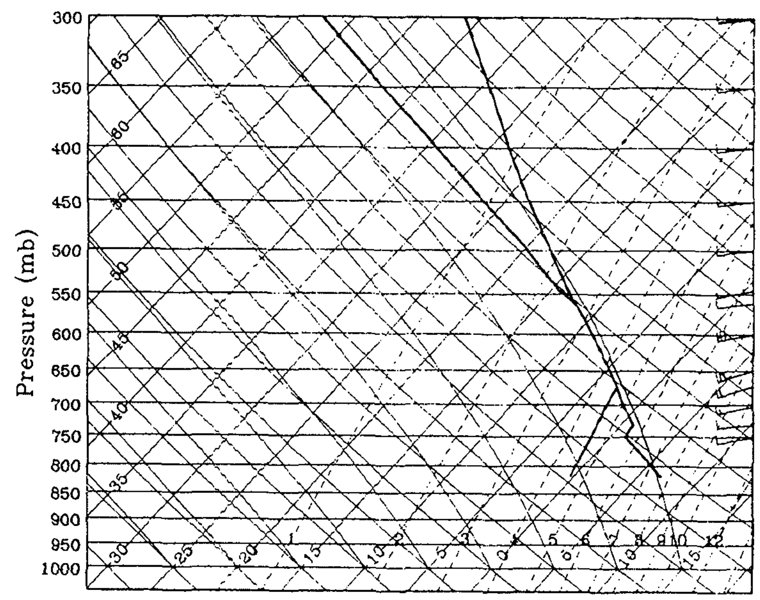
Class A



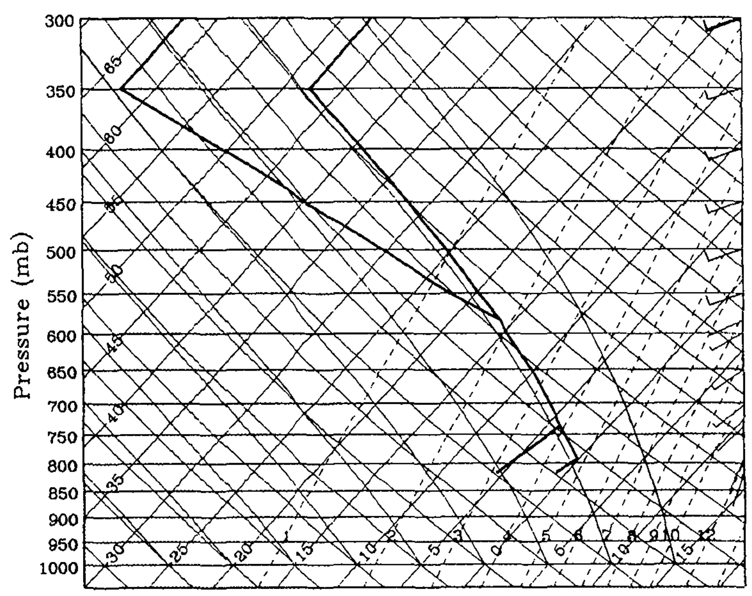
Class B



Class C



Class D



Class E

Fig. 2. Five classes of composite soundings used to initialize the Clark model. Class A is the most unstable and class E the most stable.

investigation. This research model has been in development since 1974. The Clark model is nonhydrostatic and anelastic implying vertical accelerations are permitted, but the analastic continuity equation is used to eliminate acoustic-scale waves. The model uses geo-spherical nonorthogonal coordinates. The Clark model is three-dimensioned and time-dependent which allows the microphysics to be coupled to the dynamics. The model's configuration applied to the Plateau used three interactively-nested domains to insure large-scale meteorological features contributed to the fine-scale innermost domain while conserving computer resources. 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, and 66 (S-N) by 54 for the innermost domain. Figure 1 illustrates the innermost of three nested domains. 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). The vertical grid increments are stretched starting with 50 m at the surface and expanding to 0.5 km at the top. The terrain has been run through a two-dimensional nine-point smoother twice to insure computational stability. The gross features of the terrain have been captured; however, the smaller canyons have been smoothed out.

Warm-cloud microphysics are simulated using the Kessler (1969) bulk parameterization which assumes there are two types of condensate; cloud water and rain water. Both condensation and evaporation are included. The term "warm-cloud" implies liquid condensate and is appropriate for liquid clouds with temperatures below freezing, i.e., supercooled. The ice-phase mechanism was not implemented due to uncertainty with the natural nucleation rate and the additional run time required. Since the current research is concerned with the efficiency of targeting SLW zones, simulation of warm clouds only is sufficient. Although the model can include radiational heat flux, this was not done because the cases assumed cloudy conditions which would limit this influence. The Eulerian transport algorithm of Smolarkiewicz (1984) is used in the model. This gives an instantaneous spread of seeding material through one grid element; 1 km by 1 km by 50 m for the innermost domain. The initial point of release is at the center of the grid which contains the release point. This is evident in Fig. 4, classes A through D. The initial spread is large in comparison to the true plume dimension; however, with time this contribution is small compared to the contributions by other factors.

Each model run required two "jobs". The first was the generator stage which created a series of history files. The second was the analysis stage which produced the graphical output from the history files. The model was run on a Sun SPARCStation 5, admittedly a modest computer, but still capable of this task with enough time. The three domains were simultaneously initialized with each of the composite soundings. After running for one simulated hour, releases of AgI from the three 1994 valley sites were started and the model was run an additional hour of simulated time. One run of two simulated hours took approximately 45 h cpu time for the above configuration.

5. MODELING RESULTS

Figures 3 through 5 are ensembles of model results for the 5 classes. They are arranged in the same order as in Fig. 2. All model results are for the innermost domain at the end of 2 h simulated time. The west-to-east (+x = east) versus vertical cross sections of Figs. 3 and 5 are through the RRS. The geographical points on the vertical cross sections are indicated by a + which are plotted at their projected altitudes.

5.1 Vertical Wind

All the vertical wind panels (Fig. 3) show vertical winds of alternating sign indicative of west-to-east wave structure, though in varying degrees. The strongest vertical speed (hereafter w) is for class D. The orographic stimulus of waves is apparent for all classes though to a lesser degree for E. These classes have westerly components above the surface which drive the excitation in the expected fashion.

Classes C and E show significant w over the lee portions of the San Pitch Mountains west of the Plateau. This seemingly nonintuitive character has been discusses by Smolarkiewicz and Rotunno (1989) in a paper which focuses upon the conditions necessary for lee vortices. The response of the flow over and past a barrier can be classified by the Froude number, Fr, which is a nondimensional ratio of the vertical perturbation wind speed to the horizontal wind speed,

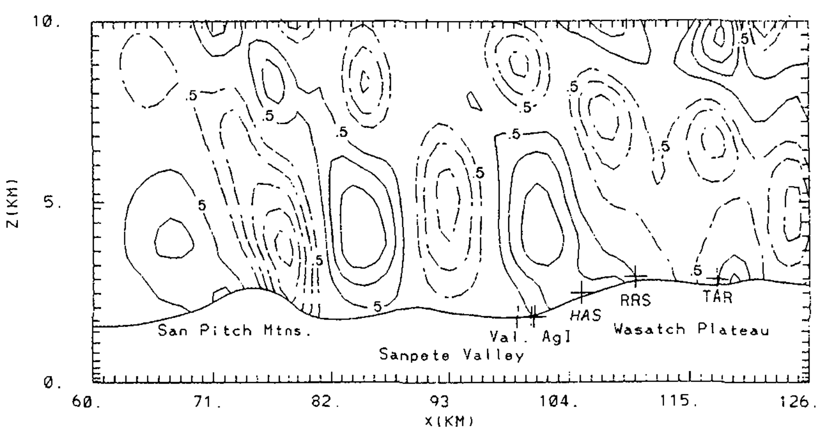
$$Fr = \frac{\nu h}{U}, \qquad (1)$$

where U = cross-barrier flow speed, ν = the Brunt-Väisällä frequency and h is the height of the obstacle. Some references define Fr as the inverse of Eq. 1. The Bruint-Väisällä frequency is,

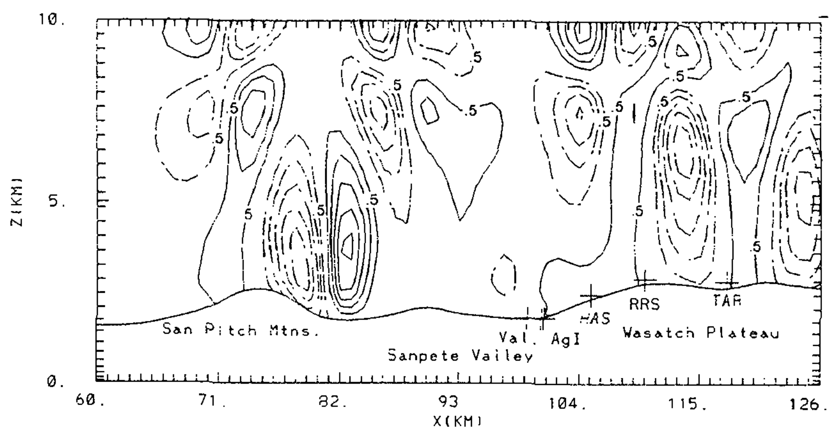
$$\nu = \left[\frac{g}{\theta}\frac{\partial\theta}{\partial z}\right]^{0.5}, \qquad (2)$$

where θ = potential temperature. Using the same model as in this paper, Smolarkiewicz and Rotunno (*ibid.*) showed a short length but high amplitude wave can be formed over the lee slope of a barrier for 1<Fr<2. Lee vortices and upwind reversed flow can form for Fr>2. Bruintjes *et al.* (1995) stated this relation more generally: gravity waves are stimulated when a regime has Fr (as defined by Eq. 1) <1. Fr>1 may result in upwind blocking effects which can limit the propagation of mountain waves.

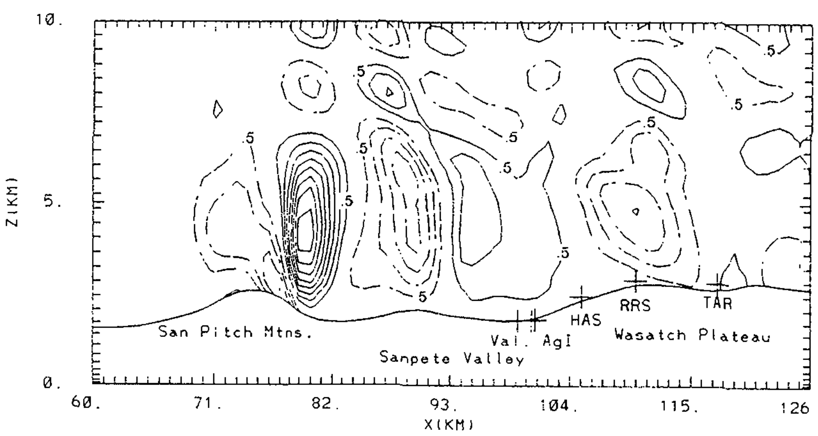
The Fr's for each class were found using parameters interpolated from the 2 h graphical output. For classes A through E, the Fr numbers were 0.5, 0.8, 1.0, 0.7 and 1.0 respectively. These values suggest that classes A, B and D should support the propagation



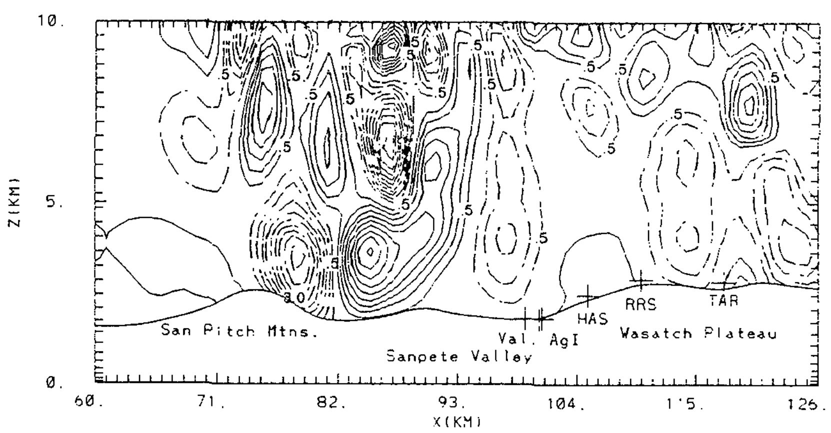
Class A



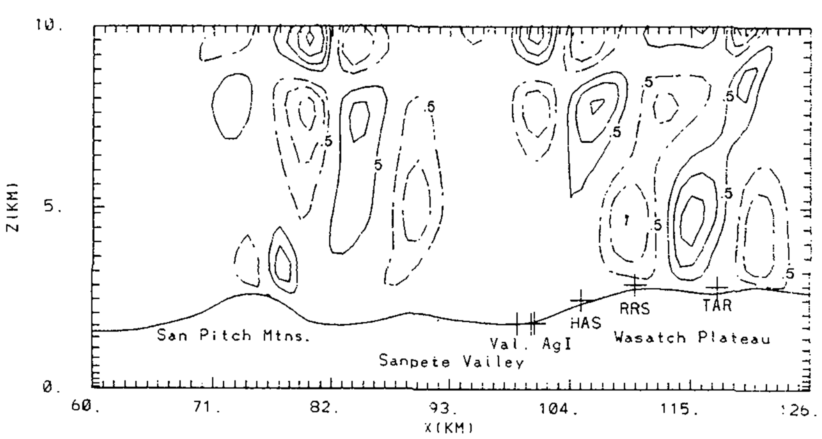
Class B



Class C



Class D



Class E

Fig. 3. West-to-east profiles of vertical wind speed after 2 h simulated time for each of the five classes of composite soundings. The positioning is the same as for the respective displays in Fig. 2.

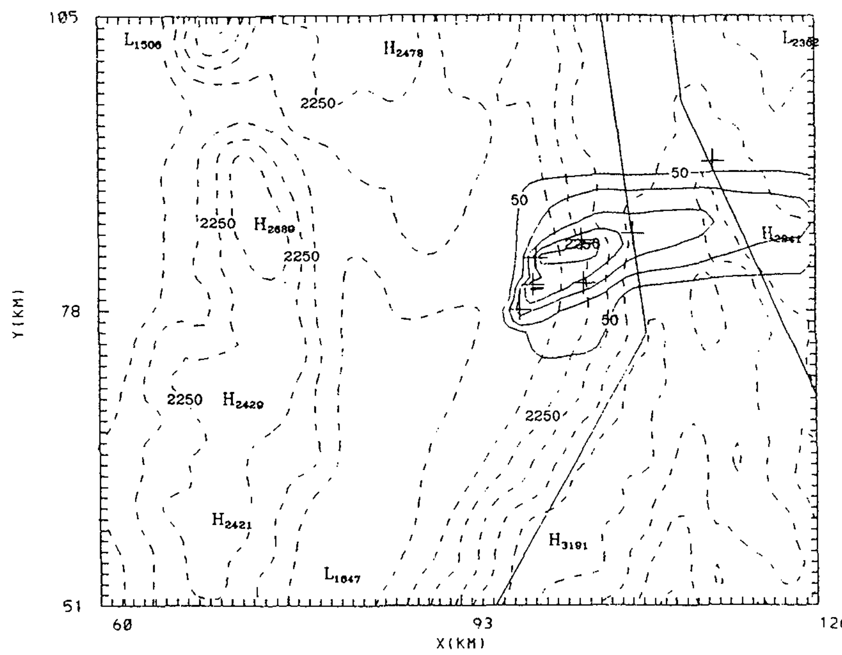
of lee mountain waves with a zone of upward motion established downwind of the leeward slope. Classes C and E should have mountain waves, but with a segment of w>0 over the lee slopes. These characteristics are borne out by Fig. 3. Bruintjes *et al.* (1995), and HHS have shown through modeling and observations that in some cases gravity waves can be crucial for transport of surface-released seeding material. The above results indicate that the interaction of speed and stability profiles can be important to the placement of waves.

5.2 Tracer Modeling Results

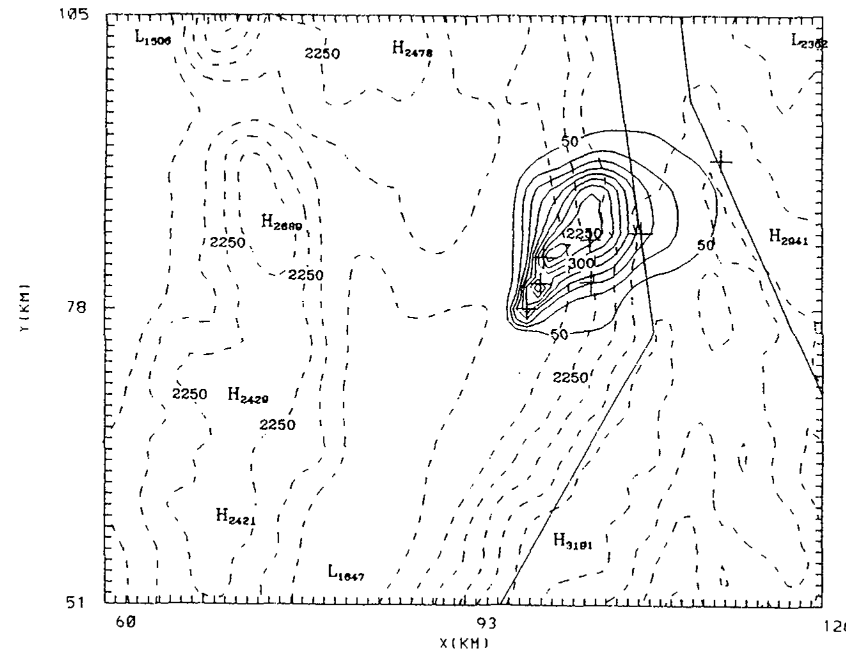
Figure 4 shows the model-derived surface concentrations of AgI at the 2 h mark (after a 1 h release). Contours of AgI are in units of picograms per cubic meter (pgm $m^{-3} = 10^{-12}$ gm m^{-3}).

Plumes from the valley releases are transported over the Plateau for class A and there is weak transport over some portions of the Plateau for class B. The remaining classes show no cross-Plateau transport. Instead, there is a drift of the AgI to the north. Class C has the plume turning toward the northwest, following the low portions of the Sanpete Valley. Classes D and E show some dispersion to the south and class E to the west. For class E, a pooling in the valley is evident. These features were observed during valley sampling by the instrumented Suburban. The character of the transport for classes C through E is influenced by light winds of predominately southerly component.

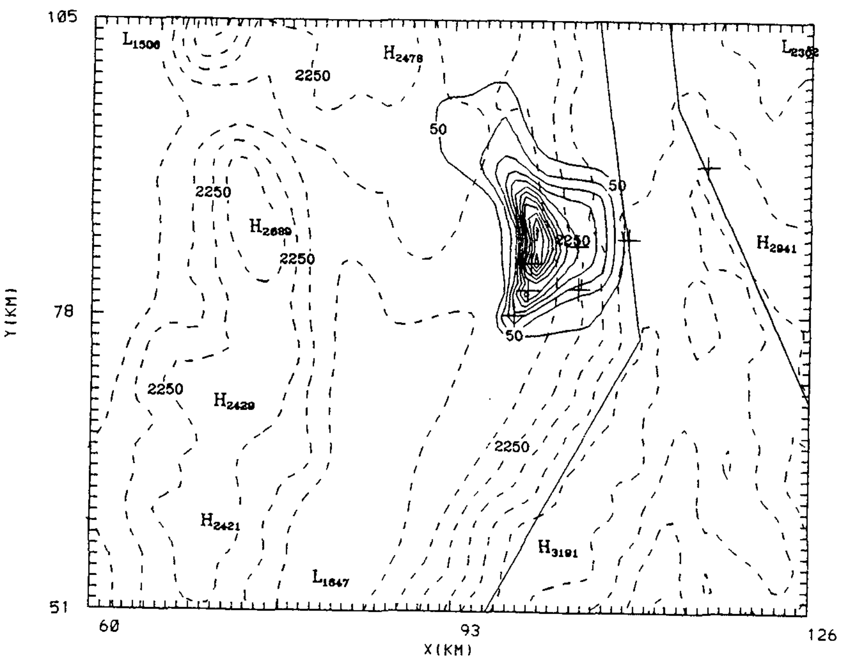
Vertical transport for all cases was limited, especially for class E. The model simulations suggested that AgI remained within several hundred meters of the surface even when transport over the Plateau occurred. This was found to be the case in field sampling where aircraft-observed IN and SF_6 concentrations were usually at least an order of magnitude less than surface measurements.



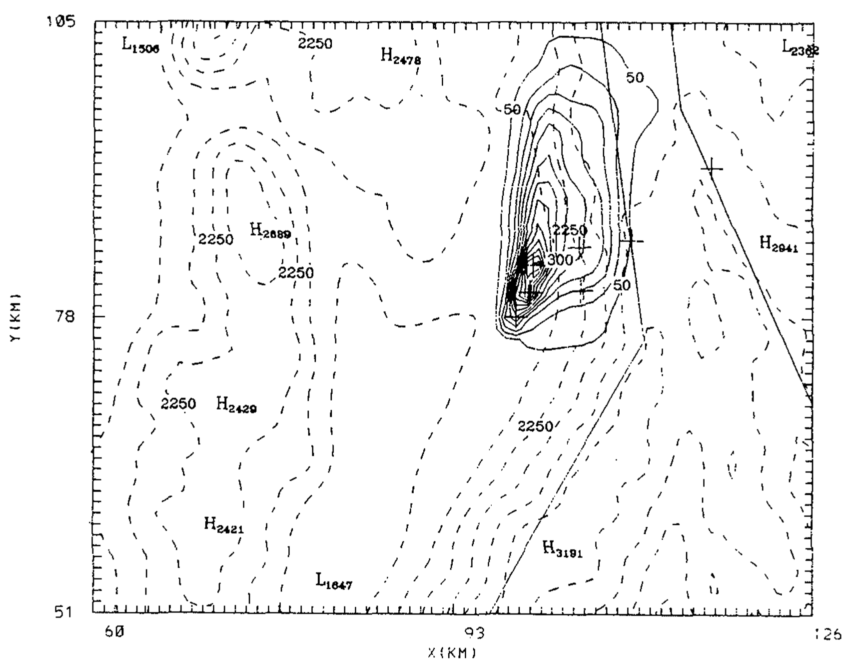
Class A



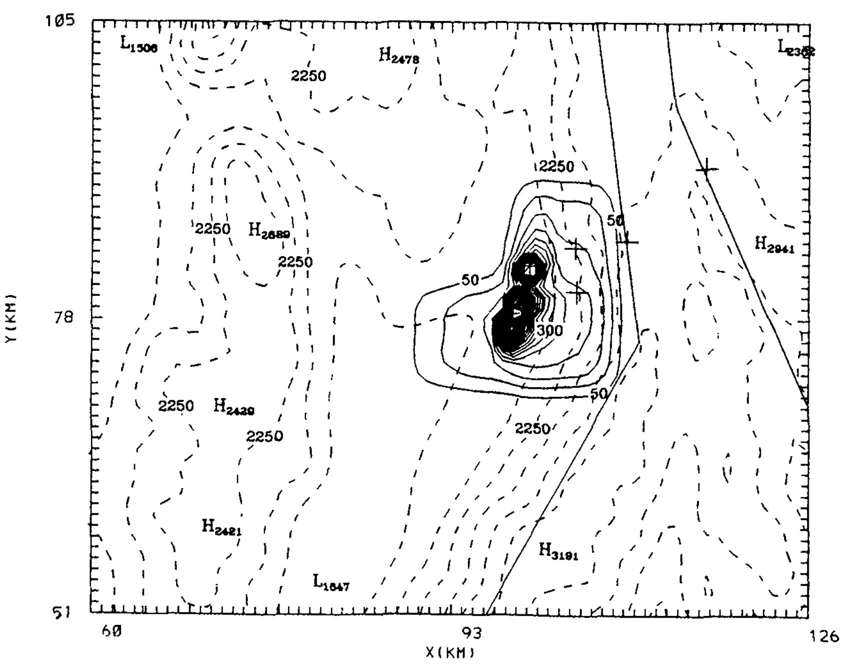
Class B



Class C



Class D



Class E

Fig. 4. Model estimates of AgI concentration at the surface resulting from three 1994 valley releases. The minimum contour and contour interval are both 50 pgm^{-3}. The dashed lines are terrain contours. The source strengths are all 8 g AgI h^{-1}. The roughly N-S lines are pre-established flight tracks. The panels' positions match the respective soundings displayed in Fig. 2.

5.3 Verification of Tracer Modeling Using Field Observations

This section details the comparison of experimental hours with model results for each class. One representative hour was selected for verification of each class, beginning at the rawinsonde release time. To be eligible for selection, the hour was during a valley release with no possibility of contamination

Table 3. Conversion of IN L^{-1} to picograms AgI m^{-3} effective at the -20 °C cloud chamber temperature of the IN detector. This conversion is for a NAWC AgI generator according to DeMott *et al.* (1995).

IN L^{-1}	1	5	10	25	50	100	200
pgm m^{-3}	0.5	3	6	14	28	56	111

from a high altitude release or extra-area operational seeding release. Sufficient field measurements to define targeting success were also required. All the selected periods come from the 1991 season because tracing of valley-released plumes was emphasized in that field program. When possible, periods having AgI releases during more than one sounding class type were avoided.

Class A, 1800/6 March 1991

The individual rawinsonde best representing the generic class A was released at 1800 (all times MST) on 6 March 1991. On this date, all eight valley generators were on by 1335 and off by 2135 . This sounding was made during the coldest storm of the 1991 field season and was associated with the movement of a short wave trough. The sounding indicated dry adiabatic conditions to 3.2 km MSL and roughly moist adiabatic above. The winds were westerly at 5 to 9 m s^{-1} at and below the Plateau top.

Field measurements are in agreement with the model's prediction. The Surburban found approximately 100 IN L^{-1} along the length of Highway 31 between 1800 and 1900. At the DOT, peak counts up to 315 IN L^{-1} were observed during this hour. Silver iodide becomes effective at temperatures below -6 to -9 °C, depending on the complex combusted. The DOT temperatures were approximately -11 °C, indicating that some of the transported IN nucleated ice crystals within the abundant SLW of that period. The aircraft made four passes along the west track and found significant IN concentrations at the minimum IFR flight altitude, to within 300 m of the surface, and also at 3.7 km MSL.

Table 3 tabulates conversions of IN L^{-1} to units of model output, pgm m^{-3}, effective at -20 °C, the temperature of the acoustic IN detector's cloud chamber. The type of generator used in the simulations is assumed to be the NAWC type. DeMott *et al.* (1995) reported its efficiency at -20°C to be $1.8X10^{15}$ IN (gm AgI)$^{-1}$, or $1.8X10^{3}$ IN (pgm AgI)$^{-1}$. Table 3 suggests reasonable quantitative modeling results for this case.

Class B, 1200/1 March 1991

All class B soundings associated with valley releases were either preceded by long-term AgI releases from the previous day or had possible contamination from high altitude releases. The B sounding most representative of the generic profile was the 1200 release of 1 March 1991. All eight valley generators were on by 0855 of the 28th, and all were operated continuously into 2 March. The experiment was during prefrontal conditions and the winds aloft were south-southwesterly to southwesterly. This date documented the fate of a valley release under stable conditions going to convective conditions by 1200.

High IN concentrations of over 1000 IN L^{-1} were found by the Suburban between 1200 and 1300 in the vicinity of RRS. Concentrations decreased to < 10 IN L^{-1} north of the RRS. At the DOT concentrations increased from approximately 5 to 60 IN L^{-1} over this hour. The aircraft detected some IN on all passes which were on the west track at minimum IFR flight levels. The valley-released AgI was clearly transported over the Plateau but in a thin layer, qualitatively matching modeling results. Quantitatively, the agreement was also reasonable (see Table 3). The warm temperatures at the DOT for this hour, -2 °C, suggest that the AgI would not be effective at Plateau top elevations. The aircraft recorded temperatures from -6 to -9 °C when IN were detected. Although these temperatures were cold enough for AgI to be effective, concentrations were too low for effective seeding (Super 1994).

Class C, 0900/16 February 1991

Eight valley generators were releasing AgI by 0740 on 16 February 1991 and continued to operate until the following day. The experimental area was ahead of a wave during the selected hour and an hourly-averaged 0.12 mm vertically integrated SLW was measured by the DOT radiometer. The winds aloft observed by the 0900 sounding were southwesterly at 5 to 10 m s^{-1} to well above the Plateau.

The Surburban began sampling in the Fairview vicinity at 0910 where it detected several 100's IN L^{-1}. In Fairview Canyon, the concentrations decreased to approximately 100 IN L^{-1}. At 0928 the Suburban parked at the DOT and detected about 50 IN L^{-1} which tapered off with time. The IN counter permanently located at the DOT detected over 50 IN L^{-1} during the same period. Late in the hour the Surburban sampled to the south of the DOT on Highway 31 and found only background levels. Sampling by the aircraft, starting at 0925, found IN concentrations only slightly above background north of the DOT in two passes on the west-track at minimum IFR altitude. The aircraft measurements may have been effected by intake manifold icing during this mission. Later in the morning, valley sampling by the Suburban found thousands of IN L^{-1} in the vicinity of Fairview, and hundreds IN L^{-1} to the south. This suggests a pooling of AgI in the valley.

Class C, having a moist adiabatic lapse rate, is a stable sounding if the lifted air mass is not saturated, as in the case for the composite sounding. This stability inhibited cross-barrier transport, turning the flow northward in the valley to ultimately have a westward component for the tracer material. This southerly (S to N) transport was commonly observed during the 1991 field program when considerable Suburban sampling was done in the Sanpete valley. There were no periods of class C which covered two or more sequential rawinsonde releases, suggesting C is a transient class.

Class D, 1200/5 March 1991

There were only three class D soundings which occurred during valley releases, and all of these had AgI releases continuing from the previous day. If there was a long-term valley AgI release, IN were likely detected over the target area, though not necessarily in high concentrations. The storm of 5 March 1991 was selected because the associated winds were assumed strong enough to eliminate pooling of AgI in the valley from earlier seeding. The MPA site recorded southwesterly winds of 10 m s^{-1} prior to 0935 with a peak of 14 m s^{-1}. The DOT site had 10 or more m s^{-1} from the west-southwest until 0845. Both of the Fairview Canyon sites recorded 7 m s^{-1} prior to 0830. The wind speeds tapered off for all these sites by 1000 after a mid-morning cold frontal passage. From 1200 to 1300, the winds were 2 to 3 m s^{-1} at MPA and the Fairview Canyon sites, and 6 m s^{-1} at the DOT. The directions were mainly westerly. The unusually intense storm of this date forced the closure of Highway 31 limiting ground sampling to the DOT and the Suburban parked there. The winds aloft were from the west-southwest at 6 to 25 m s^{-1} and the air mass was saturated from 2.3 to 4.0 km, well above the Plateau top. There was no aircraft sampling on this date because of excessive turbulence and icing in the AM, and maintenance problems in the PM.

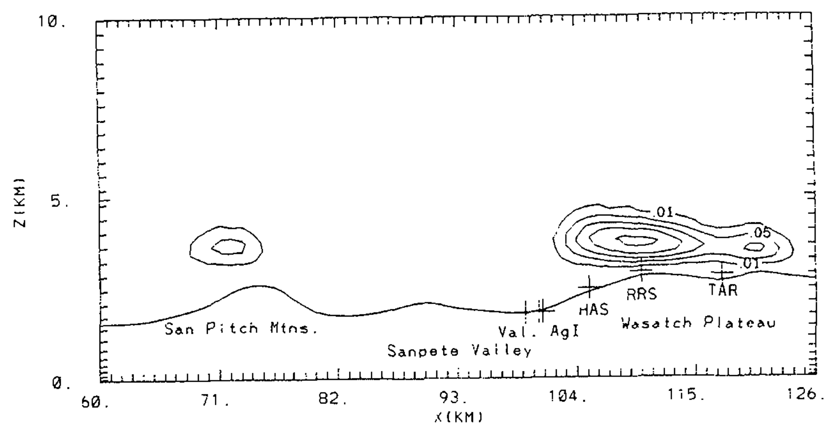
Prior to 1200 the Suburban was in the valley where up to 30 IN L^{-1} were detected. The Suburban started up Fairview Canyon at 1208 and by 1210 IN concentrations were at background levels. The Surburban was in the vicinity of the DOT site for the remainder of the hour, finding background IN levels until 1248 when 5 to 10 IN L^{-1} were detected. After 1300, up to 30 IN L^{-1} were found. The DOT IN detector recorded several IN L^{-1} starting at 1200, increasing to over 100 IN L^{-1} by 1300 and more afterwards, suggesting the influence of diurnal destabilization confirmed by the 1800 sounding which was class C. The DOT ambient temperature was -4.2 °C implying that the IN which reached the Plateau top were not effective.

The model showed a northward drift of the AgI plume with the eastern plume edge bounded by the Plateau's western foothills. There was a suggestion of some transport over the plateau having lower elevation well to the north of the DOT. The other two D cases with valley releases successfully targeted the Plateau top, but after AgI was released for at least 5 h.

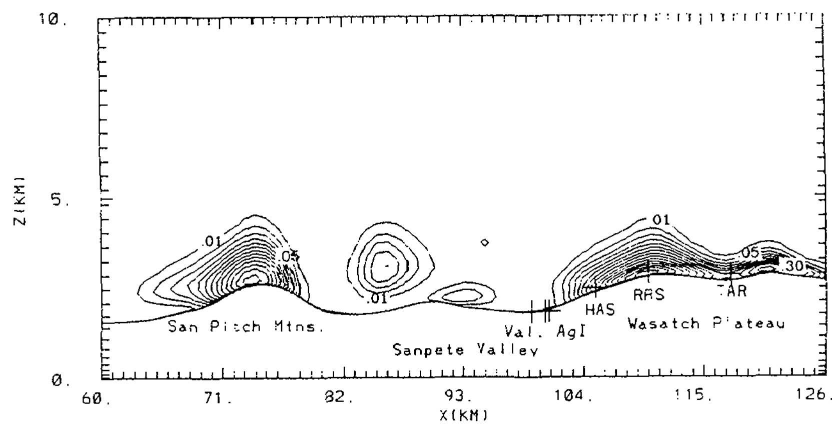
Class E, 0600/5 March 1991

None of the seven class E soundings involving valley releases were appropriate for use in verification. One had possible contamination from a high-level AgI release, one had evidence of extra-area contamination from operational seeding well south of the experimental area, four had valley network releases from the previous day or more, and one was reported by HHS to have had model and field evidence of gravity wave-assisted transport over the Plateau.

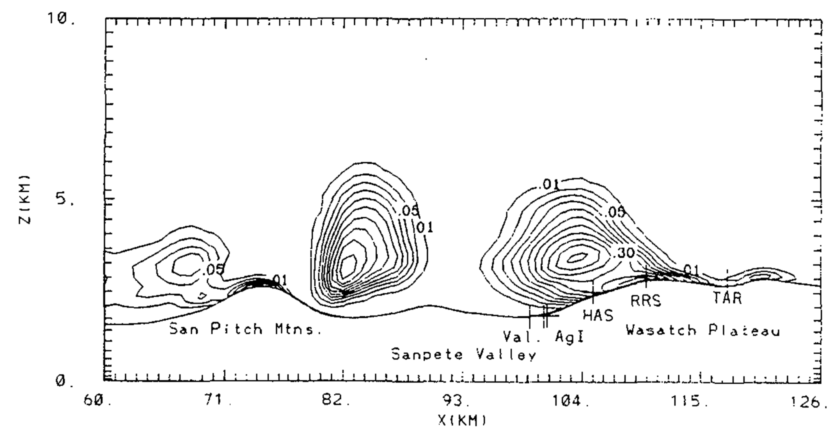
An eighth sounding during a valley release was clearly class E but was not included in the tabulation of Table 2 because it was prematurely terminated at 738 hPa (2.6 km). It was launched at



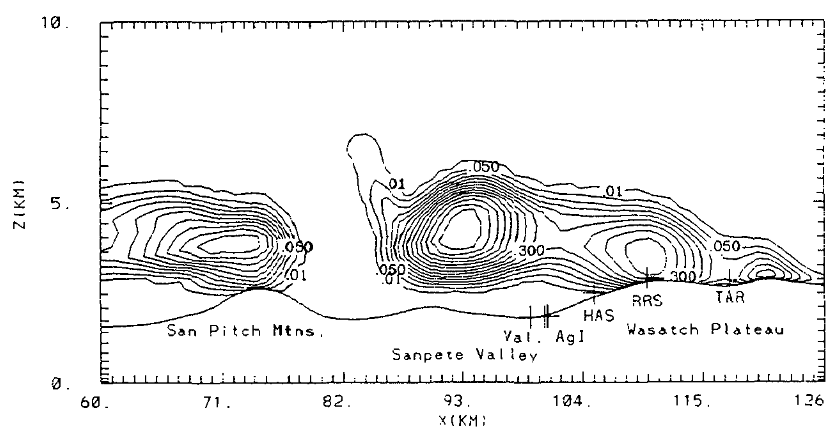
Class A



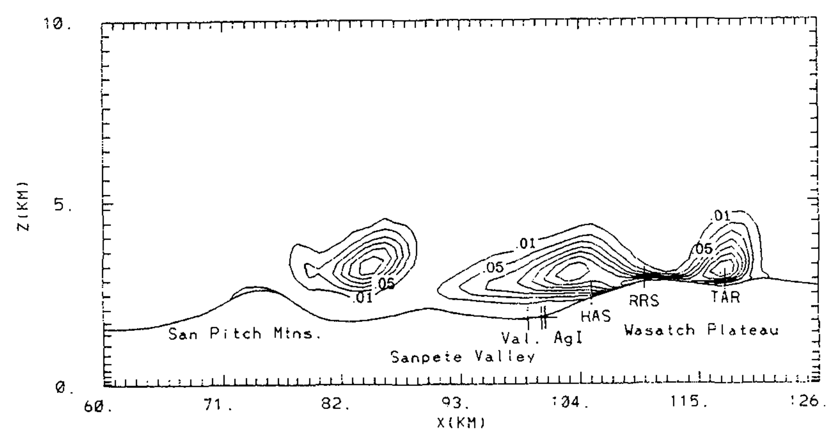
Class B



Class C



Class D



Class E

Fig. 5. Cross sections of cloud water concentrations corresponding to the five classes of soundings shown in Fig. 2. The contour interval is 0.05 gm

0600 on 5 March 1991. All eight valley generators were releasing AgI by 1120 on 4 March and were left on until 1805 of the 5th. A notable difference with other days of long-term releases is that this period was characterized by high wind speeds; 10 m s^{-1} from the southwest at the surface increasing to 30 m s^{-1} at 748 hPa. The AM flight was canceled due to excessive turbulence as for the previous day. The Surburban began sampling at 0810; however, its data are believed representative for the selected hour. High IN concentrations were found by the Surburban in the valley with counts tapering off to background levels in Fairview Canyon. The Surburban parked in the vicinity of the DOT and only had background IN levels before returning to base after 1100. The IN detector at the DOT had high counts for periods in the previous day, the last ending about midnight. During the period 0600 - 0700, 3 or less IN L^{-1} were detected. There were no significant increases until after 1100. The winds at the various valley sites were southwesterly to westerly. However, Doppler acoustic sounder data from the MPA showed calm at the surface changing to Sly near the surface, then veering to southwesterly just prior to 0800, the closest time available to the period of interest.

Overall model verification of class E is tenuous because of the sparsity of clear-cut tracing data and the gravity wave issue. However, for this case the model was in agreement with field observations. Class E showed a westward drift of the valley-release which was partially confirmed by HHS who documented a drift of tracer material toward the north-northwest for the 7 February 1994 case.

6. SIMULATIONS OF THE WARM CLOUD PROCESS

The warm clouds, i.e., liquid water clouds, generated by the model (see Fig. 5) show a diversity

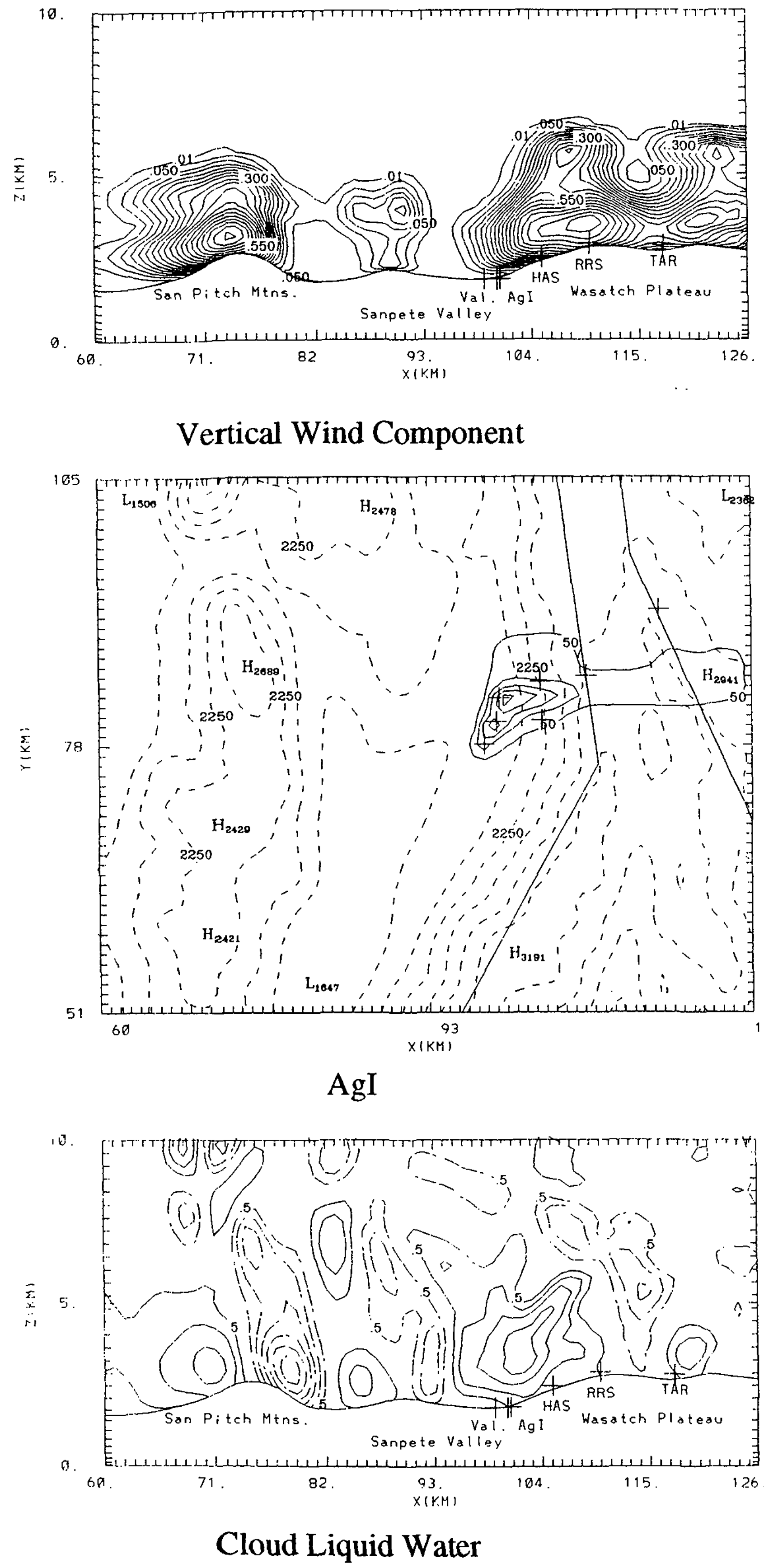


Fig. 6. Modeling results for class C initializing with strong westerly winds..

across the five classes. There were two factors controlling the warm cloud generation: depth of the saturated layer and the robustness of the vertical wind speeds. The latter is controlled by the organization of the westerly wind component and terrain. Class A had a thin elevated saturated layer. As a result, class A produced weak clouds which were not surface-based. The other classes, produced strong warm clouds due to the thicker, and for B, C and E lower, saturated layers in spite of the poor organization of the westerly component at low elevations.

Cloud development is well-correlated with the mountain waves (see Fig. 3) whose wavelengths range from 10 to 15 km. Over the Plateau, the model frequently predicted cloud development over the windward slope and over the eastern side with a zone of dissipation between caused by subsidence warming. This is most evident in Fig. 5E. This cloud pattern was frequently observed by the aircraft crew during the 1991 and 1994 field programs.

7. MODEL ADJUSTMENT

The composite soundings for the five classes were derived in as objective a manner as possible. The initializing low-level light wind speeds with significant southerly component limited the possibility of cross-barrier transport for C, D and E classes. However, field observations suggested successful targeting for valley releases during class C conditions and sometimes for classes D and E. This issue was examined by applying field-measured wind profiles in one of the composite sounding classes.

Only the results of class C substitutions are discussed. For this the wind profile of 2 March 1991/1000 was used as a guide. The surface wind was from 240 degrees and the directions veered to 300 degrees at 650 hPa, then backed somewhat above. Several runs were made inputting surface winds of 2, 4.5 and 9 m s^{-1}. Only the last showed well-organized transport over the Plateau. The actual surface wind speed for this rawinsonde was 10 m s^{-1}. The results of this run are summarized in Fig. 6. The gravity wave structure is well-defined, and there is more liquid water production. The plume pattern from this model run is more consistent with field observations than the other runs for this case. This highlights the sensitivity of the model to the initialization parameters, in this case the surface wind speed.

8. DISCUSSION

To estimate AgI effectiveness, one must consider the dependance of efficiency on temperature. If it is assumed that seeding must nucleate at least 10 ice crystals L^{-1} to effectively enhance snowfall (Super 1994), knowing the temperature at a point and the generator's characteristics will enable calculation of a minimum AgI concentration required for effective seeding. This was done for the RRS. Each class had the average temperature and range defined for 703 hPa, the standard pressure for the RRS. The generators used in the simulations are assumed to be the NAWC type used in the Utah operational seeding program. If the efficiency of the NAWC generator is E(T) with units of IN per gram AgI, then the concentration required for 10 IN L^{-1} is,

$$\chi\,(pgm\ m^{-3}) = \frac{10^{16}}{E(T)}. \qquad (3)$$

E(T) is a logarithmic interpolation from tabulated values for the NAWC generator on p. 7 of DeMott *et al.* (1995) using natural draft conditions. The mean and range of temperatures, and the corresponding concentrations required to achieve 10 IN L^{-1} are shown in Table 4. For example, for class A, the average temperature at the RRS elevation was -8.1 °C, and the range for that class was -13.4 to -0.9 °C. The efficiency of the NAWC generator at -8.1 °C is $6.3X10^{13}$ IN per gm AgI. For there to be 10 effective IN L^{-1}, the model-simulated AgI concentration would need to be 159 pgm m^{-3}. The range of AgI concentrations needed to produce 10 effective IN L^{-1} are 7 pgm m^{-3} for -13.4 °C to undefined because -0.9°C is warmer than the activation threshold.

Table 4. Concentrations of AgI, χ, (pgm m^{-3}) necessary for 10 effective IN L^{-1} at the RRS elevation. The U implies undefined. The lower limits of χ for all but D are the same because the minimum temperatures for the majority are approximately equal.

	Sounding Class				
	A	B	C	D	E
$\bar{T}_{703}$	-8.1	-6.1	-7.7	-1.0	-6.2
Min T	-13.4	-13.4	-13.7	-5.4	-13.1
Max T	-0.9	-2.3	-2.1	+2.7	+2.7
$\chi_{\bar{T}}$	159	2041	263	U	1786
Range of χ	7 - U	7 - U	7 - U	U	7 - U

There is a significant effect of temperature on the IN concentrations required for effective seeding at the RRS altitude. None of the soundings of class D were cold enough for the AgI to become effective. Class A has the best potential for successful seeding from the combined effect of colder temperatures and best chance of successful transport over the Plateau. Class B, though warmer, still has some potential for effective seeding due to the favorable transport. Class C holds some possibility of successful valley seeding provided there is sufficient cross-barrier wind speed. Both classes D and E have poor transport over the Plateau and class D has temperatures too warm for effective AgI IN.

9. CONCLUSIONS

The purpose of this paper is to describe the general character of transport and diffusion of valley-released AgI under various stability regimes observed in the Plateau region. Five sounding types were partitioned from the 92 soundings taken during the Utah/NOAA AMP 1991 and 1994 field programs. The five composite soundings covered a reasonable span of reality. The Clark model was initialized by each class and run using simulated releases of AgI from 3 valley sites.

There are several factors highlighted by the modeling applied in this investigation, most of which were confirmed by field observations.

- There is a frequent tendency for a low-level northward drift of valley-released AgI in the Sanpete Valley.

- Under some circumstances there can be a westward or northwestward drift of AgI in the Sanpete Valley in spite of organized westerly flow aloft.

- Strong upward motion over the lee slopes is possible under some stability and speed conditions because of gravity wave transport.

- Mechanical forcing is important for transport over a barrier.

- Targeting from valley releases is poor for classes D and E which comprise 18% of the soundings released during the 1991 and 1994 field programs.

- Though properly targeted, the effectiveness of AgI can be handicapped by warm temperatures over the Plateau This was particularly true for class D which comprises 5% of the soundings.

- Class A appears to hold the best prospects of effective cloud seeding because of the successful targeting and characteristic cold temperatures. Thirteen percent of the soundings were class A.